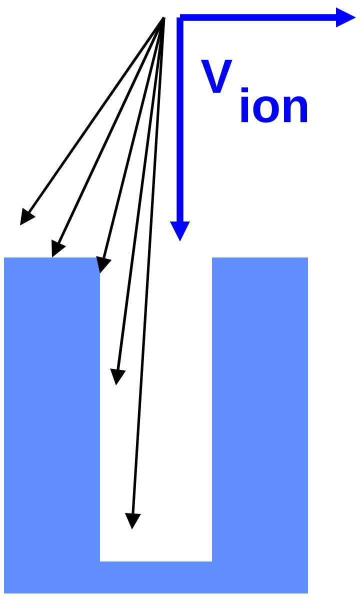
Energy Transport and frequency dependent ion kinetics in a capacitively-coupled plasma reactor



Greg Hebner, Ed Barnat, Paul Miller

Sandia National Laboratories

&

Alex Paterson, John Holland

Applied Materials

University of Michigan

September 9, 2009

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Sandia –– in round numbers.

8,500 regular on-roll employees

~7,400 at Sandia New Mexico

~800 at Sandia California

~300 at Other Locations

~1200 buildings; >7 million sq. ft.

~1,500 PhDs, 2,800 Masters

- Total Engineering – 52%
  - Electrical, Mechanical, other
- Total Science – 36%
  - Computing, Physics, Chemistry, other
- Other Technical Fields – 11%

Annual budget $2.4B (FY09)

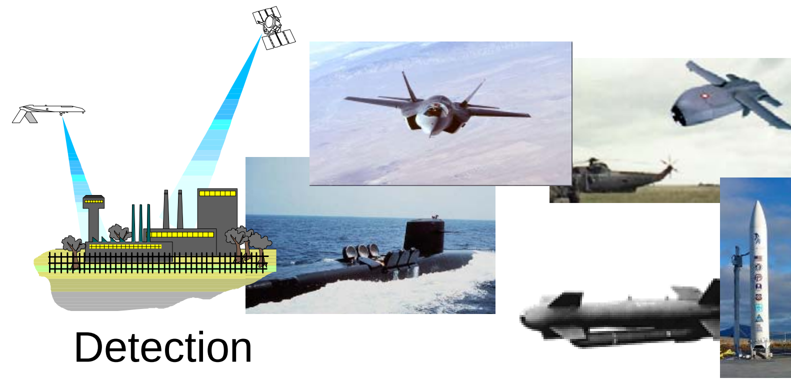
Sandia National Laboratories

Sandia is a National Security Laboratory

Nuclear Weapons

Safe, Secure, Reliable Weapons

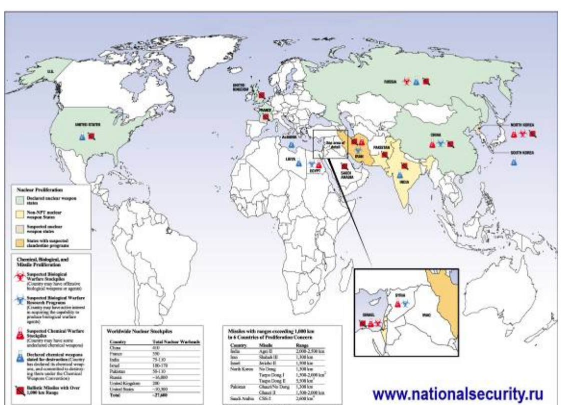
Defense Systems & Assessments



Detection

Energy, Resources & Nonproliferation

Energy



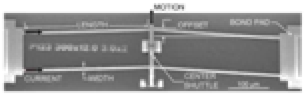
Homeland Security & Defense

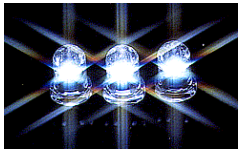
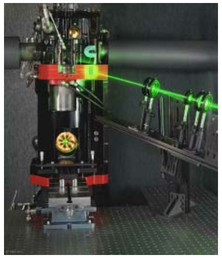
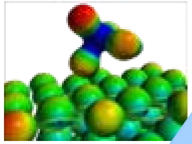
Architectural Surety

Anti-crime and anti-terrorism technology

Smart Weapons

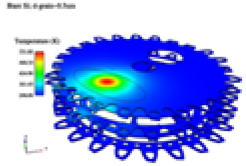
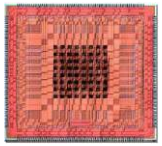
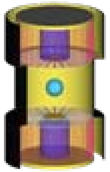
Science and Technology provides the basis for future Sandia missions



Solutions

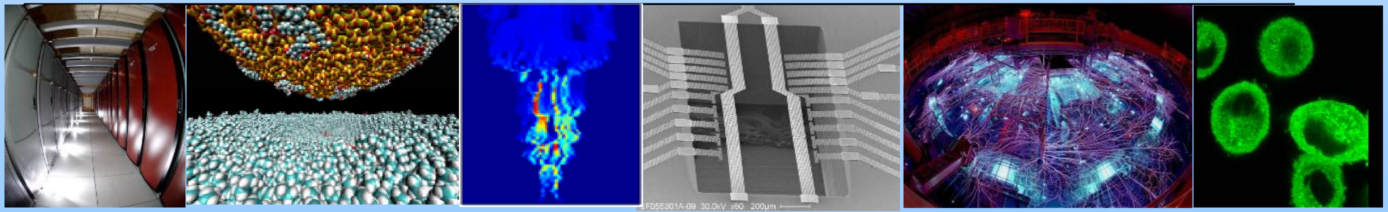
Rad Hard Microelectronics
Use Control
Solid-State Lighting
ICF Technology
µ-Chem Lab
...


Integrating STE Capabilities

Nano/Micro Science & Engineering
Complex Predictive Simulation
Science of Extreme Environments
Bioscience & Technology

Research Foundations



Computer & Information Sciences–Materials Science–Engineering Sciences–Microelectronics & Microsystems–Pulsed Power Sciences–Bioscience

Goals and Questions

- How does frequency influence….
  - energy deposition, uniformity, density, chemistry….
- What is the field distribution within the chamber
  - Standing waves?, Impact on the plasma characteristics
  - For the highest frequencies of 180 MHz, the *effective* wavelength can be 0.3 m, on the order of the electrode dimensions.
- How are the ions heated?
  - Ions respond to the time averaged local electric field.
  - What temperature distribution is expected for ions drifting in an electric field?
  - Can the ion temperature be controlled as functions of space and time?
  - What is the optimum ion temperature?
  - Does ion temperature have an impact on etch characteristics or spatial etch profiles?

- Ion motion and local electric field are fundamental plasma parameters that touch areas such as Langmuir probe analysis, particle charging and sheath kinetics.

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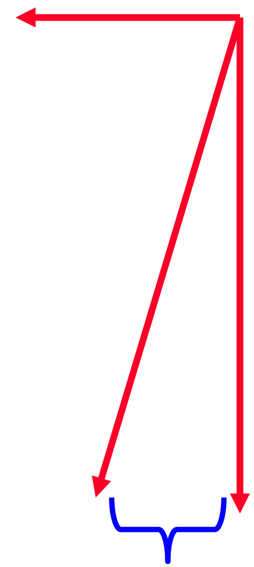
Why is ion temperature important?

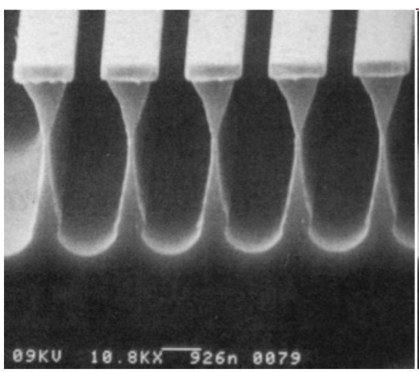
- Ions respond to the total vector sum of every electric field they encounter
- The angle that ion strike the surface influence etch trench shape
- Ions seldom have one velocity but rather a distribution
- Ion heating in the bulk adds transverse energy.
  - Issue for high aspect ratio etch

Thermal temperature
300 K or 400 m/s

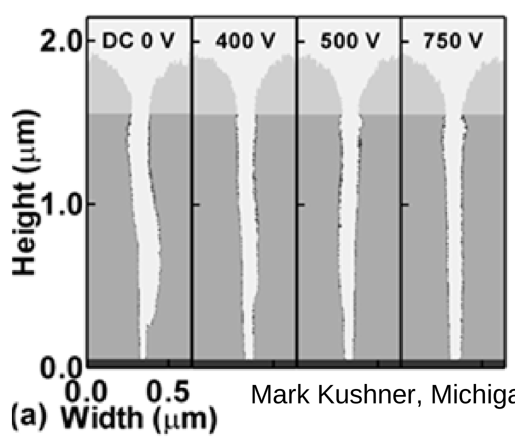


Sheath Voltage
500 V

0.4 degrees is near complete offset for a 1:100 aspect etch



Mark Johnson, Purdue



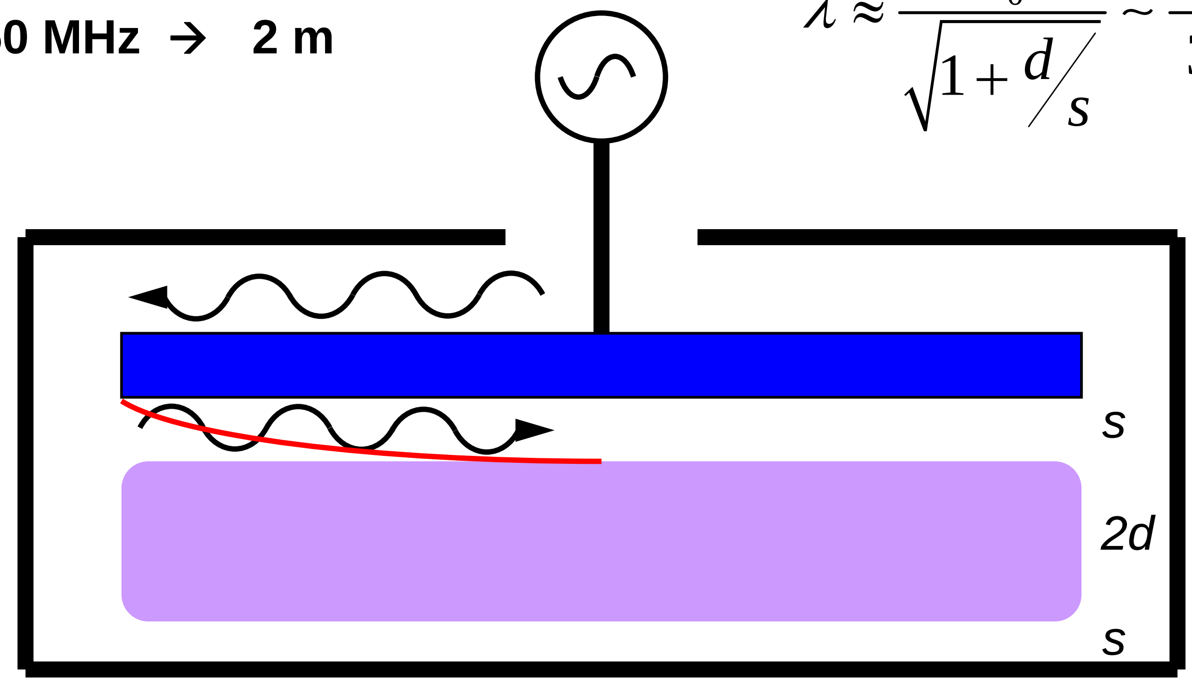
Mark Kushner, Michigan

Spatial effects are important at higher rf excitation frequency

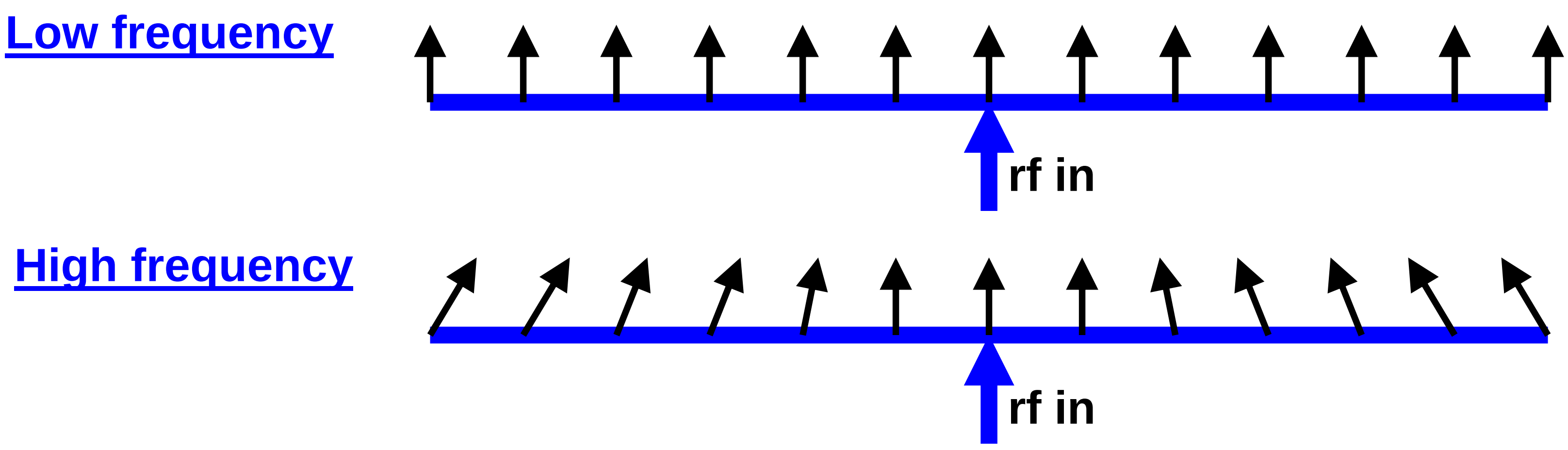
- Rf does not go through the electrodes
- Surface waves deposit power into the plasma
- Evanescent effects provide end effects
- Radial wavelength in the low density limit:

150 MHz → 2 m

$$\lambda \approx \frac{\lambda_0}{\sqrt{1 + d/s}} \sim \frac{\lambda_0}{3}$$

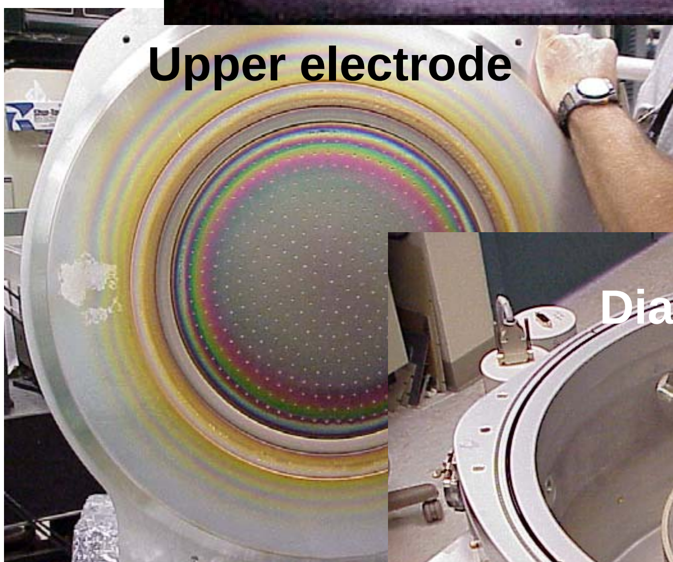


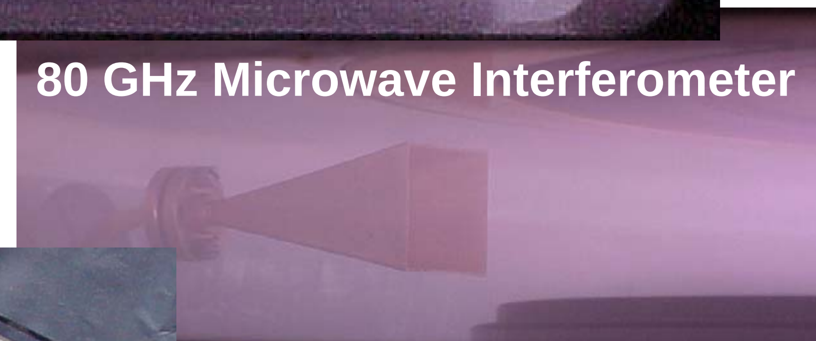
Models indicate that spatial effects lead to non normal sheath electric fields

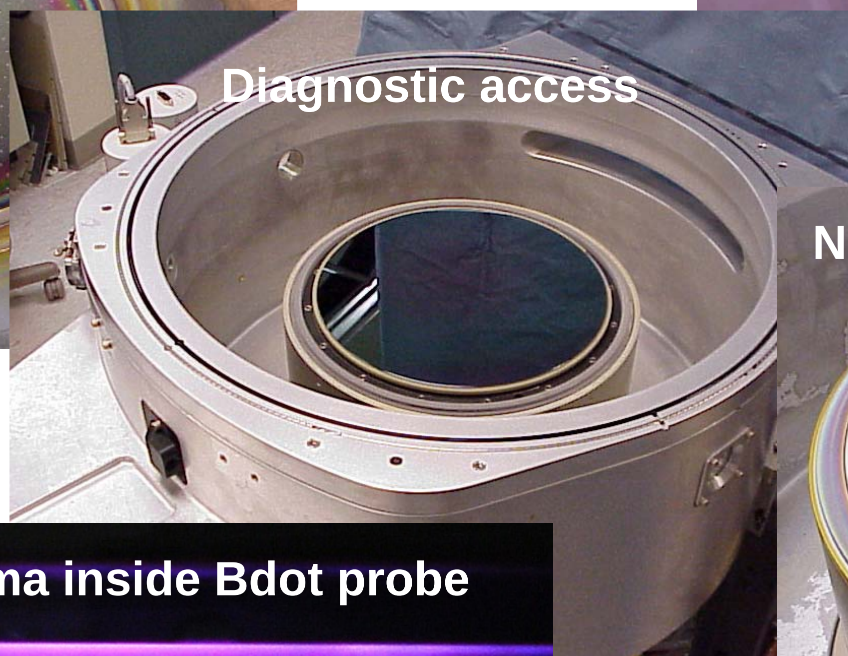


Jim Stevens, Joe Cecchi, Pascal Chabert, Mike Lieberman, et al

Experiments performed in 300 mm etch chamber



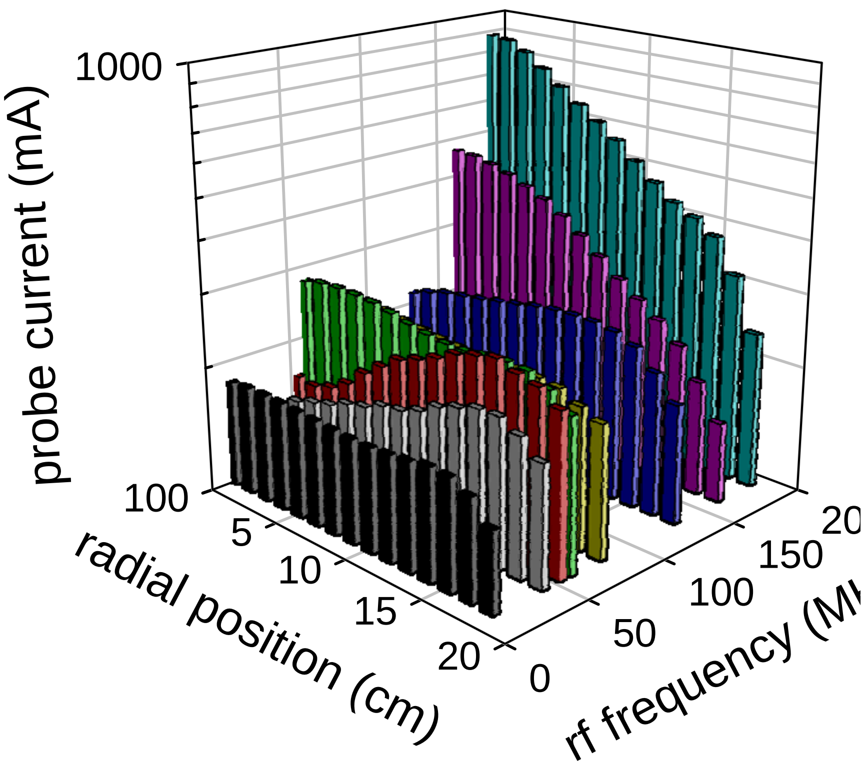


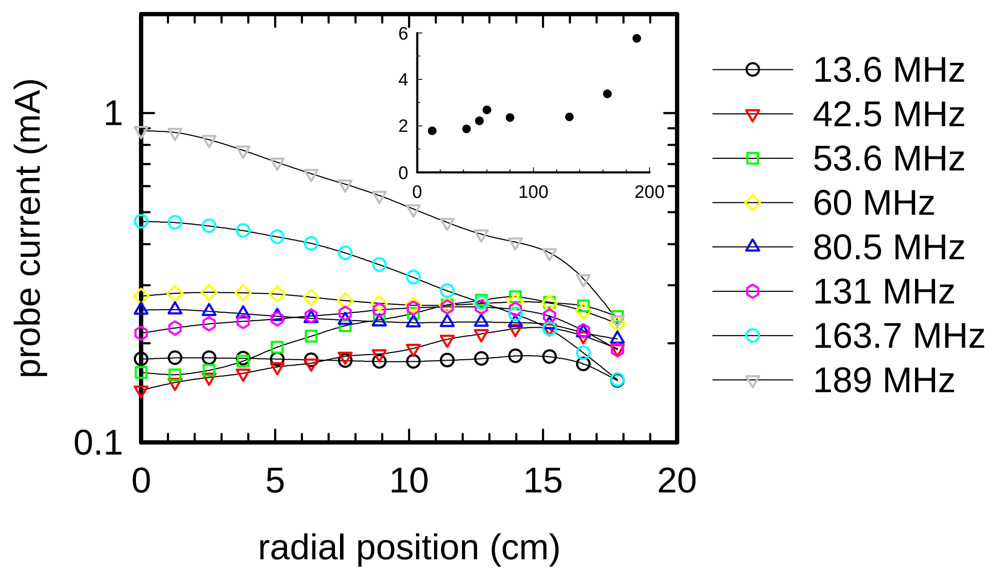


Our previous work showed that the spatial ion distribution depended on frequency

- Ion saturation current measurements of the spatially resolved ion density.
- Constant power – 300 W, 50 mTorr
- Several different matching networks
- At the highest frequencies, the spatial distribution is center high

Two ways to look at the data





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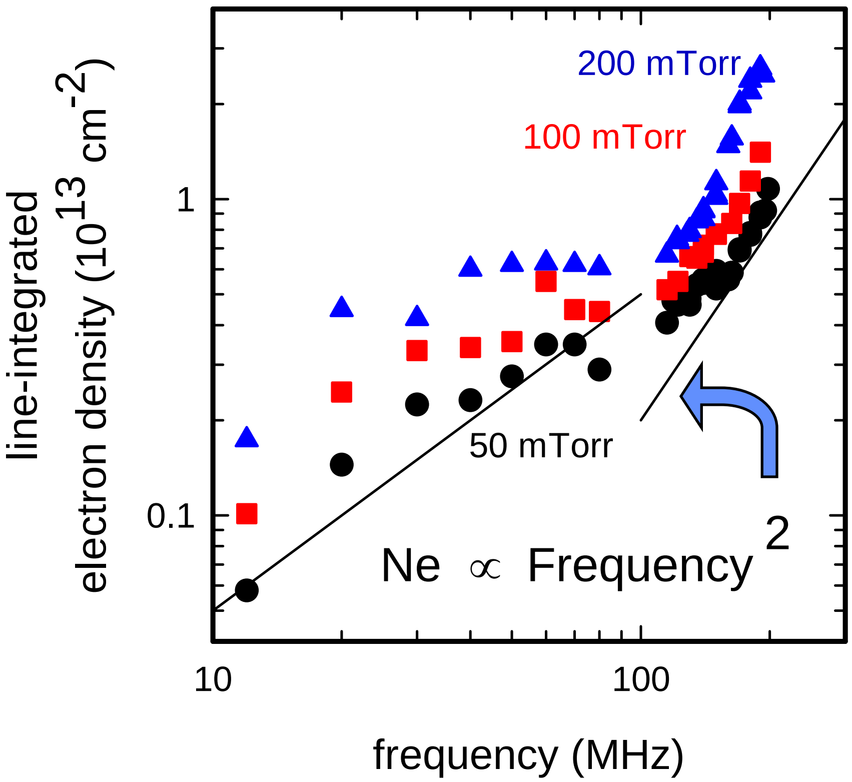
First measurements of large increase in electron density with increased frequency

- The electron density scaling with frequency had 2-3 distinct regions for constant source power
  - f < 30 MHz
    N_e increased with frequency, match efficiency low, coil heating?
  - 30 < f < 130 MHz
    N_e independent of frequency
  - f > 130 MHz
    N_e increased with frequency, scales as F^2

- Repeated at Applied Materials

Argon, 300 W forward power



What role do frequency dependent changes in the Ne spatial distribution play in this behavior?

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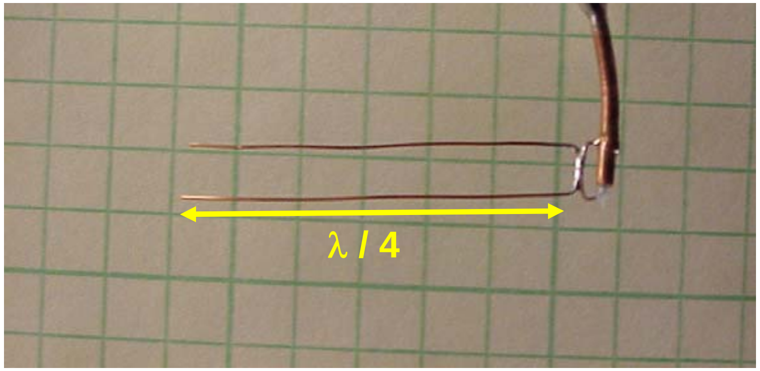
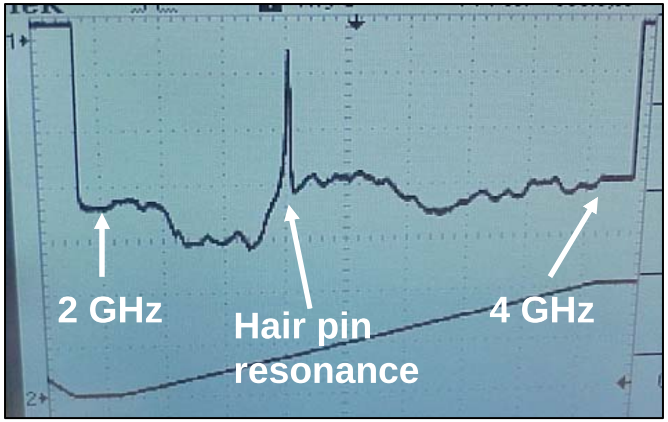
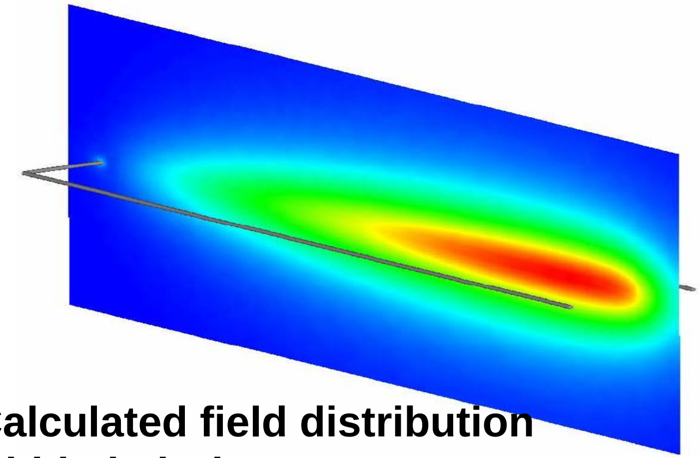
Measure spatially resolved electron density without using traditional Langmuir probes

- There were questions about the results obtained from Langmuir probes at frequencies above 13 MHz
  - Weird Te, IEDF from probe
- Developed new techniques for hairpin measurements.
- Most detailed model to date of the performance of this probe.







Calculated field distribution within hairpin resonator

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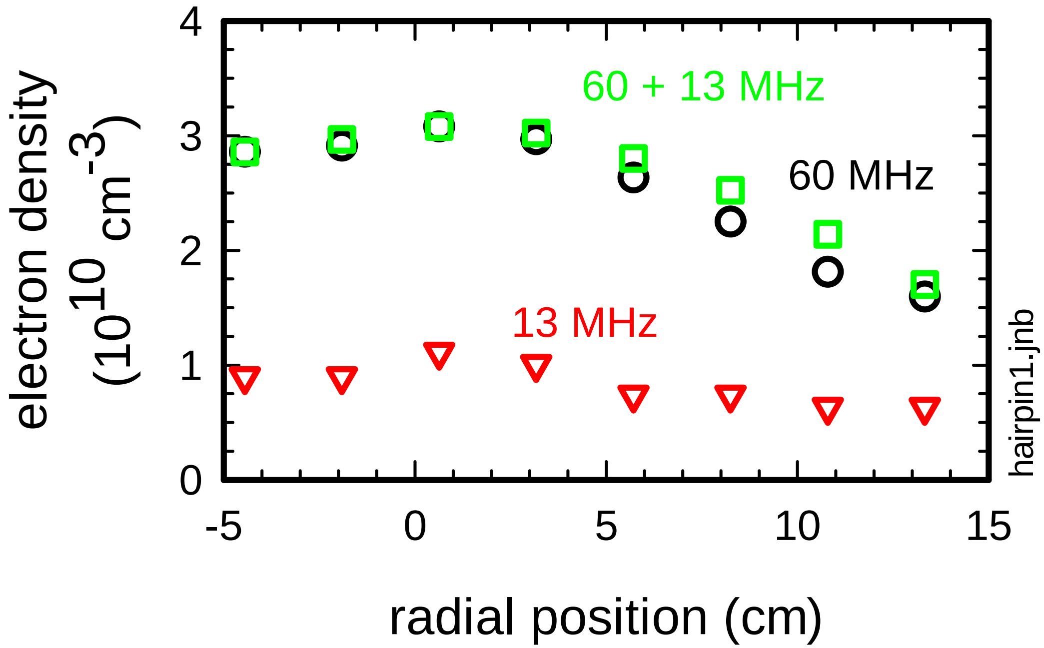
Dual frequency scaling similar to 60 MHz alone

- Hairpin probe confirms Isat probe and interferometer measurements
- Electron density was symmetric about the center of the electrode – the probe does not significantly skew the density.
- Why is the density not additive?
  - 60 MHz creates electrons and 13 MHz power goes into the ions



60 MHz – 300 W
13 MHz – 300 W
20 mTorr Argon

What is the origin of the center high density distribution and implication for etch uniformity

- Set probes aside and use tools that provide access to the fundamental energy deposition processes within the plasma, *electric fields*.
- Use two laser diagnostic techniques to
  - Measure the spatially resolved ion temperature and velocity
  - Measure the spatial and temporal sheath electric fields
- Laser diagnostics are nonperturbative
- Spatial and temporal information determined

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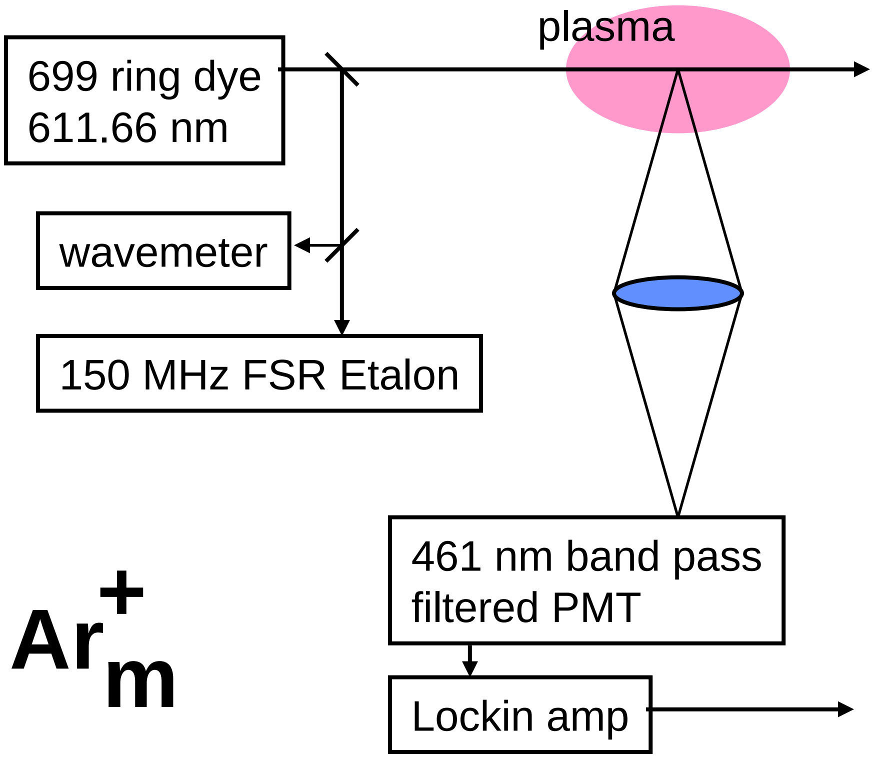
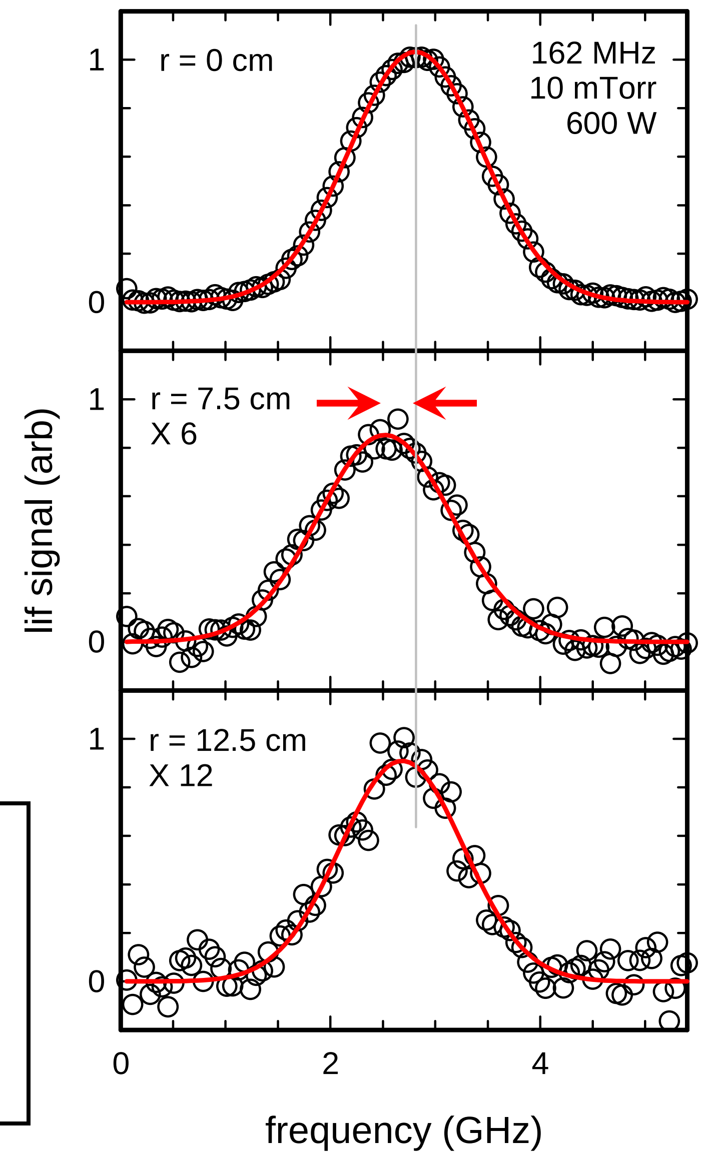
LIF used to measure ion energy distribution function parallel to the electrodes

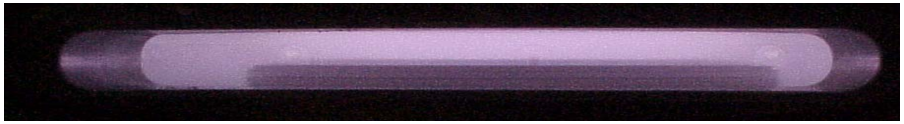


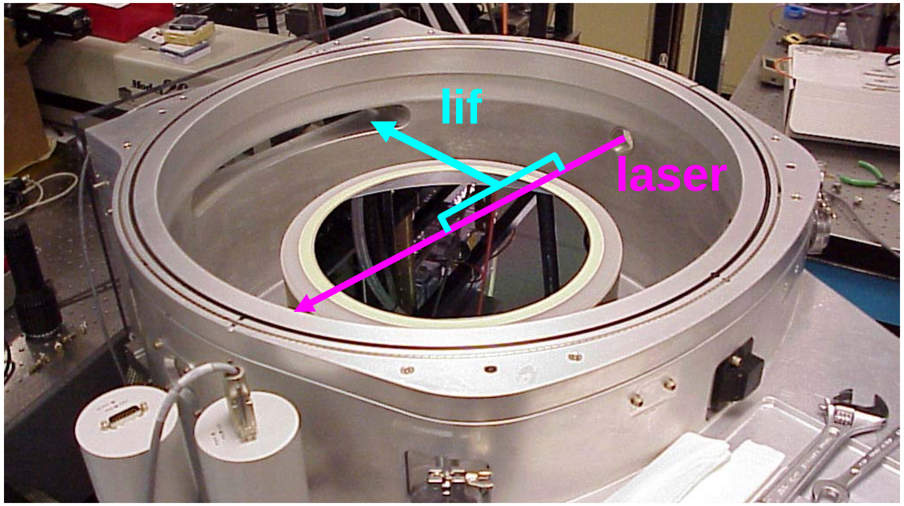


- **Gaussian fits provide temperature, velocity and relative density**
- **Drift velocity ⇔ radial electric field**
- **100 m/s ⇔ 10 V/cmTorr ⇔ 0.1 V/cm @ 10 mTorr**

Large-area dual-frequency capacitively coupled plasmas offer opportunities and challenges

- RF applied to lower electrode
  - 13, 60 and 13 + 60 MHz
  - 162 MHz
- Argon.
- Up to 10 – 60 mTorr.
- Standard 13, 60, and 162 MHz high power sources, 3, 2 and 3 kW.
- Navigator and Z-Scan.
- Non anodized chamber, good chamber ground.
- 1 – 220 MHz 500 W amplifier





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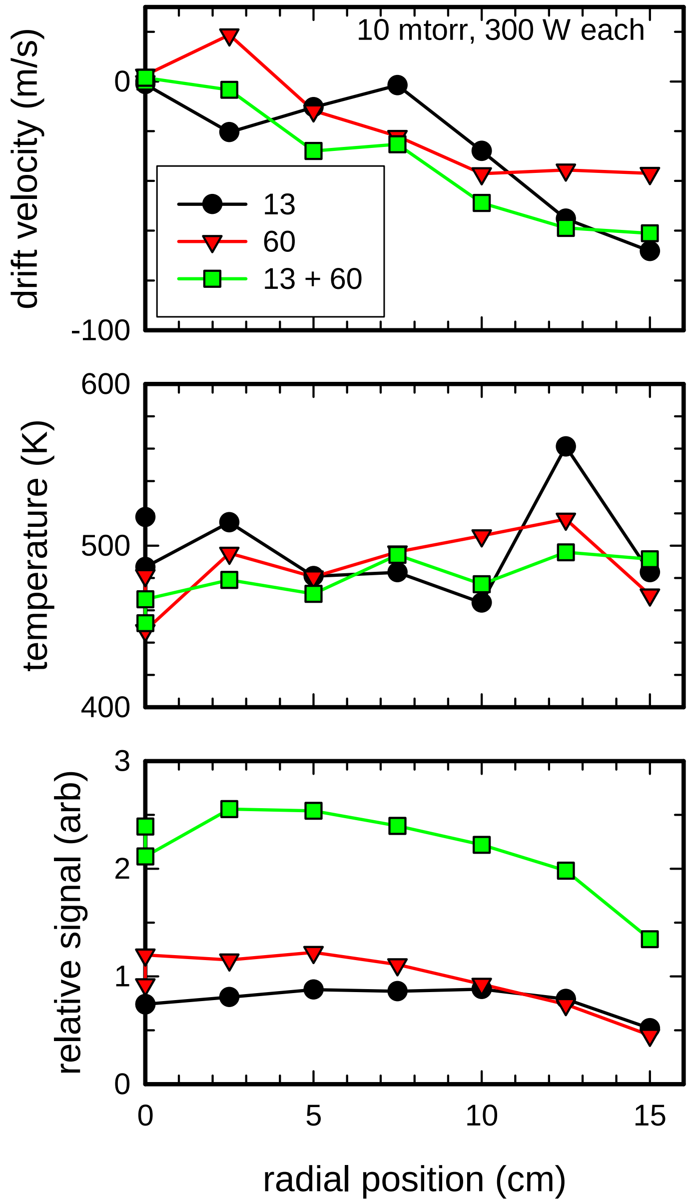
Dual frequency operation at 13 and 60 MHz does not impact the drift velocity or ion temperature



- Drift velocity implies radial electric fields of less than 0.1 V/cm.
  - Less than 1.0 V average potential drop from center to edge
- Ion temperature is relatively cool.
  - Cooler than the 1000K measured in Argon ICP for similar power and pressure.
- Ion temperature is not a function of radial position or frequency in this range.
- Ion density is roughly additive.

- Plasmas can be made adequately uniformity for 13 and 60 MHz rf excitation.

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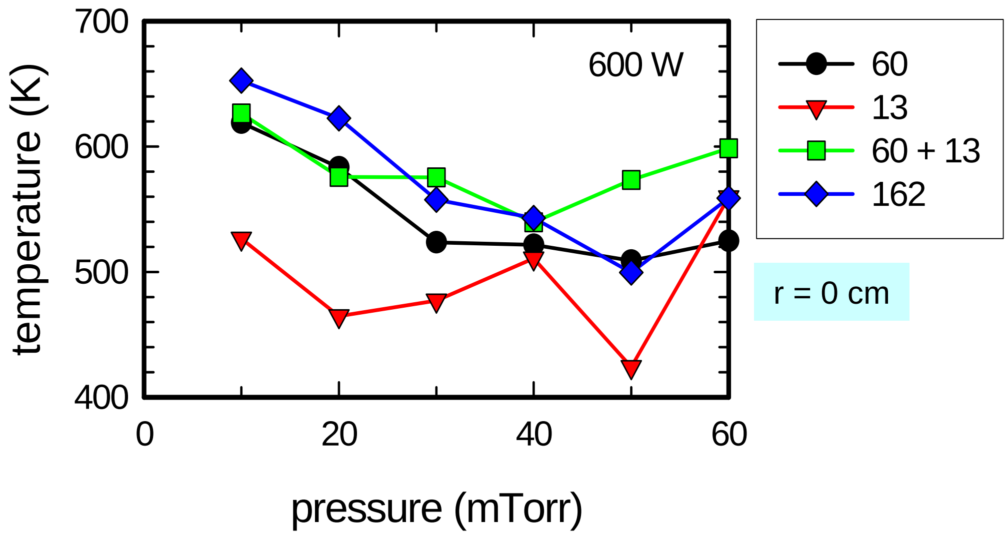
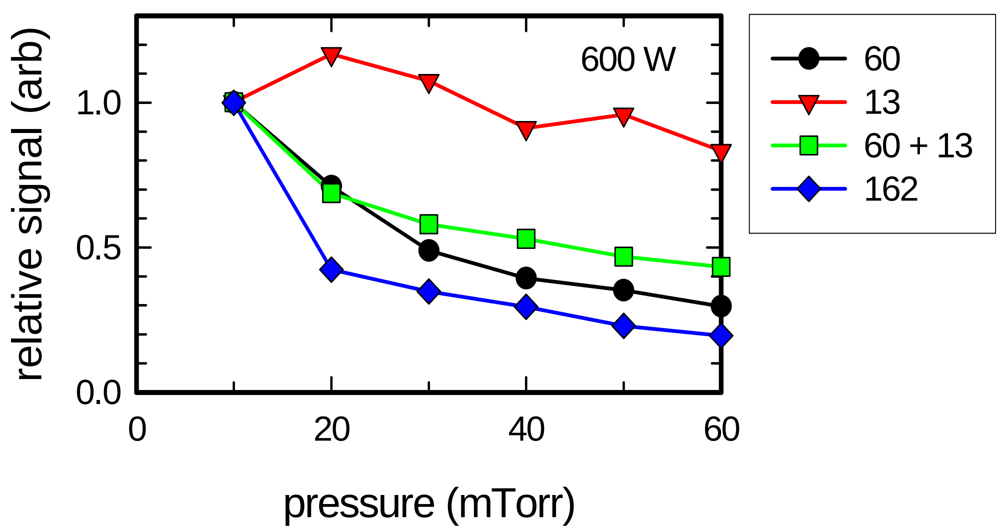
Ion temperature not a strong function of pressure

- The ion temperature in the center appears to decrease slightly for drive frequencies of 60 and 162 MHz.
- 13 MHz data is relatively noisy due to low signals

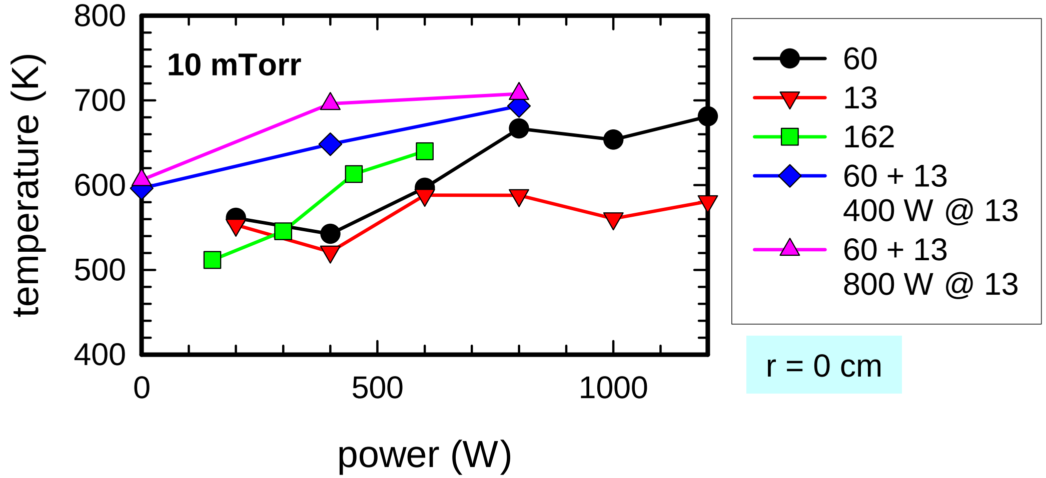


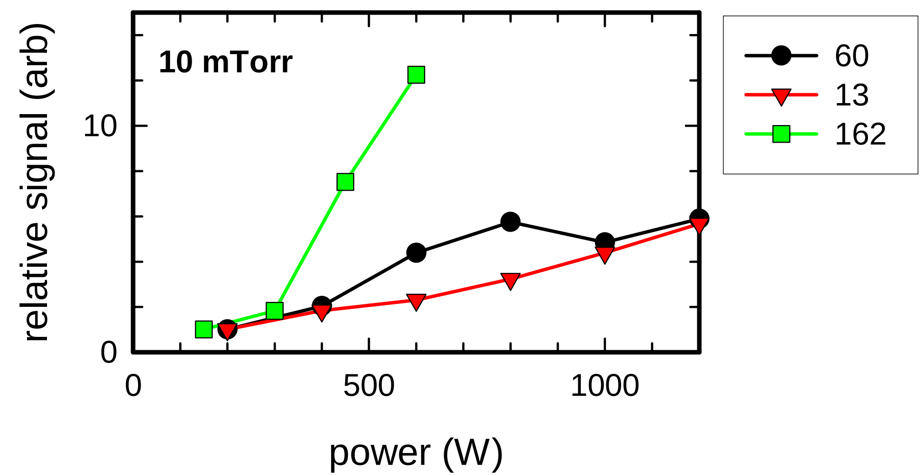
- The density scaling of the ion excited state with increased pressure depended on frequency.
  - Changes in EEDF?
  - Later verified by Langmuir probe
- At 13 MHz the density changed less than 20 %.
- At 60, 162 and 13 + 60 MHz the density decreased, have similar trends.



Ion temperature increased with rf power

- Increasing the power also increased the ion temperature slightly.
- The relative signal strength, indicative of the ion density increased linearly
  - Scaled with electron density
- Argon ion metastable density higher at higher frequencies
  - We also observed an increased electron density with increased rf drive frequency.
- Argon ion state produced by single electron excitation





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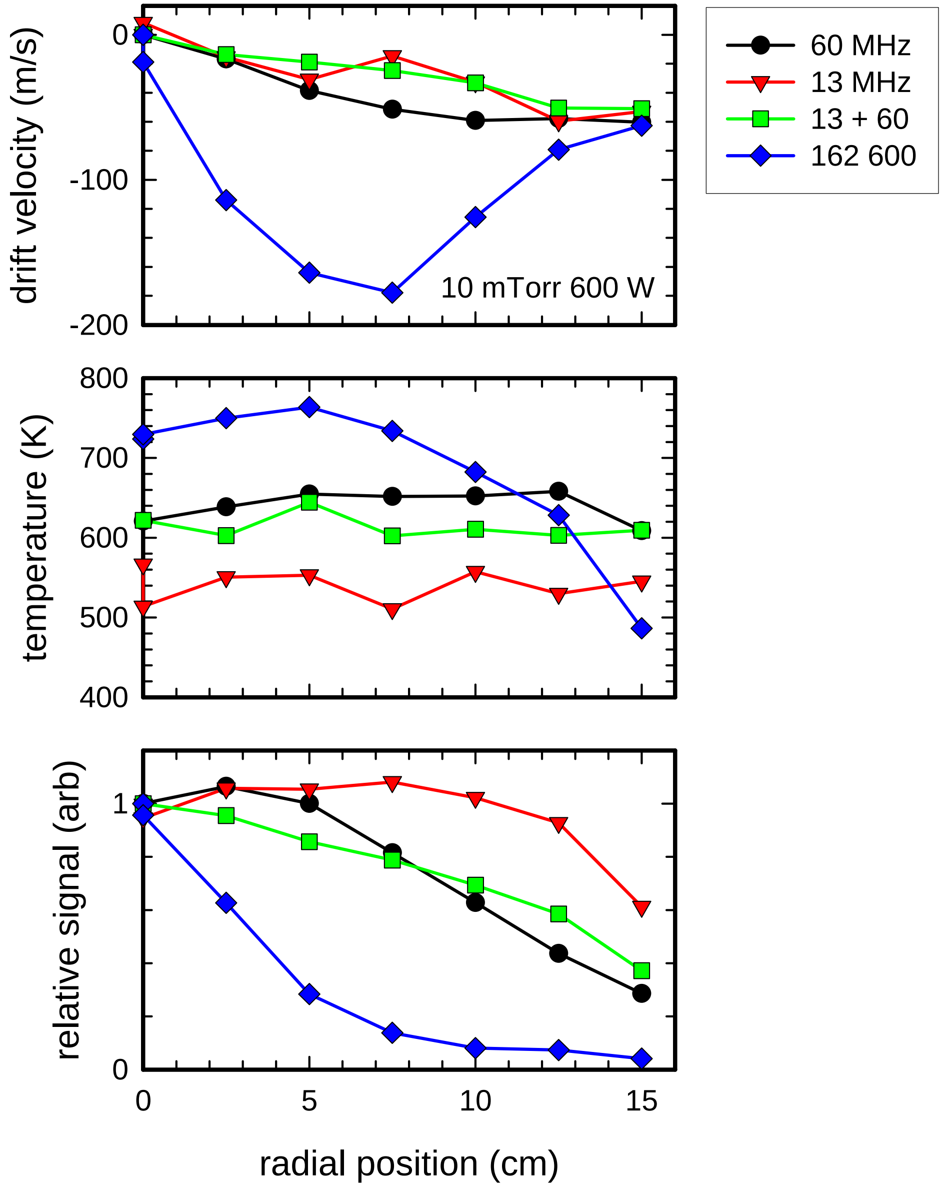
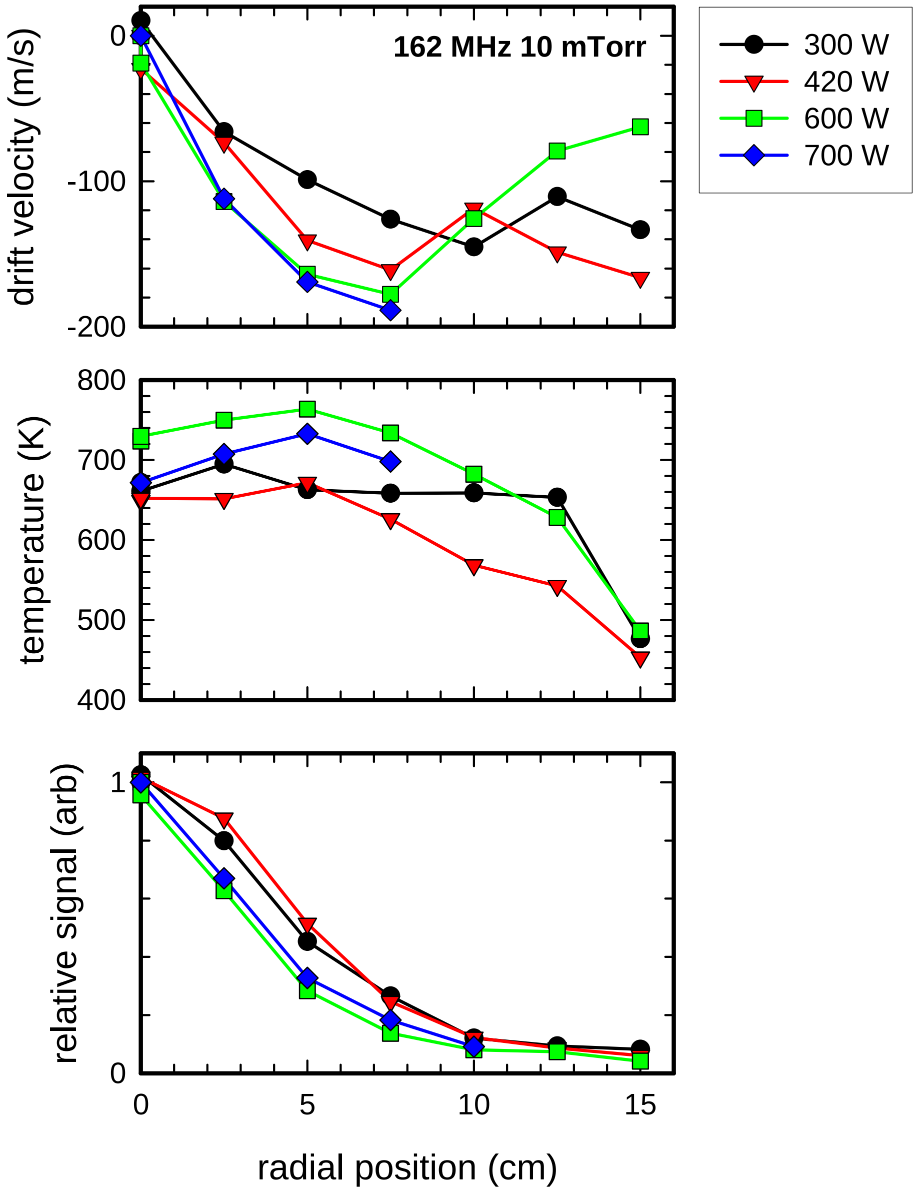
Radial drift velocity is complicated at higher rf frequencies

- The radial drift velocity was not a monotonic function of radial position.
- Peak in drift velocity = a peak in time average radial electric field.
  - Indicative of a radial change in the power deposition mechanism?
- Ion temperature decreased at the edge of the wafer.
- Relative ion density strongly peaked in the center
- Probe, optical emission, and sheath electric field measurements show a distinct peak in the electron and ion density for these conditions.



Radial profiles are a function of power

- At higher frequencies, the radial variation is a function of power.
- Peak in the drift velocity / radial electric field moves towards the center of the electrode with increased power.
- The ion temperature is not a strong function of power.
- The relative ion spatial distribution is not a function of the power.
  - The absolute density increased linearly with power, as does the electron density.



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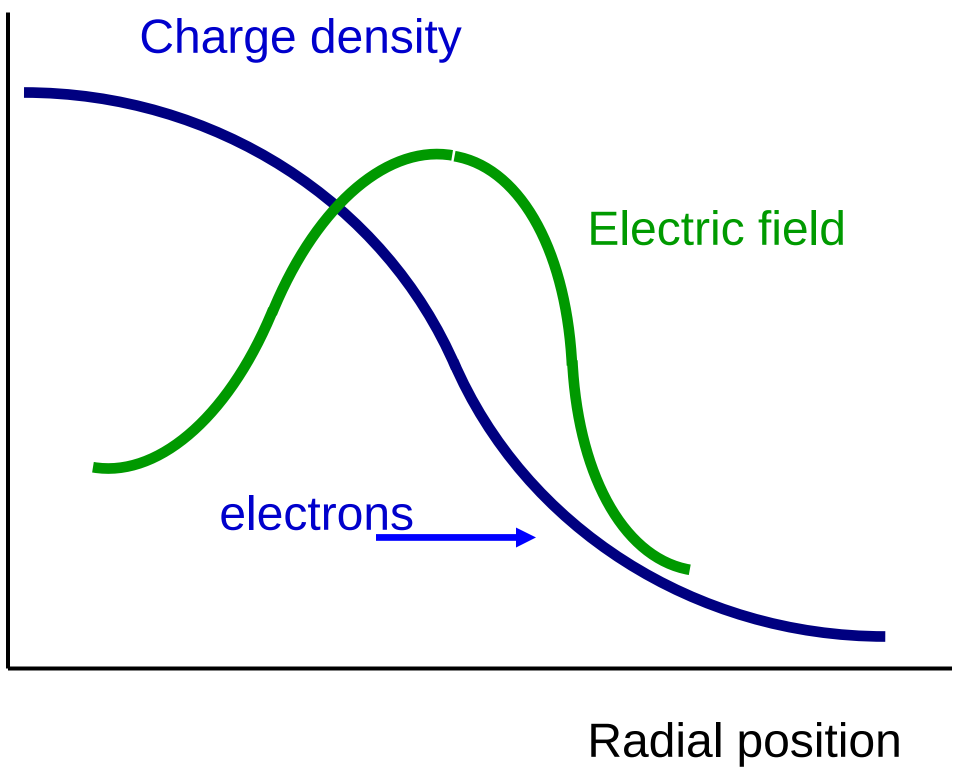
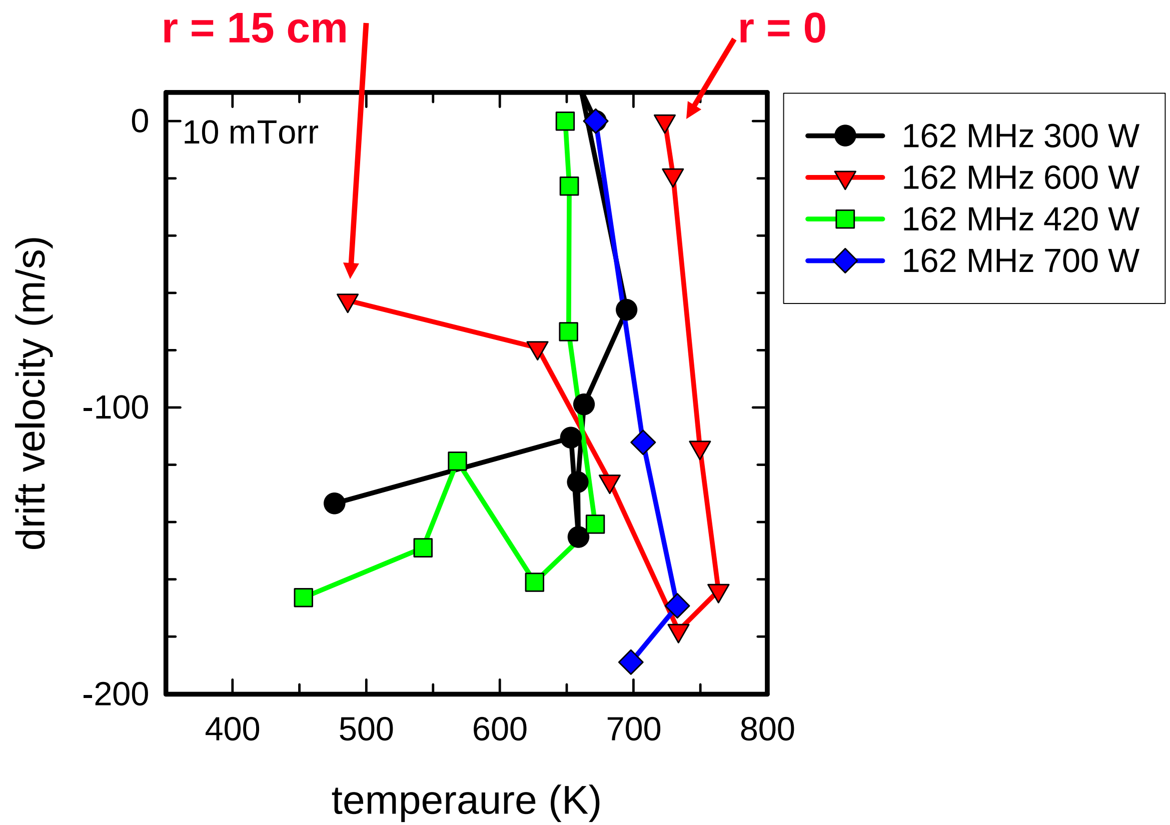
Charge gradient produces an electric field



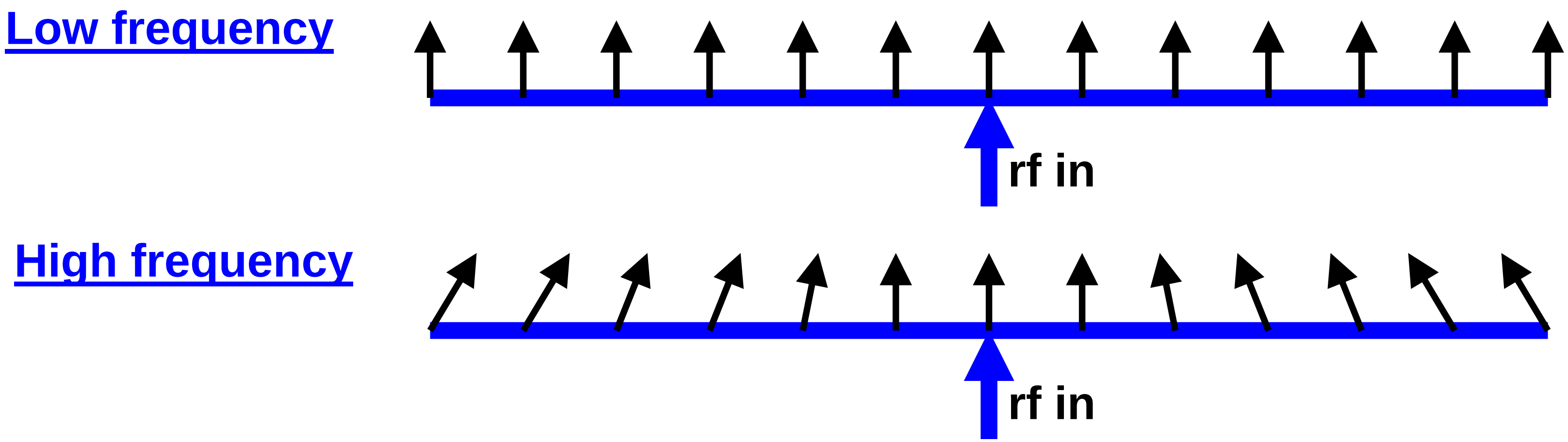
Electric field inhibits the electron diffusion while extracting ions to maintain quasi charge neutrality

Drift velocity not a linear function of ion temperature

- At the highest frequency there is not a linear relationship between ion drift velocity and ion temperature.
- Additional ion heating mechanism in the center of the plasma could explain the different temperatures.
- Implies an non uniform electric sheath electric field distribution or standing waves.



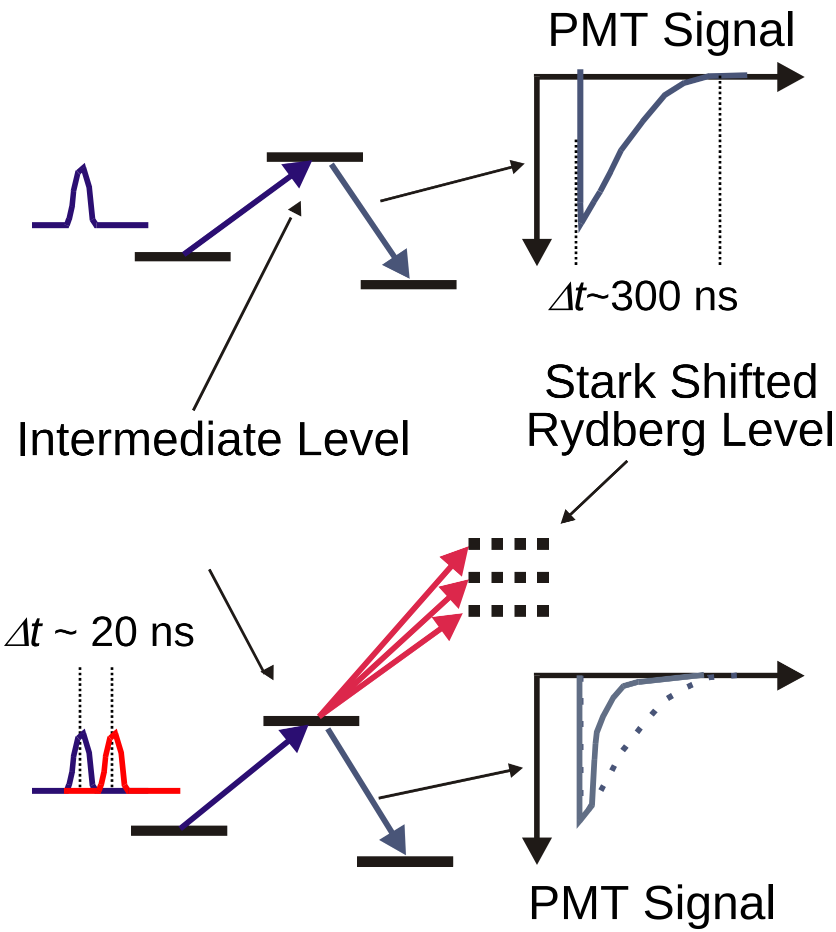
Models indicate that spatial effects lead to non normal sheath electric fields



Jim Stevens, Joe Cecchi, Pascal Chabert, Mike Lieberman, et al

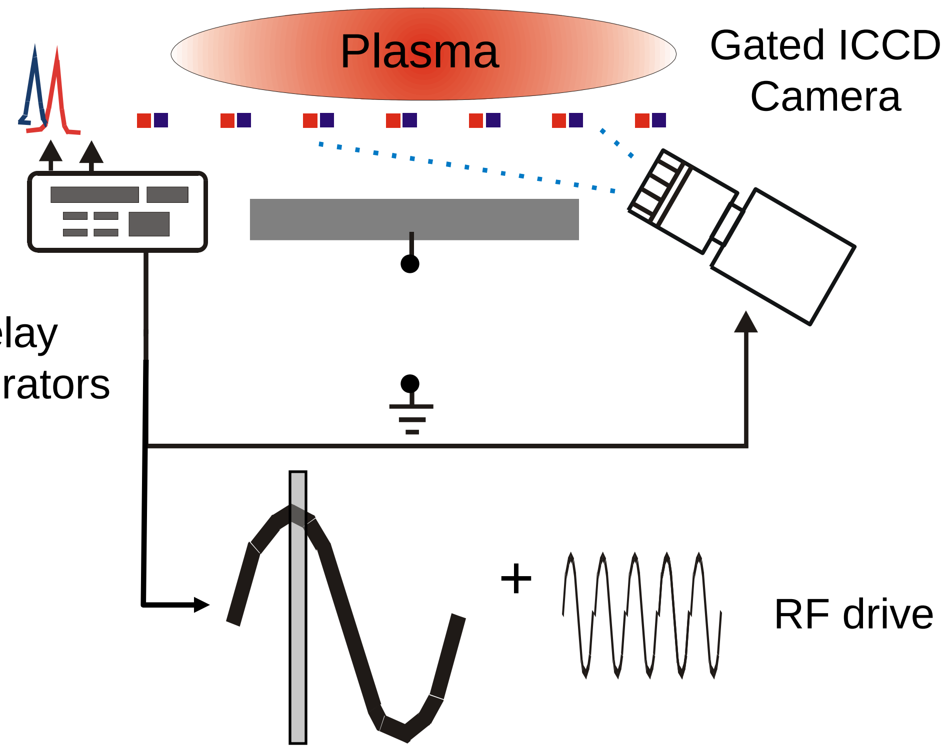
Spatial and temporal sheath electric fields measured using LIF-dip of Stark shifted Rydberg states

- **Fluorescence dip spectroscopy is a two laser technique**
- **The pulsed pump laser populates an intermediate state**
- **The pulsed probe laser transfers population to a Rydberg level**
- **Transition to the Rydberg level is monitored by a "dip" in the fluorescence from the intermediate state**
- **Only sensitive to the magnitude of the electric field vector**



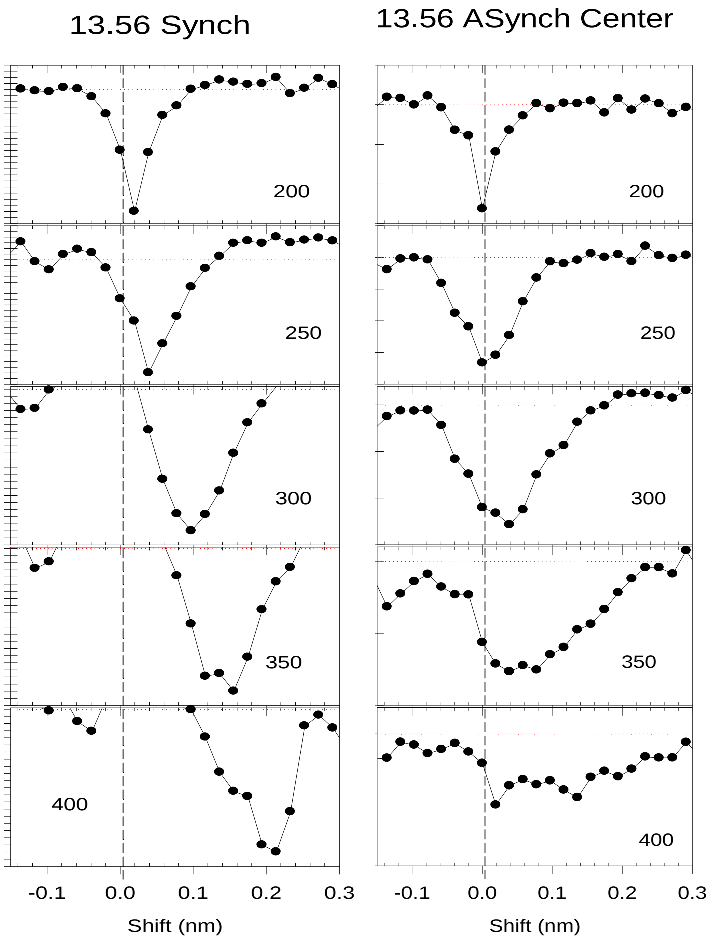
“General” setup for sheath field measurement

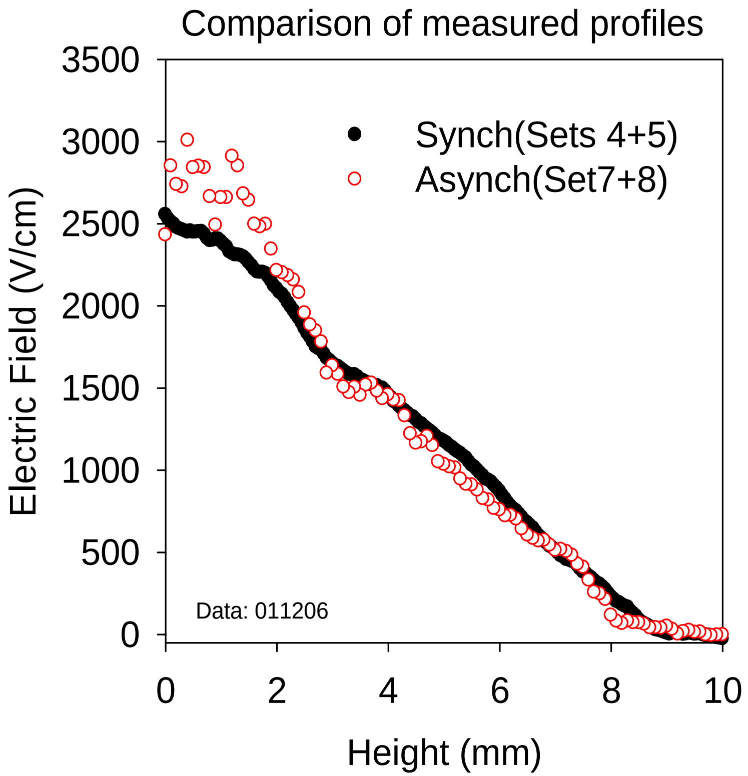
- **Firing of lasers synched to rf phase (13.56 MHz).**
  - **Temporal resolution ~ 5 ns.**
- **Spatial maps of LIF captured with gated, intensified CCD.**
  - **Spatial resolution ~ 50 μm.**
- **Phase locked laser source**



Above 13 MHz the laser pulse timing is not synchronized to the rf excitation

- Develop new way to analyze the Rydberg energy level shifts to account for broadening
- Measure maximum fields by field distribution





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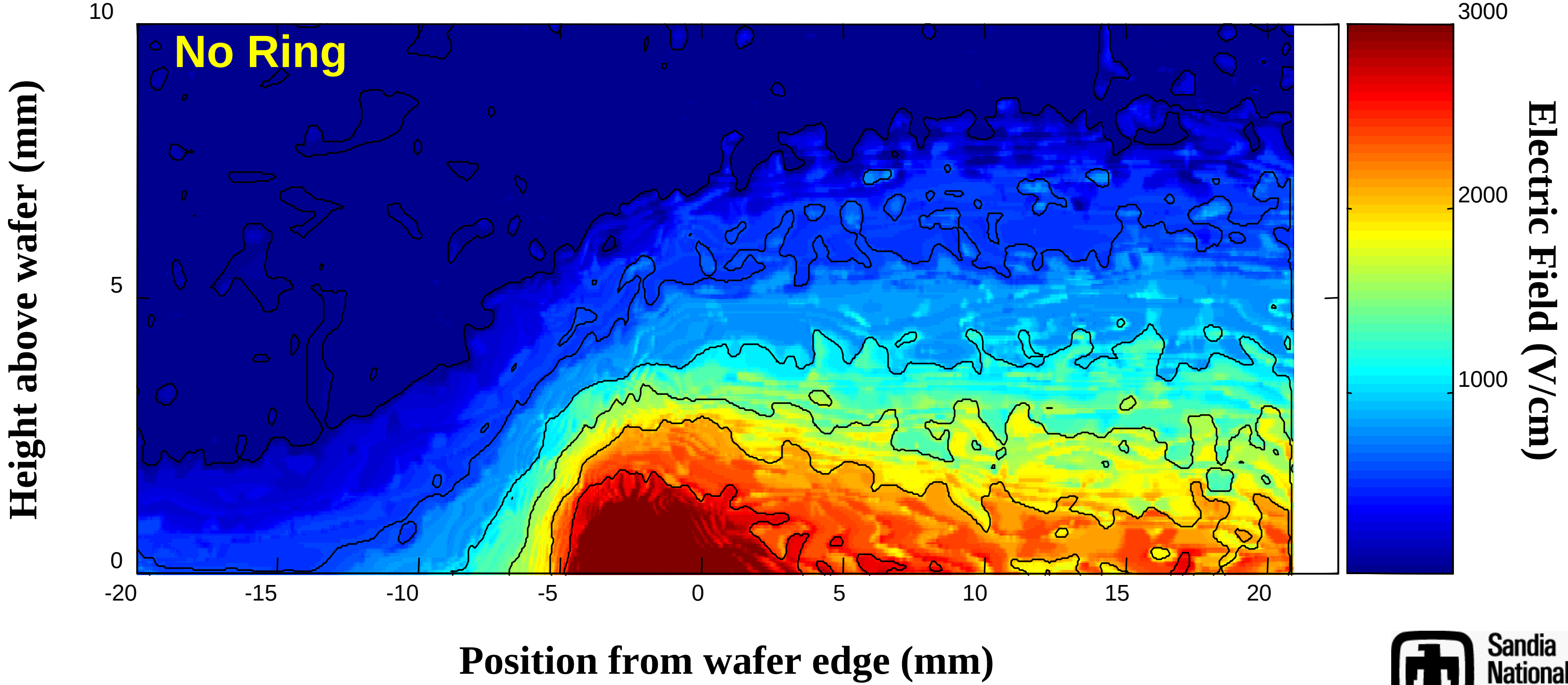
LIF-dip provides spatial electric field distributions

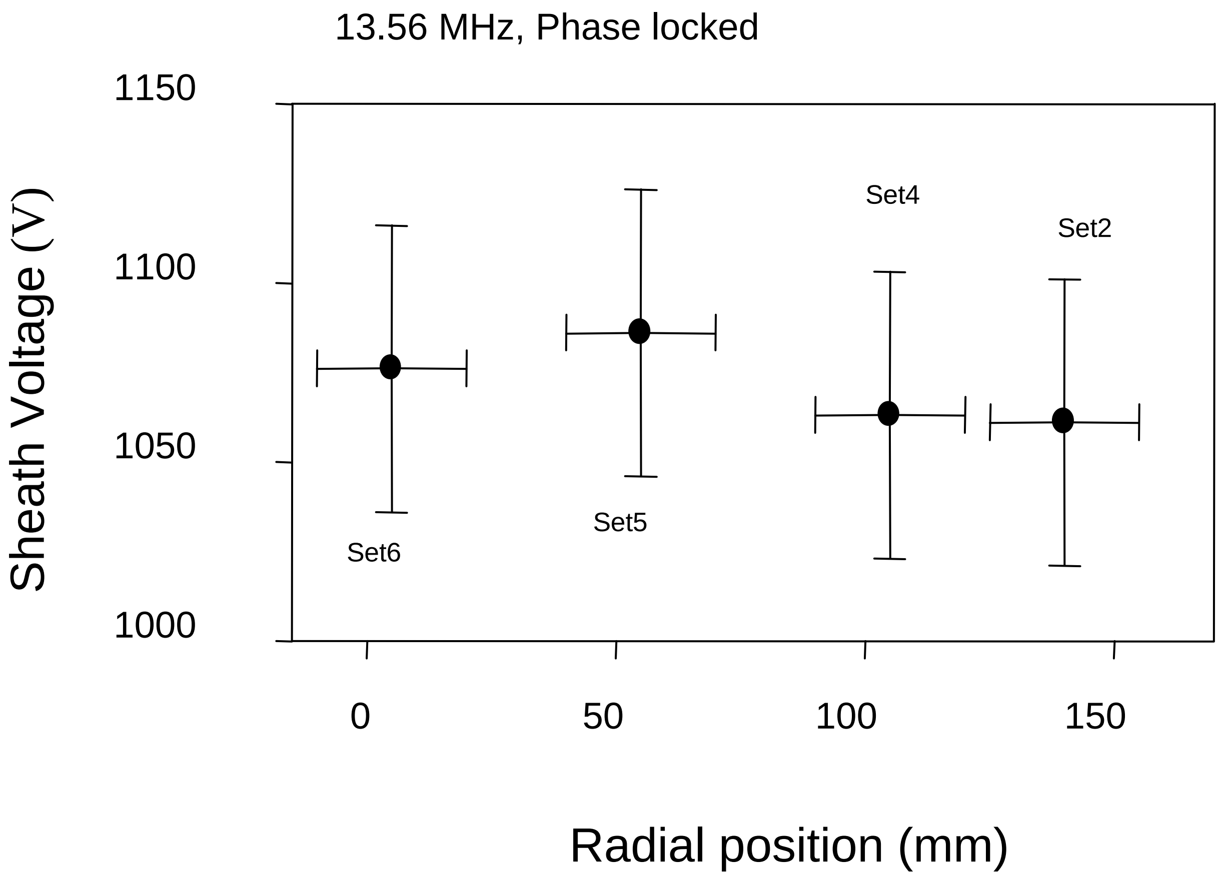
- Strong electric field at the edge of the wafer in the absence of a guard ring

- 360 Watts @ 13.56 MHz, 50 mTorr argon



Sheath electric field is uniform at 13 MHz

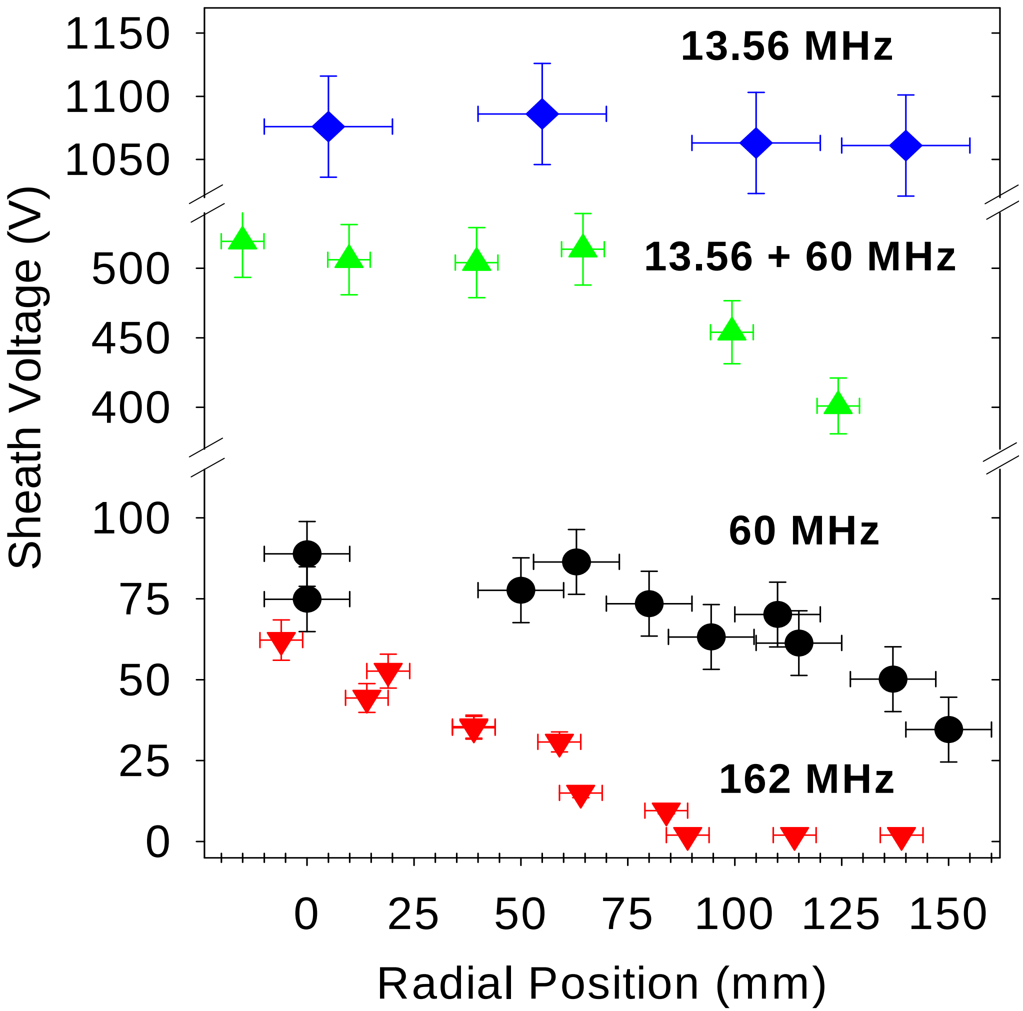
- 13.56 MHz is (with-in error) quite uniform across the entire electrode
  - +/- 50 volts in ~ 1050 Volts = 5 %



Sheath electric field is a function of radius and rf excitation frequency

- 13.56 MHz is uniform over wafer
- Sheath voltage reduced by ~ 1/2 at 60 MHz
- Sheath voltage can not be measured at 162 MHz
- Effect is still present with dual frequency
- Radial fields should be present (somewhere) to compensate for this voltage drop
  - 50 V per 50 mm ~ 10 V/cm

- Center high excitation at 162 MHz may be the source for nonuniform ion temperature and change the ion heating mechanism



Ion energy and sheath field measurements share many common points

- Observe standing wave effects for the highest frequency rf excitation
  - These will be a challenge to smooth out for uniform etching
- Off axis peak in ion velocity due to ambipolar fields and non uniform charge density.
  - LIF may provide a good method to benchmark uniformity for high aspect etch systems
- The energy deposition due to the sheath electric fields was frequency and spatial dependent
  - The field at low frequency is radially uniform while for higher rf frequencies it was peaked in the center of the plasma
  - The frequency difference in sheath voltage could translate into spatially dependent EEDF.   Weak double layer?
- If these results translate to etch chemistries, center to edge etch anisotropy driven by EEDF or ion temperature will be important.
- Not clear why the ions are several 100’s K above ambient.
- Student visits and joint experiments?

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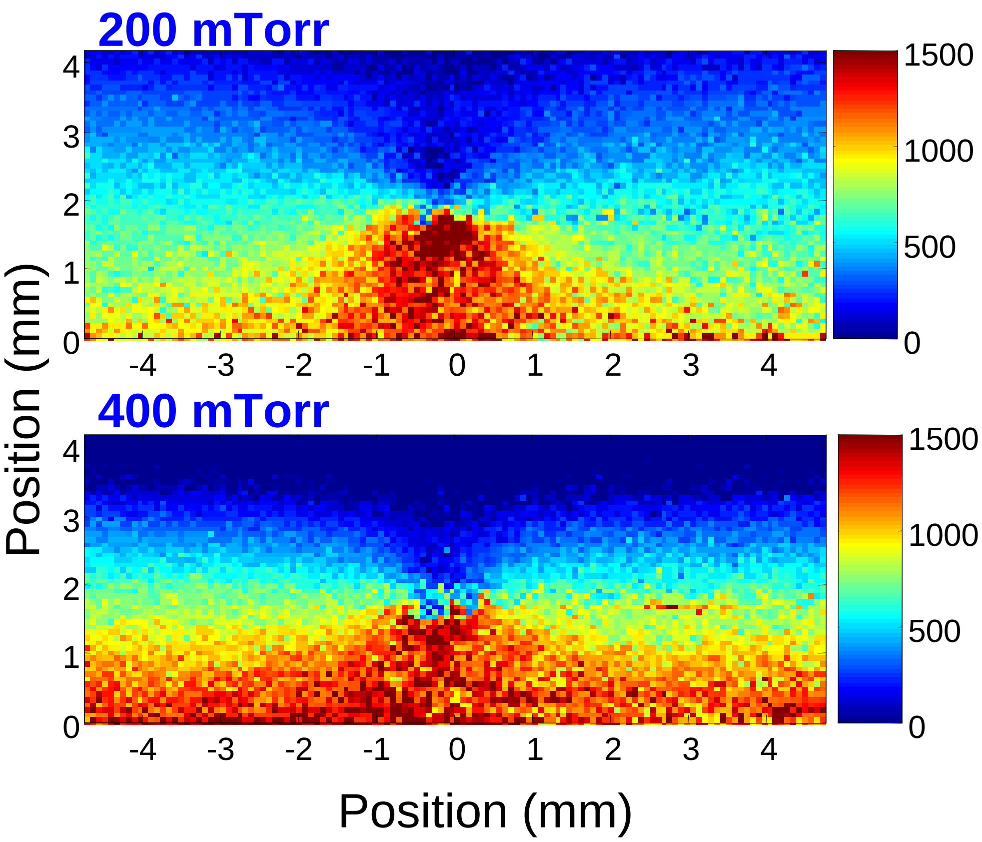
Langmuir probes can have a huge effect of the plasma

- The field pertubations due to the probe extend far into the sheath.
- While folklore accepted that probes were pertubative, the degree of insult to the plasma is far in excess of what was believed to occur.
- The dust can no longer be viewed as a benign component of the plasma. A layer of dust has a profound influence on the sheath physics, charge transport and possibly ionization.
- Fundamental assumption (wrong!) is that dust does not change the background plasma properties.



320 V_{pp} @ 13.65 MHz

Grounded Probe, Cathode Phase

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Thank you