

Recommended Practices for Design and Use of RPAs in Electric Propulsion

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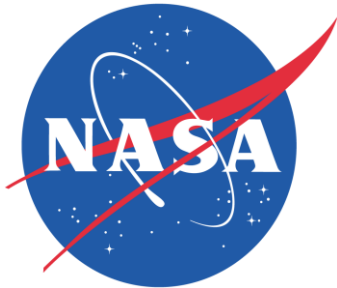
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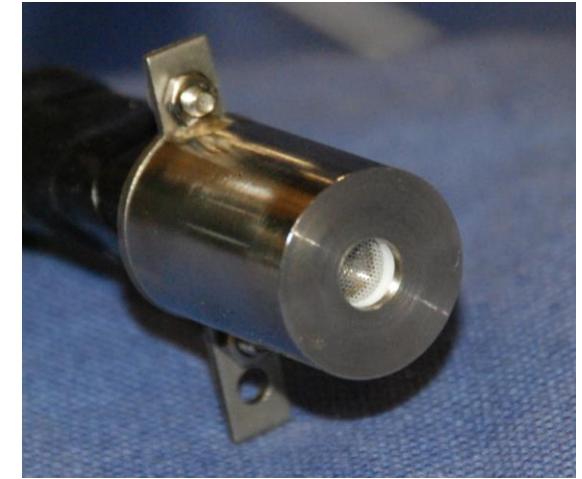
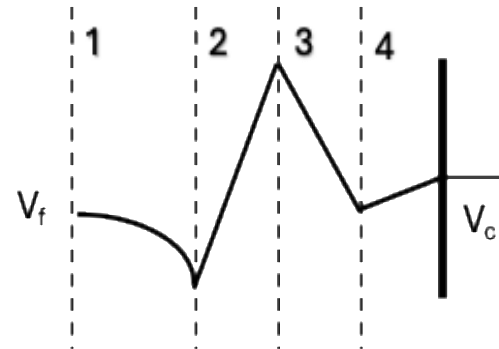
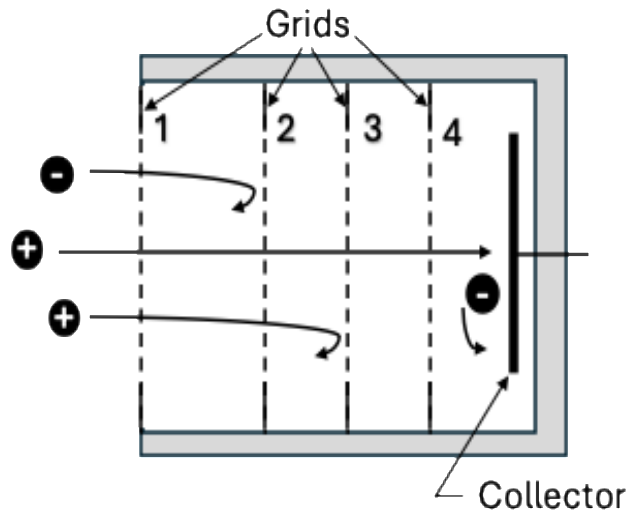
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Retarding Potential Analyzer (RPA)

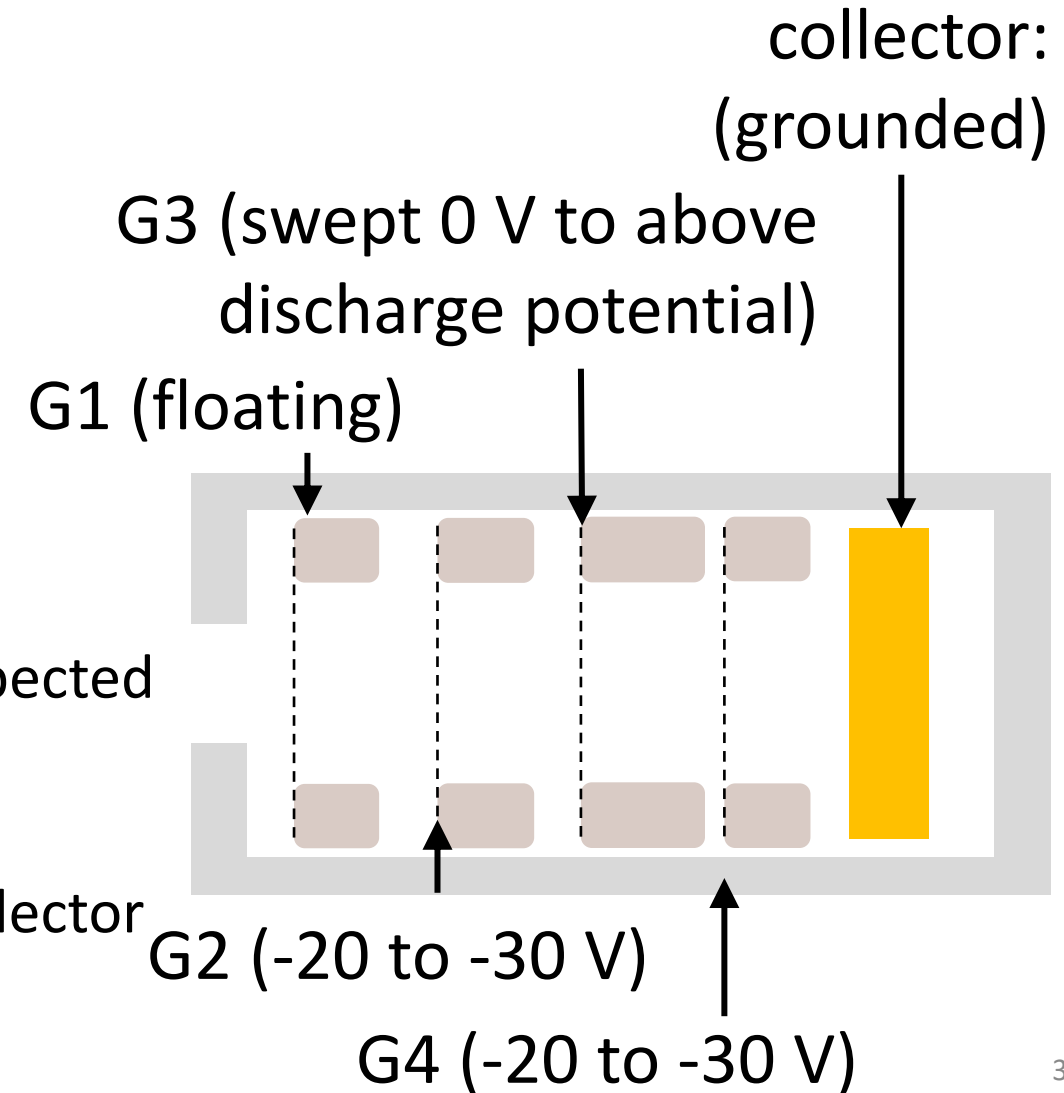
- Measure ion energy distribution function
- Easy to build
- Portable
- Simple data analysis





4-Grid Configuration

- Grid 1 – floating/attenuator grid
 - Reduce space charge effects/ minimize plasma perturbation
- Grid 2: electron repelling grid
 - Repel plasma electrons from analyzer
 - Nominally -20 to -30 V
- Grid 3: ion discriminator grid
 - Filter ions by energy level
 - Sweep from 0 V up to a potential above the expected energy of the ions
- Grid 4: electron suppression grid
 - Suppress secondary electron emission from collector and other grids
 - Nominally -20 to -30 V





RPA design



• Design Parameters:

- Grid spacing – Key distance is between electron repelling and ion retarding
 - Potential due to grids alone:
 - Space Charge limitations cause weird stuff between and around the grids
 - Worst case scenario is between E & I

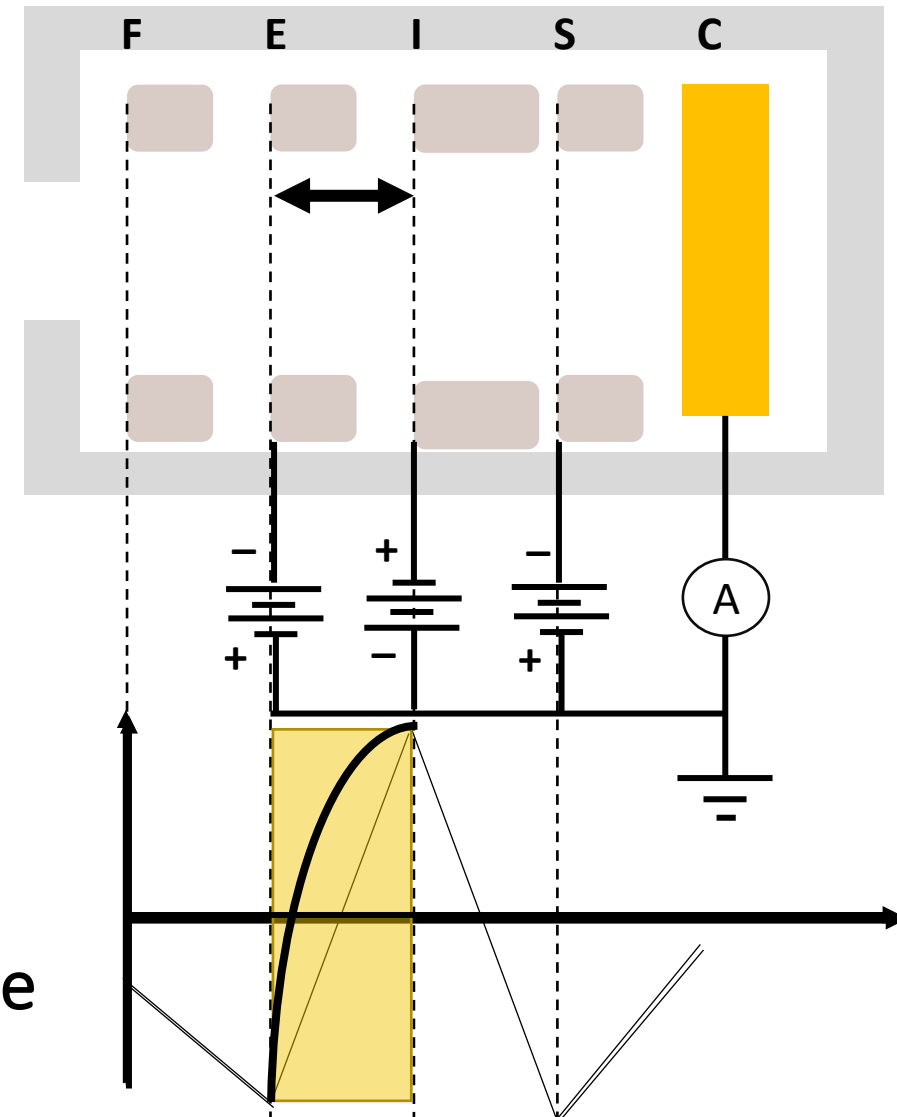
$$\frac{x_s}{\lambda_D} = \frac{2}{3} \left[\frac{2}{\exp(-1)} \right]^{\frac{1}{4}} \left[\left(\left(-\frac{e\phi_0}{T} \right)^{\frac{1}{2}} - \frac{1}{\sqrt{2}} \right)^{\frac{1}{2}} \left[\left(-\frac{e\phi_0}{T} \right)^{\frac{1}{2}} + \sqrt{2} \right] \right]$$

- Debye Length comes from plasma density between electron repelling and floating grids
 - Less the number of ions that impact the electron repelling grid

- Therefore, to avoid space charge limitations:

$$x_{EI} < \begin{cases} 4\lambda_D \text{ for hydrogen} \\ 5.3\lambda_D \text{ for xenon} \end{cases}$$

We just use $4\lambda_D$ to be safe



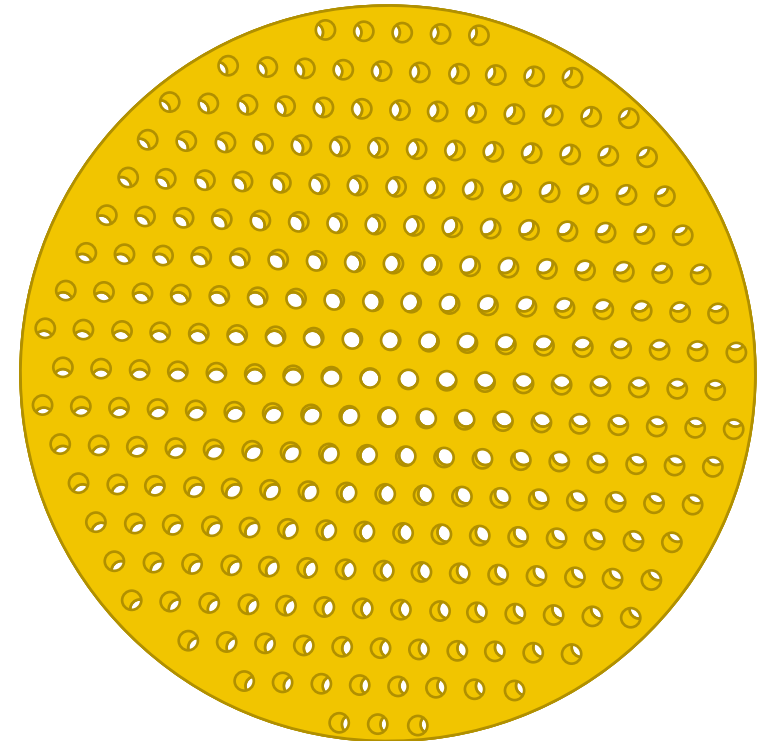


RPA Design – Grid Alignment



- Design Parameters:
 - Grid spacing
 - Grid alignment

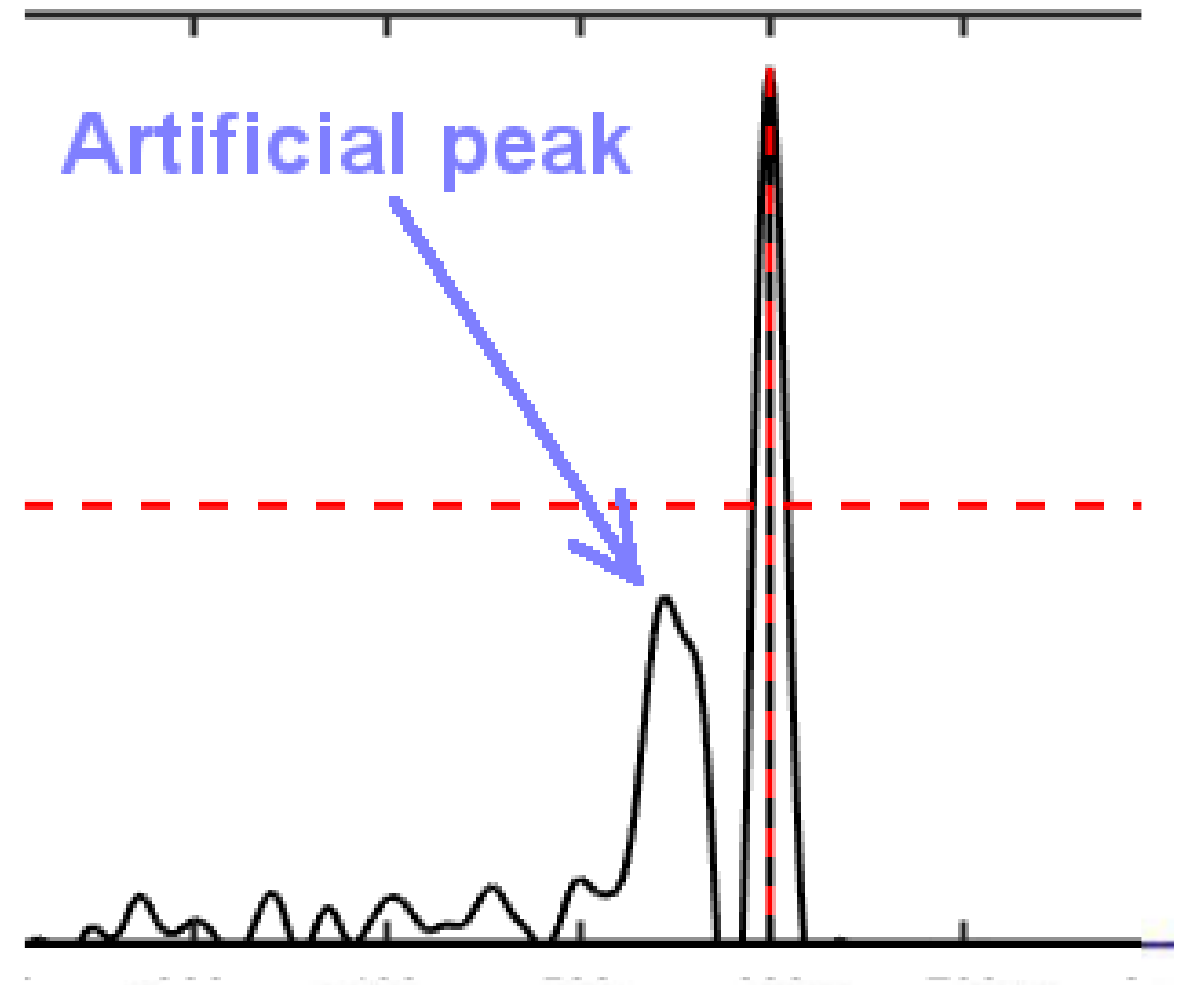
Paramater	Aligned-grid	Unaligned-grid
SNR	Higher	Lower
Acceptance angle	Narrow, well-defined	Wide, less defined
Energy resolution	Finer	Coarser
Cost and construction complexity	Higher, require high precision manufacturing	Lower, require thinner grids





RPA Design – Grid Thickness

- Design Parameters:
 - Grid spacing
 - Grid alignment
 - Grid thickness
- Example I-V curve where grid thickness matters
- Ions are impinging on electron suppression grid





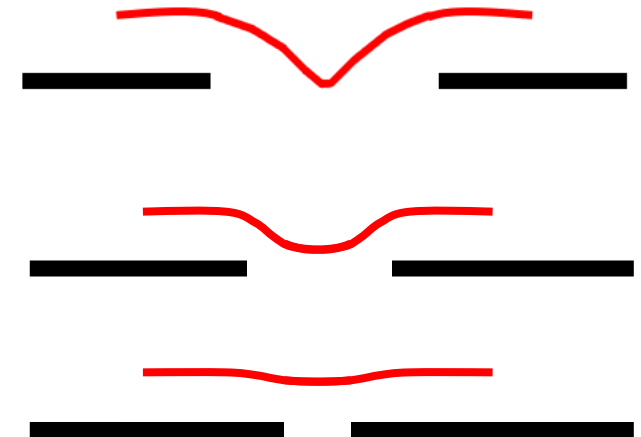
RPA Design – Grid Aperture Size



- Too big mesh/grid aperture
 - Aperture must be smaller than Debye length, λ_D (or wires in mesh closer than λ_D)
 - Else, particles pass through without discrimination

$$\frac{\Delta\phi_r}{\phi_r} = 1 - \frac{2\pi\left(\frac{x}{a}\right) - \ln 4}{2\pi\left(\frac{x}{a}\right) - 2 \ln\left(2 \sin\left(\frac{\pi r}{a}\right)\right)}$$

- Too small mesh – SNR gets real bad





RPA design



- Design Parameters:

- Grid spacing
- Grid alignment
- Grid thickness
- Aperture size
- Probe size
 - Larger probe will disturb plasma more, reduce spatial resolution, and have a higher SNR
 - Small probe will disturb plasma less, increase spatial resolution, and have lower SNR
- Grids need to be flat and parallel to each other



RPA Implementation

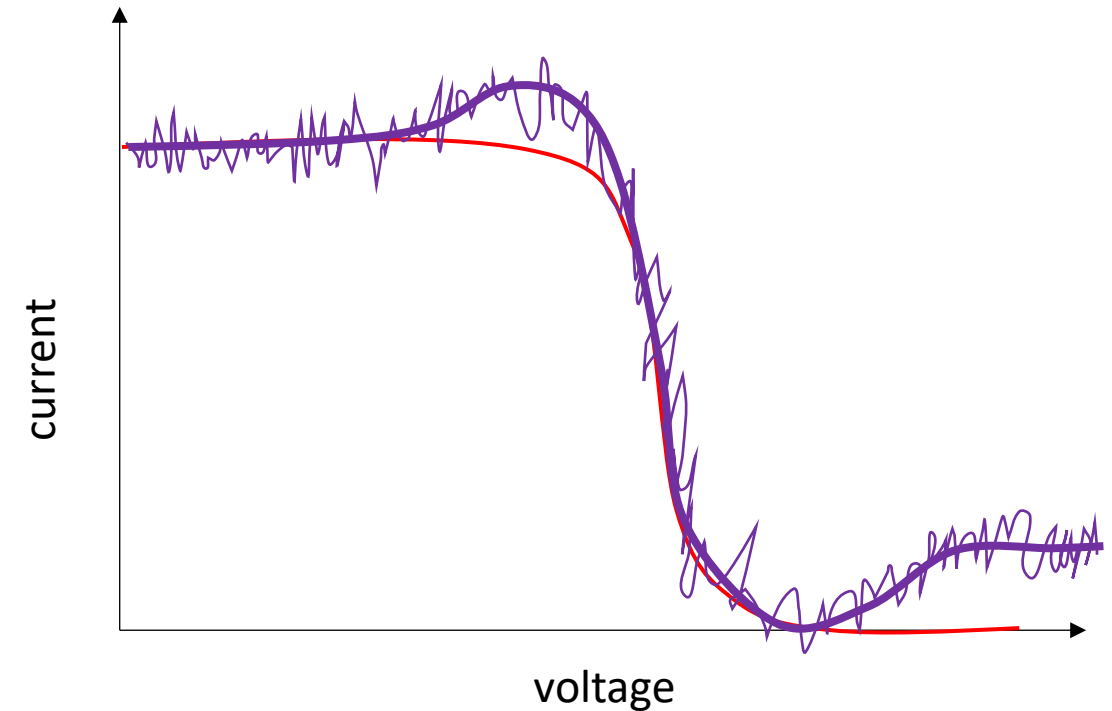
- First, calibrate your RPA using a source with a known ion energy
 - Kauffman style ion source
- Use batteries for electron repelling and ion suppression
 - No worry about external interference
 - Constant voltage (as long as the batteries don't get drained)
- Voltage-current source meter or make your own circuit
 - Current measurement should be in nA – μ A range





RPA implementation

- LabView or Simulink or similar
 - Source voltage
 - Measure current
 - Change voltage
 - Measure current
 - Change voltage
 - Measure current
 - And on and on until you reach ~
1.5x most probable ion energy
- Multiple traces to average together





RPA Theory



Define IEDF units in a manner that the total ion flux is the 0th moment:

$$J_{total-ion-flux} \equiv \int_0^{V_{max}} IEDF(V) dV$$

Using ion energy, $\mathcal{E} = V_{retarding} - V_{plasma}$, and invoking the probability distribution function:

$$1 \equiv \int_0^{\mathcal{E}_{max}} f_{pdf}(\mathcal{E}) d\mathcal{E} \text{ with } f_{pdf}(\mathcal{E} = V - V_p) = \frac{dI_{collector}}{dV} \left[\int_0^{V_{max}} \left(\frac{dI_{collector}}{dV} \right) dV' \right]^{-1}$$

The IEDF can be rewritten using prior equation, which provides the IEDF from in units of flux per eV directly from the experimental RPA measurements of the collector current at each discriminator bias. Accounting for the normalized solid angle field of view and the total ion flux for and energy of zero we get:

$$IEDF(\mathcal{E} = V_{retarding} - V_{plasma}) = \frac{I_{collector}(V_{retarding} = V_{plasma})}{A_{inlet} T_{grid} \Omega_{RPA}} \frac{dI_{collector}}{dV} \left[\int_0^{V_{max}} \left(\frac{dI_{collector}}{dV} \right) dV' \right]^{-1}$$

with effective grid transparency T_{grid} which can be or empirically determined (eg using Faraday probe measured total ion flux) using a generalized transmission factor $F_{transmission}$.



RPA Analysis



The recommended approach to calculating the averaged ion energy is to calculate the first moment of the ion energy per charge distribution.

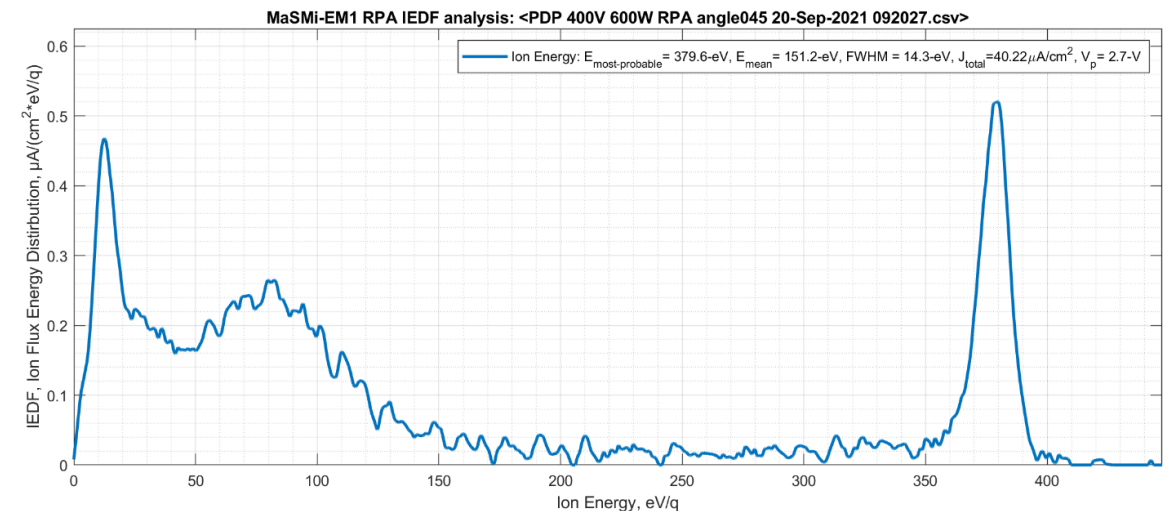
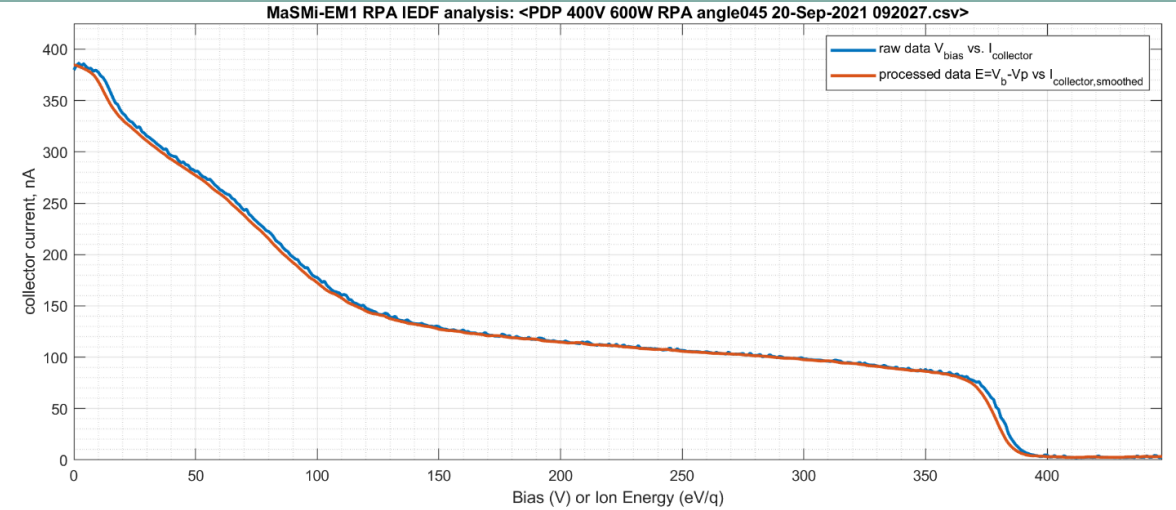
$$\langle \mathcal{E} \rangle = \frac{\int_0^{\mathcal{E}_{max}} IEDF(\mathcal{E}) \mathcal{E} d\mathcal{E}}{\int_0^{\mathcal{E}_{max}} IEDF(\mathcal{E}) d\mathcal{E}}$$

Which readily provides thruster voltage utilization efficiency:

$$\eta_V = \frac{\langle \mathcal{E} \rangle}{V_D}$$

Erosion measurements ($\dot{h}_x [\frac{m}{s}]$) can also be obtained from RPA IEDFs using the appropriate ion-material sputter yield curves $Y_x(\mathcal{E})$:

$$\dot{h}_x = \frac{FW_x m_p}{e \rho_x} \int_0^{\mathcal{E}_{max}} Y_x(\mathcal{E}) IEDF(\mathcal{E}) d\mathcal{E}$$





High Speed RPA

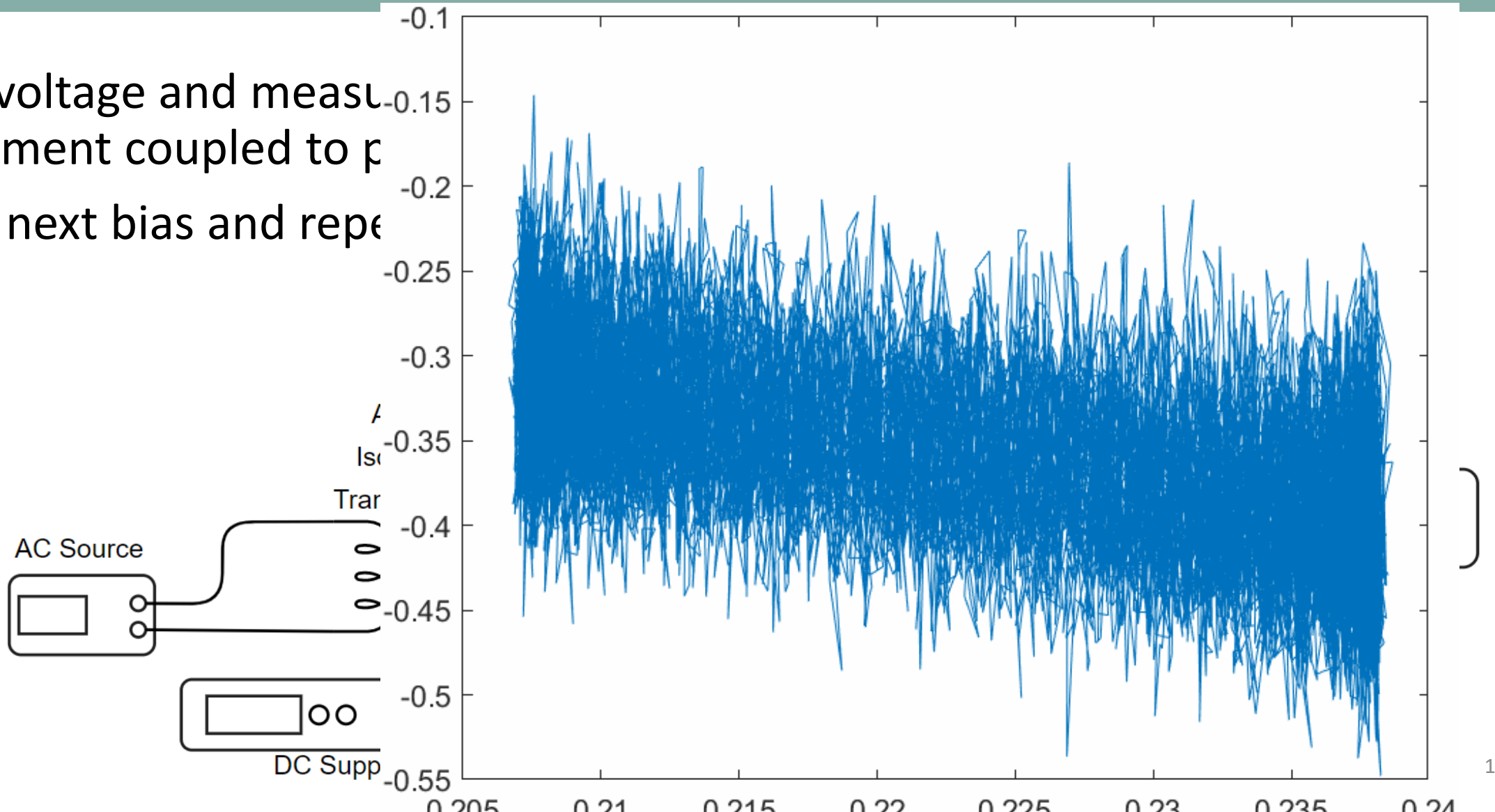


- RPA can be used to get temporally resolved IEDFs using data fusion techniques
 - Hold bias potential constant for a given sample period and collect current
 - Change bias potential and collect current for same sample period
 - Requires a known signal to use for data fusion – discharge current
- Why not just sweep the discriminator voltage at high speeds?
 - Unable to sweep voltage in analyzer at a sufficiently high frequency to get meaningful measurements
 - Space-charge limitations
 - Ion velocity issues within analyzer



HSRPA Data Collection Process

- Set bias voltage and measurement coupled to p
- Move to next bias and repeat





Data Fusion Techniques



- Empirical Transfer Function Method (TF)
 - Linear time invariant method utilizes Fourier transform
 - Converts a finite data set into frequency space revealing any periodicities
 - Obtain a transfer function which linearly maps an input time series to an output times series
- Shadow Manifold Interpolation (SMI)
 - Non-linear method relies on Taken's theorem and common correlation matrix theory
 - Creates a shadow manifold from time lagged samples in phase space
 - Utilizes a training data set and test data set to temporally reconstruct an output signal (test) from its input signal (test)

Recommended Reading:

Lobbia, R., "A time resolved investigation of the Hall Thruster Breathing mode," Ph.D. Dissertation, University of Michigan, 2010

Lobbia, R., and Gallimore, A., "Temporal limits of a rapidly swept Langmuir Probe," Phys. Plasmas, 2010

Recommended Reading:

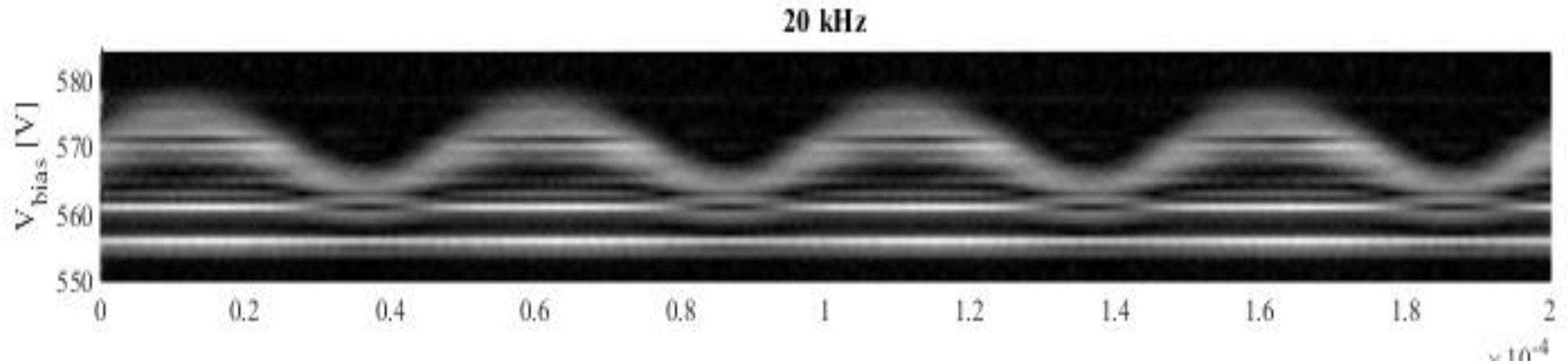
Takens, F., "Detecting Strange attractors in Turbulence," Lecture Notes in Mathematics, 1980

Eckhardt, D., Koo, J., Martin, R., Holmes, M., and Hara, K., "Spatiotemporal data fusion and manifold reconstruction in Hall thrusters," Plasma Sources Sci Technol, 2019

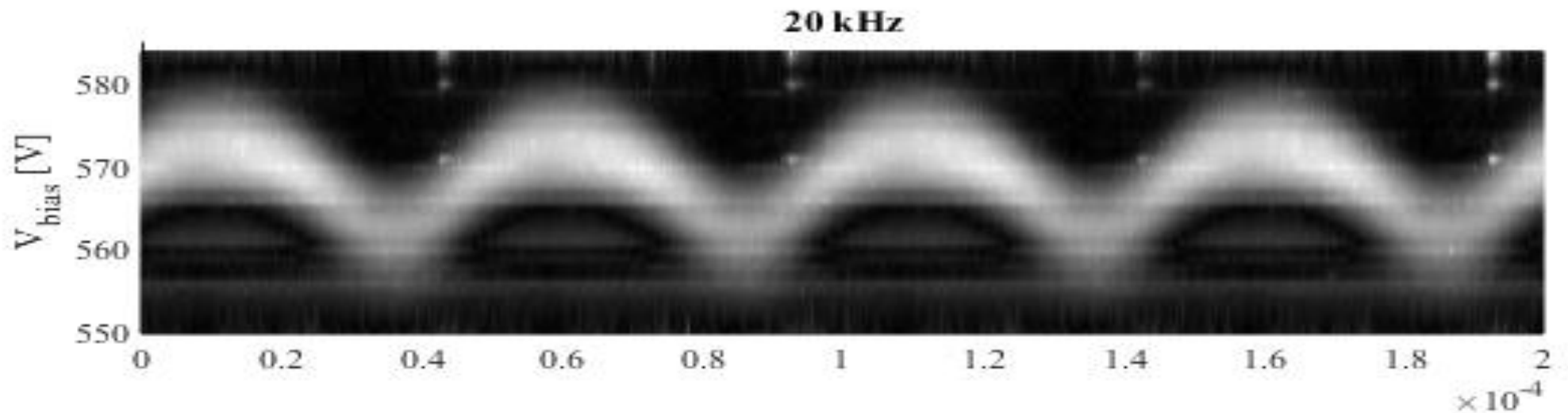


Comparison 20 kHz Sine Wave

TF



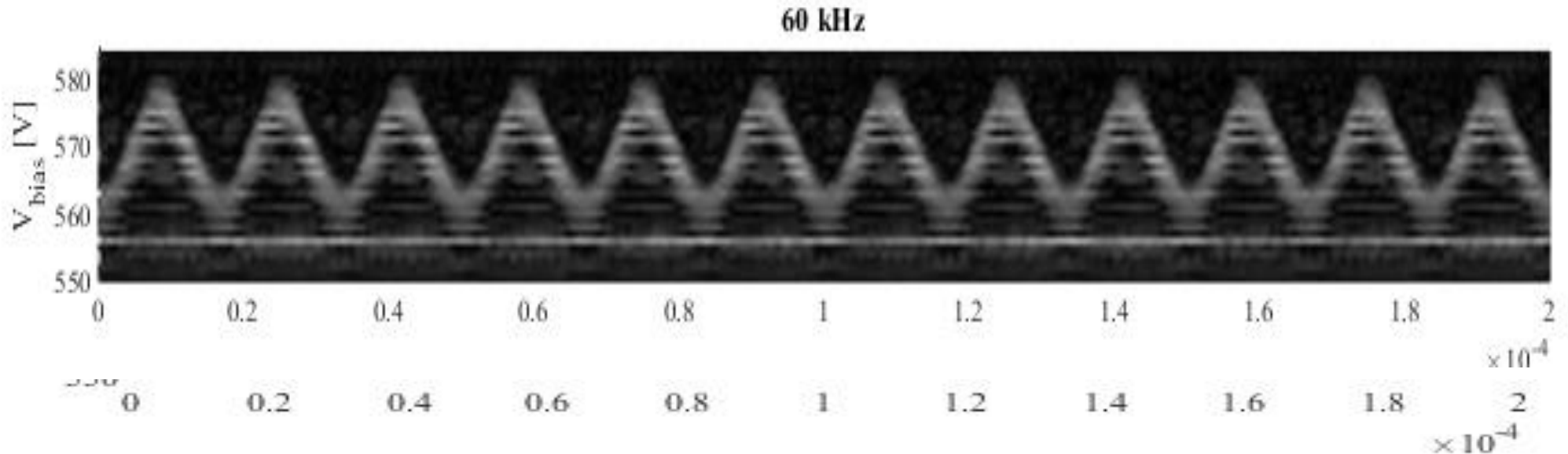
SMI



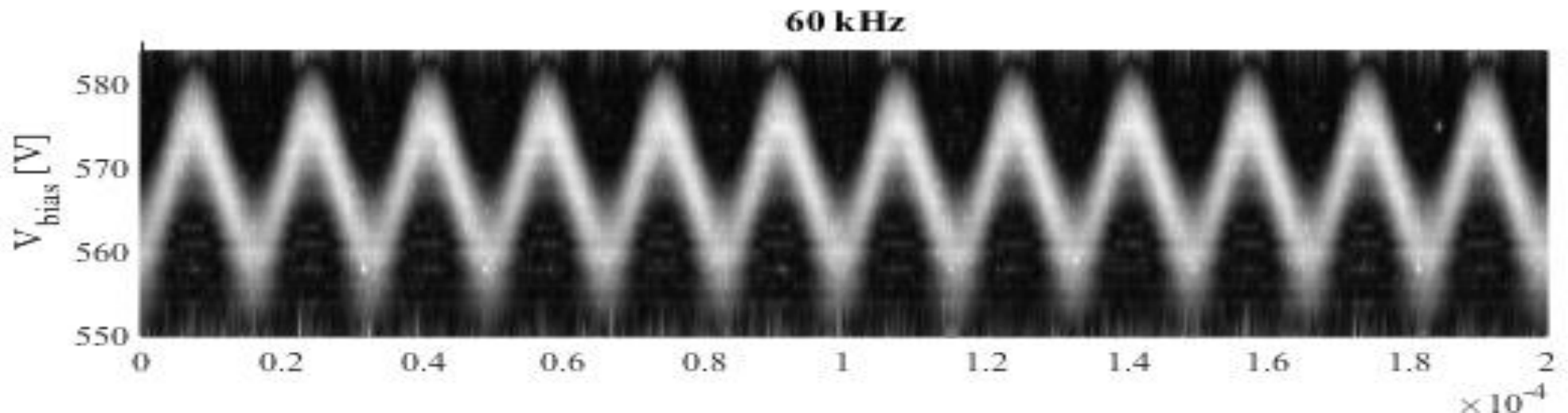


Comparison 60 kHz Sine Wave

TF



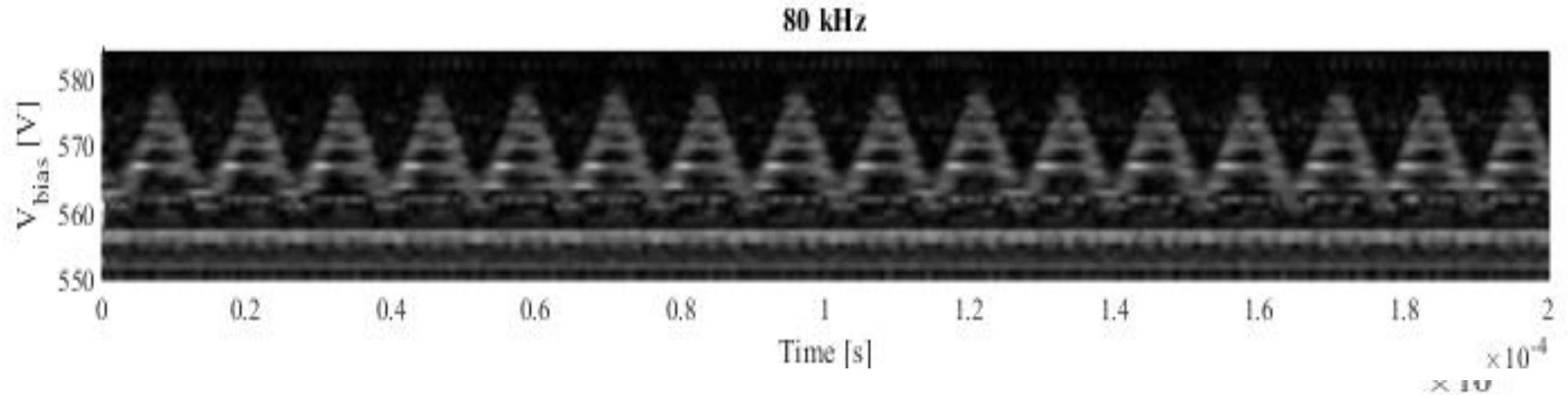
SMI





Comparison 80 kHz Sine Wave

TF



SMI

