Ion Energy Distribution Measurements
Past, Present and Future

(*Focus on Retarding Field Analyser Technology*)

David Gahan CTO
S. Sharma PhD candidate, Mike Hopkins CEO

Impedans
Plasma Measurement

Talk Outline

Past

- The Ion Energy Distribution Function (IEDF)
- Retarding Field Analyser (RFA)
  - IEDF of IVDF?
- Previous state of the art in RFA Technology

Present

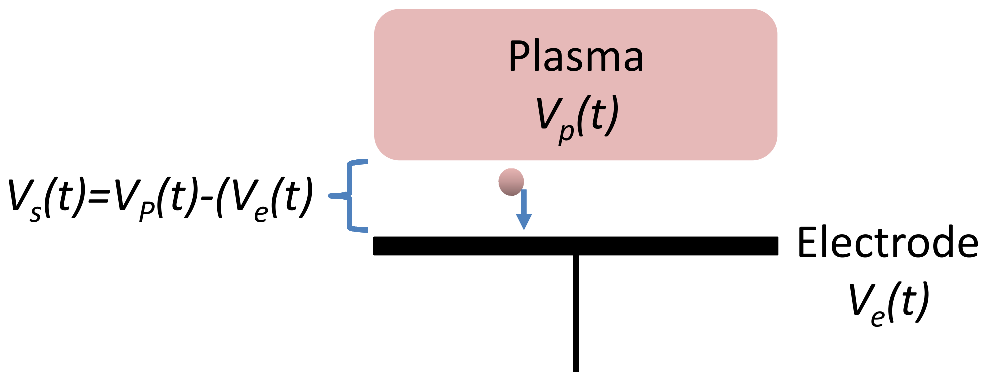
- Recent advances in RFA Technology
  - Floating RFAs for (rf) biased electrodes
  - Pulsed rf and time resolved functionality
  - RFA with spatial resolution
  - Ion Angular Distribution measurement

Future

- RFAs with ion mass resolution
- Wireless sensors

The Ion Energy Distribution Function

- Shape of IEDF determined by:
  - sheath potential $V_s(t)$
    - ion transit time τ_i
      - period of sheath potential waveform τ_{rf}



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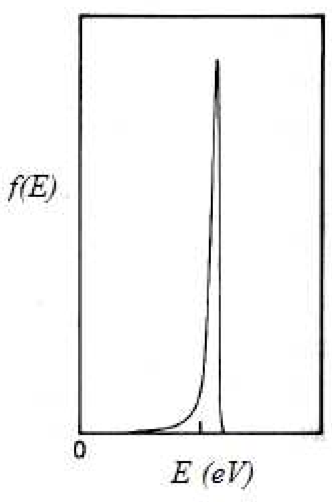
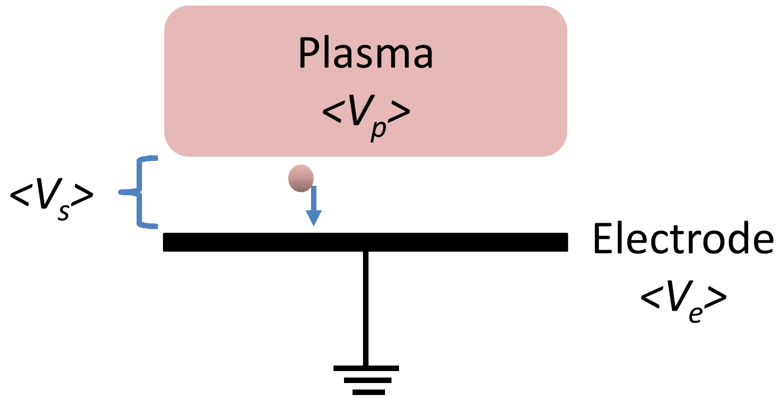
The Ion Energy Distribution Function

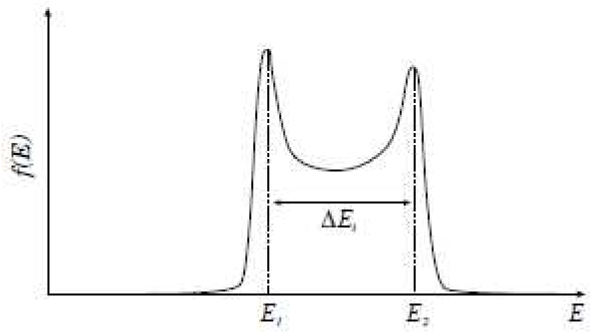
- For DC sheath
  - $<E> \rightarrow <eV_s>$
    - $\Delta E \rightarrow 0$
      - FWHM 2 – 3eV

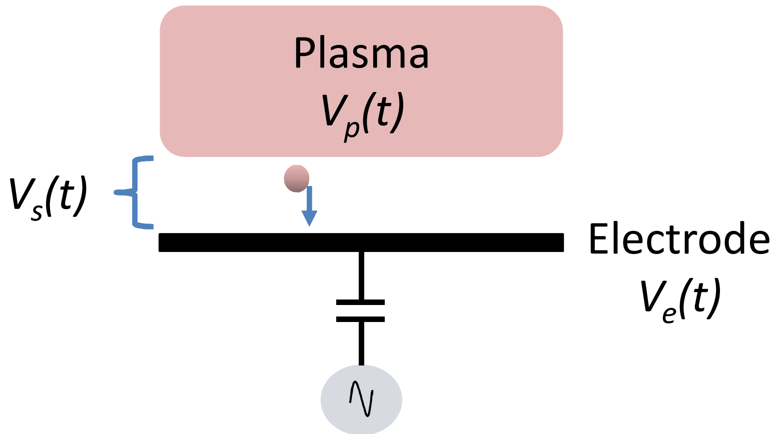




The Ion Energy Distribution Function

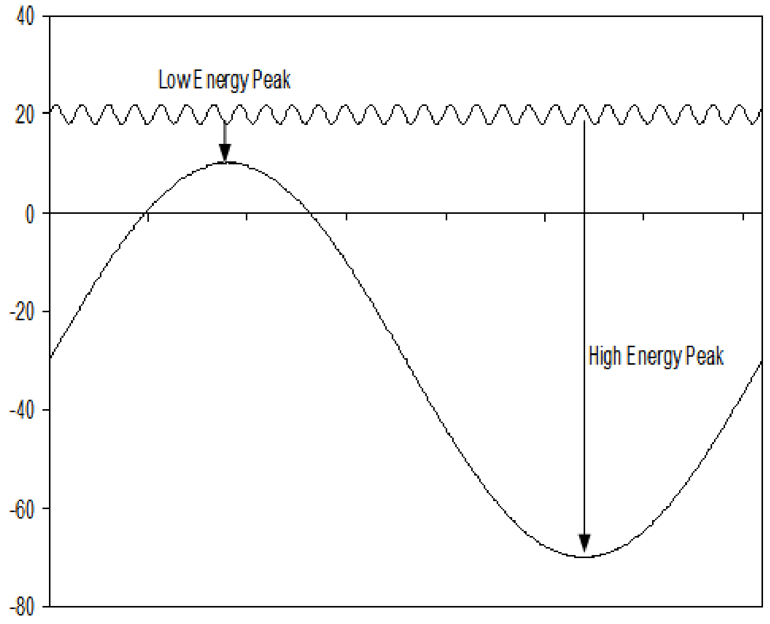
- For RF sheath
  - Ion transit time $\tau_i = 3\bar{s}\sqrt{m_i/(2e\bar{V}_s)}$
  - $$f(E) = \frac{\mathrm{d}n}{\mathrm{d}E} = \frac{2n_t}{\omega \Delta E_i}\left[1 - \frac{4}{\Delta E_i^2}(E - e\bar{V}_s)^2\right]^{-1/2}$$
  - $$\Delta E = \frac{4e\tilde{V}_s}{\pi}\left(\frac{\tau_{rf}}{\tau_i}\right)$$

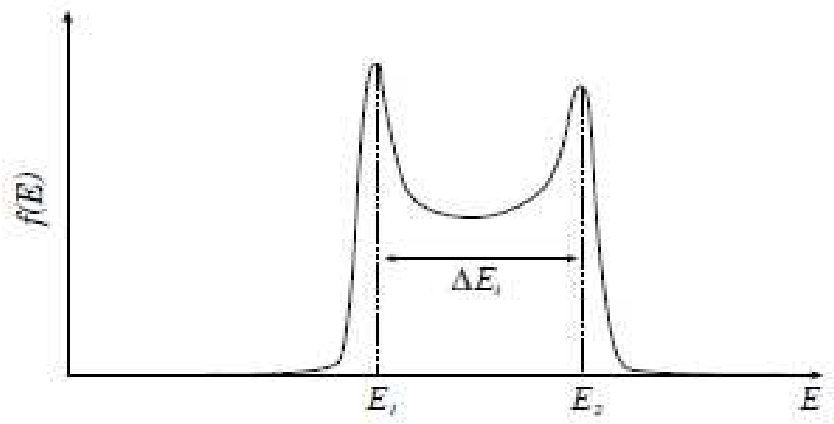




Benoit-Cattin P, Bernard L C and Bordenave-Montesquieu A 1967 Dispersion en énergie des ions produits par une source à excitation de haute fréquence *Entropie* **18** 29

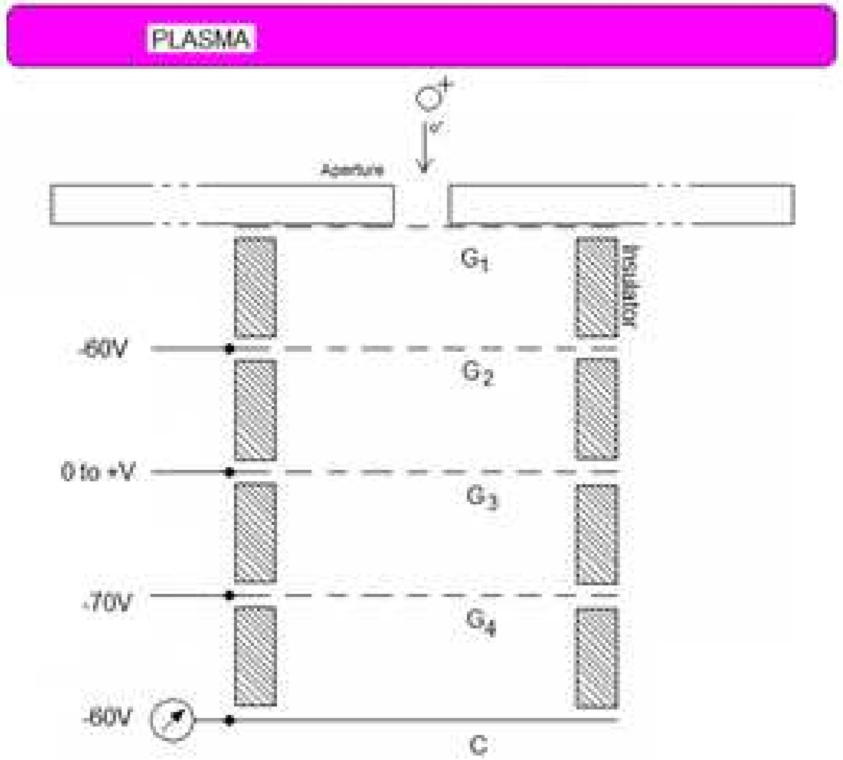
The Ion Energy Distribution Function





The Retarding Field Analyser (RFA)

- Planar, Gridded Structure
- G1 prevents plasma entering RFA
- G2 repels plasma electrons
- G3 retards ion flow
- G4 prevents secondary emission from C
- C collects current of ions



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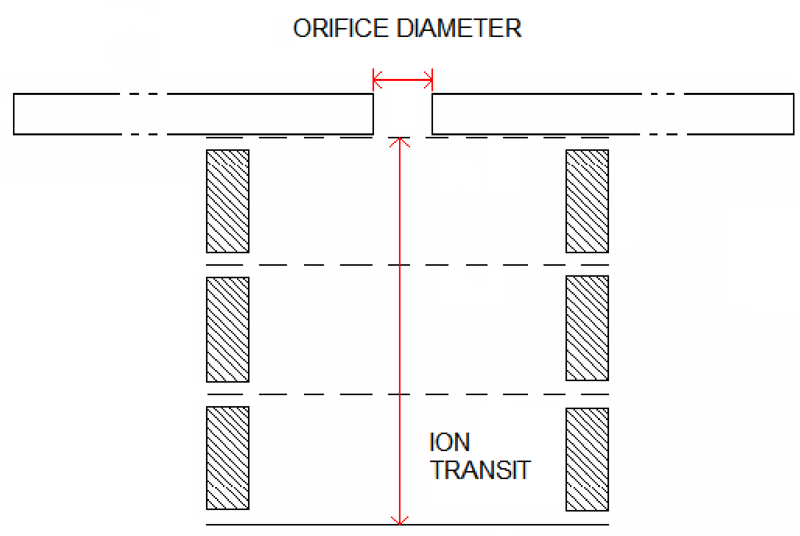
The Retarding Field Analyser (RFA)

- Orifice diameter < Debye length λ_D
  - $\lambda_D = \left(\frac{\varepsilon_o k T_e}{n_e e^2}\right)^{1/2}$ e.g. T_e=3eV, N_e=$10^{17}m^{-3}$ …… λ_D~40µm
- Ion transit length < Ion mean free path λ_i
  - $\lambda = \frac{1}{\sigma n}$
  - *RFEA depth 0.8mm ~ 100mTorr in Argon*



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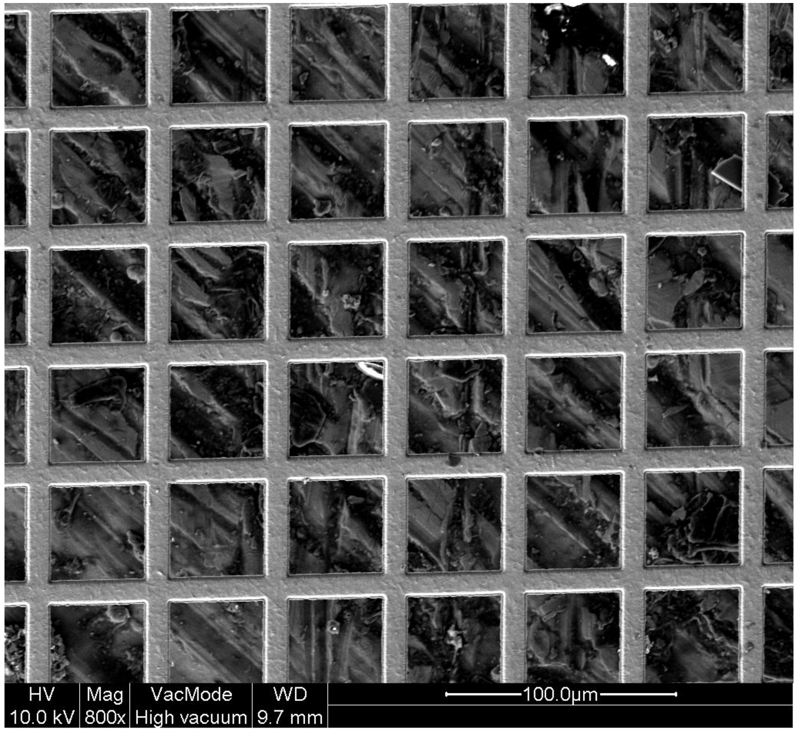
The Retarding Field Analyser (RFA)

Nickel Grid



RFA

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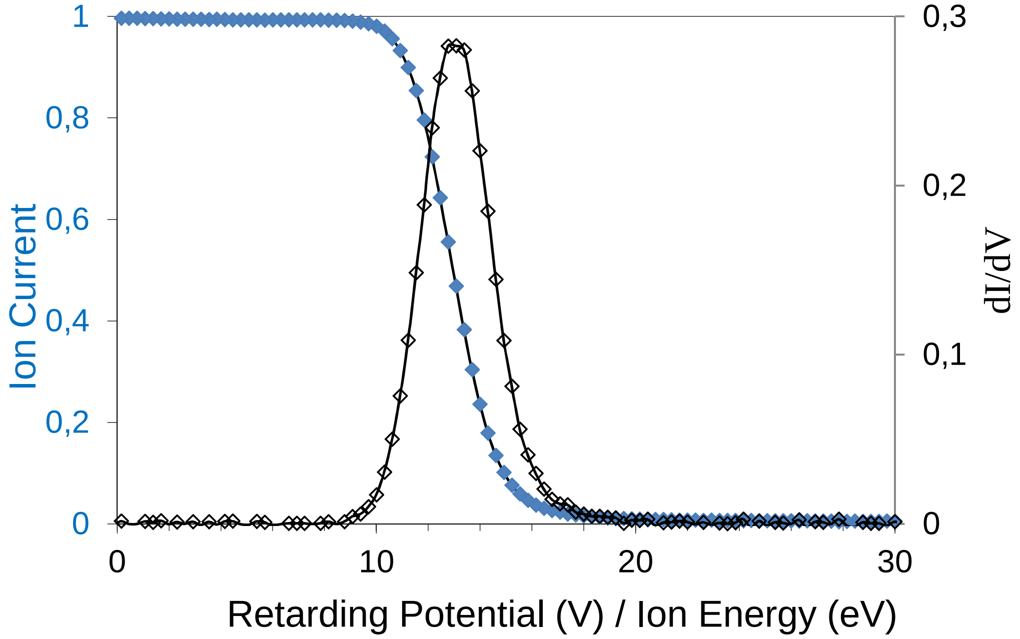
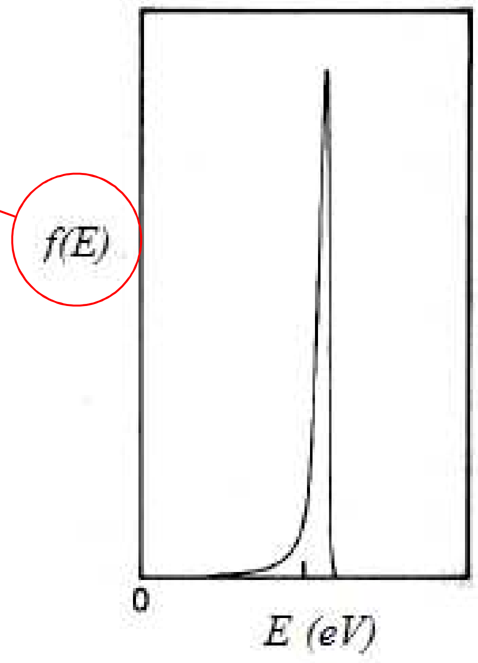
The Retarding Field Analyser (RFA)

- Ion Energy = eV_{G2}
- $f(E) = dI_c / dV_{G2}$??



IVDF or IEDF??

- Ion Energy distribution function
  - *Variable on Y axis must be a function of E*
- $dI_c / dV_{G2} = f(E)$??
  - $I_c \propto nev$
    - $v = (2E/m)^{1/2}$
      - $\therefore I_c \propto (E/m)^{1/2}$
      - $dI_c / dV_{G2} = f((E/m)^{1/2} = f(v) = IVDF!!$
- RFA gives IVDF versus Energy



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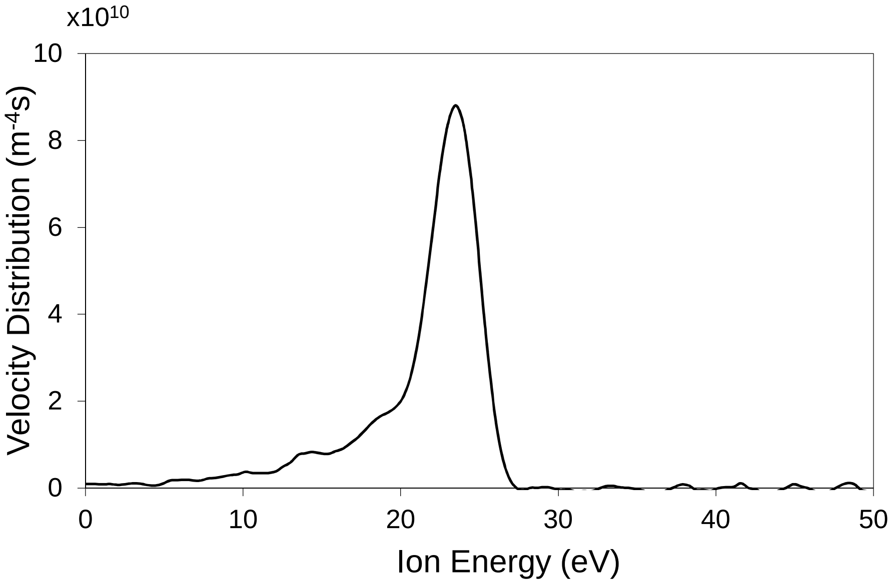
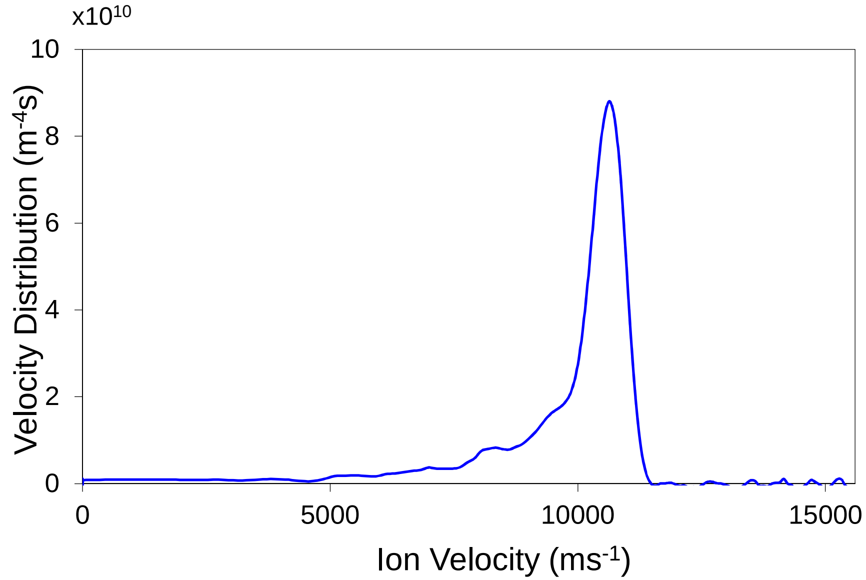
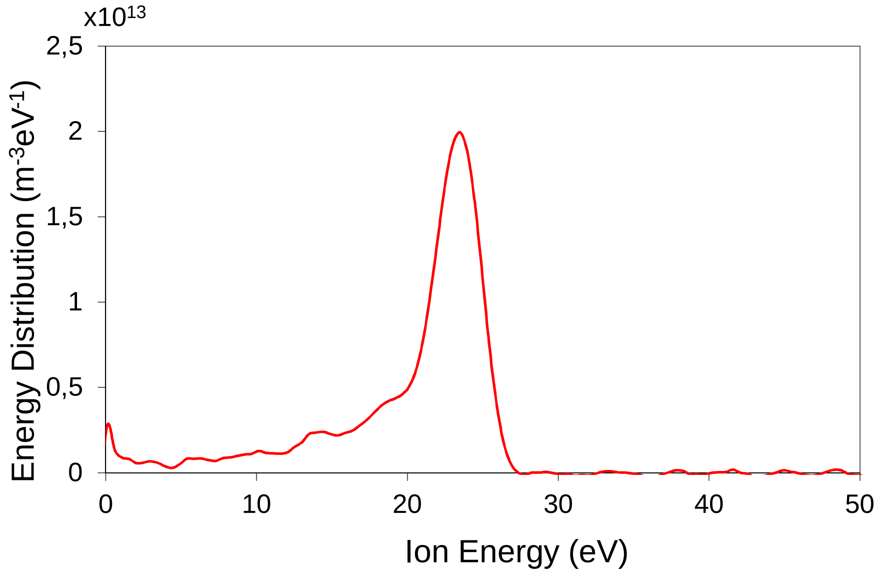
IVDF or IEDF??







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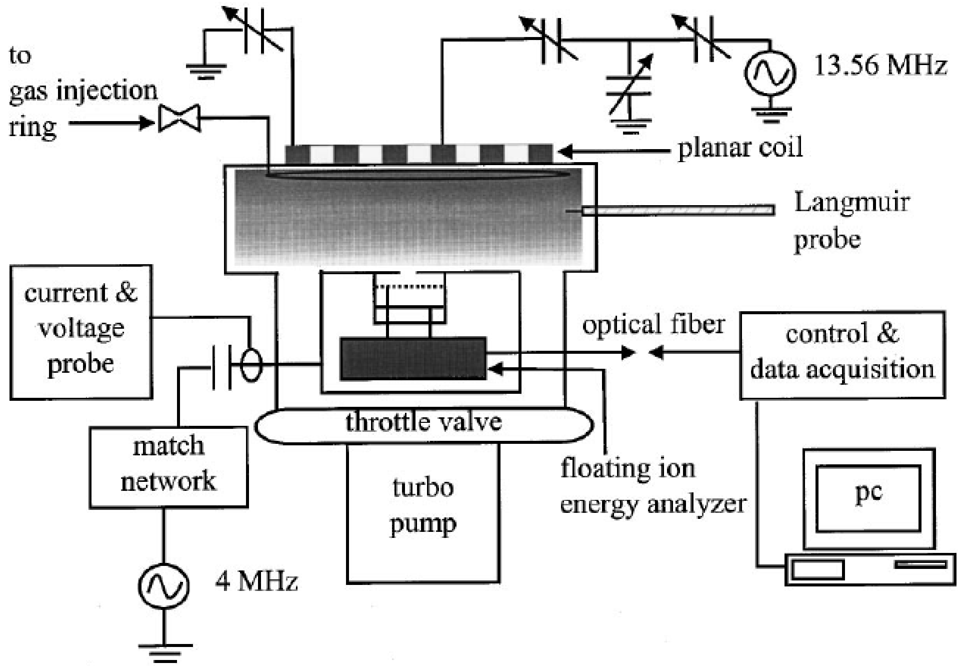
Previous State of the Art

- Previous state of the art
- Disadvantages:
  - Complex electronics
  - Redesign of rf chuck
  - Not commercially viable as instrument



REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 70, NUMBER 6 JUNE 1999

Compact floating ion energy analyzer for measuring energy distributions of ions bombarding radio-frequency biased electrode surfaces

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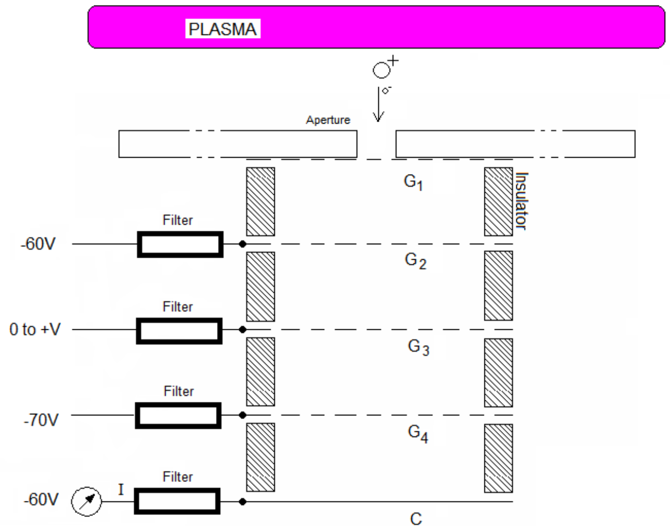
  - Floating RFAs for (rf) biased electrodes
  - Pulsed rf and time resolved functionality
  - RFA with spatial resolution
  - Ion Angular Distribution measurement

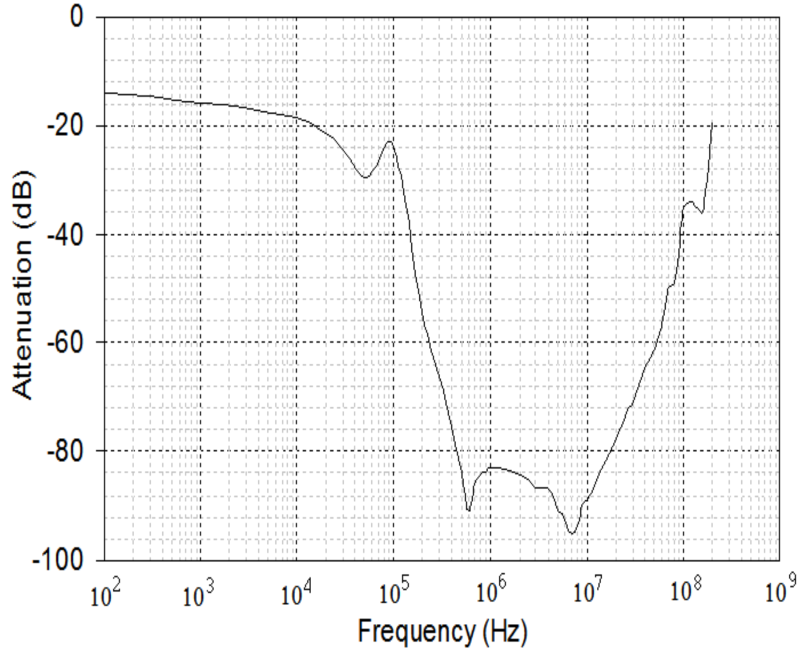
Future

- RFAs with ion mass resolution
- Wireless sensors

Recent Advances in RFA Technology

- RFA design compatible with rf biased electrode



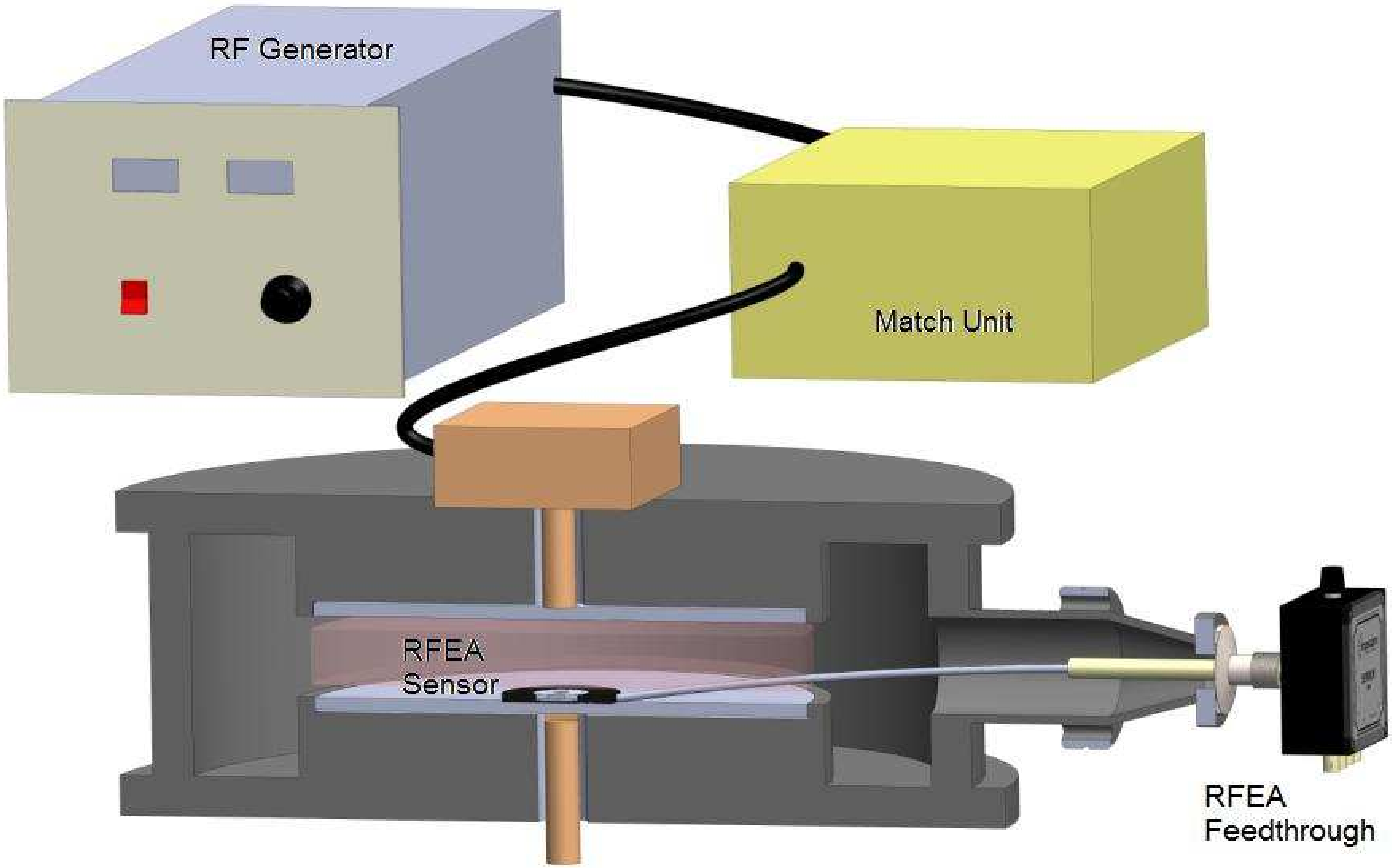


REVIEW OF SCIENTIFIC INSTRUMENTS 79, 033502 (2008)

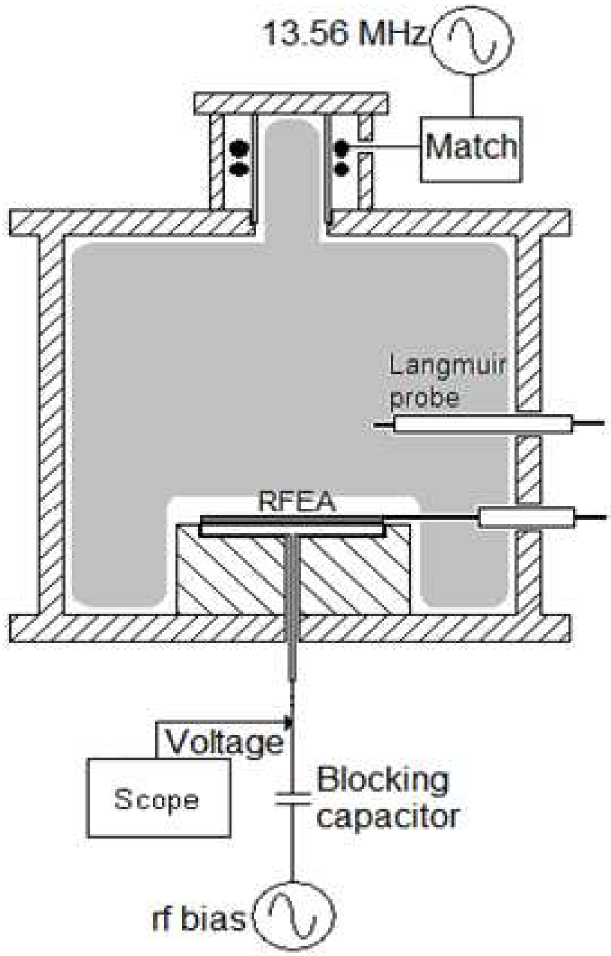
Retarding field analyzer for ion energy distribution measurements at a radio-frequency biased electrode

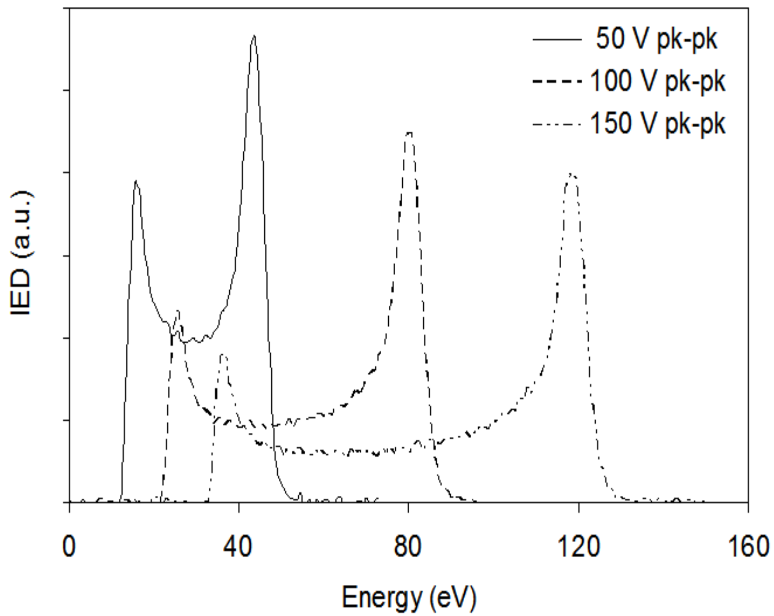
D. Gahan, B. Dolinaj, and M. B. Hopkins

Typical installation



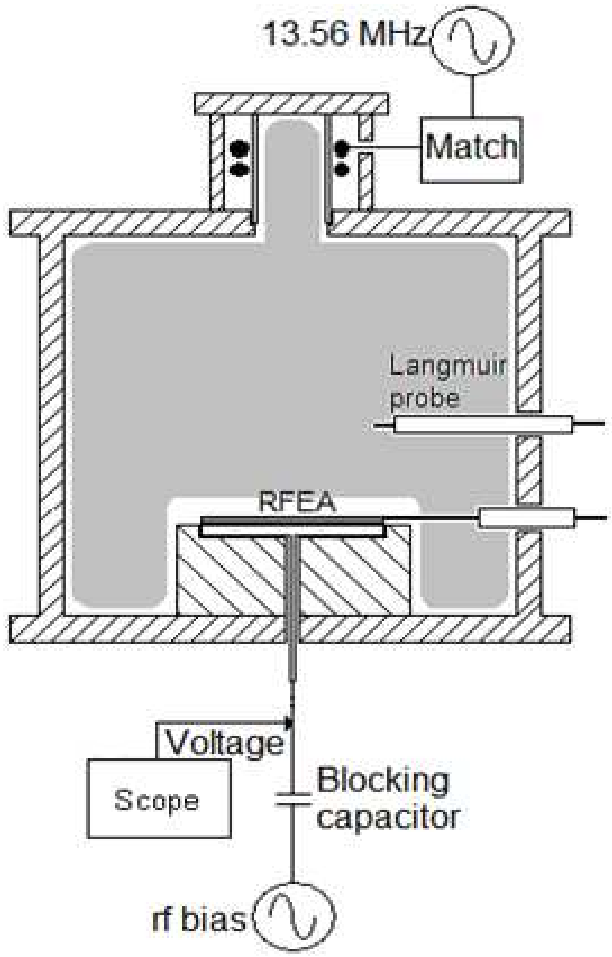
Typical results

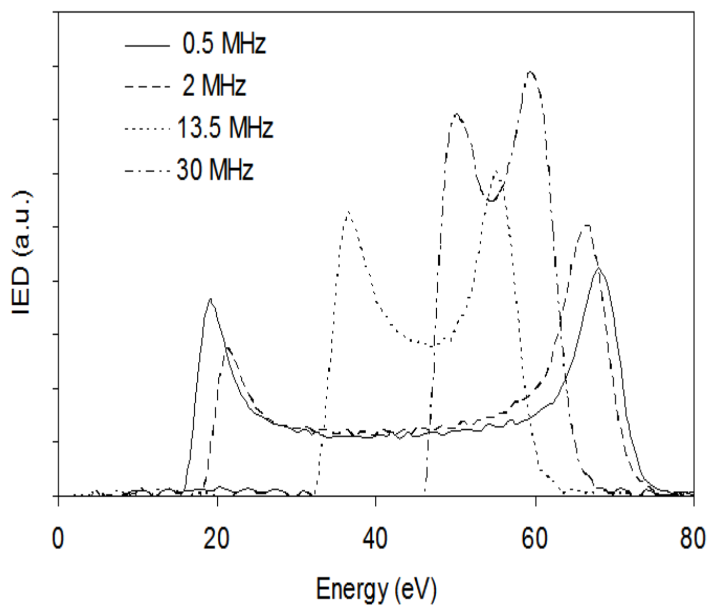




$$\Delta E = \frac{4e\tilde{V}_s}{\pi}\left(\frac{\tau_{rf}}{\tau_i}\right)$$

Typical results

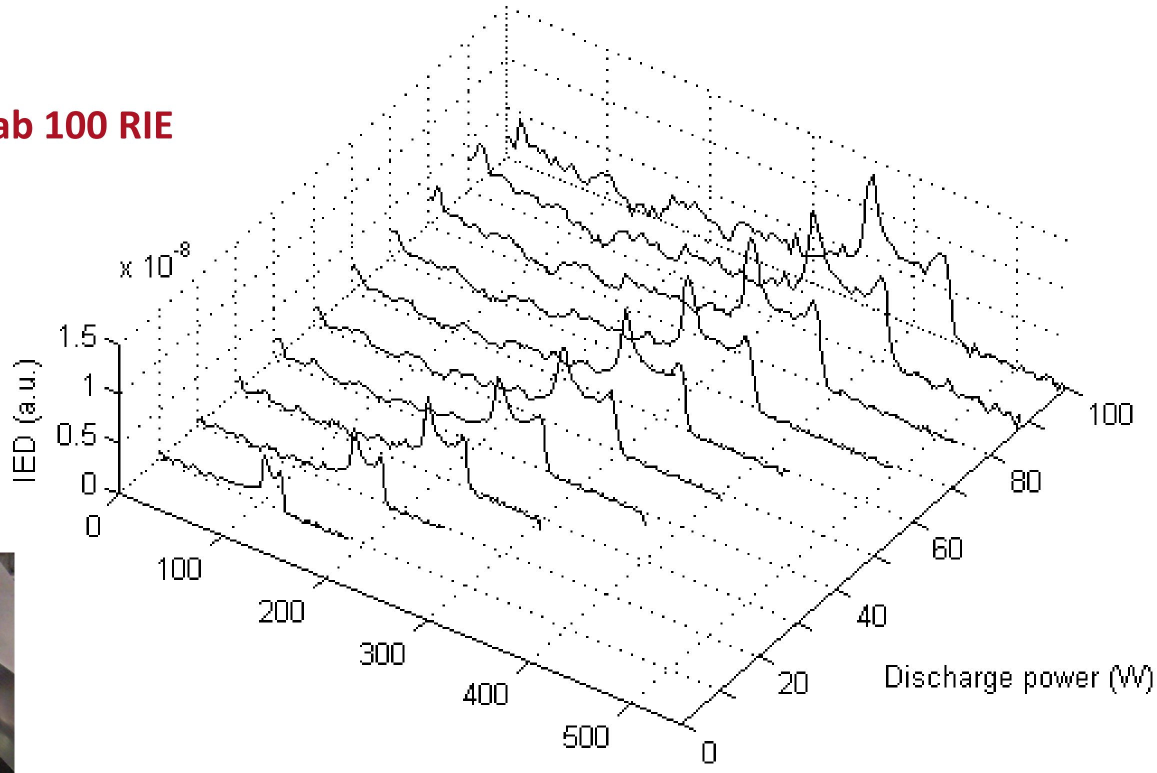


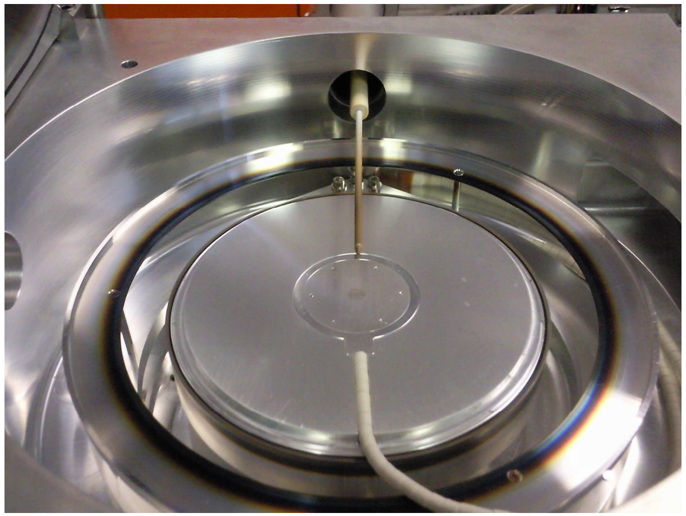


$$\Delta E = \frac{4e\tilde{V}_s}{\pi}\left(\frac{\tau_{rf}}{\tau_i}\right)$$

Typical results

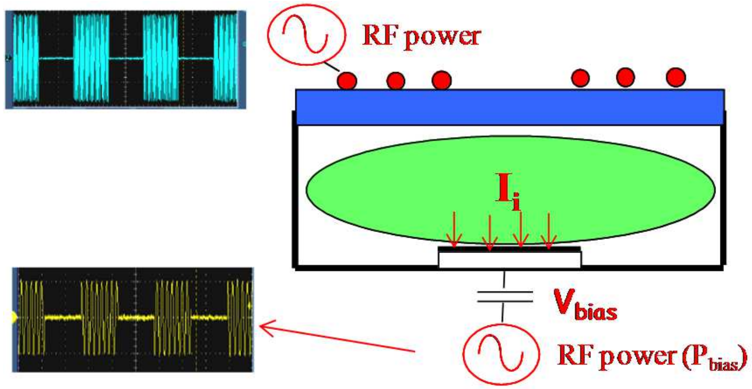
CCP Oxford Instruments PlasmaLab 100 RIE

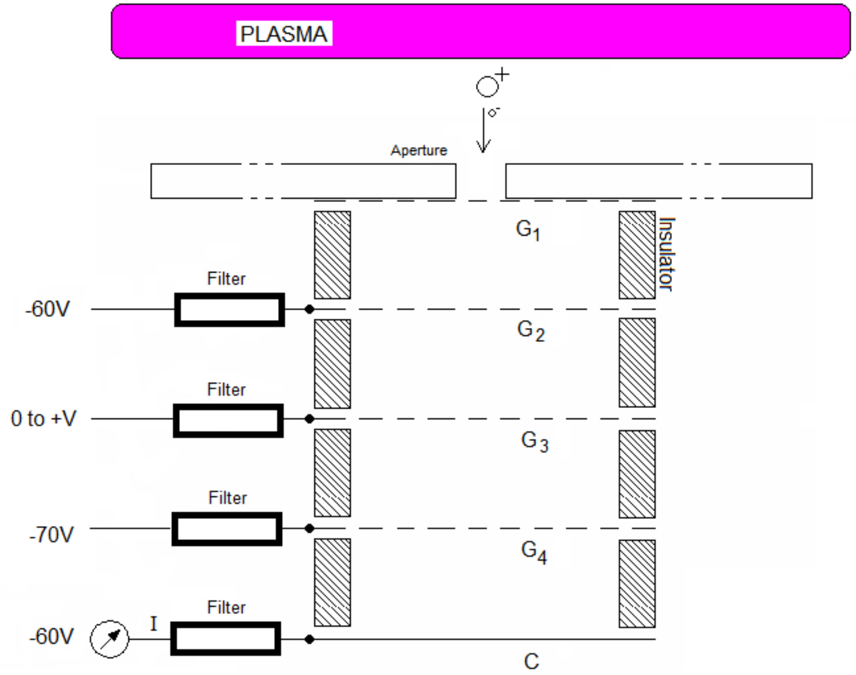




Pulsed RF Requirements

Pulse frequencies in kHz range





Ion flux and ion distribution function measurements in synchronously pulsed inductively coupled plasmas

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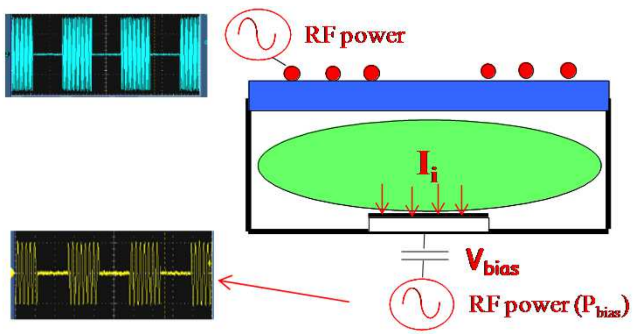
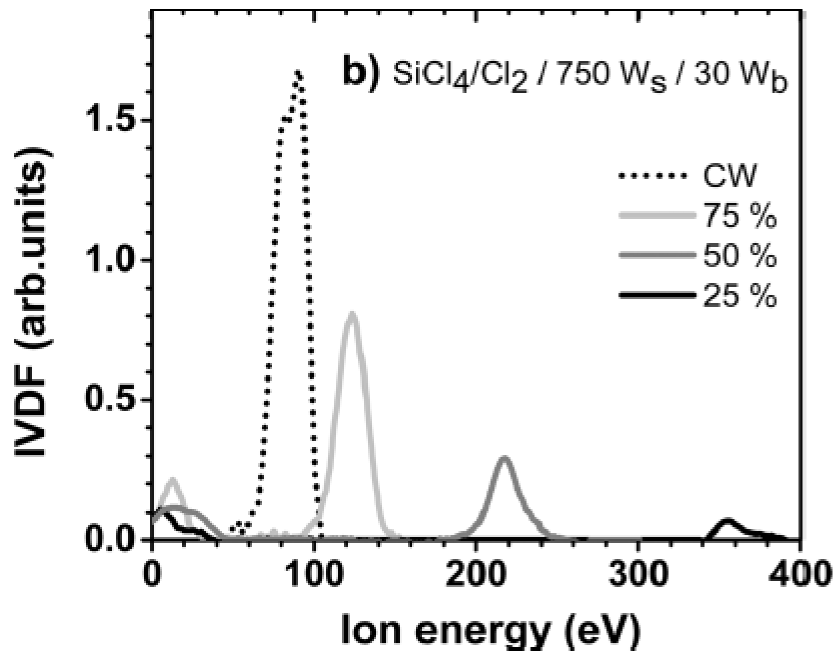
Pulsed RF Plasma

IEDF in synchronous pulsed plasmas (with bias power)





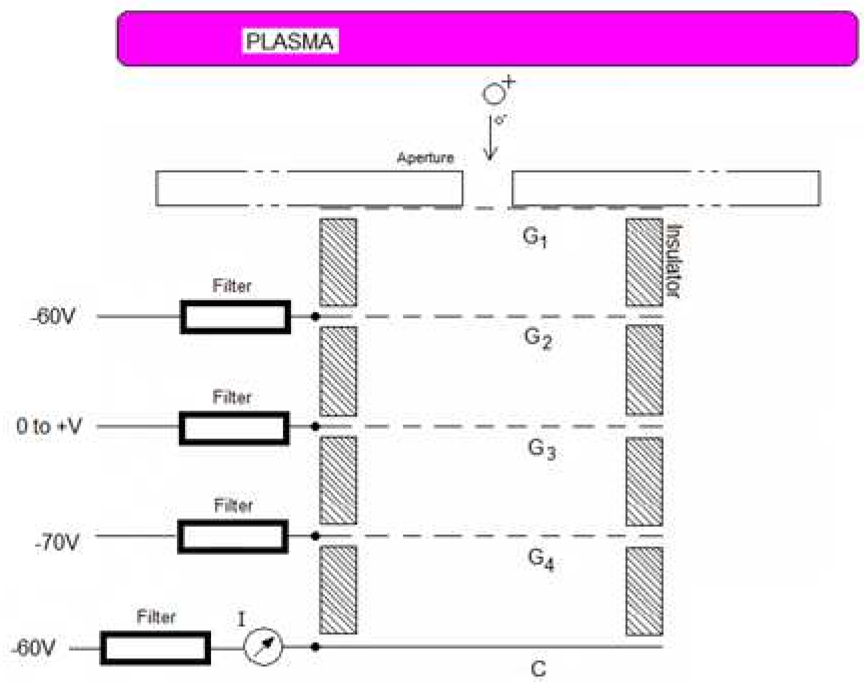
- Bi-modal IEDF (corresponding to ions from ON and OFF periods)

Ion energies accessible that are beyond the capabilities of CW ICP plasma with bias power

Time Resolved Functionality

Filtering prevents good time resolution generally

- Measurement circuit designed to sit on RF side of filter
- 1us resolution just released for pulsed RF application



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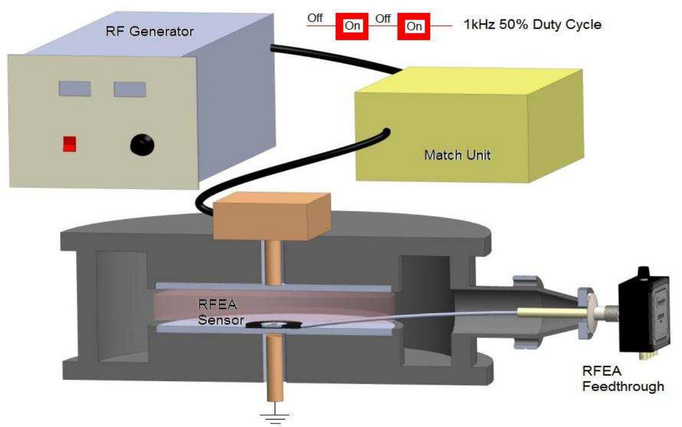
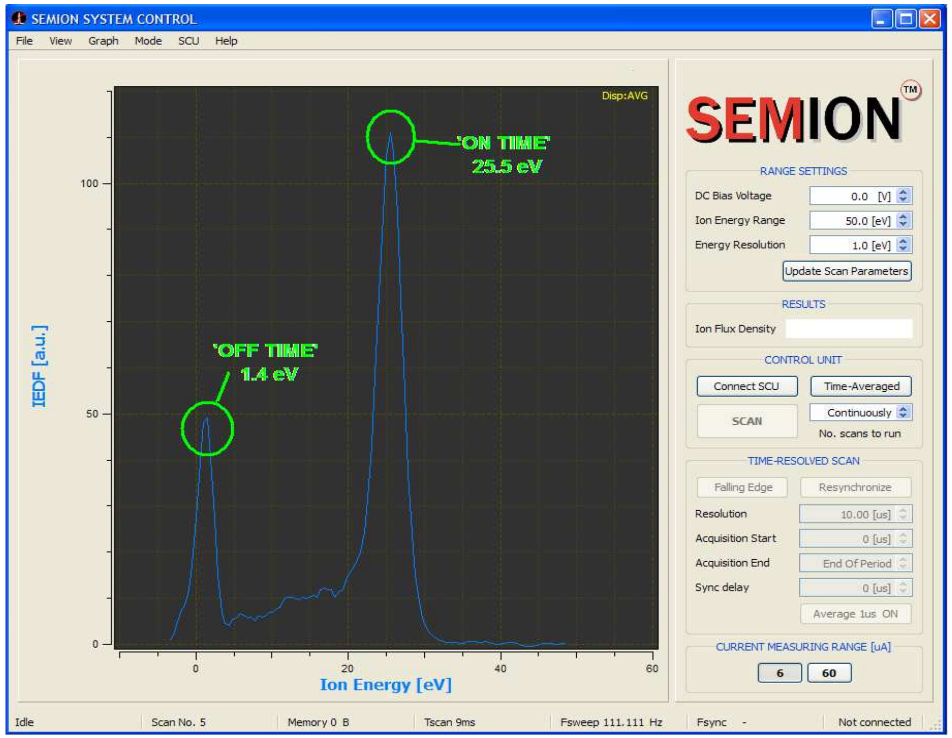
Time Resolved Functionality

Pulsed CCP example

- Bottom electrode grounded (till now design only suitable for grounded or floating electrode)
- Source modulated at 1 kHz
- Square wave modulation, 50%
- Time Averaged measurement





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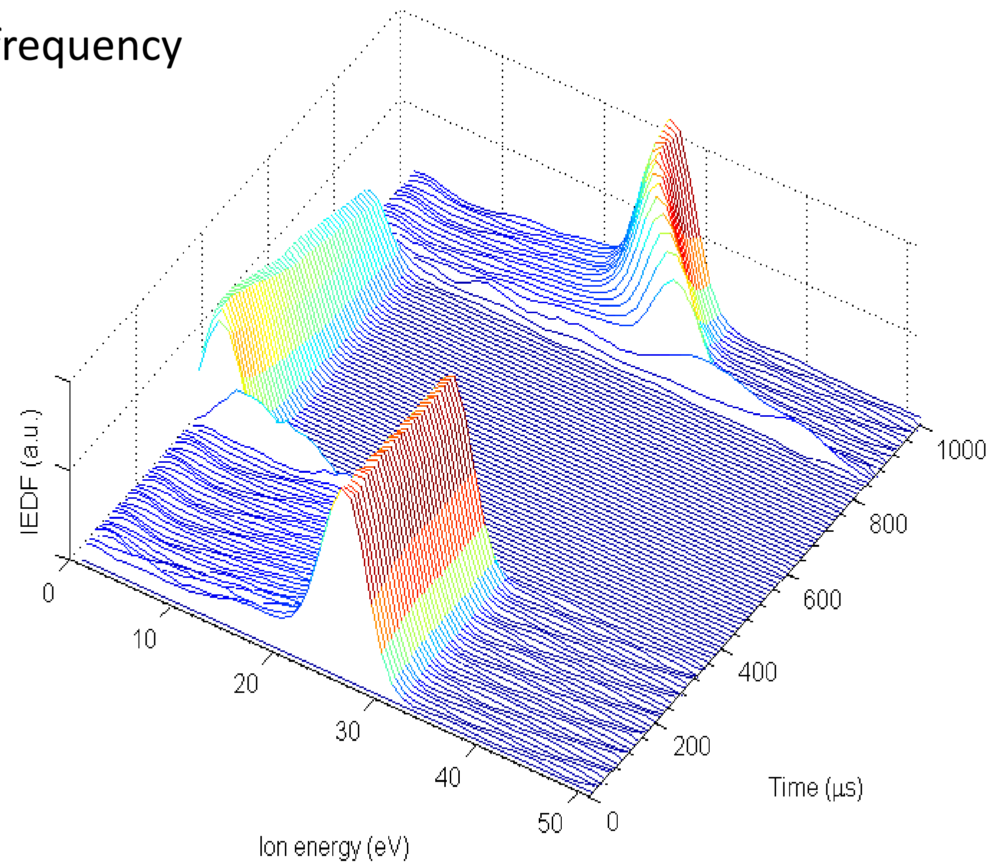
Time Resolved Functionality

Pulsed CCP example

- Time resolved measurement
- 10us resolution, 1kHz pulse frequency



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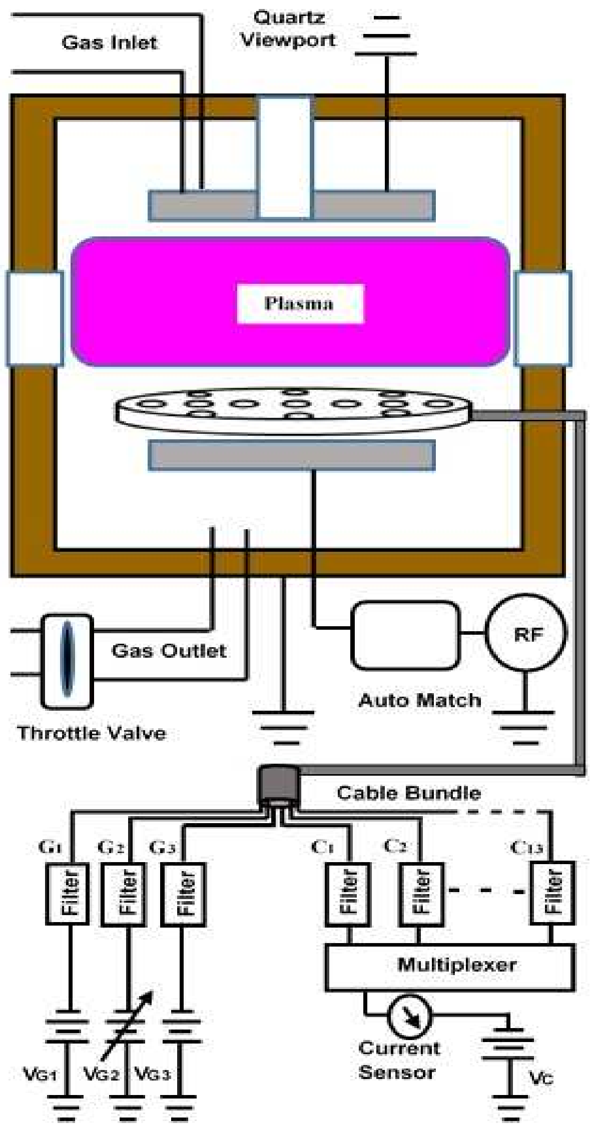
RFA with Spatial Resolution

- Measures
  - Ion Energy
  - Ion Flux
  - Temperature
  - Spatial Profile from 13 (300mm) and 17 (450mm) Different Locations
- Ion Energy Range 0 to 2500eV (5keV on request)

RFA with Spatial Resolution



A spatially resolved retarding field energy analyzer design suitable for uniformity analysis across the surface of a semiconductor wafer

S. Sharma,[1,2,a)] D. Gahan,[1,b)] S. Kechkar,[2] S. Daniels,[2] and M. B. Hopkins[1]
[1]*Impedans Ltd., Unit 8 Woodford Court, Woodford Business Park, Santry, Dublin 17, Ireland*
[2]*National Centre for Plasma Science and Technology, Dublin City University, Glasnevin, Dublin 9, Ireland*

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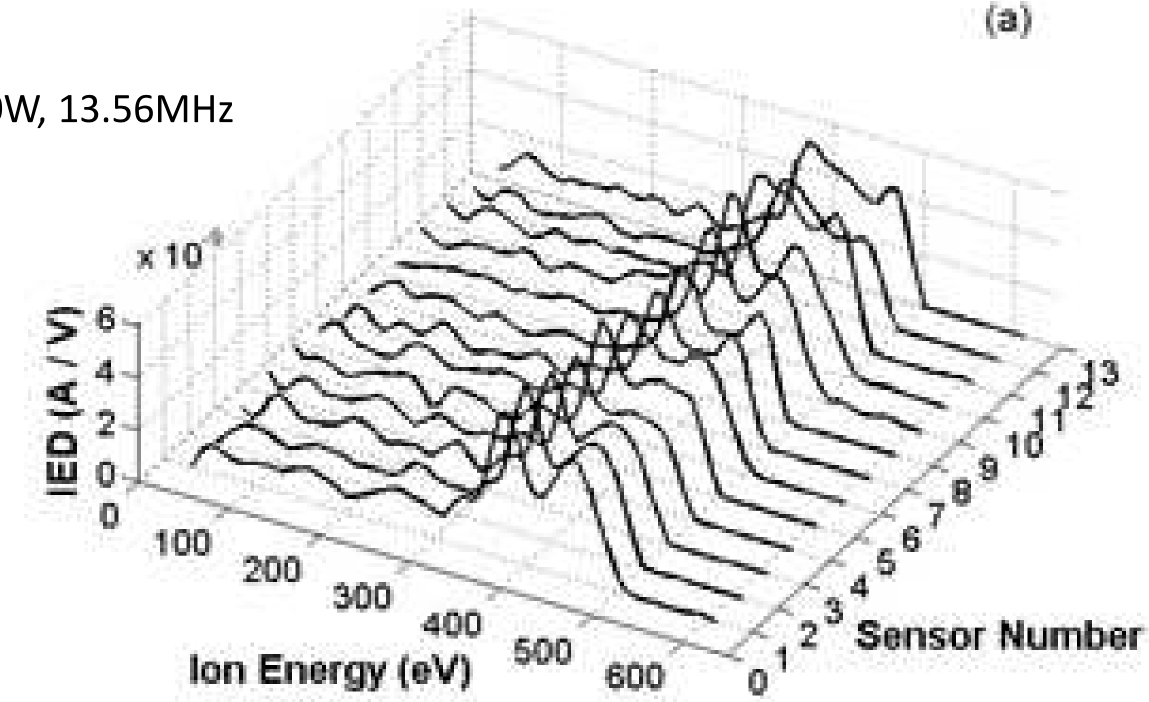
RFA with Spatial Resolution

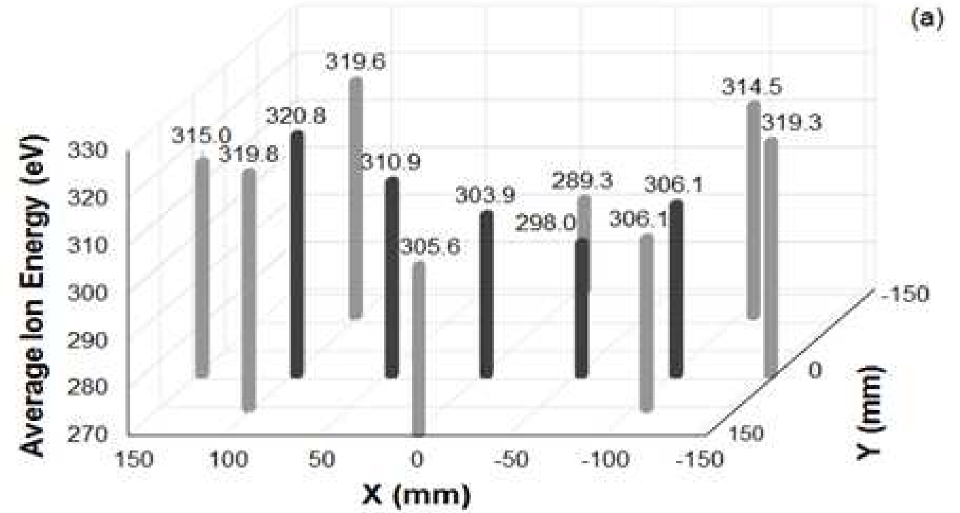
- Argon Plasma, 20mTorr, 100W, 13.56MHz

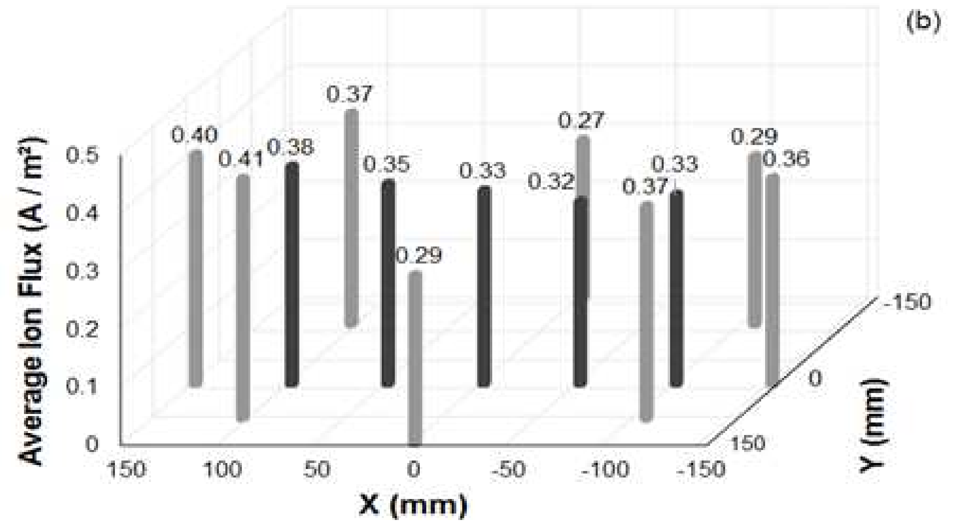


$$Ji = \left(\int_{Emin}^{Emax} IED\, dE \right) / AT$$

$$Ei = \left(\int_{Emin}^{Emax} E\,(IED)\, dE \right) \Big/ \left(\int_{Emin}^{Emax} IED\, dE \right)$$

RFA with Spatial Resolution





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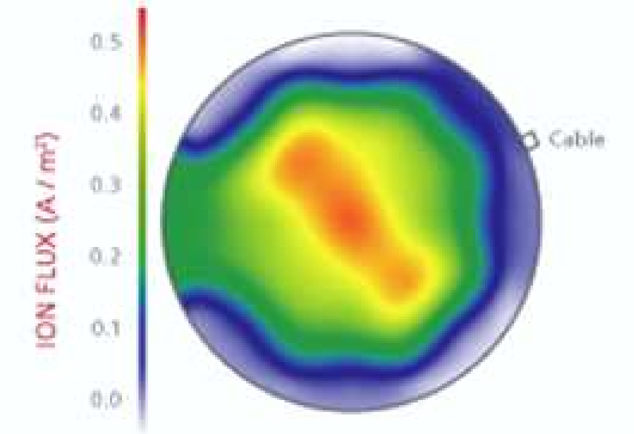
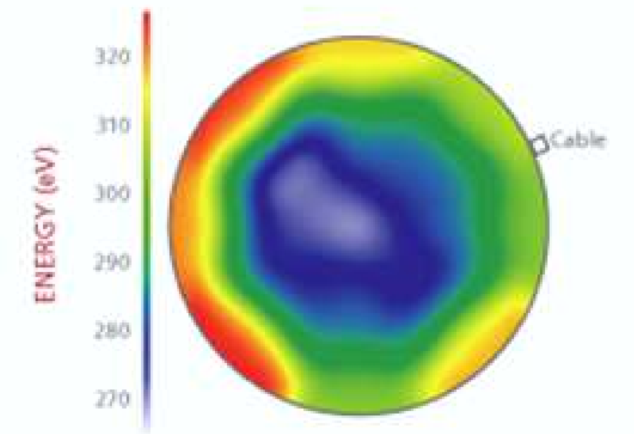
RFA with Spatial Resolution





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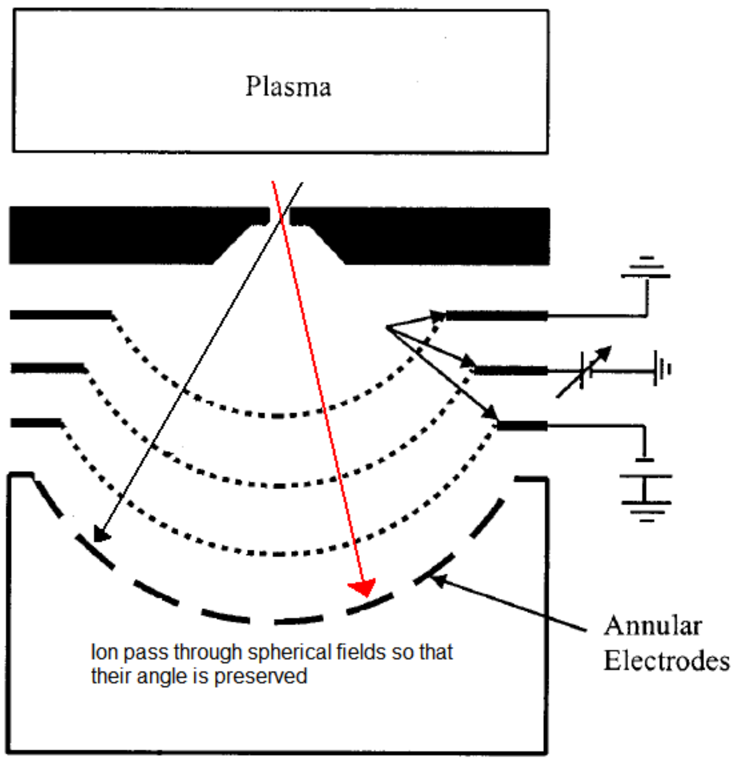
Ion Energy Distribution as a function of Angle

Important parameter for anisotropic etching

• Angular ions travel straight through the spherical fields

• Multiple detectors located at appropriate angles to collect the ion coming ions



Disadvantages

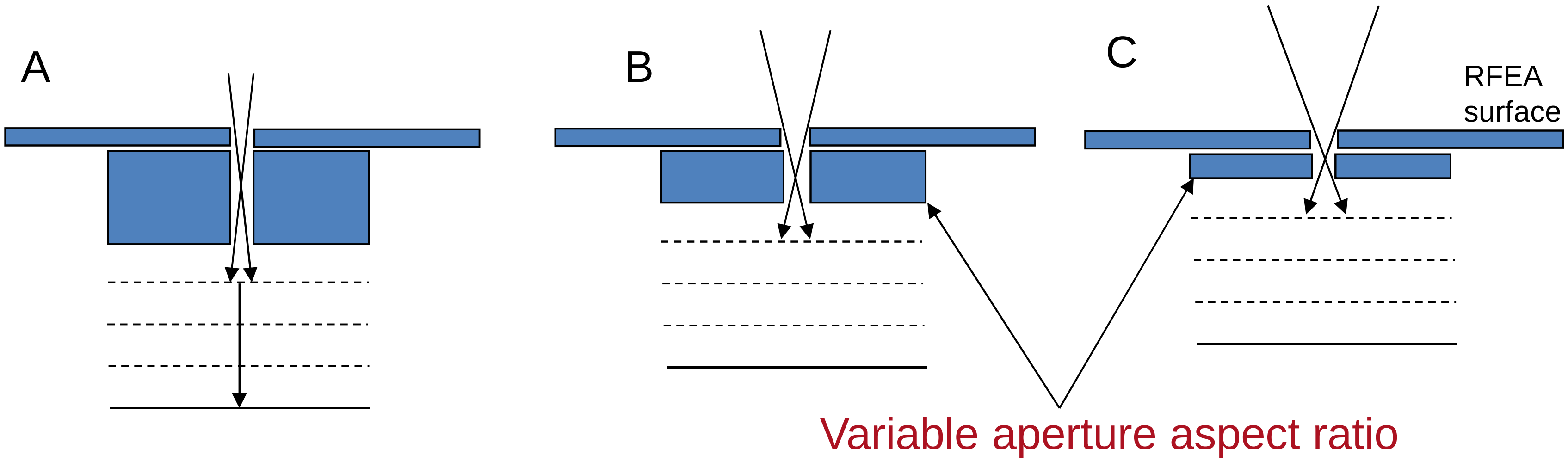
• Spherical grids difficult to manufacture

• Physical depth of sensor is large (25mm)

• This limits operating pressure i.e. 25mm sensor limited to 2mTorr upper pressure range

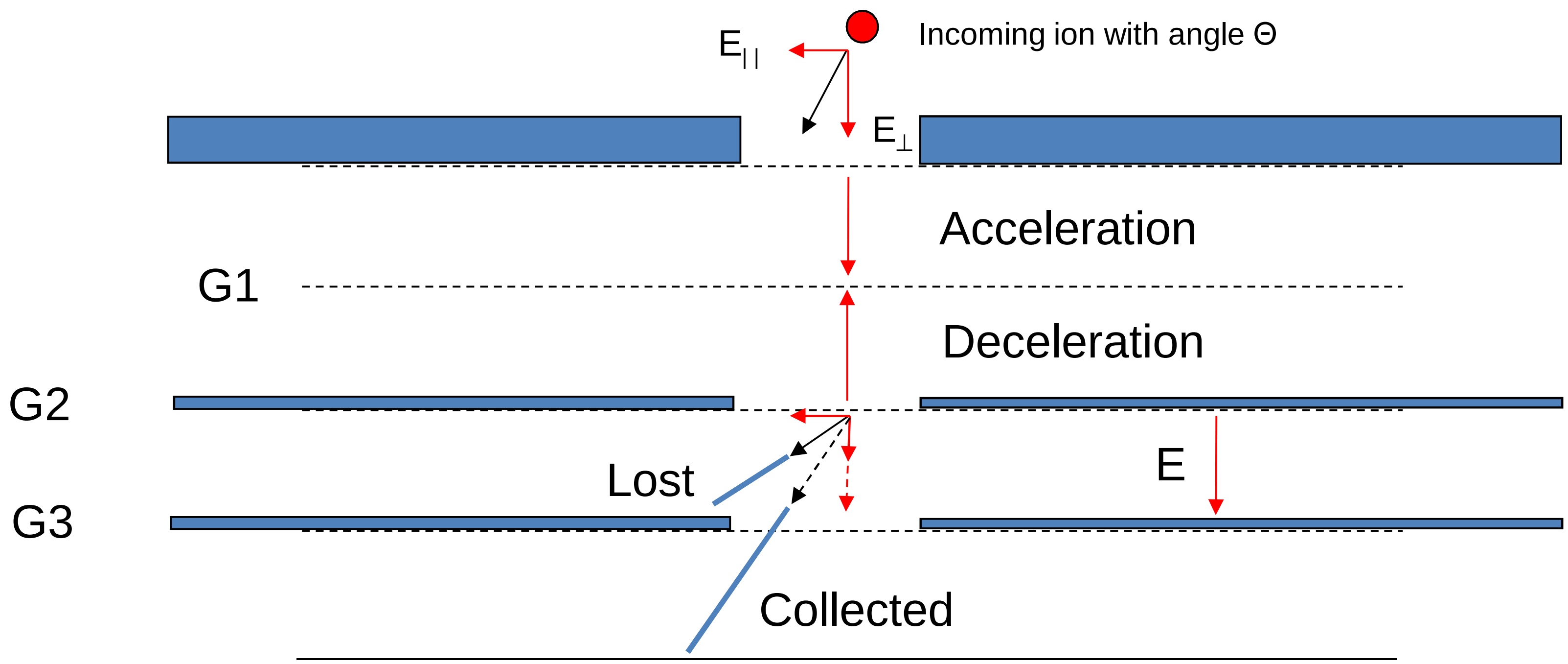
Ion Energy Distribution as a function of Angle

Additional aperture added inside standard RFEA structure



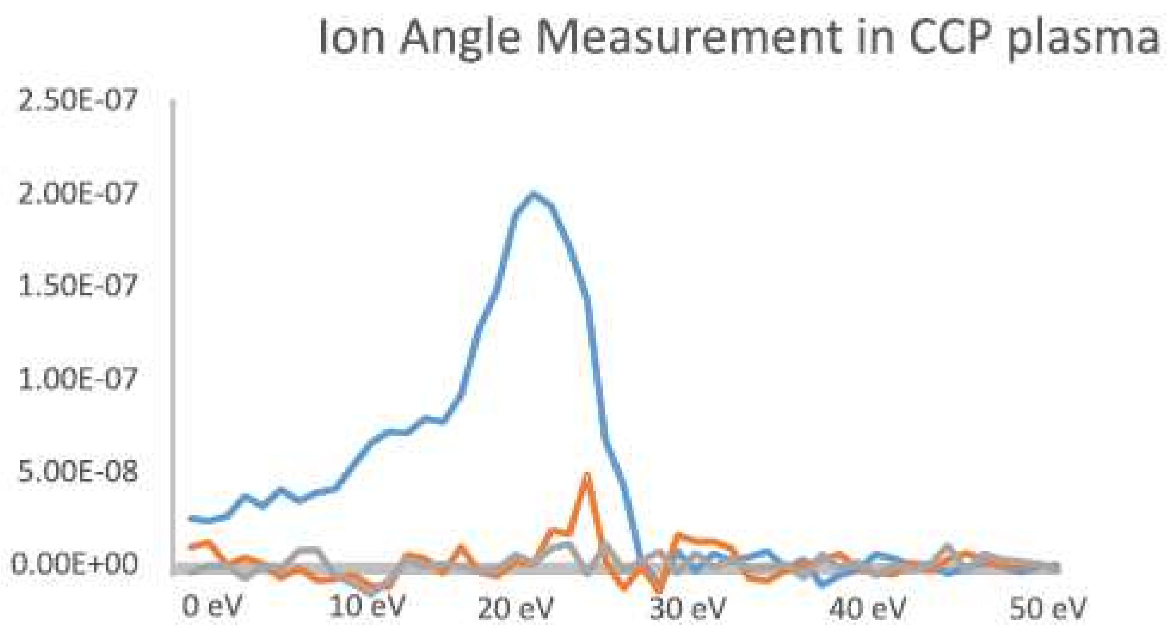
- Mechanical aspect ratio variation complicated

Ion Energy Distribution as a function of Angle



- G2 selects the Ion energy
- Potential of G3 varied wrt G2 to scan angular distribution
- Energy and angle in integral form – multiple derivatives required

Ion Energy Distribution as a function of Angle



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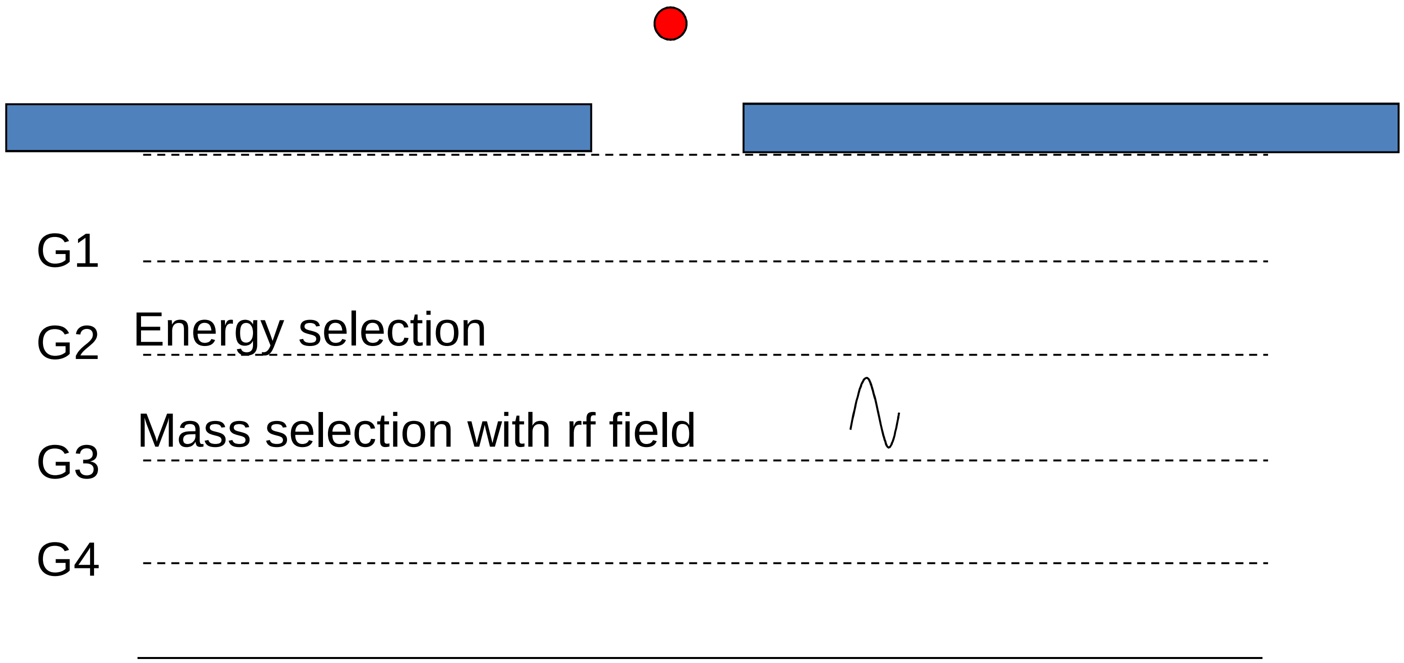
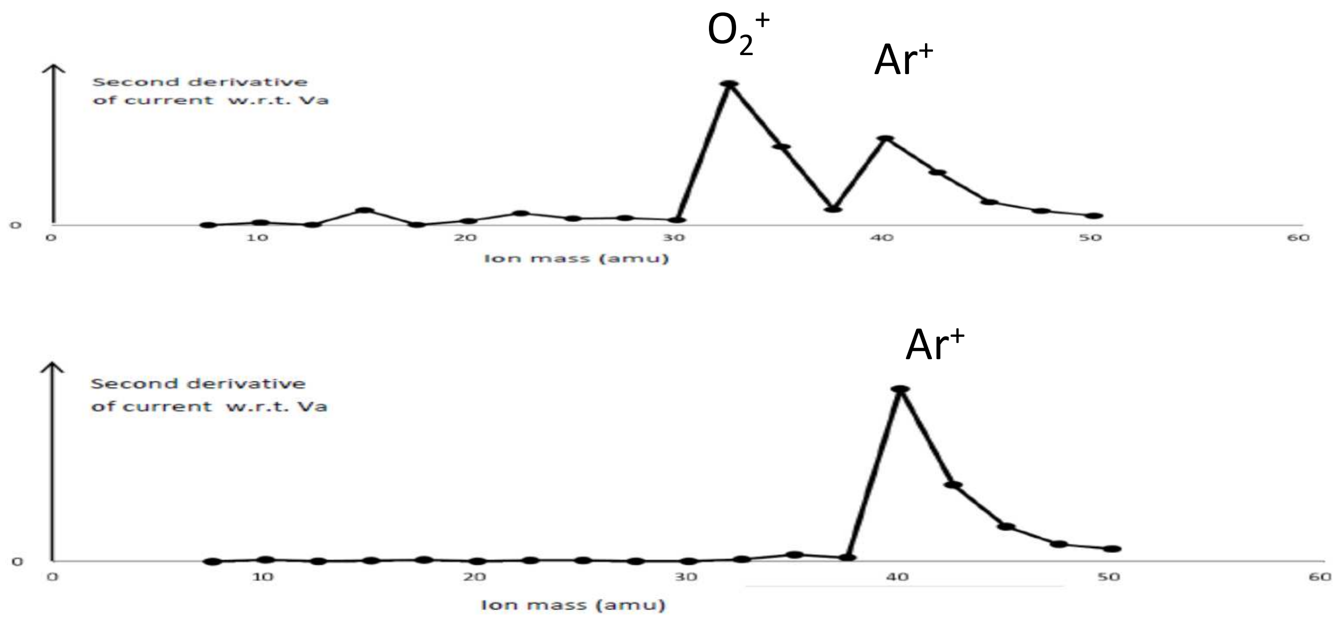
Ion Mass Resolution



- G2 selects the Ion energy
- RF field between G2 and G3, scan over suitable frequency range
- Energy of ions dispersed, proportional to ion mass
- Energy and mass in integral form – complex numerical solutions required

Ion Mass Resolution

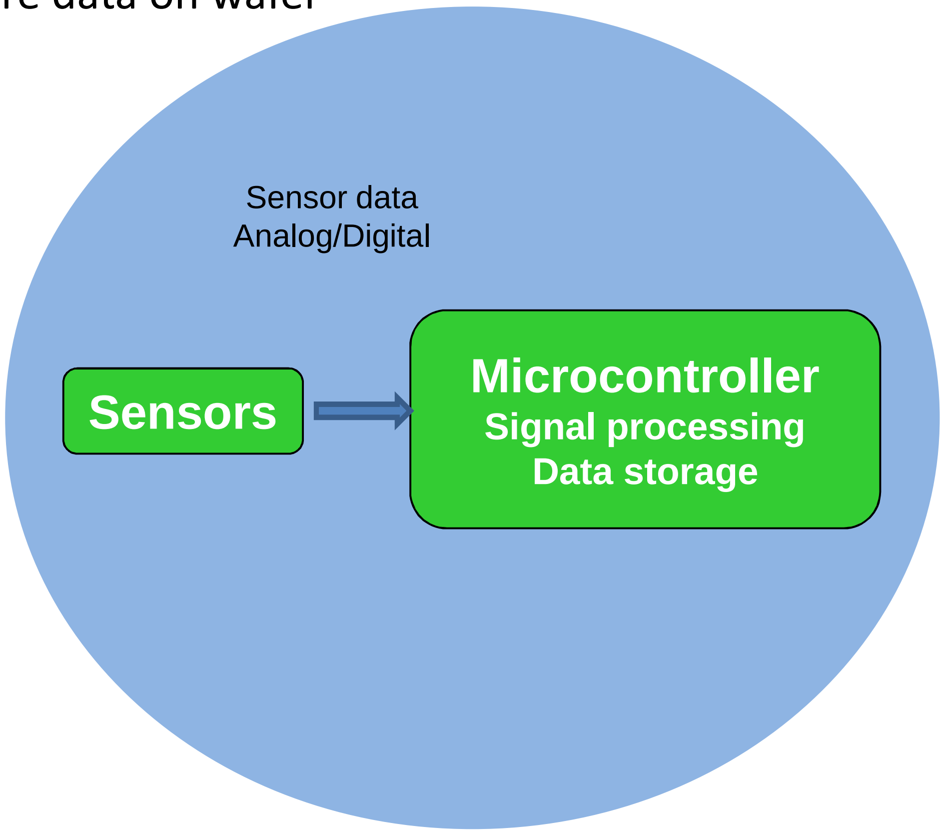
Initial data from an Argon and Argon Oxygen plasma shows that Semion mass can currently resolve to better than 5 AMU. The first product will be released in late 2014.

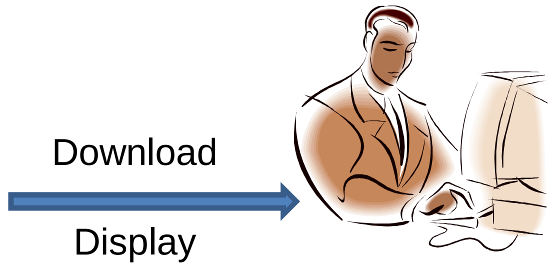


Wireless Sensors

KLA On Wafer Approach
Measure and store data on wafer

IP Minefield

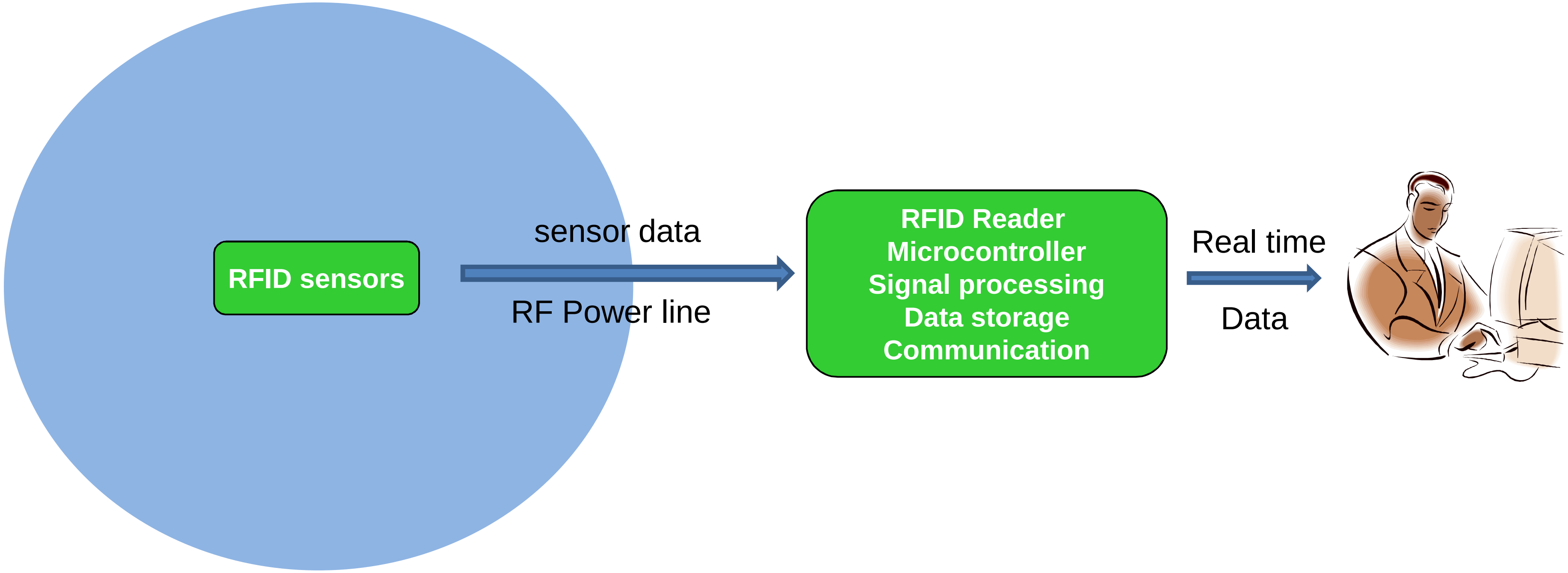




Wireless Sensors

Impedans Approach **Patent WO 2011/131769 A1**

Transmit data from RFID sensor to external reader on RF power line

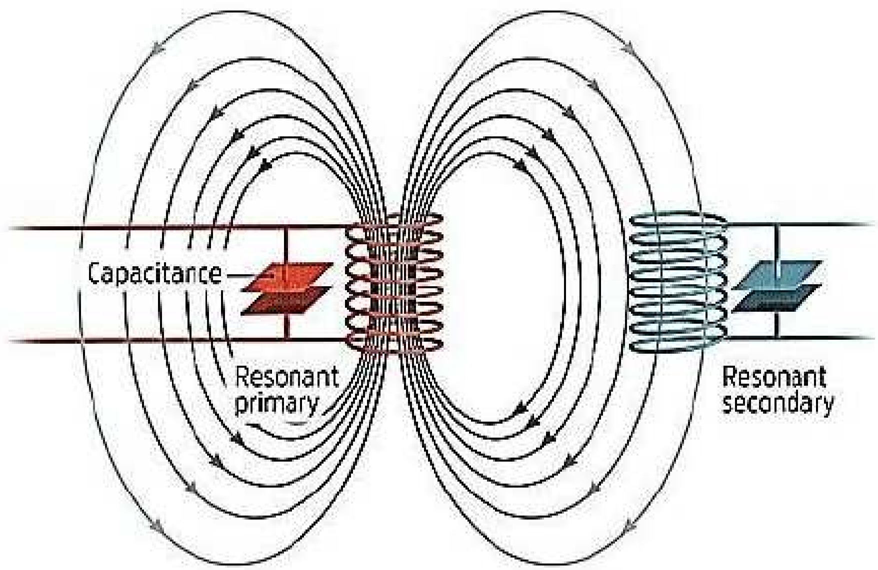


Wireless Sensors

- RFID Tags
- Near field (13.56MHz typically)

- Inductive coupling of tag to magnetic field circulating around antenna (like a transformer).
- Varying magnetic flux induces current in tag.
- Modulate tag load to communicate with reader
- Field energy decreases proportionally to $1/R^3$ (to first order)

Near Field

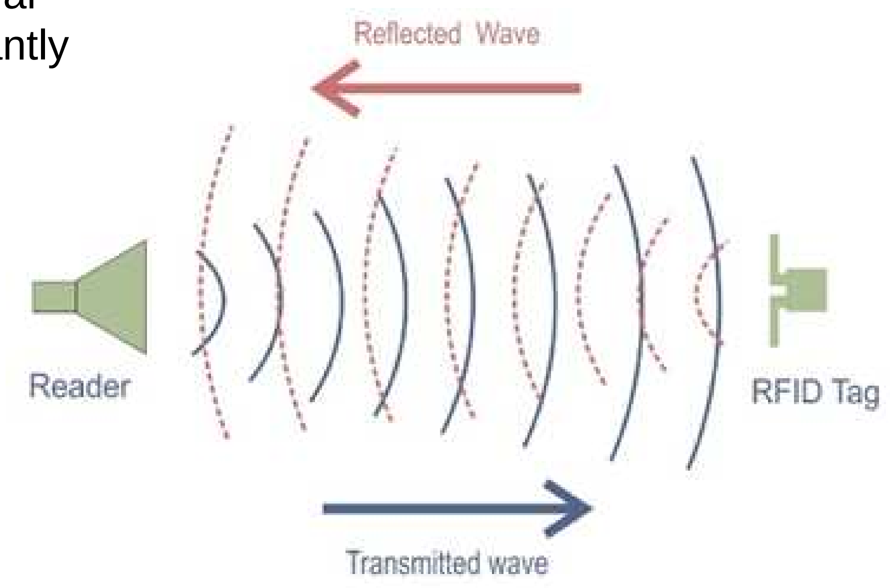


Wireless Sensors

- RFID Tags
- Far field (UHF, microwave):

- Backscatter.
- Modulate back scatter by changing antenna impedance.
- Field energy decreases proportionally to 1/R. Boundry between near and far field: R = wavelength/2 pi so, once you have reached far field, lower frequencies will have lost significantly more energy than high frequencies

Far Field

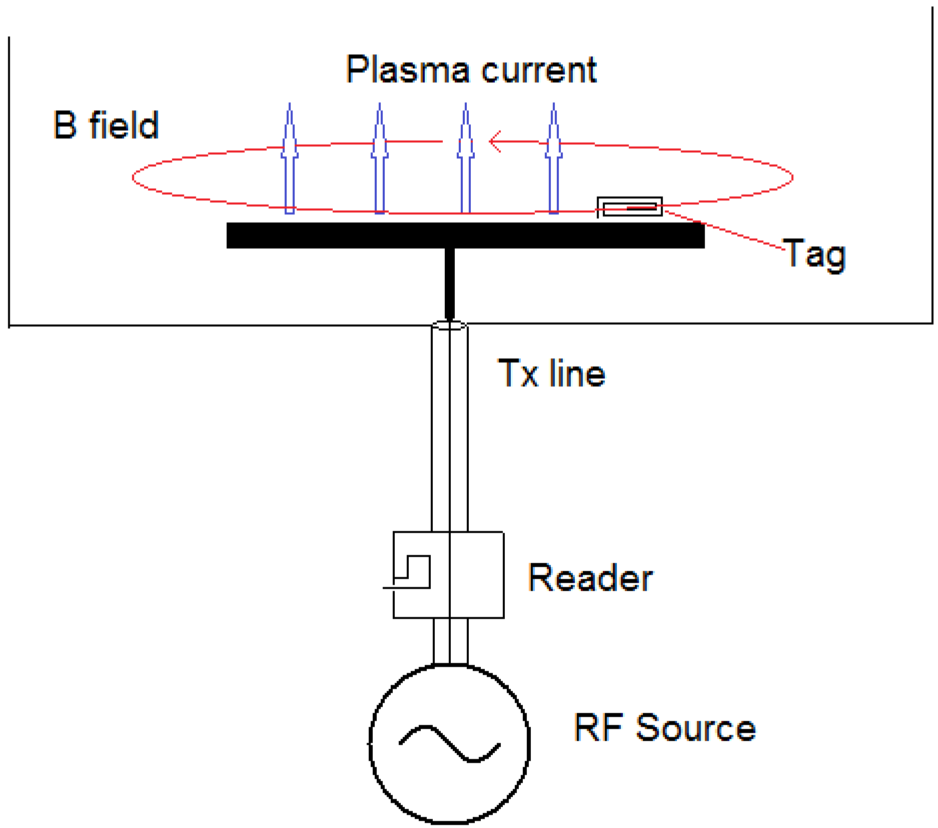


Wireless Sensors

- RFID Tags
- Transmission Line coupling

TX Field

- Energy is coupled into transmission line and data transmitted back via line.
- No loss of field energy over long distances.
- Similar to near field
- Primarily inductive coupling.
- Reader does not need to be source of RF energy.
- Tags embedded in wafer



Wireless Sensors are the Future

Impedans will engage with a strategic partner to productize the wireless wafer solution in the Semiconductor market.

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