Haleakala Research and Development, Inc.

Comprehensive Presentation and Reference of Plasma Antennas, Plasma FSS, Plasma Waveguides.

Dr. Ted Anderson, CEO Haleakala R&D, INC

Haleakala Research and Development, Inc.

Comprehensive Presentation and Reference

Commercial Prototype Smart Plasma Antenna, RFID Applications, High Powered Plasma Antennas, Low Thermal Noise and High Data Rates Plasma Antennas, Compact Low Frequency Electronically Steerable Plasma Antennas, InTop Solutions, Plasma Reflector Antennas, Nested Plasma Antennas, Stacked Plasma Antenna Arrays, Plasma Waveguides, Plasma FSS, IED Defeater and ADS Applications, Satellite Plasma Antennas, Lab Prototypes, Mathematical Models, Focusing

Dr. Ted Anderson, CEO
www.ionizedgasantennas.com
518-409-1010
tedanderson@haleakala-research.com

October 9, 2008

Table of Contents

Haleakala R&D, Inc News

- **We have an article which came out in Scientific American February 2008 issue on our plasma antenna technology.**

- **http://www.aps.org/meetings/unit/dpp/vpr2007/upload/anderson.pdf**

- **http://www.msnbc.msn.com/id/22113395/from/ET/**

- **http://sciencenow.sciencemag.org/cgi/content/full/2007/1114/1**

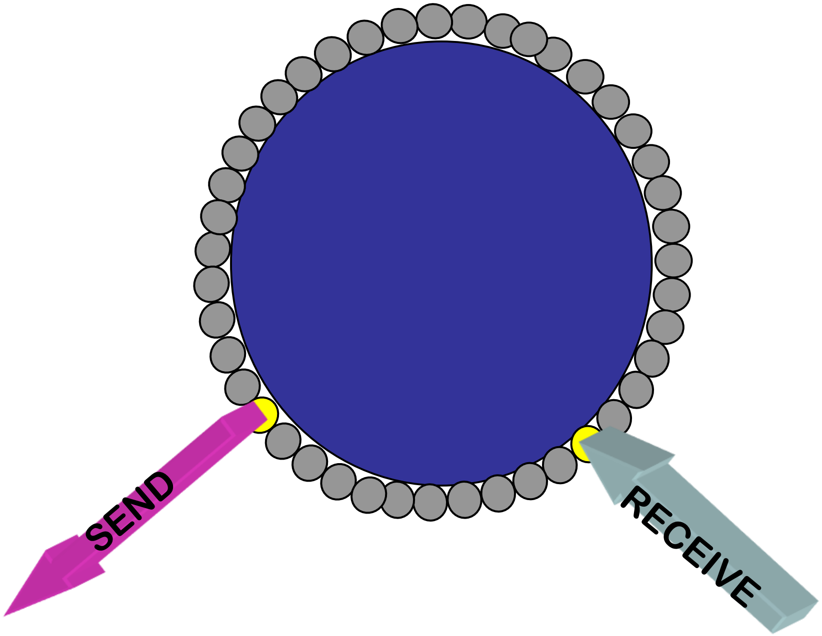
Haleakala R&D, Inc. Peer Reviewed Journal Articles Published

- **Alexeff, I , Anderson, T.*, Experimental and Theoretical Results with Plasma Antennas,* IEEE Transactions on Plasma Science, Vol. 34, No.2, April 2006 and Anderson, T., Alexeff, I.,**
- **Anderson, T*.,* Alexeff, I , *Plasma Frequency Selective Surfaces*, IEEE Transactions on Plasma Science, Vol. 35, no. 2, p. 407, April 2007**
- **Alexeff, I , Anderson, T*., Recent Results of Plasma Antennas, Physics of Plasmas*, 15, 057104(2008)**
- **We have two more journal articles being processed for publication on our smart plasma antenna windowing and another on the lower thermal noise in plasma antennas**

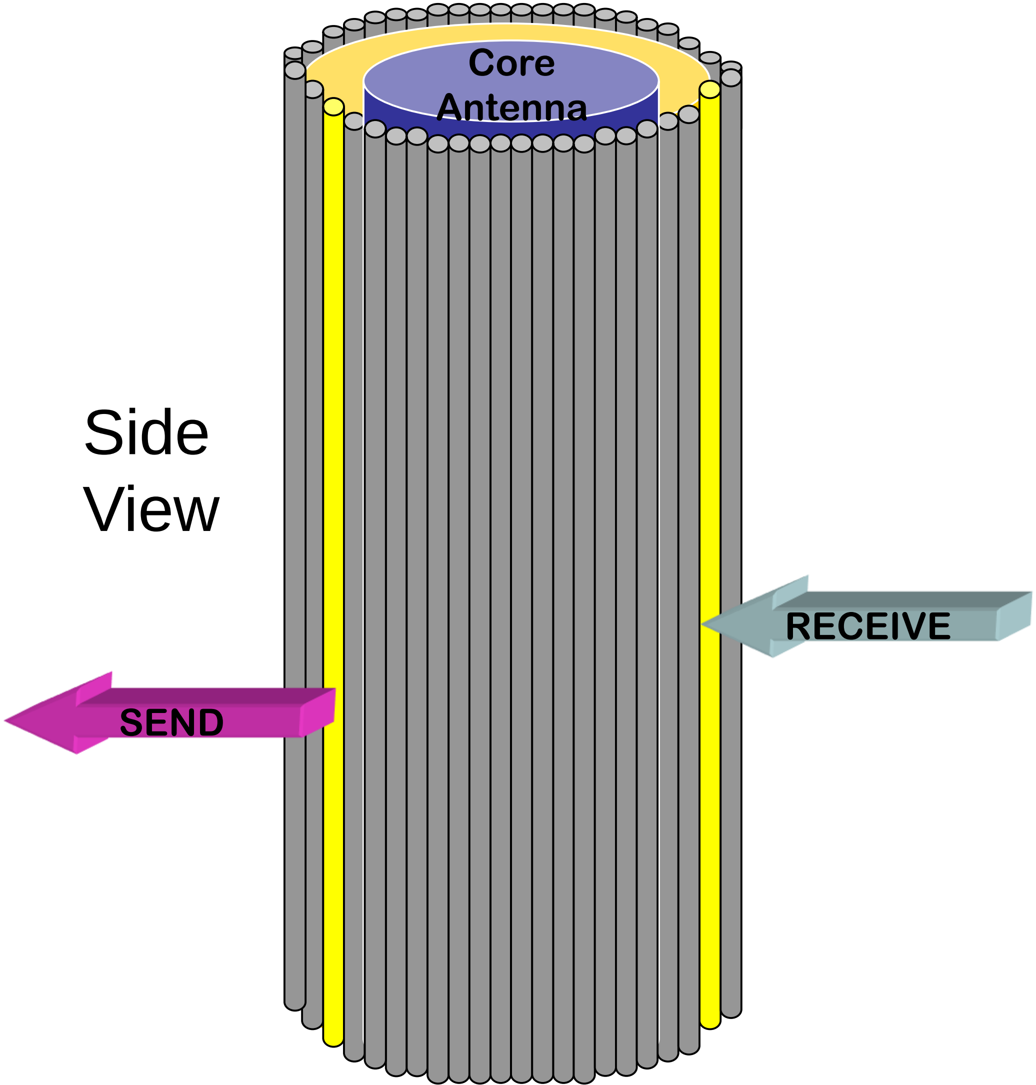
The Haleakala R&D, Inc. Commercial Smart Plasma Antenna Prototype

SMART PLASMA ANTENNA

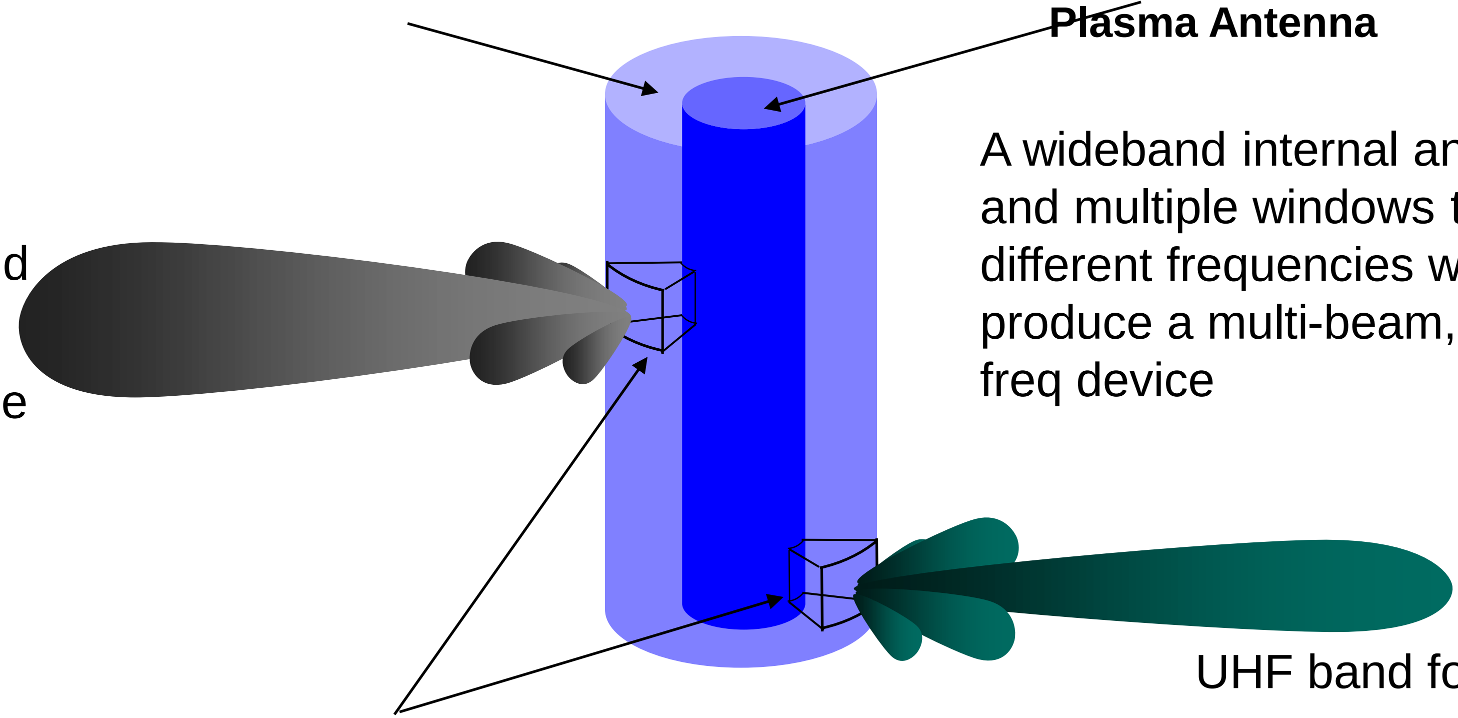
Top View



Side View



Tactical Capabilities Plasma Windowing Concept



External Plasma Blanket

Internal Omnidirectional metal or Plasma Antenna

A wideband internal antenna and multiple windows tuned to different frequencies would produce a multi-beam, multi-freq device

HF band for example

UHF band for example

Low Density Plasma Windows Opened for Transmit or Receive

Figure 7.9

Features of our Commercial Prototype

- It currently weights about 10 pounds.
  - Some weight (but not much) will be added when we make the base rugged and surround the tubes with SynFoam to protect the tubes.
  - Future iterations of the prototype can be made smaller.
  - But nevertheless it is much smaller and lighter than large phased array antennas, and the performance is in many ways better.
  - Even in the prototype stage, our prototype is relatively inexpensive for a steerable smart antenna. Manufacturing would significantly reduce the price.
- It can steer the antenna beam 360 degrees in milliseconds.
  - Our future prototypes will steer in microseconds using Fabry-Perot-Etalon Effects.

Features of our Commercial Prototype

- **It is intelligent and smart.**
  - **It can find and lock on to a transmitter.**
  - **In addition, one plasma window can lock on to a transmitter and a second plasma window can find a second transmitter.**
  - **It can reconfigure from single lobe, to multilobe, to no lobe configurations.**
- **It can run on a 12 volt car battery.**
- **It can be mounted on a tank, a humvee, a surface ship, a sub, etc. conveniently.**
  - **Other applications: last mile, Wi-Fi, base stations, etc.**
- **This commercial prototype will be packaged and made rugged by encasing it in SynFoam .**
  - **SynFoam is a lightweight, heat resistant, and very strong material.**
  - **SynFoam has an index of refraction of nearly one, making it invisible to RF waves.**

Figure 7.10

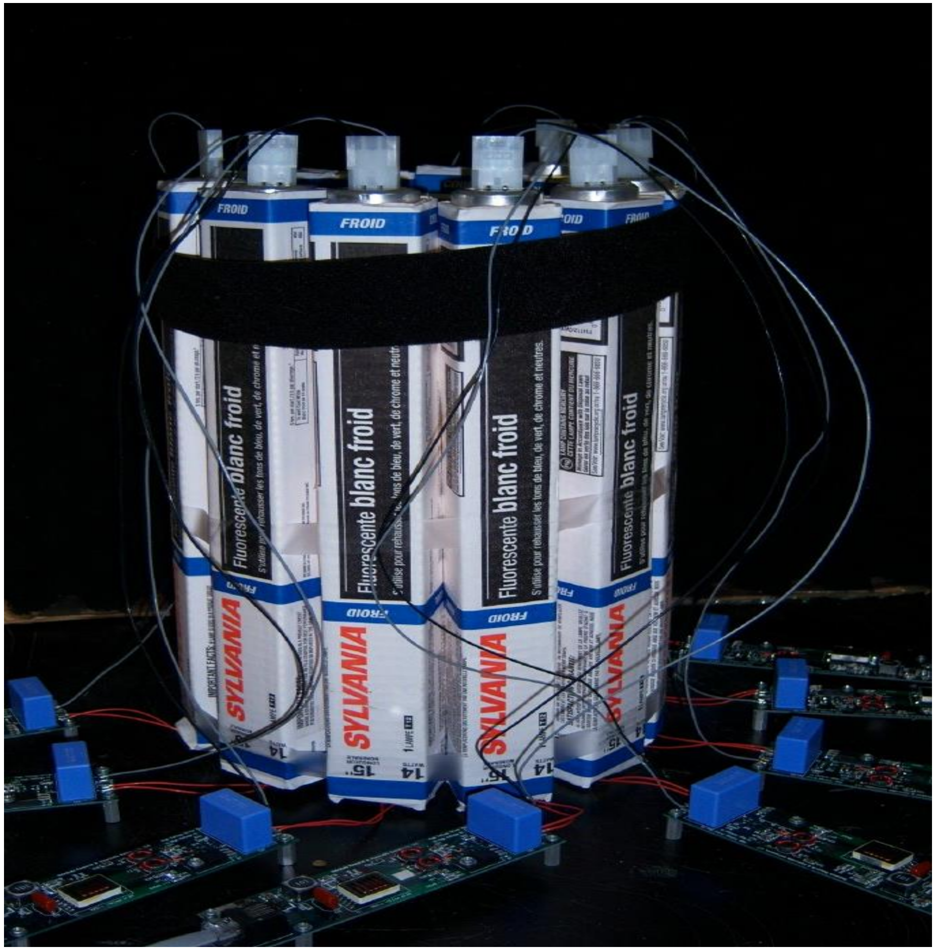


Figure 7.11

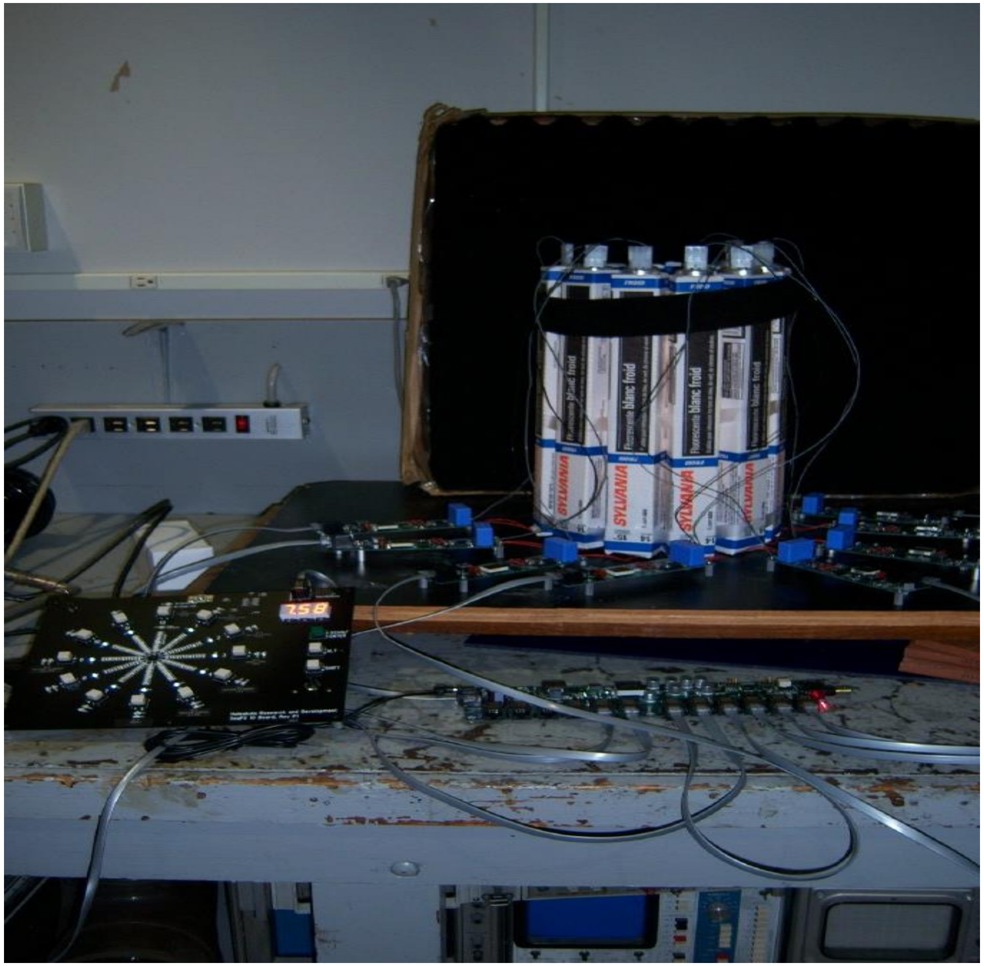
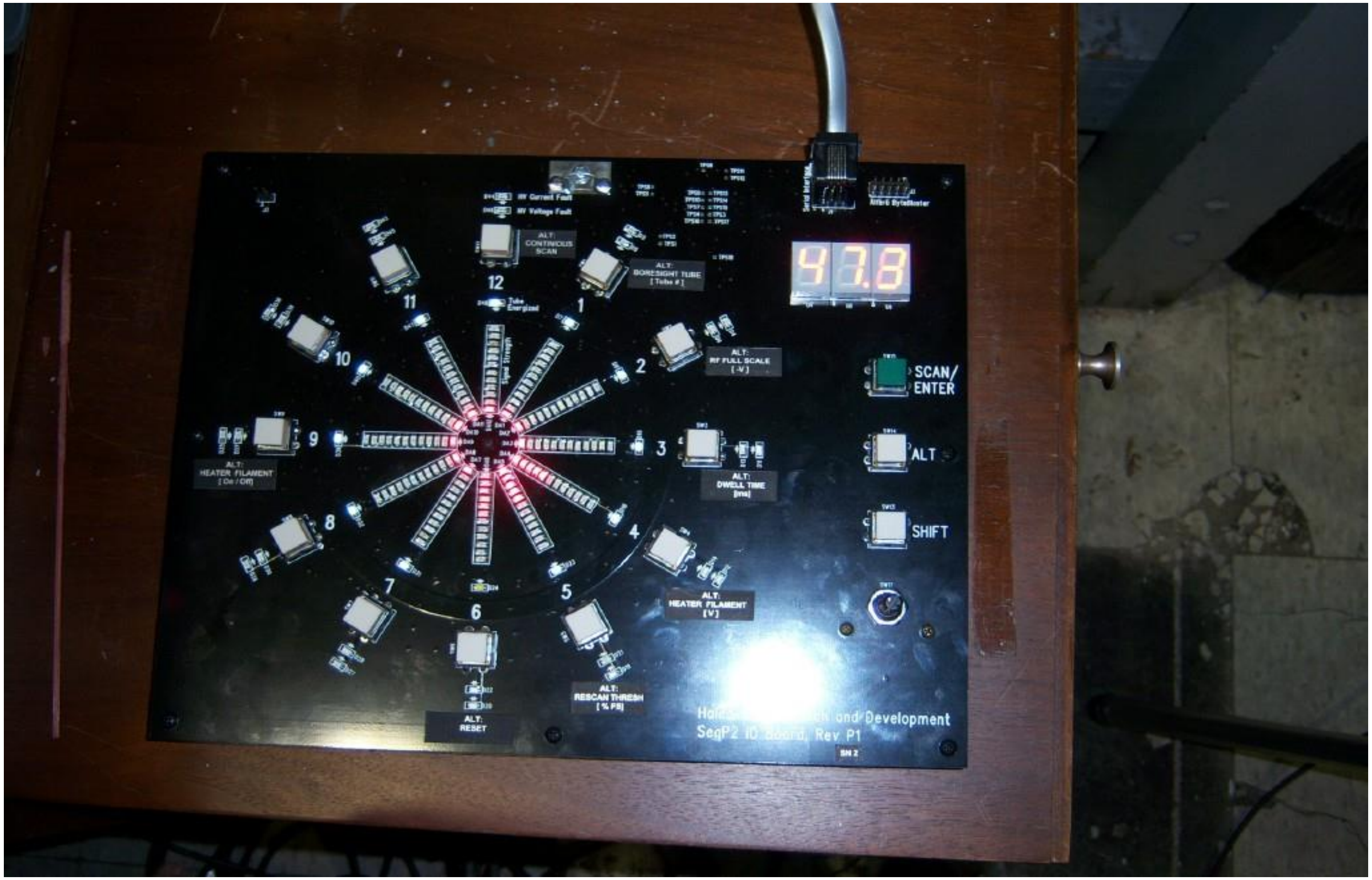


Figure 7.12.

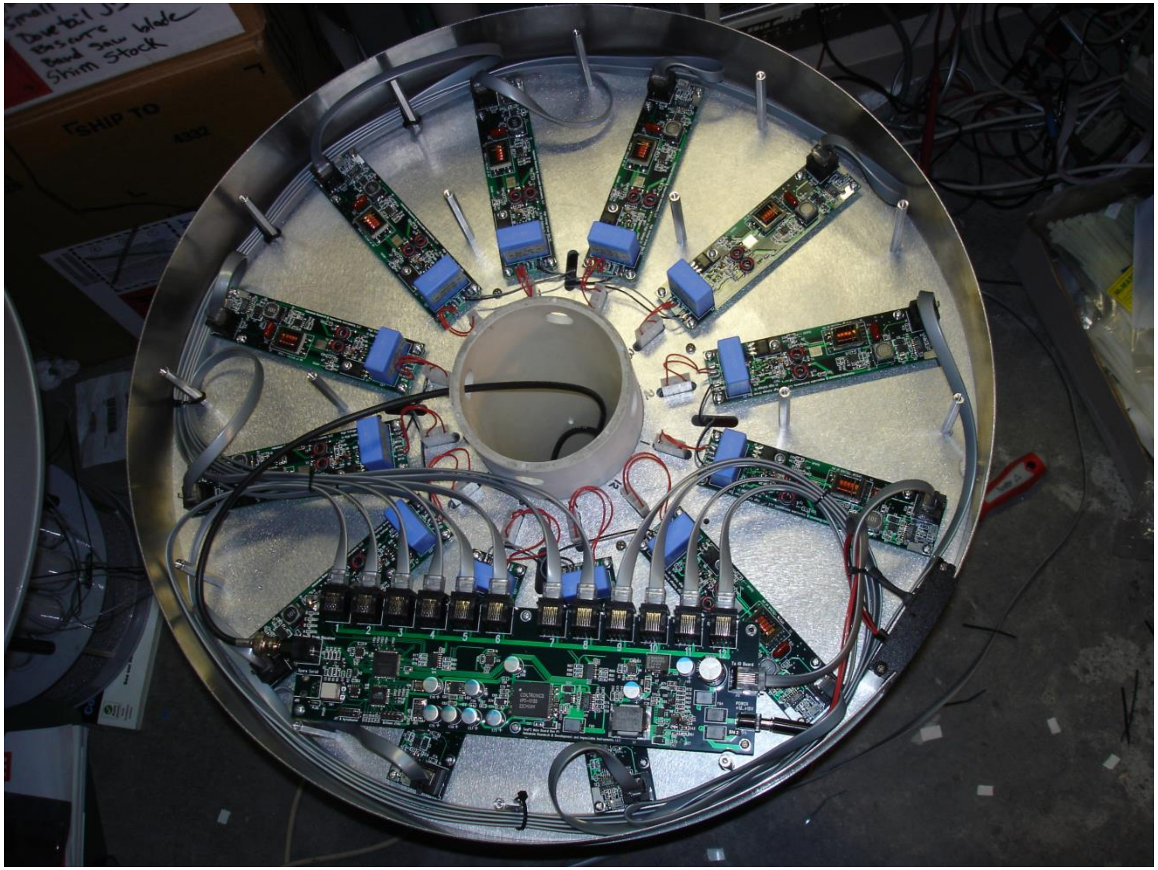

HV Current Fault
HV Voltage Fault
ALT: CONTINUOUS SCAN
ALT: BORESIGHT TUBE [Tube #]
Tube Energized
Signal Strength
12
1
2
3
4
5
6
7
8
9
10
11
ALT: RF FULL SCALE [-V]
ALT: DWELL TIME [ms]
ALT: HEATER FILAMENT [V]
ALT: RESCAN THRESH [% FS]
ALT: RESET
ALT: HEATER FILAMENT [On / Off]
Serial Interface
Altera ByteBlaster
45.1
SCAN/ ENTER
ALT
SHIFT
Haleakala Research and Development
SeqP2 IO Board, Rev P1
SN 2

Our Commercial Prototype

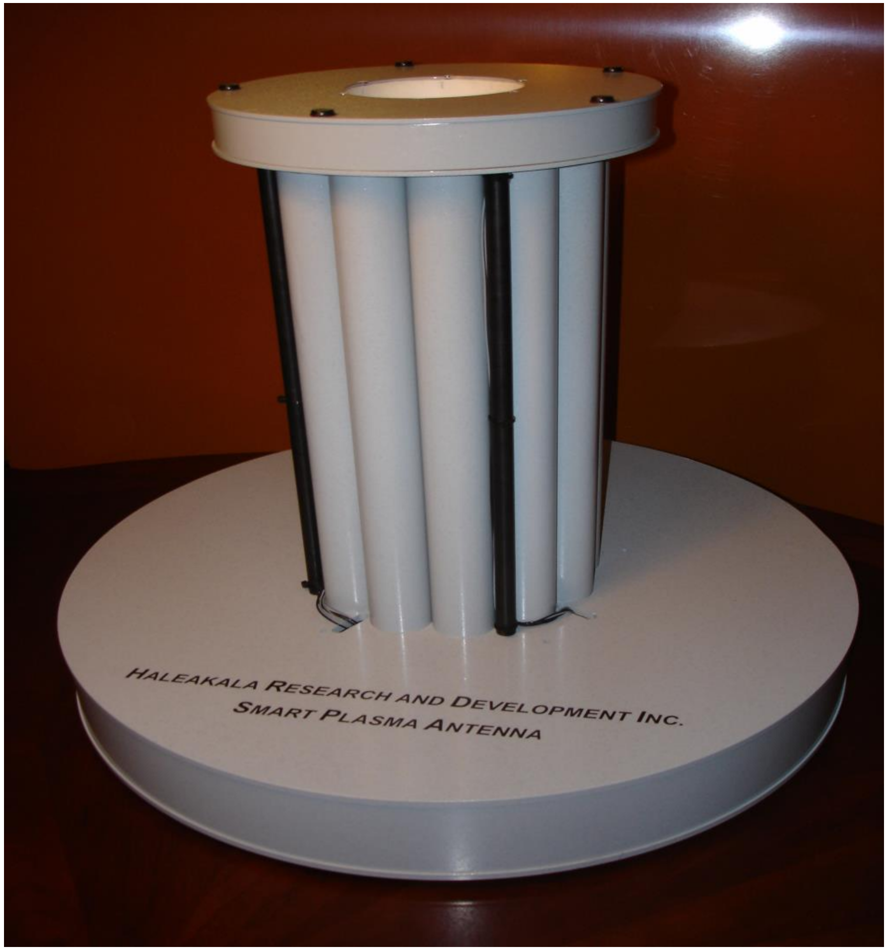
Open plasma window indicator. Orange color represents magnitude of power transmitted or received through an open plasma window.



Wiring for Ruggedized Smart Plasma Antenna

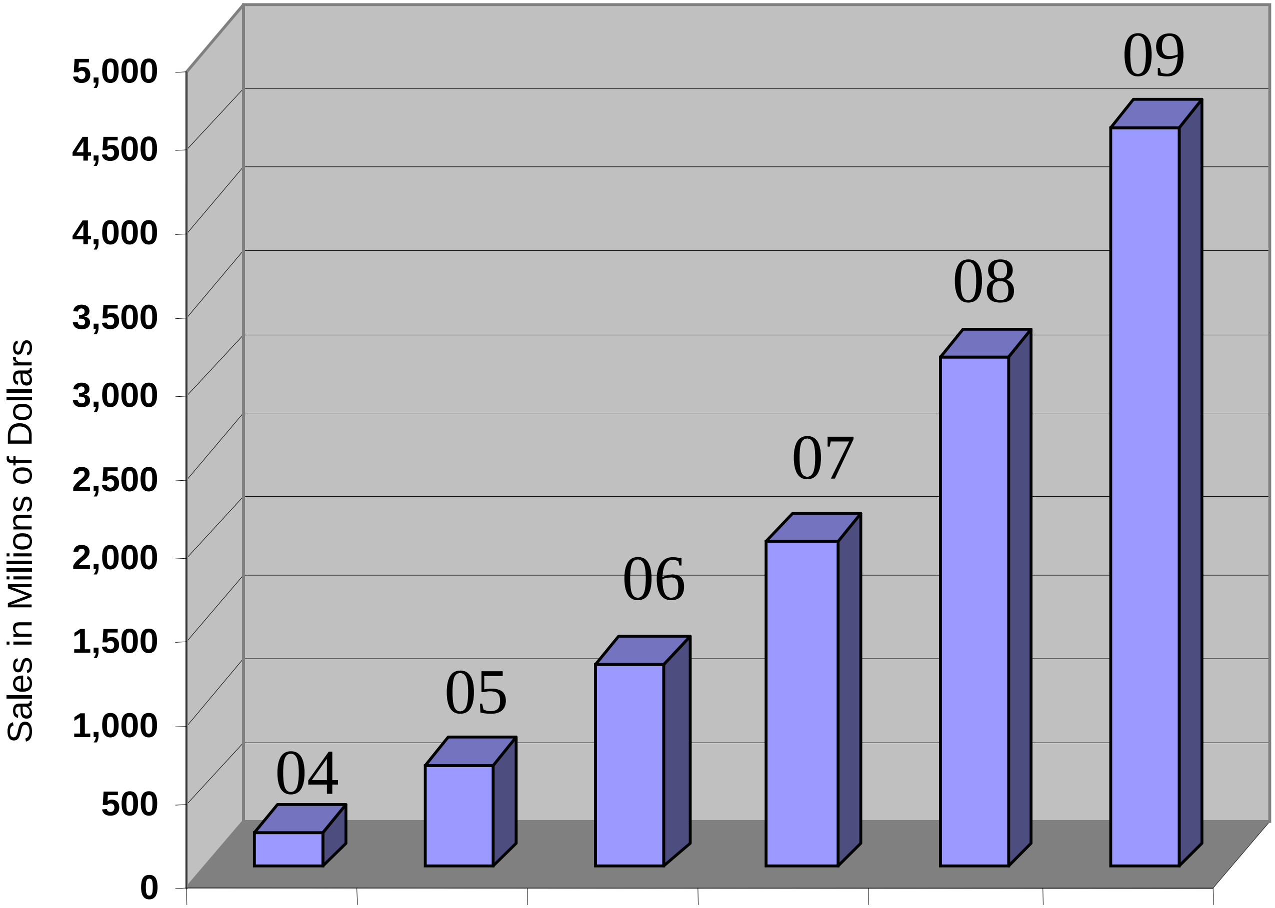


Ruggedized Smart Plasma Antenna



GROWTH OF SMART ANTENNAS

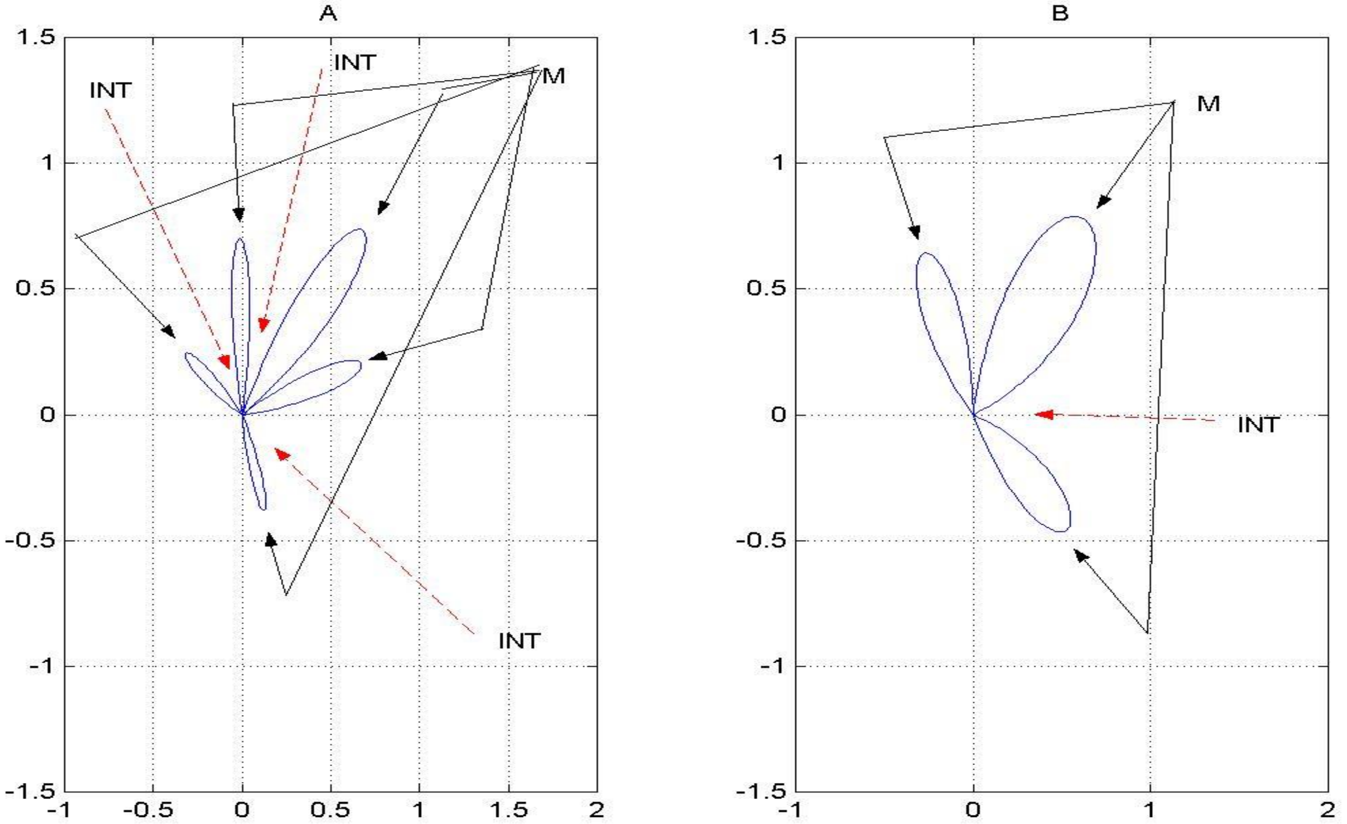
West Technology Research Solutions, LLC, "*Smart Antennas Market Report and Analysis*," 2005.



The smart antenna market is expected to grow from $229 Million in 2004 to around $4.5 Billion in 2009!

Antenna lobes for peak hour service with many interfering signals or many reflecting surfaces.

Antenna lobes for low demand period or few reflecting surfaces



A Meshed High-Speed Wireless Distribution Network Using our Smart Plasma Antennas

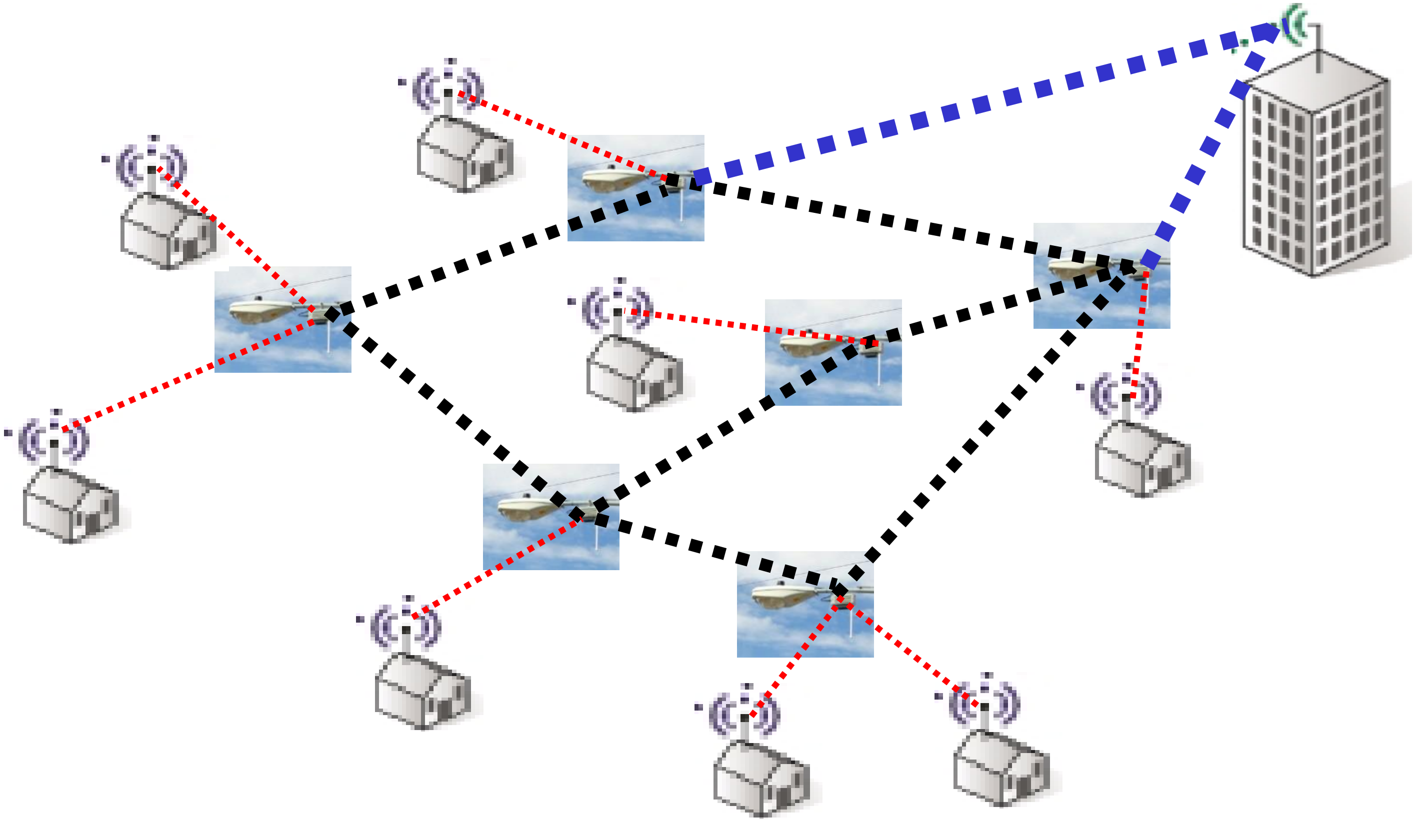


Figure 7.26

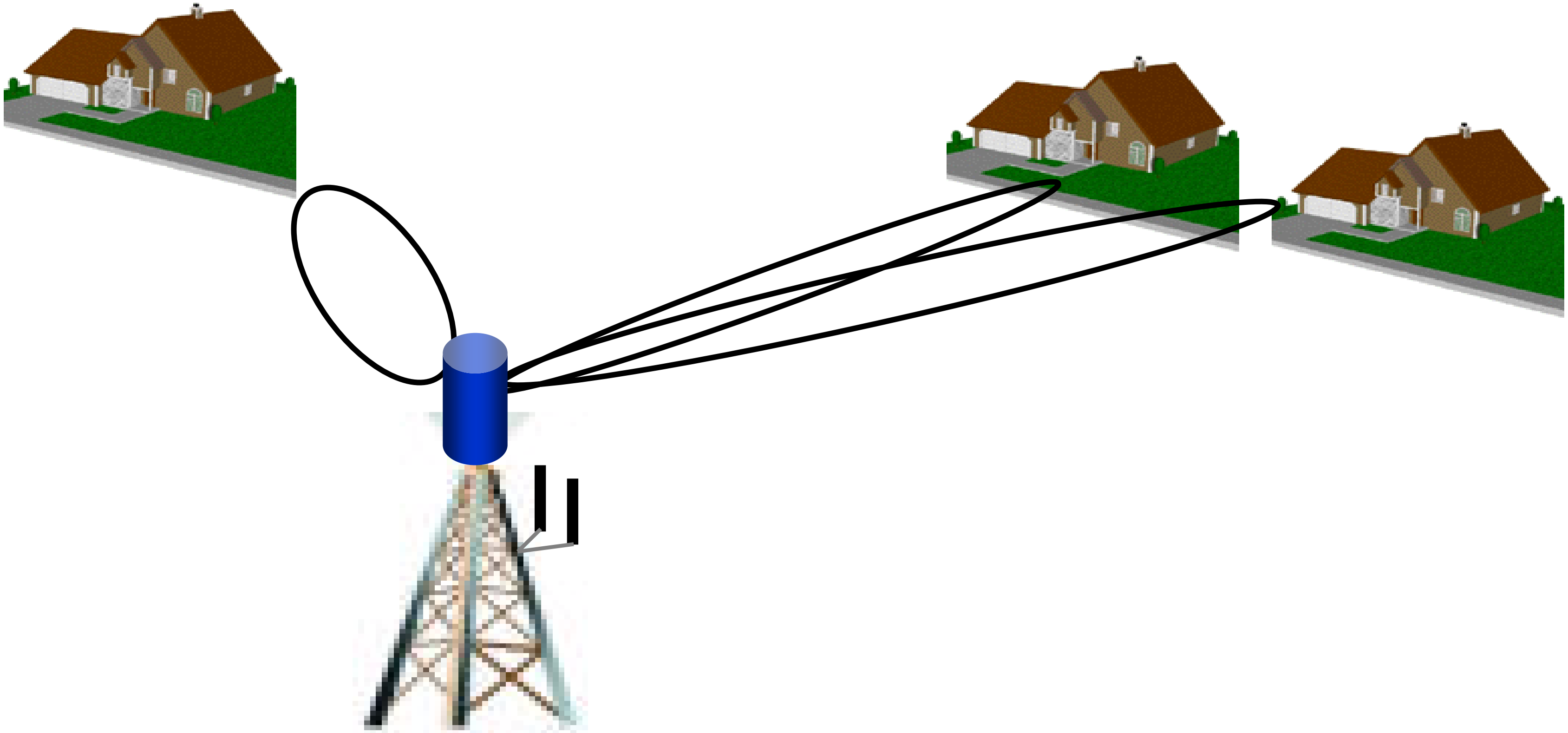
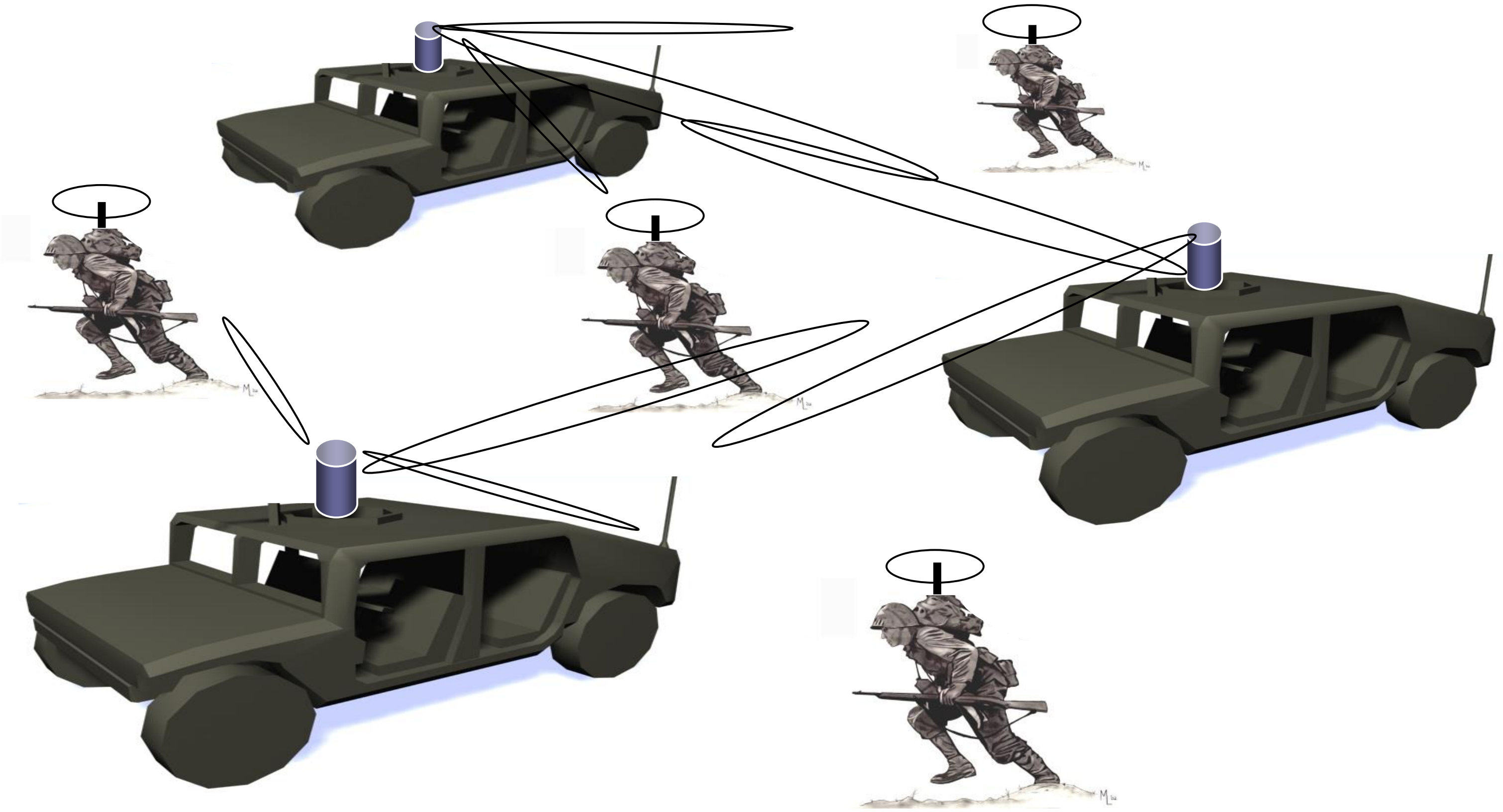


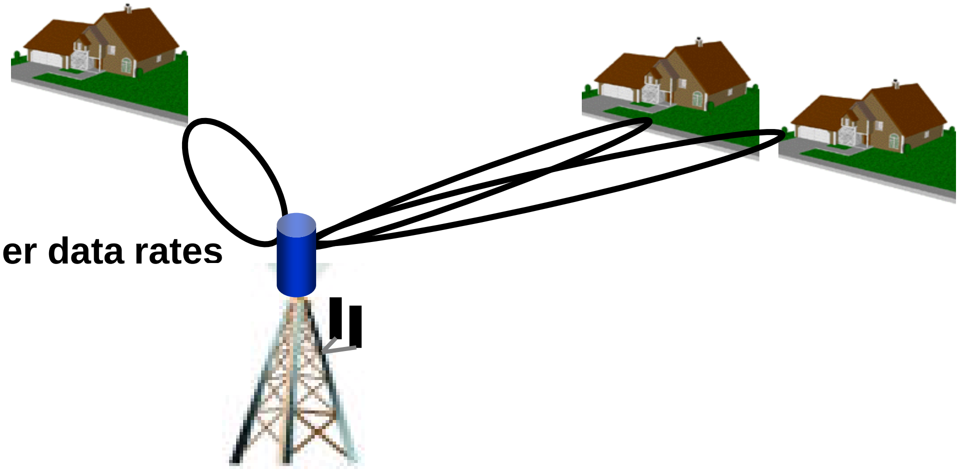
Figure 7.25



SERVING CRITICAL MARKET NEEDS

- **Can replaces conventional metal antennas, 1 for 1**
- **Can retrofit existing antennas**
- **Can improves data rates**
- **Interference-resistant technology**
- **Resists radar detection**
- **Can improves security**

TARGET MARKETS



- Military
  - IED defeater as a jammer
  - Radar
  - Satellite receiving antennas with higher data rates
  - Space base antennas
  - Surface ships, tanks, humvees
  - Aircraft
- RFID
- Emergency Services
- Cellular Phones
- Data Communications
- Home and small office computing
- Media and entertainment
- “Last Mile” applications (High bandwidth wireless for homes and small offices)

Conclusions on the Commercial Smart Plasma Antenna Prototype

- **This is an intelligent, high performance steerable antenna with:**
  - **Compact size**
  - **Light weight**
  - **Stealth and jam resistant**

- **Rugged packaging has been done**
- **We have manufacturing capability on our commercial prototype with:**
  - **Impeccable Instruments, Inc. (CEO, Jeff Peck) in the Knoxville, TN area.**
  - **Industrial Instruments, Inc. (CEO, Fred Dyer) in the Knoxville, TN area.**
- **Complete manufacturing can be done in USA.**

Conclusions on Our Commercial Prototype and Summary of Applications

- Commercial prototype could be used as a HDTV antenna especially after
  - Feb, 17, 2009 date when all through the air TV transmissions will switch to digital.
    - In the United States by no later than February 17, 2009,
      - all U.S. television broadcasts will be exclusively digital,
      - under the Digital Television and Public Safety Act of 2005.
  - the big advantage is that it is thermally more quite than a metal antenna and it is relatively small and compact compared to any other smart antennas.

  - it can be reconfigured from omnidirectional to very directional and rapidly(right now in milliseconds) and find TV transmitters.
- Even before Feb 2009, it would be great in areas where people cannot get cable.
- Customer buys one smart plasma antenna.
  - no monthly cable fees
  - portable

Our SynFoam Hosuing for the Plasma Tubes.

House the plasma tubes in strong and lightweight synthetic foam called Synfoam which can be molded into any shape we want. UDC SynFoam is a high performance syntactic foam combining high strength and low density with very low moisture absorption. SynFoam's syntactic foam products feature a density of less than 20 pcf and a compressive strength greater than 2000 psi. The index of diffraction of the Synfoam is nearly one so it is invisible to rf signals. See website: http://www.udccorp.com/products/synfoamsyntacticfoam.html.

Synfoam Housing for our Plasma Tubes. We have cushioning foam to put around the tubes in this encapsulation. We can mold Synfoam into any shape we want. We will make custom made rugged tubes as well.

Gain and Increasing Gain of our Smart Plasma Antenna

Current gain of our smart plasma antenna:

- **In our smart plasma antenna with two tubes off and at 2.5 GHz, the gain is 14.3 dB.**

Methods we can use to increase the gain of our current smart plasma antenna are:

- **Place a higher gain omnidirectional antenna than a half wave dipole in the center.**
- **Place a ring of interior plasma antennas inside the smart plasma antenna at one half radius and not in the center.**
- **Increase the frequency.**
- **Open one plasma tube (window) at a higher frequency.**
- **Increase the radius of our smart plasma antenna. More tubes will be involved.**
- **Make custom made plasma tubes with smaller radii.**

Gain and Increasing Gain of our Smart Plasma Antenna

- Use plasma lenses by varying the plasma density from one tube to the next to focus the antenna beam.
  - **We have developed convergent plasma lenses in the lab by having two or more concentric rings of plasma tubes instead of the current one ring.**
  - **The plasma tubes along the direction of the antenna beam are off.**
  - **In the first plasma ring layer the center plasma tube is off and the two on the side are on.**
  - **In the second plasma ring layer the center plasma tube is off and two on the side are on**
  - **In the third plasma ring layer the center tube is off and three on each side are on.**
- Another way to make a plasma convergent lens in our smart plasma antenna is:
  - In the outer ring of tubes the center tube is off and the two surrounding tubes are on but can pass EM waves.

Gain and Increasing Gain of our Smart Plasma Antenna

- Continue to take advantage of the soft surface effects of the plasma to lower the side lobes.

- Continue to take advantage of the lower thermal noise in the plasma antenna to increase the data rates.

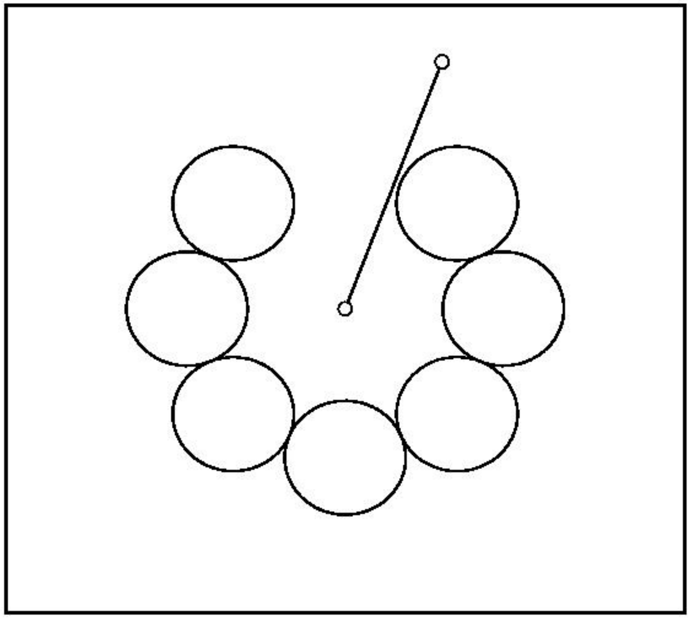
- By doing some or all of the above, we can probably increase the gain to considerably high levels.

Advantages on Plasma Windowing

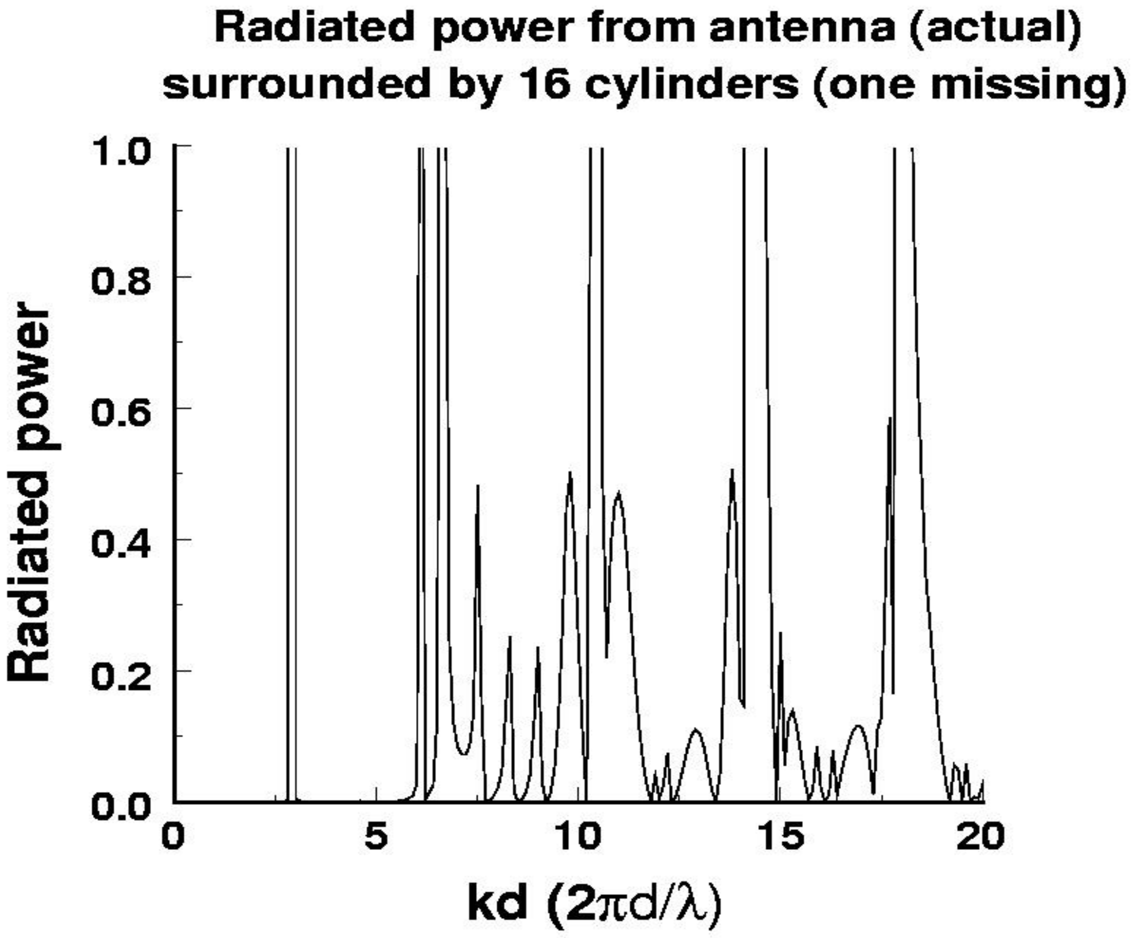
The advantages of the plasma blanket windowing design are:

1. Less space than an array
2. A re-configurable directivity and beamwidth
3. The beamwidth can vary from an omni-directional radiation pattern with all the plasma windows open or a very directional radiation pattern when only one plasma window is open.
4. Opening and closing of plasma windows in sequence leads to a steerable antenna beam
5. Plasma windowing theory and mathematical derivations are on the next page.

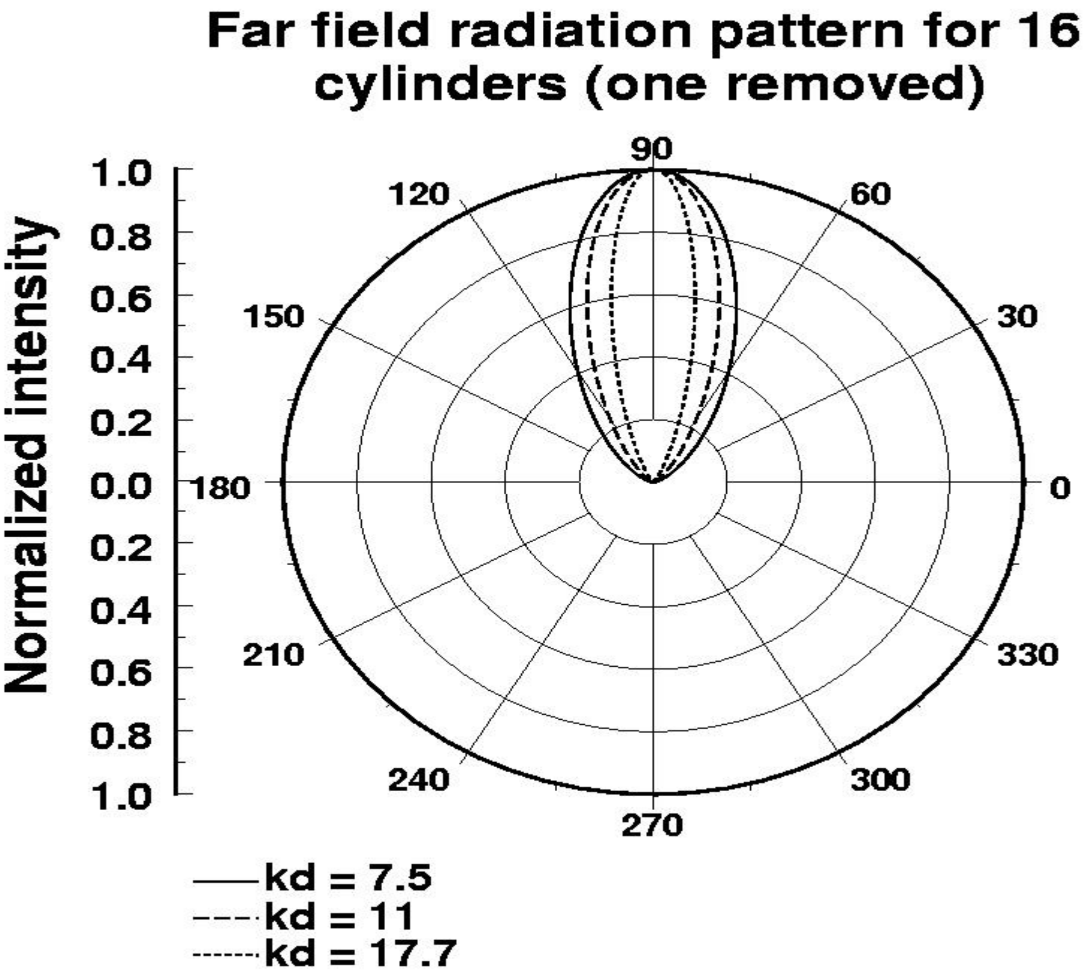
Geometry of eight touching cylinders (one removed) with source and observation point



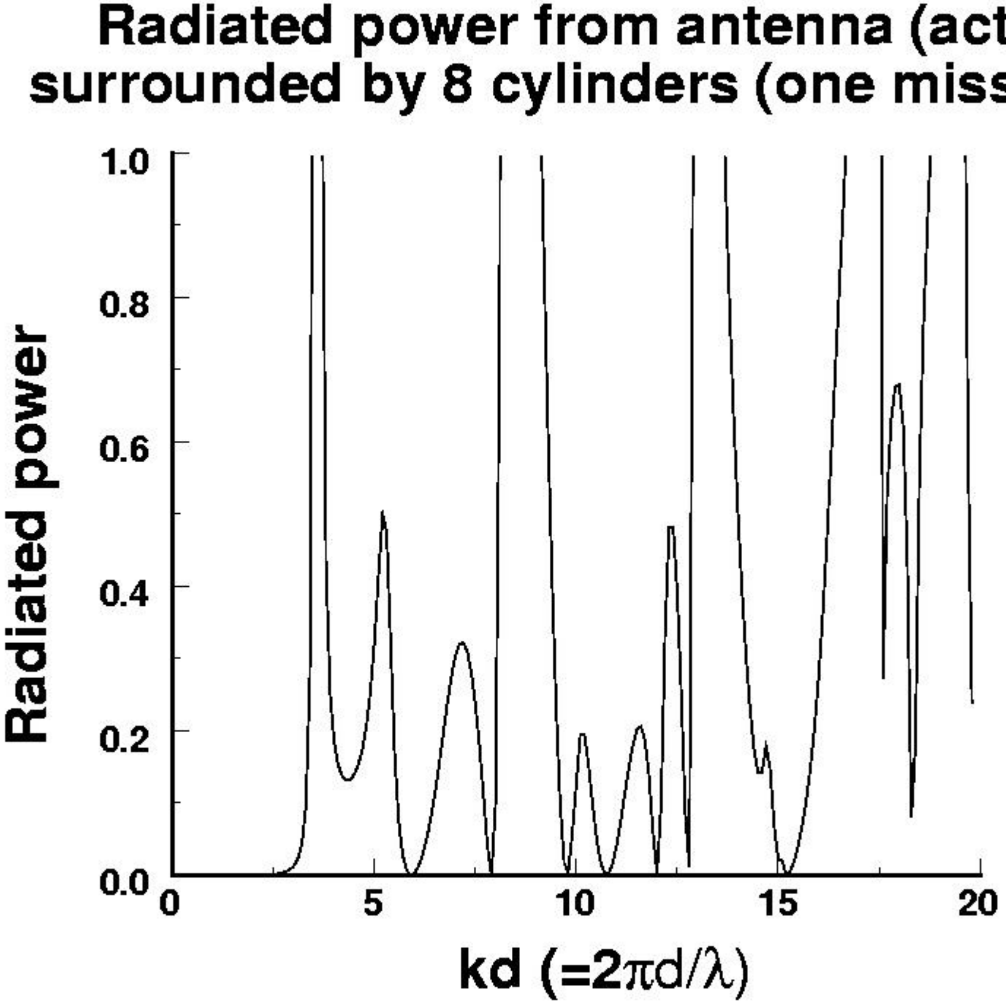
Plasma windowing theory and mathematical derivations. **Plasma window antenna consisting of seven touching cylinders. The cylinders are arranged with their centers lying on a common circle of a given radius and their radii are chosen so that they are touching. By adding one more cylinder, a complete plasma shield is formed. The source and an arbitrary observation point are also illustrated.**



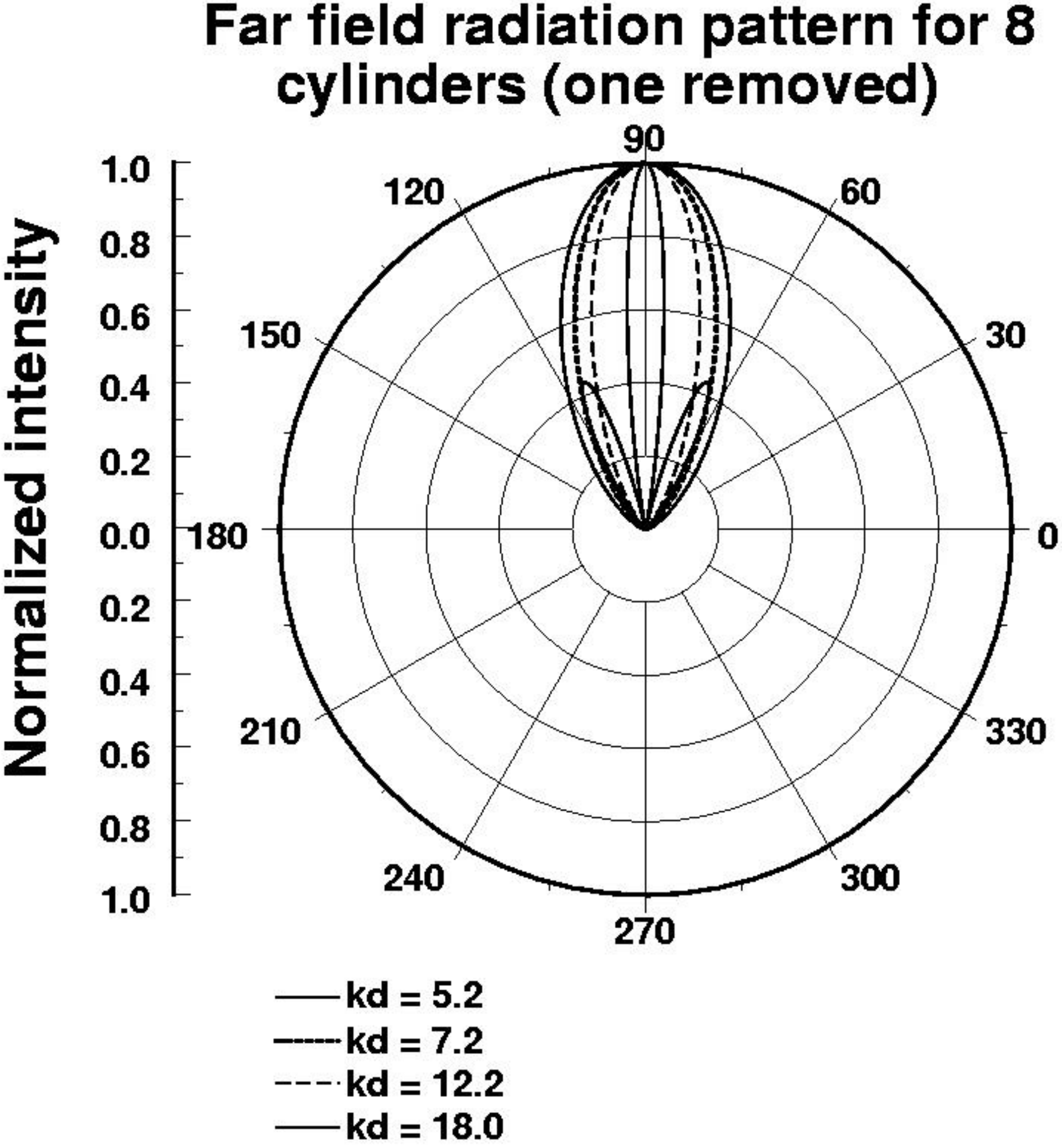
Plot of the physical solutions to the radiation from the 15-cylinder plasma window antenna.



Far-field radiation patters for the 15-cylinder plasma antenna.

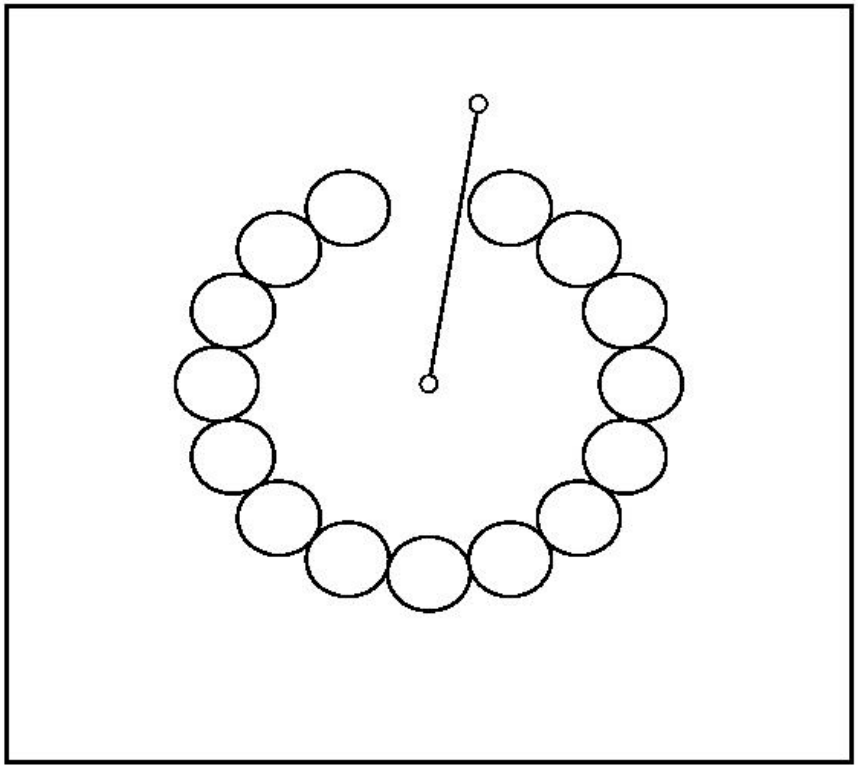


Radiated power for the physical solutions. This plot is the same data as plotted in but the scale is limited only the physically allowed values between zero and one.



Far-field radiation patterns for various solutions.

Geometry of sixteen touching cylinders (one removed) with source and observation point



Plasma window consisting of 15 touching cylinders.

IED Defeater Applications

IED Defeater Applications

- Our smart plasma antenna can solve problems that current IED defeaters have
  - We can find and lock onto transmitters
  - We can jam these transmitters with our high powered plasma antennas
  - We can create a reconfigurable notch filter to transmit and receive communication signals while jamming takes place
    - This is a major problem with metal antenna jammers that we can solve using our smart plasma antenna.

IED Defeater Applications

- **Our smart plasma antenna design can create a reconfigurable notch filter for communications while our smart plasma antenna locks onto and jams transmitters used to set off IEDs**
  - **Plasma antennas have a high frequency cut-off that is proportional to the square root of the plasma density.**
  - **For frequencies above this, the plasma is transparent to the microwave radiation.**
  - **Below this frequency, the plasma acts as a metal, and transmits and receives microwave radiation.**

IED Defeater Applications

The Concept of Cut-off and Filtering using Plasma Antennas

- The plasma frequency is proportional to the density of unbound electrons in the plasma or the amount of ionization in the plasma. The plasma frequency sometimes referred to a cutoff frequency is defined as:

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{me}}$$

where n_e is the density of unbound electrons, e is the charge on the

electron, and me is the mass of an electron

- If the incident EM frequency on the plasma is greater than the plasma frequency

$$\omega > \omega_p$$

the EM radiation passes through the plasma and the plasma is transparent.

IED Defeater Applications

The Concept of Cut-off and Filtering using Plasma Antennas

When

$$\omega < \omega_p$$

the plasma acts as a metal, and transmits and receives microwave radiation.

Note, the incident frequency in the next slide is given as:

$$\nu = \omega / 2\pi$$

IED Defeater Applications

- **We can surround our plasma antenna by a ring of plasma tubes that act as a reflector.**
  - **If the plasma frequency in this ring is lower than that of the received signal, the signal passes on to the plasma antenna.**
  - **However, only those frequencies that are lower than the plasma frequency in the plasma antenna will be received.**
  - **All higher frequencies pass through both the ring of plasma tubes and the plasma antenna without interacting.**
  - **Mathematically, we can state that**

$$\upsilon_{p\,ring} \prec \upsilon_{signal} \prec \upsilon_{p\,antenna}$$

  - **where the received signal is between the plasma frequency of the ring and the plasma frequency of the enclosed antenna.**
  - **Since both the plasma frequency of the ring and the plasma frequency of the antenna can be reconfigured in milliseconds, the receiving notch can be moved about as desired**

ADS Applications

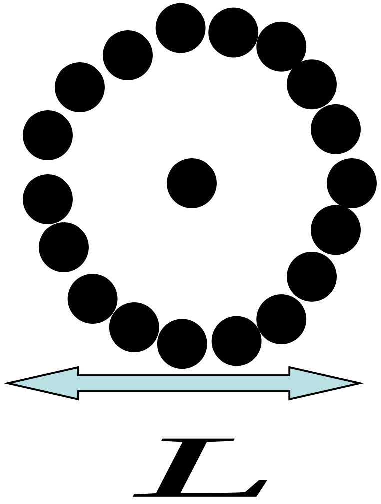
ADS frequency operational capabilities

- The cut –off for microwaves goes as the square root of the electron plasma density.
- Using publishes gas pressure in commercial plasma tubes, and assuming complete ionization,
  - we calculate that the tubes will interact with microwaves up to a frequency of 3 THz.
  - Reference: COBINE, JAMRD DILLON **Gaseous Conductors Theory and Engineering Applications** McGraw-Hill Book Company. 1941
- Custom made plasma tubes can be made to operate as antennas at even higher frequencies.

Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

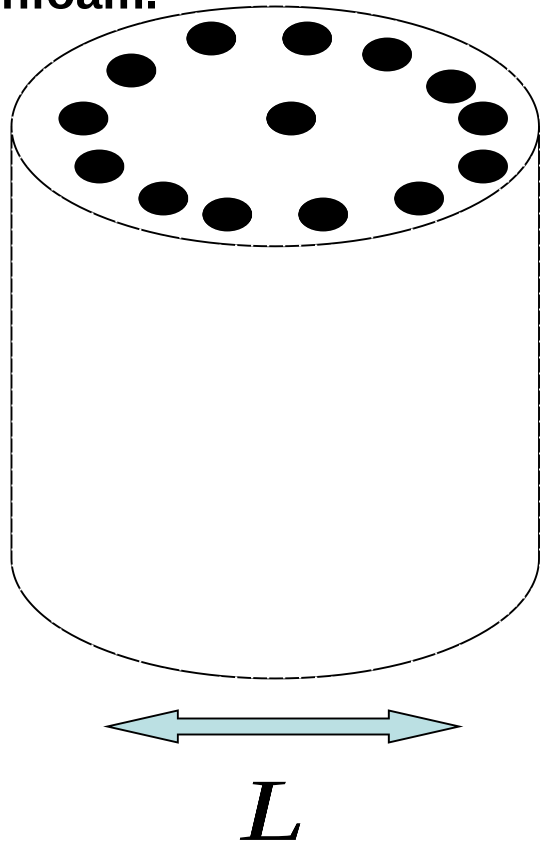
Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

Ring of plasma antennas (now all off) of diameter L with a plasma antenna in the center:



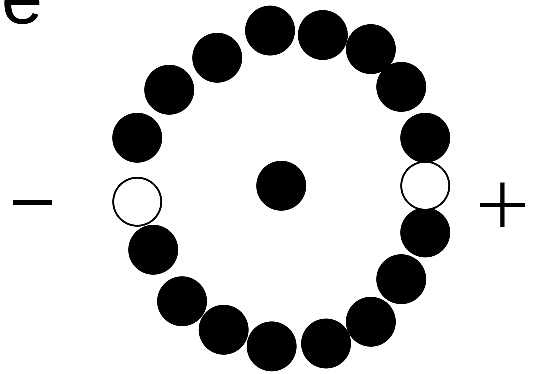
Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

All plasma antennas placed in cylindrical mold of synfoam.

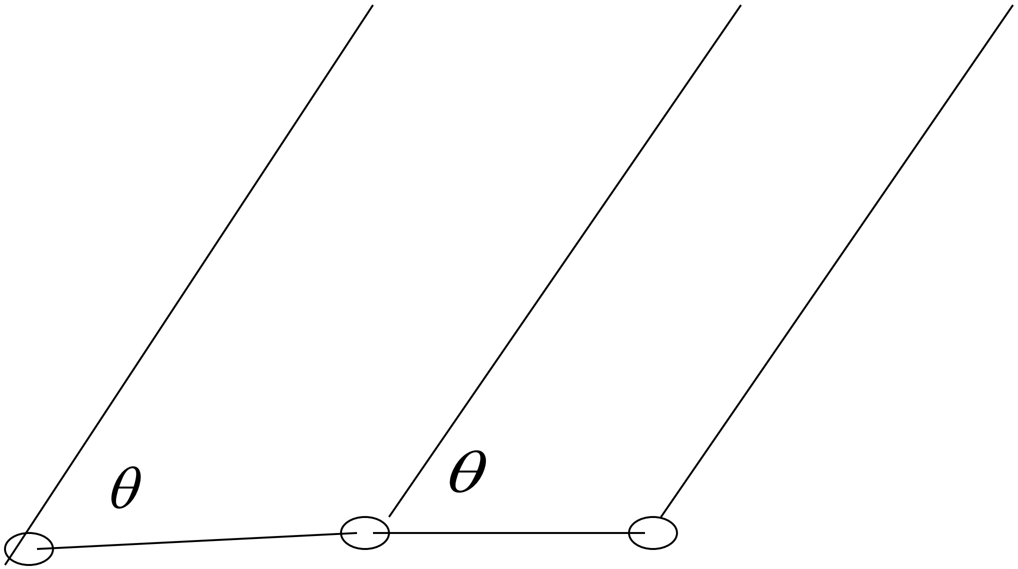


Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

Two plasma antennas turned on at opposite sides out of phase



Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle



$$E = E_0 \cos k(x - \frac{L}{2}\cos\theta) - E_0 \cos k(x + \frac{L}{2}\cos\theta)$$

Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

- Assume that

$$\frac{kL}{2} < 1$$

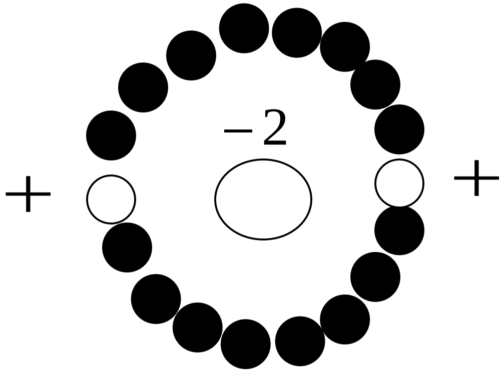
  - The wavelength is large compared to the plasma antenna system of diameter L.
  - The result is:

$$E = E_0 (\sin kx) kL \cos\theta$$

- This is a two lobe radiation pattern, but directional.
- The two lobes of the plasma antenna are oscillating out of phase.

Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

- Three plasma antennas in a straight line
  - Two outside antennas radiating in phase
  - The center antenna radiating out of phase but with double the signal strength



Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

- The far field E field with the two plasma antennas radiating in phase and a plasma antenna with double the signal strength and oscillating out of phase is:

$$E = E_0[\cos k(x - \frac{L}{2}\cos\theta) - 2\cos kx + \cos k(x + \frac{L}{2}\cos\theta)]$$

Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

- Assume that

$$\frac{kL}{2} < 1$$

  - The wavelength is large compared to the antenna diameter L.
  - The result is:

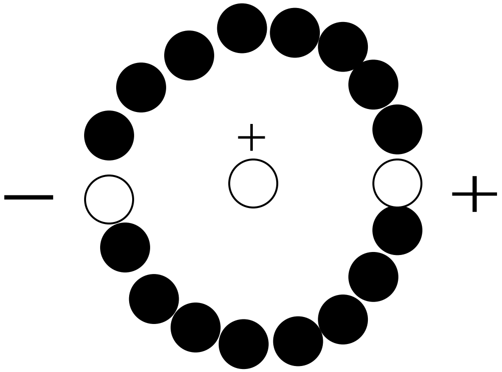
$$E = E_0[-\cos kx[(\frac{kL}{2}\cos\theta)^2]$$

- This is a two lobe plasma antenna with both lobes in phase

Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

- Three plasma antennas in a straight line.
  - The two outside

    plasma antennas are radiating out of phase (a dipole).
  - The center antenna is oscillating in phase with one of the antennas in this case the one on the right
  - (a monopole).



Low Frequency Directional and Electronically Steerable Plasma Antenna that can fit on a Vehicle

- **The resulting radiation E field from the plasma dipole and monopole plasma antennas is:**

$$E = E_0\left[1+\cos\theta\right]\sin kx$$

- **This is a one lobe directional radiation pattern which is un-attenuated in wavelength.**

Lower Thermal Noise and Higher Data Rate Plasma Antennas than Corresponding Metal Antennas

Higher Signal to Noise Ratio and Higher Data Rate Plasma Antennas over Corresponding Metal Antennas.

Misconceptions we have encountered on plasma antennas

- Plasma antennas, reflectors, frequency selective surfaces have more thermal noise than their corresponding metal counterparts.
  - *This is not true.*

- Plasma antennas have an infrared (IR) signature greater than metal antennas.
  - *This is not true.*

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

- **The Nyquest Theorem [see reference below] states that the thermal noise generated in a resistor is:**
- **Equation [1]** $$F(T,R) = \frac{2}{\pi} kTR$$

K is Boltzmann's constant, T is the absolute temperature in degrees K

- **The misconception is:**
  - **Since T is higher in a plasma antenna "obviously" the noise in the plasma antenna is higher.**
- **This expression for the Nyquest Theorem is an approximation [see reference below].**

Reference: * Fundamentals of Statistical and Thermal Physics, F. Reif, McGraw-Hill, 1965, Section 15. 16, pp 587-589.

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

- Rigorous derivation of thermal noise shows that the approximate expression of the Nyquest Theorem becomes:

- Equation [2]

$$H(T,R,\omega,\nu)=\frac{2kTR}{\pi}\left(\frac{1}{1+\frac{\omega^2}{\nu^2}}\right)$$

Where ν is the electron-atom collision frequency and

$$f=\frac{\omega}{2\pi}$$

is the operating antenna frequency

- Derived by Dr. Ted Anderson in 1997, but never published
- Checked and derived independently by Professor Igor Alexeff in November 2007.

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

In the limit of very large collision frequency ν compared to the antenna operating frequency characteristic of a metal antenna: $\nu >> \omega$,

equation [2] reduces to equation [1] characteristic of thermal noise in a metal:

$$H(T,R,\omega,\nu)=\frac{2kTR}{\pi}\left(\frac{1}{1+\frac{\omega^2}{\nu^2}}\right)\Rightarrow\frac{2kTR}{\pi}$$

$$\nu >> \omega$$

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

Numerical Example

- **Let ν be 1 GHz, typical of fluorescent lamp electron–atom collision frequency.**
- **R(metal) = 8 Ohms/meter (at 10 GHz , the metal skin depth is small)**
- **R (plasma) = 26 Ohms/meter (experimental observation)**
- **T (metal) = 300 degrees Kelvin**
- **T(plasma) = 10 thousand degrees Kelvin (operating fluorescent lamp)**
- **f (operating antenna frequency) = 10 GHz**

Using these numbers, we see that thermal noise of the metal antenna is 38 times higher than for the corresponding plasma antenna.

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

- The thermal noise of a plasma antenna decreases compared to a metal antenna as the frequency increases because:
  - The thermal noise in a metal antenna is higher at higher operating frequencies because of the thin skin depth and corresponding higher electrical resistance.
  - The thermal noise of the plasma antenna decreases as the operating frequency increases as seen in the power spectral density of thermal noise for the plasma antenna:

$$H(T,R,\omega,\nu)=\frac{2kTR}{\pi}\left(\frac{1}{1+\frac{\omega^2}{\nu^2}}\right)$$

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

- **Other factors which further lower thermal noise in a plasma antenna:**
  - **Ramsauer -Townsend Effect is an effect in which the cross section of electron –atom scattering is minimal.**
  - **This effect is energy dependent and our plasma antennas operate in the energy region of the Ramsauer-Townsend Effect.**
  - **The Ramsauer – Townsend Effect means that the collision frequency ν is small and is minimal**
  - **This means even less noise thermal noise in the plasma antenna as equation [2] becomes smaller.**
- **Operating the plasma antenna in the afterglow state may further reduce thermal noise**

Thermal Noise in A Plasma Antenna Compared To a Metal Antenna

- With the Ramsauer- Townsend Effect and operation in the afterglow state will broaden the frequency range in which plasma antennas have less thermal noise than metal antennas.
- Thermal noise in a plasma antenna can further be reduced by reducing plasma pressure, plasma temperature, and plasma resistance.
- Thermal noise , like other properties of plasma antennas or devices, is reconfigurable

Reducing Thermal Noise Further in a Plasma Antenna by Reducing Electron Temperature

- Igor Alexeff found a way of varying electron temperature. The hot electrons are confined in a positive potential well.
- By using a hot, electron emitting filament, we were able to replace the hot electrons with cold ones.
- The temperature change was verified by observing the velocity change of ion-acoustic waves.

Conclusions on Plasma Antenna Thermal Noise

- **Less thermal noise in a plasma antenna than in a corresponding metal antenna means:**
    - A higher signal to noise ratio in the plasma antenna than in the corresponding metal antenna
    - A higher effective aperture in the plasma antenna than in the corresponding metal antenna
    - Higher antenna sensitivity of the plasma antenna than in the corresponding metal antenna
    - Higher data rates
- **In addition to plasma antennas, the low thermal noise results and concepts apply to plasma antenna arrays, plasma frequency selective surfaces, nested plasma antennas, stacked plasma antenna arrays, plasma waveguides, plasma coaxial cables, plasma screens, etc.**

Infrared Signature of Plasma Antennas

The effective noise temperature formula commonly used in antenna texts is not applicable to a plasma antenna.

- **Plasma antennas are not blackbody radiators.**

Glass traps IR radiation, i.e. Greenhouse effect in cars with closed windows.

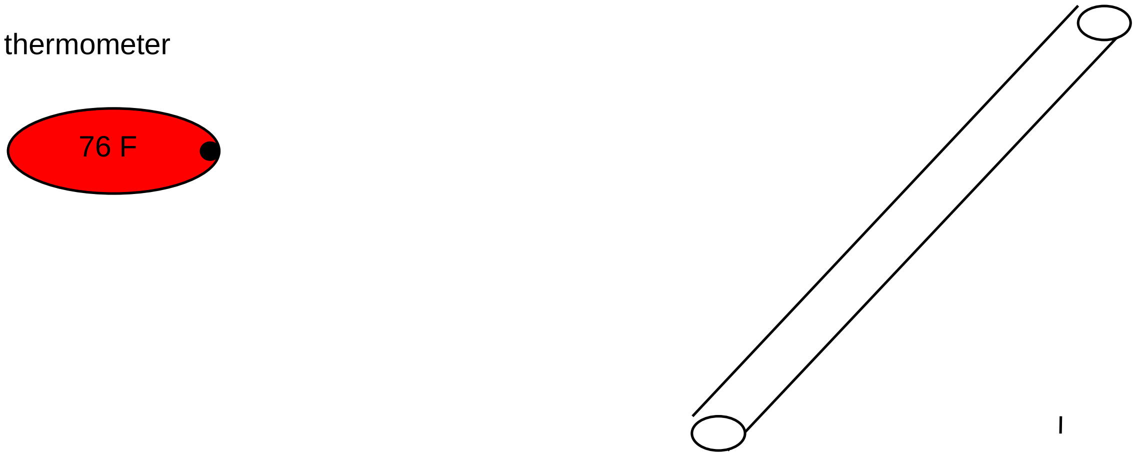
Plasmas do not always radiate as a blackbody radiator.

- **The magnetically confined plasma used for the possibility of generating thermonuclear fusion is at a temperature of 10exp (8) degrees and is not radiating all its energy away. It is not a blackbody radiator.**
- **The hot solar corona does not radiate as a blackbody although its temperature is 10exp(9) degrees.**

The experiment done on the next slide resulted in no observed IR signature of a plasma antenna. The infrared thermometer measure room temperature.

Infra-Red Temperature Measurement: Experiment showed that fluorescent lamp in the on mode produced no IR signature

Test Setup



Plasma antenna

Infra-red thermometer

Higher Data Rates using Plasma Antennas than Metal Antennas.

Very Useful for Receiving Satellite Data or Space Based Antennas

- Since noise is a random number, it accumulates as the square root of the integration time.
  - For example reducing the noise by a factor of 2 should up the data input rate by a factor of 4.
- Accumulated noise = random noise * square root of time.
- Our signal is coherent, and increases linearly with time.
- Accumulated signal = signal input * time.
- So keeping the accumulated signal to accumulated noise constant so we
  - can see our signal over the noise, and reducing the random noise by a factor of 2, our integrating time is reduced (because of the square root) by a factor of 4.

Higher Data Rates using Plasma Antennas than Metal Antennas. Nomenclature

$AS \equiv$ Accumulated signal

$AN \equiv$ Accumulated noise

$SI \equiv$ Signal input

$RN \equiv$ Radom noise

$RN_p \equiv$ Radom noise for plasma antenna

$RN_m \equiv$ Radom noise for metal antenna

$t \equiv$ integration time

Higher Data Rates using Plasma Antennas than Metal Antennas. Nomenclature

$DR_m \equiv$ Data rate of metal antenna

$DR_p \equiv$ Data rate of plasma antenna

Higher Data Rates using Plasma Antennas than Metal Antennas

$$AS = (SI)t$$

$$AN = (RN)\sqrt{t}$$

$$\frac{AS}{AN} = \frac{SI}{RN}\frac{t}{\sqrt{t}} = \frac{SI}{RN}\sqrt{t}$$

Now at 1 GHz the plasma antenna radom noise is reduced from the noise of the corresponding metal antenna by a factor of 38.

$$RN_p = \frac{RN_m}{38}$$

Higher Data Rates using Plasma Antennas than Metal Antennas

$$\frac{AS}{AN} = \frac{SI}{RN_m/38}\sqrt{t_p} = \frac{SI}{RN_m}\sqrt{38^2 t_p} = \frac{SI}{RN_m}\sqrt{t_m}$$

$$38^2 t_p = t_m$$

$$DR_p \equiv 1/t_p = (38^2\ 1/t_m) = 38^2 DR_m$$

In general

$$DR_p = n^2 DM_m$$

Where n is the factor in which radom noise is reduced by using a plasma antenna instead of a metal antenna.

Conclusions on Plasma Antenna Thermal Noise, Data Rates, and IR Signature

- **Plasma antennas over a wide range of operating conditions have less thermal noise than corresponding metal antennas.**
  - **This is due to:**
    - **Effects of modification of the classical Nyquest Theorem by equation[2]**
      - **And further reductions in plasma antenna thermal noise by:**
        - » **Ramsauer-Townsend Effects**
        - » **Operation in the afterglow state**
        - » **Higher frequency effects**
        - » **Decreased plasma pressure**
- **Plasma antennas have higher data rates due to lower thermal noise at a wide range of frequencies.**
- **Plasma antennas do not have an IR signature over metal antennas.**
- **The effective noise temperature formula commonly used in antenna texts is not applicable to a plasma antenna.**
  - **Plasma antennas are not blackbody radiators.**

Conclusions on Plasma Antenna Thermal Noise: New Frontier in Antenna Technology. The Future of Low Thermal Noise, High Data Rate Antennas.

- **By using new technologies to lower R, T, and ν in the power spectral density for plasma antenna thermal noise:**

$$H(T,R,\omega,\nu)=\frac{2kTR}{\pi}\left(\frac{1}{1+\frac{\omega^2}{\nu^2}}\right)$$

- **Thermal noise in plasma antennas may be reduced and data rates can be increased to open up new frontiers in antenna technology.**
- **Plasma antennas have higher data rates than metal antennas**
  - **Useful for ground based antennas receiving satellite information**
  - **Useful for space based antennas**

Higher Gain with Plasma Antennas

- Lower side lobes in a plasma antenna
  - Soft surface effects of plasma
- Lower thermal noise
- Higher data rates
- Plasma lens effects
  - Beam focusing with plasma lens

Conclusions on Our Commercial Prototype and Summary of Applications

- Compact smart steerable antenna without phased arrays or phase shifters
- Applications :
  - IED Defeaters
  - High Power
  - ADS frequency operational capabilities
  - Low frequency electronically steerable antennas that can fit on a vehicle
  - RFID
  - Last Mile
  - Base stations
  - Satellite receiving antennas
    - Satellite radio
  - New HDTV antennas for digital air waves

Plasma Antenna Technology Applied to InTop Program

The InTop Program

- **InTop is a program that will give:**
  - **support Radio Frequency (RF) multi-functionality and**
  - **resource management in order to enable**
  - **greater flexibility to adapt platform capabilities**

InTop Problem

- **In the current condition U.S. Navy surface combatants are increasingly employing large numbers of federated RF apertures to perform**
  - Electronic Warfare,
  - Communication, and
  - Radar functions
- **Each function (and hence system) historically has its own aperture, electronics, operator, and logistics/maintenance tail.**
- **This classic stand-alone RF systems approach results in Electromagnetic Interference/Compatibility (EMI/EMC) problems that**
  - degrade system performance and
  - increase life-cycle cost for the combatant

The InTop Solution

- **Plasma antennas are reconfigurable.**
- **Plasma antennas can be reconfigured from:**
  - Electronic Warfare antennas to
  - Communication antennas to
  - Radar antenna
- **One plasma antenna aperture can be reconfigured to other apertures.**

The InTop Solution

- Plasma antennas are reconfigurable in:
  - Antenna radiation pattern
  - Beamwidth
    - The Haleakala smart plasma antenna has reconfigurable beamwidth.
  - Bandwidth
    - Nested plasma antennas and stacked plasma antenna arrays can be reconfigured from broadband to multiband to narrow band.
  - Frequency
    - Plasma antenna can be reconfigured in frequency by changing the:
      - Plasma density
      - Electrical size of the plasma antenna
      - Turning one or more plasma antennas on in a plasma antenna nest or plasma antenna stacked arrays with the rest off.
      - When several plasma antennas are together for multifunctional tasks, turn only the plasma antenna on for a selected frequency or function and leave the rest off.

The InTop Solution

- Plasma antennas have stealth
  - Our plasma reflector antenna dropped by 22 dB in reflectivity in milliseconds when it was turned off.
  - When it was on, it performance was the same as a metal reflector of the same size.
    - It was observed that the plasma reflector antenna had lower side lobes than the corresponding metal reflector antenna.
- Plasma antennas reduce electromagnetic interference.
  - EMI can be reduced by reducing the density of the plasma in the plasma antennas.
  - EMI can be reduced by turning the plasma antennas off except the plasma antennas you need on.

The InTop Solution

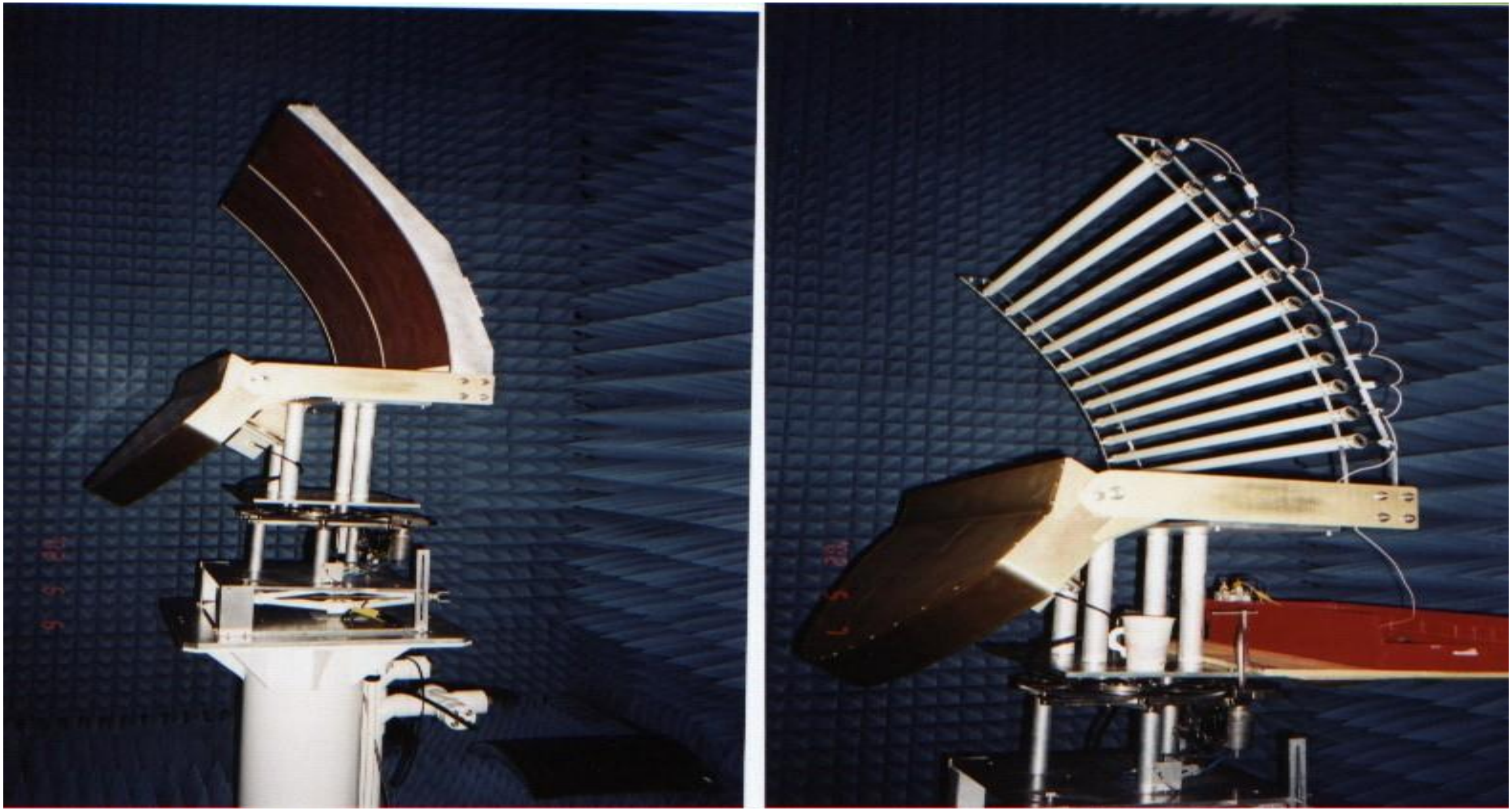
- **Multiple contract and task order awards are anticipated to investigate and adapt new technologies to:**
  - **support affordable multifunction capabilities,**
  - **develop ADMs to test/demonstrate these new capabilities,**
  - **and transition InTop capabilities for SDD and the Fleet.**

AM/FM Plasma Antenna Radio Antenna

Basic Experimental Plasma Antenna Prototype: Plasma tube antenna is a receiver for a FM/AM Radio.

This is on display at the Booz Allen” Technology Petting Zoo” in Mclean, VA

Plasma Reflector Antenna

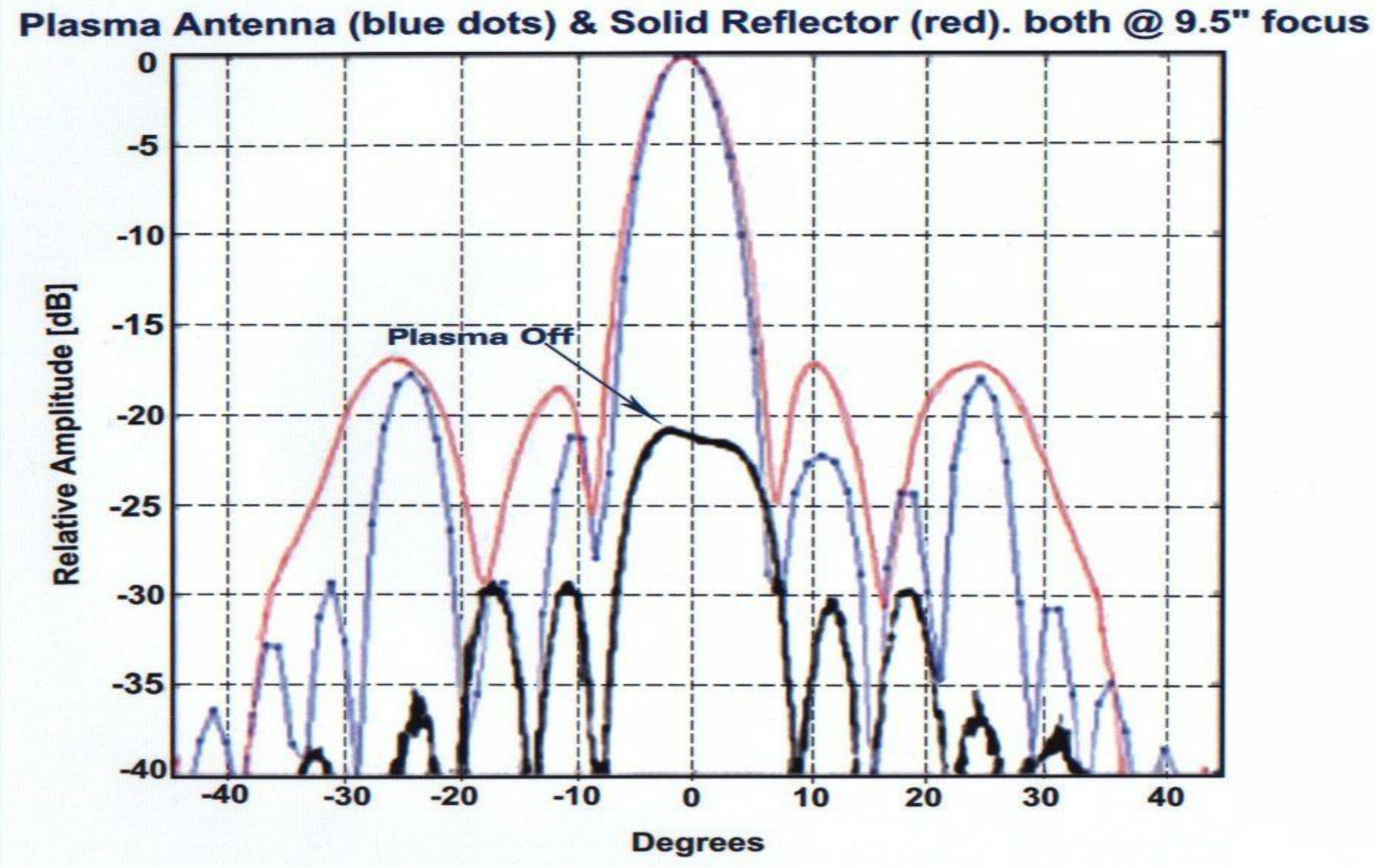


Plasma Reflector Antenna: Right – plasma reflector antenna installed in an electrical anechoic chamber

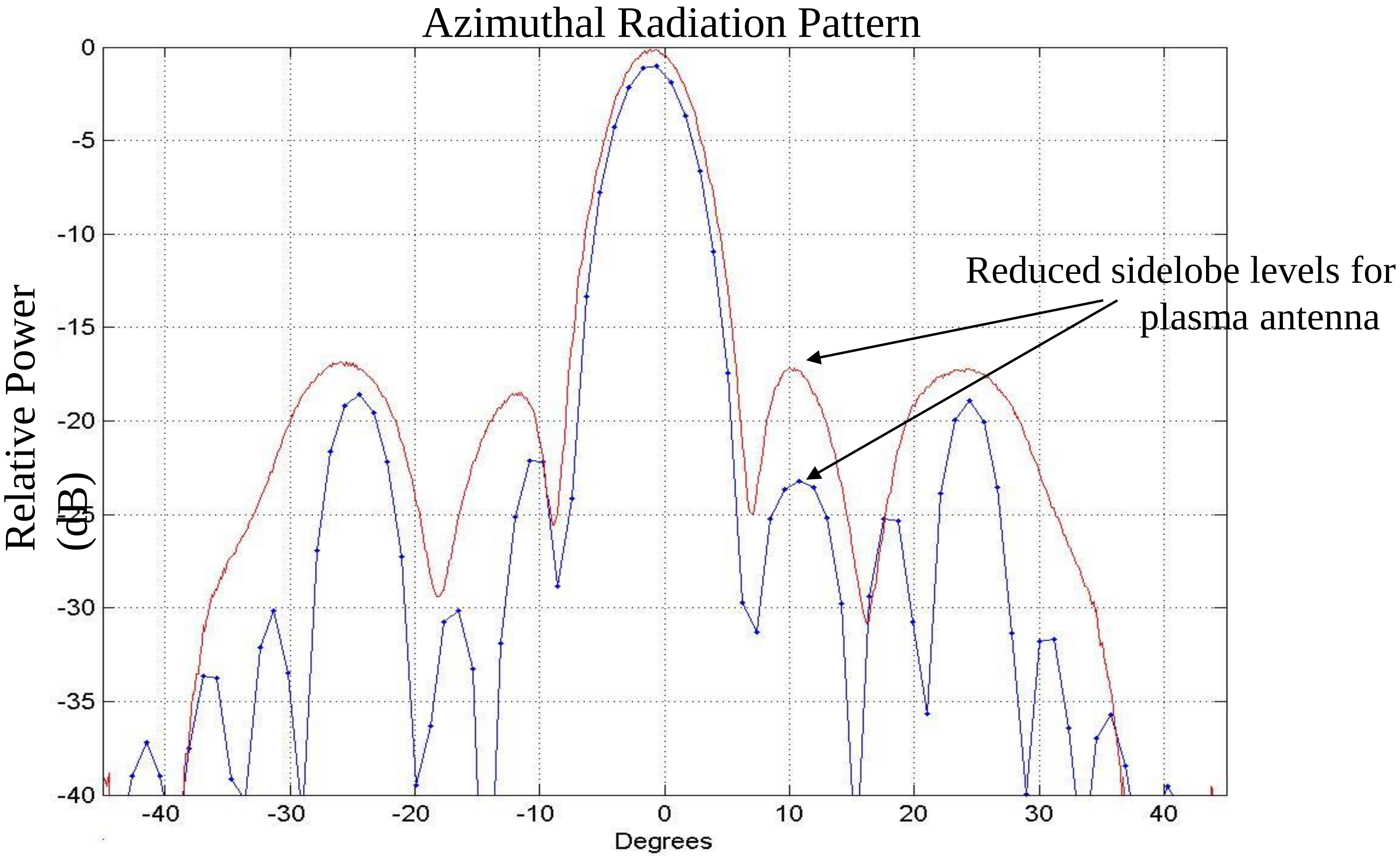
Left - metal reflector antenna designed to be an identical twin to the plasma antenna

The microwaves are generated by a line antenna, focused in one dimension by the metal pillbox, and focused in the second dimension by either the plasma antenna or a metal twin

Radiation Pattern – Previous Slide



Reduced Side Lobes for Plasma Reflector Antenna



Azimuthal Radiation Pattern

Reduced sidelobe levels for plasma antenna

Conclusions on Plasma Reflector Antenna

- The main lobe plasma reflector antenna is identical to the main lobe of the corresponding metal reflector antenna.
- When the plasma antenna is turned off it is invisible to all RF frequencies.
- The plasma reflector antenna can operate at lower frequencies and be stealth at high frequencies.
  - higher frequency RF waves will pass through a lower density plasma.
- The side lobes of the plasma reflector antenna are less than the side lobes of the corresponding metal reflector antenna.
  - Soft surface effects of plasma

Physics of Reflection and Transmission of Electromagnetic Waves through Plasma

Physics of Reflection and Transmission of Electromagnetic Waves through Plasma

- An electromagnetic wave from an antenna of frequency ω is incident on a plasma with a plasma frequency ω_p
- The plasma frequency is proportional to the square root of the density of unbound electrons in the plasma or the amount of ionization in the plasma.

Physics of Reflection and Transmission of Electromagnetic Waves through Plasma

- The plasma frequency is defined as

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{me}}$$

- ne is the density of unbound electrons, e is the charge on the electron

- me is the mass of an electron

Physics of Reflection and Transmission of Electromagnetic Waves through Plasma

If the incident antenna frequency on the plasma is much greater than the plasma frequency ω_p

Such that $\omega > \omega_p$

the antenna radiation passes through the plasma un-attenuated

Stacked Plasma Antenna Arrays

Stacked Plasma Antenna Arrays

- Metal antenna arrays cannot be stacked
  - Metal from one layer blocks radiation of another layer
- Plasma density from higher frequency antenna arrays is higher than the plasma density from the lower frequency arrays
- Higher frequency plasma antenna arrays emit high enough frequencies to propagate through the lower frequency plasma antenna arrays

Stacked Plasma Antenna Arrays

- When antenna frequency from the ith plasma antenna layer exceeds the plasma frequency from the ith +1 layer
- the antenna radiation from the ith layer passes through the ith+1 layer
  - Antenna radiation from ith+1 plasma antenna array layer through ith+2 plasma antenna array layer
  - Antenna radiation from ith+N-1 plasma antenna array layer passes through ith+N plasma antenna array layer
  - This goes on until all the plasma antenna array layers are transmitting independently in free space

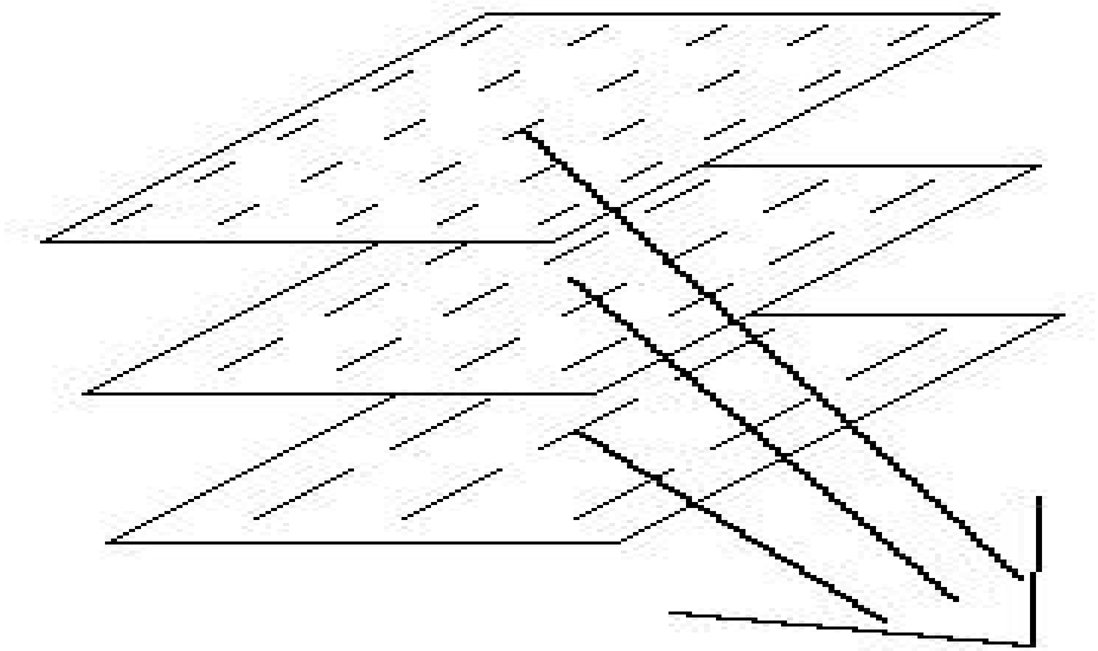
Stacked Plasma Antenna Arrays

- Higher frequency antenna radiation from higher frequency arrays propagate through lower frequency arrays
- Bandwidths add
- Power adds
- Compactness
  - Stacked arrays occupy less space than metal arrays
  - Stacked arrays have smaller RCS
  - Less EMI

Impedance matching of stacked plasma antenna arrays

- Each plasma antenna array is tuned to have a narrow band frequency
  - Reduces problem of impedance mismatching that broad band antennas have
- The bandwidths of each layer of a plasma antenna array adds
  - flexible bandwidth
  - reduced impedance mismatching

Stacked Plasma Antenna Arrays



Advantages of Stacking Plasma Antenna Arrays

- Plasma antenna arrays stacked produces greater
  - Bandwidths
  - Multiband widths
    - Turn any number of plasma arrays on or off
  - power
- But less
  - physical space
    - helps reduce antenna farm on surface ships
  - RCS

Nested Plasma Antennas

Nested Plasma Antennas

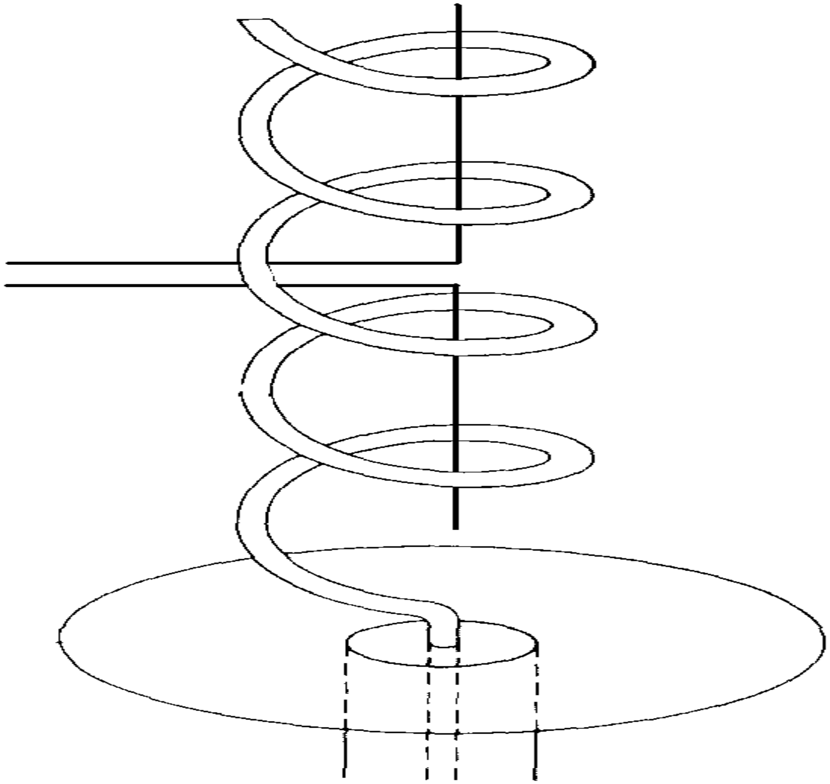
- Higher frequency nested plasma antennas emit higher frequencies which propagate through lower frequency nested plasma antennas
- Bandwidths add
  - Large bandwidths Multiband widths
    - Turn any number or sequence of nested plasma antennas off or on.
- Power adds
- Nesting antennas means compactness
- Maintains impedance matching
  - Each nested plasma antenna is narrow band but adds up to wide band

Nested Plasma Antennas

- Results
  - Antenna that is
    - Compact
    - Wideband
    - Multiband
    - High power
    - Impedance matched
    - Reconfigurable
      - Various radiation patterns including isotopic
    - Low RCS

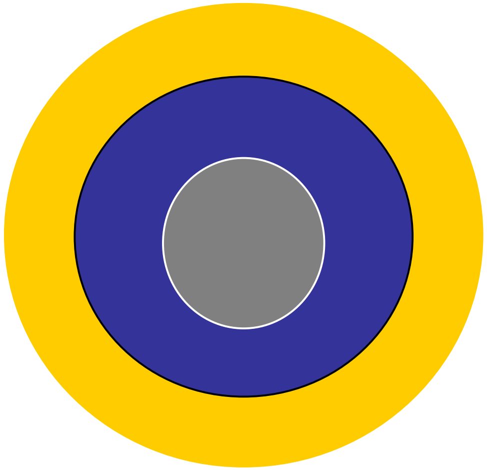
Nested Plasma Antennas

Example of Concept: Higher Frequency Dipole Plasma Antenna Nested inside Lower Frequency Plasma Helical Antenna and Transmission is Simultaneous with Radiation Patterns, Bandwidths, and Power Adding.

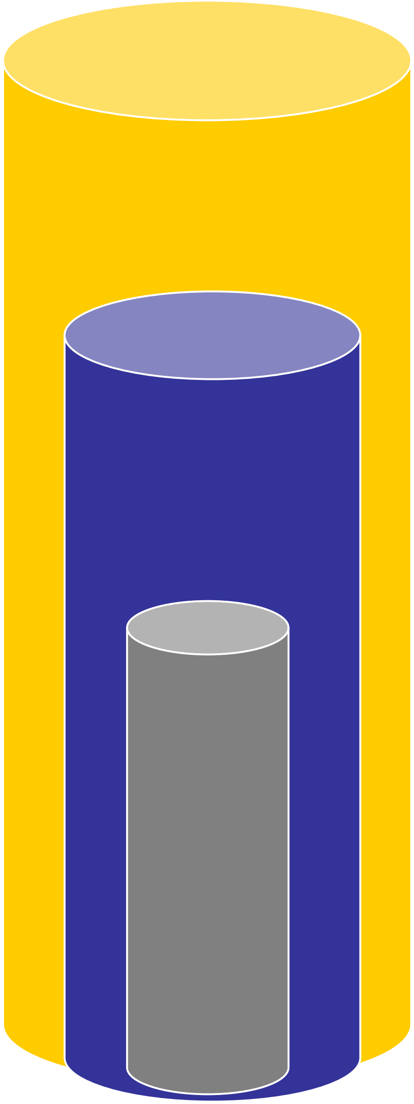


Nested Plasma Antenna: Concept of High Frequency Plasma Antennas Transmitting And Receiving Through Low Frequency Plasma Antennas

Top View



Side View



Low frequency plasma antenna

Medium frequency plasma antenna

High frequency Plasma antenna

Nested Plasma Antennas

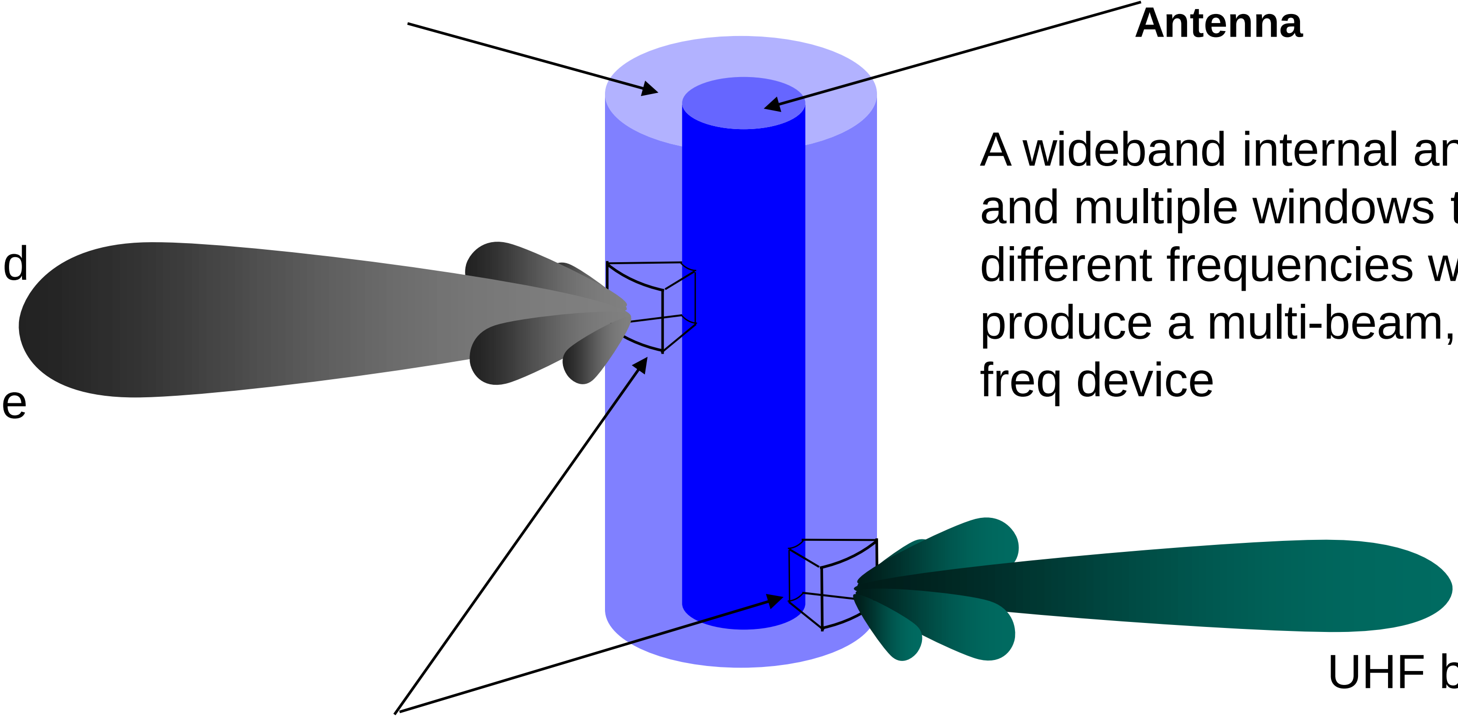
- Higher frequency plasma antennas are nested inside lower frequency plasma antennas

- Geometric compatibility
  - Higher frequency plasma antennas are smaller
  - Lower frequency plasma antennas are larger
  - Higher frequency plasma antennas fit inside lower frequency plasma antennas

Nested Plasma Antennas with Plasma Windowing

- Inner antenna is omnidirectional
  - Omnidirectional in azimuth direction when mounted on the aircraft
  - Use existing broadband COTS antenna such as a COTS biconical
  - Higher iterations would use nested plasma antennas
- Surround inner omnidirectional antenna with plasma windows

Tactical Capabilities Plasma Windowing Concept with Plasma Antenna Nesting



External Plasma Blanket

Internal Omnidirectional Nested Plasma Antenna

HF band for example

UHF band For example

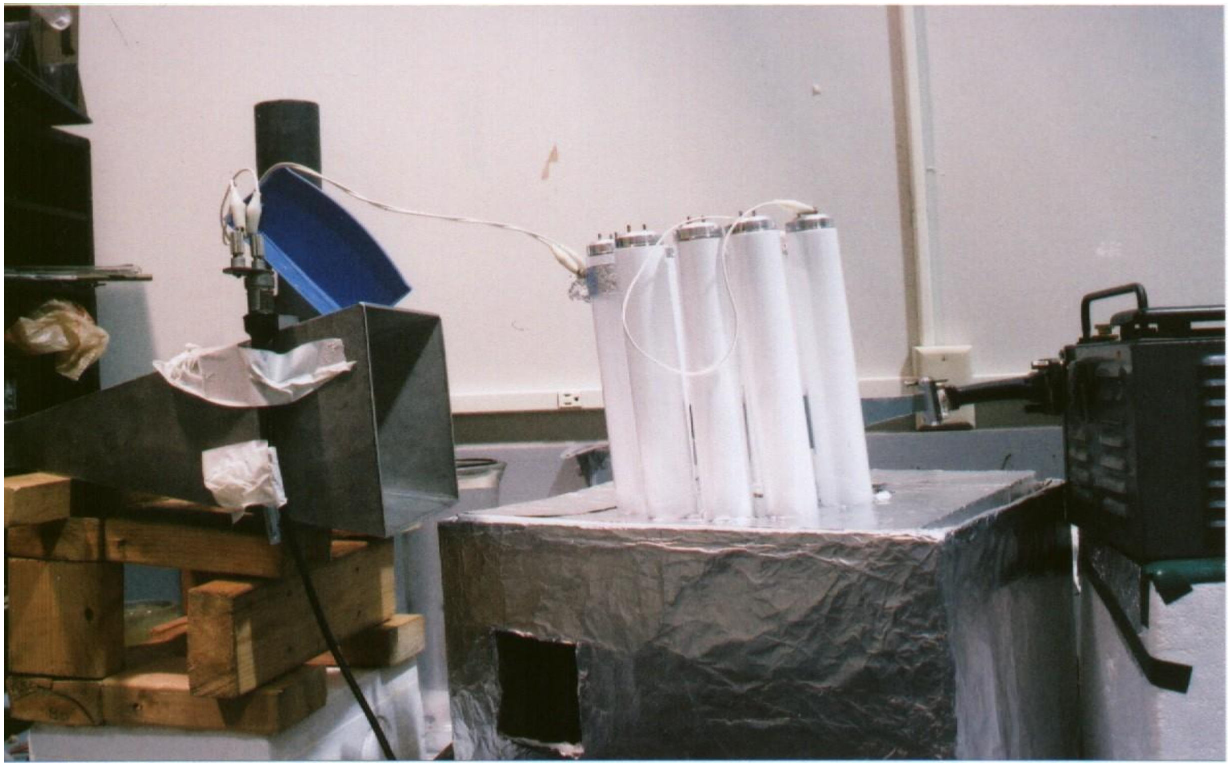
Low Density Plasma Windows Opened for Transmit or Receive

A wideband internal antenna and multiple windows tuned to different frequencies would produce a multi-beam, multi-freq device

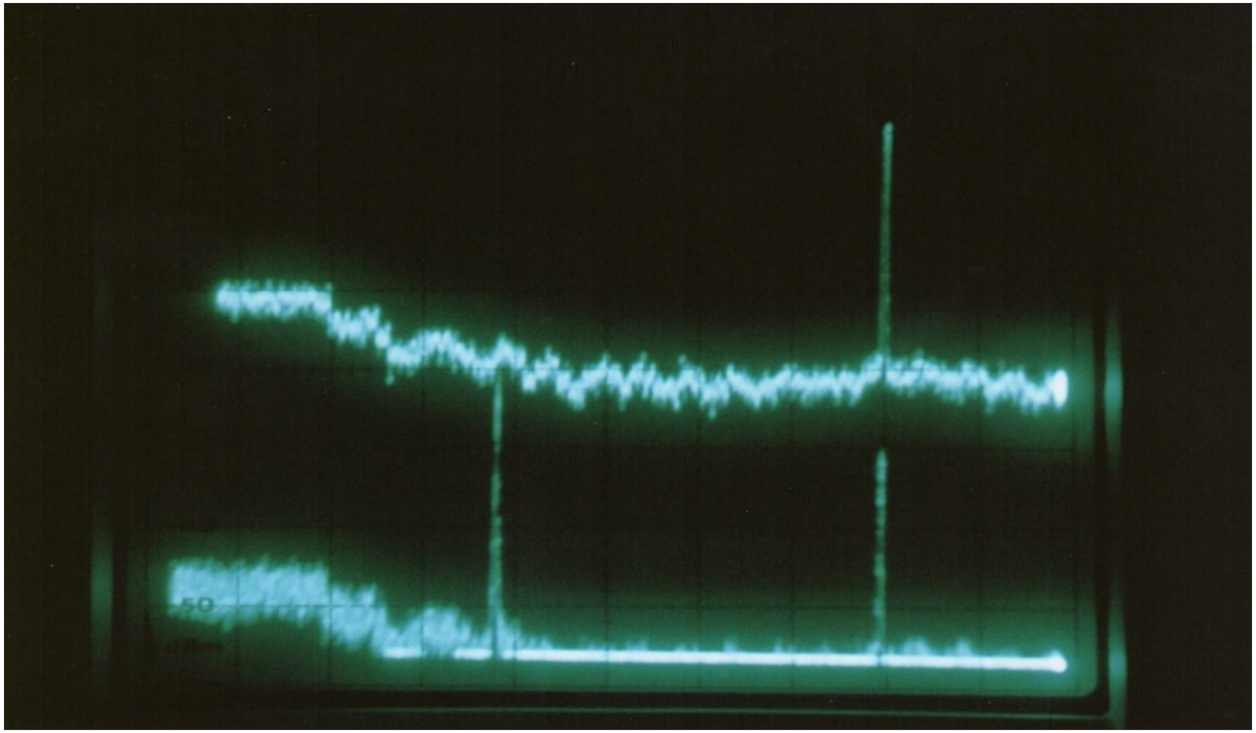
Nested Plasma Antennas

- **Higher frequency plasma antennas can be nested inside lower frequency plasma antennas**
  - **The high frequency plasma antennas will send signals that can propagate through the lower frequency plasma antennas**
  - **Bandwidths and power add of the various nested layers.**
  - **Large bandwidths, narrow bandwidths, and multiband widths are possible.**
  - **Nesting antennas is not possible with metal antennas**
  - **Stacked plasma antenna arrays can be done with the higher frequency arrays sending signals through the lower frequency arrays.**
- **The frequencies used were 4 GHz and 8 GHz.**
- **The higher frequency was emitted from a microwave horn. This horn was placed inside a half-circle of plasma tubes (fluorescent lamps).**
- **These tubes are energized by high – current pulses of 2 microsecond duration repeated every millisecond, which forms a dense steady – state plasma.**
- **The lower – frequency signal is applied to the two tubes directly in front of the high – frequency microwave horn by capacitive couplers.**
- **This results in forming a plasma loop antenna in front of the higher – frequency microwave emitting horn when the plasma tubes are energized.**
- **Both low and high frequencies are received by a broad – band microwave horn, amplified by a traveling wave tube amplifier, and displayed on a panoramic receiver.**

Nested Plasma Antennas



Nested Plasma Antenna



Nested Plasma Antennas

- **The experimental results are shown in the above photo.**
- **When the plasma antenna is not energized, the 8 GHz signal appears.**
- **However, the 4 GHz signal is not visible, even though the 4 GHz transmitter is operating.**
- **When the plasma antenna is energized, both the 8 GHz and the 4GHz signals are received.**
- **In this case, the 8 GHz signal is penetrating the plasma antenna operating at 4 GHz.**
- **Note that the 8 GHz signal is not appreciably attenuated by the operating 4 GHz plasma antenna.**

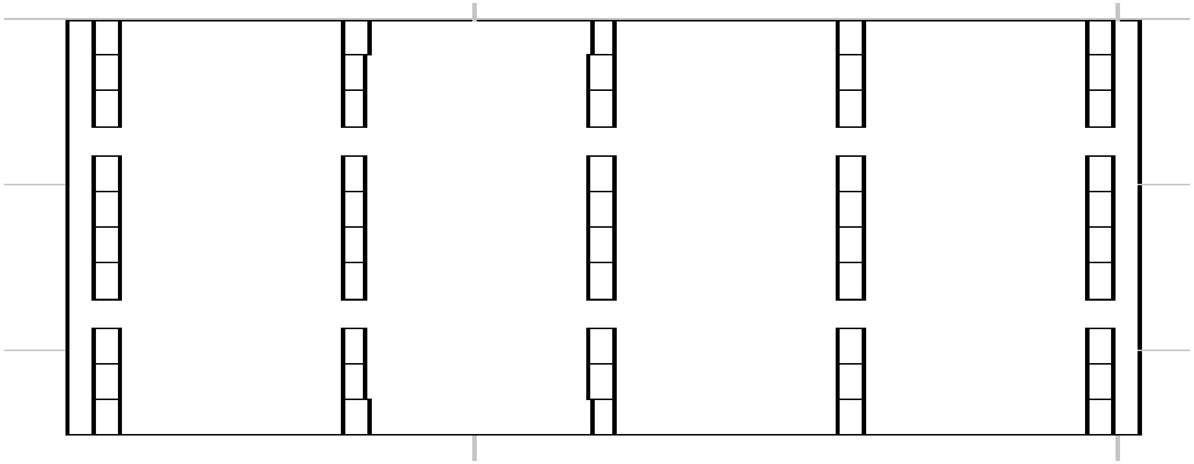
Nested Plasma Antennas

- **The gain for both traces is the same.**
- **Only the baseline has been moved to display before and after traces on the same display.**
- **This constitutes the successful demonstration.**
- **The plasma density has been so chosen that the 8 GHz signal passes through the antenna.**
- **At higher plasma densities, the 8 GHz signal is observed to be reflected.**
- **We have tested this effect by increasing the plasma density.**
- **The 8 GHz signal is observed to be completely cut – off, while the 4 GHz signal continues to be emitted.**

Plasma Frequency Selective Surfaces and Plasma Radomes

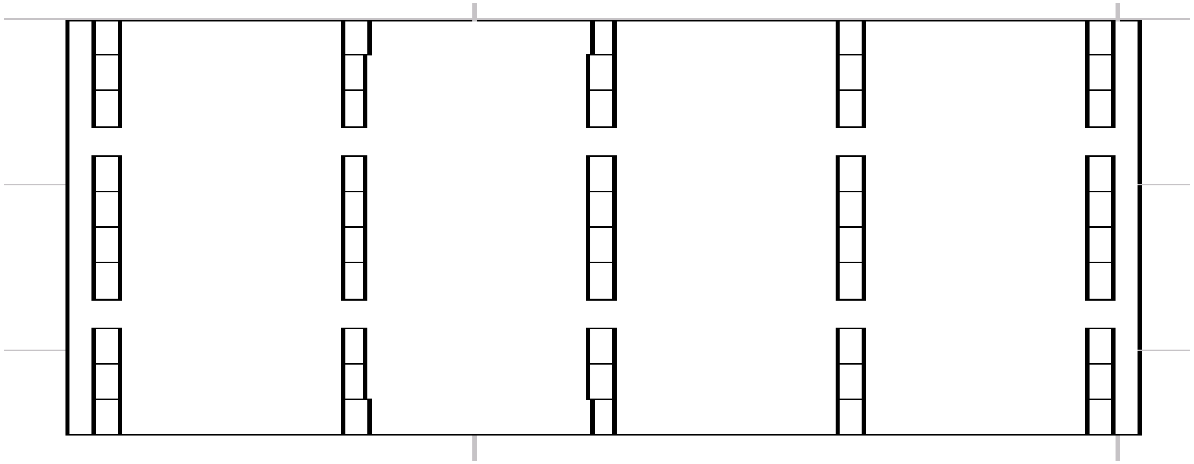
- Reconfigurable electromagnetic filtering
- The foundation of plasma antenna arrays.

Theoretical Plasma FSS Work



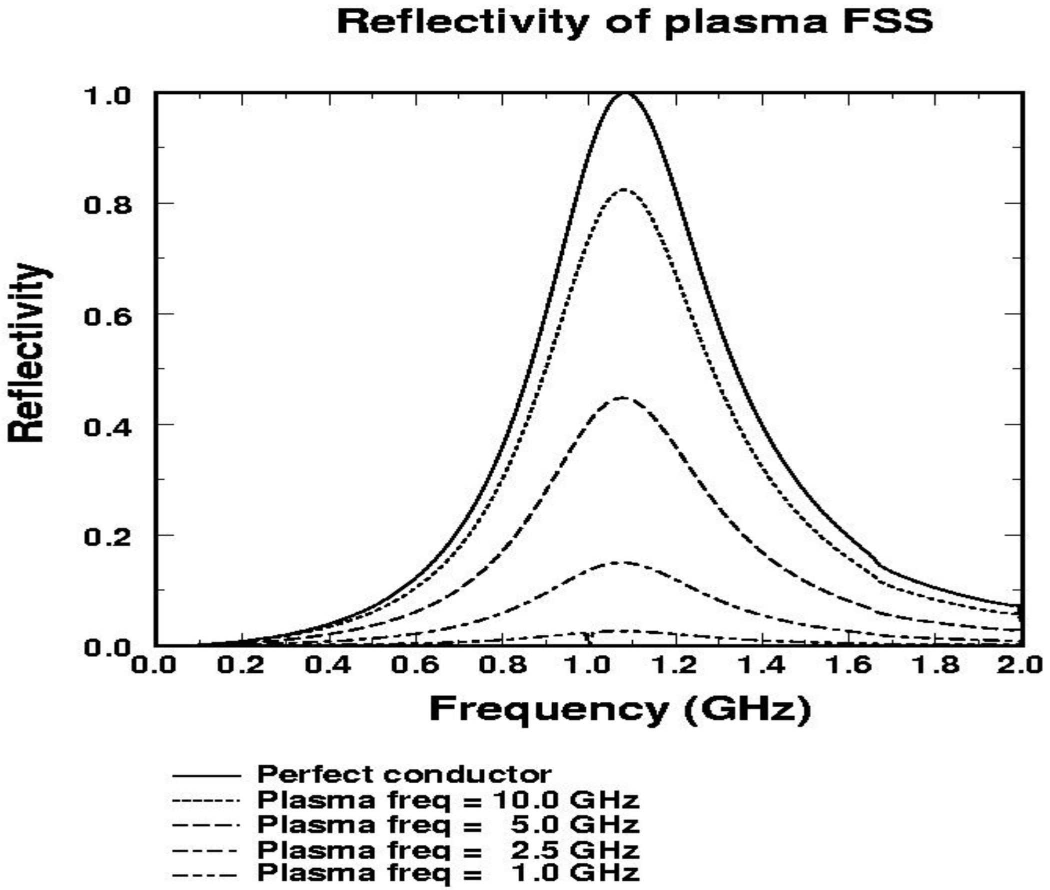
Schematic representation of an FSS dipole array. This sketch illustrates a finite section of an FSS dipole array. The array elements are the vertically aligned rectangular regions. The horizontal lines on the rectangles indicate the way in which the elements are broken up into segments for the purpose of defining current modes (as is discussed in the text). For convenience of analysis, the array is assumed to extend infinitely in the plane

Theoretical Plasma FSS Work



Schematic representation of an FSS dipole array. This sketch illustrates a finite section of an FSS dipole array. The array elements are the vertically aligned rectangular regions. The horizontal lines on the rectangles indicate the way in which the elements are broken up into segments for the purpose of defining current modes (as is discussed in the text). For convenience of analysis, the array is assumed to extend infinitely in the plane

Theoretical Plasma FSS Work



Calculated reflectivity of a dipole, plasma FSS array for several values of the plasma frequency. The results for the perfectly conducting case were obtained using the Periodic Moment Method. Results for the partially conducting plasma FSS were obtained by scaling the perfectly conducting results using the scaling function of.

Theoretical Plasma FSS Work

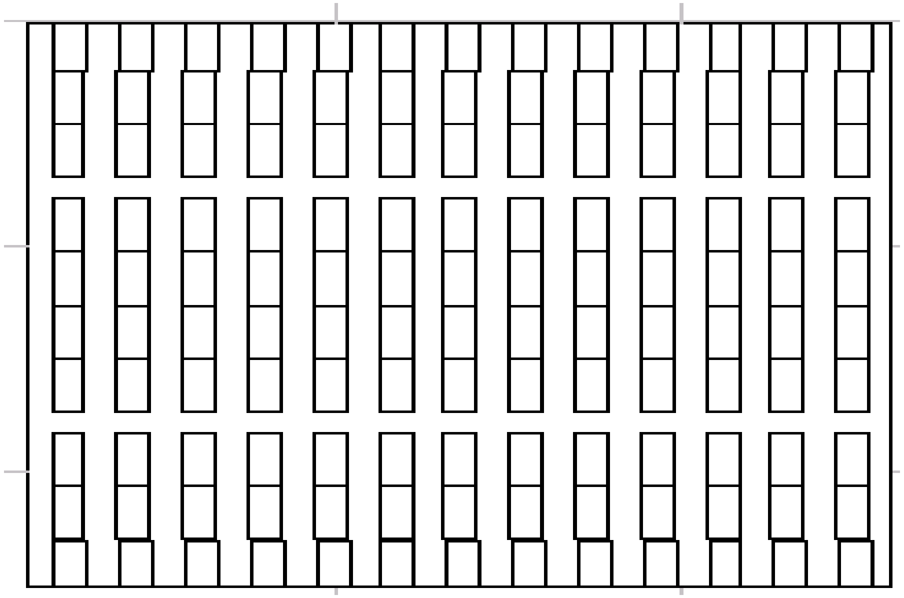
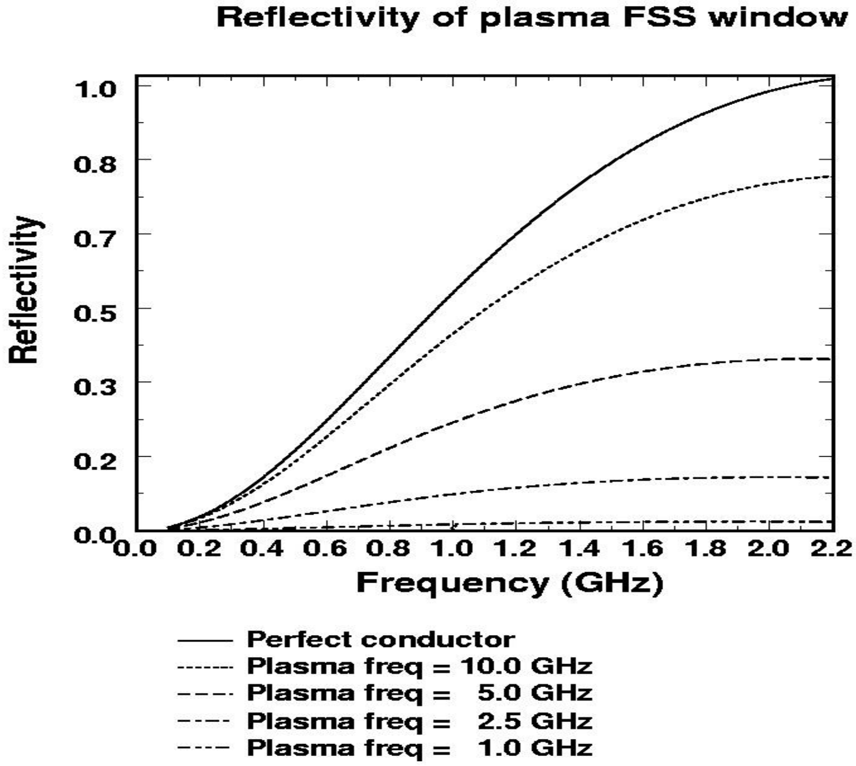


Illustration of a switchable reflector..

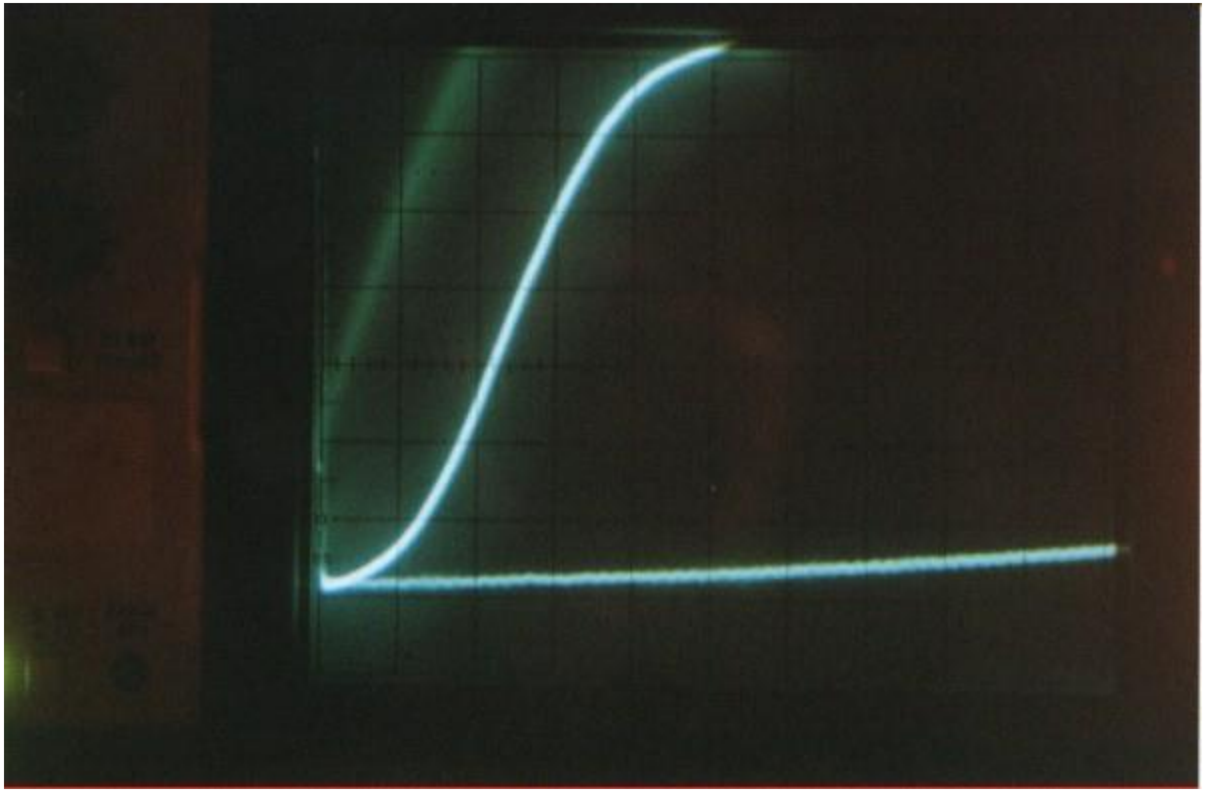
Theoretical Plasma FSS Work



Reflectivity for switchable plasma reflector. Frequencies between the structure operates as a good reflector for sufficiently high values of the plasma frequency.

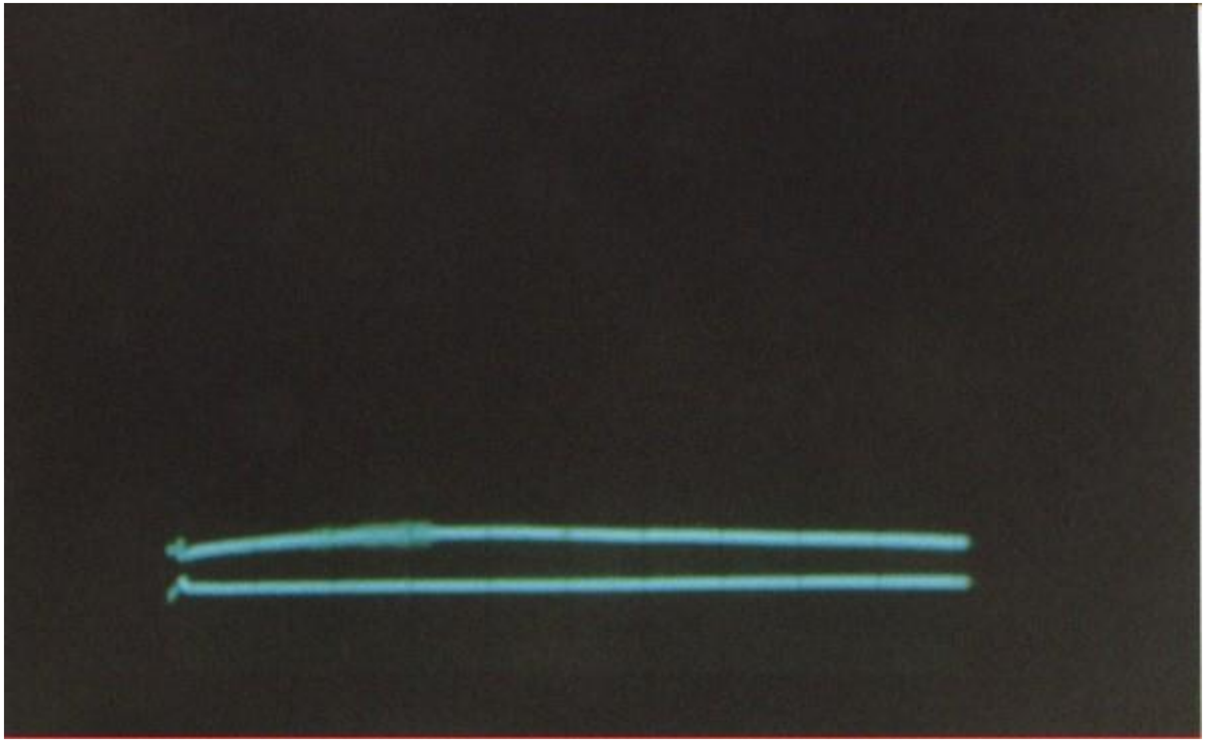
Experimental Plasma FSS Work

.



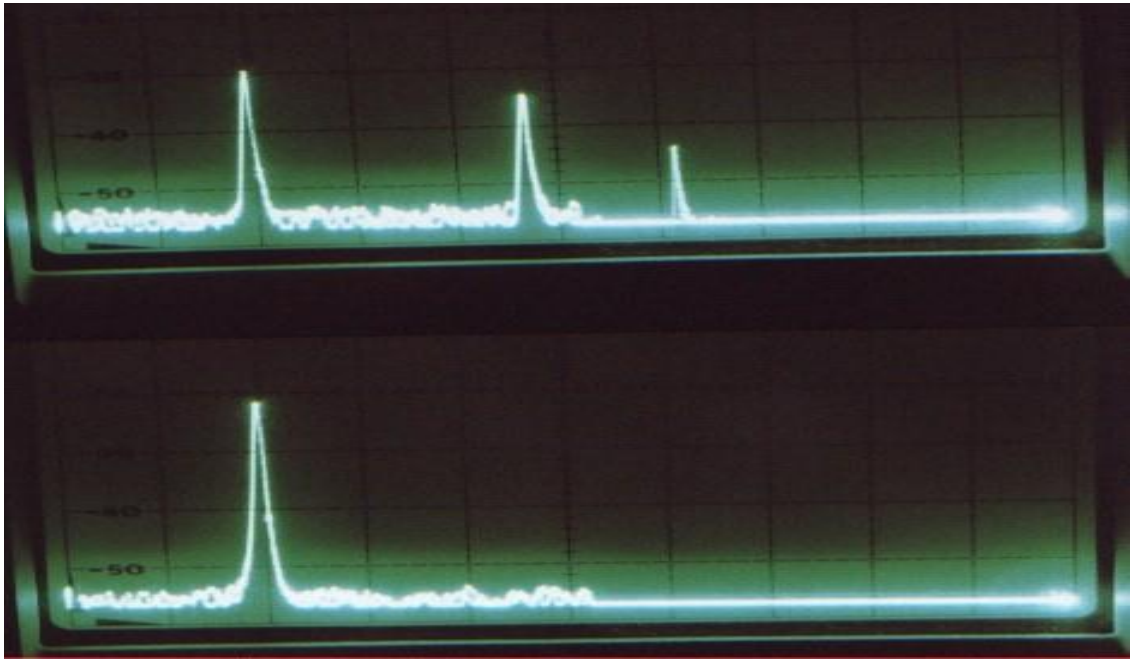
In the this photograph the transmitting antenna was emitting at .9 GHz. There was cutoff (reflection) initially, but as the plasma decayed we see transmission through the plasma FSS.

Experimental Plasma FSS Work



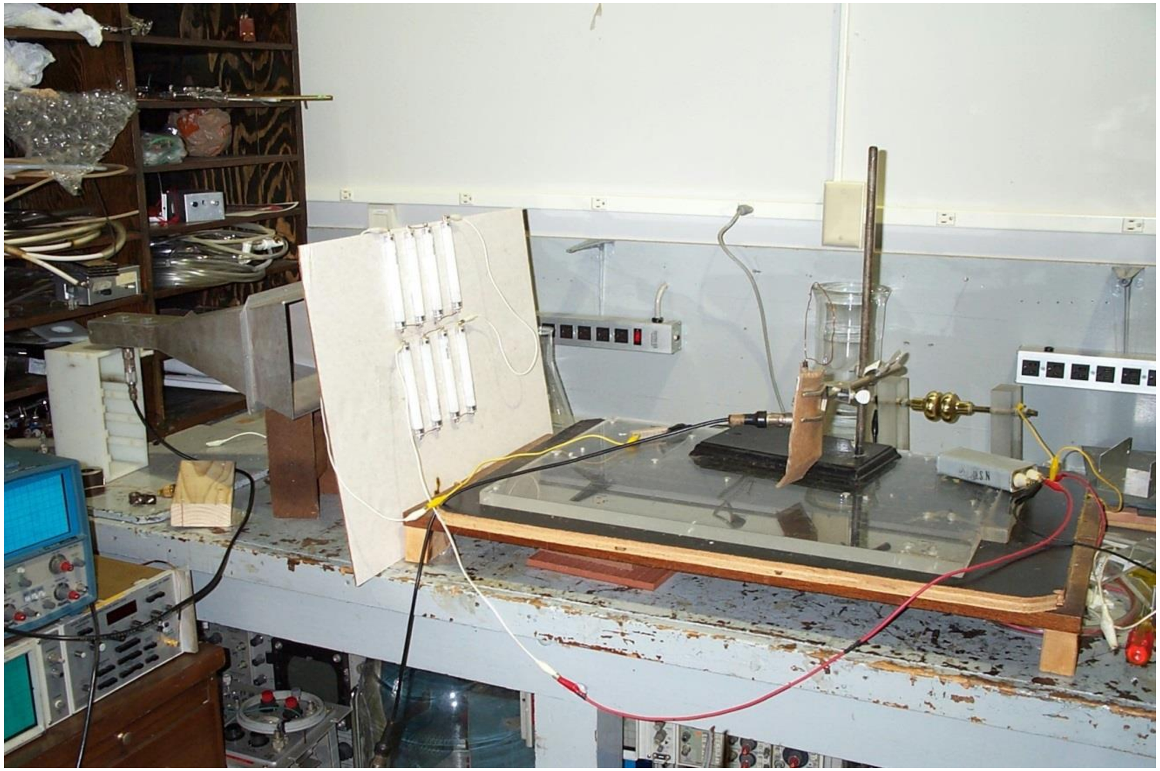
This photograph with the transmitting antenna emitting at 4 GHz with an oscilloscope scale of .1msec/cm. In this case the electromagnetic waves go through the plasma FSS as expected.

Experimental Plasma FSS Work

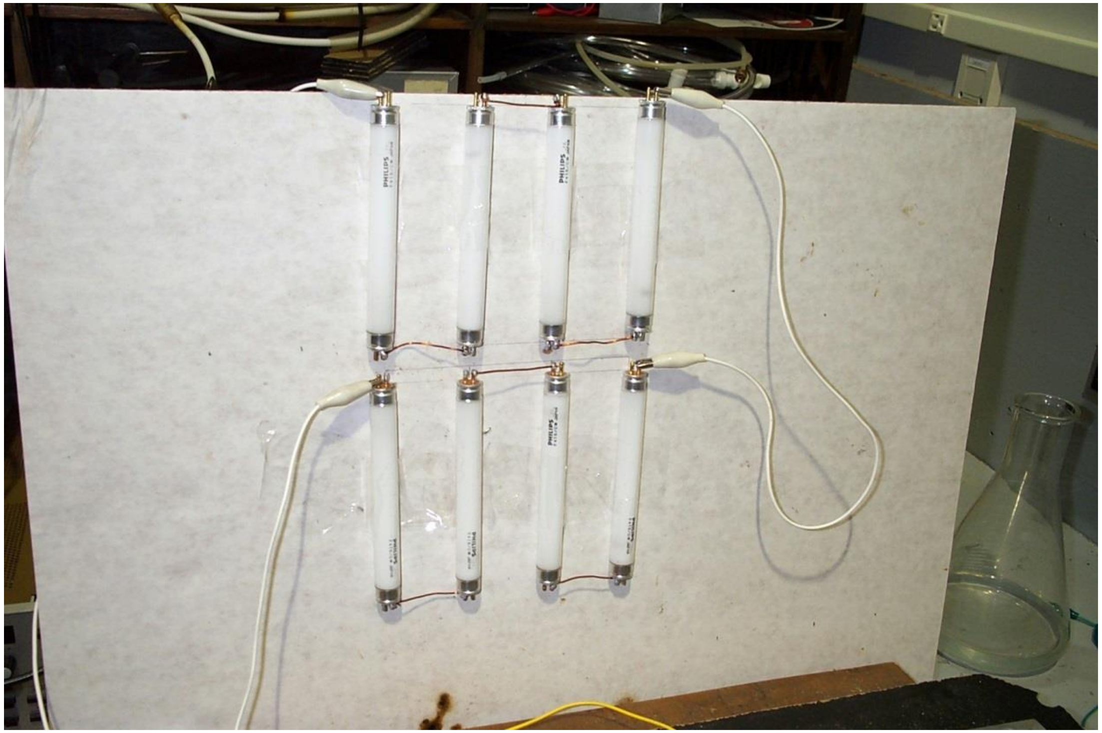


Putting in the passband between transmitter and receiver removes the 2nd and higher harmonics. (2 dB per square)

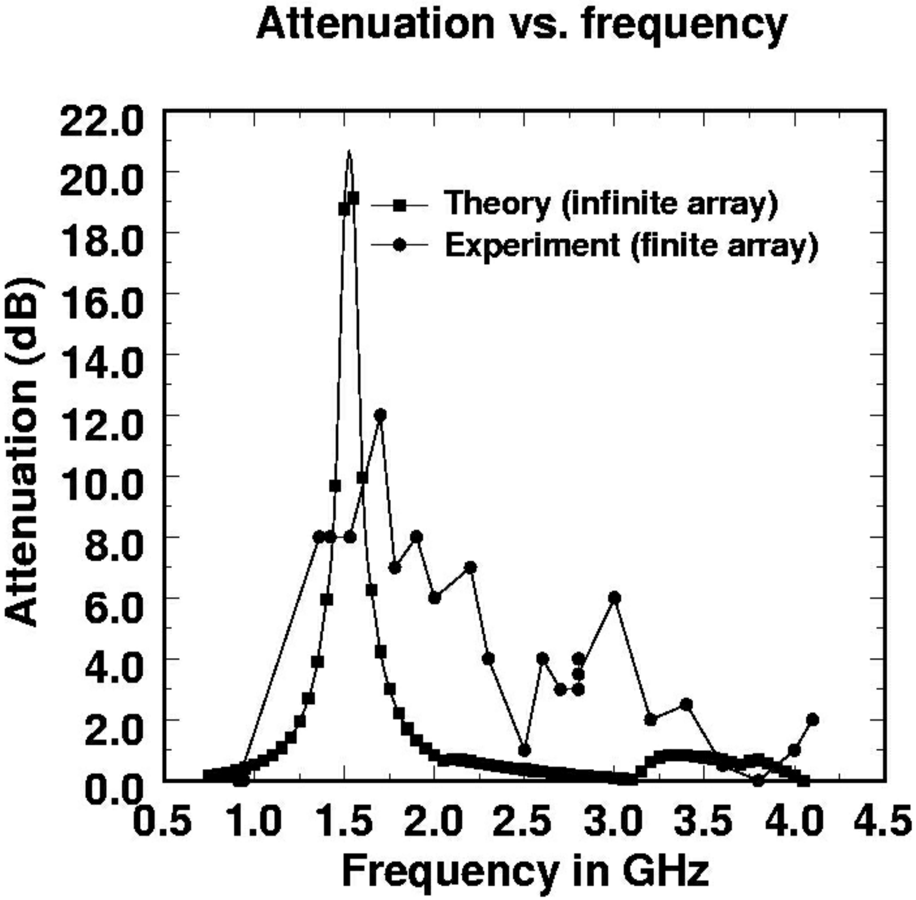
Photograph of the lab setup showing the built plasma dipole FSS with the horn receiver antenna.



Experimental plasma dipole FSS



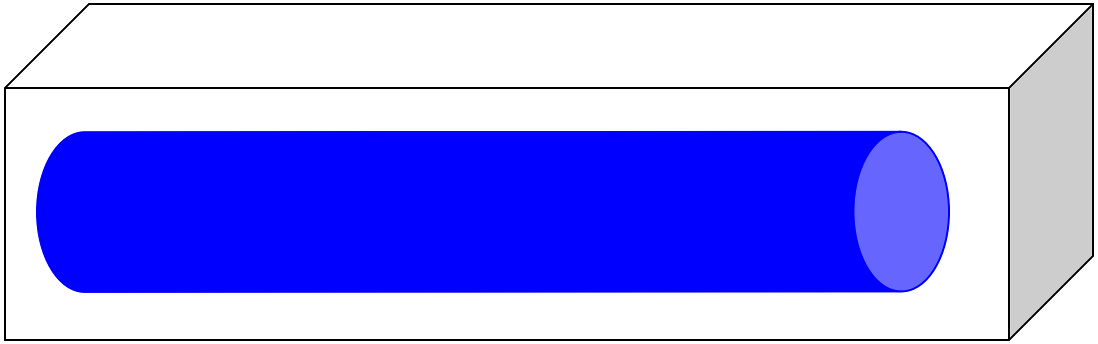
Theoretical and Experimental on a single plot



Plasma Waveguide and Plasma Coaxial Cable

Plasma waveguide

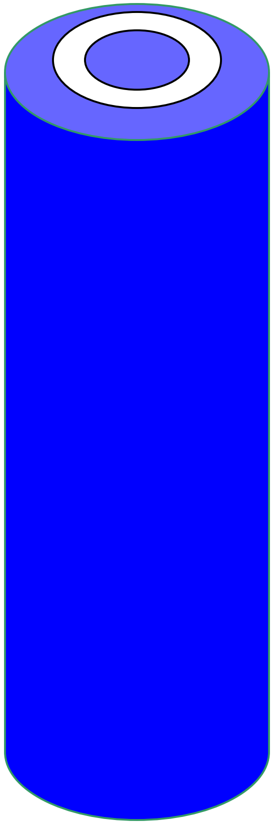
PLASMA IN BLUE INSIDE WAVEGUIDE



Plasma Waveguide

- Plasma in inner tube is formed and evanescent energy is released
- Tube can be flared open to produce a plasma horn antenna
- When inner plasma tube is off waveguide is below cutoff
  - No propagation
  - Evanescent energy storage

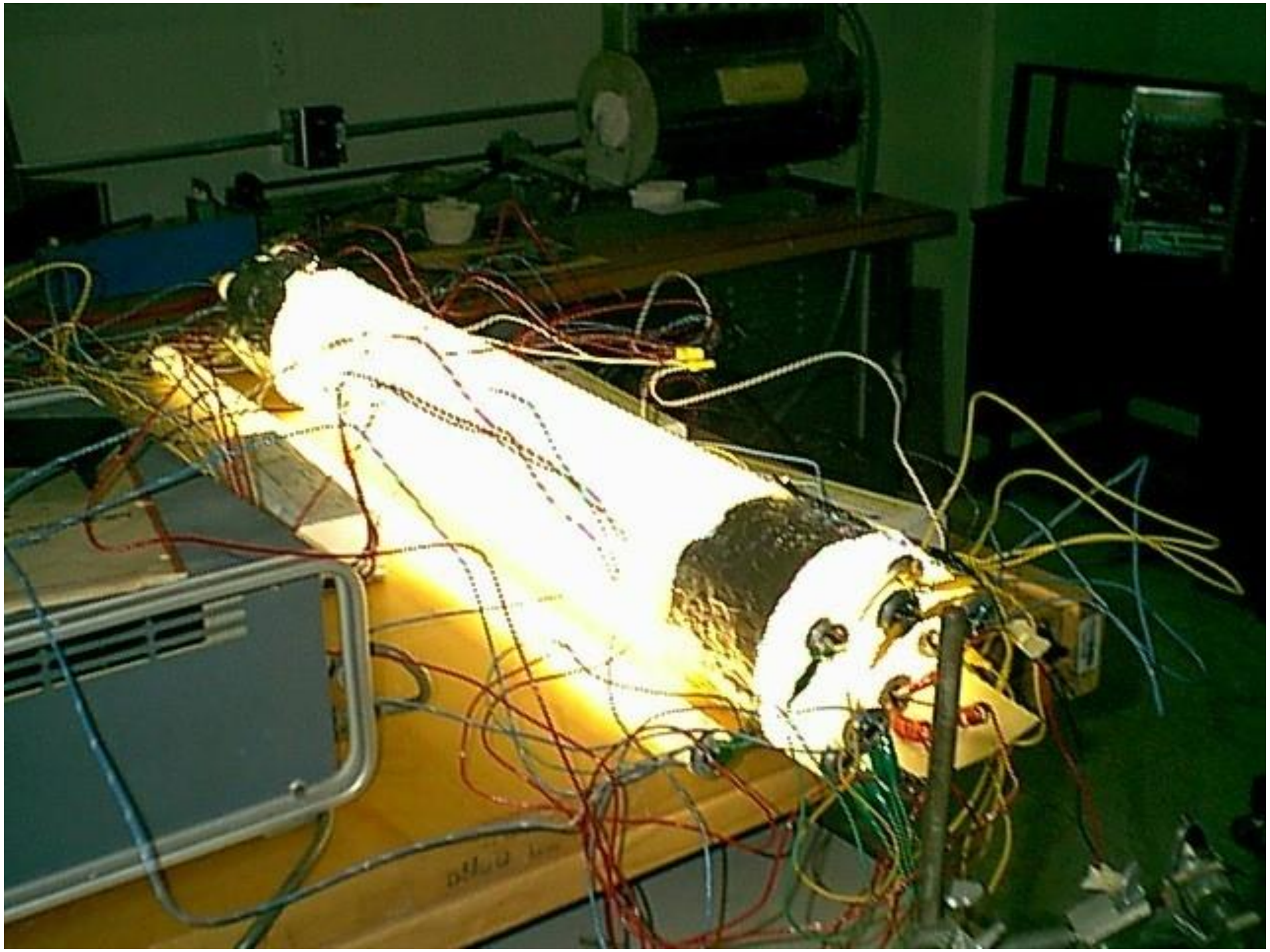
A Second Plasma Waveguide Design



- Inner cylinder filled with plasma (blue)
- Outer annular ring is filled with plasma
- Non conducting region (white) in between inner cylinder and outer cylindrical annular ring

- Plasma skin depth is reconfigurable creating a reconfigurable waveguide

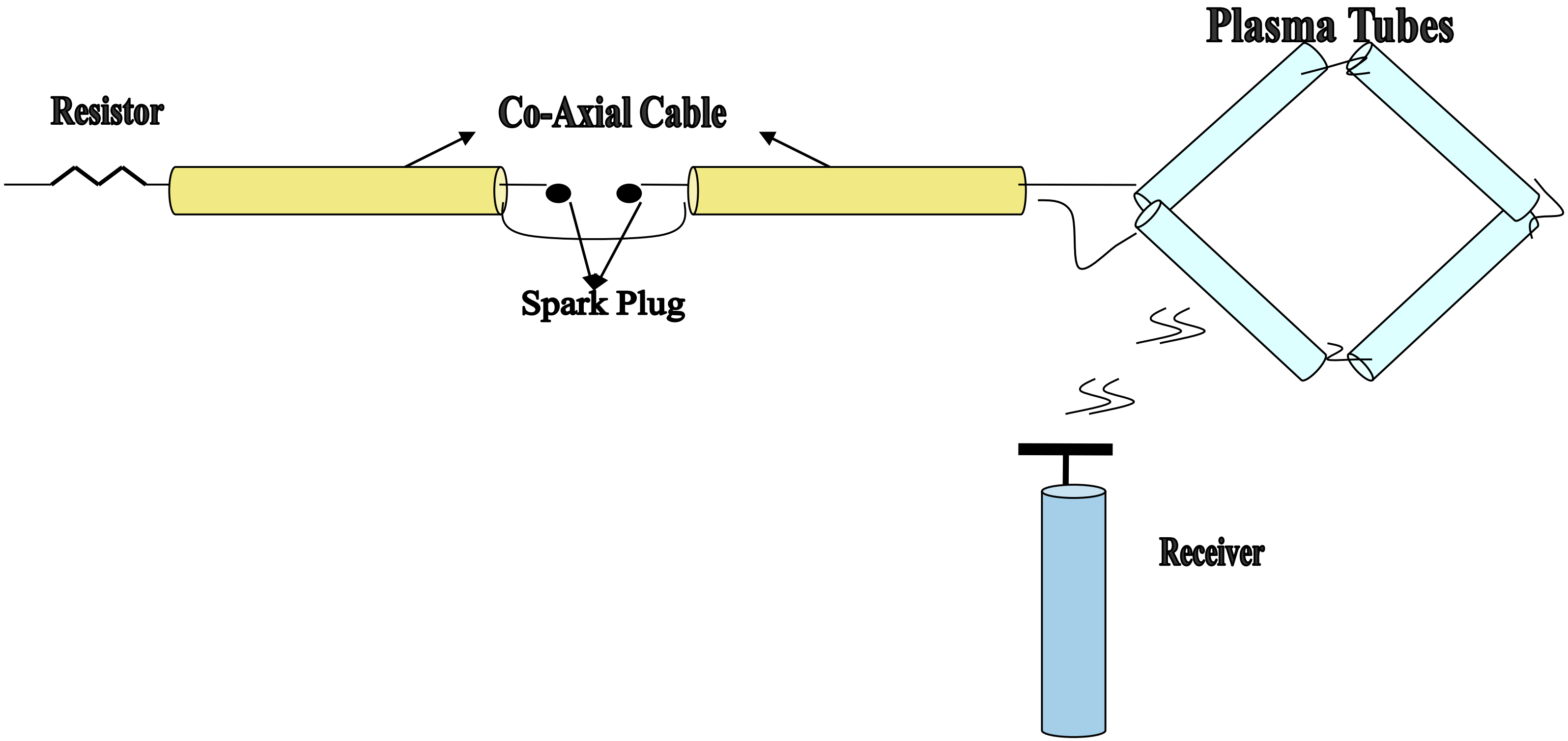
Plasma Waveguide Prototype



High Power Plasma Antenna

Applications as a Jammer

High Powered Plasma Antenna



High Powered Plasma Antennas

- We have tested a 2 megawatt pulsed power supply on a plasma antenna.
  - We found that in the transmitting mode, the plasma antenna was as efficient as a metal antenna for high power.
  - The plasma antenna has the added advantages of reconfigurability which a metal antenna does not have. This reconfirms what we found for lower powers.
- We have tested a megawatt power supply on a plasma antenna.
  - We used a pulsed power supply similar to the one used at the Naval Research Laboratory to generate megawatt radiation pulses with metal antennas. The design of the apparatus is shown in previous slide.
  - A section of 50 Ohm coaxial cable is charged to 25 Kilovolts. It then discharges through a spark gap into a second section of coaxial cable, then into four fluorescent lamps connected in series, forming a loop antenna.
  - Previous experiments have shown that if the pulse repetition rate is over a Kilohertz, the plasma in the fluorescent lamps is in essentially the steady-state The pulse of microwave radiation entering the plasma antenna radiates and is received on a small wire antenna about one meter away.

High Powered Plasma Antennas

- The received signal is about 5 Volts in amplitude. Since the input impedance of the antenna is 50 Ohms, as determined by terminating resistors, the received power is ½ Watt. The frequency of the radiation is about 13 Megahertz, in approximate agreement with the Naval Research Laboratory results with metal antennas.
- To calibrate the power output from the transmitter, we replaced the plasma antenna with a wire loop antenna of the same physical dimensions.
- We found that the received power from the pulsed power transmitter was the same as for the plasma antenna.

.

High Powered Plasma Antennas

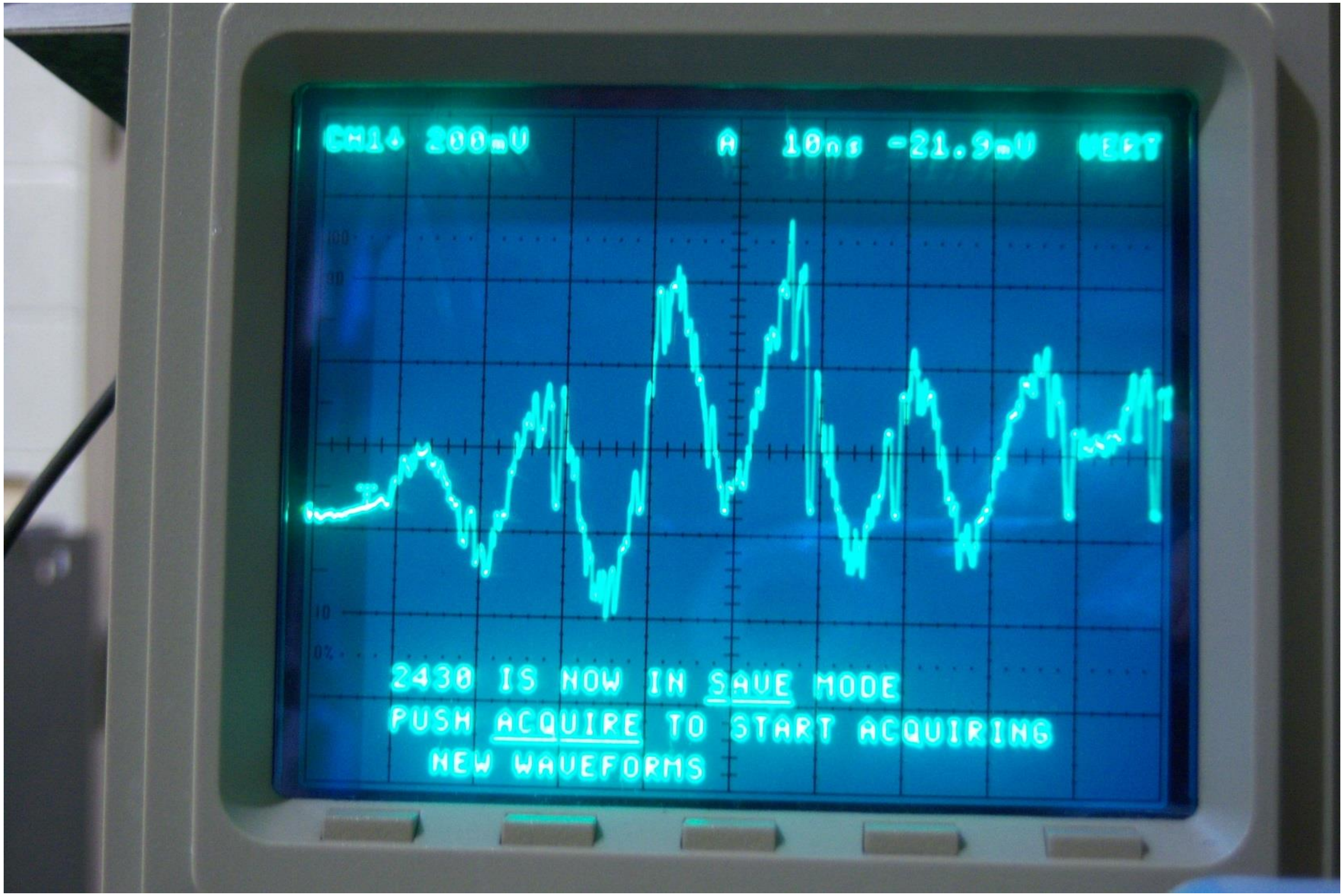
- We then disconnected the wire antenna from the pulsed power supply, and connected it to a 10 Megahertz transmitter, and measured the received power on a panoramic receiver.
- We then connected the transmitter directly into the panoramic receiver, adjusted the signal strength to the previous value, and recorded the attenuation needed to do so. The attenuation required was 70 decibels.
- If we multiply the power received from the pulsed power supply via the plasma antenna by 70 decibels, we get the radiated power from the plasma antenna to be **5 Megawatts**! This result is in agreement with the measured radiation output from the Naval Research Laboratory, except that they used a metal antenna, and we used a plasma antenna

High Powered Plasma Antennas

- The power output from the pulsed plasma antenna is impressive. We used a hand-held fluorescent lamp illuminated by radiation from the pulsed power supply.
- The radiation does not ignite the fluorescent lamp-it must be pre-ignited.
- In addition, we attempted to calibrate the plasma antenna by coupling in radiation from a 10 Megahertz oscillator.
- The oscillator was immediately destroyed, a result that would be expected for electronic warfare!

Megawatt Power Output

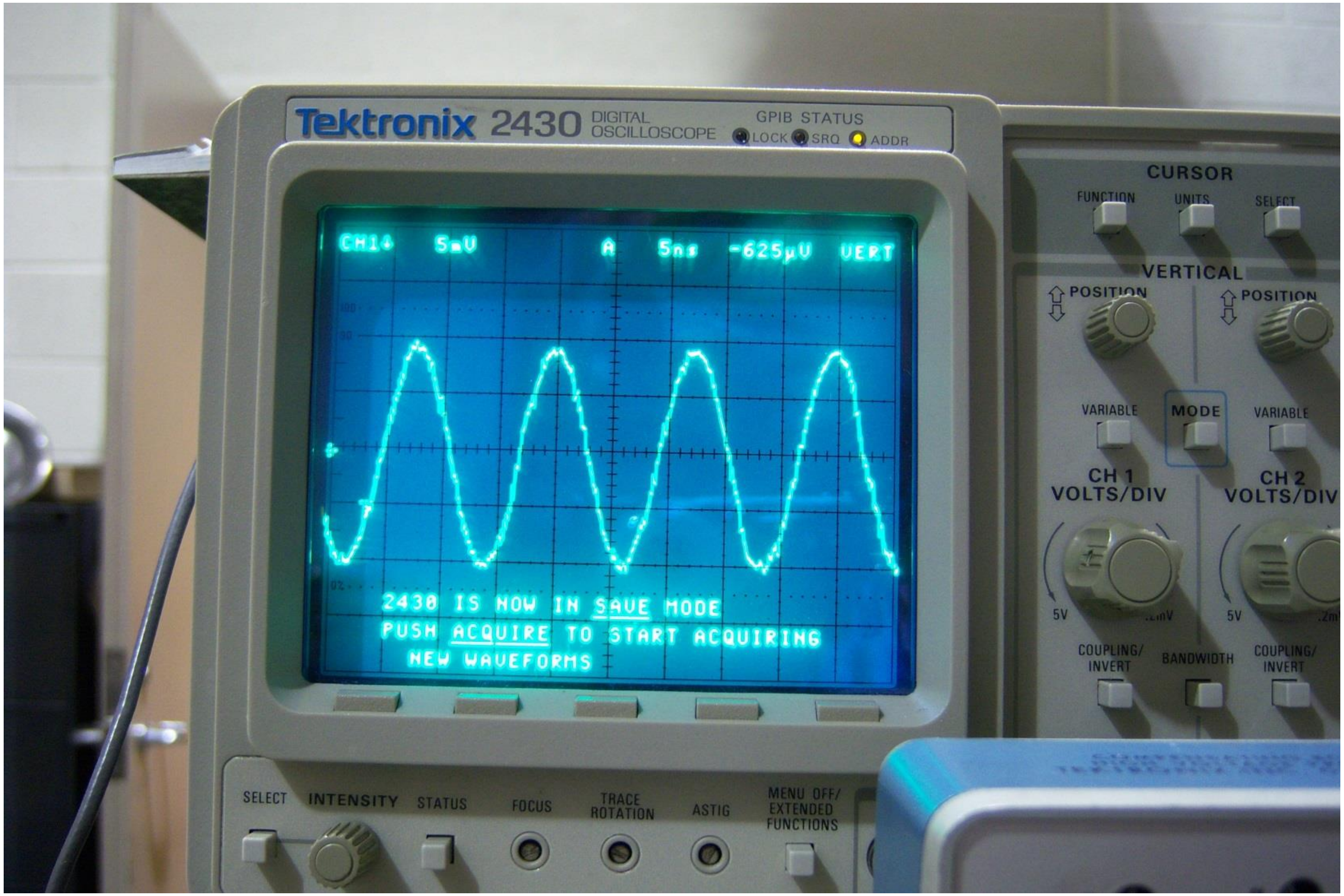
This is a repeat of one of the older slides showing the wavewform from our pulsed power system, but using the newer, digital oscilloscope. The time scale is shown on the screen.



2430 IS NOW IN SAVE MODE
PUSH ACQUIRE TO START ACQUIRING
NEW WAVEFORMS

Calibration Signal

This is a calibration slide using a local oscillator. It also uses the newer digital oscilloscope. The time scale is shown on the screen.



High Powered Plasma Antennas

Summary

We have constructed and tested a plasma antenna operating at a power level of Megawatts. We found that in the transmitting mode, the plasma antenna was as efficient as a metal antenna for high power. The plasma antenna has the added advantages of reconfigurability which a metal antenna does not have. This reconfirms what we found for lower powers

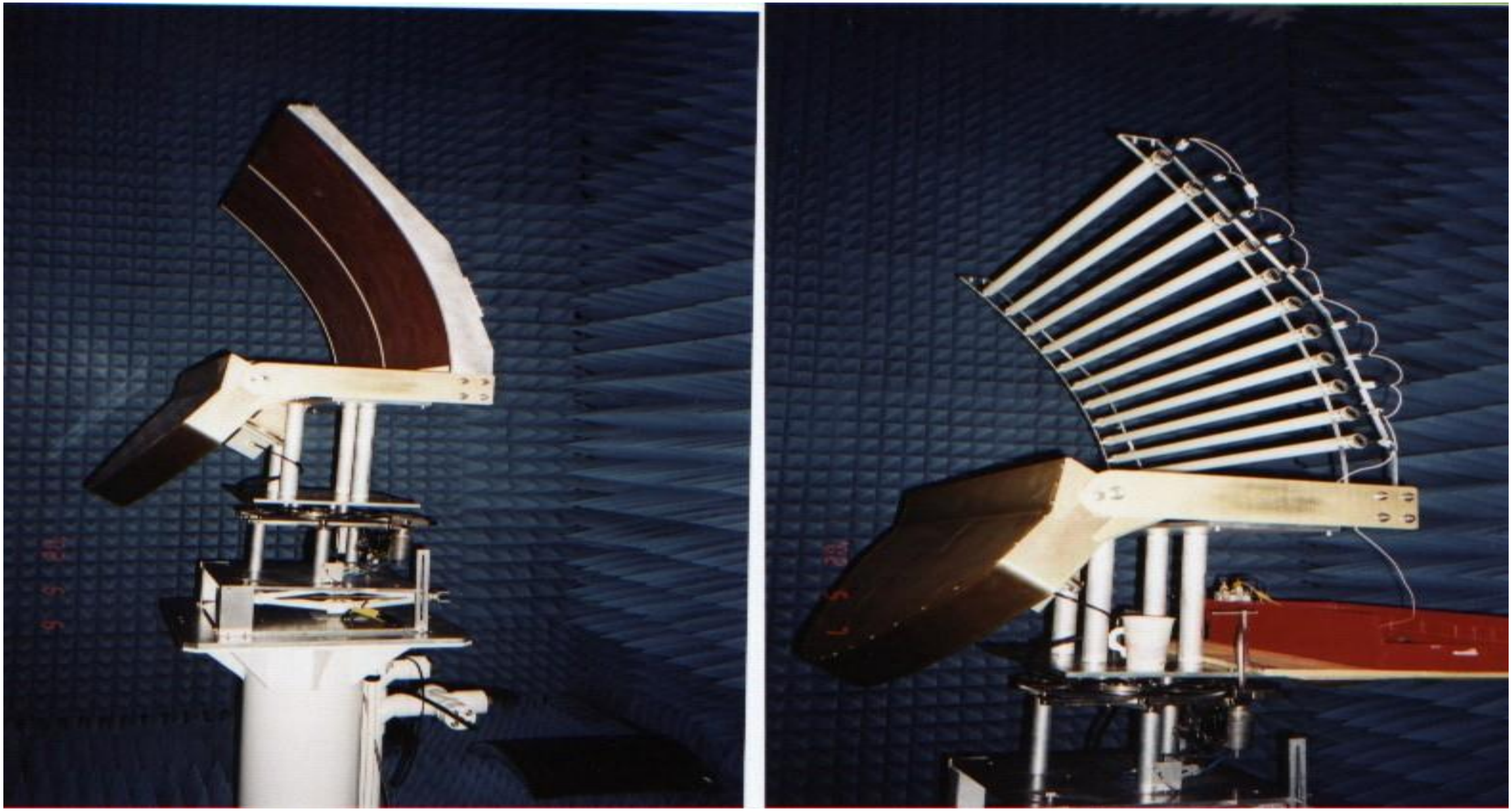
Satellite Plasma Antennas

Plasma Antenna Advantages over Metal Antennas as Satellite Antennas

- Plasma antennas have much less thermal noise than metal antennas at satellite frequencies.
  - Plasma antennas have higher data rates than corresponding metal antennas at satellite frequencies
- Plasma antennas are reconfigurable and metal antennas are not.
- An arrangement of plasma antennas can be flat and effectively parabolic.
  - Better for antenna aesthetics.
- An arrangement of plasma antennas can electronically focus and steer RF signals without phased arrays.
  - Applications for both static (e.g. Direct TV) and dish antennas attached to vehicles, ships, or aircraft.

Non-Steerable but Reconfigurable Plasma Reflector Antenna

Previous Work

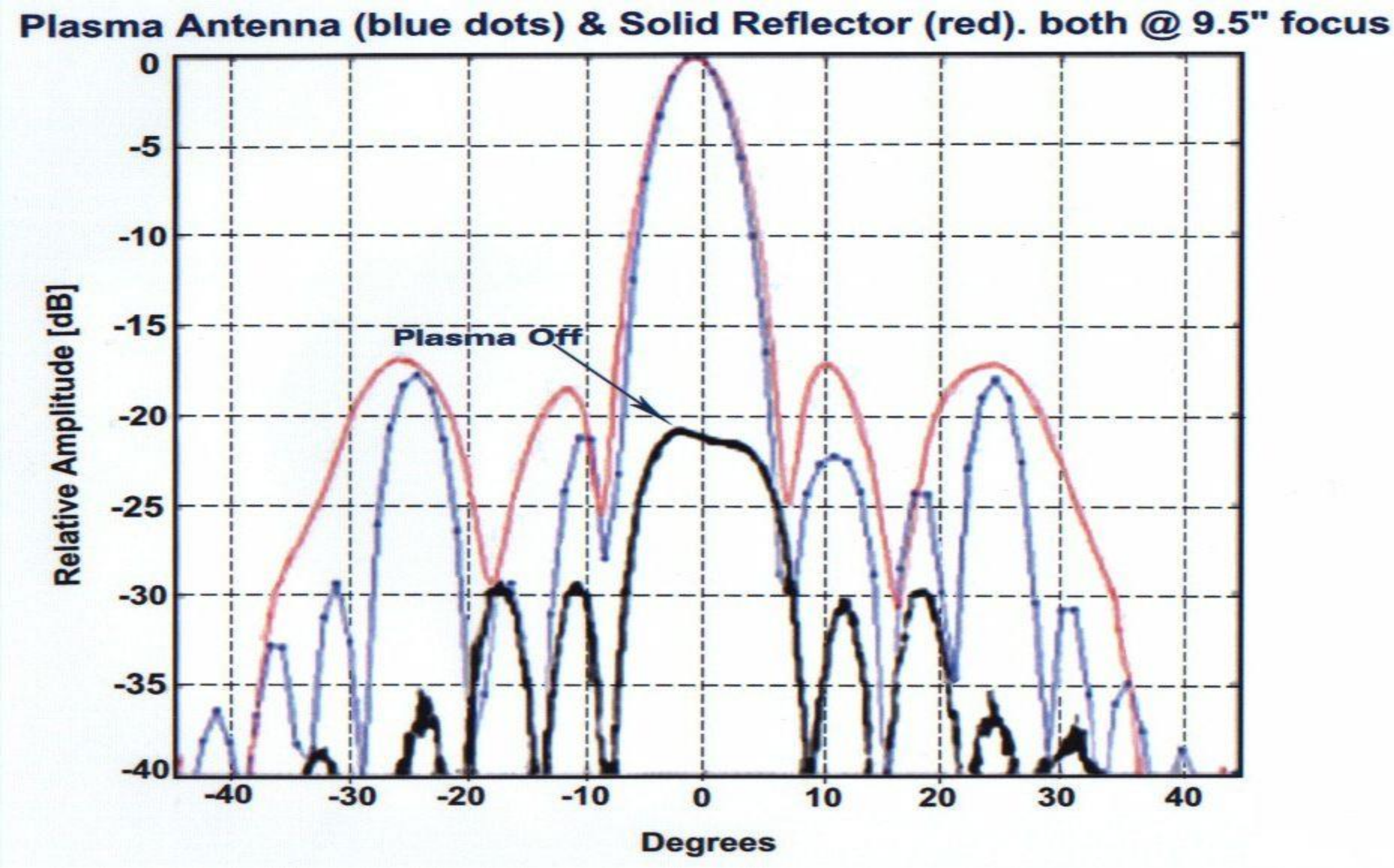


Plasma Reflector Antenna:

- **Right – plasma reflector antenna installed in an electrical anechoic chamber**
- **Left - metal reflector antenna designed to be an identical twin to the plasma antenna**
- **The microwaves are generated by a line antenna, focused in one dimension by the metal pillbox, and focused in the second dimension by either the plasma antenna or a metal twin**

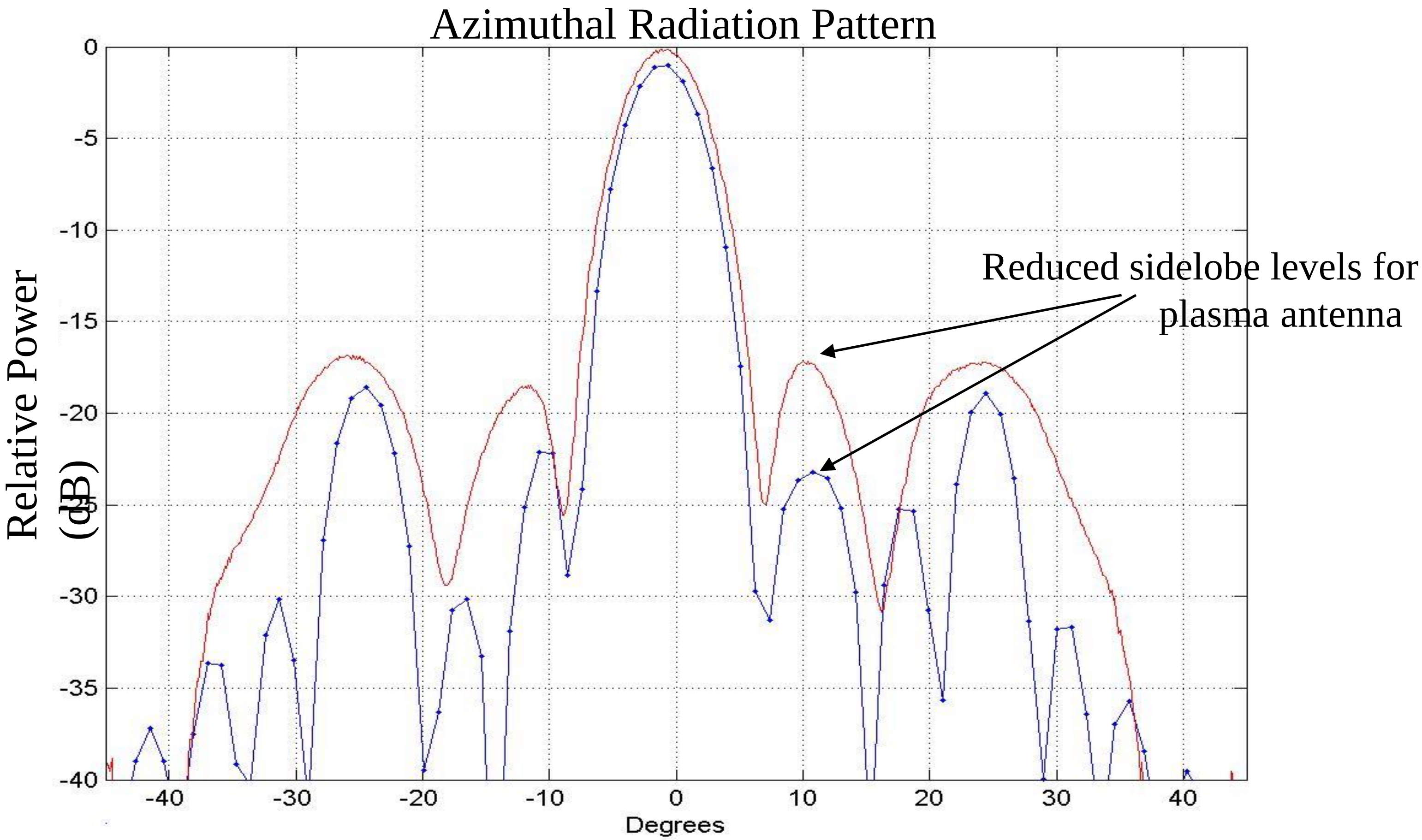
Non-Steerable but Reconfigurable Plasma Reflector Antenna

Radiation Pattern – Previous Slide



Non-Steerable but Reconfigurable Plasma Reflector Antenna.

Reduced sidelobes


Azimuthal Radiation Pattern

Reduced sidelobe levels for plasma antenna

Conclusions on Non-Steerable but Reconfigurable Plasma Reflector Antenna

- **The main lobe plasma reflector antenna is identical to the main lobe of the corresponding metal reflector antenna.**
- **When the plasma antenna is turned off it is invisible to all RF frequencies.**
- **The plasma reflector antenna can operate at lower frequencies and be stealth at high frequencies.**
  - higher frequency RF waves will pass through a lower density plasma.
- **The side lobes of the plasma reflector antenna are less than the side lobes of the corresponding metal reflector antenna.**
  - Soft surface effects of plasma

An Electronically Steerable and Focusing Plasma Reflector Antenna

New Work on Plasma Reflector Antennas

Some Physics of Plasma Transparency and Reflection

- The plasma frequency is proportional to the density of unbound electrons in the plasma or the amount of ionization in the plasma. The plasma frequency sometimes referred to a cutoff frequency is defined as:

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{me}}$$

where n_e is the density of unbound electrons, e is the charge on the

electron, and me is the mass of an electron

- If the incident RF frequency on the plasma is greater than the plasma frequency the EM radiation passes through the plasma and the plasma is transparent.

$$\omega > \omega_p$$

- When the opposite is true, plasma acts as a metal, and transmits and receives microwave radiation.

An Electronically Steerable and Focusing Plasma Reflector Antenna

- A plasma layer can reflect microwaves.
- A plane surface of plasma can steer and focus a microwave beam on a time scale of milliseconds.
- Definition of cutoff: the displacement current and the electron current cancel when electromagnetic waves impinge on a plasma surface. The electromagnetic waves are cutoff from penetrating the plasma

- The basic observation is that a layer of plasma beyond microwave cutoff reflects:
  - microwaves with a phase shift that depends on plasma density.

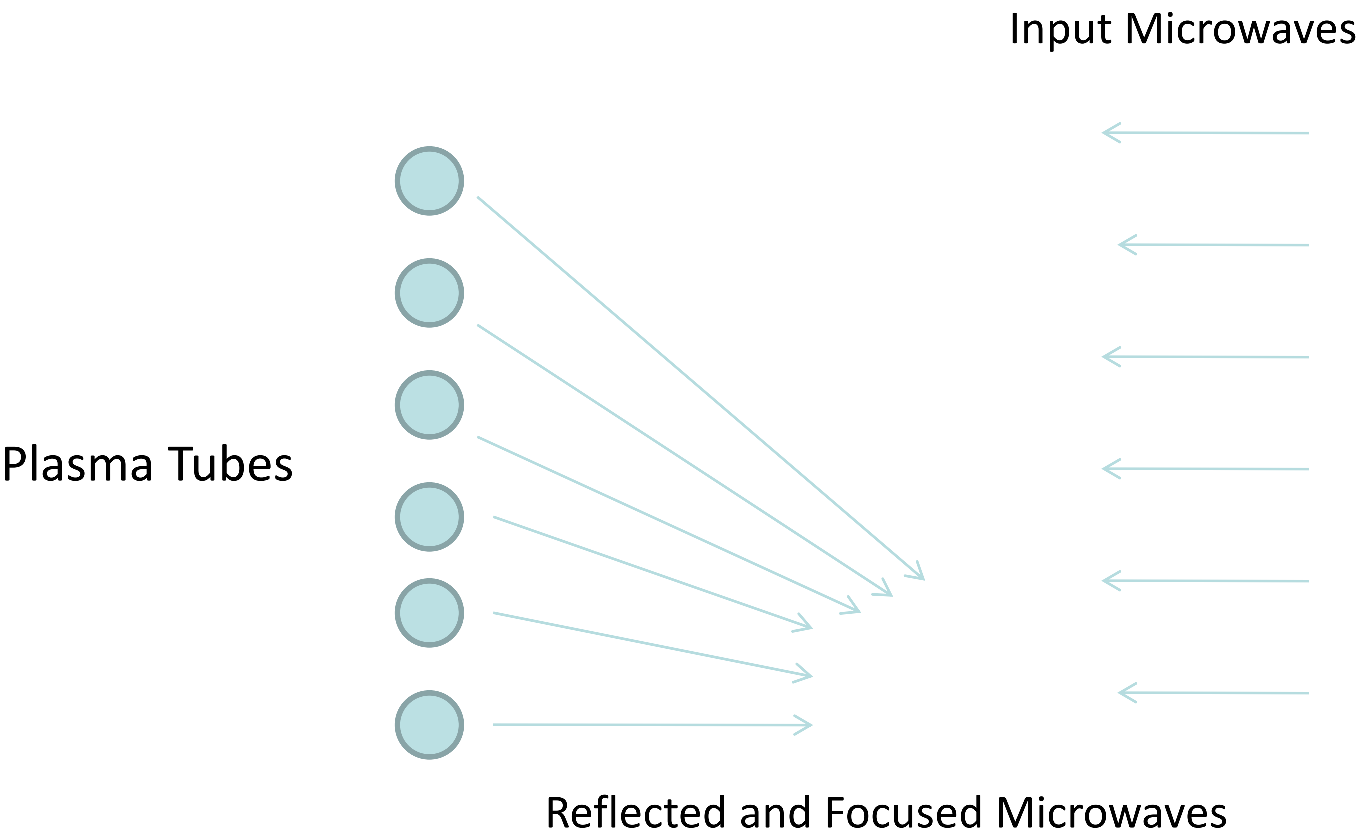
An Electronically Steerable and Focusing Plasma Reflector Antenna

- Exactly at cutoff, the displacement current and the electron current cancel
- Therefore there is a antinode at the plasma surface, and the electric field reflects in phase.
- As the plasma density increases from cutoff the reflected field increasingly reflects out of phase.
- Hence the reflected electromagnetic wave is phase shifted depending on the plasma density.
  - This is similar to the effects of phased array antennas with electronic steering except that the phase shifting and hence steering and focusing comes from varying the density of the plasma from one tube to the next and phase shifters used in phased array technology is not involved.

An Electronically Steerable and Focusing Plasma Reflector Antenna

- This allows us to use a layer of plasma tubes to reflect microwaves.
- By varying the plasma density in each tube, the phase of the reflected signal from each tube can be altered.
  - so the reflected signal can be steered and focused in analogy to what occurs in a phased array antenna.
- The steering and focusing of the mirror can occur on a time scale of milliseconds.

Schematic for an Electronically Steerable and Focusing Plasma Reflector Antenna



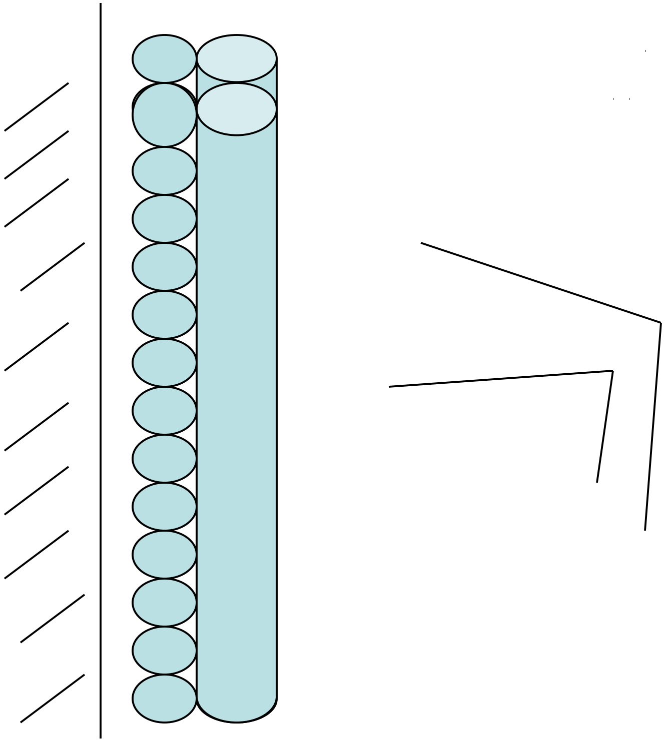
Input Microwaves

Plasma Tubes

Reflected and Focused Microwaves

Basic Plasma Satellite(other frequencies apply) Reflector Antenna Design with Two Banks of Perpendicular Plasma Tubes for Steering and/or focusing in Two Dimensions.

This system can apply to both a moving or static surface and steer and/or focus satellite signals by varying the plasma density among the plasma tubes with computer control in space and/or time.



Plasma satellite (other frequencies apply) antenna can be flush with a wall, roof, or any static or moving surface which can be flat or curved.

Receiving or transmitting Plasma or Metal Horn Antenna Carrying Signal to TV, etc.

This system eliminates the parabolic dish

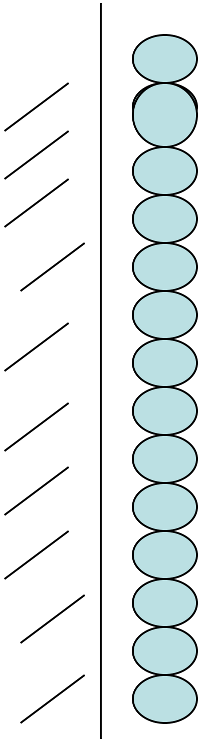
Tubes can be within a wavelength apart. Such a wavelength corresponds to the transmitted or received frequency.

This system can be completely encapsulated in Synfoam of an aesthetical shape.

Plasma in tubes into the page steer and/or focus satellite signals in the z direction. Plasma in tubes parallel to the page steer and/or focus satellite signals azimuthally.

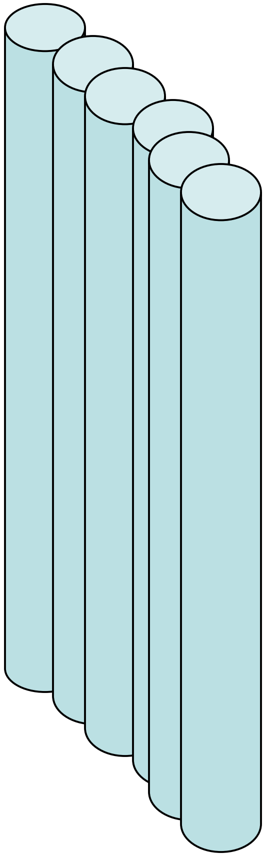
One dimensional (with one bank of tubes) steering and/or focusing may be enough for the static satellite plasma antenna.

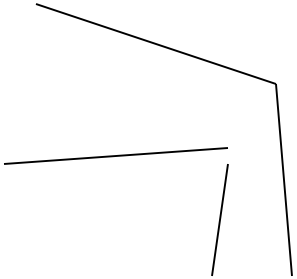
Banks of tubes containing plasma displaced and perpendicular to each other



Plasma satellite (other frequencies apply) antenna can be flush with a wall, roof, or any static or moving surface which can be flat or curved.

They can also be mounted in other ways





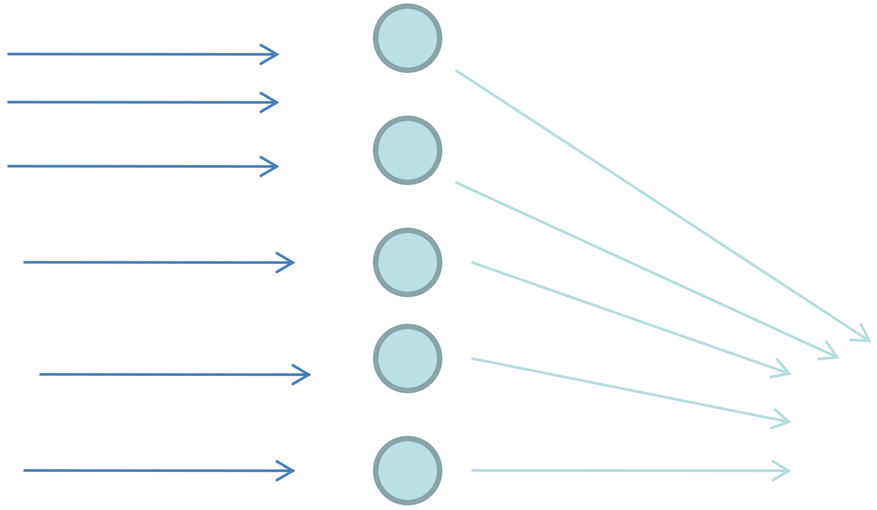
On the left a band of tubes containing plasma reflects EM waves and steers and focuses the beam in one direction. On the right a perpendicular bank of tubes containing plasma reflects and steers and focuses the EM waves in the perpendicular direction. A horn antenna in the lower right transmits or receives the EM waves. The banks of tubes containing plasma can be flush with a surface or supported in other ways

Steering and Focusing when the Plasma Density is Below Cutoff.

- Steering and focusing can also be achieved when the Plasma Density is below cutoff.
- An effective Snells Law causes refraction of electromagnetic waves passing through a plasma of variable density (plasma density varying from container to container containing plasma)
- The speed of electromagnetic waves in a plasma is a function of plasma density.

Steering and Focusing when the Plasma Density is Below Cutoff.

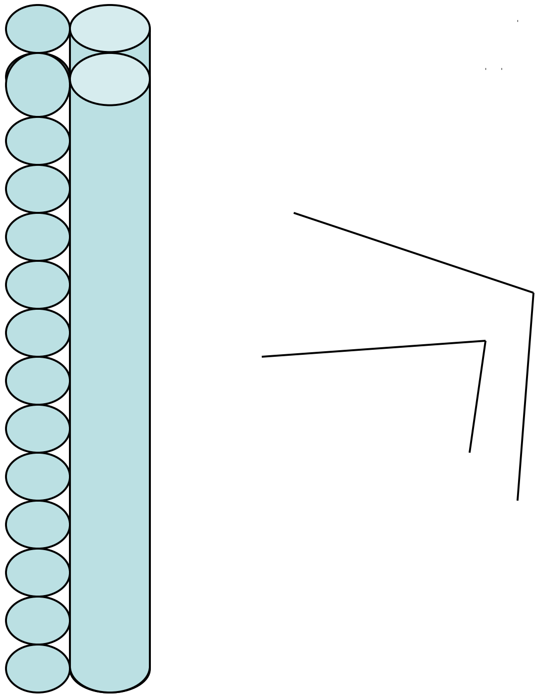
Incident RF waves on the left impinge on plasma tubes with different densities but with the plasma densities below cutoff. Focusing or steering can be achieved depending on how the plasma densities are varied from tube to tube.



Focused and/or steered Microwaves

Basic Plasma Satellite (works at other frequencies) Antenna Design with Two Banks of Perpendicular Plasma Tubes for Steering and/or focusing in Two Dimensions.

This system can apply to both a moving or static surface and steer and/or focus satellite signals by varying the plasma density among the plasma tubes with computer control in space and/or time.



Plasma satellite

(works at other frequencies) antenna is mounted between the received or transmitted antenna signals in which the two banks of tubes with plasma with variable density from one tube to the next to steer and focus the antenna beam.

Receiving or Transmitting Plasma or Metal Horn Antenna Carrying Signal to TV, etc.

This system eliminates the parabolic dish.

Tubes can be within a wavelength apart. Such a wavelength corresponds to the transmitted or received frequency.

This system can be completely encapsulated in Synfoam of an aesthetical shape.

Plasma in tubes into the page steer and/or focus satellite signals in the z direction. Plasma in tubes parallel to the page steer and/or focus satellite signals azimuthally.

One dimensional (with one bank of tubes) steering and/or focusing may be enough for the static satellite plasma antenna.

Conclusions

- An electronically steerable and focusing plasma reflector antenna can be made by having plasma densities in the tubes above cutoff but with the plasma densities varying from tube to tube.
- An electronically steerable and focusing bank of plasma tubes can be made by having plasma densities in the tubes below cutoff but with the plasma densities varying from tube to tube.
- Electronic steering and focusing in either of the above cases can be made in two dimensions by having two perpendicular banks of tubes.
  - This can also steer and focus horizontal, vertical, circular, and elliptically polarized signals.

Conclusions (continued)

- With plasma electronic steering and focusing:
  - parabolic reflector antennas are not needed.
  - is in many ways a superior alternative to electronic steering with phased arrays.
- At satellite frequencies the plasma antenna has much less thermal noise than metal antennas
- The plasma antenna can provide better performance satellite communications antennas than metal antennas.

Lab. Prototype Smart Plasma Antenna

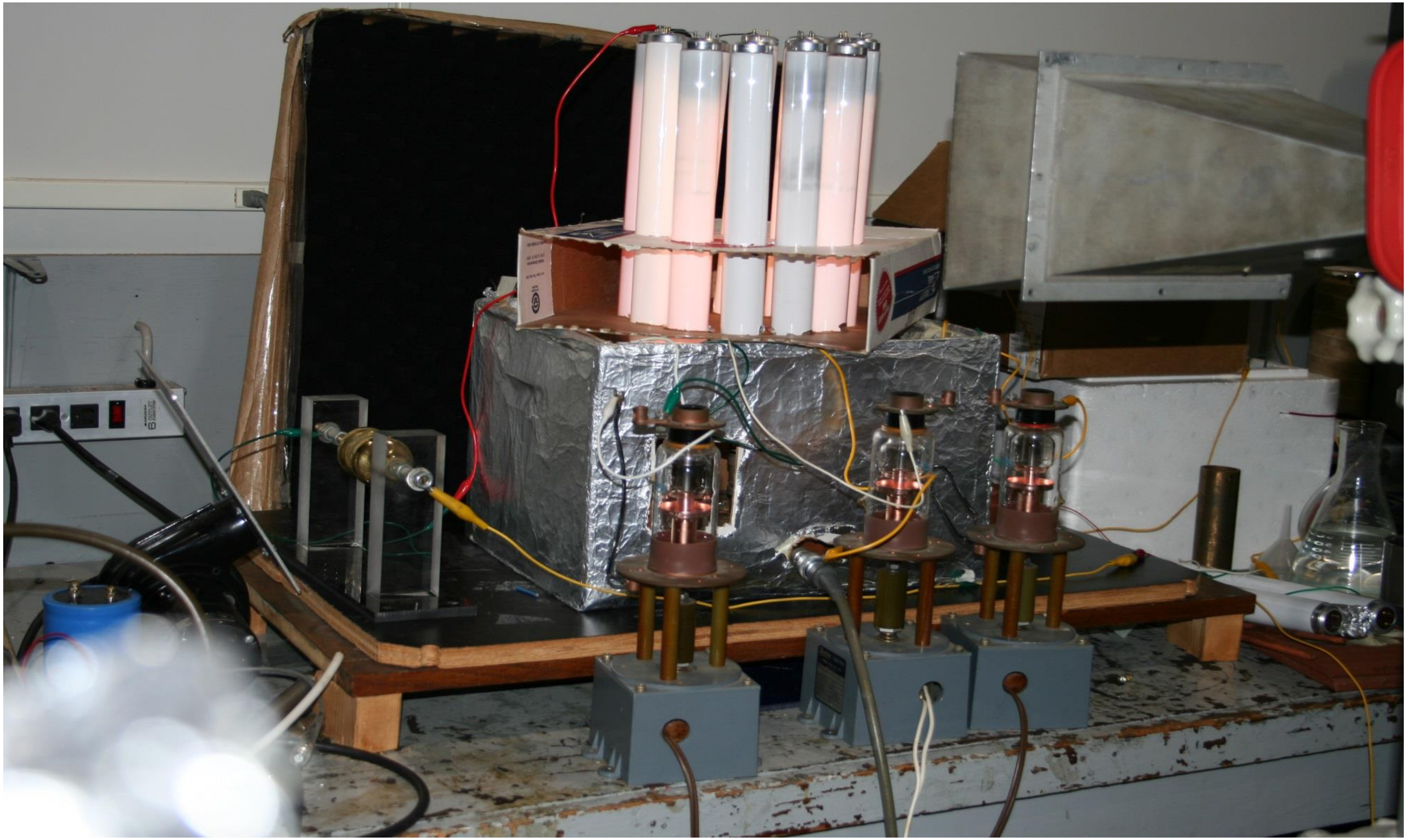
Lab. Prototype Smart Plasma Antenna

- A ring of plasma tubes operating beyond microwave cut-off surrounds a metal transmitting antenna.
- A computer de-energizes a plasma tube, causing a lobe of microwave radiation to be emitted.
- Sequentially de-energizing the plasma tubes causes the radiation lobe to scan in azimuth. When a receiving antenna is detected, the computer ceases scanning, and locks onto the receiving antenna.
- When the receiving antenna is disconnected, the computer recommences scanning, looking for another receiving antenna.

Lab. Prototype Smart Plasma Antenna

- The plasma tubes are common fluorescent lamps, operating in the cold-cathode mode and wired in series to a high-voltage DC supply. To de-energize a specific tube, it is short-circuited by a high voltage Jennings switch.
- The individual tubes are de-energized in sequence by a computer, custom designed by Impeccable Instruments.
- The signal is received on a simple diode detector, and is fed into the computer.
- When the received signal exceeds a designated, adjustable threshold, the computer ceases scanning, and holds this window open.
- If the received signal subsequently drops below this threshold, the computer recommences the scanning process.

Experimental Smart Plasma Antenna Lab Prototype



A plasma antenna can be more efficient (in the sense we can reconfigure the, beamwidth, directivity and gain) than a metal antenna

- Note that the plasma antenna concentrates the radiation from the omni-directional wire antenna into a lobe. This demonstrates that a plasma antenna can be made more efficient than a metal antenna!!
- More efficient in the sense we can reconfigure the, beamwidth, directivity and gain

Some Recent Basic Research Findings

We have demonstrated that plasma windows can open in microseconds.

1. If a closed ring of plasma tubes is excited by a signal with a wavelength comparable to the ring size, remarkable resonance effects can be observed.
2. At high plasma density, the radiation is transmitted through plasma tubes with a plasma density above CUT-OFF.
3. At intermediate density the radiation is CUT-OFF.
4. As the plasma density decays, the transmission rises to normal.
5. Such effects are only observed with a closed plasma ring.
6. These effects may be of great value in future applications.

We have demonstrated that plasma tubes intercept microwaves regardless of polarization.

- We have been designing a plasma shield intended to protect sensitive microwave equipment from intense electronic warfare signals.
- A layer of plasma tubes is used as a microwave reflector. The plasma tubes work extremely well in intercepting microwave radiation when the incident wave electric field is parallel to the tubes.
- However, if the electric field is perpendicular to the tubes, the normally induced plasma current cannot flow, and the plasma effects are not expected to appear.
- To our surprise, when the plasma tubes were experimentally tested with the electric field perpendicular to the tubes, the plasma tubes not only intercepted the microwave signal, but the observed cut-off with a pulsed plasma lasted about twice as long.

Summary on Recent Basic Research

- We have demonstrated that plasma windows can open in microseconds.
- We have demonstrated that plasma tubes intercept microwaves regardless of polarization.

Basic Mathematical Theory of Plasma Antennas: An Example

NET RADIATED POWER OF PLASMA ANTENNA

- The momentum equation for electron motion is:

$$m\left(\frac{d\vec{v}}{dt}+\nu\upsilon\right)=-e\left(Ee^{j\omega t}-\nabla\phi\right)$$

- The continuity of charge equation for electrons in the plasma antenna is:

$$\frac{\partial n}{\partial t}+n_0\frac{\partial v}{\partial t}=0$$

NET RADIATED POWER OF PLASMA ANTENNA

- Combining the momentum equation with the conservation of charge equation yields:

$$n = \frac{jn_0 e}{\omega(v - j\omega)}\left[\frac{\partial E}{\partial z} - \frac{\partial^2 \phi}{\partial z^2}\right]$$

- Now using Gauss's Law:

$$\frac{\partial^2 \phi}{\partial z^2} = \frac{en}{\varepsilon}$$

NET RADIATED POWER OF PLASMA ANTENNA

- The dielectric constant for the arcing in the plasma is:

$$\varepsilon = 1 - \frac{\omega^2{}_p}{\omega(\omega - jv)}$$

- Where the plasma frequency is:

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{me}}$$

NET RADIATED POWER OF PLASMA ANTENNA

- Integrating the electron density times the z coordinate over the length of the antenna which is in the z-direction yields the dipole moment of the plasma antenna

$$p = a \frac{e^2 n_0 E_0 d}{2m\left[\omega(\omega + jv) - \omega^2{}_p\right]}$$

- A triangular electric field which is a maximum at the feeds and vanishes at the ends of the tube is assumed.

NET RADIATED POWER OF PLASMA ANTENNA

- The total radiated power from the plasma antenna is proportional to the dipole moment times its complex conjugate:

$$P_{rad} = \frac{1}{2} a^{2} \frac{k^{2}\omega^{2}e^{4}n^{2}E^{2}{}_{0}}{24n\varepsilon c m^{2}\left[\left(\omega - \omega_{p}\right)^{2} + \upsilon^{2}\omega^{2}\right]}$$

$$= \left(\frac{\varepsilon_{0} a^{2}}{12\pi c}\right)(kd)^{2}\left(\frac{\omega_{p}{}^{2}}{\nu}\right)\frac{\left(\nu\omega E_{0}\right)^{2}}{\left[\left(\omega - \omega_{p}{}^{2}\right)^{2} + \nu^{2}\omega^{2}\right]}$$

CONCLUSIONS

- Plasma antennas are:
  - Reconfigurable in:
    - Beamwidth
    - Bandwidth
    - Directivity
  - Steerable without phase shifters and/or phased arrays
  - Resistant to EMI and electronic warfare.
  - Lower in side and back lobes
    - Soft surface effects of plasma
  - Lower in thermal noise than metal antennas
  - Stealth
- Plasma antenna arrays can be stacked
- Plasma antennas can be nested

Haleakala
Research and
Development, Inc.

Progress on Plasma Focusing

Dr. Ted Anderson, CEO of Haleakala R&D, Inc

Proprietary: April 2017

Summary of Achievements

- Re-designed the smart plasma antenna in two ways.
  - Same design but leakage problems fixed.
  - More compact design.
- Addressed EM leakage.
- Calculated directivities and gain.
- Achieved beam focusing, spreading, and steering with refraction of EM waves through a plasma.
- Reduced power needed to maintain ionization.
- Wrote code for computer controls.
- Reconfirmed plasma resonance

Improvements on Original Smart Plasma Antenna

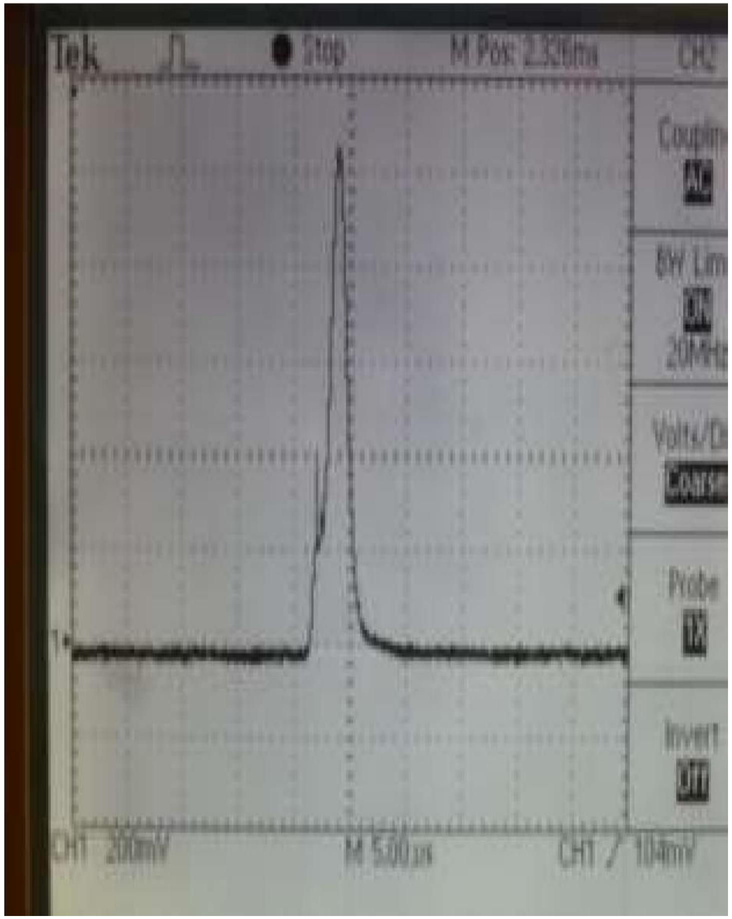
Improvements on Original Smart Plasma Antenna

- The cylindrical smart antenna works well at 2.4 GHz, but needed improvements.
  - When we measured the radiation pattern, we found that there was too much electromagnetic leakage through the tubes and the results show that the radiation patterns need to be sharper.
  - The solution to this is to increase the plasma density and remove the gaps between the plasma tubes.
    - To increase the plasma density and lower power requirements we have redesigned the pulsing circuit.

Improvements on Original Smart Plasma Antenna

- We realized after testing of our smart antenna (and further theoretical calculations) that we should be driving the plasma tubes with higher voltage and current.
- The maximum voltage and current capability had been 800 Volts (peak voltage) and 1 Ampere (peak current).
- We designed and built an improved high voltage pulsing circuit that will supply up to 3000 Volts (peak voltage) and 20 Amperes (peak current) ; a factor of 20 more current than is now possible with the smart antenna.

This figure shows a current pulse waveform from out new circuit. Peak current is 5 Amps with a pulse width of 4 microseconds. A Pearson precision current transformer (Fig. 2) is used to accurately measure current without interfering with the circuit.



Wave form of current pulse from new circuit.

Improvements on Original Smart Plasma Antenna

- Our initial work concentrated on eliminating issues that have caused our Smart Plasma Antenna to have less than optimal performance. The basic design and concept have not been changed.
- The plasma density has been increased by an order of magnitude by having a much higher peak current inside the tube. Average power dissipation remains low and there is very little heat generated.
- A small gap (~0.1 in.) between each tube has been closed by placing adjacent tubes in direct contact with each other.
- A new prototype was built using nine fluorescent tubes placed in a circle.
- A Zigbee 2.45 GHz transmitter with a ½ wave dipole is placed inside the circle of plasma tubes.

Improvements on Original Smart Plasma Antenna

- Another ½ wave dipole (for receiving) is placed ~ 3 ft from the side of the antenna and connected to a B&K Precision 3 GHz spectrum analyzer.
- Our experiments consisted of a smart plasma antenna transmitting to a receiving dipole connected to a spectrum analyzer.
- Higher pulse current was achieved by pulsing with a higher peak voltage (3000 V) and higher peak current 20 A compared to our original Smart Antenna. This original Smart Antenna has a peak current of 1 A and peak voltage of 800 V.

Improvements on Original Smart Plasma Antenna

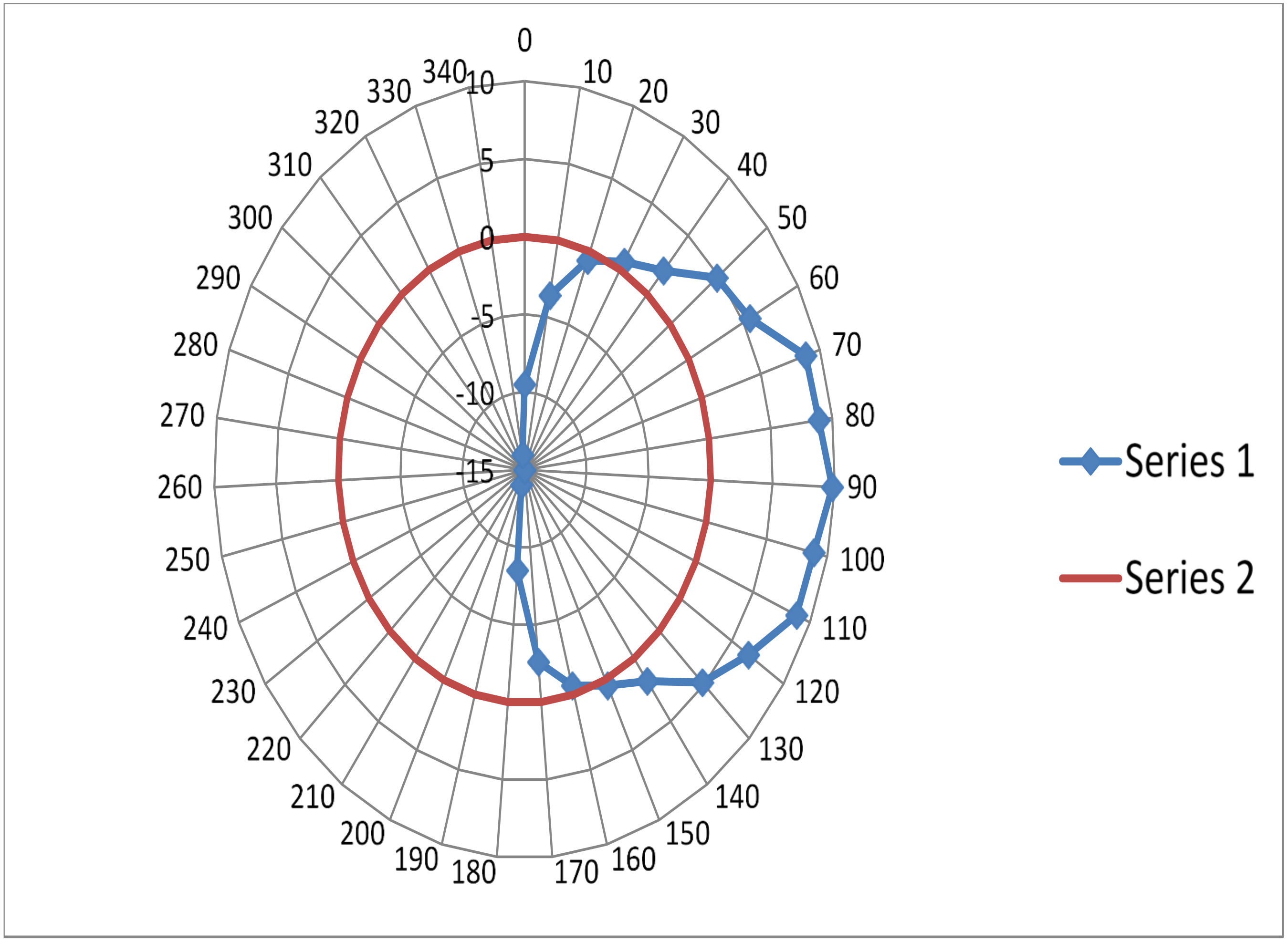
- Replaced Zigbee transmitter with video transmitter for higher power and narrower bandwitdth.
- The transmitter in the center of the smart antenna was a Zigbee 2.4 GHz with attached ½ wave dipole.
- This Zigbee transmitter is not the best device for our application:
  - It has low output power (for short range communication) and frequency-hops over a 2 MHz band; similar to WiFi devices. The low power and frequency shifting from the Zigbee transmitter limits our ability to accurately measure received power at the spectrum analyzer.

Improvements on Original Smart Plasma Antenna

- We used a higher power transmitter for video applications with a higher power of about 700 mW.
  - It is compact, battery operated and will fit easily into the center of the smart plasma antenna. This change allowed us to have better measurements for testing the radiation pattern.
- The dipole at the center of the array of plasma tubes was attached to an RF connector, enabling the antenna to be connected to a signal generator or spectrum analyzer.
- Therefore the antenna can be used as either a transmitter or receiver. Currently a 2.4 GHz transmitter is mounted inside the antenna along with the dipole.

Improvements on Original Smart Plasma Antenna

- In the next slide we show the results of these improvements.
- However, the radius is not optimized.
- There is leakage along the axis of the smart plasma antenna.
- There is leakage where the tubes touch since there is no plasma at these points.



Radiation Pattern (2.1 GHz). Unity gain is shown in red.

Gain 9.5 dB; f = 2.1 GHz; Optimum frequency was found experimentally by tuning the signal generator.
Signal power ~ 10 mW from signal generator.

Improvements on Original Smart Plasma Antenna

Conclusions

- We improved the results for by closing the gaps between the tubes and increasing the plasma density.
- As a result, the gain improved but by doing this we had to decrease the radius of the smart plasma antenna so that was no longer optimized.
- The only way to optimize all the parameters simultaneously is to use custom made plasma tubes for this purpose.
- Further optimizing can be done by using annular rings of plasma rather than tubes so that the plasma density in the cylindrical annular ring is uniform.
- Where the tubes touch, the plasma density and thickness is negligible and increases at the axes of the tubes.
- We redesigned the smart plasma antenna and developing new electronics and controls to increase the plasma density.

Improvements on Original Smart Plasma Antenna

Conclusions continued

- The pulsed DC power supplies are being packaged more ruggedly and mounted at the base of the plasma tubes. Shorter wire connections between the power supplies and tubes are resulting in less stray capacitance and faster rise and fall times.

Alternative Smart Plasma Design

- We also determined that we could make the smart plasma much smaller by building a 4 beam smart plasma antenna with 4 plasma windows at right angles and creating a single or multibeam plasma antenna by switching the plasma windows on or off.
- This also allows us to use horizontal tubes with vertical tubes superimposed on the horizontal tubes. This would enable transmission and reception of vertical, horizontal, and circular polarizations.

Reconfigurable Beam Lensing (beam focusing and spreading) and Reconfigurable Steering with Refraction through a Plasma

Beam Lensing and Steering with Refraction

- Antenna beam focusing, beam spreading, and beam steering using refraction of RF waves in a plasma.
- This is our first iteration of the plasma lens work and it can only improve. We found it was easier to show the lensing effects of plasma at 24 GHz since the size and shape of COTS plasma tubes are amenable to a 24 GHz.
- These effects all scale according to wavelength.
- Cylindrical annular rings of plasma are the best way to control the plasma density variations of plasma to optimize the engineering effects of plasma refraction to control beam focusing, beam spreading, and beam steering

Beam Lensing and Steering with Refraction

- We have demonstrated the ability to use a plasma for manipulation of antenna signals by focusing a wide beam into a more narrow beam and also by steering the beam.
- Shows the experimental set-up for beam steering and lensing. A narrow-beam 24 GHz signal is directed into the side of a 1.5 inch diameter plasma tube.
- Metal shields are on both sides of the plasma tube to block any extraneous signals from passing through the plasma tube.
- If the electron plasma frequency (wp) of the plasma is lower than the signal frequency (24 GHz in our case) then the phase velocity (V_p) of the signal is faster than the speed of light in a vacuum.
- V_p = C / (1- (wp/w)^2)$^{1/2}$ (ω = 2πf)

Beam Lensing and Steering with Refraction

- This change in velocity of the signal inside the plasma results in a lensing effect if the beam passes through varying lengths of plasma similar to light passing through glass of varying thickness to make a lens.
- But there is an important and interesting difference between an ordinary lens made of glass or plastic and a plasma lens:
- The glass lens slows-down the signal while a plasma lens speeds-up the signal.
- Therefore a convex glass lens focuses a signal to a point while a convex plasma diverges the signal similar to a concave glass lens that diverges the signal while a concave plasma lens focuses to a point.
- We have built converging and diverging plasma lenses using plasma tubes. A single plasma tube with the beam passing through its diameter acts as a diverging plasma lens and two plasma tube side-by-side form a converging (focusing) lens.
- ***Note: Plasma focusing lenses are concave and plasma spreading lenses are convex. The terms concave and convex in plasma lenses are opposite of the terms of lenses in optics.***

Beam Lensing and Steering with Refraction

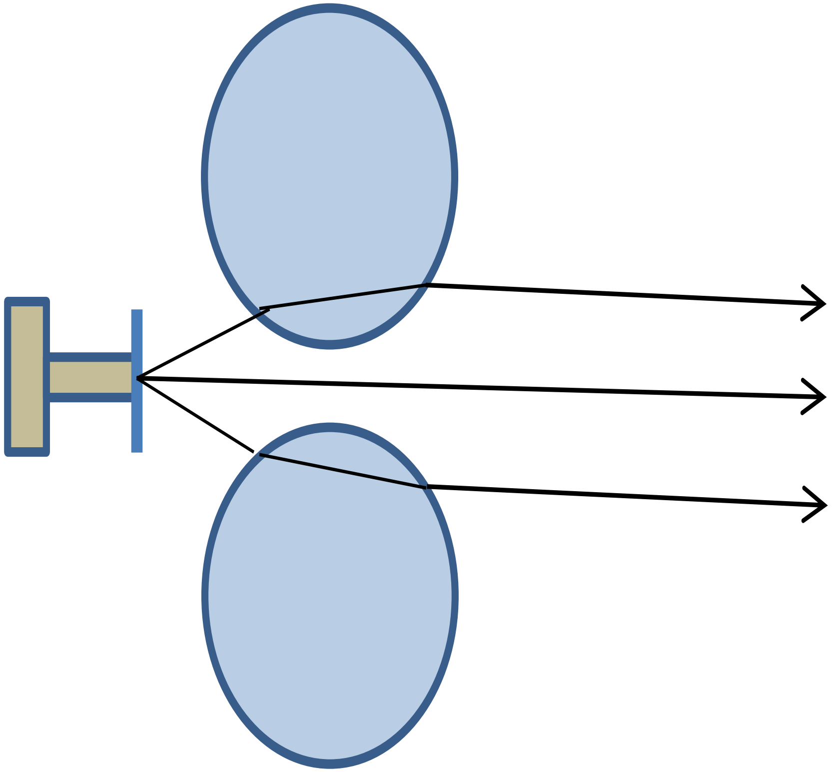
- We have built the focusing set-up for beam shown.
- A 24 GHz, 5 mW Gunn diode is used as the microwave source with the signal radiating from the open waveguide, which gives a unfocused microwave output.
- This setup allows us to focus the beam in the forward direction resulting in a gain of 2 (3 dB).
- This is our first iteration of the engineering of plasma lensing and it can only get better.

Beam Lensing and Steering with Refraction

- We are the only group that has utilized a pulsed high voltage power supply to give a much higher average plasma density.
- We show an interesting effect caused by the initial high plasma density at the time of the pulse followed by a decay in plasma density as ions drift to the wall.

Beam Lensing and Steering with Refraction

- In regard to a relatively lower pulse current:
  - The focusing effect occurs immediately after the current pulse but stops as current decreases.
  - Using a higher current (8 A), that best focusing occurs later after the pulse. These figures indicate that focusing can be “tuned” by changing density of the plasma inside the tube.
- This ability to tune the focusing of a RF beam is very useful because the same lensing structure can be used with different frequencies and plasma densities to vary focal length as needed.

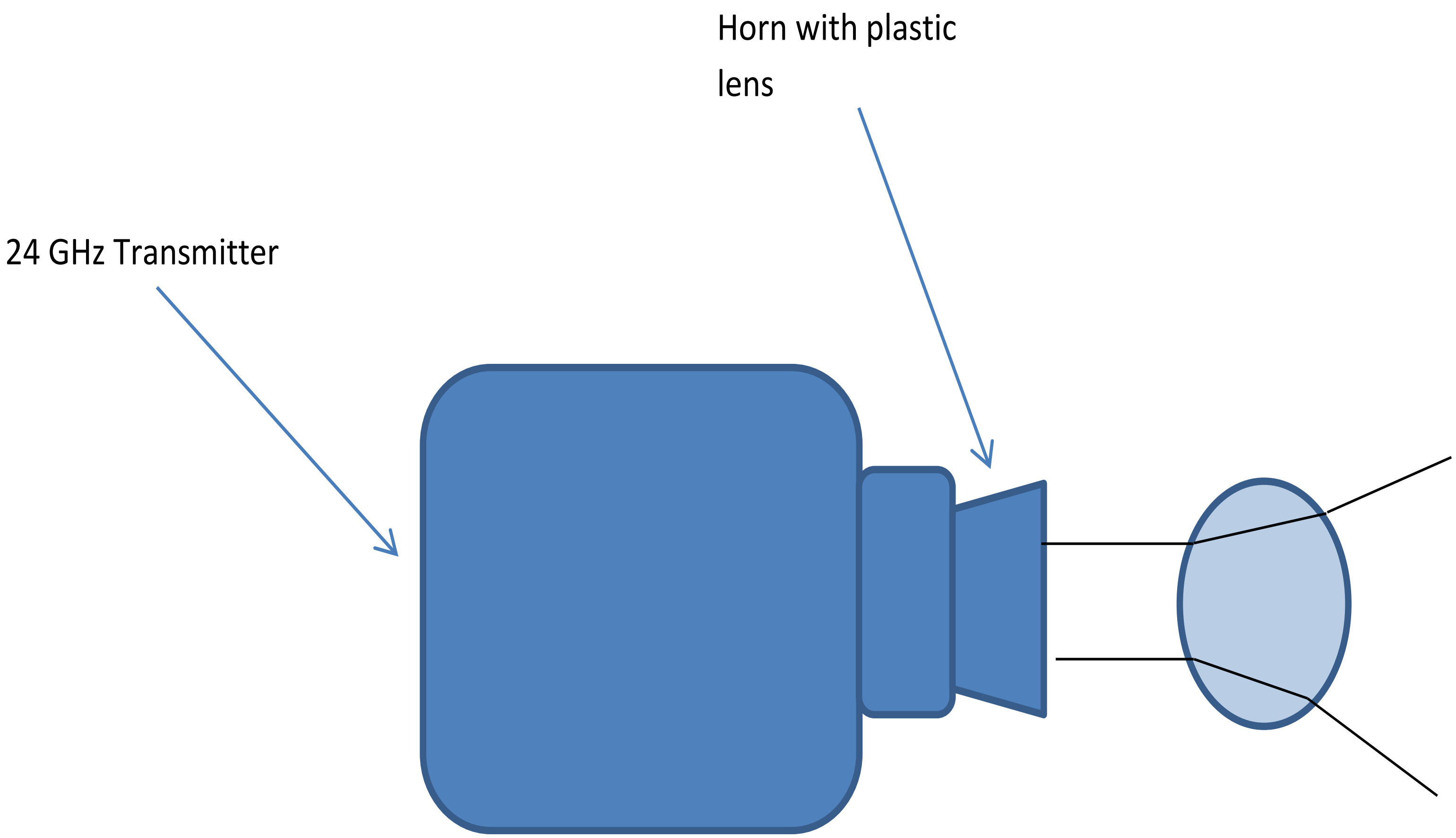


24 GH Diode

Transmitter

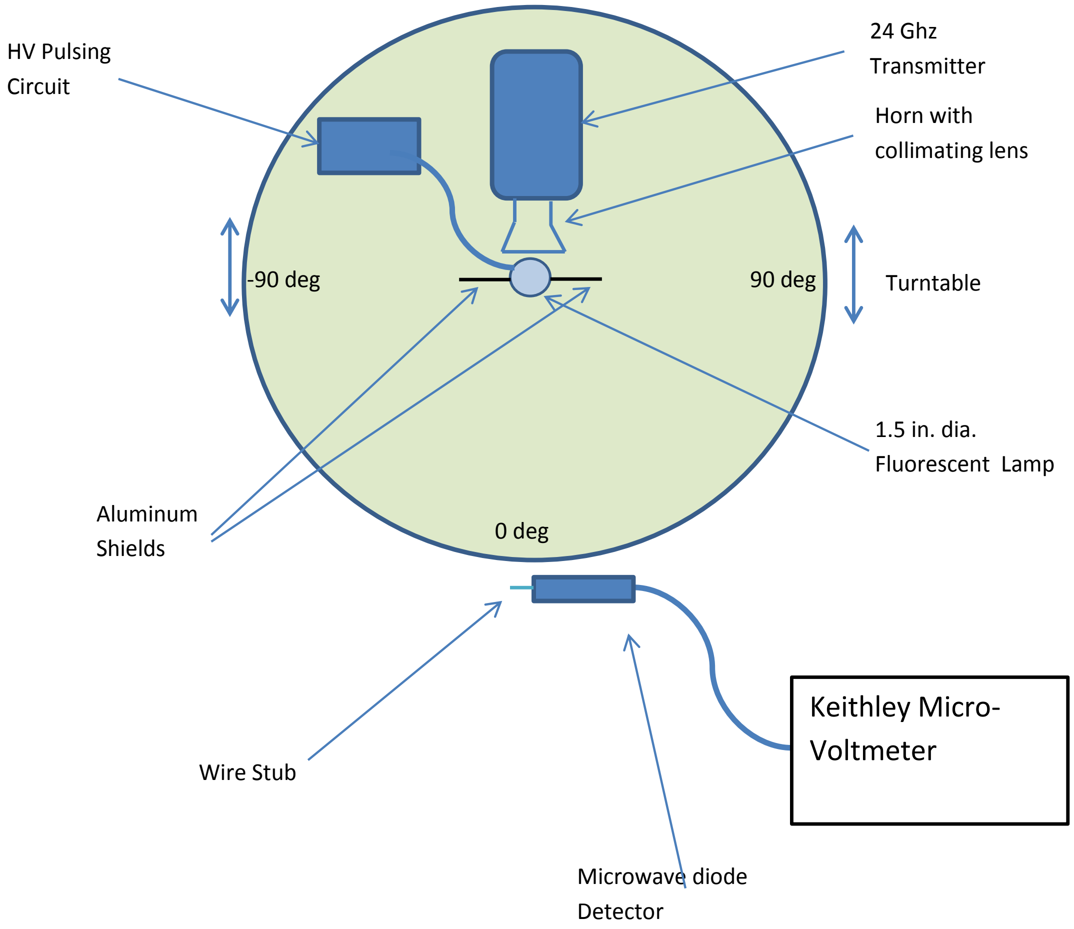
Fluorescent

Lamps 1.5 dia.



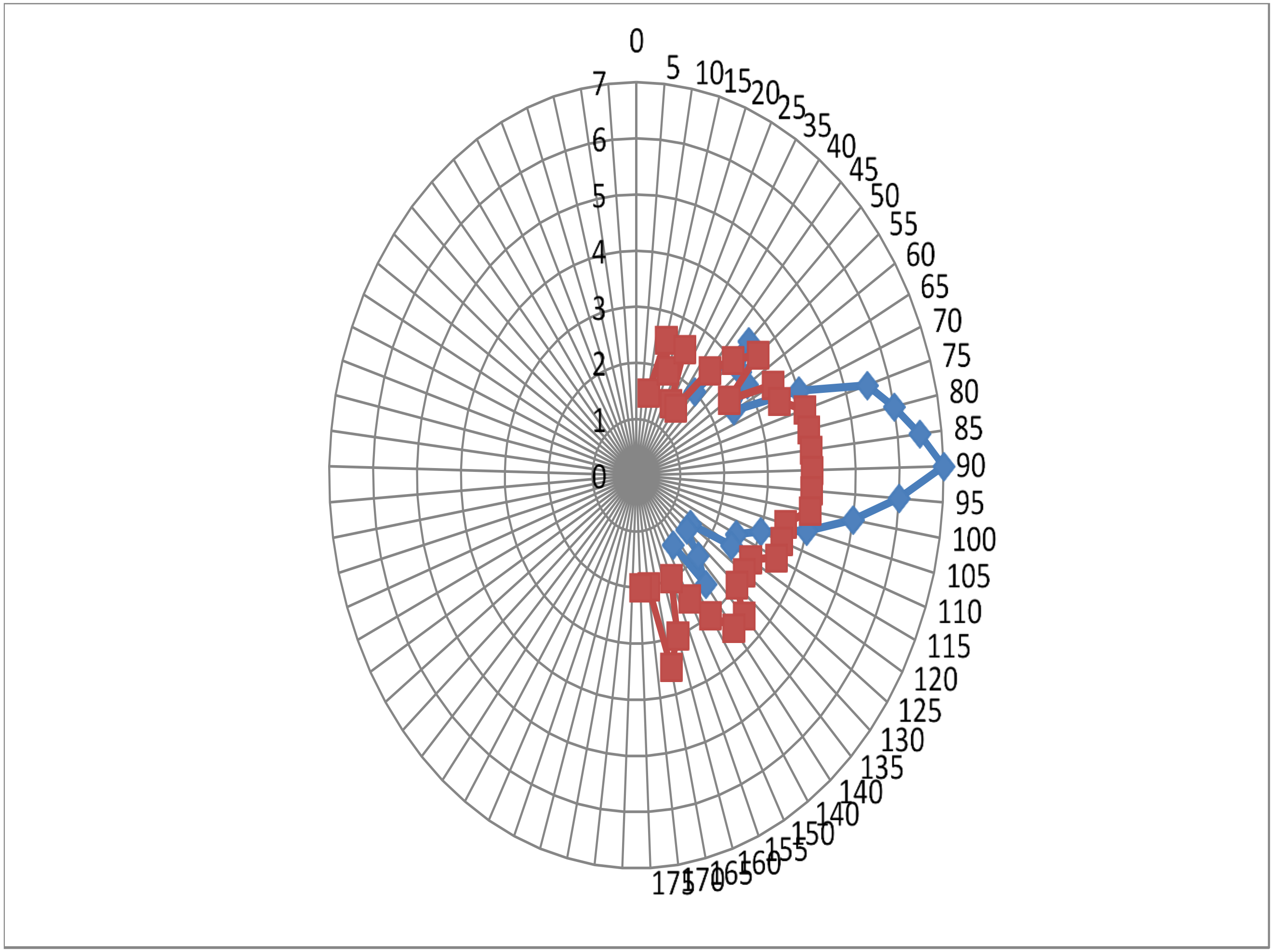
Horn with plastic lens

24 GHz Transmitter



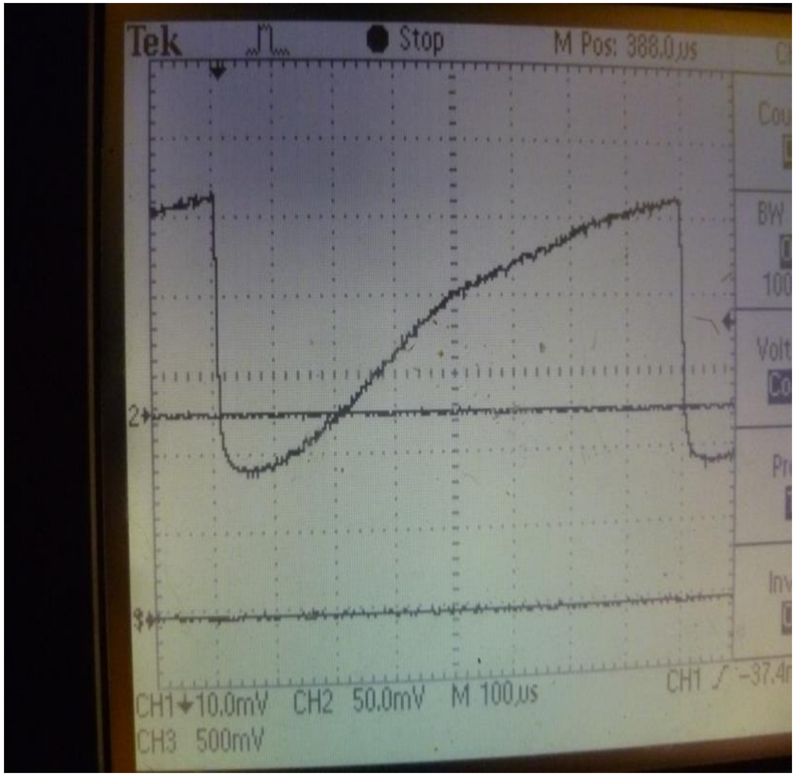
Set-up for measuring plasma lensing effect

Beam Focusing



24 GHz beam focus with plasma. Red line is with no plasma. Blue line is with plasma. Note that the plasma focus increases beam amplitude by a factor of two compared to no plasma (~3 dB gain)

Oscilloscope photo. Plasma beam focus at 24 GHz. Bottom trace is with microwave signal off. Middle line "2" is with plasma turned off. With plasma on, signal is increased by approx. a factor of two (3 dB) as shown in top trace



Beam Lensing and Steering with Refraction

- In the antenna beam focusing experiment, the beam passes through (and between) two side-by-side fluorescent bulbs.
- The flat trace at the bottom of the screen is the zero-level for the microwave signal as detected by an 18-26 GHz diode detector.
- The flat trace near the middle of the screen is the microwave signal with no plasma.
- The top trace shows the effect on the microwave beam caused by refraction and focusing caused by the plasma inside the tubes.

Beam Lensing and Steering with Refraction

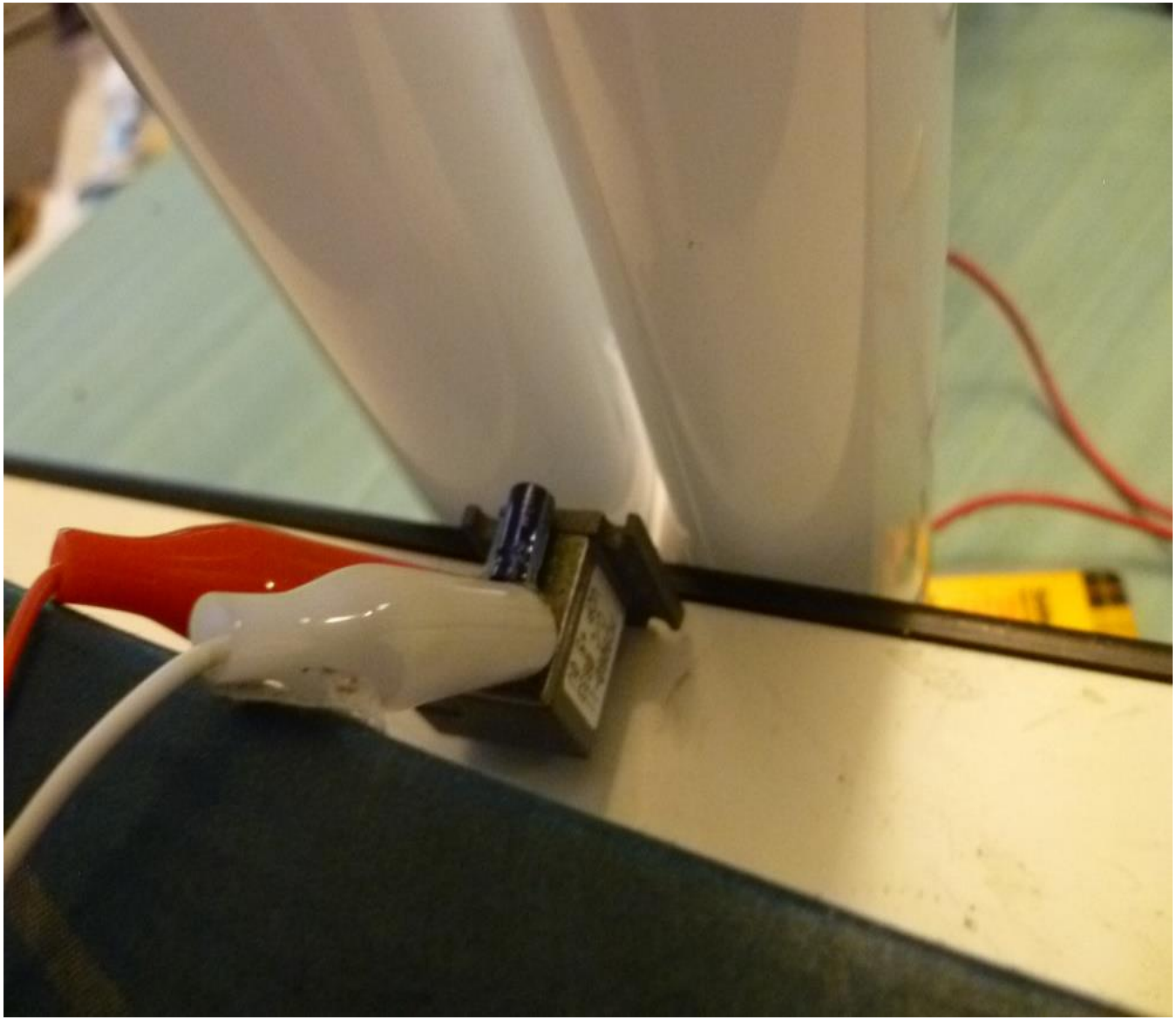
- The fast drop in amplitude (left of screen) coincides with a short current pulse (4 A, 5 µs).
- This relatively high current pulse produces a high plasma density that reflects most of the 24 GHz beam.
- The plasma ionizing current ends after 5 µs, but the plasma ion density takes much longer (1 ms) to decay; resulting in the increasing amplitude with time shown in the figure.
- The maximum signal amplitude (right side of trace) occurs when plasma density is optimum for focus of the beam; and gives a gain compared to unfocused signal of a factor of two (3 dB).

Beam Lensing and Steering with Refraction

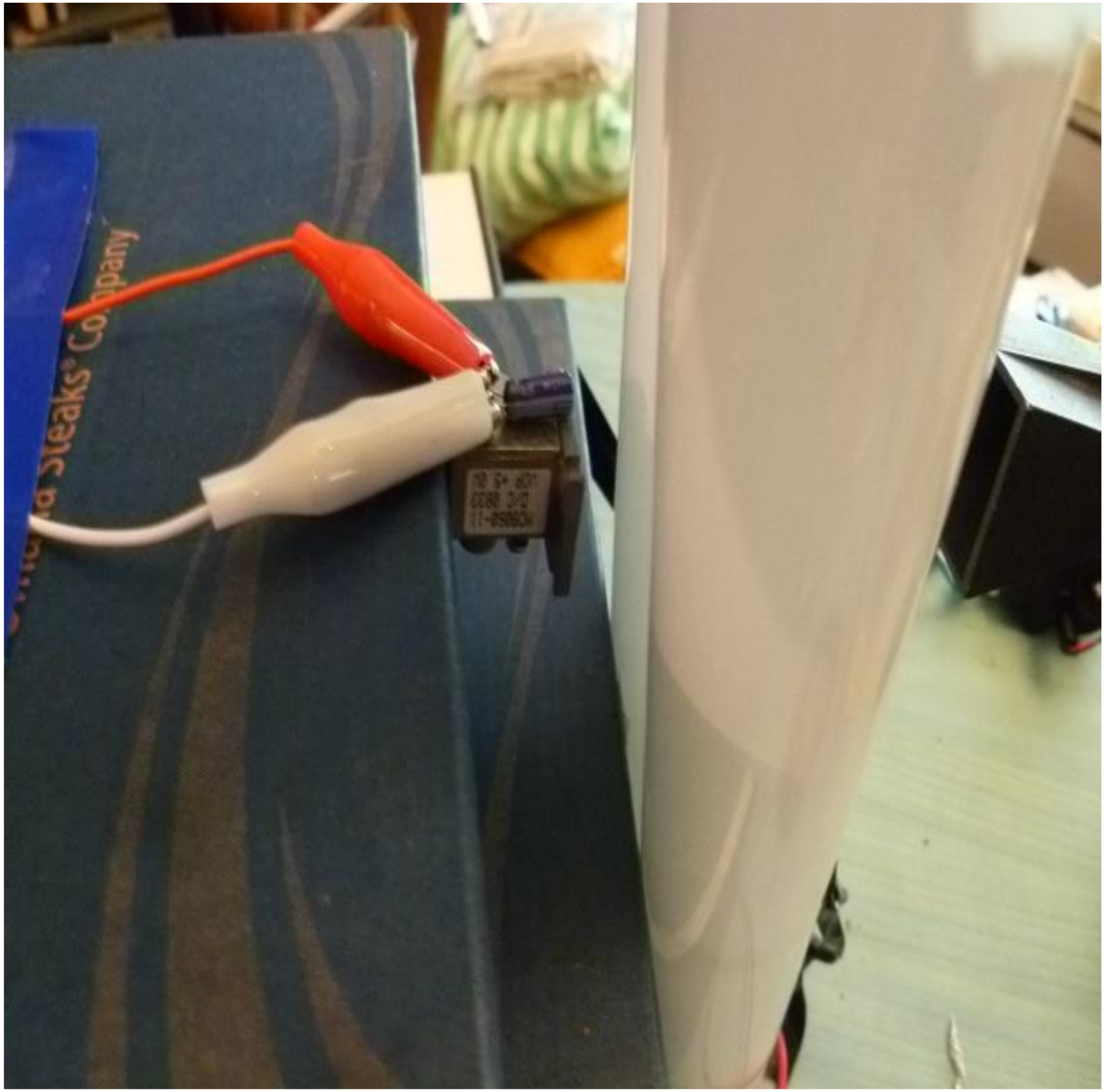
- We show the focusing effect of a relatively lower pulsed current (3 A). The beginning of each drop in signal level corresponds to the current pulse; resulting in a dip in signal level (reflection) that quickly recovers to more optimum focusing as plasma density decreases.

Beam Lensing and Steering with Refraction

- Peak Current in pulse vs DC from power supply
- Peak ionizing currents are rather high (2-20 A), but current required from the DC power supply is much lower:
- A 3 A pulse requires 15 mA DC from power supply.
- A 10 A pulse requires 40 mA DC from power supply.



. Plasma focusing experimental setup. Gunn diode 24 GHz transmitter with fluorescent tubes used for plasma beam focus.



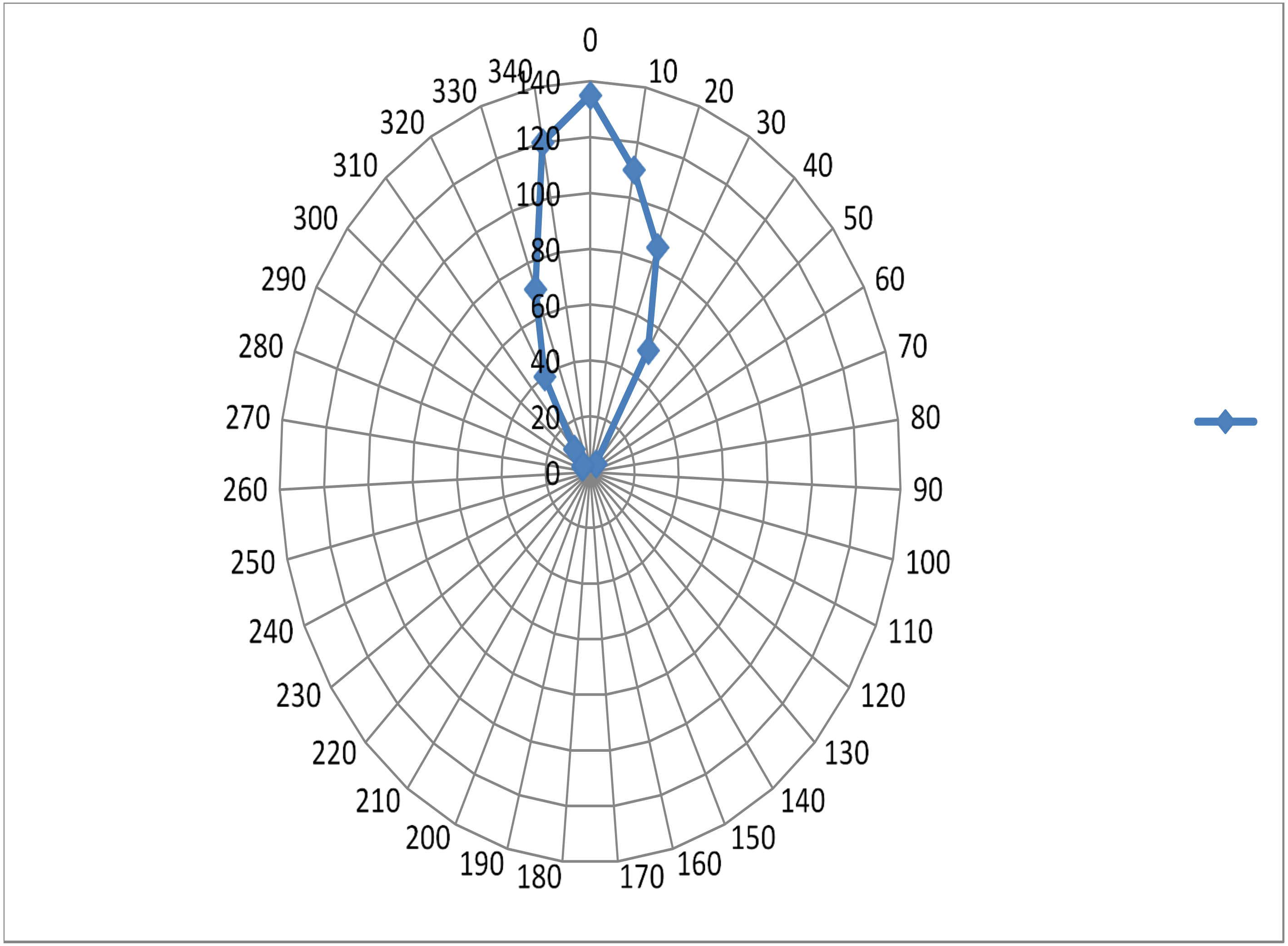
. Plasma focusing experimental setup. Gunn diode 24 GHz transmitter with fluorescent tubes used for plasma beam focus.

Beam Spreading

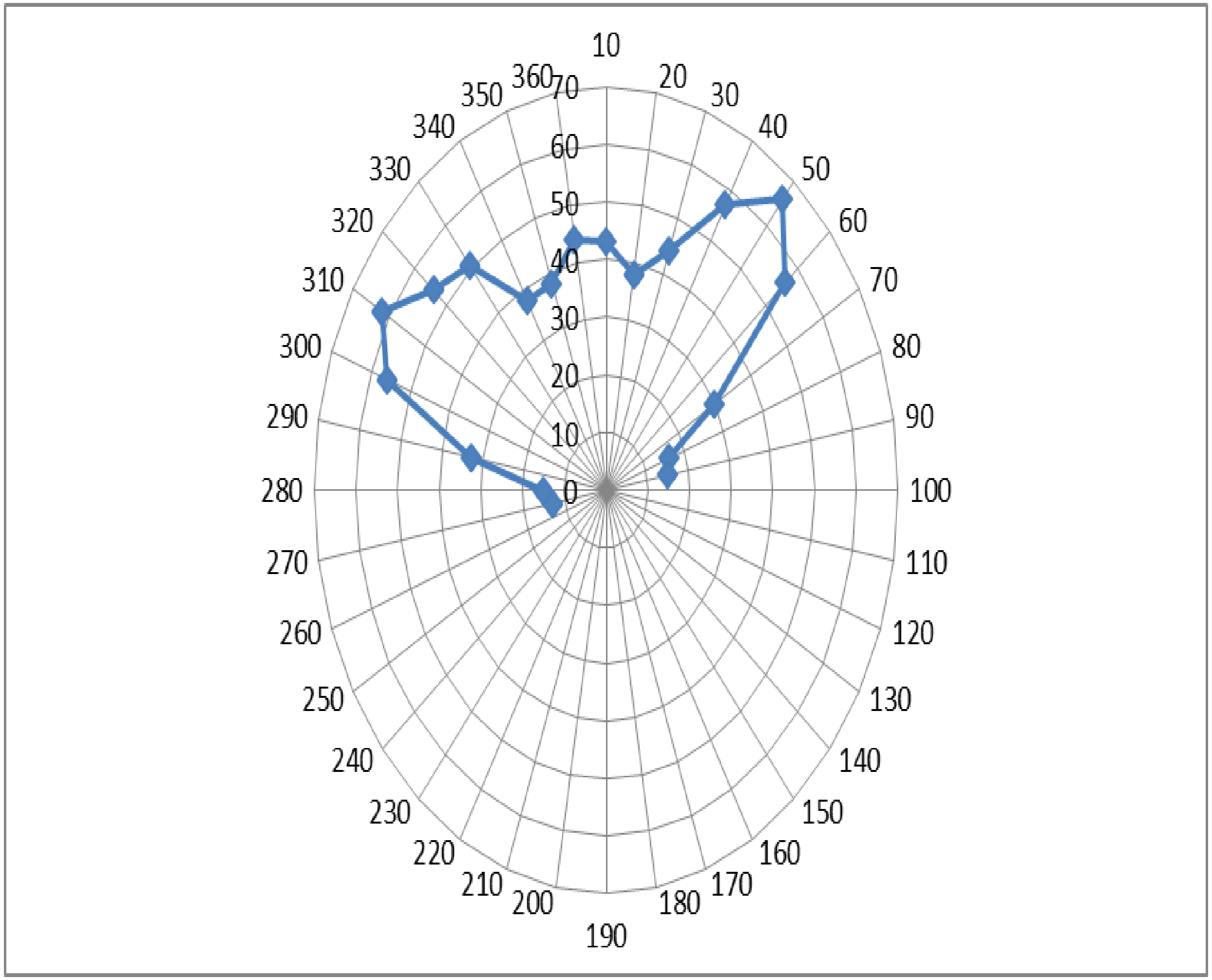
Beam Lensing and Steering with Refraction

Beam Spreading

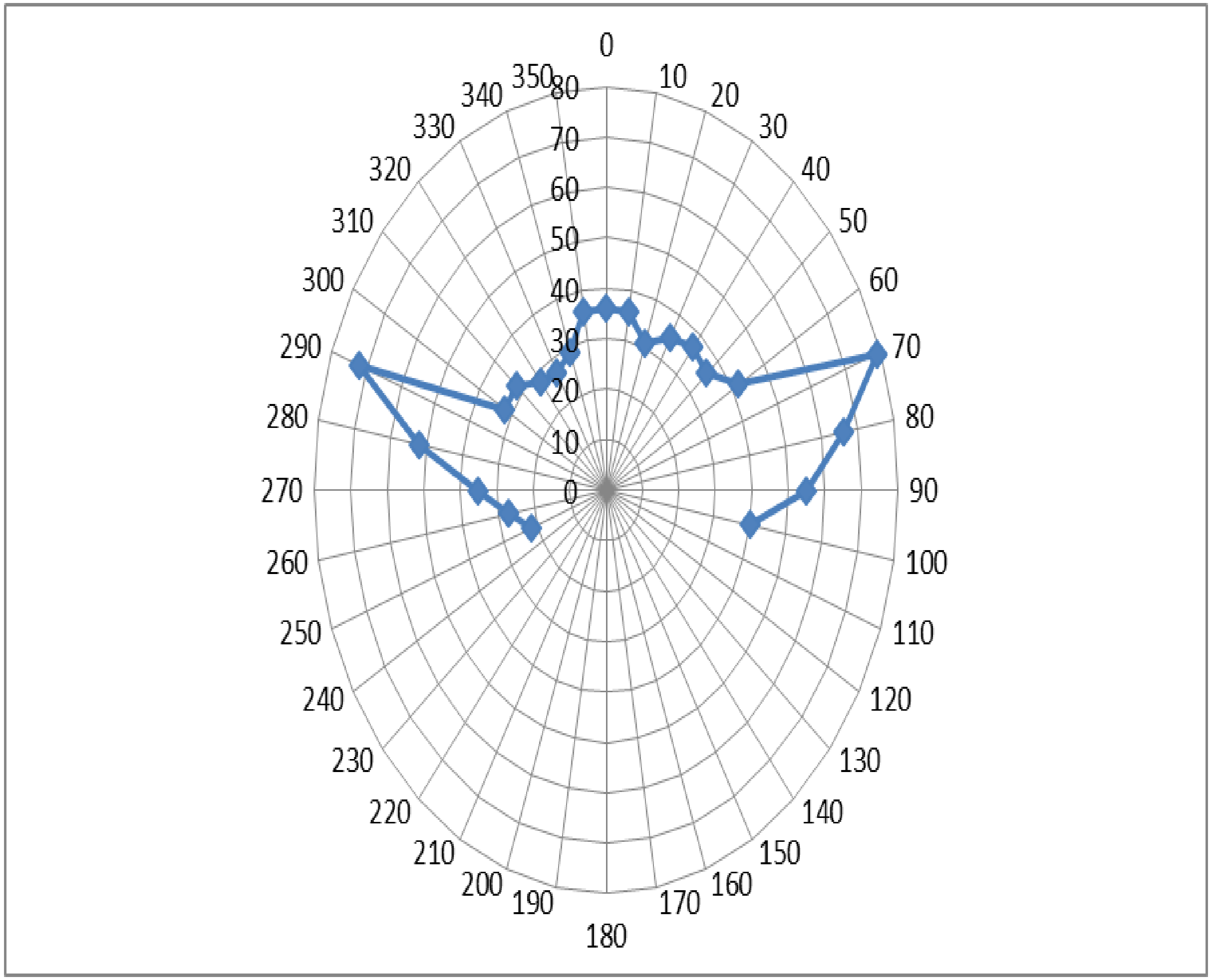
- A single plasma tube acts as a convex plasma lens.
- We show radiation pattern with no plasma.
- The transmitter with horn radiates a rather narrow beam.
- With the plasma turned on to a peak current of 6 A we show beam spreading.
- The narrow forward beam has now been spread by the convex plasma lens!
- When peak plasma current is increased to 15 A, the beam spreads even more.



Radiation pattern with plasma tube turned off.



Radiation Pattern. Peak current 6 Amp.



Beam spreading radiation pattern. Current 15 A peak

Beam Steering with Focusing

Beam Lensing and Steering with Refraction

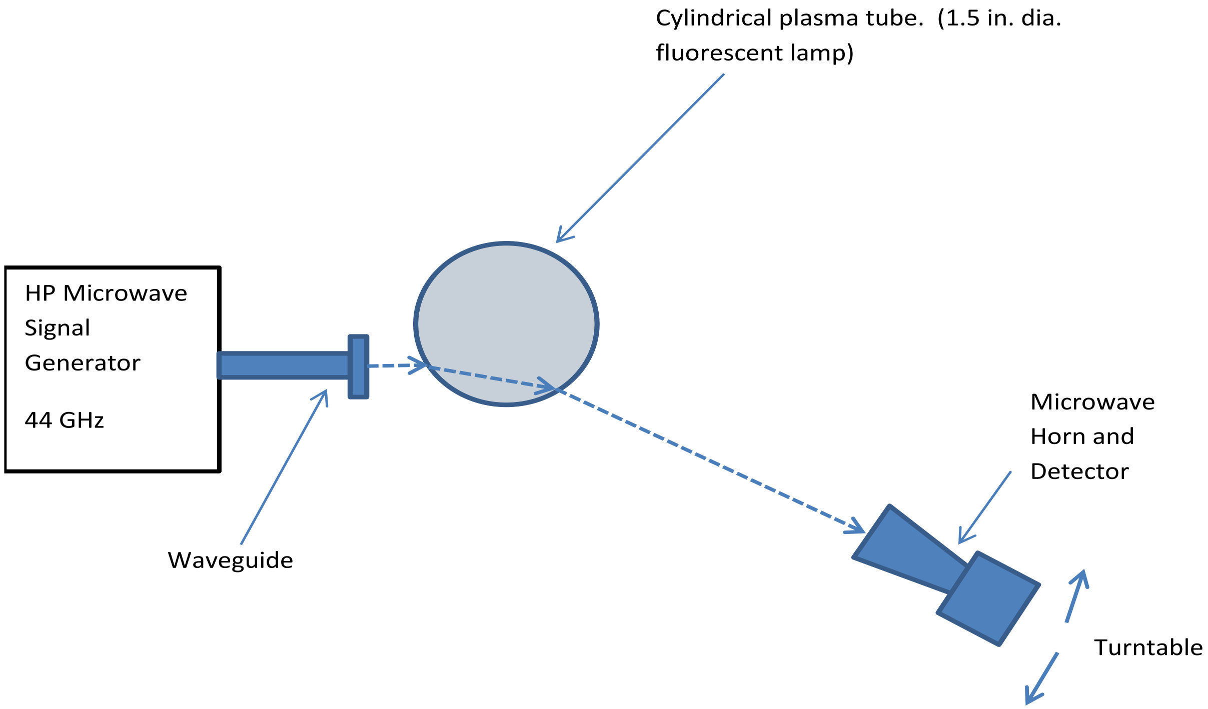
- Our beam steering testing has shown surprisingly positive results. We expected to see steering angle change as plasma current is varied; but we did not expect to see the observed very narrow deflected beam (compared to the incident signal beam-width) emerging from the plasma.
- These are of course very good and encouraging results, but we need to do further testing to confirm that there is not another process going on that we are unaware of.
- We will modify our current pulsing circuit to deliver the high current pulses with a shorter period of less than 100 µs. This should eliminate the need to monitor the signal corresponding to maximum plasma density. We can instead simply record the average receive signal level.

Beam Lensing and Steering with Refraction

- We will also increase signal frequency to 50 GHz, the maximum generated by the HP microwave oscillator.
- Maximum frequency has been limited to 44 GHz because of the relatively low sensitivity of the horn / detector combination at the high end of the frequency range.
- We will use a more directional horn or more sensitive detector as required for improved signal to noise at 50 GHz.

Beam Lensing and Steering with Refraction

- A new much higher frequency application for WiFi is in the range of 70 GHz and is sometimes called WiGig.
- We will obtain a signal source in this range in order to begin testing in this new and interesting millimeter wave application.
- As far as we know, we are the first and only researchers in the world who are using plasma selective surfaces in the millimeter wave range above 30 GHz.



Cylindrical plasma tube. (1.5 in. dia. fluorescent lamp)

HP Microwave
Signal
Generator

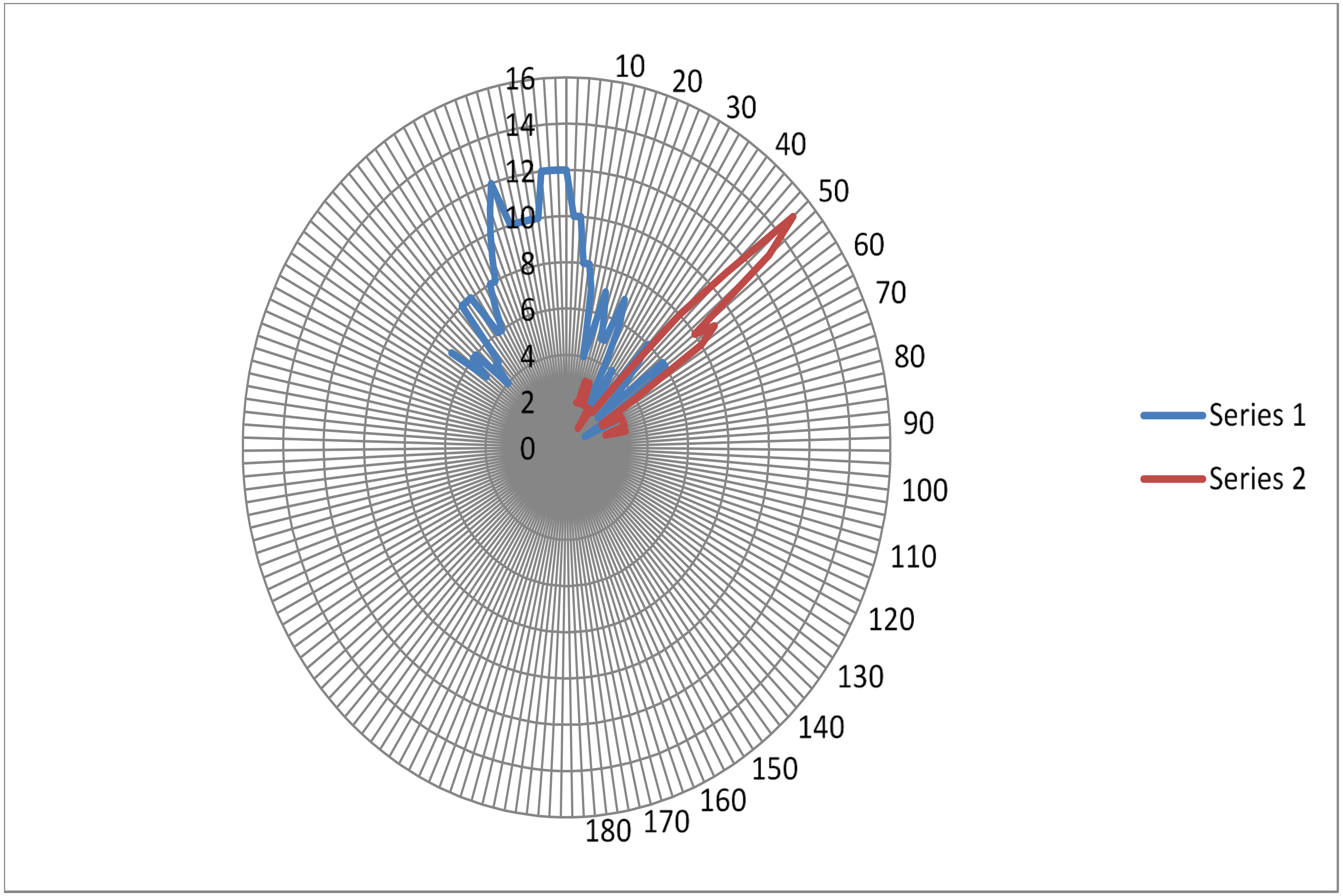
44 GHz

Waveguide

Microwave
Horn and
Detector

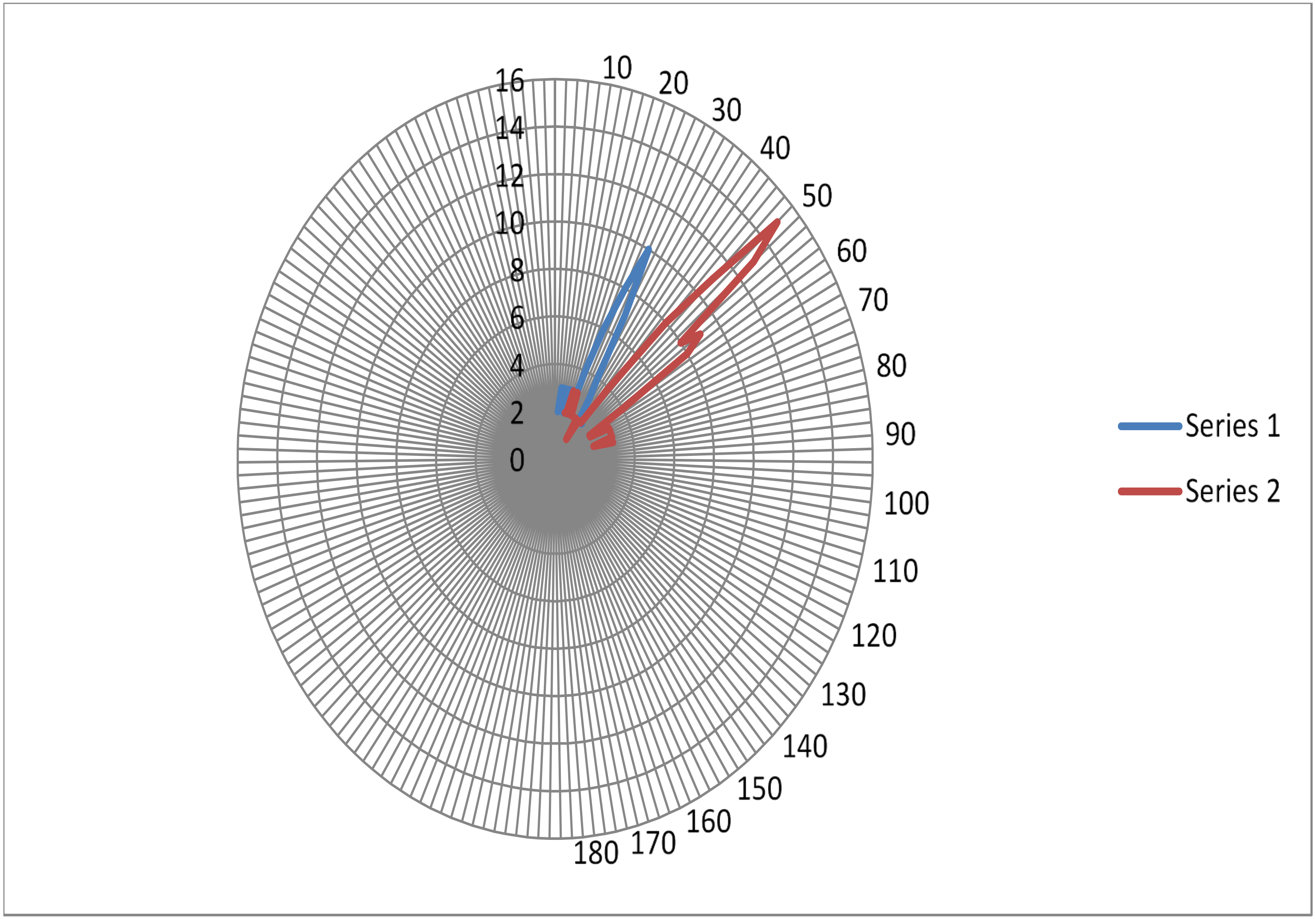
Turntable

Schematic layout of 44 GHz beam steering experiment.



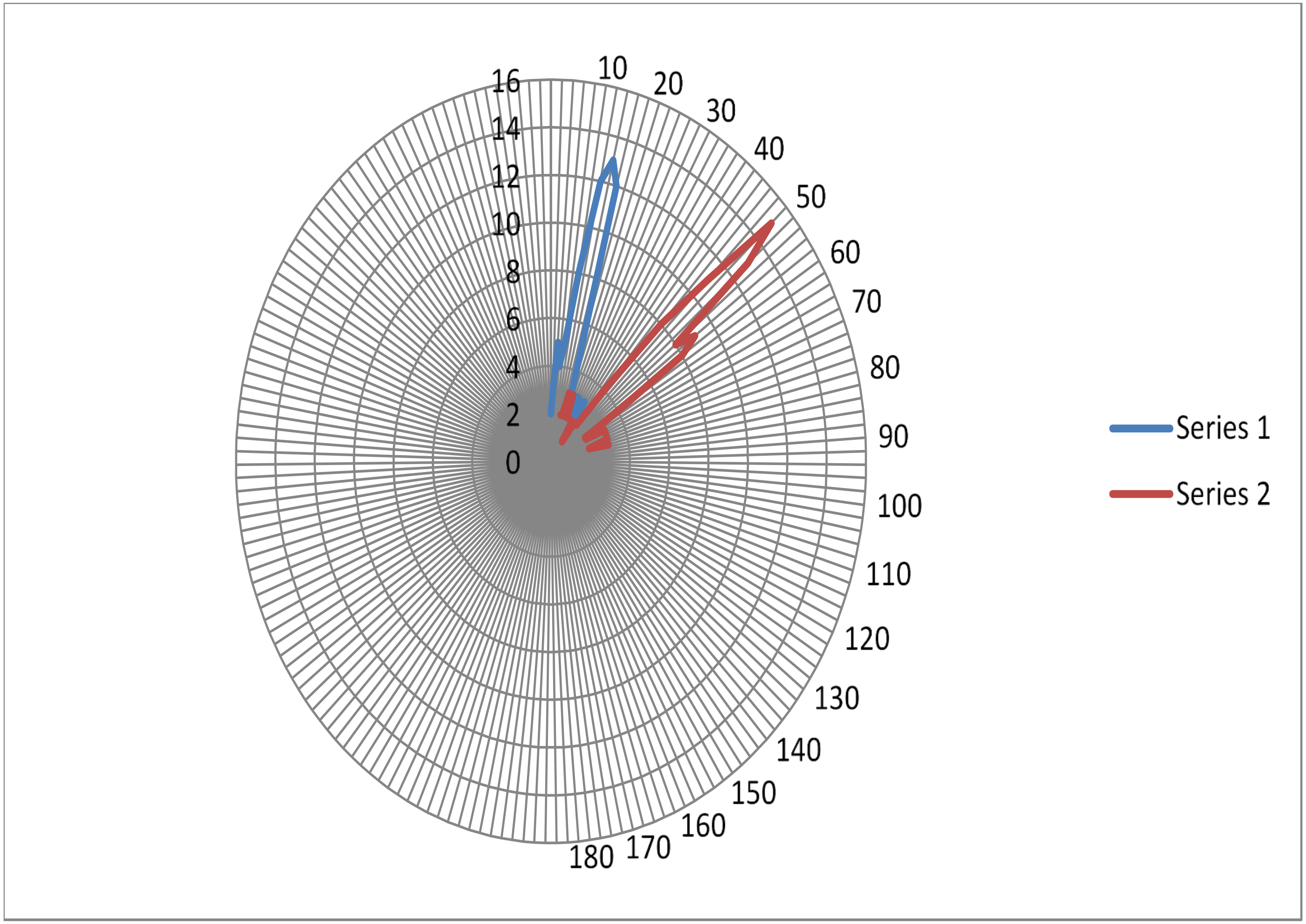
Plasma Beam steering. Beam is steered ~45 degrees clockwise.

Blue line: No plasma; Red line: 8 A peak ionizing current.



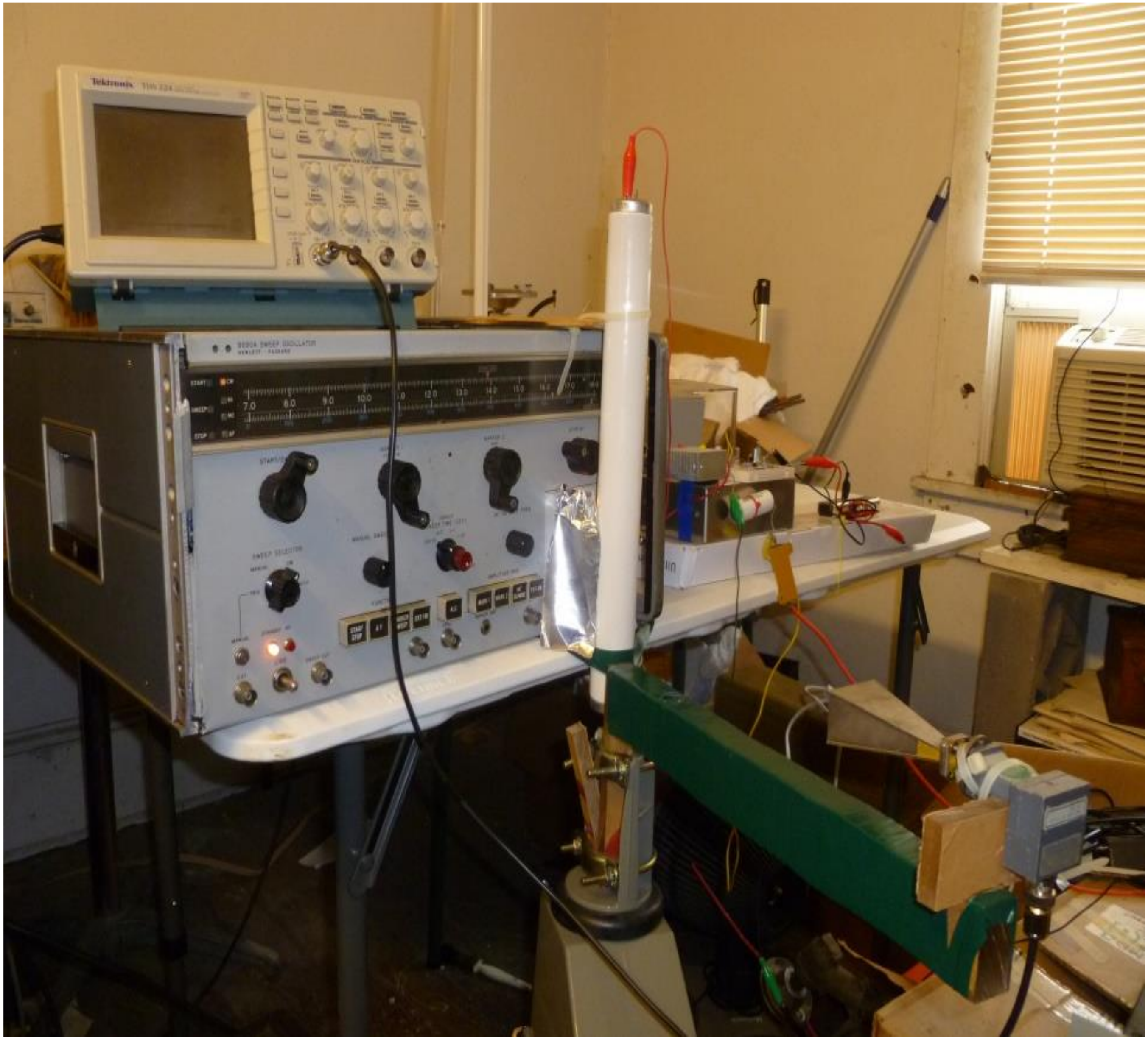
Beam steering for two different plasma ionizing currents.

Blue line: 5 A peak. Red line: 8 A peak



Beam steering for two different plasma ionizing currents,

Blue line: 3 A peak. Red line: 8 A peak



Plasma beam steering experiment. Antenna rotator with holder (green) and receiver horn / detector is in the foreground. The oscilloscope used to monitor the signal waveform is on top of the HP signal generator. The solid state pulser is to the right of the signal generator.

Fluorescent plasma tube is located in front of the output waveguide on the HP signal generator. Aluminum shield on left of tube prevents stray RF from bypassing the plasma. High voltage pulser is on the right.

Pulsed Plasma Driver Circuit

Pulsed Plasma Driver Circuit

- Our plasma antennas are able to work at high frequencies (>40GHz) because of a concept invented by Igor Alexeff and Theodore Anderson that uses fast high-current pulses; instead of DC current.
- The plasma initiates quickly in less than a microsecond, but when plasma ionizing current is turned off, the ions take about a millisecond to recombine with electrons.
- Therefore plasma density stays high for almost a millisecond even though the ionizing current is no longer on.
- If we use an even shorter pulse width, and therefore less power is required to run the antenna.
- We developed a pulsed voltage doubler circuit, allowing us to use a lower voltage DC power supply for the input power to the pulsing circuit.

Pulsed Plasma Driver Circuit

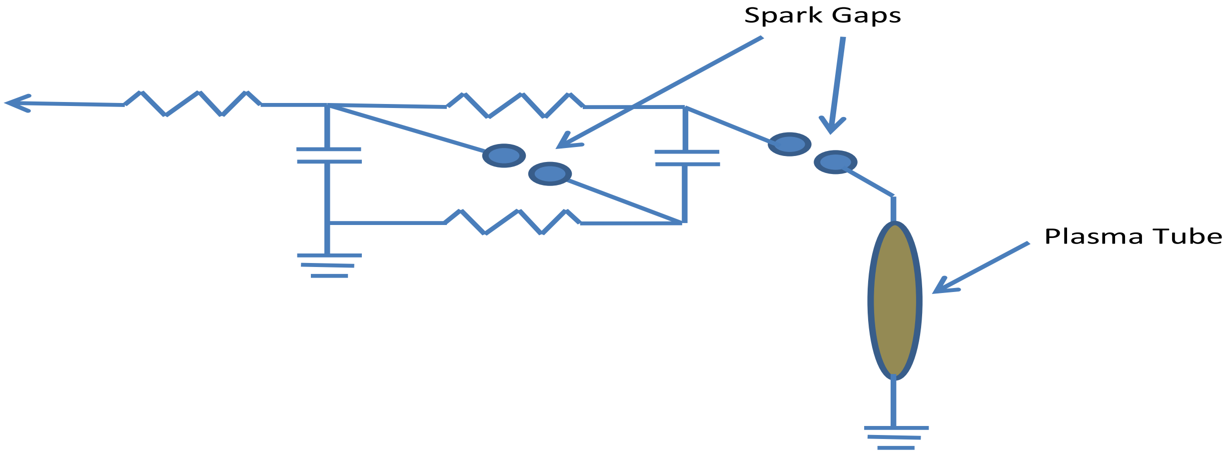
- Modified Marx Generator
- A Marx Generator is a pulsed voltage multiplier .
- A series of capacitors is charged in parallel and then discharged in series through spark gaps.
- We present a two stage voltage doubler circuit.
- We have built and tested a modified Marx Generator that replaces the first spark gap with an IGBT electronic switch.

Pulsed Plasma Driver Circuit

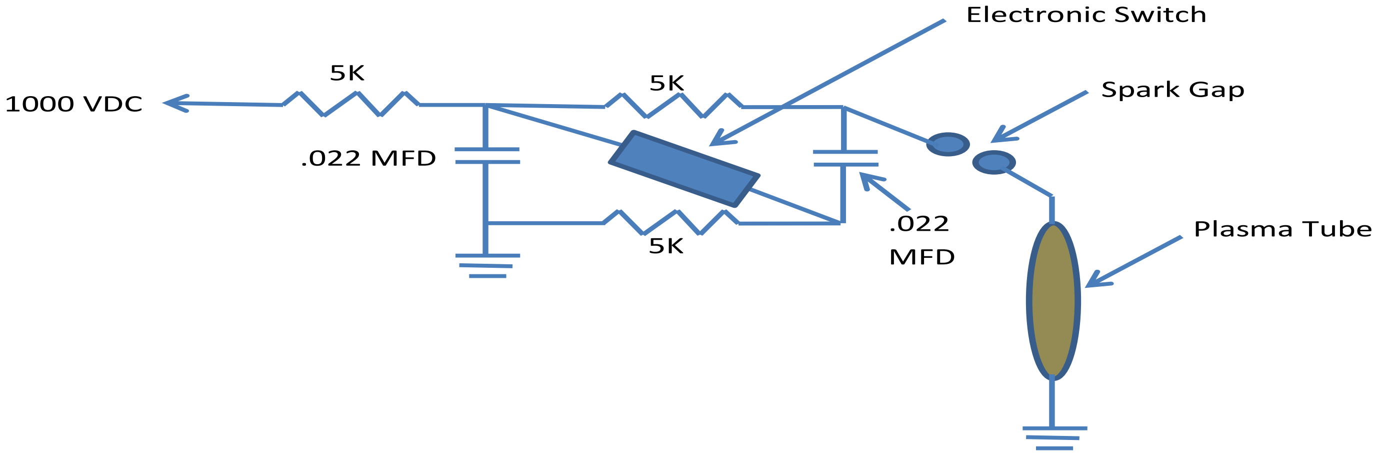
- Our new modified Marx Generator works even better than expected.
- Keeping the second spark gap in the circuit results in a faster rise time than in our previous pulsing circuits.
- The voltage doubler allows the use of a 1000VDC power supply instead of a 2000VDC power supply.

Pulsed Plasma Driver Circuit

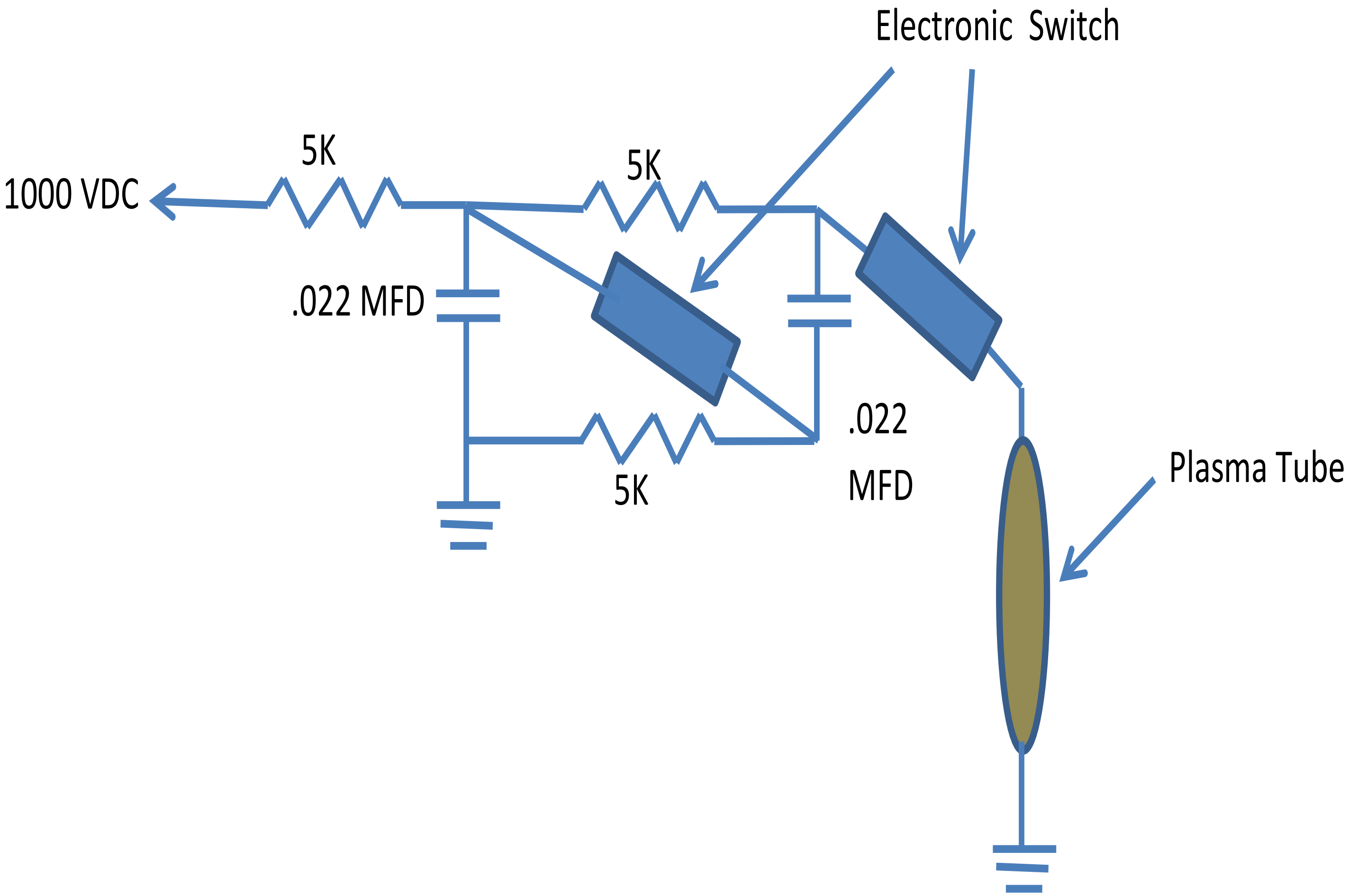
- The IGBT switch and pulsing driver circuit is shown in Fig 5. A CMOS timer IC is used to generate short 1 µs pulses with a repetition time of 750 µs.
- An IXYS brand 2500 Volt IGBT is high voltage switch.
- Our figure shows the new faster pulse current waveform compared to the pulse waveform used until recently.
- The pulse from the Marx Generator circuit is about 1 µs in width compared to 5 µs from the previous pulser circuit.
- Since pulse width is a factor of five shorter, then power consumption is a factor of five lower!



Marx Generator Pulse Voltage Doubler



1000 Volt DC to 2000 Volt Pulse Circuit Using Modified Marx Generator



1000 Volt DC to 2000 Volt Pulse Circuit Using Modified Marx Generator

With No Spark Gap

Custom Made Tubes and Ruggedization

Custom Made Tubes and Ruggedization

- American Scientific Glassblowers Society
- Taken from website:
- http://asgs-glass.org/mo/index.php/about-the-society
- “Founded in 1952 and incorporated in 1954, the American Scientific Glassblowers Society began as a professional, not-for-profit organization of scientific glassblowers and suppliers associated with the field. The objectives of the Society are to further the education of its membership through the gathering, promotion, and dissemination of technical and scientific information concerning all aspects of scientific glassblowing.
- Today the ASGS comprises approximately 650 members and a variety of affiliate members. Regional Sections offer local members an opportunity to meet with other glassblowers in their area.”

Custom Made Tubes and Ruggedization

- SynFoam
- Taken from website:
- http://synfoam.com/
- “SynFoam syntactic foam consists of hydrospace quality hollow glass microspheres dispersed in a high strength plastic matrix.
- Upon curing, the resultant syntactic foam composite provides high strength and low density with very low moisture absorption.
- Synfoam products are used in the marine and oceanographc industry for use as floats, buoys and as a void filler in submarines, capable of withstanding depths below 7,000 feet.
-

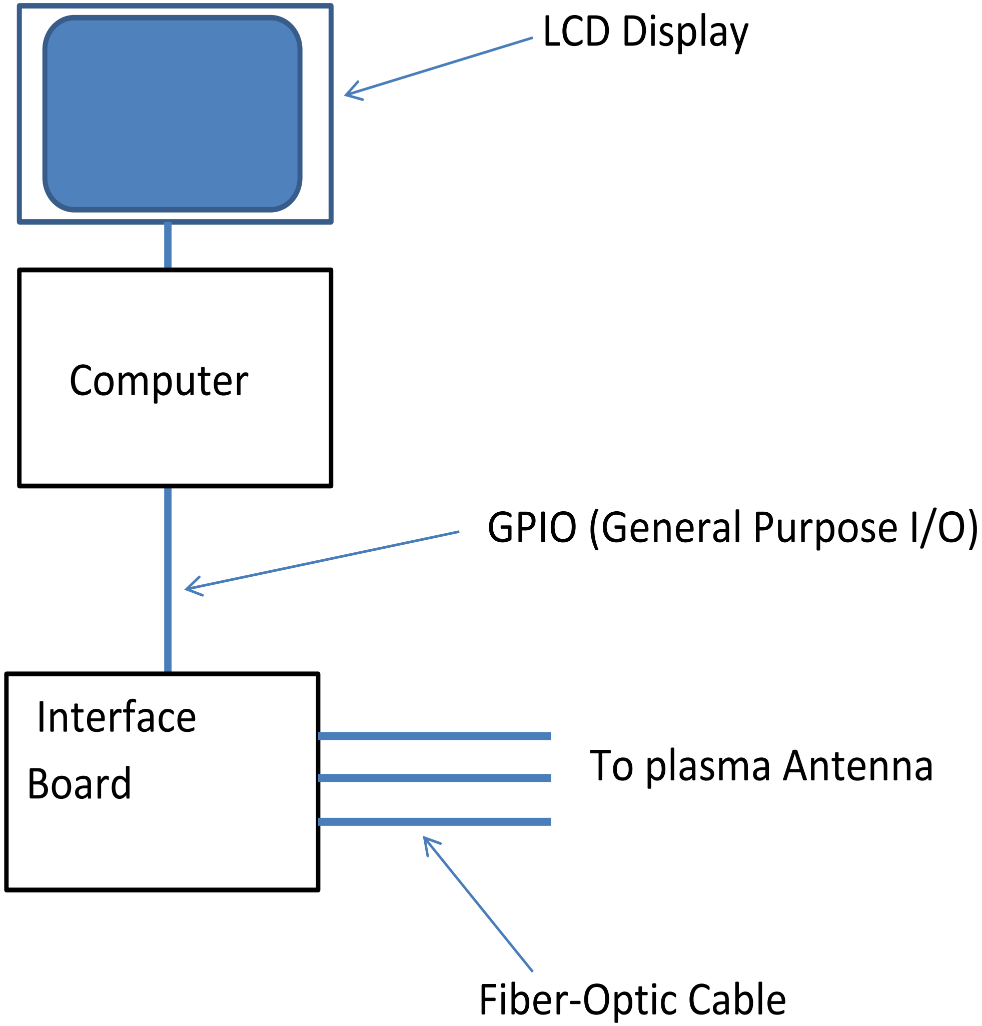
Custom Made Tubes and Ruggedization

- SynFoam buoyancy modules are being used for Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), deep water moorings, torpedo target and sonar arrays, and scientific instrument applications.
- Synfoam products are also used in aerospace industries as cores for sandwich structures and as a repair and replacement for existing honeycomb structures.
- SynFoam products can also be tailored to meet acoustic characteristics such as transparency, absorption, reflection, and refraction in underwater applications including transducer isolators and decouplers in addition to providing buoyancy related properties.”

Software Controls Development

Software Controls Development

- Stand-alone controller with touch screen.
- Interface to Smart antenna with fiber-optic cable
- Wireless interface now under construction.
- Software written in Python language.
  - A relatively new language that is ideal for engineers and scientists.
  - User interface is currently done by text commands.
  - Python is GUI capable!
  - Software will be written to use GUI and touch screen.



LCD Display

Computer

GPIO (General Purpose I/O)

Interface Board

To plasma Antenna

Fiber-Optic Cable

Computer with control board and fiber-optic interface.

Refraction for steering and focusing in a plasma

- Refraction in a plasma depends on:
  - Plasma density
  - Path length
  - Gradient of plasma density
- Good results above 23 GHz
- Made custom made tube and refraction worked well at 10 GHz.
- Continue work on refraction for focusing and steering at 2.4 GHz

Next Steps – Test Hypothesis

Version A:

- Complete each phase sequentially
- Toll gate reviews in each phase
- Phase completion equates to milestone
- Working prototype completed after each phase

	MRI Image Improvement	PET Image Improvement	Cost Productivity	Enhanced Experience
Phase 1 $1.5M, 9 months	X	X		
Phase 2 $1.4M, 5 months	X	X		X
Phase 3 $965K, 5 months	X	X	X	X

Version B:

- Combine phase 1,2 during initial project
- Toll gate review for combined phase and phase 3
- Milestone completed after combination of phase 1/2 and Phase 3
- Working prototype completed after each phase

Phase 1/2 $2.5M, 12 months	X	X		X
Phase 3 $965K, 5 months	X	X	X	X