Applied Physics lab for PLasma Engineering

The influence of arcing on radio-frequency capacitively coupled plasma

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Applied Physics lab for PLasma Engineering

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The influence of arcing on radio-frequency capacitively coupled plasma

Contents

- Introduction
- Experiment details
- Results and discussion
- Concluding Remarks

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Applied Physics lab for PLasma Engineering

Contents

Introduction

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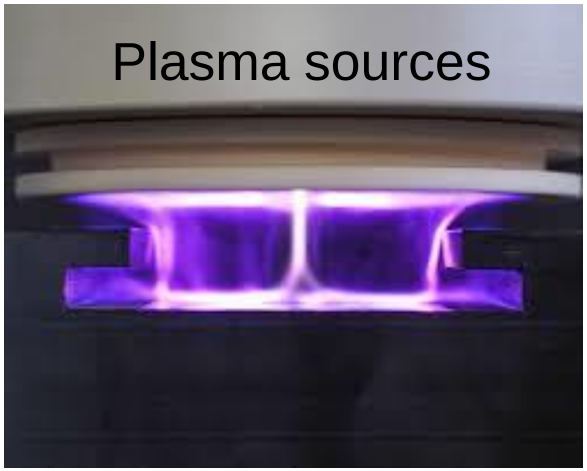
Concluding Remarks

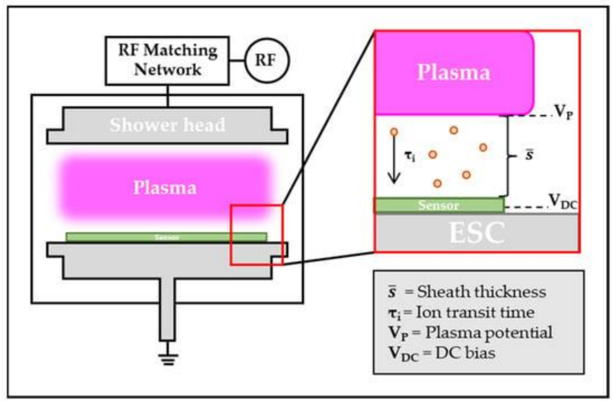
What do we research about?

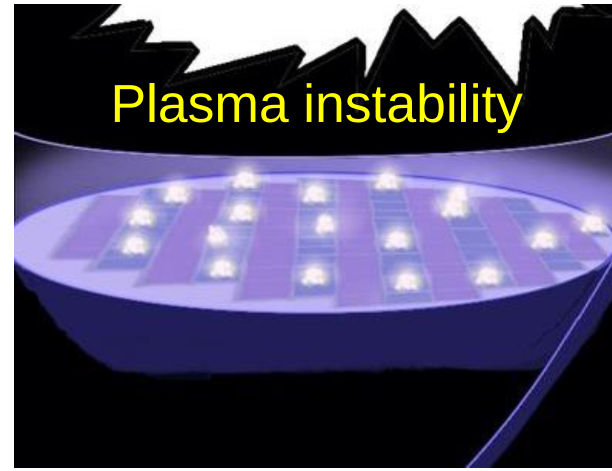
Introduce about my lab

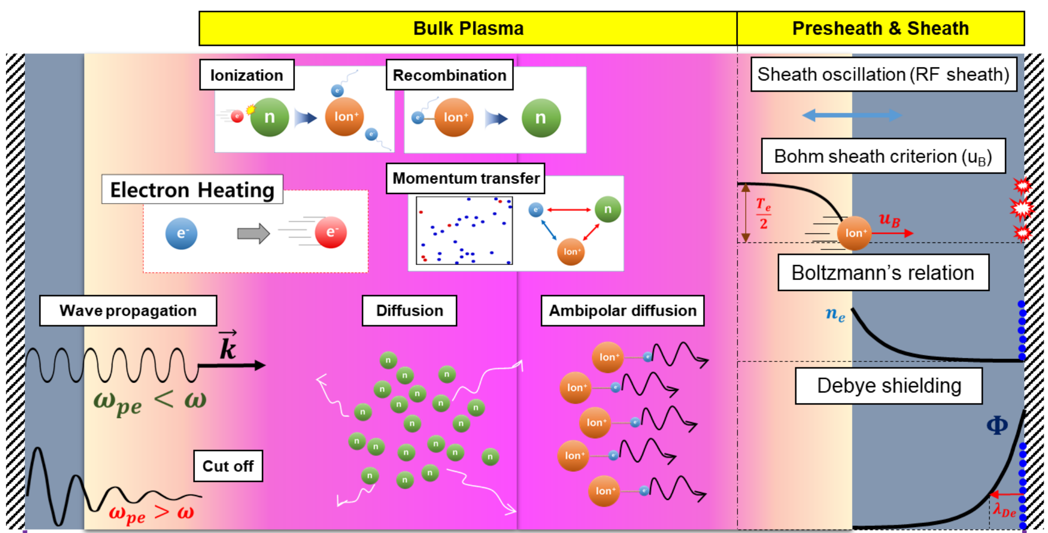
- Lab name's : "***A**pplied **P**hysics lab for **Pl**asma **E**ngineering*"



Plasma processing

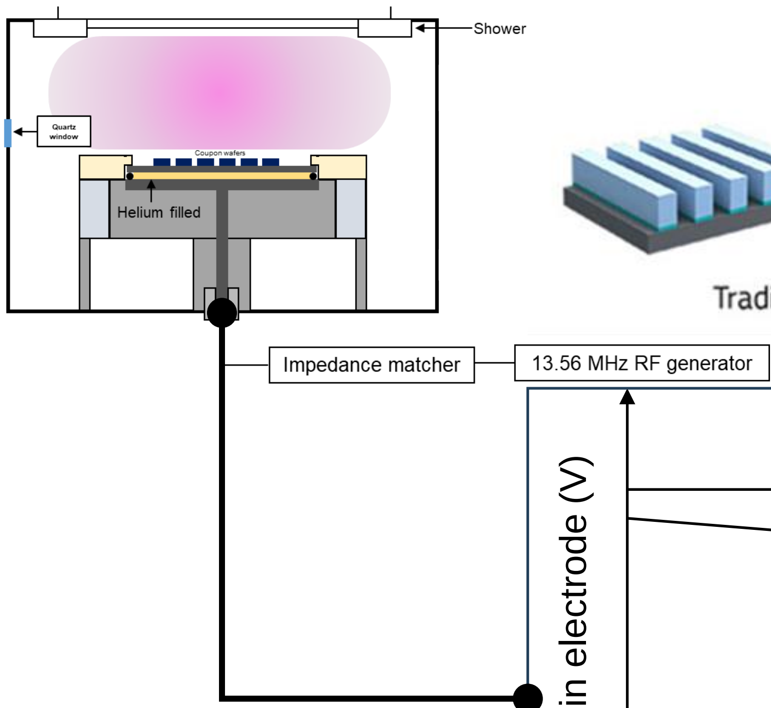


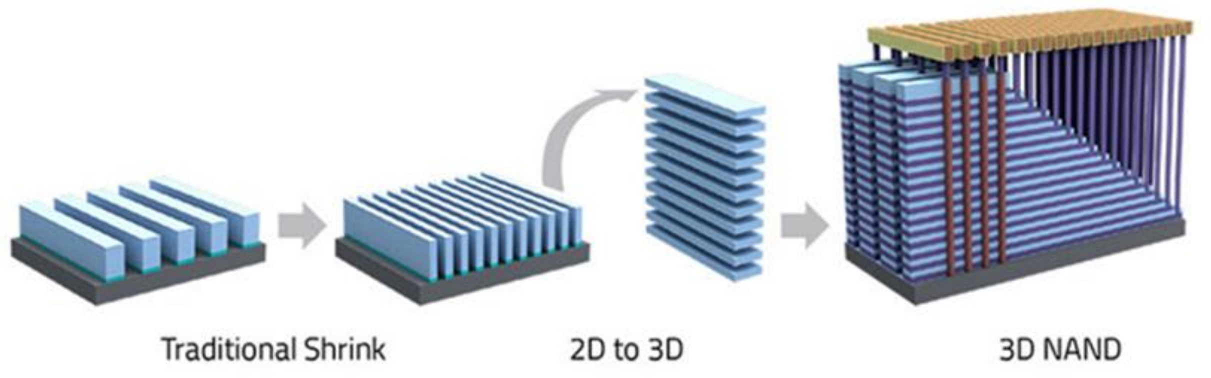


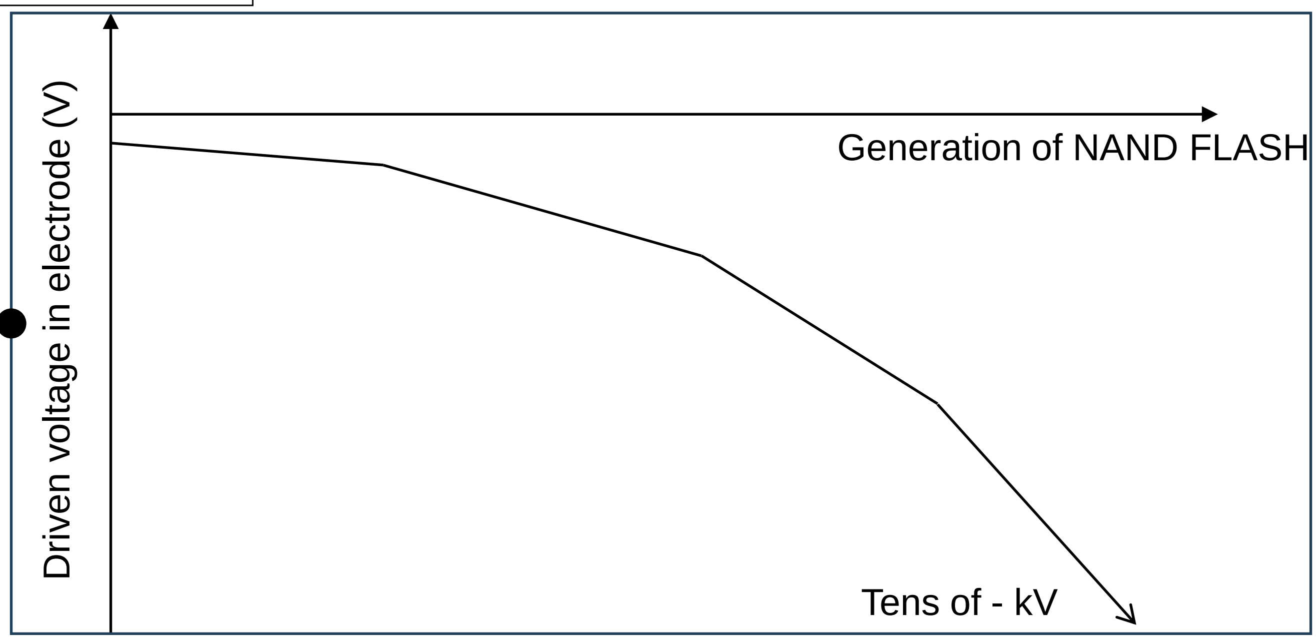


Arcing in plasma process

- **Applied high voltage in electrode, arcing can generate on electrode**





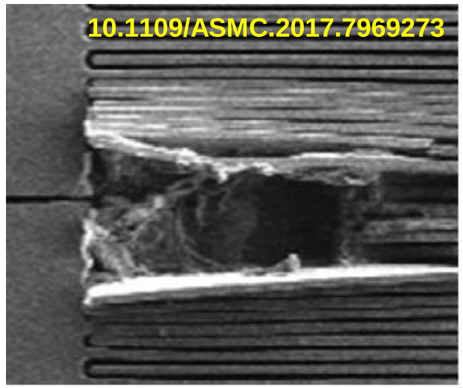


Introduction

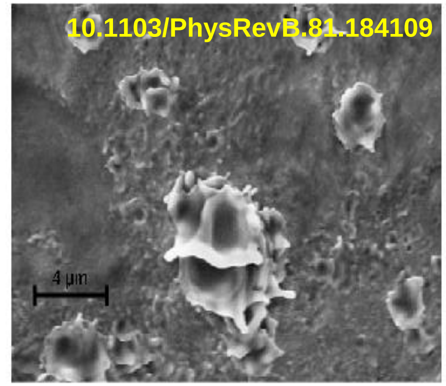
Arcing Induced Damage in plasma processing

Chamber wall

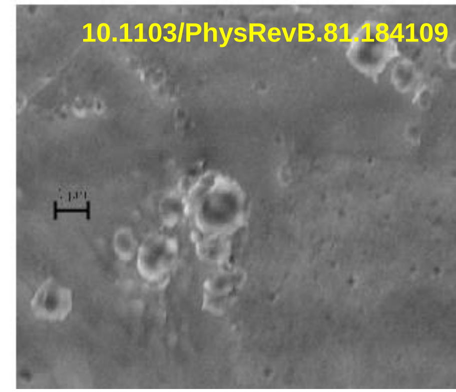
Micro-pattern



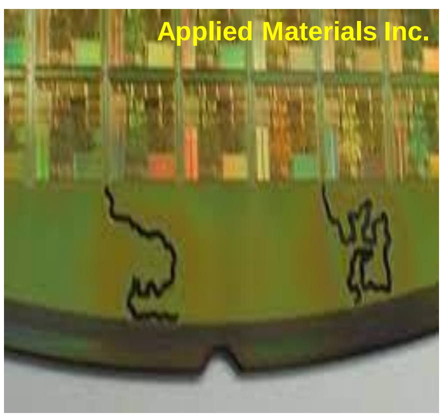
Metal Surface I



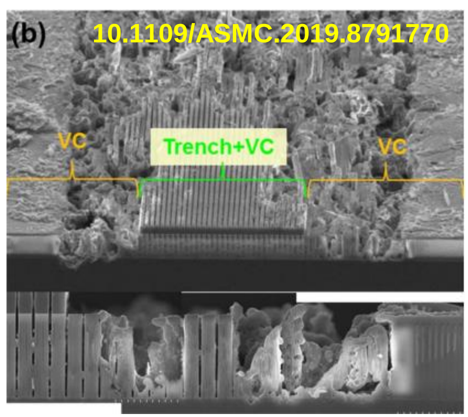
Metal Surface II



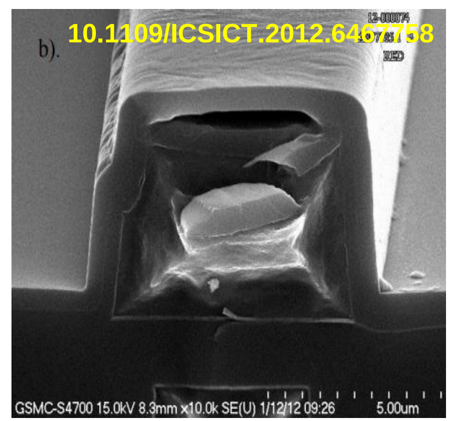
Wafer surface



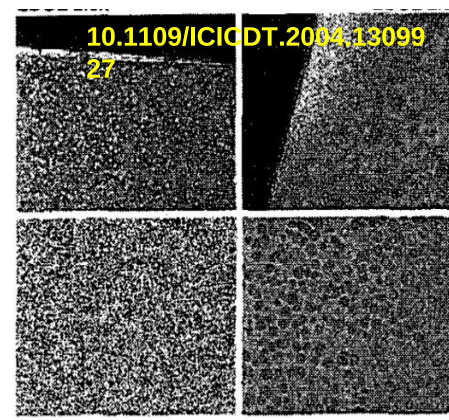
Nano-Pattern I



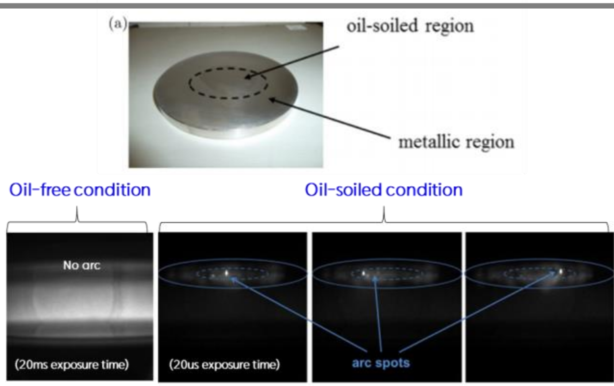
Nano-Pattern II



Metal Surface III



Literature review : Plasma analysis with arcing



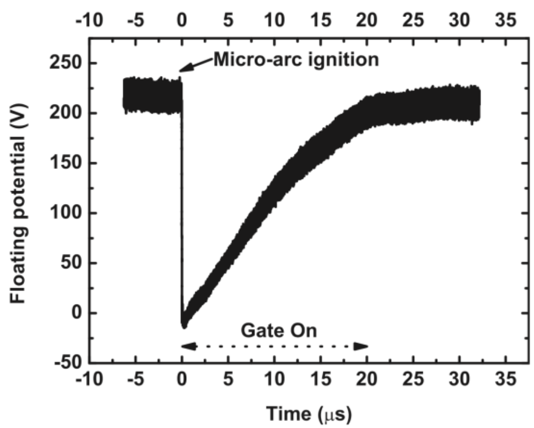


Fig. 4. Typical floating potential variation during micro-arc at argon pressure = 50 mTorr and RF power = 50 W.

Y. Kim et al., Current Applied Physics **15** 313 (2015)

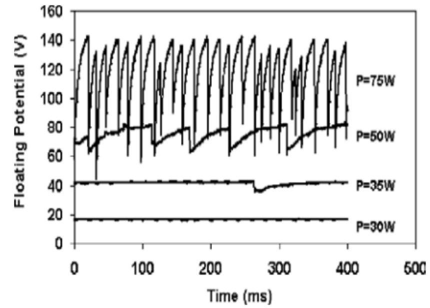


Figure 4. Floating potential spectra of arcing for mode D at different RF power levels.

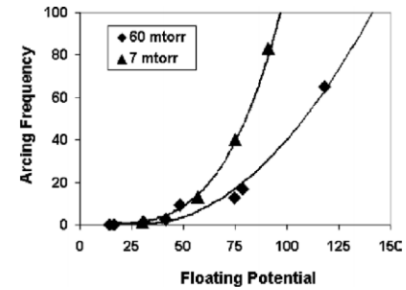
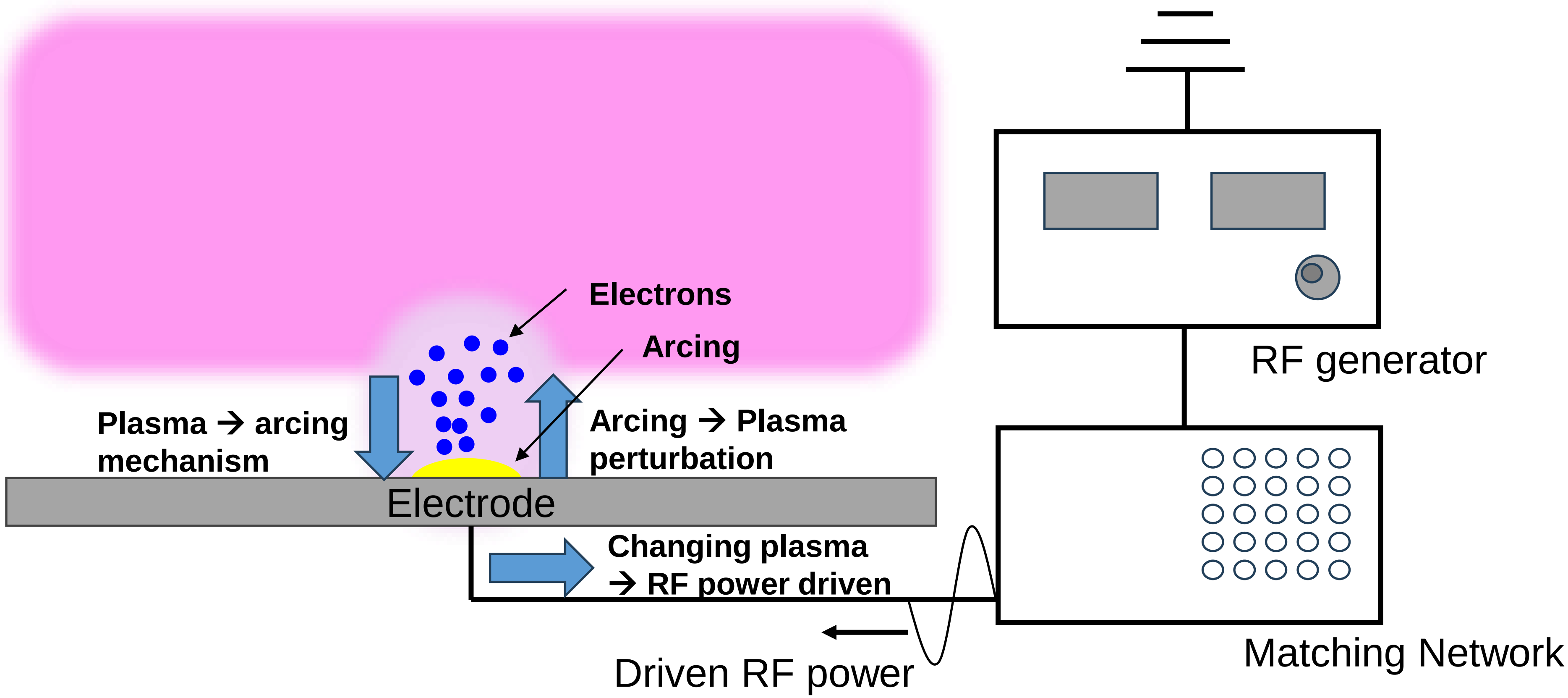


Figure 5. Arcing frequency plotted as a function of floating potential for different pressures. Curve fitted as guideline only.

Y. Yin et al., J. Phys. D: Appl. Phys. 37 (2004) 2871–2875

Motivation : Lack of the plasma behavior when the arcing generation



- Generation arcing : amount of electrons emission
- **Plasma (sheath, electron) can be influenced** by arcing electrons
- **The power system can be influenced** by influenced plasma

Contents

Introduction

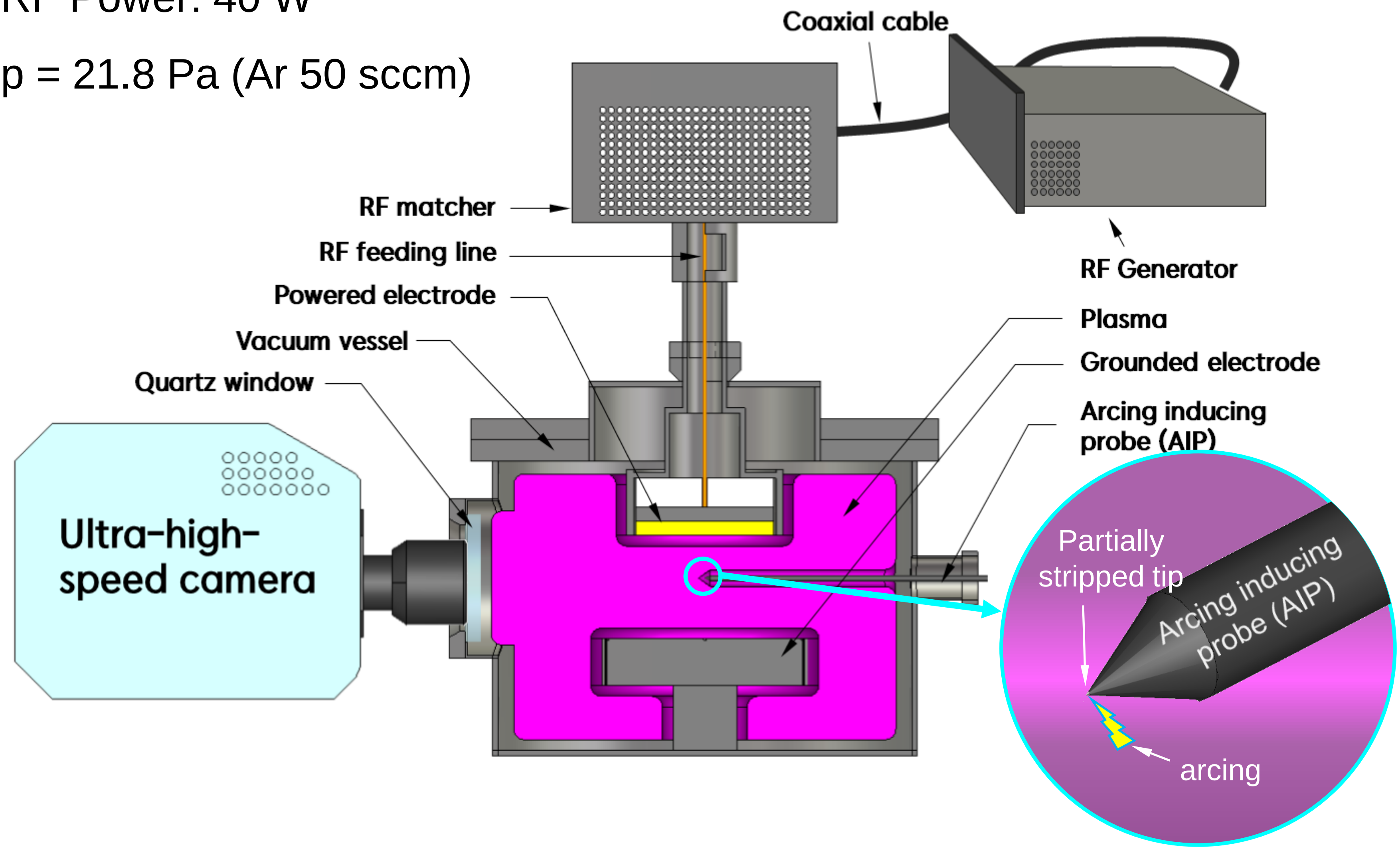
Experiment details

Results and discussion

Concluding Remarks

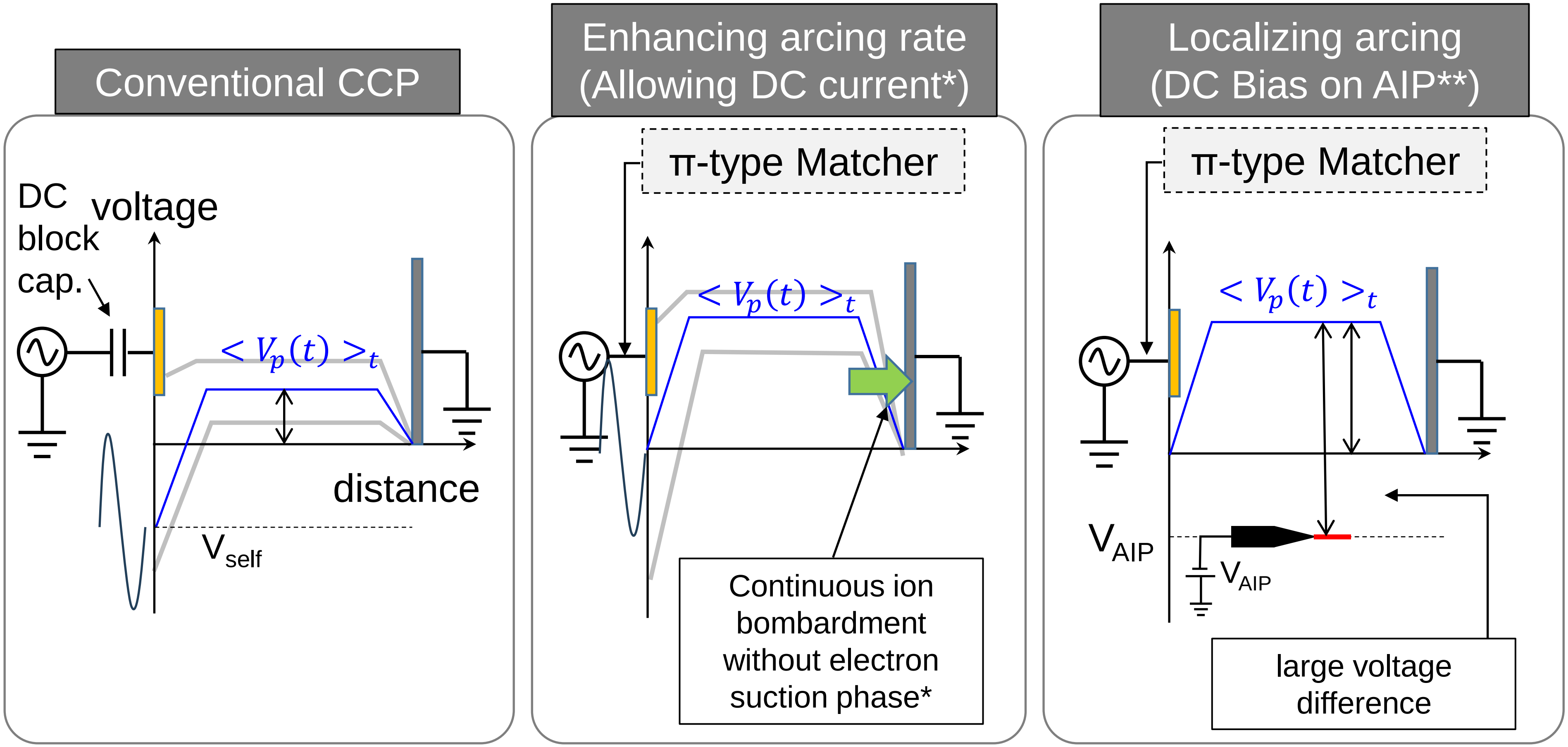
Experimental configuration and condition

- Background Plasma - RF Capacitively Coupled Plasma (13.56 MHz)
- RF Power: 40 W
- p = 21.8 Pa (Ar 50 sccm)



How to improve arcing rate and localization

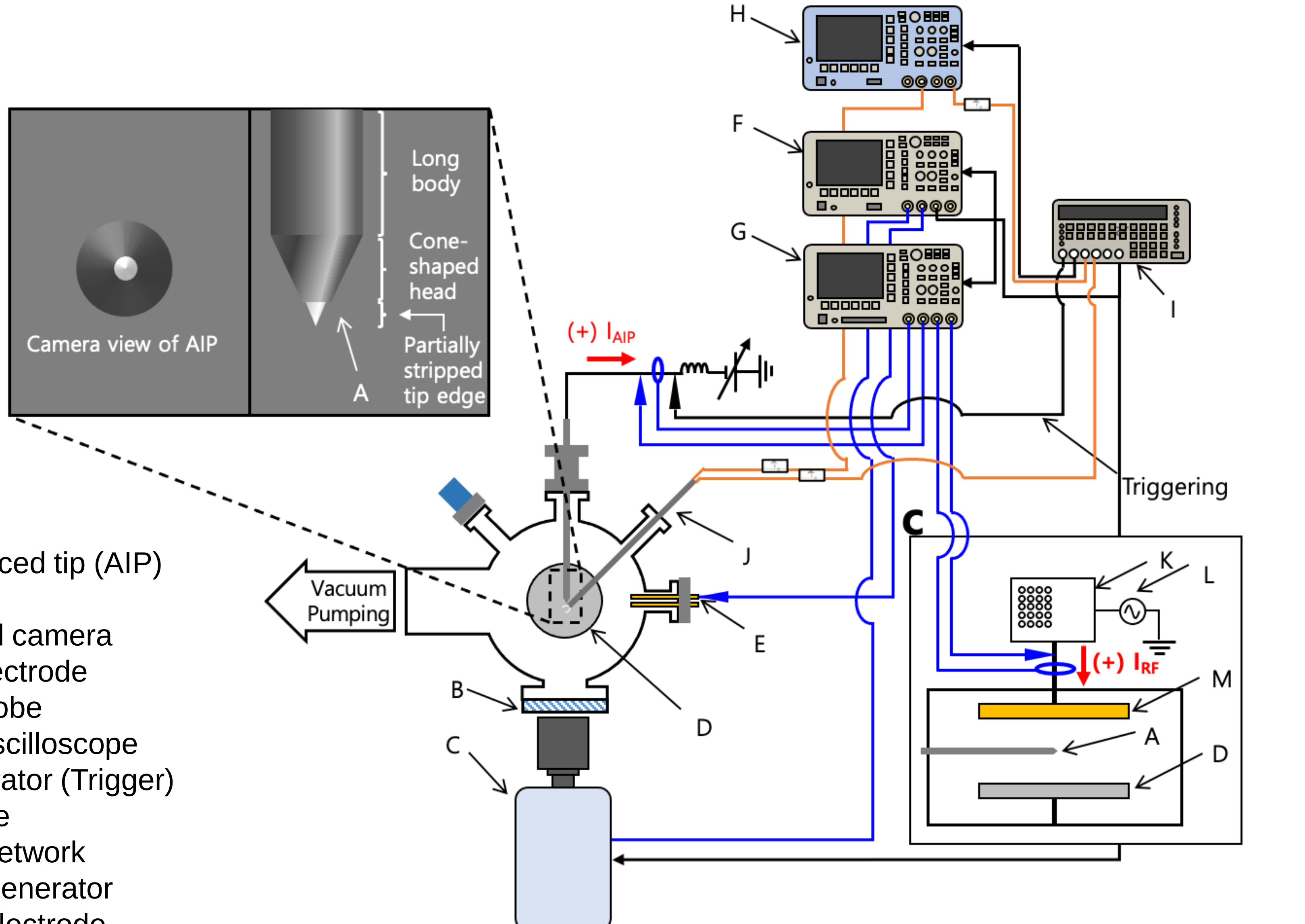
- Arcing rate: Allowing DC current* (V_p ~ 200 V_{DC} by an emissive probe**)
- Localization: Arcing Inducing Probe (AIP) with DC Bias, -25 V_{DC}



*Y. Yin et al. J. Phys. D: Appl. Phys. **37** 2871–2875 (2004)
S. J. Kim et al., *Sci. Reports* **12 20976 (2022)

Experiment details

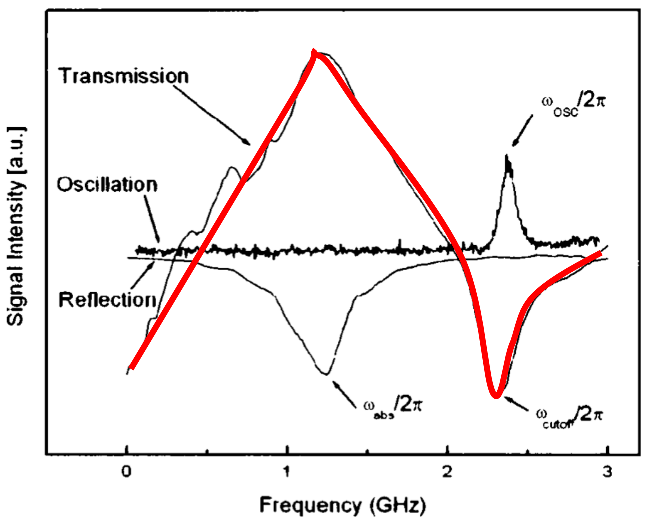
Schematic Diagram of Measurement System



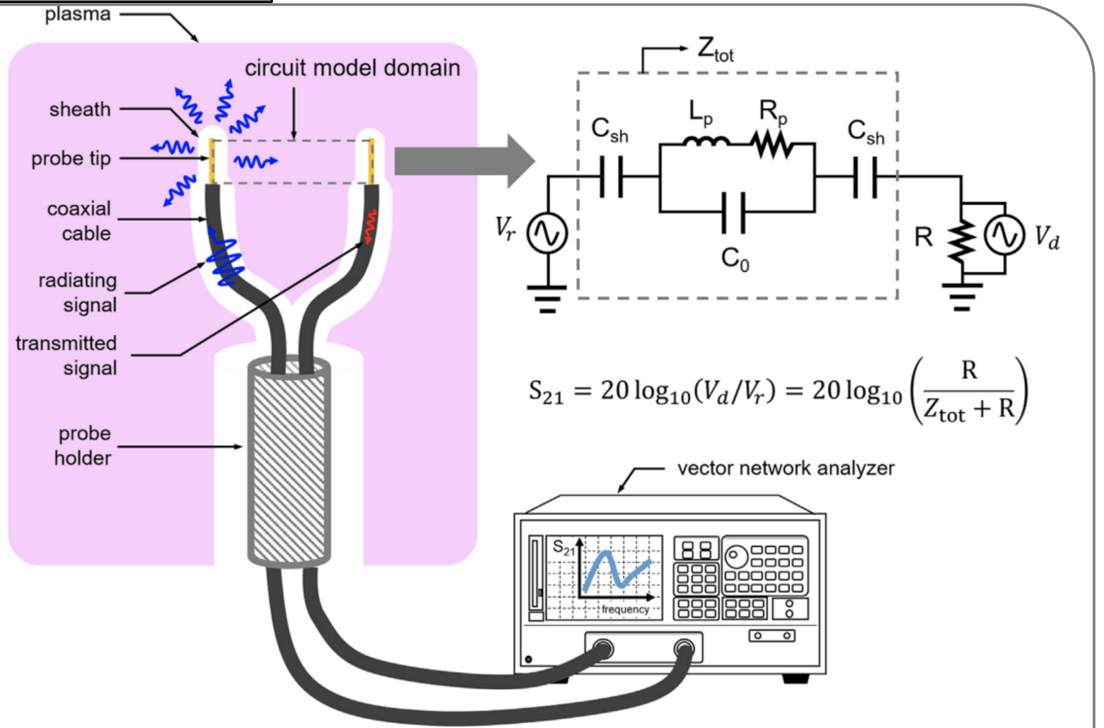
A : Arcing induced tip (AIP)
B : Window
C : High speed camera
D : Ground Electrode
E : Floating probe
F & G & H : Oscilloscope
I : Delay generator (Trigger)
J : Cutoff probe
K : Matching network
L : RF power generator
M : Powered electrode

Method of electron density, sheath thickness

Electron density measurement method



ref) Kim, J.-H., Choi, S.-C., Shin, Y.-H., & Chung, K.-H. (2004). Wave cutoff method to measure absolute electron density in cold plasma. Review of Scientific Instruments, 75(8), 2706–2710. doi:10.1063/1.1771487

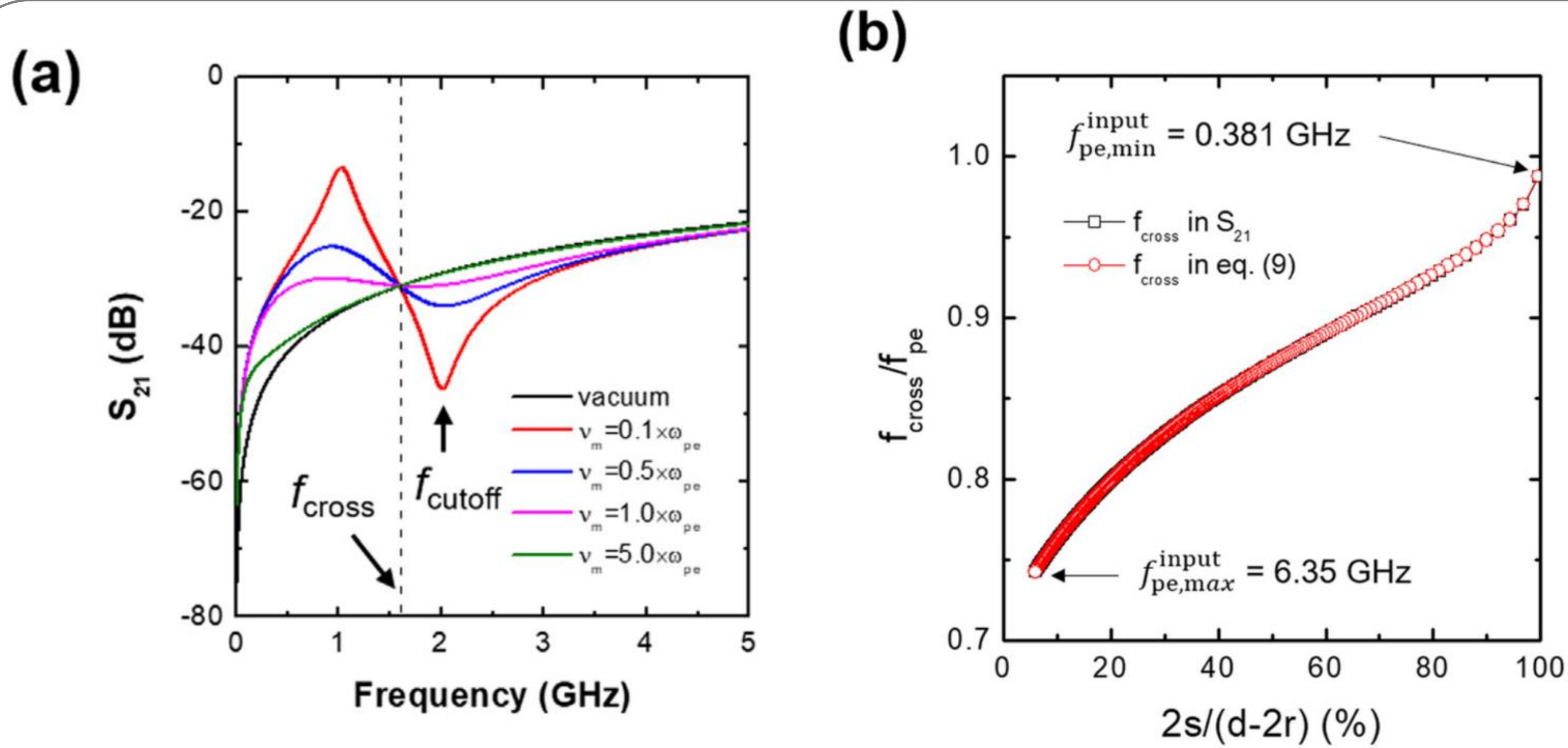


Ref) S.J. Kim et al. Analysis on crossing frequency in transmission microwave frequency spectrum of the cutoff probe, Physics of Plasmas, 30, 024501 (2023)

- Electron density : $n_e = \left(\frac{f_{cutoff}}{8980}\right)^2$

Method of electron density, sheath thickness

Sheath thickness measurement method



❖ Sheath thickness : $\frac{f_{crossing}}{f_{cutoff}} = \frac{1}{\sqrt{2}}\sqrt{\frac{1+\frac{4C_0}{C_{sh}}}{1+\frac{2C_0}{C_{sh}}}}$, $C_{sh} = \frac{2\pi\varepsilon_0 \mathrm{h}}{\log\left(\frac{\mathrm{r+s}}{\mathrm{s}}\right)}$, $\mathrm{C}_0 = \frac{\pi\varepsilon_0 \mathrm{h}}{\mathrm{acosh}\left(\frac{d}{2(r+s)}\right)}$

Ref) S.J. Kim et al. Analysis on crossing frequency in transmission microwave frequency spectrum of the cutoff probe, Physics of Plasmas, 30, 024501 (2023)

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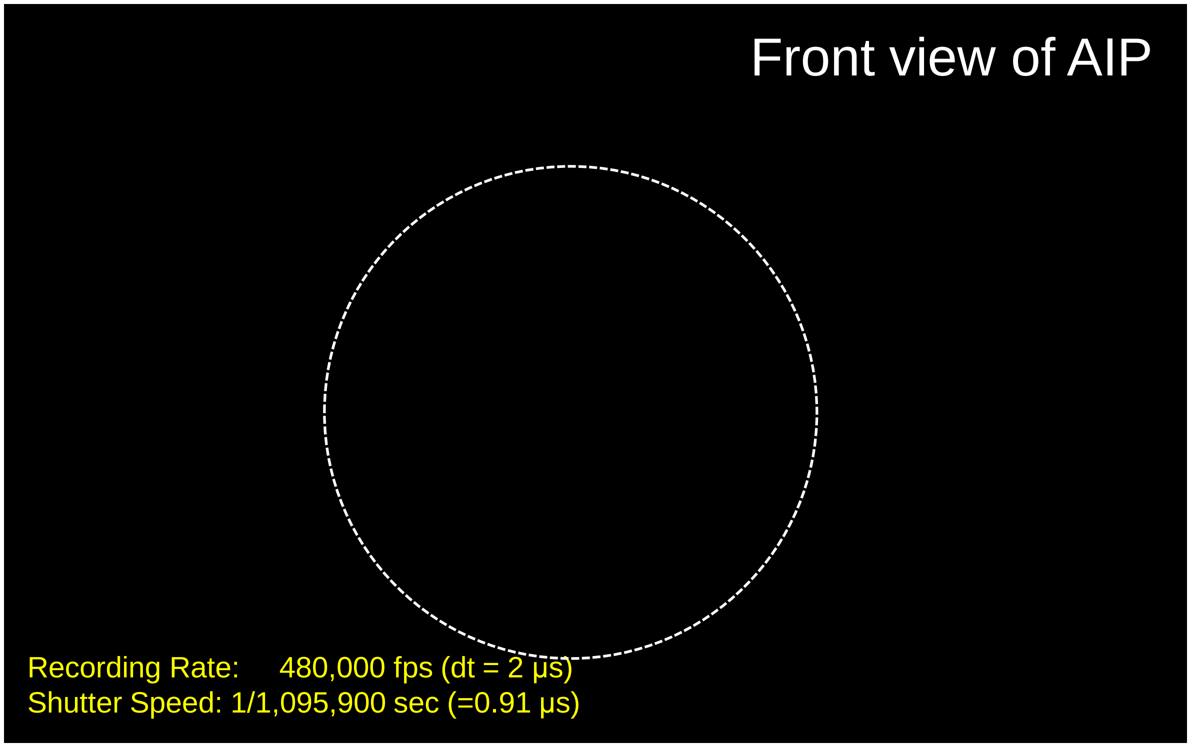
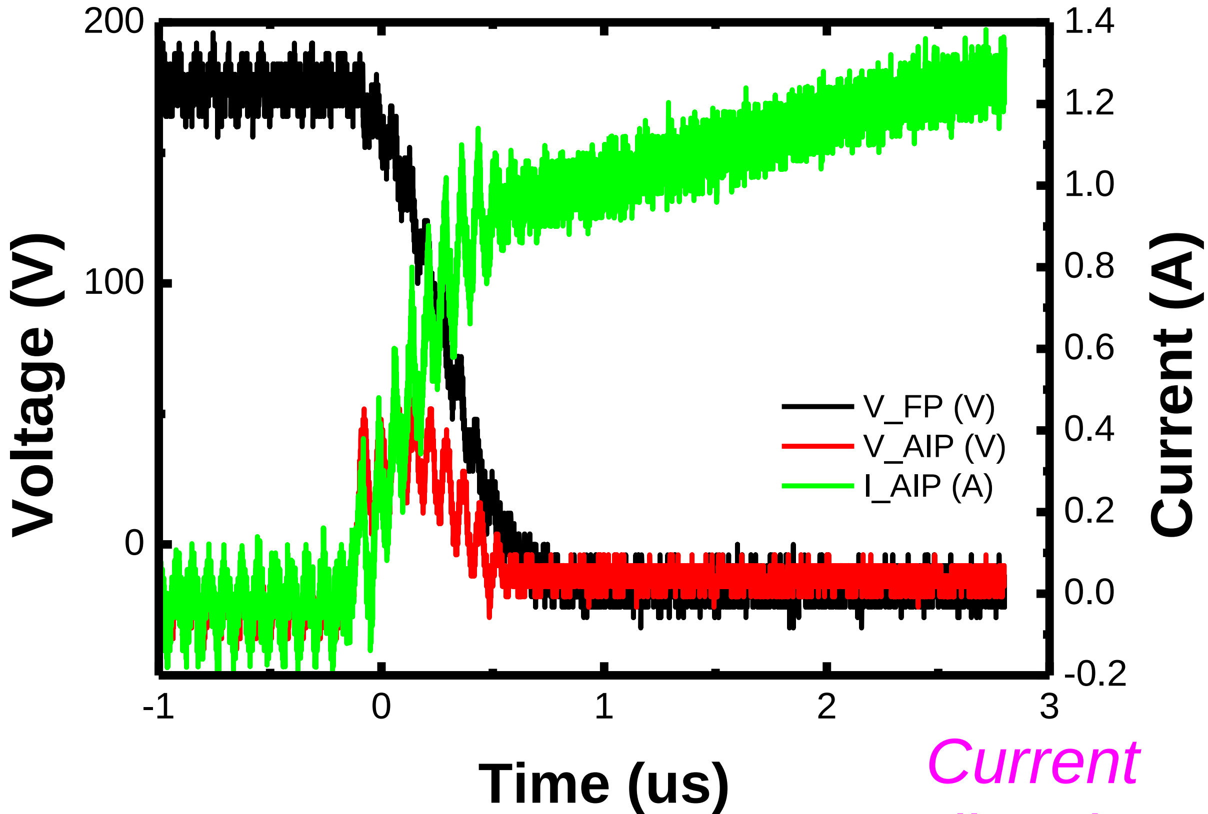
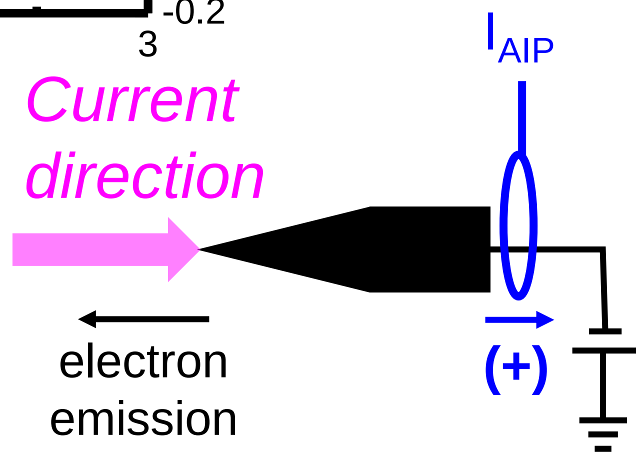
Arcing initiation

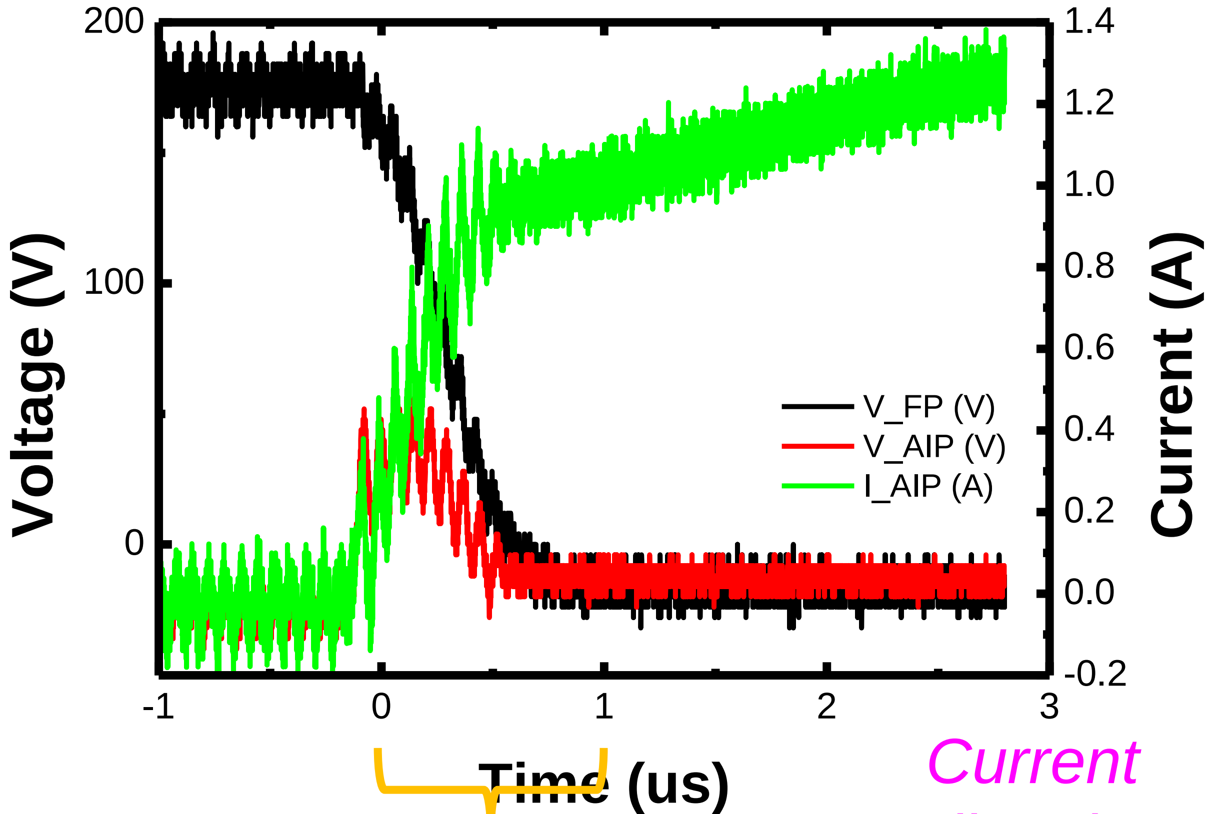


Electrical signal analysis

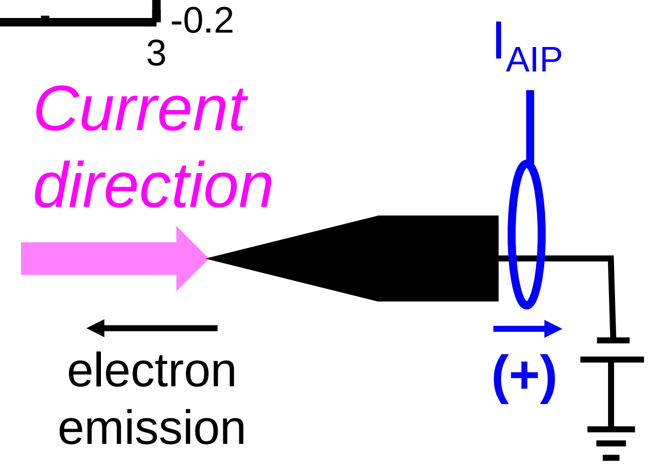




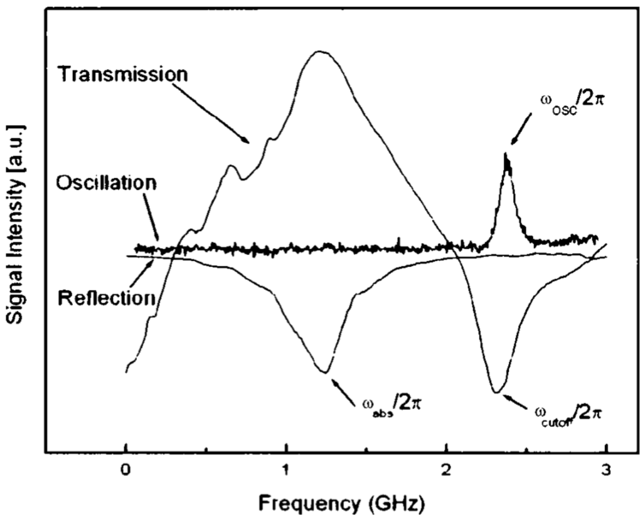
Electrical signal analysis



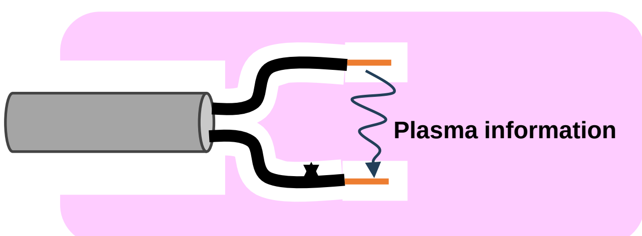
Measuring plasma information

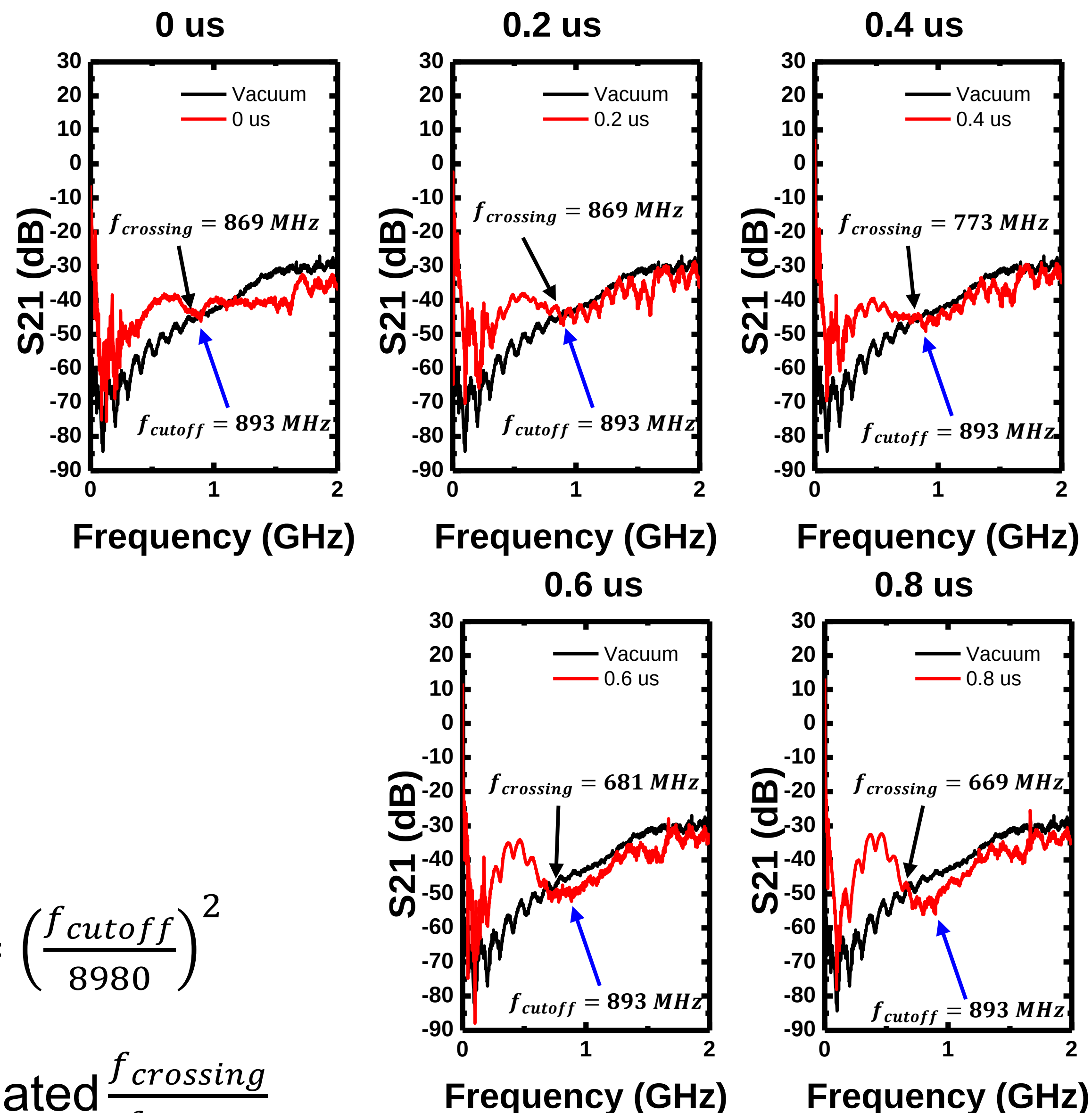


Electron density and sheath thickness



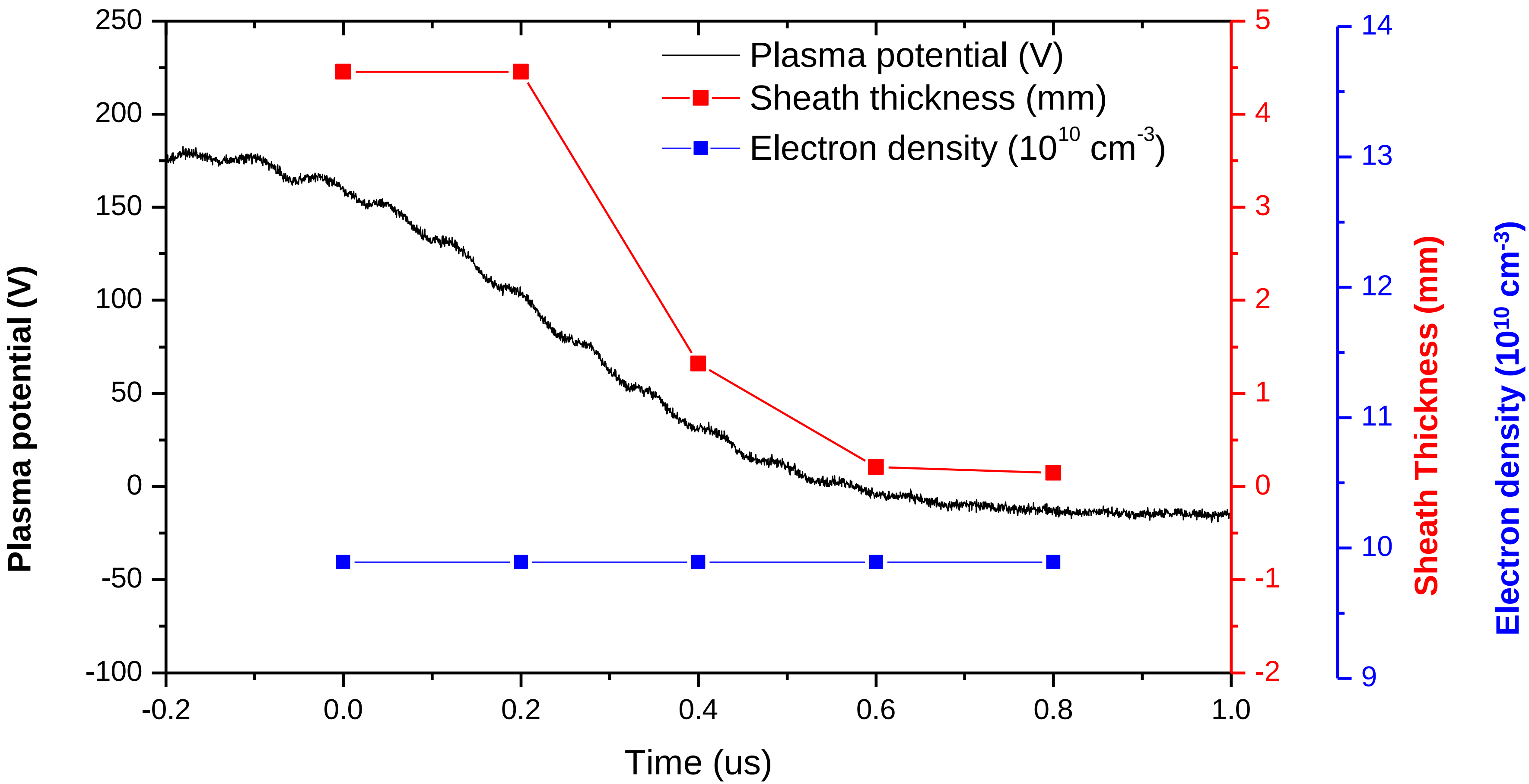
ref) Kim, J.-H., Choi, S.-C., Shin, Y.-H., & Chung, K.-H. (2004). Wave cutoff method to measure absolute electron density in cold plasma. Review of Scientific Instruments, 75(8), 2706–2710. doi:10.1063/1.1771487





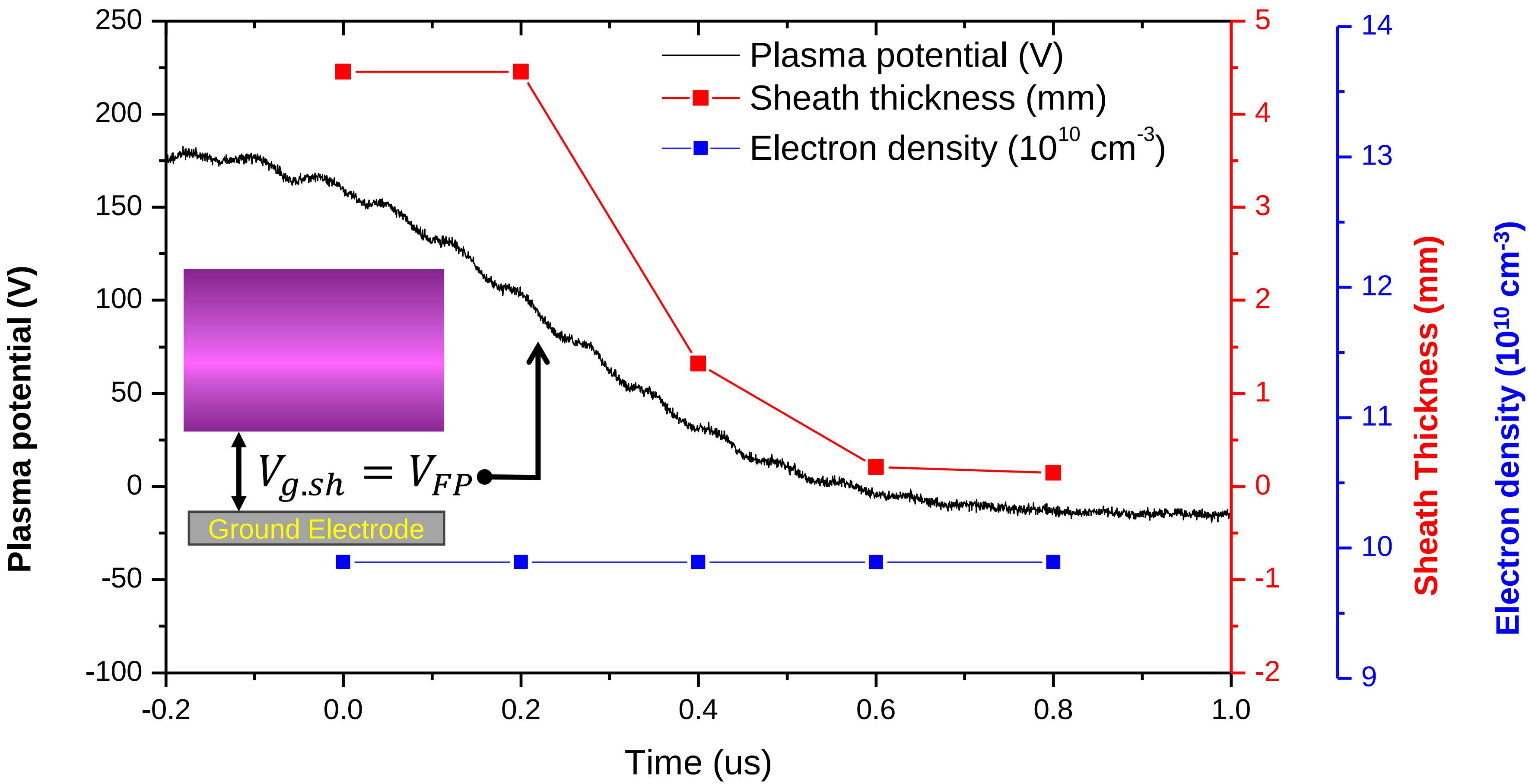
- Electron density : $n_e = \left(\frac{f_{cutoff}}{8980}\right)^2$
- Sheath thickness : s related $\frac{f_{crossing}}{f_{cutoff}}$

Electron density and sheath thickness



❖ Sheath thickness ∝ Plasma potential

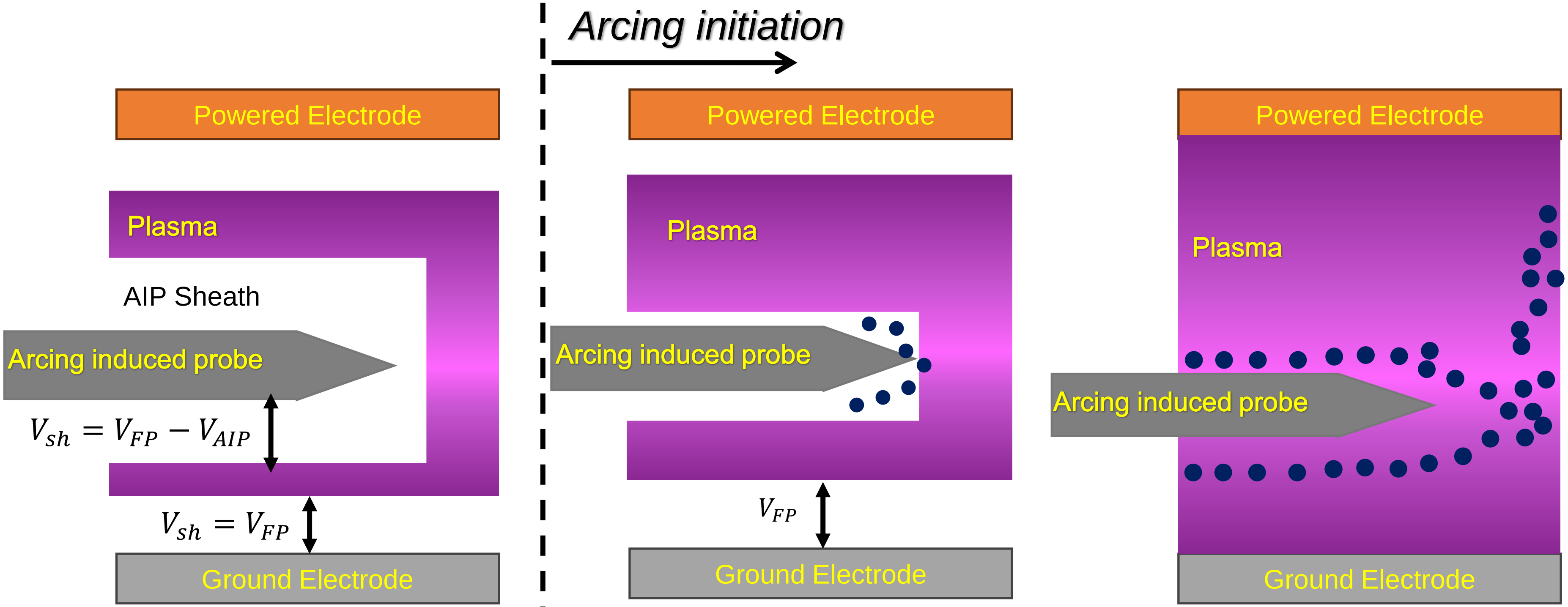
Electron density and sheath thickness

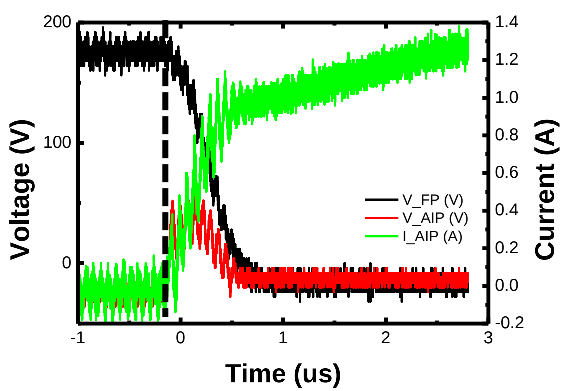


- Sheath thickness ∝ Plasma potential

Results and discussion

Plasma behavior with arcing initiation





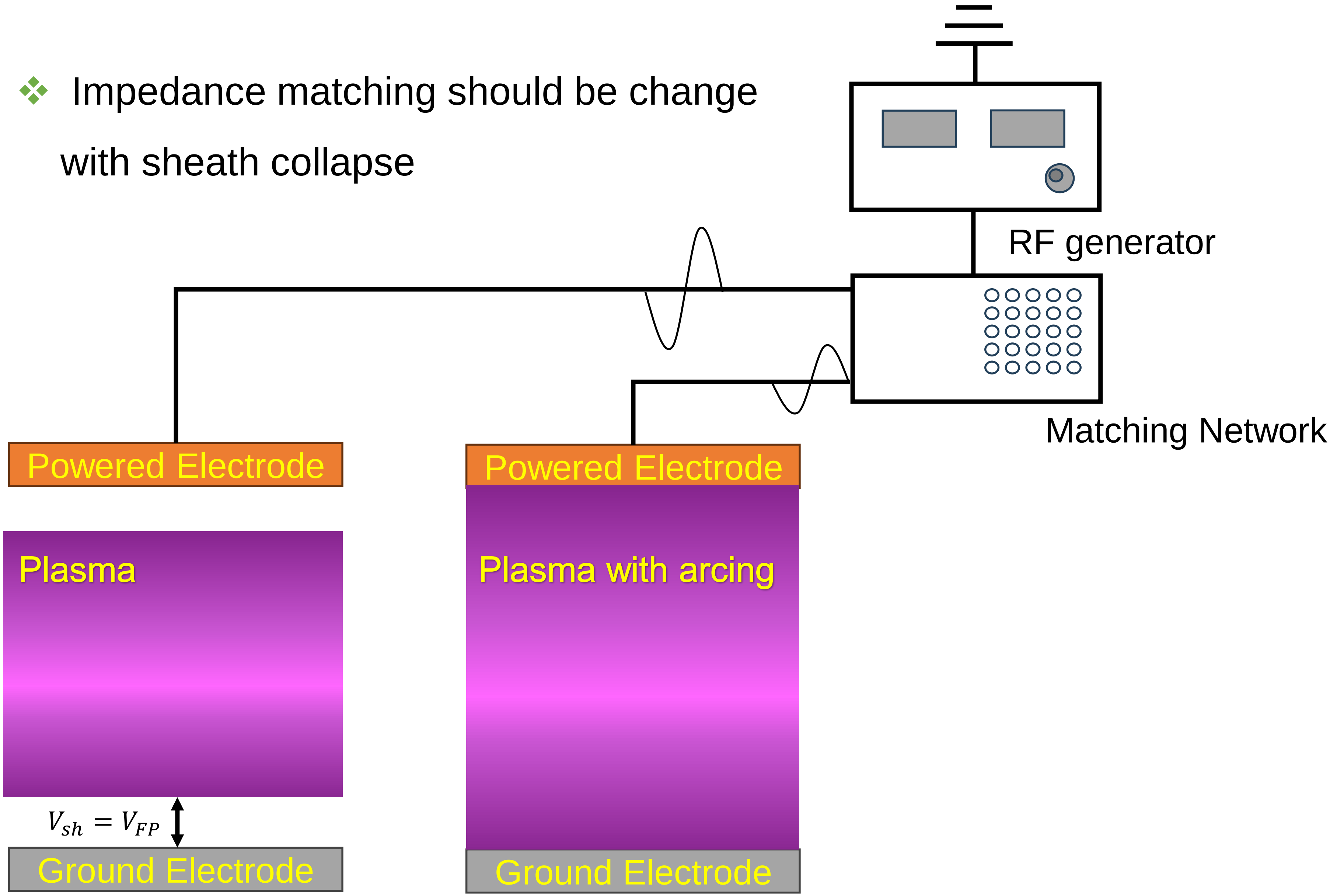
- Electron emission (I_{AIP})
- Reduce AIP sheath ($V_{sh} = V_{FP} - V_{AIP}$)

- Emission increase
- Plasma potential decrease
- Collapse sheath

Results and discussion

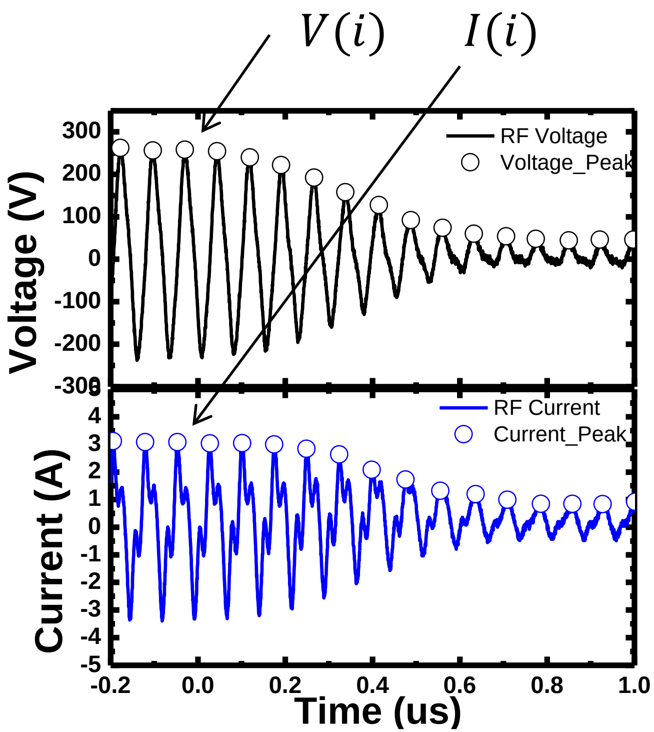
Power system change with plasma variation

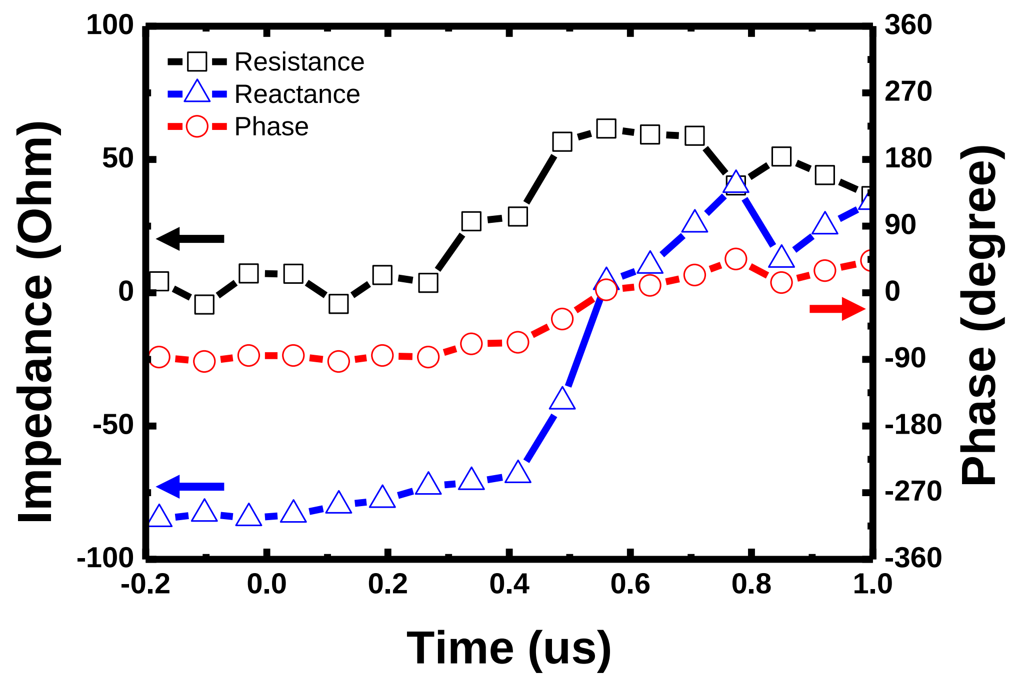
- Impedance matching should be change with sheath collapse



Results and discussion

RF impedance calculation

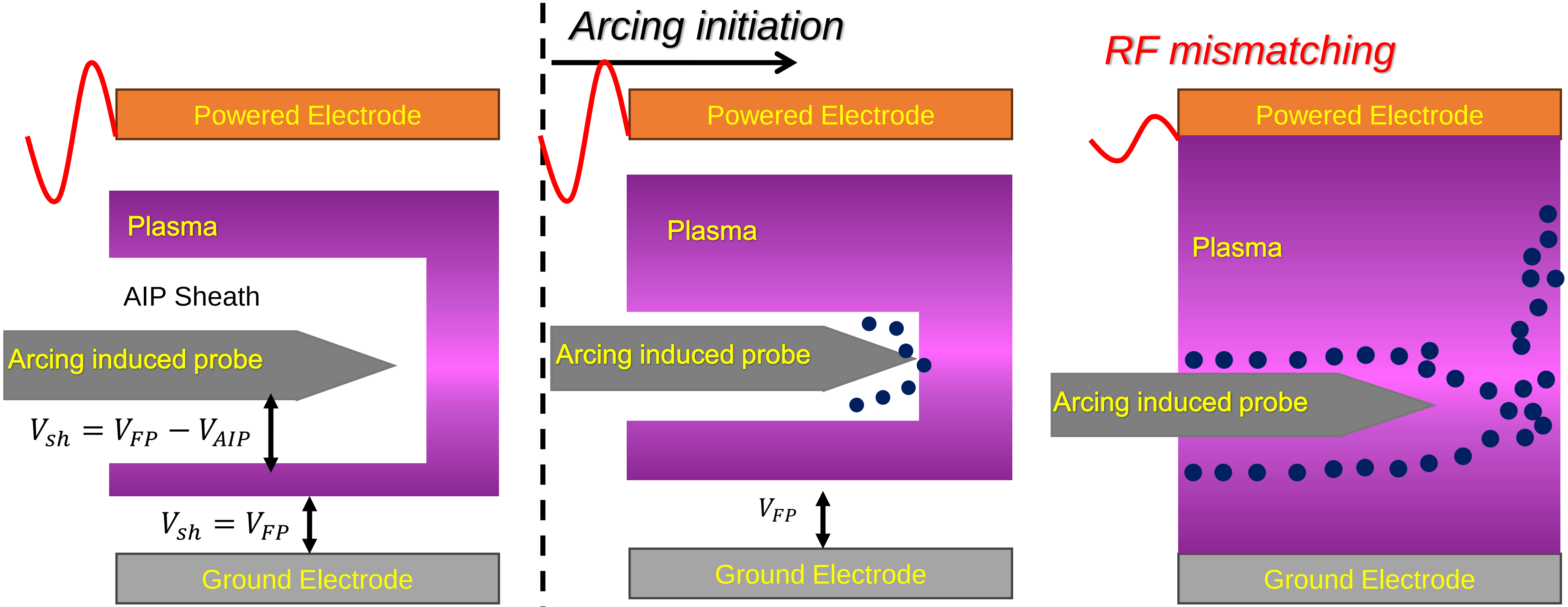


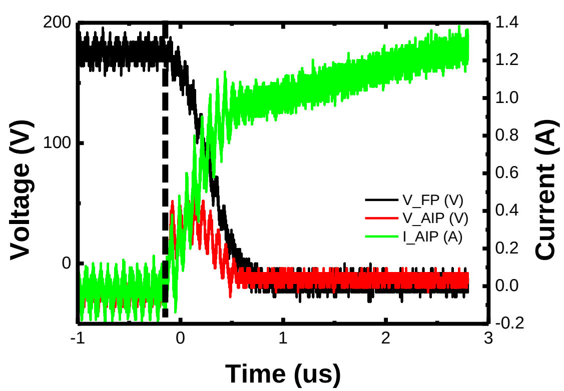


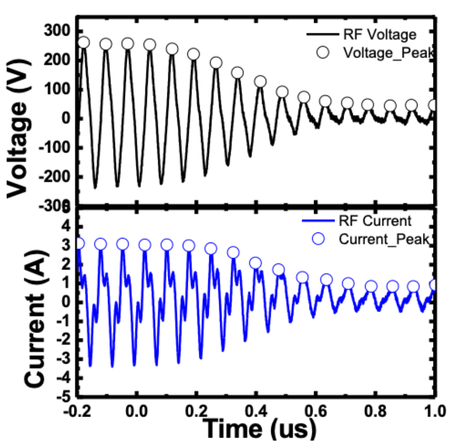
- Impedance : $Z = \frac{V(i)}{I(i)} e^{i\phi}, \phi = \frac{t(V_i) - t(I_i)}{t_{RF}} 2\pi$
- Reactance change minus to plus (Main impedance change from C to L)
- Impedance variation causes RF mismatching.

Results and discussion

Plasma behavior with arcing initiation







- Plasma potential decrease
- Sheath collapse
- RF mismatching

The influence of arcing on radio-frequency capacitively coupled plasma

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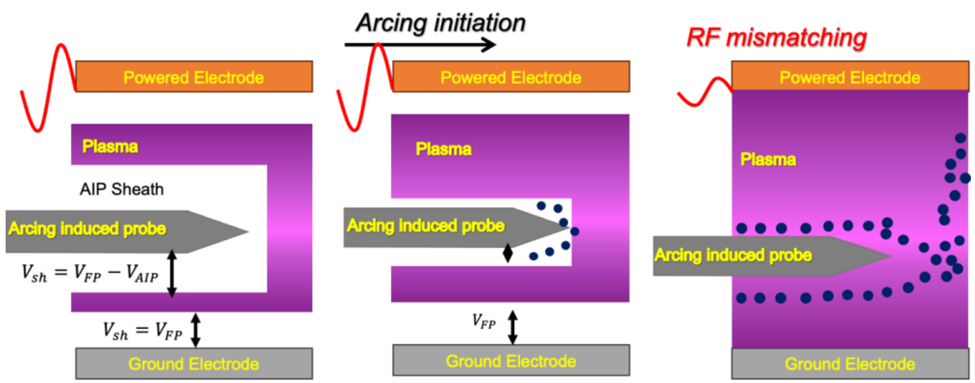
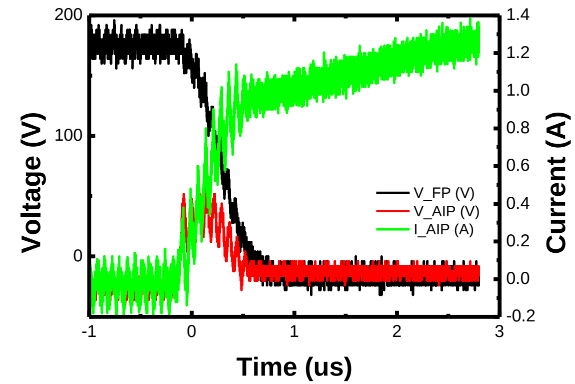
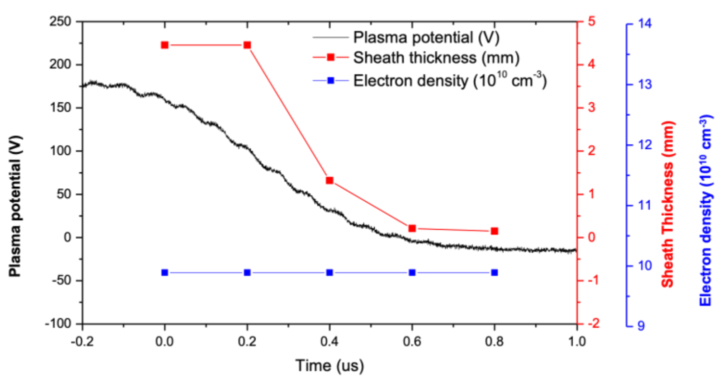
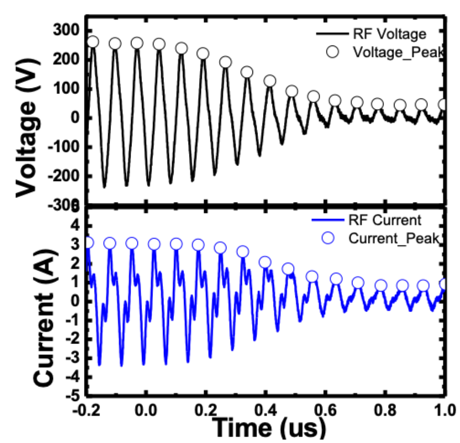
Conclusion

- We established arcing initiation and diagnostic system
- Sheath thickness and electron density were obtained by cutoff probe.
- The sheath collapsed when the arcing initiation, but electron density does not change.
- The impedance is changed by arcing, and applied RF is decreased by RF mismatching









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Thank you for your attention!!

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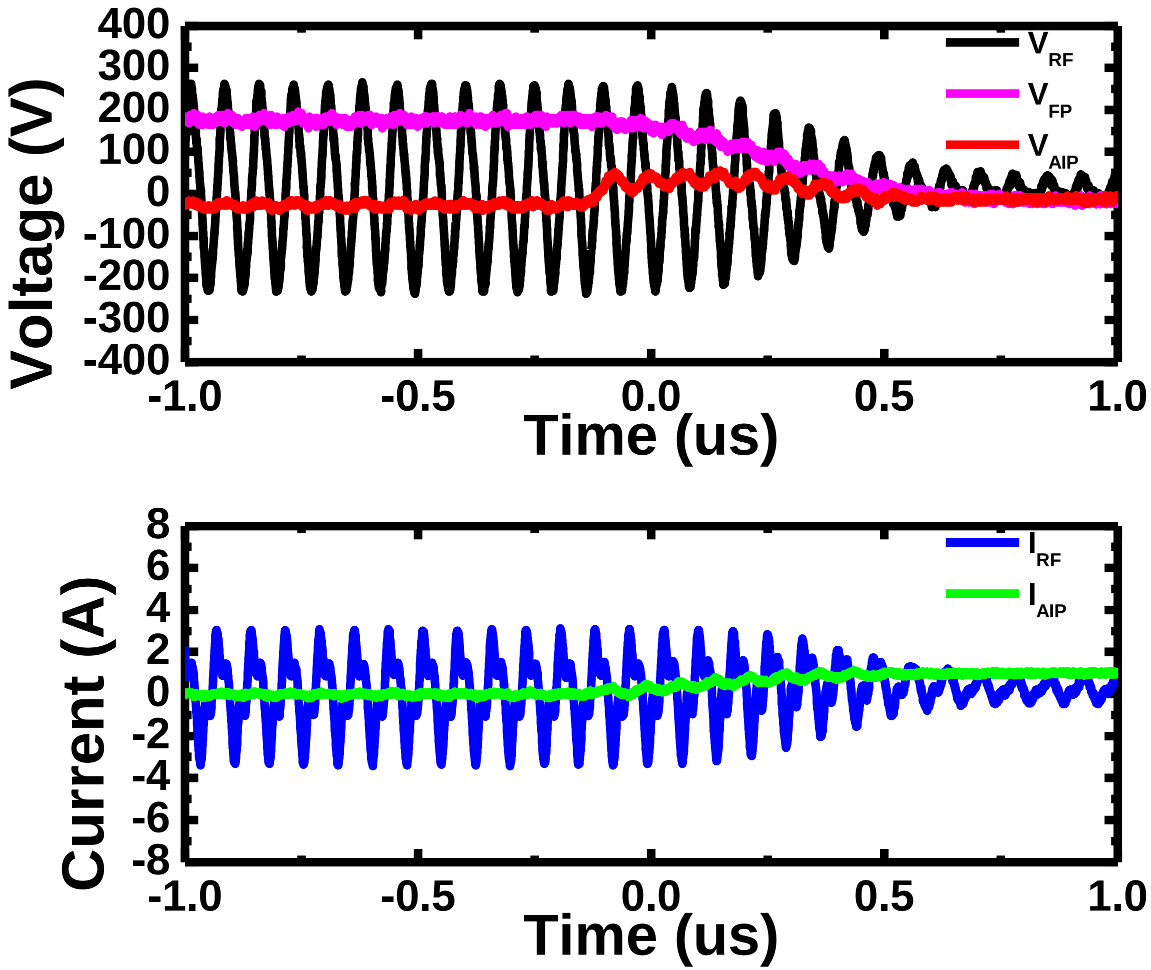
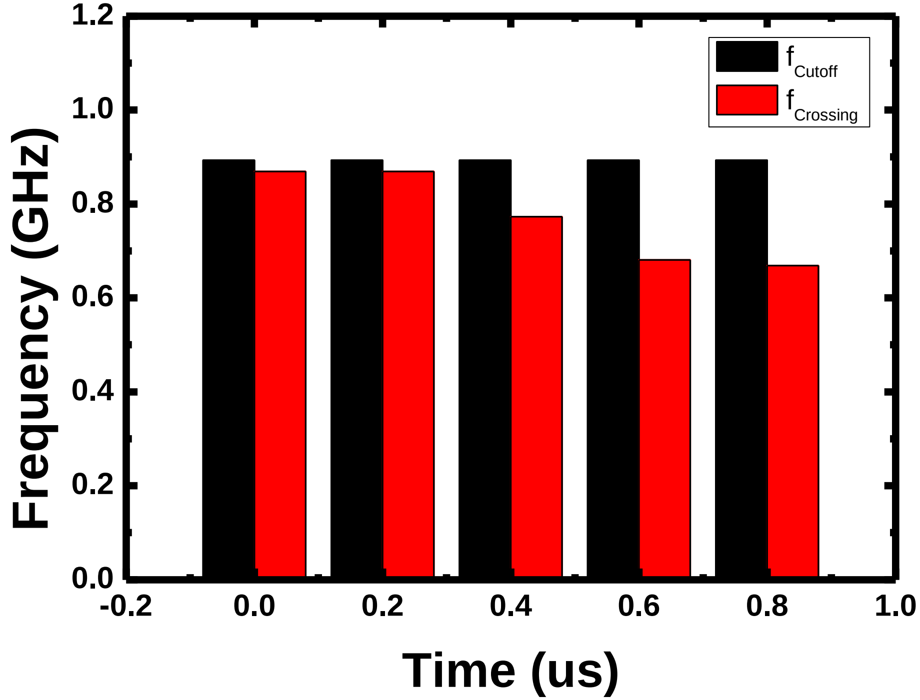
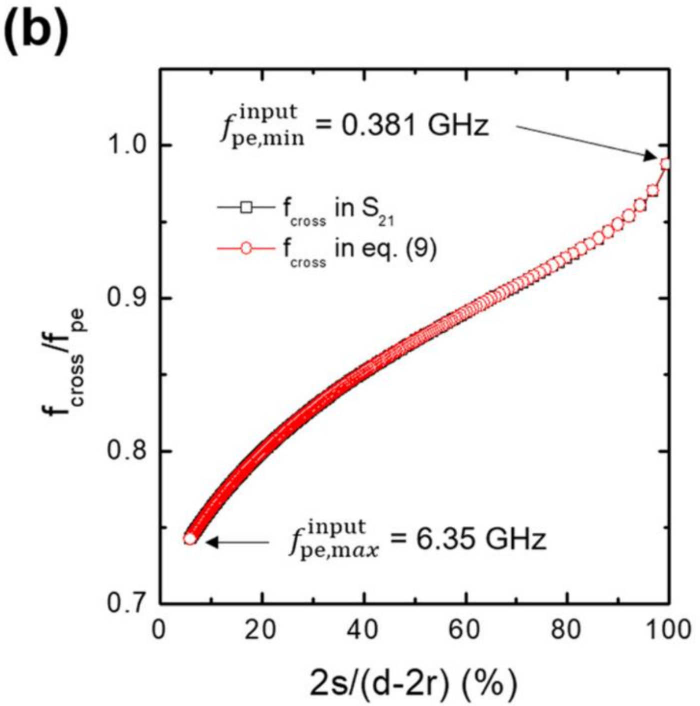
Electrical signal analysis



Electron density and sheath thickness





Experiment details

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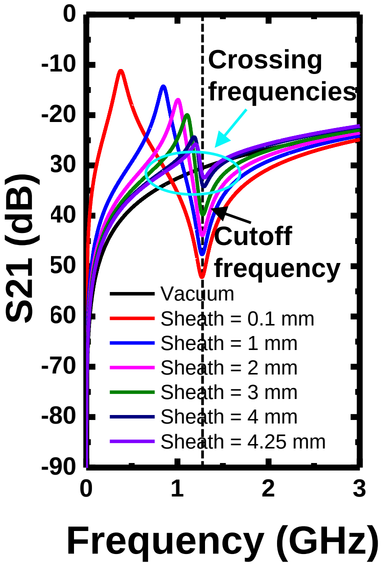
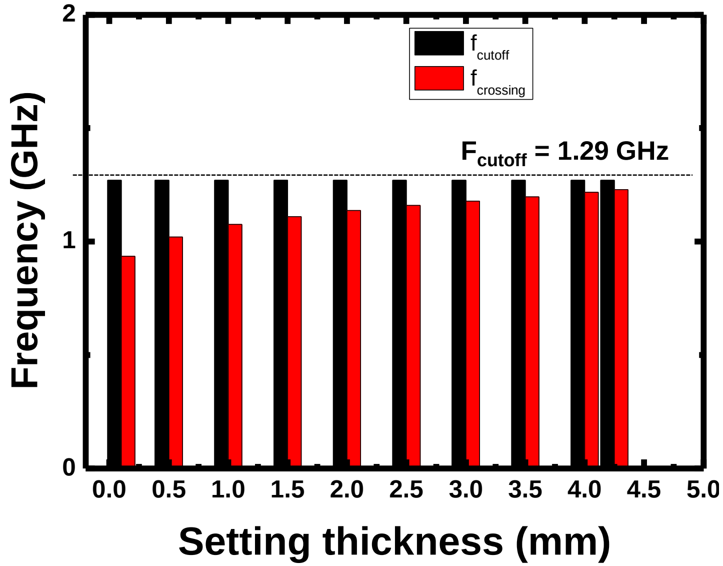
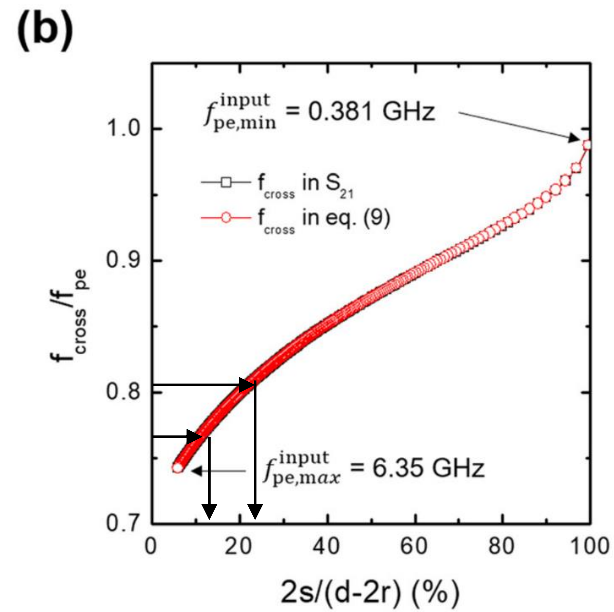
- **Method – Verifying sheath thickness measurement method with circuit simulation**

Circuit model simulation





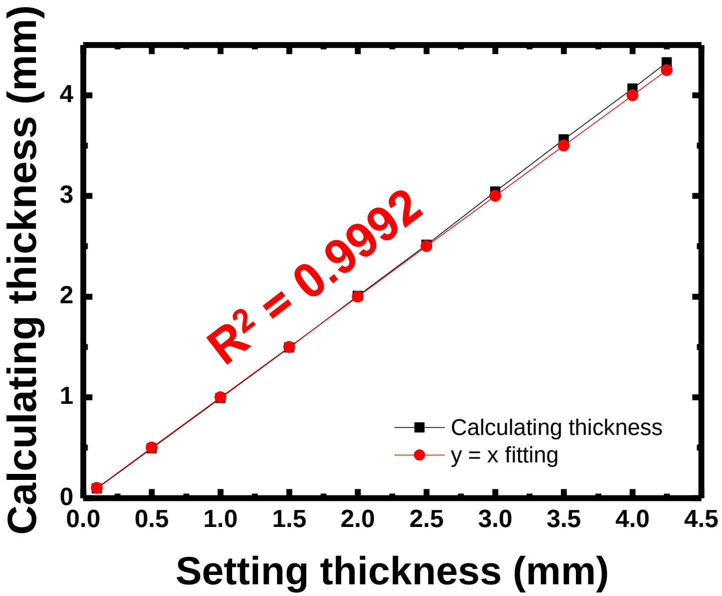


- The cutoff probe is simulated with circuit model. (Setting electron density = 2*10[10] *cm*[3], pressure = 170 mTor r)
- When the setting sheath thickness increases, cutoff frequency is not change but crossing frequency shift toward right.
- Therefore, crossing frequency is closed to cutoff frequency when the sheath thickness increases.
- Obtained $f_{crossing}/f_{cutoff}$ from second figure, it can change sheath thickness by substituting third figure

Experiment details

- **Method – Verifying sheath thickness measurement method with circuit simulation**

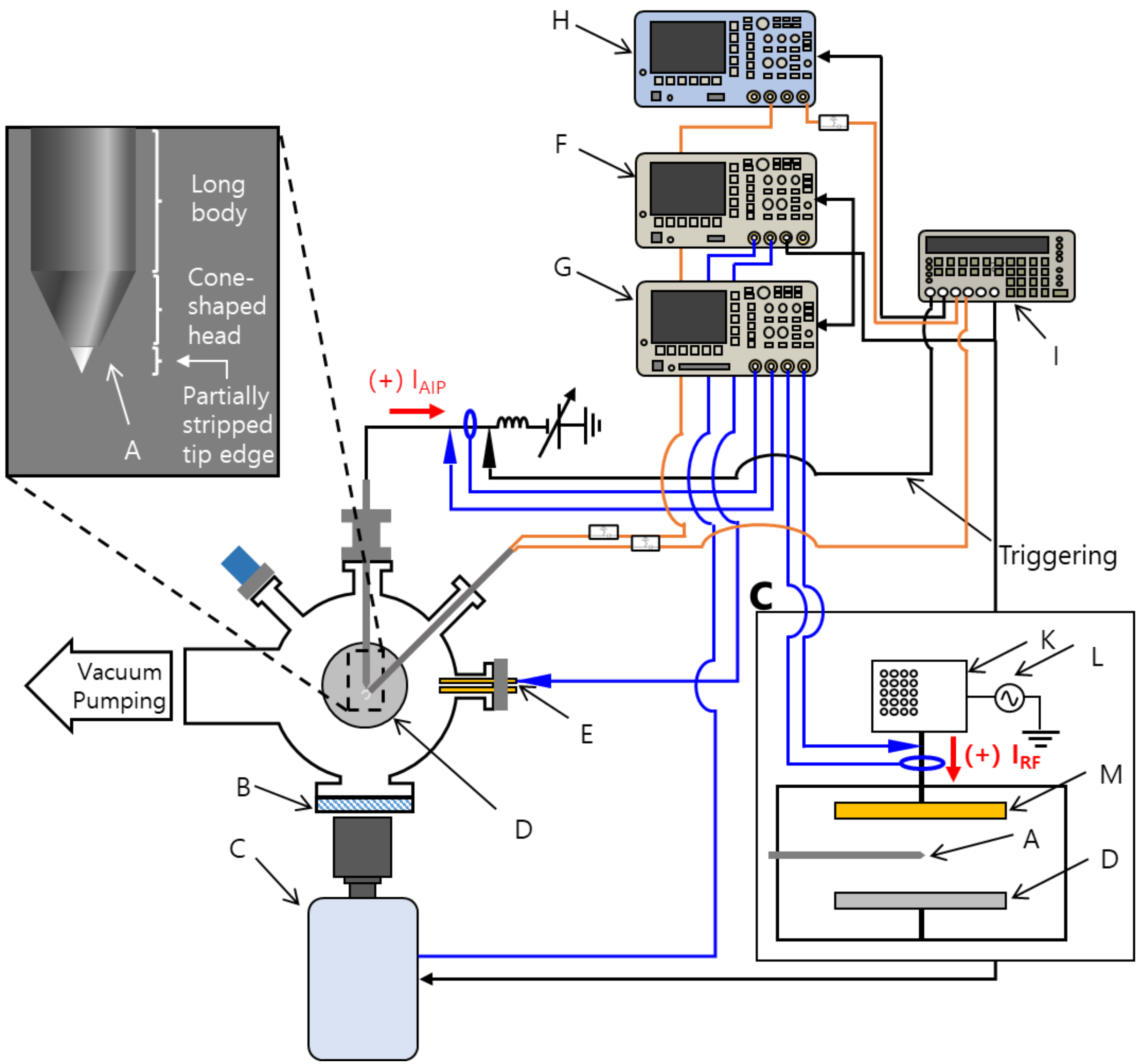
Circuit model simulation



- From the above results, sheath thickness is calculated.
- The X axis is setting thickness, and Y axis is calculating thickness. It shows that almost same.
- Calculating R^2, it is almost 1.

Plasma analysis – Electron density, sheath thickness

Experiment set-up



- Orange line : Cutoff probe measurement set – up (Cutoff probe, oscilloscope, delay generator)

Plasma analysis – Electron density, sheath thickness

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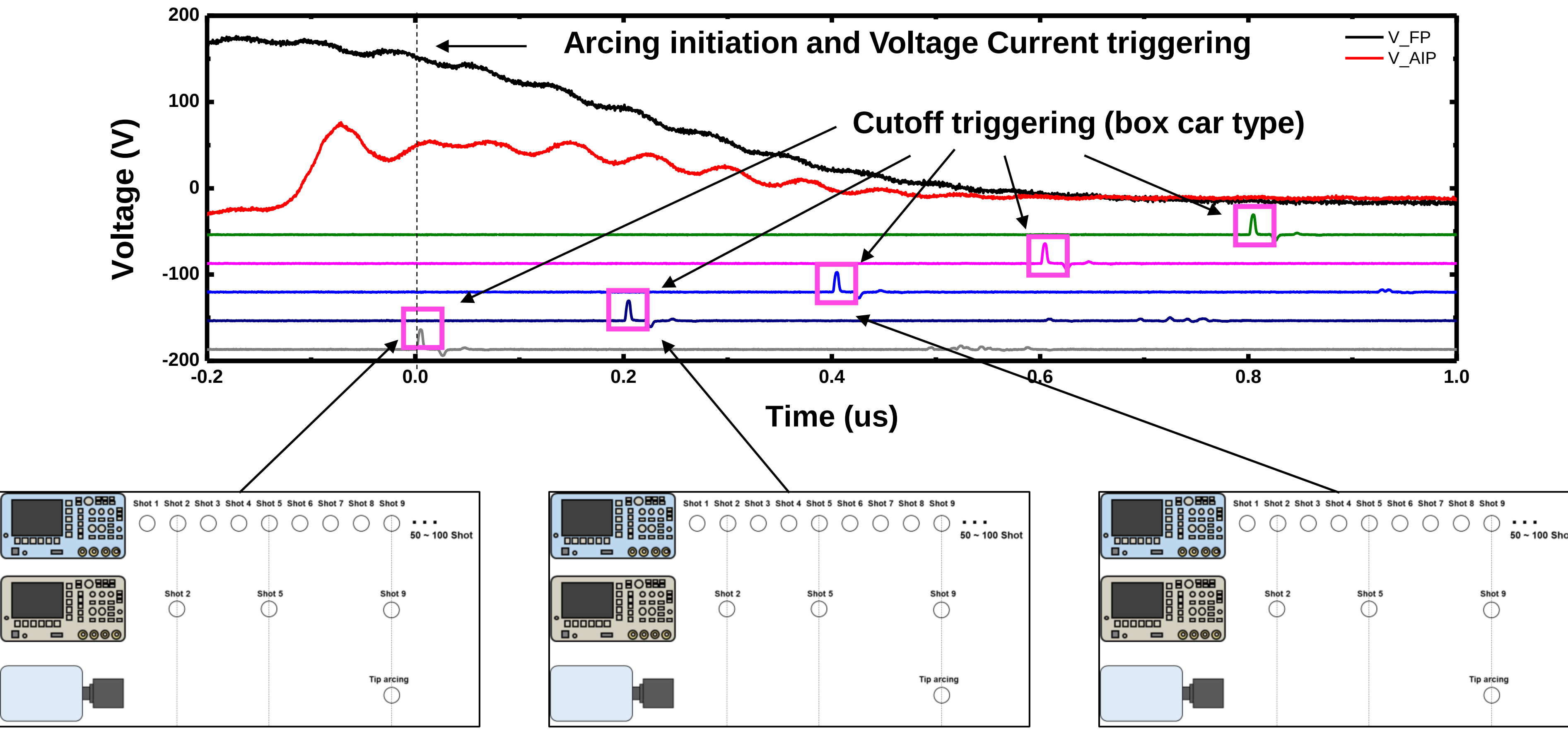
- Experiment set-up : Data Acquisition



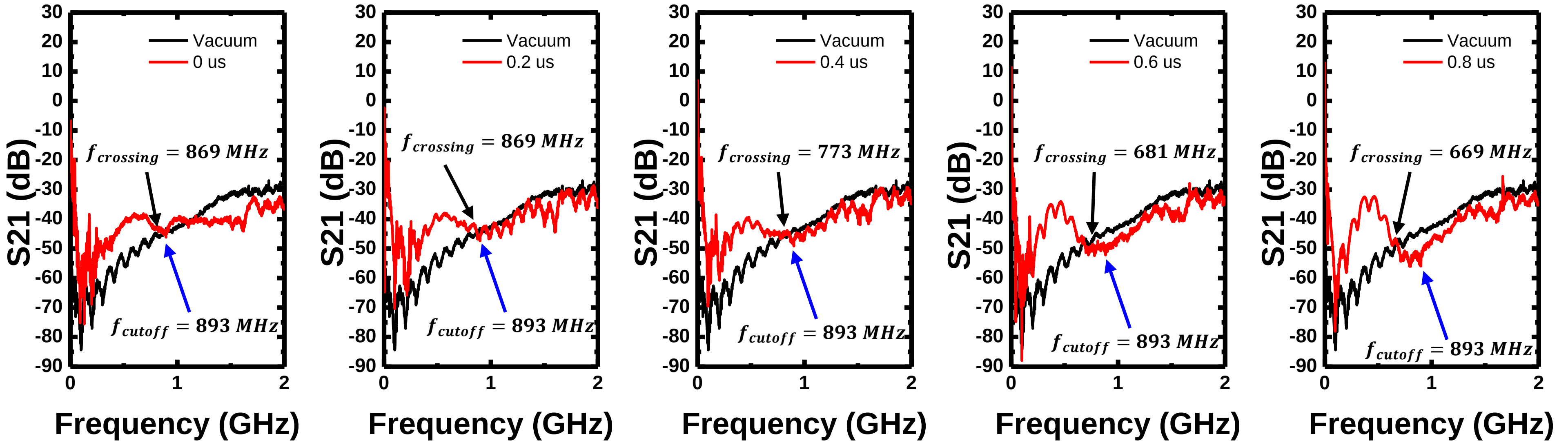
WaveMaster
- Cutoff measurement

TDS3054B
- Plasma IV measurement

High speed camera
- Tip arcing image

Plasma analysis – Electron density, sheath thickness

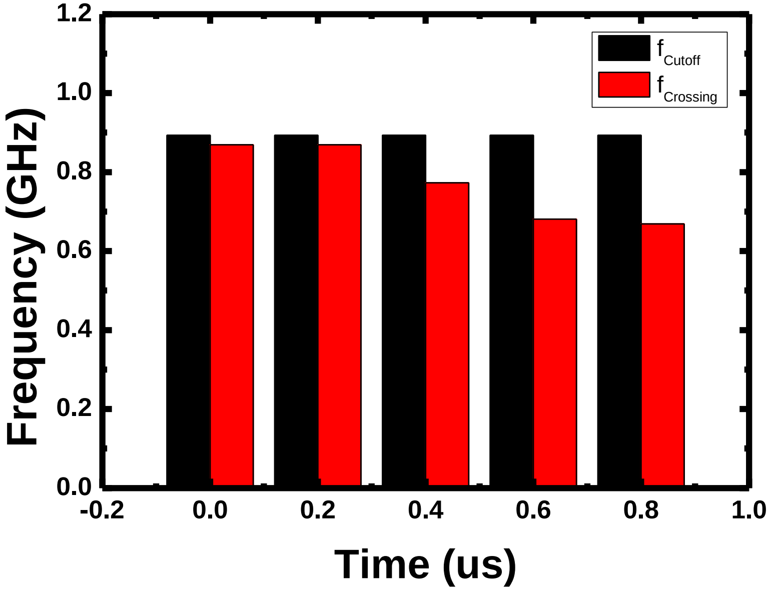
Results and discussion : Cutoff probe results

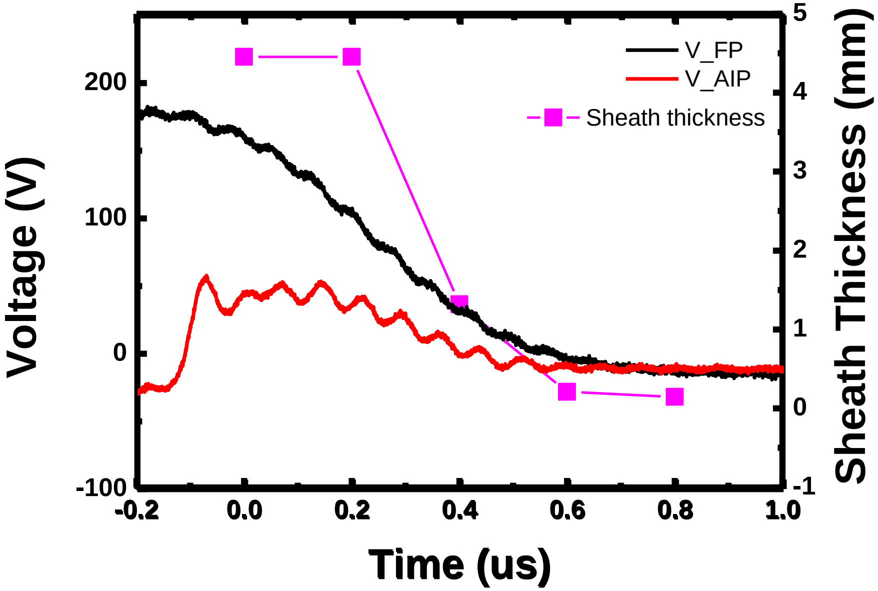


- There're the cutoff probe results via arcing initiation.
- To obtain the crossing frequency vacuum spectrum and plasma spectrum are measured.
- The cross point with black and red line is crossing frequency, and the minimum value in N- shape is the cutoff frequency.
- The cutoff frequency is not changed with varying time, but the crossing frequency decreases.
- Note that, the floating potential is decrease with flowing time, so we expected that sheath thickness is decrea se.

Plasma analysis – Electron density, sheath thickness

Results and discussion : Sheath thickness in arcing

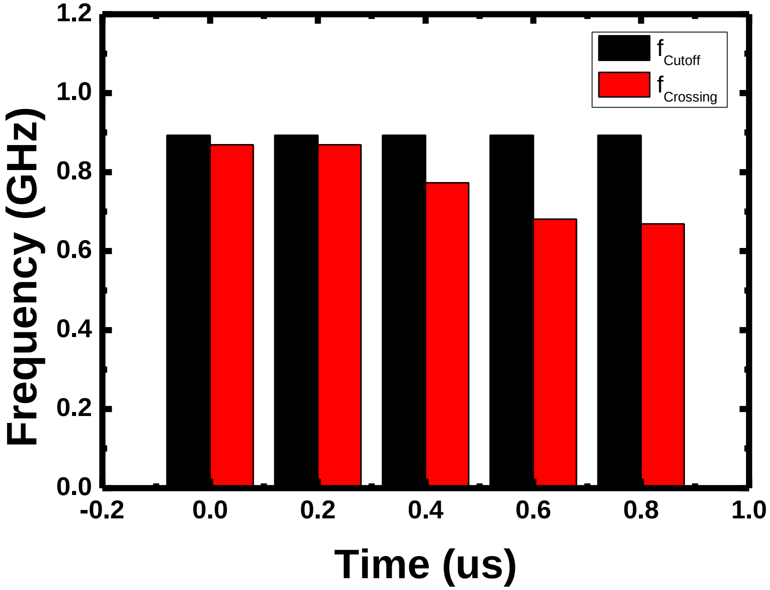


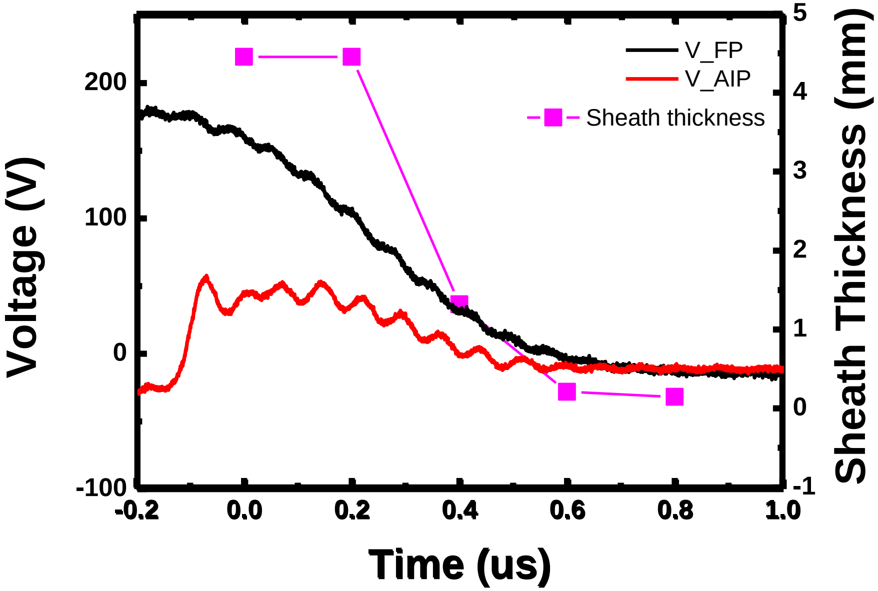


- When we plot the crossing frequency and cutoff frequency as time, we can check that crossing/cutoff ratio stiffly decrease.
- Using the crossing/cutoff frequency ratio, the sheath thickness can be obtained. In here, the cutoff probe distance is 10 mm.
- Before the arcing initiation, the sheath thickness is near 4.5 mm, it is the highest value. This is because, the floating potential is very high, so sheath thickness is also thick.
- After the arcing initiation, the thickness is decreases, near 1.3 mm at 0.4 us.
- When the floating potential value is near zero, the sheath is almost collapse, the value is near zero.
- However, the electron density is not changed (Cutoff frequency is not differ). $n_e \approx 10^{16}\ m^{-3}$
- The sheath thickness from cutoff probe is matched well with floating potential tendency.
- Therefore, it is certain that the sheath collapses as arcing occurs.

Plasma analysis – Electron density, sheath thickness

Results and discussion : Sheath thickness in arcing





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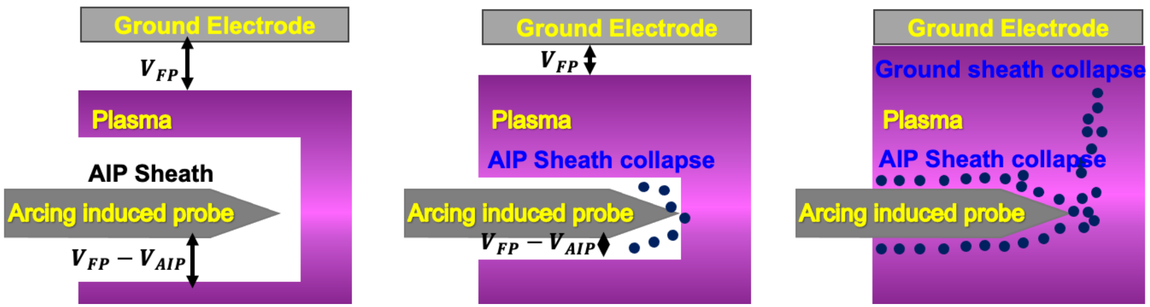
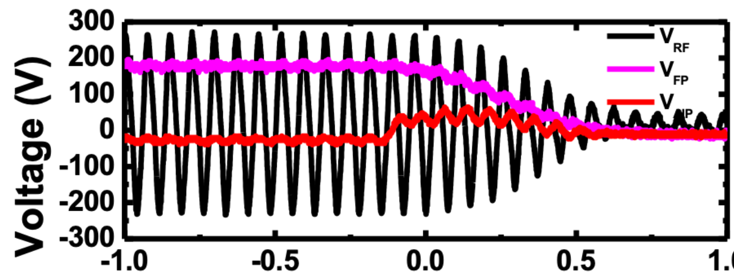
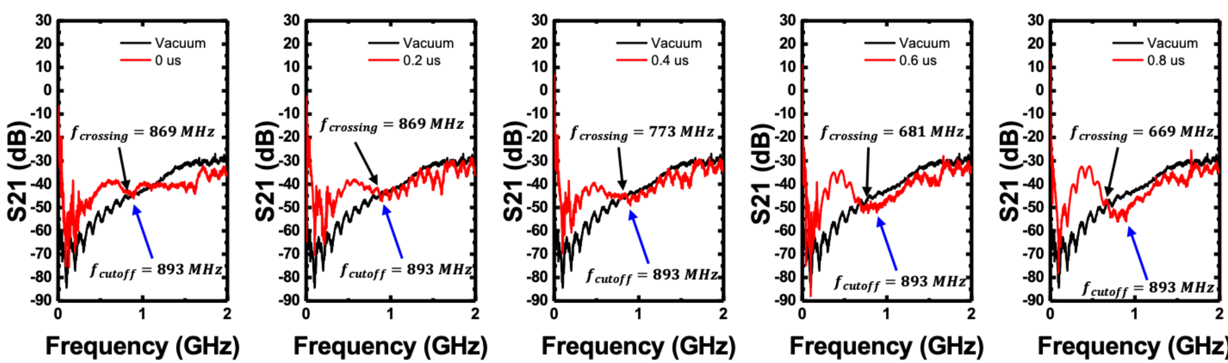
- The sheath thickness from cutoff probe is matched well with floating potential tendency.
- Therefore, it is certain that the sheath collapses as arcing occurs.

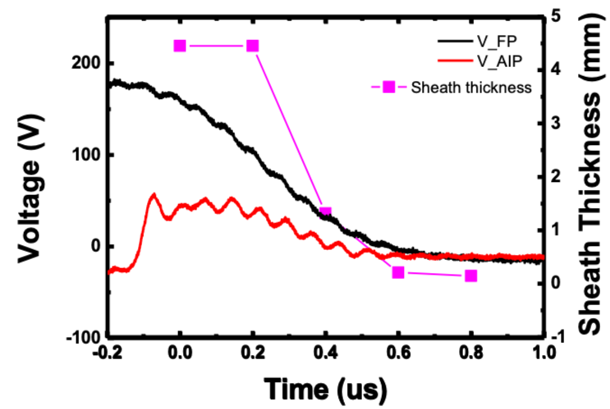
Summary

- Using the high voltage probe, and current probe, the arcing is analyzed.
- Making the hypothesis : Plasma sheath is collapse from floating potential decreases.
- The hypothesis is verified : Sheath thickness calculated method by Cutoff – Crossing frequency method



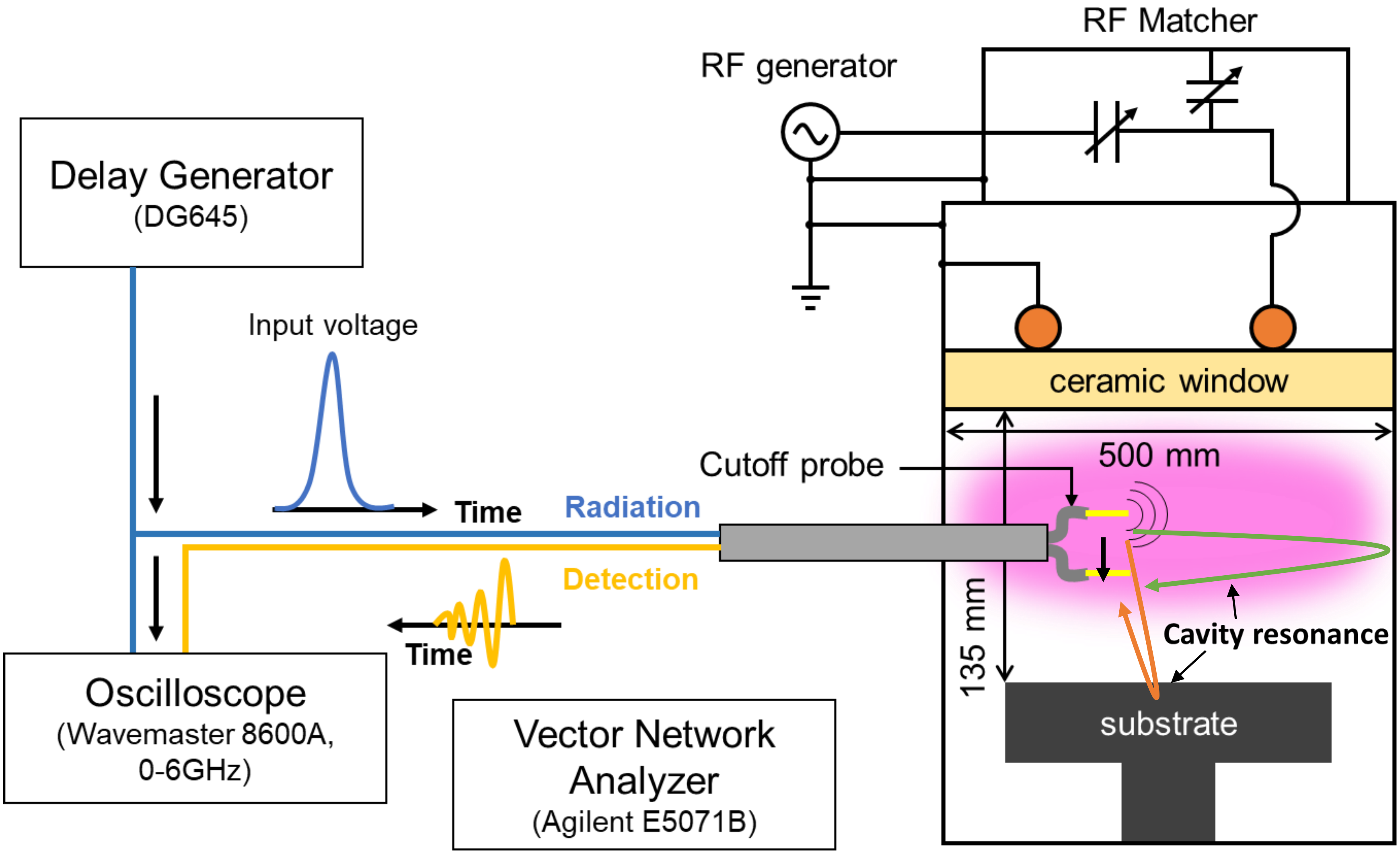






Appendix

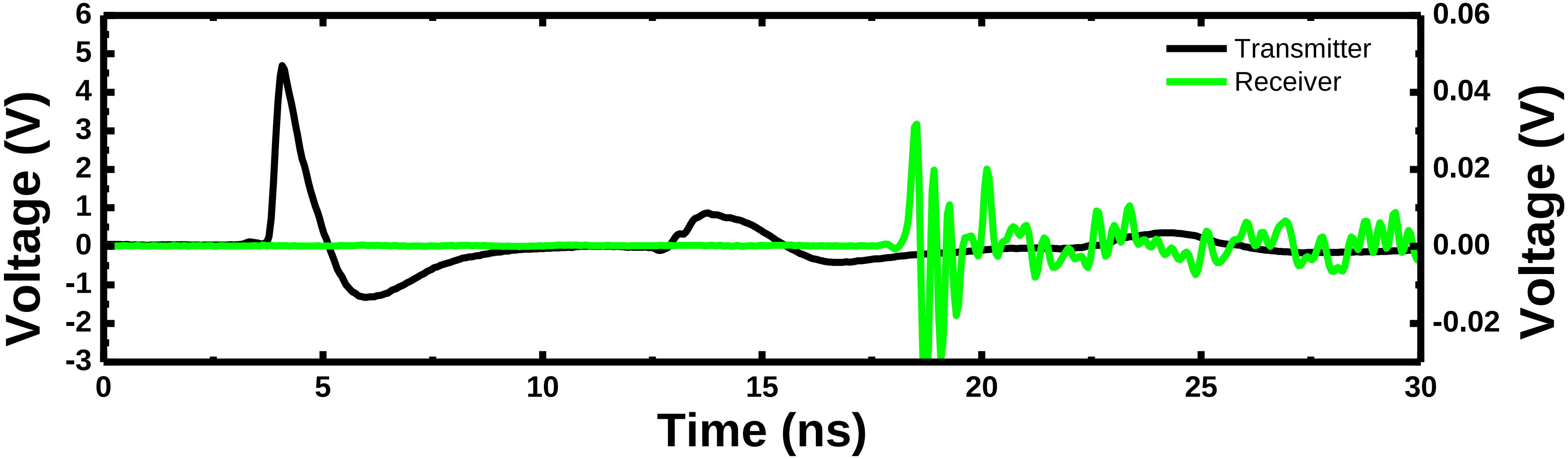
- Cutoff probe measurement with delay generator (FCP method)

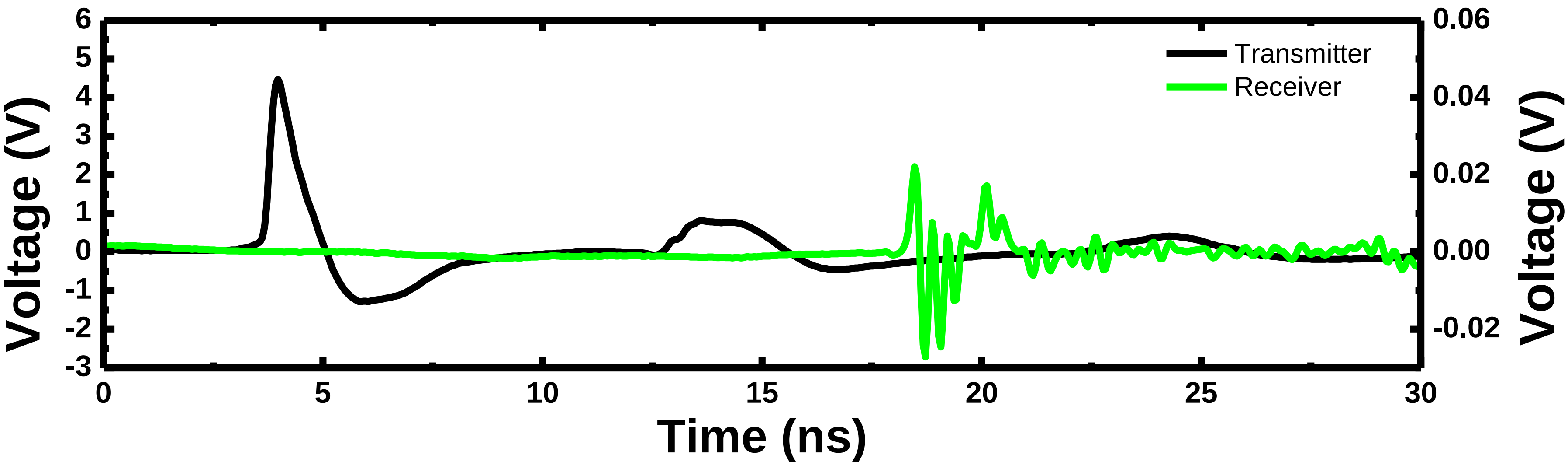


(c.f.) B. K. Na et al. *RSI* **83** 013510 (2012)

Appendix

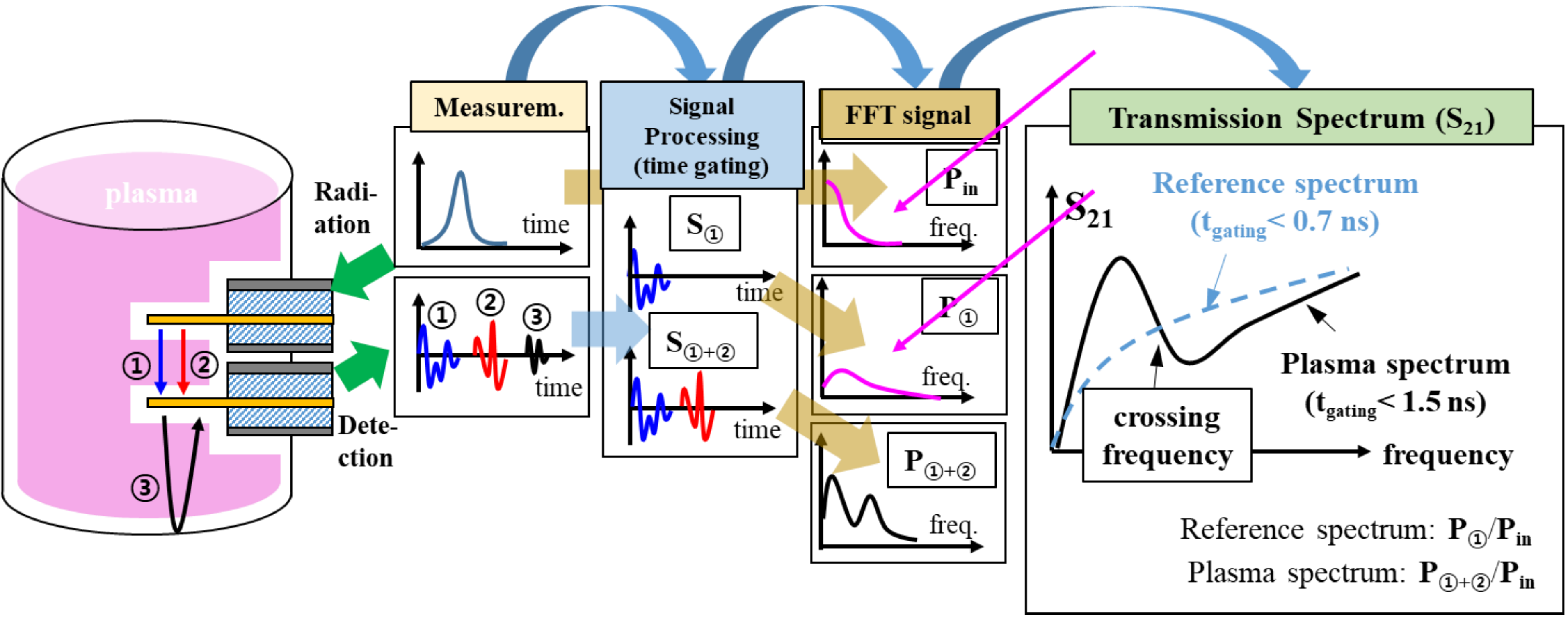
- Raw data of the signal





Appendix

- Time-gating, experiment order



- $S21 = 20\log_{10}\frac{V_{out}}{V_{in}}$

Appendix

$$\omega = \omega_{\text{cross}} = \frac{\omega_{\text{pe}}}{\sqrt{2}} \sqrt{\frac{\left(1 + \frac{4C_0}{C_{\text{sh}}}\right)}{\left(1 + \frac{2C_0}{C_{\text{sh}}}\right)}},$$

where Z_{tot} is the total impedance of the circuit model domain. Circuit elements are as follows: C_{sh} is $2\pi\varepsilon_0 h/\log((r+s)/r)$; C_0 is $\pi\varepsilon_0 h/\text{acosh}(d/(2(r+s)))$; L_p is $1/\omega_{\text{pe}}^2 C_0$; and R_p is $\nu_m L_p$, where r, d, h, and s are the probe tip radius, tip distance, tip length, and sheath width, respectively. Here, s is assumed as the floating sheath, which is the five times of the Debye length, λ_{De} ($5 \times \lambda_{\text{De}}$). Here, R is the same with Ref. 7. In this paper, the probe tip length (5.0 mm), tip radius (0.26 mm), and tip distance (3.0 mm) are fixed.

(b)