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# Temporal evolution behaviors during the re-ignition phase of pulsed CCRF discharges

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# Outline

1. Motivation

2. Breakdown process

3. Pulse-off time effects

4. Conclusions and outlook

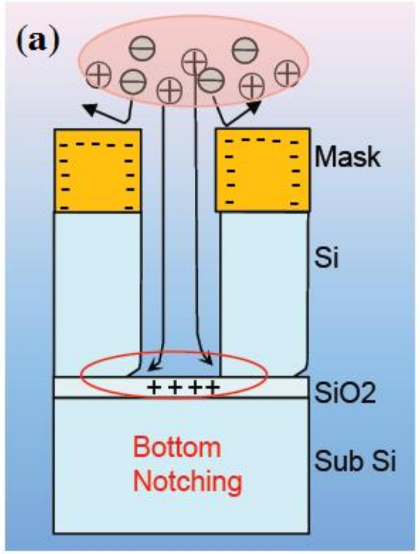
# Motivation

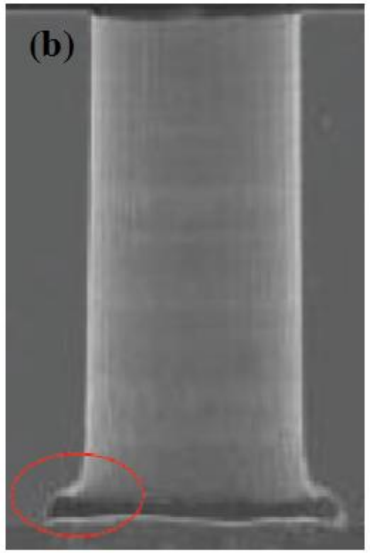


## Problems of continuous-wave driven：

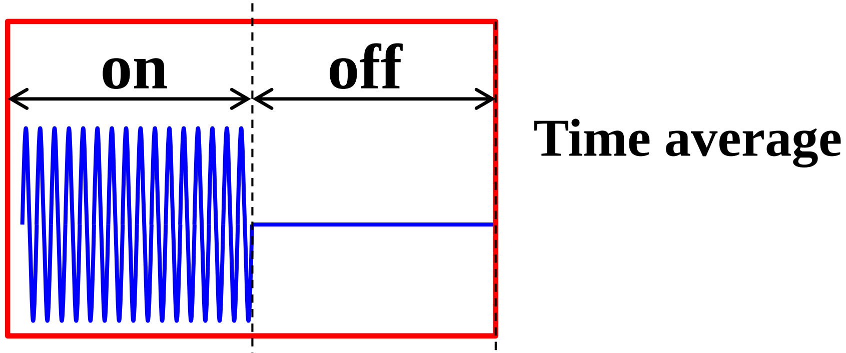
1. Surface damage due to continuous ion bombardment;
2. Damage caused by VUV photon irradiation;
3. Device demage by the charging effect on the wafer surface;

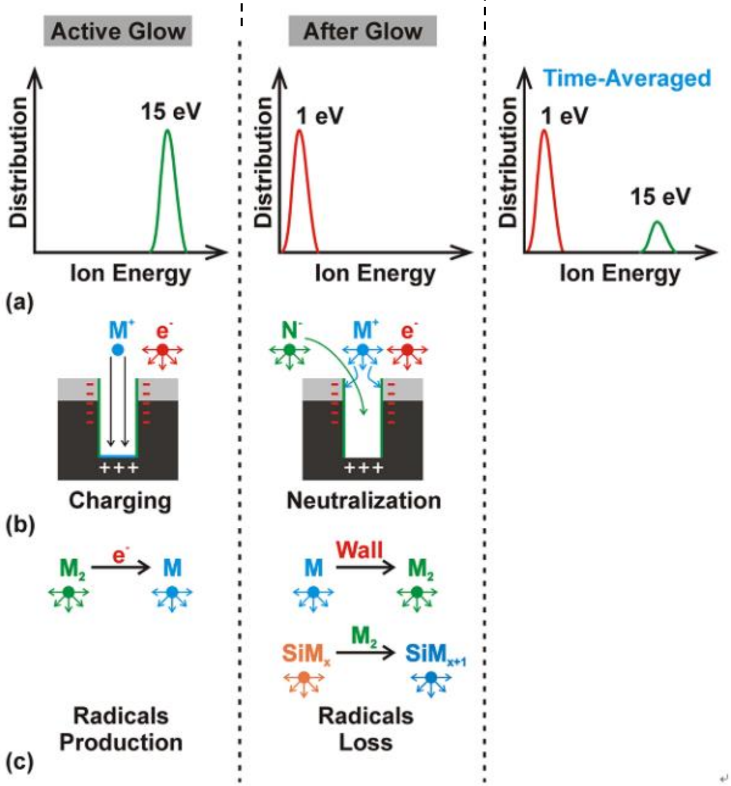
………




## Superiority of a pulsed plasma：

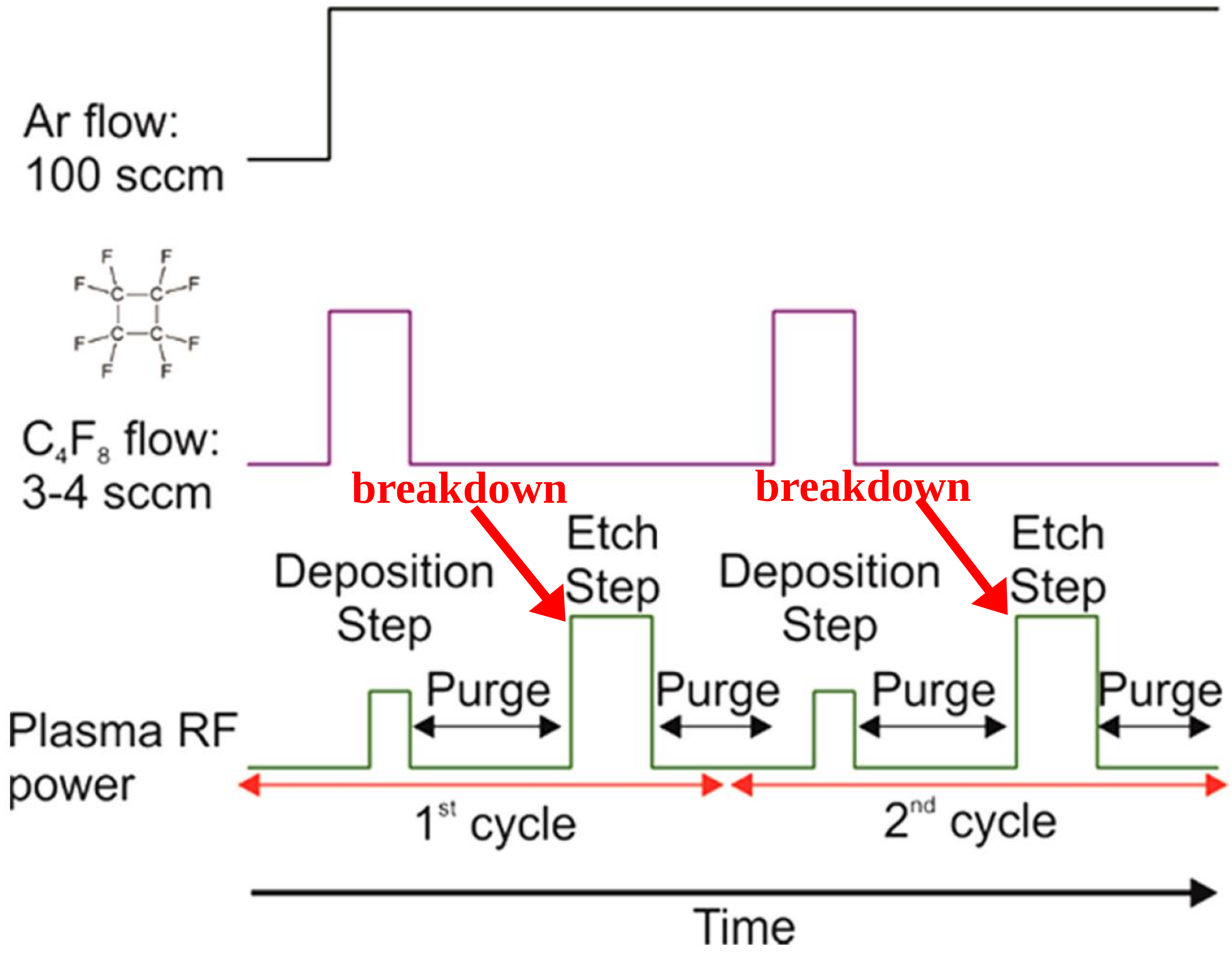


# Motivation



**Schematic of gas and plasma pulsing times employed during the ALE process.**

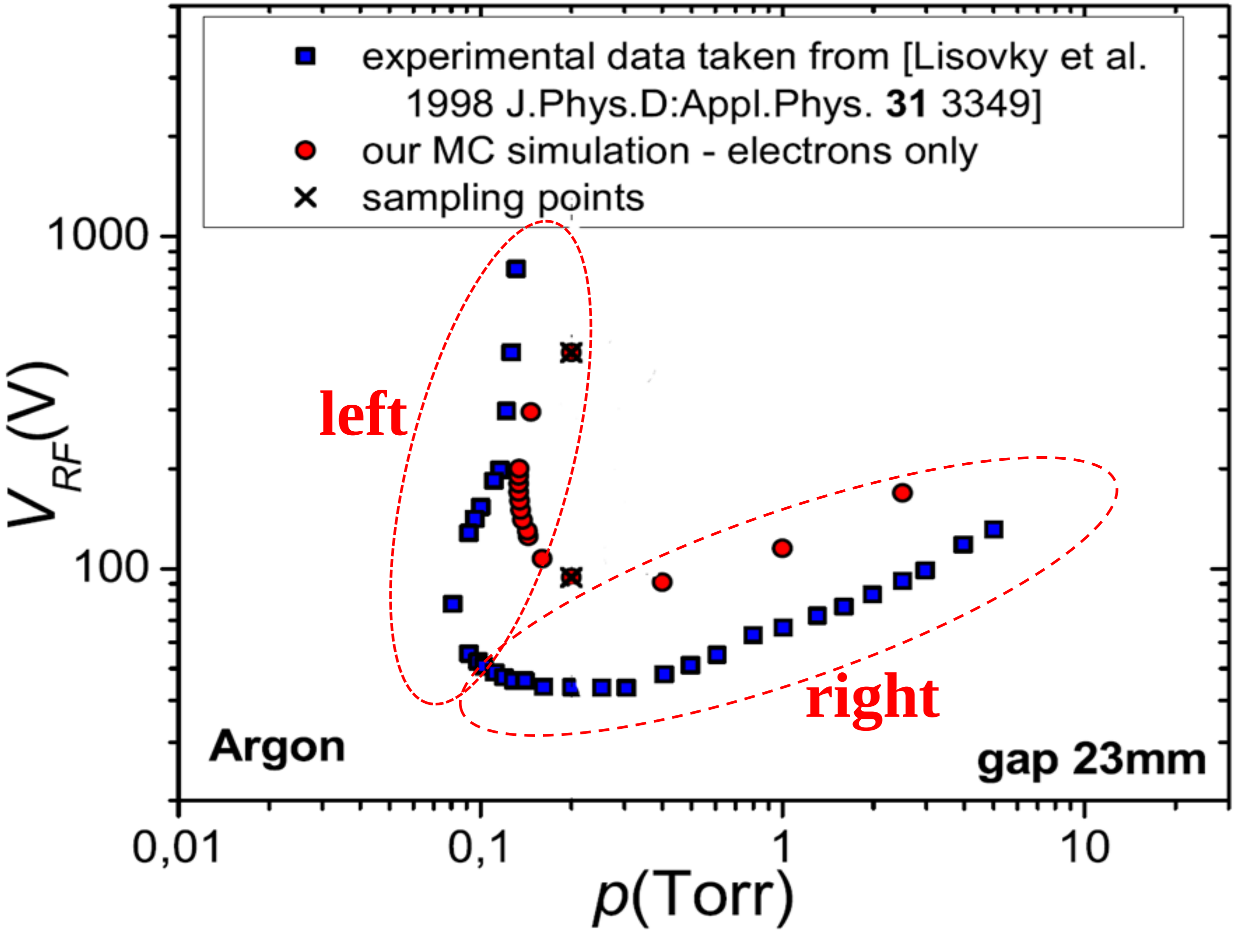



During ALE process, each re-ignition processing of a plasma, when rf power is turned on, behaves like a breakdown process, due to long afterglow duration.

Gasvoda, et. al., ACS Appl. Mater. Interfaces 2017, 9, 31067−31075

# Motivation

Argon， $f$ = 13.56 MHz， $L$ = 23 mm




**How to determine a breakdown curve?**

**Left branch：**

For a fixed voltage， increase pressure；

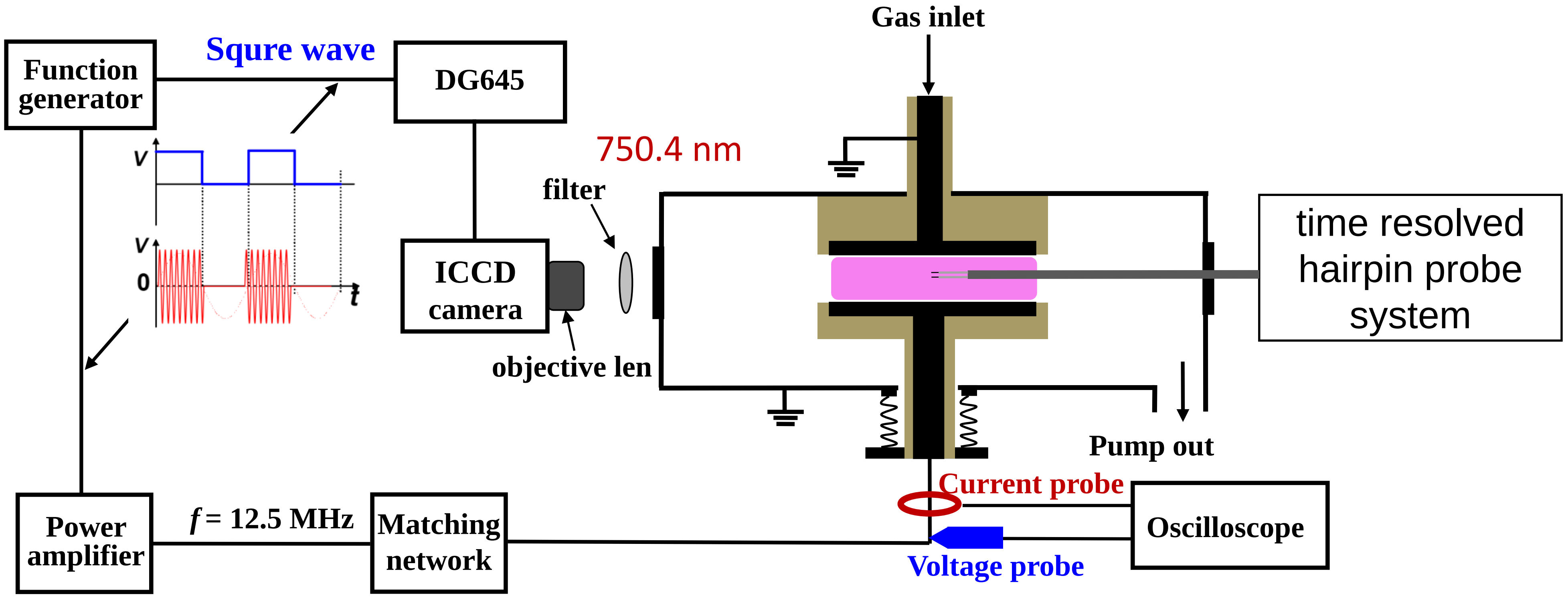
**Right branch：**

For a fixed pressure， increase voltage.

M. Puac, et al., Plasma Sources Sci. Technol. 27 (2018) 075013

# Experimental setup - breakdown






Time-resolved measurements：

1）PROES；

2）hairpin probe；

3）voltage， current probe.

Ar gas,
$p$ = 450 mTorr,
$f$ = 12.5 MHz,
pulse $f$ = 2 KHz,
on time = 100 μs,
off time = 400 μs.

# Experimental setup - breakdown



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time resolved hairpin probe system

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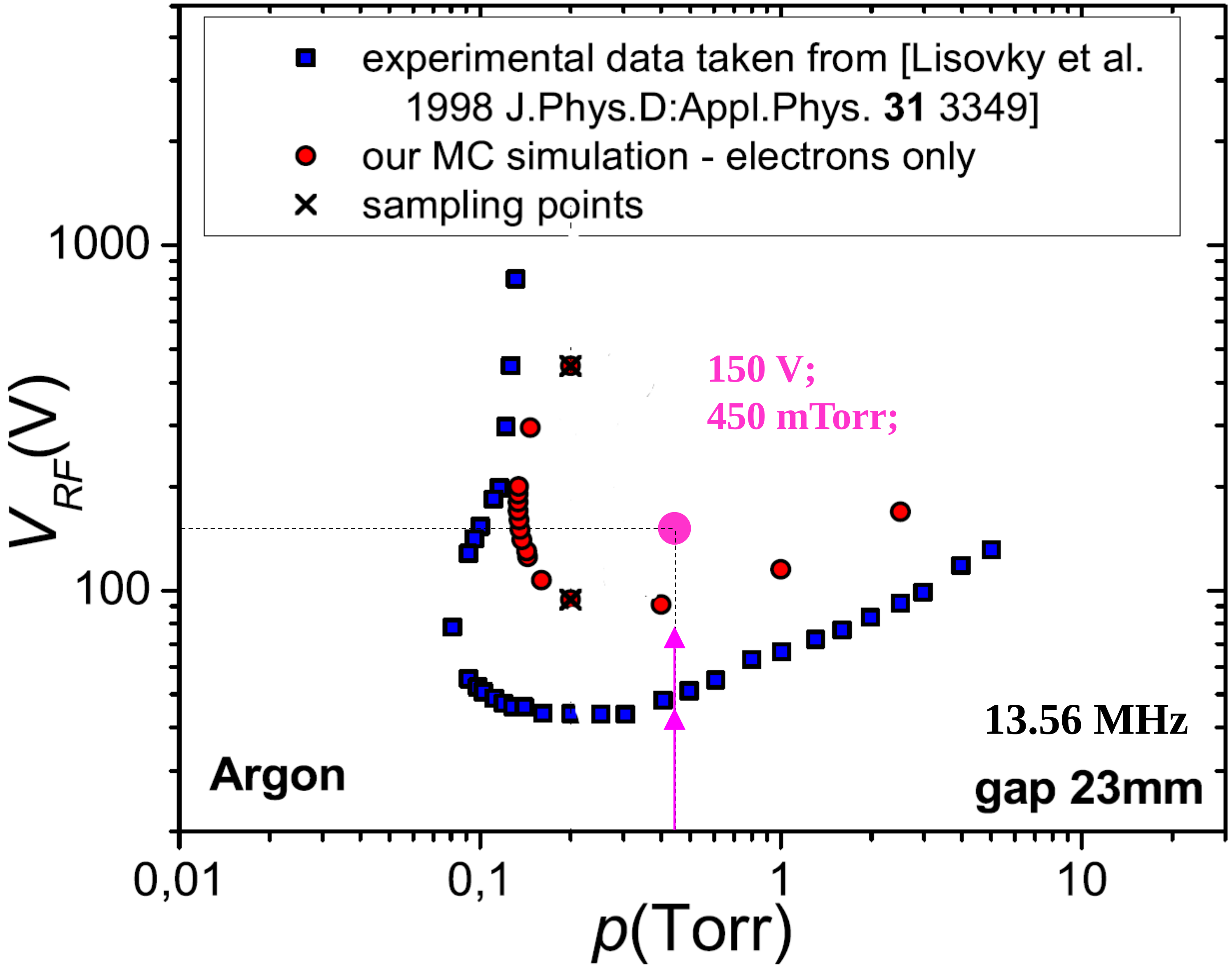


3）voltage，current probe.

Ar gas,
$p$ = 450 mTorr,
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# PIC/MCC simulations

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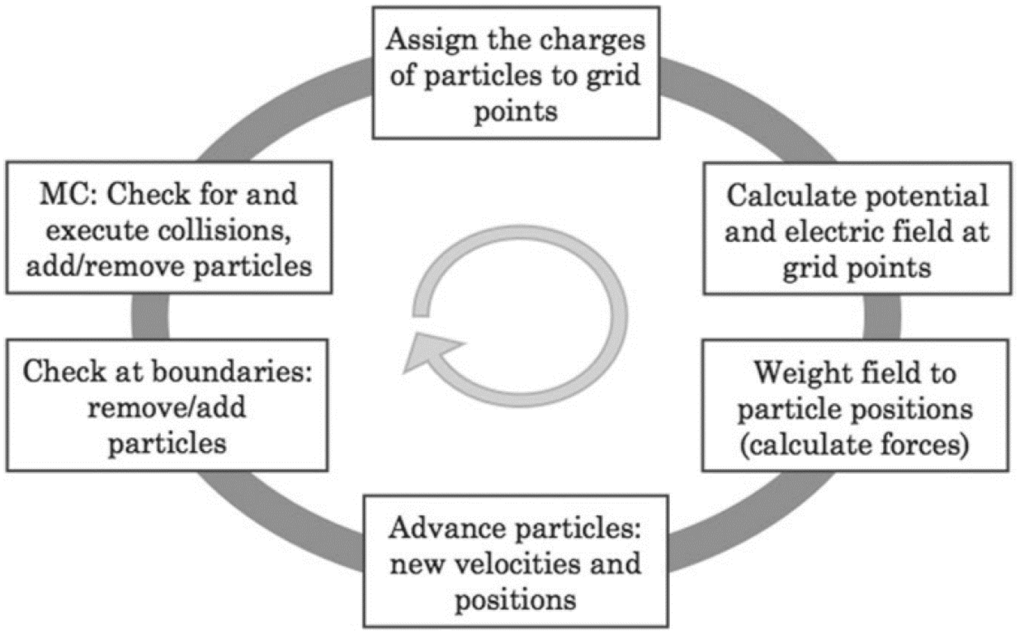
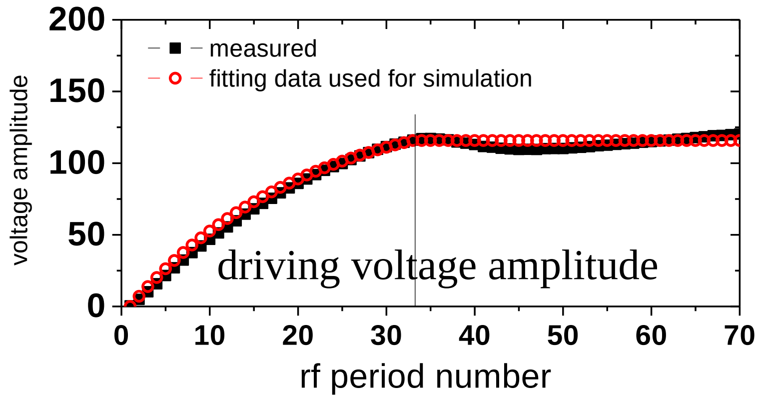
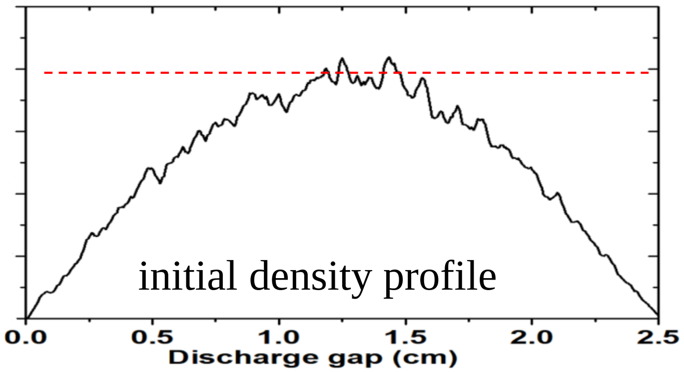
1d3v electrostatic PIC/MCC simulations




1. The 12.5 MHz driving voltage has an amplitude that results from fitting to the measured voltage waveform for the first 33 rf cycles and then is kept constant.

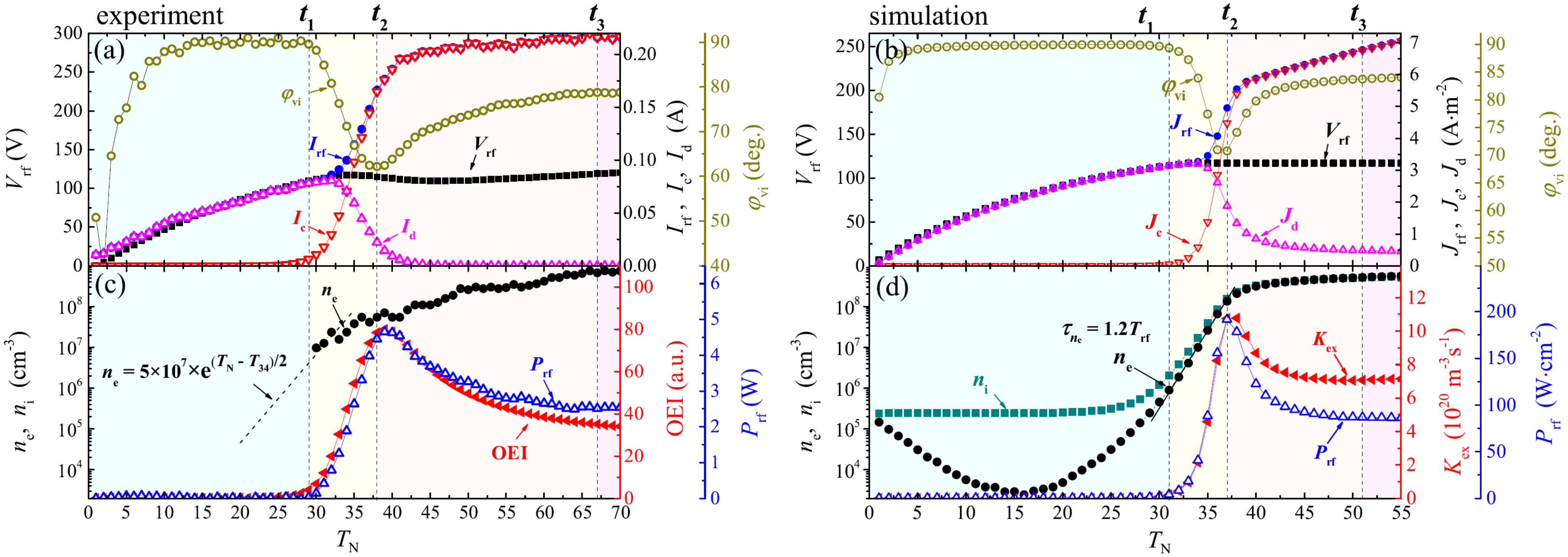
2. For the initial electron and ion densities, a diffusion profile is adopted, with a maximum of $2.5\times10^5$ cm$^{-3}$

3. Ion induced secondary electron coefficient $\gamma$ = 0.08; electron reflection coefficient=0.6

4. The simulation includes ionization, excitation and elastic scattering for electrons, and elastic collisions (with a backward and an isotropic channel) for ions.

# Electrical and macroscopic parameters

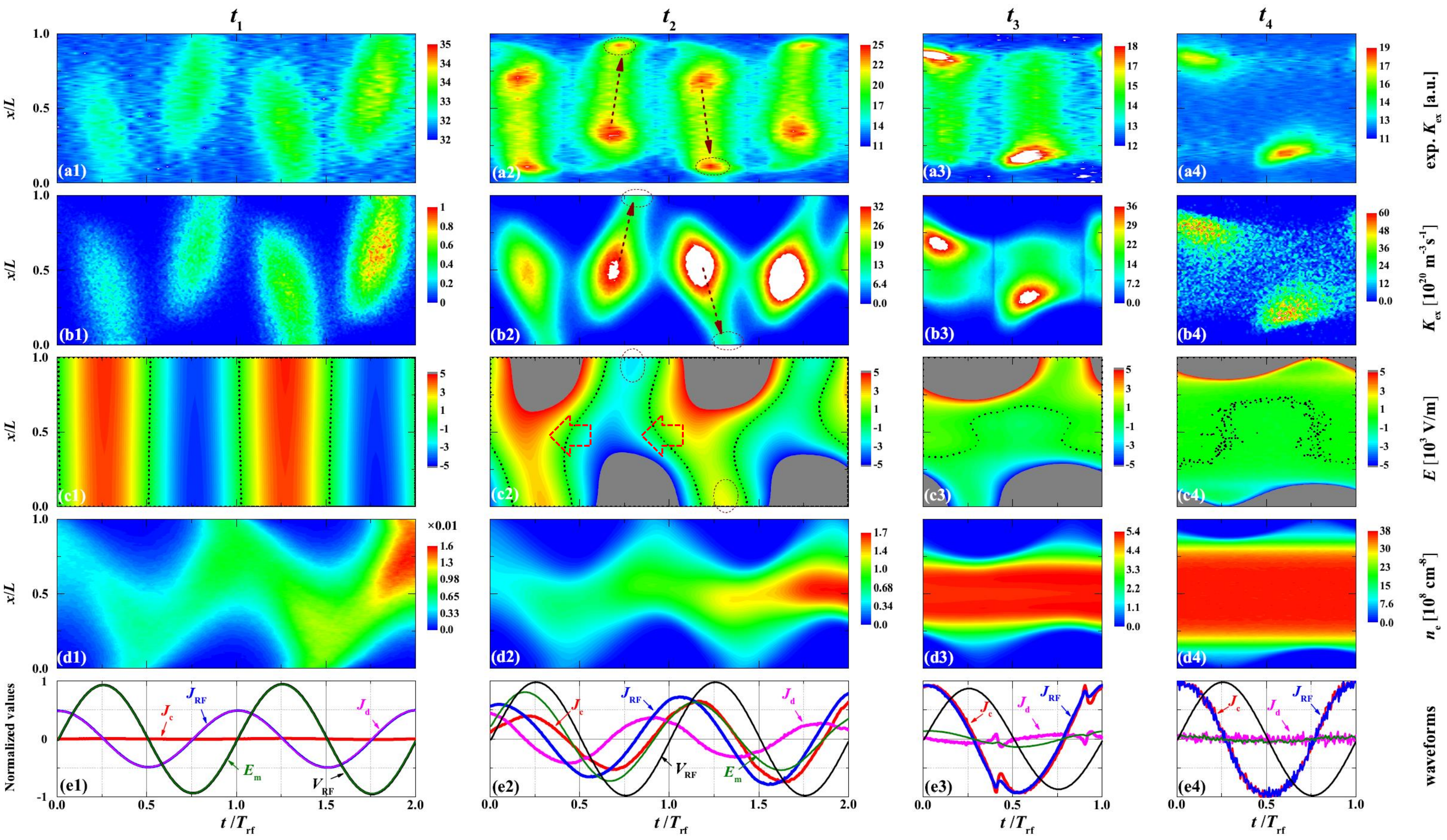
Experiment 450 mTorr, 12.5 MHz, 2.5 cm, Ar Simulation and model




| $t < t_1$ | $t_1 < t < t_2$ | $t_2 < t < t_3$ |
|---|---|---|
| **Pre-breakdown** | **Breakdown** | **Post-breakdown** |
| displacement current dominates<br>V-I phase = 90° | Conduction current increases,<br>displacement current decreases<br>V-I phase deviates from 90° | V-I phase approaches 90°<br>Parameters tend to stabilize. |

The experimental observations are very well reproduced by the simulation!

# Spatiotemporal evolution of microscopic parameters



# Temporal evolution of the current period

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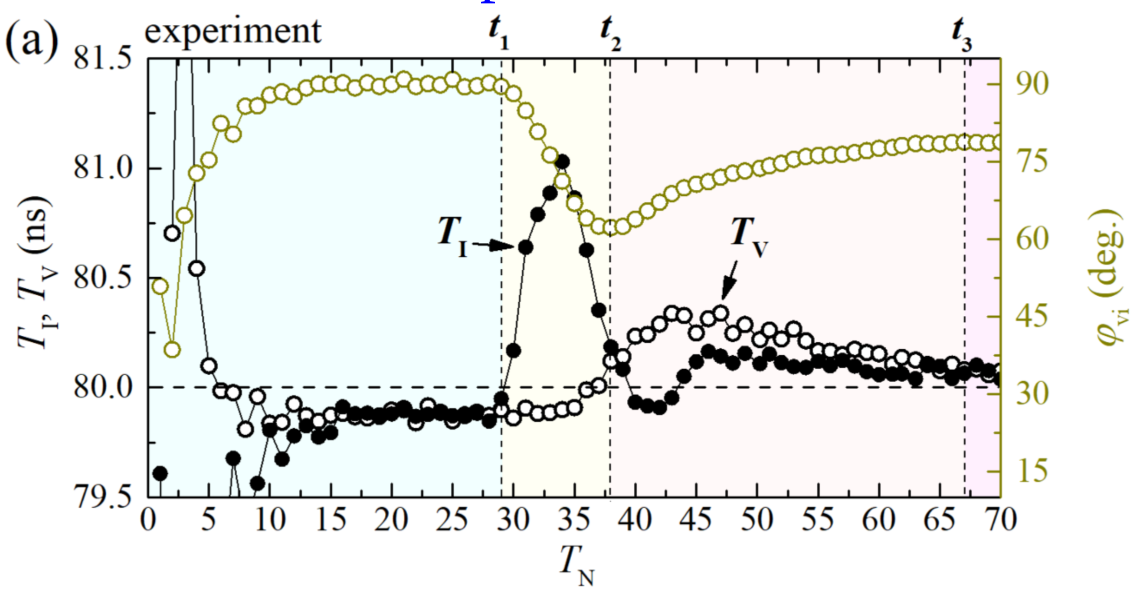
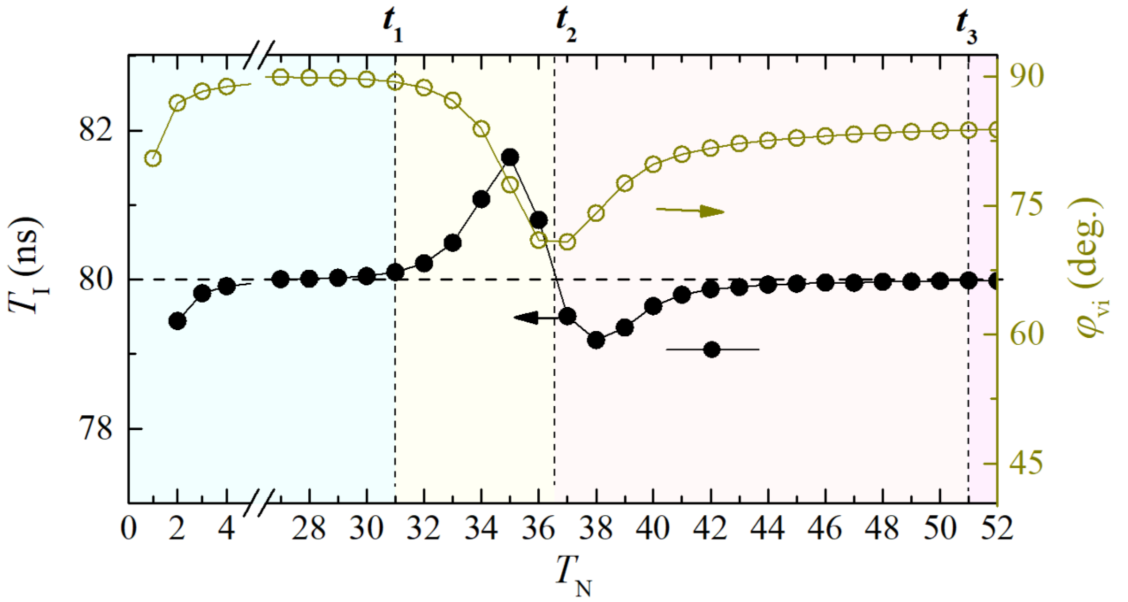
## Experiment




## Simulation and model




Definitions: $T_I$ = current period; $T_V$ = voltage period; $\varphi_{vi}$ = V-I phase

1. During the pre-breakdown phase (T15 < t < T29), $T_I \approx T_V \approx$ 80 ns and $\varphi_{vi} = 90^\circ$.

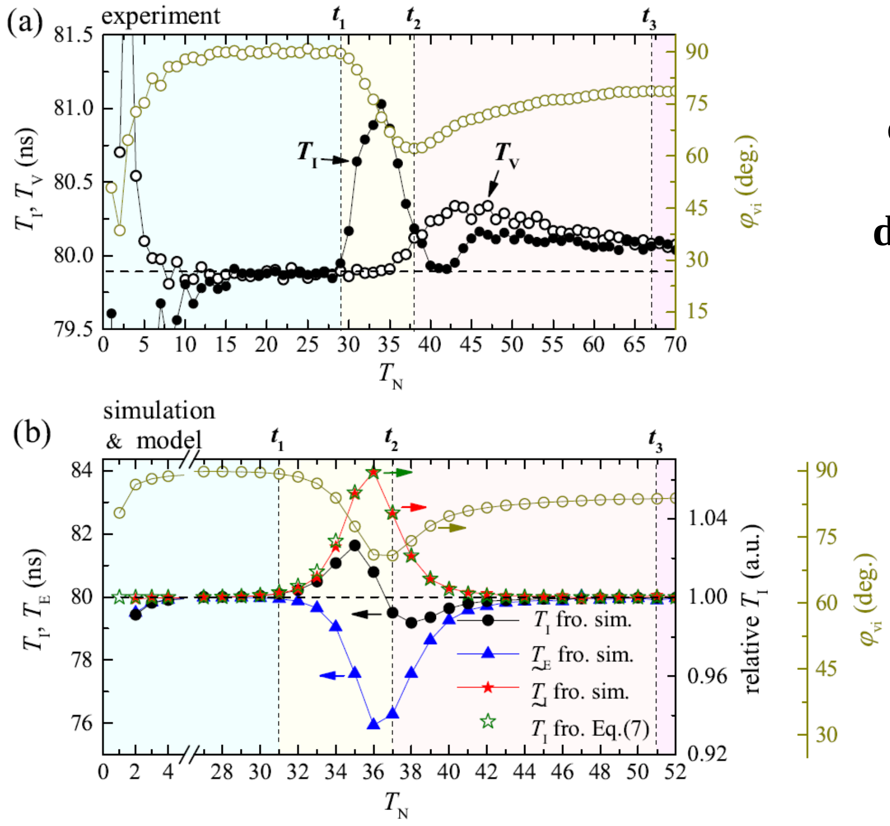
2. During the breakdown phase (t1 < t < t2), $T_I > T_V$ leads to a decrease of $\varphi_{vi}$ from 90° to $\varphi_{min}$.

3. During the post-breakdown phase (t > t2), $T_I < T_V$ leads to a increase of $\varphi_{vi}$ from $\varphi_{min}$ to 90° .

The computed $T_I$ also exhibits a ”rise-decay-rise” trend from t1 to t3 around $T_V$ =80 ns;

# Analytical mode of current period






$$\tau_{n_e} = 1.2\,T_{rf}$$

$$T_{max} = T_{35.8}$$

## Analytical mode of current waveform (x=L/2)：

**conduction current:** $J_c = \sigma E_m = \sigma E_A \sin(\omega t),$

**displacement current:** $J_d = \epsilon_0 \partial_t E_m = \epsilon_0 \omega E_A \cos(\omega t) + \cancel{\epsilon_0 \partial_t E_A \sin(\omega t)}$

**total rf current:** $\boxed{J_{rf}(t) = J_c(t) + J_d(t) = \sqrt{J_{Ac}^2(t) + J_{Ad}^2(t)}\,\sin[\omega t + \varphi(t)]}$

$$\begin{cases} \varphi(t) = \tan^{-1}[\eta(t)] \\ \eta = \dfrac{J_{Ad}}{J_{Ac}} = \dfrac{\omega \nu_m \epsilon_0 m_e}{e^2 n_e} \end{cases}$$

Differentiating $\varphi(t)$ with respect to the time step of $T_{rf}$ yields

**Current period:** $T_I(T_N) = T_E(T_N)\{1 - \boxed{\dfrac{\varphi(t+0.5T_{rf}) - \varphi(t-0.5T_{rf})}{2\pi}}\}$, with $T_E = 2\pi/\omega$

**relative current period:** $\tilde{T}_I(T_N) = \dfrac{T_I(T_N)}{T_E(T_N)} = 1 - \dfrac{\partial_t \varphi(t) T_{rf}}{2\pi}$

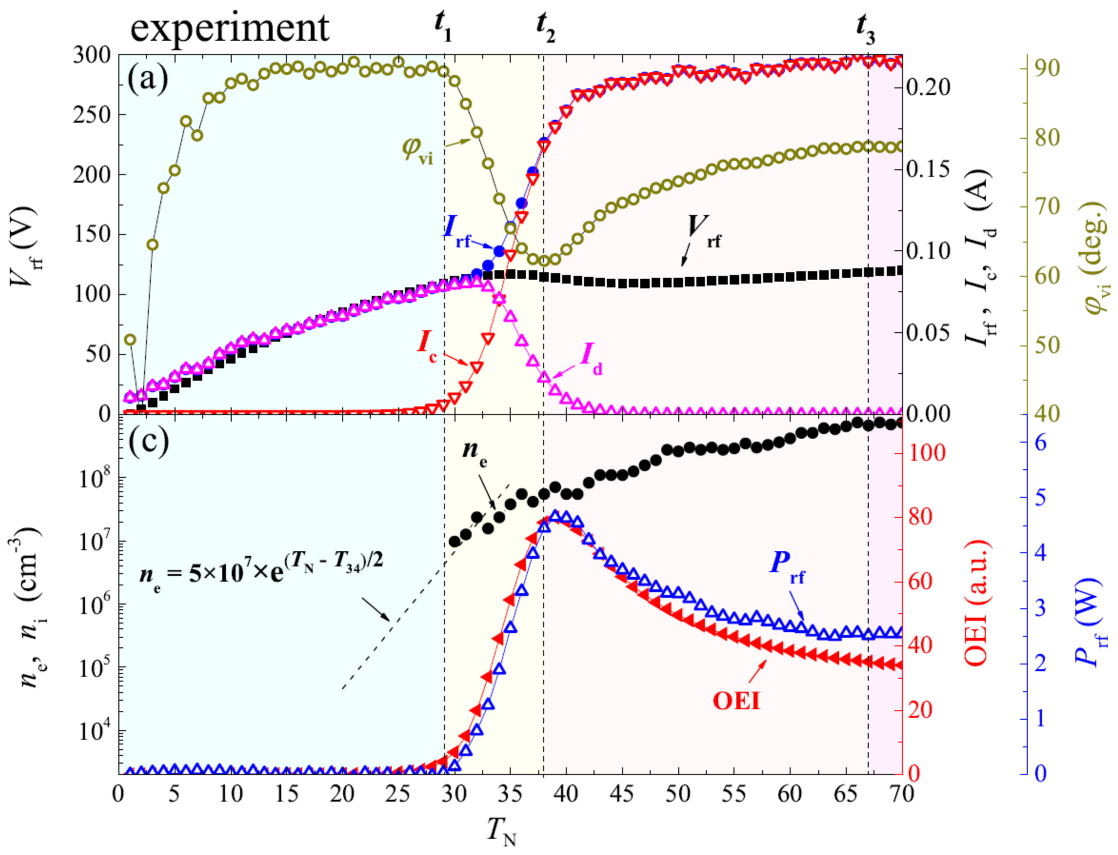
We made two assumptions: $n_e(t)$ ~ exponential growth; $\nu_{en}$ ~ constant

**phase angle :** $\varphi(t) = \tan^{-1}[\eta(t)] = \tan^{-1}[e^{(t_{max}-t)/\tau_{n_e}}]$, with $\tau_{n_e}$ is time constant of $n_e(t)$

**relative current period:** $\tilde{T}_I(T_N) = 1 + \dfrac{T_{rf}}{2\pi \tau_{n_e}} \cdot \dfrac{e^{(T_{max}-T_N)\cdot T_{rf}/\tau_{n_e}}}{1 + e^{2(T_{max}-T_N)\cdot T_{rf}/\tau_{n_e}}}$

# Determination of $I_c$ and $I_d$ amplitude






$$\begin{cases} J_{rf} = J_c + J_d = \sqrt{J_{Ac}^2 + J_{Ad}^2}\sin[\omega t + \varphi(t)] \\ \varphi(t) = \tan^{-1}[\eta(t)] = \tan^{-1}[e^{(t_{max}-t)/\tau_{ne}}] \\ \eta = \frac{J_{Ad}}{J_{Ac}} \end{cases}$$

$$I_c(T_N) = \frac{I_{rf}(T_N)}{\sqrt{1+\eta^2(t)}}, I_d(T_N) = \frac{\eta(t) I_{rf}(T_N)}{\sqrt{1+\eta^2(t)}}$$

$$\text{with } \tau_{ne} = 2T_{rf} \text{ and } T_{max} = T_{34}$$

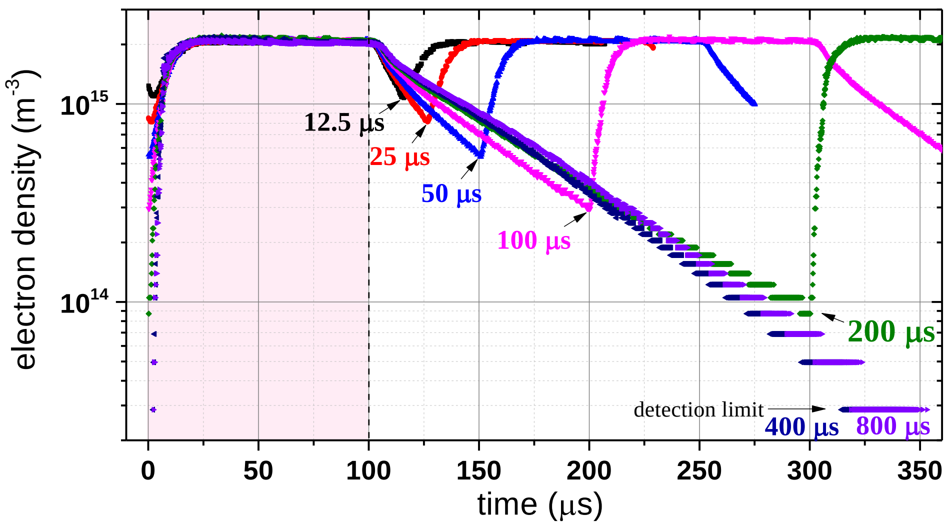
time constant of the exponential growth
of measured excitation rate

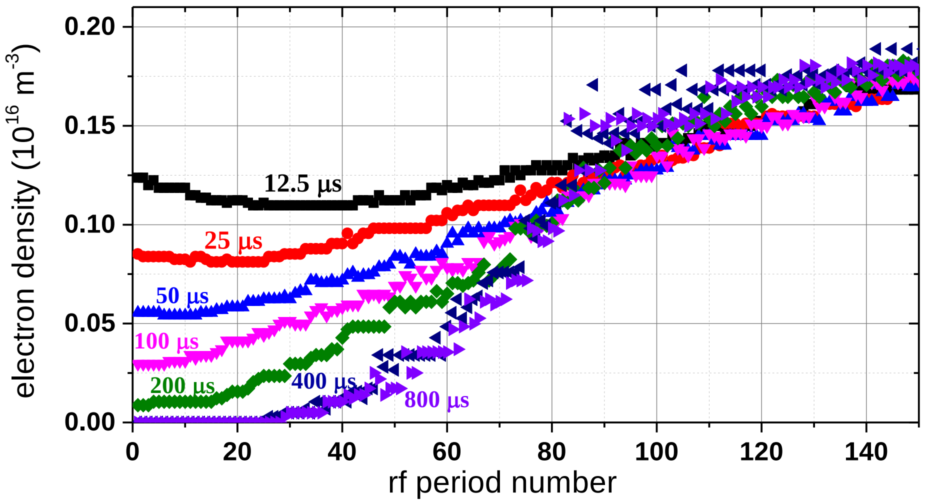
# Pulse-off time effect

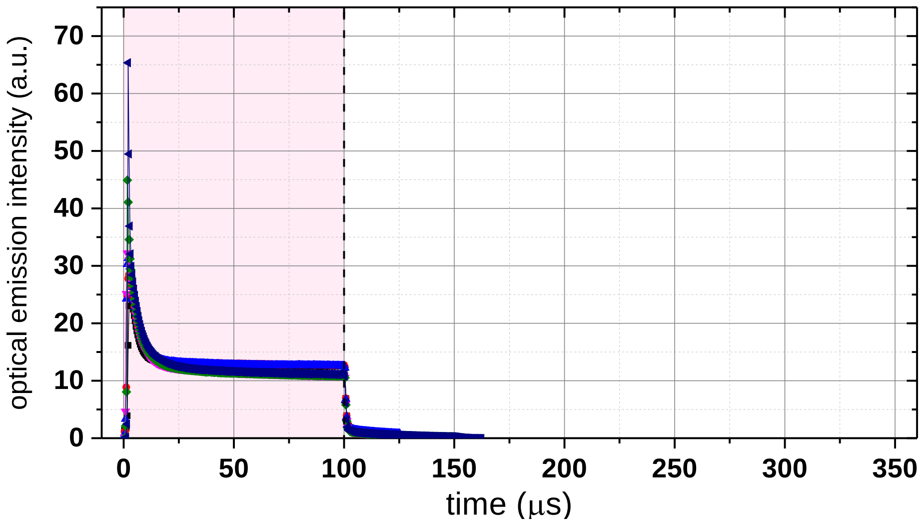
# Afterglow duration effect: $n_e$ & light intensity

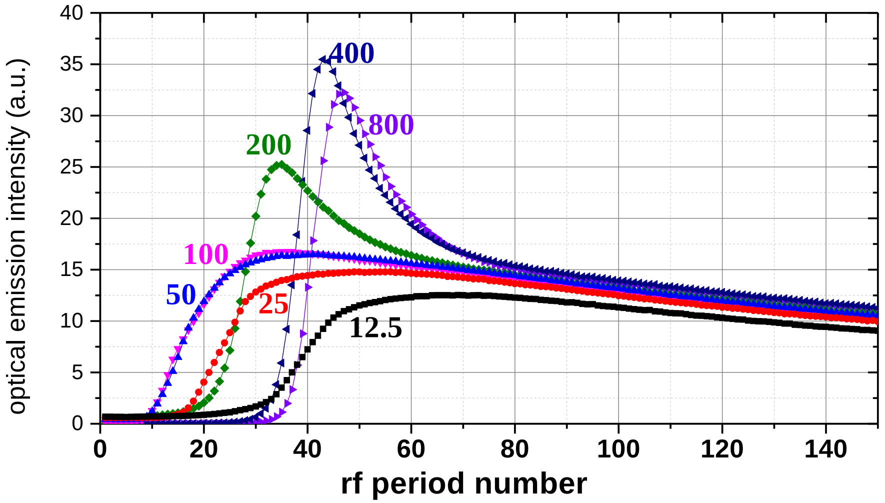
450 mTorr, 12.5 MHz, 2.5 cm, Ar

on time



# light intensity & power deposition

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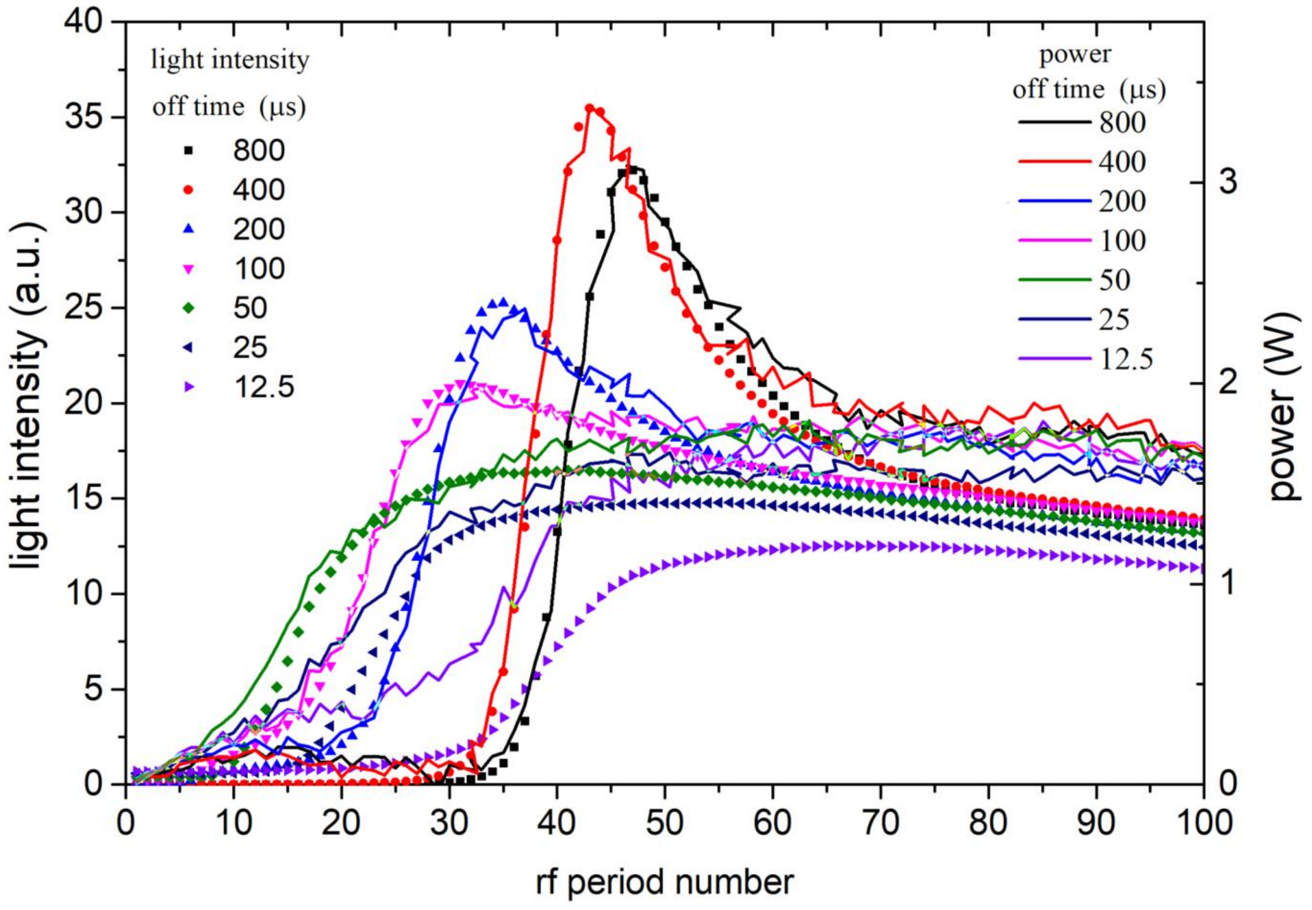
450 mTorr，12.5 MHz，2.5 cm，Ar



# V-I phase angle

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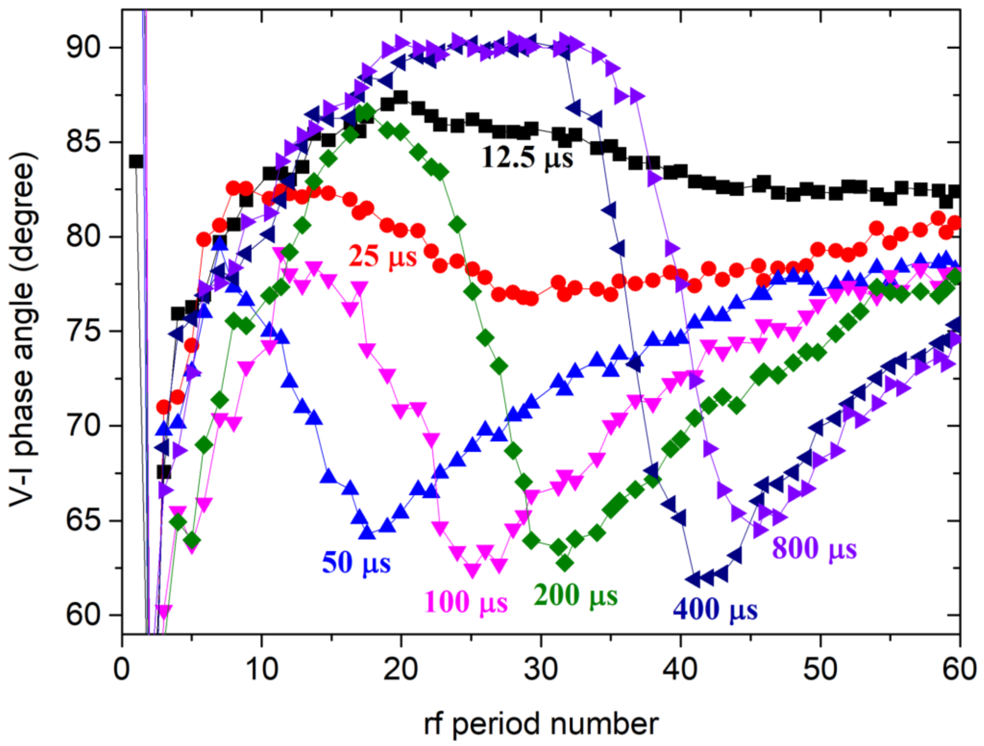
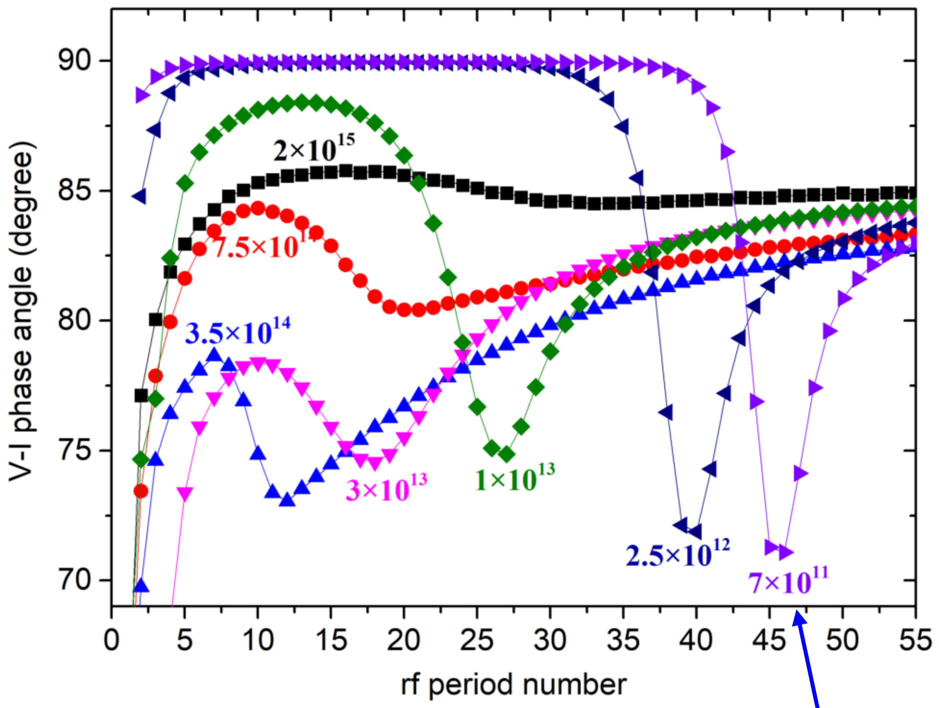
450 mTorr， 12.5 MHz， 2.5 cm， Ar

**Experiment**




**PIC Simulation**




Initial density / m^3

$$P_{\mathrm{rf}} = 1/2\ V_{\mathrm{rf}} \cdot I_{\mathrm{rf}} \cdot cos(\varphi_{\mathrm{vi}})$$

# Conclusions and outlook

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## Conclusion：

1. The time evolution of electrical and plasma parameters, and their intrinsic correlations during gas breakdown have been analyzed in a pulsed capacitive rf discharge in argon.

2. PIC/MCC simulations and an analytical model aided the understanding of the experimental observations.

3. We found that the system goes through different modes of electron power absorption, which were found to be highly correlated with the rapid impedance change.

4. The variation of relative V-I phase is caused by the time-dependent current period, which is related to the time constant of the exponentially increasing electron density via a current waveform model.

5. We are studying the effect of the afterglow duration on the re-ignition of a pulsed ccrf discharge.

## outlook：

1. Breakdown process under various conditions, and especially at relatively low pressures.

2. Breakdown in electronegative gases, e.g., CF4, O2…

3. Spatio-temporal evolution of a breakdown process.