Streamer discharge instabilities under repetitive nanosecond pulses

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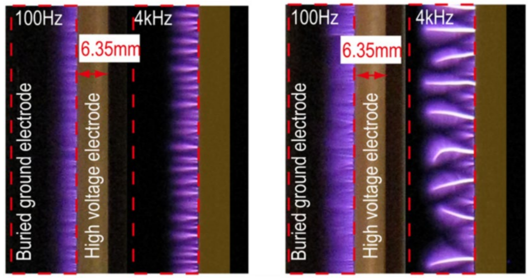
Outline

- 01 Background
- 02 Discharge instability coupled with pulsed power supply
- 03 Discharge instability affected by gas flow
- 04 Concluding remarks

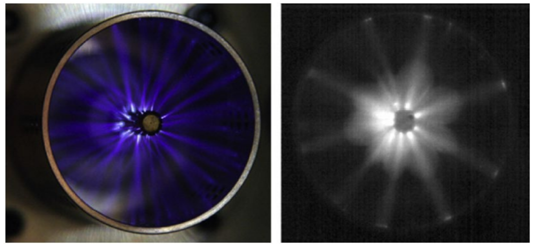
Background: Nanosecond repetitively pulsed discharge

Nanosecond repetitively pulsed (NRP) discharge plasma: high frequency pulses

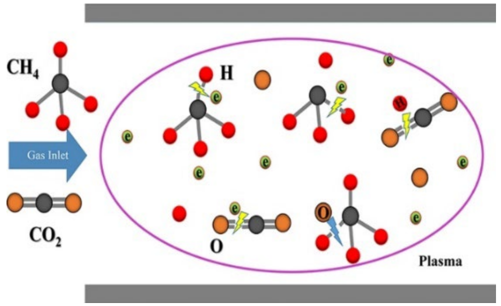
- Exclusive capabilities (overvoltage ratio) for non-equilibrium plasma-assisted applications



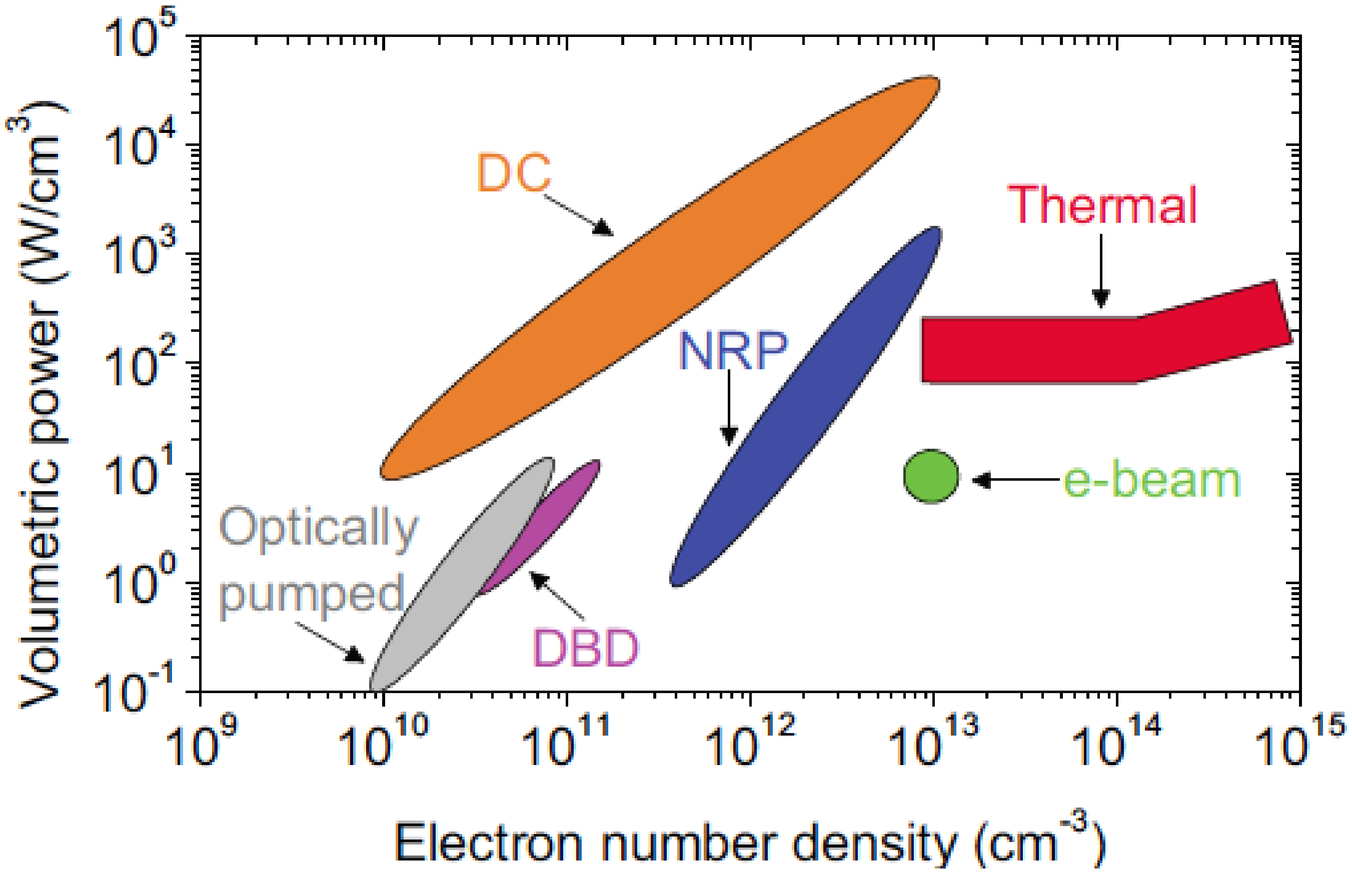
Surface DBD flow actuator



Plasma-assisted combustion



Methane dry reforming

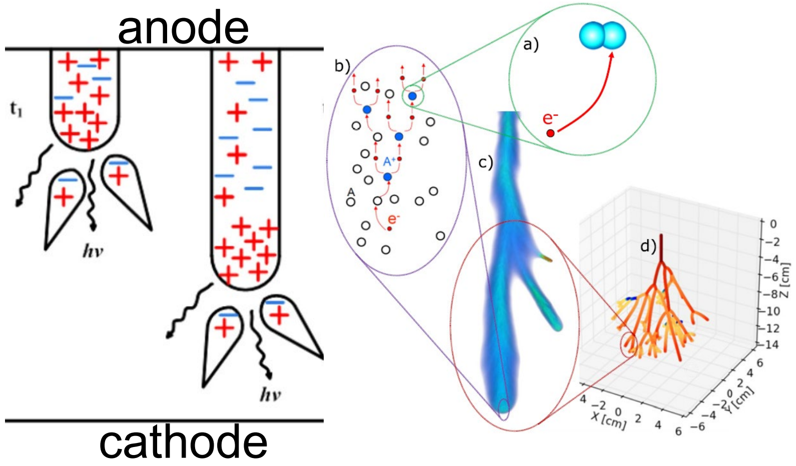


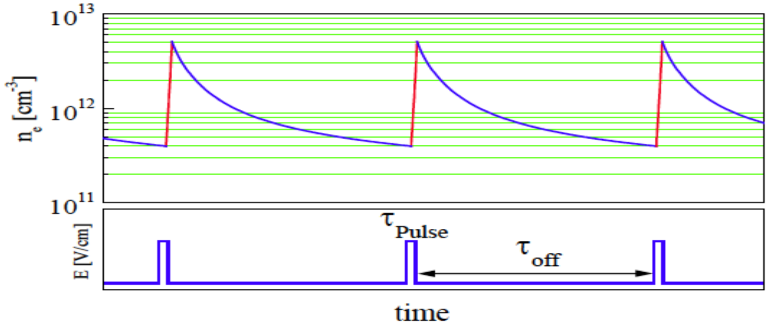
[1] Takashima, PSST, 2011, 20, 055009. [2] Wang, Applied Energy, 2019, 243: 132-144. [3] D. Rusterholtz, PhD thesis, 2012.

Background: Why we prefer NRP streamer discharge

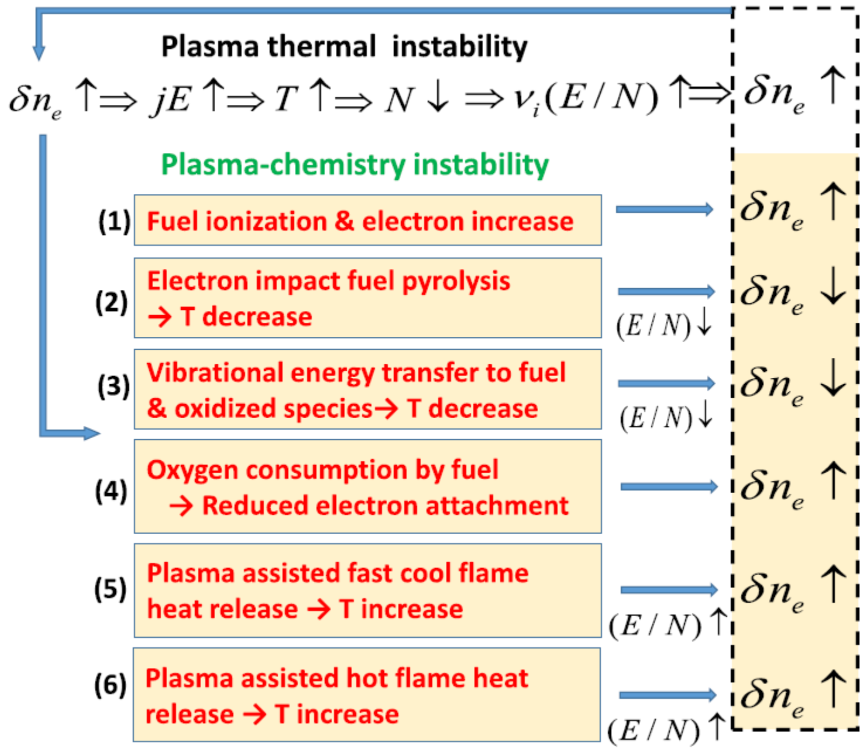
- **Nanosecond repetitively pulsed streamer discharges have many advantages over conventional medium-frequency AC and microsecond pulse driven plasma!**

Higher *E*/*N*, higher n_e





Rich physical and chemical processes, but more complicated



Plasma thermal instability

$$\delta n_e \uparrow \Rightarrow jE \uparrow \Rightarrow T \uparrow \Rightarrow N \downarrow \Rightarrow \nu_i(E/N) \uparrow \Rightarrow \delta n_e \uparrow$$

Plasma-chemistry instability

(1) Fuel ionization & electron increase → $\delta n_e \uparrow$

(2) Electron impact fuel pyrolysis → T decrease → $(E/N)\downarrow$ $\delta n_e \downarrow$

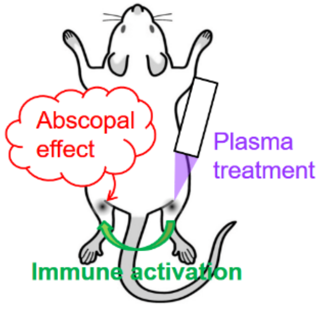
(3) Vibrational energy transfer to fuel & oxidized species → T decrease → $(E/N)\downarrow$ $\delta n_e \downarrow$

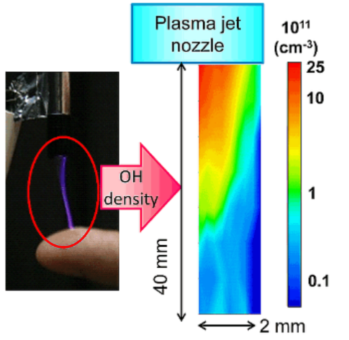
(4) Oxygen consumption by fuel → Reduced electron attachment → $\delta n_e \uparrow$

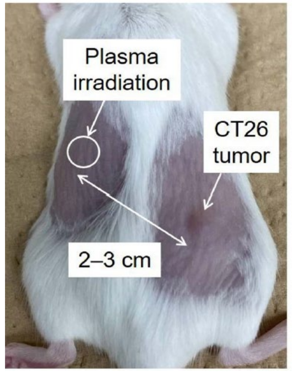
(5) Plasma assisted fast cool flame heat release → T increase → $(E/N)\uparrow$ $\delta n_e \uparrow$

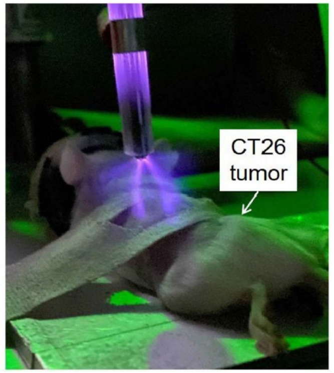
(6) Plasma assisted hot flame heat release → T increase → $(E/N)\uparrow$ $\delta n_e \uparrow$

Novel applications: plasma medicine





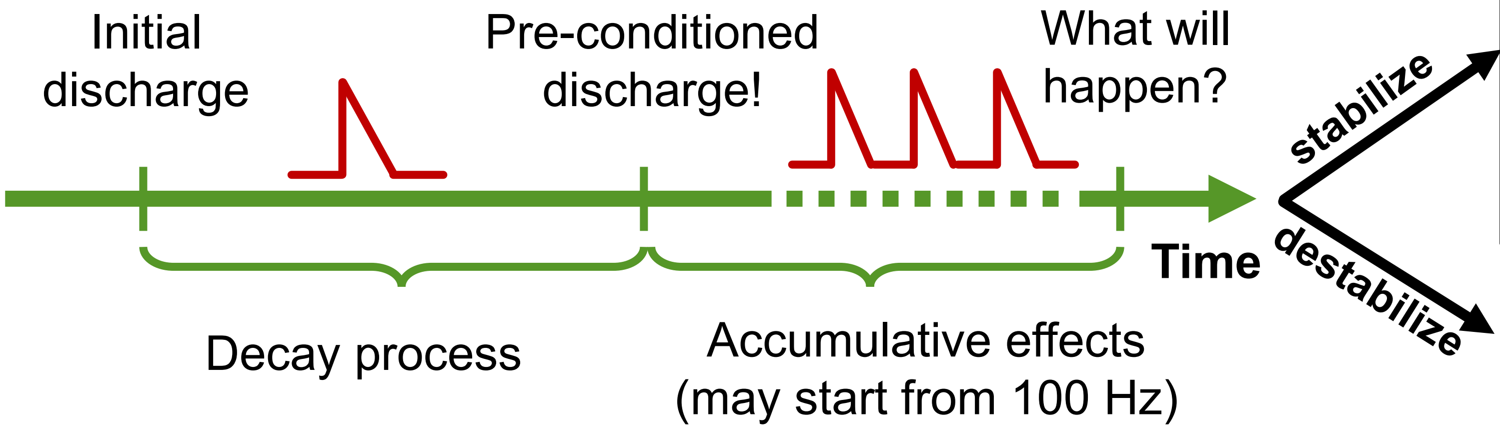


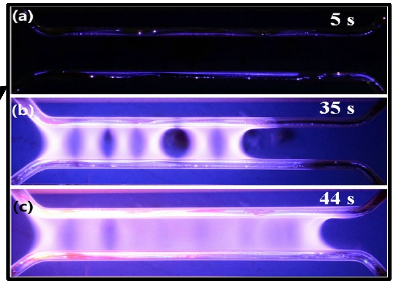


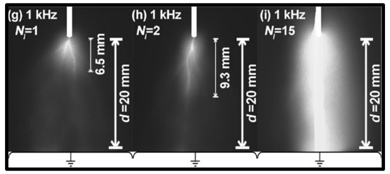
[1] Nijdam S, PSST, 2020, 29, 103001. [2] Rousso A, PSST, 2020, 29, 105012. [3] Jinno R, JPD, 2022, 55, 17LT01

Background: NRP streamer discharge is “memorized”

Discharge evolutions under repetitive pulses (especially at high PRF!)



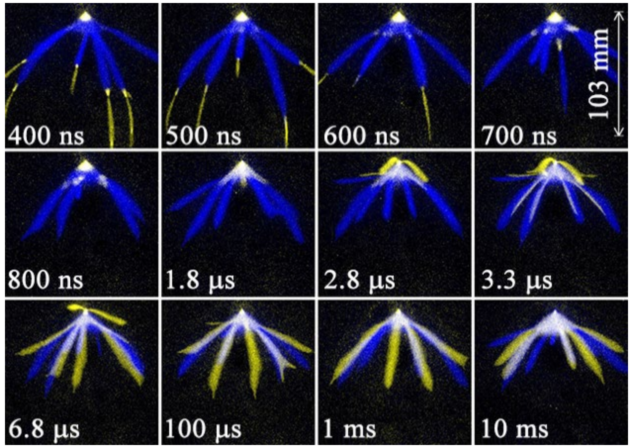


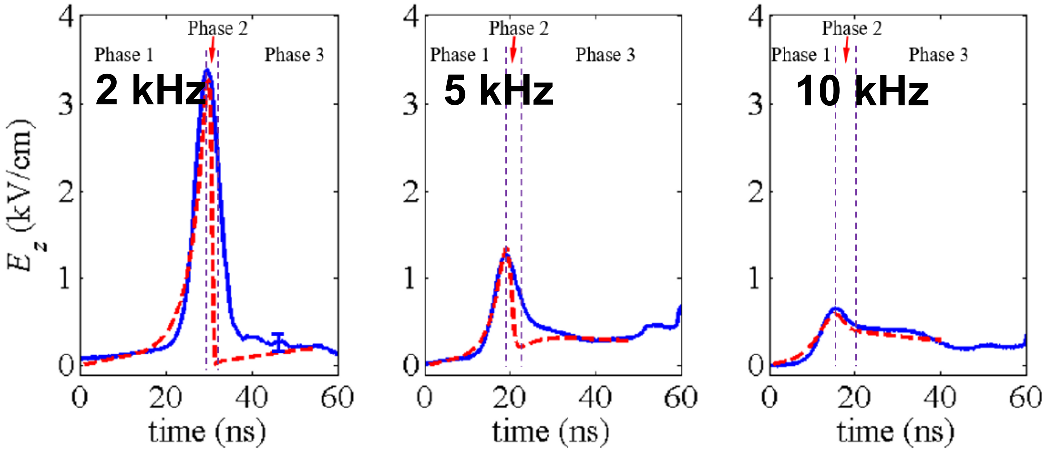


Discharge instabilities ≠ stochastics

Memory effect agents with different influential mechanisms

- Metastable species
- Residual electrons
- Space charges
- Residual conductivity
- Surplus heat
- …



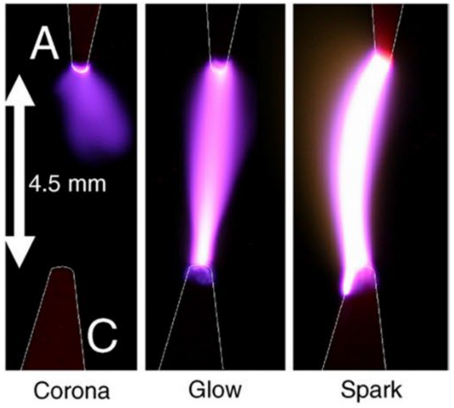


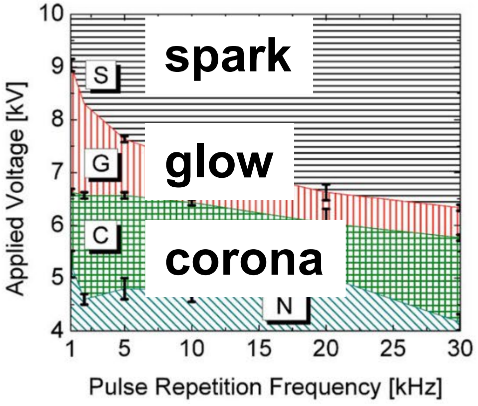
[1] Qi F, APL, 2019, 115, 194101. [2] Nijdam S, PSST, 2014, 23, 025008. [3] Huang B, JPD, 2018, 51, 225202.

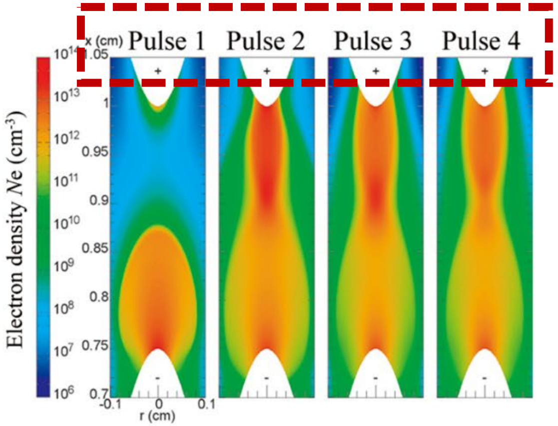
Background: low-temperature plasma instabilities

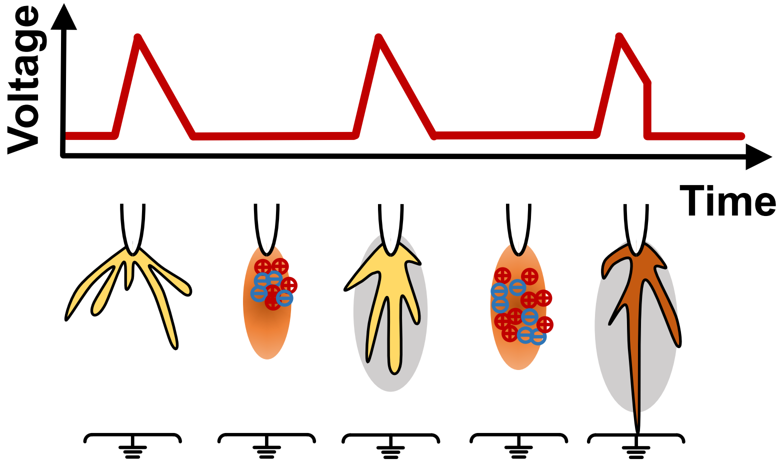
One instability example: NRP discharge regime transition

- Fundamental parameter, corona-glow-spark transition, voltage parameter dependences, “binary” operation



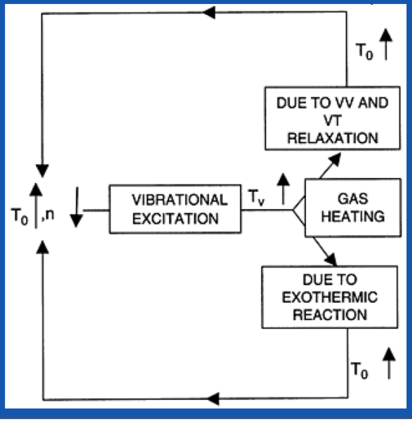






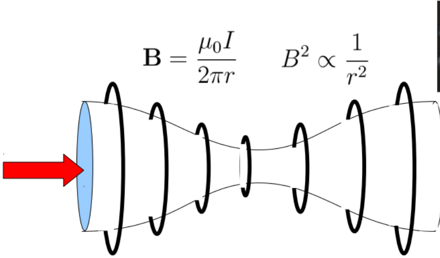
Low-temperature plasma instabilities

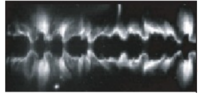
- Thermal-ionization instability
- Chemical reactions (e.g., exothermic reactions)
- Strong coupling with environment factors

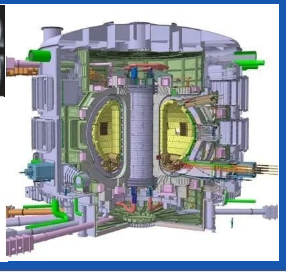


High-temperature plasma instabilities

- Drift wave instabilities
- Rayleigh-Taylor instability



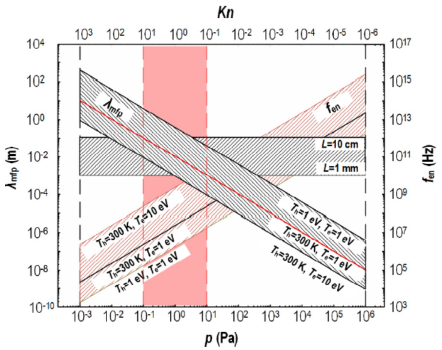




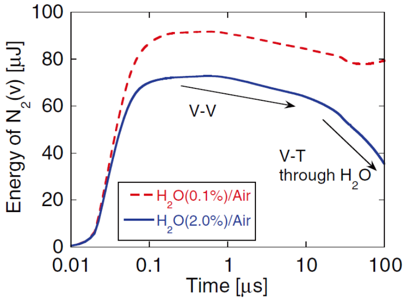
Background: NRP streamer instabilities uniqueness

Complicated discharge evolution

Boundaries: open air, humidity



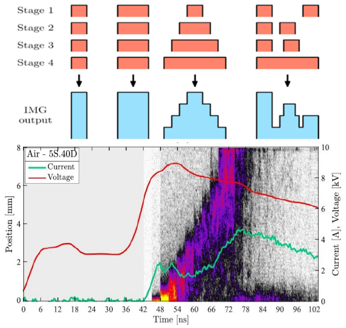
$f_{en} > f_{pe}$ collision-dominated plasmas



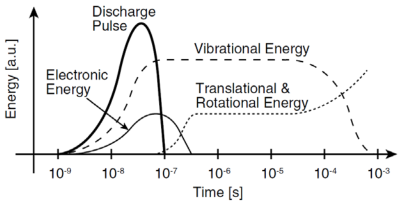
humidity→ heavy species and fast heat release

Coupling with pulsed power supply

Modulated by power supply



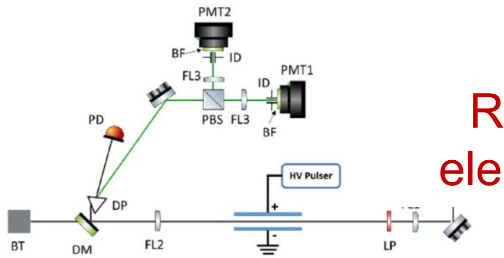
Coupling mechanisms plasma→pulsed power supply



Energy transfer (e.g., V-T process)

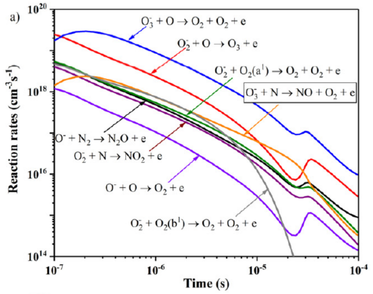
Opaque plasma parameters

Parameter diagnostics



EFISH

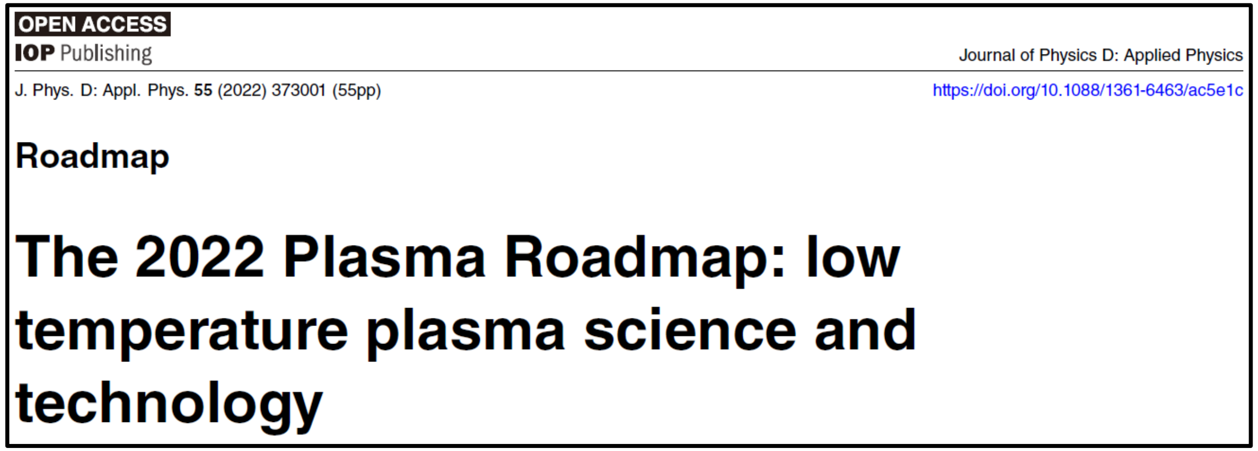
Reduced electric field



Reaction mechanisms with discharge instability

[1] Li H, Physics Reports, 2018, 770-772. [2] Komuro, PSST, JPD,2014, 47, 155202.
[3] Huiskamp, JPD, 2022, 55, 024001. [4] Chng TL, Optics Letters, 2020, 45, 1942-1945

Motivations: NRP discharge instability and modulation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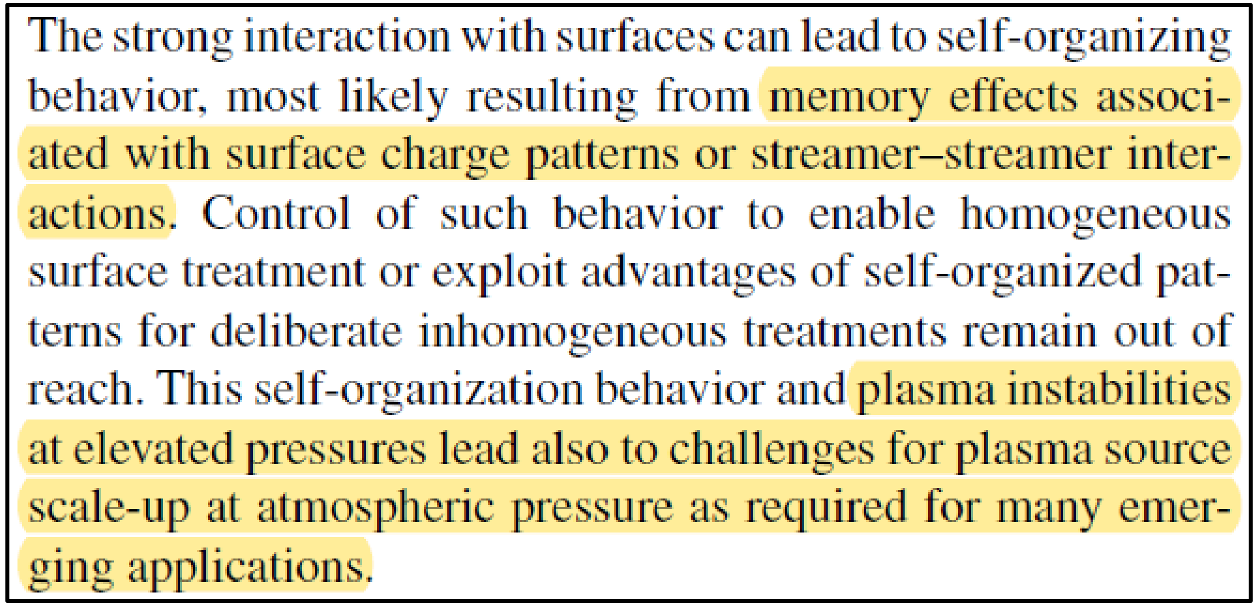
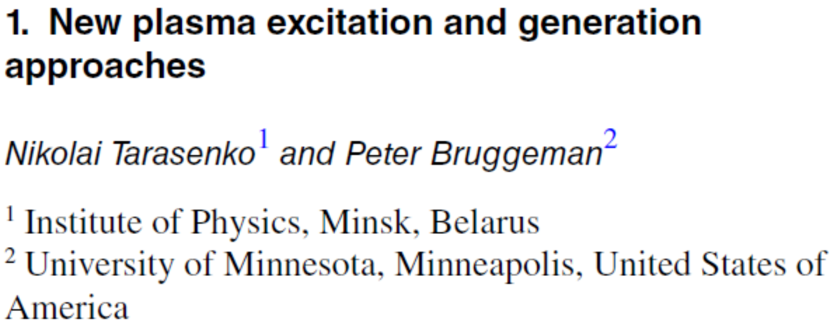
Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **55** (2022) 373001 (55pp)
https://doi.org/10.1088/1361-6463/ac5e1c

Roadmap

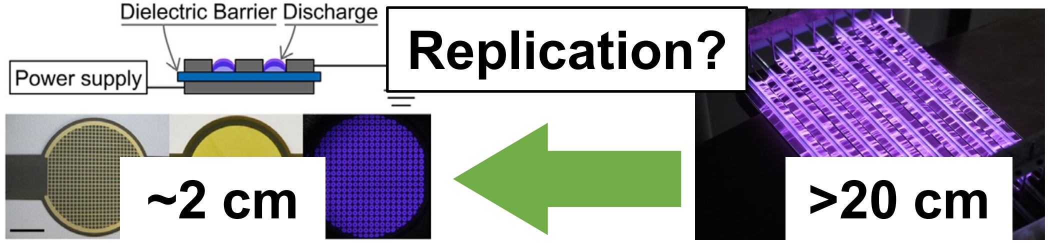
The 2022 Plasma Roadmap: low temperature plasma science and technology

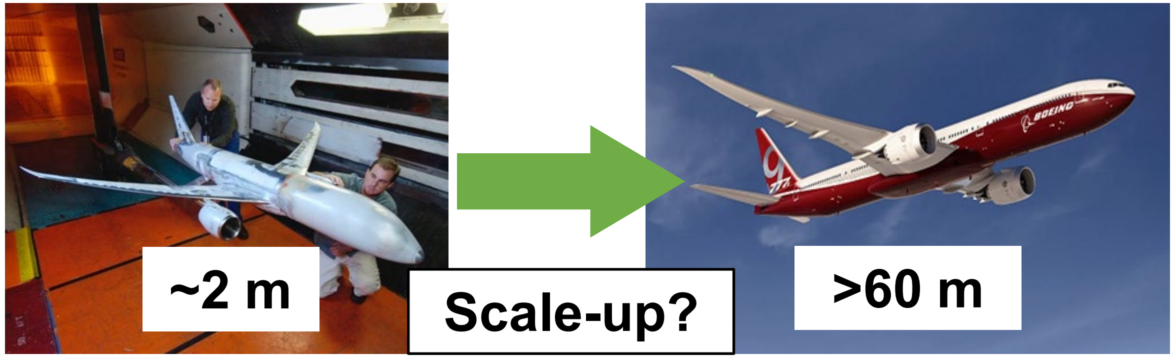

The strong interaction with surfaces can lead to self-organizing behavior, most likely resulting from memory effects associated with surface charge patterns or streamer–streamer interactions. Control of such behavior to enable homogeneous surface treatment or exploit advantages of self-organized patterns for deliberate inhomogeneous treatments remain out of reach. This self-organization behavior and plasma instabilities at elevated pressures lead also to challenges for plasma source scale-up at atmospheric pressure as required for many emerging applications.


1. New plasma excitation and generation approaches

Nikolai Tarasenko[1] *and Peter Bruggeman*[2]

[1] Institute of Physics, Minsk, Belarus
[2] University of Minnesota, Minneapolis, United States of America





Scaled-down model

Scaled-up application

[1] B Boekema *et al* 2016 *JPD.* **49** 044001

Outline

01 Background

02 Discharge instability coupled with pulsed power supply

03 Discharge instability affected by gas flow

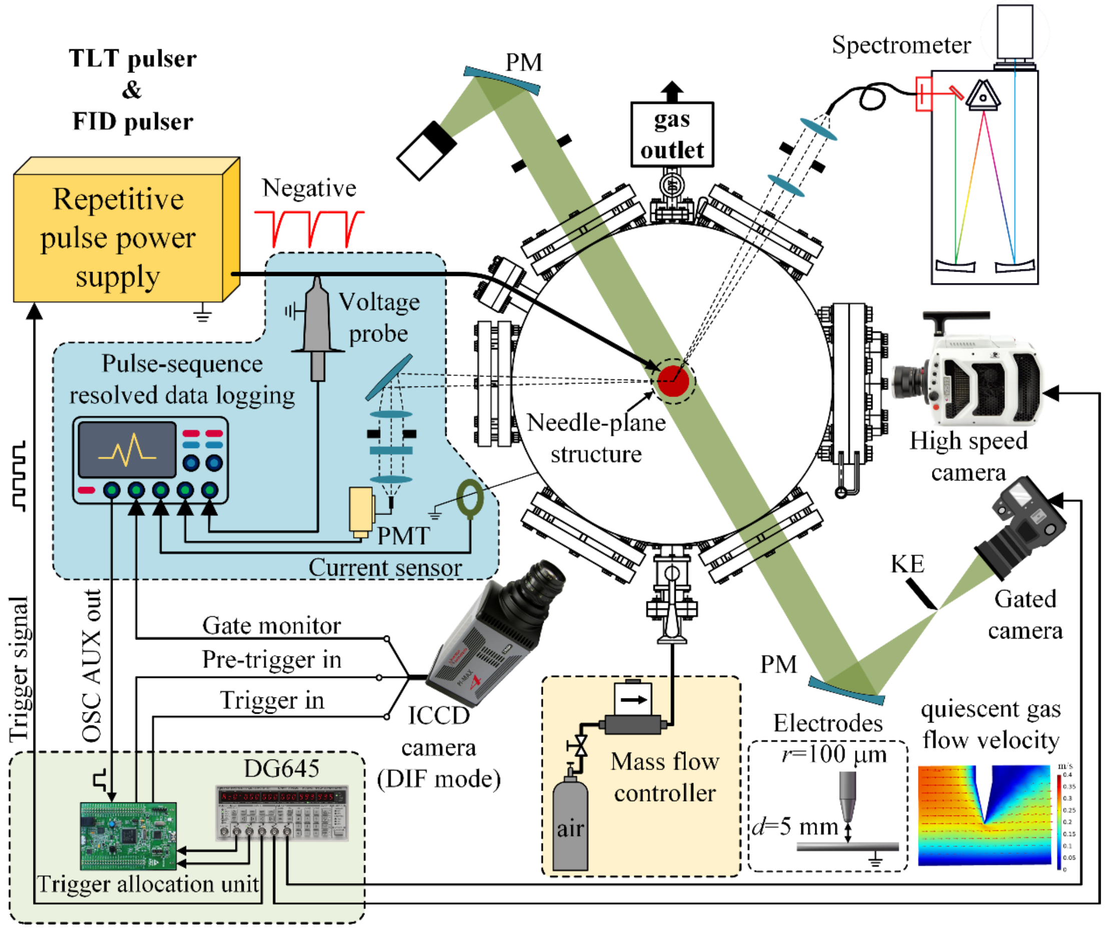
04 Concluding remarks

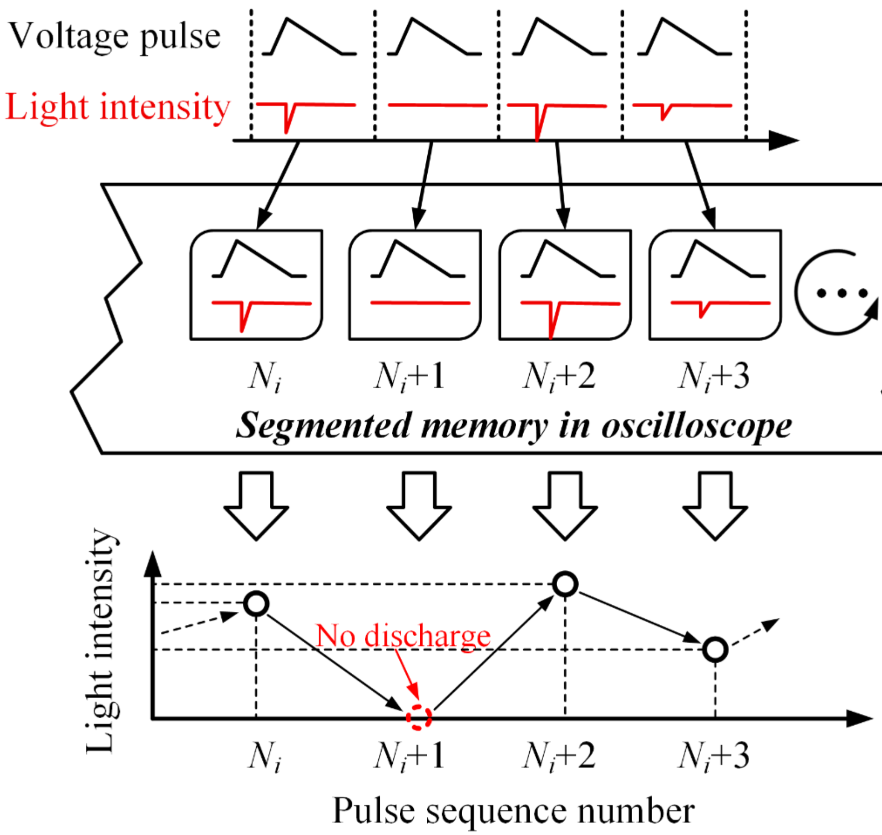
Experiment setup: pulse sequence resolved

Electrical and optical diagnostics: voltage/current waveforms, emission light intensity

ICCD images: temporally and pulse-sequence resolved images

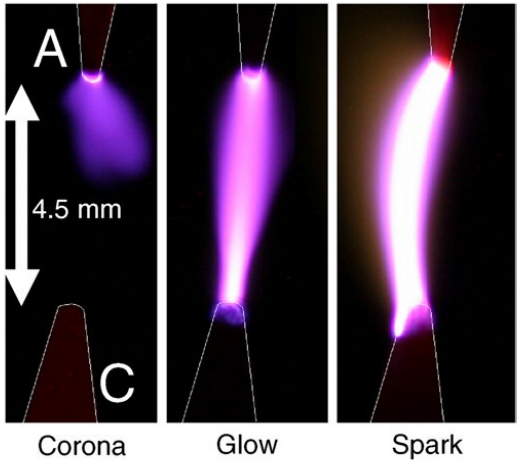
Data logging method: sequence mode for pulses with extremely low duty cycle

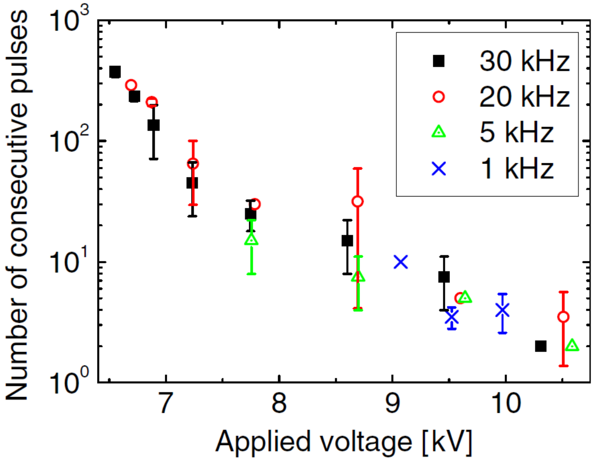




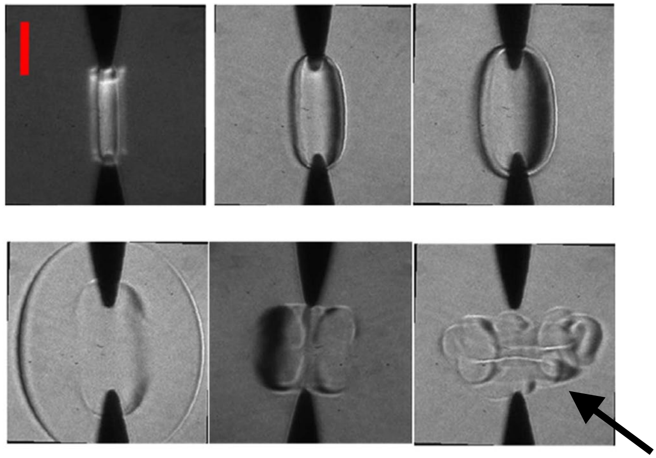
Main finding: Spark discharge disappears periodically

Conventional development pattern: enhancing transition pattern and no reversion





Pai 2010
PSST



Lo 2017
PSST

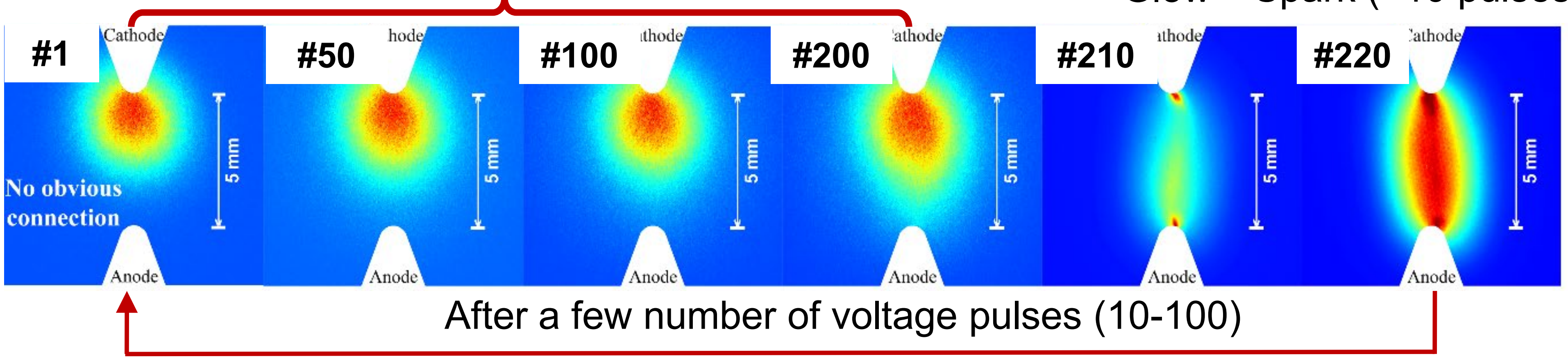
Surplus
heat

Discharge regime instabilities: periodical spark quench and reestablishment ?

Corona

Glow

Spark (~10 pulses)

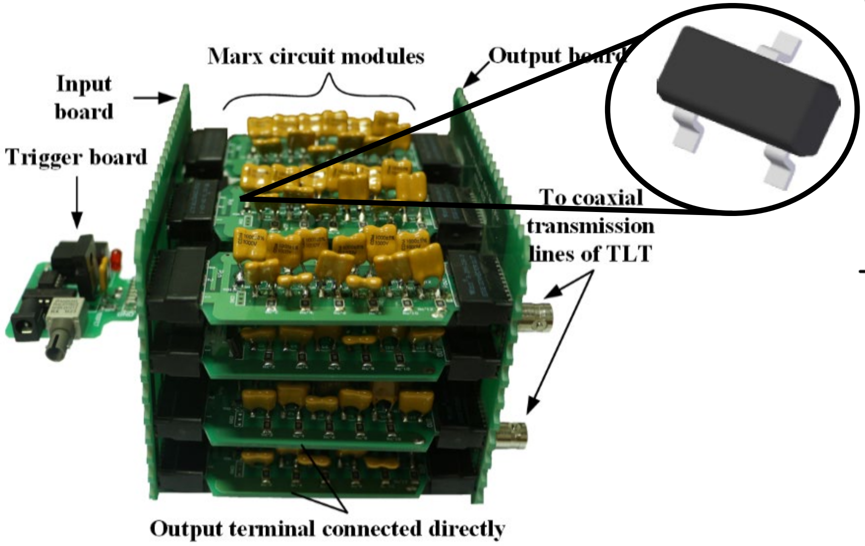


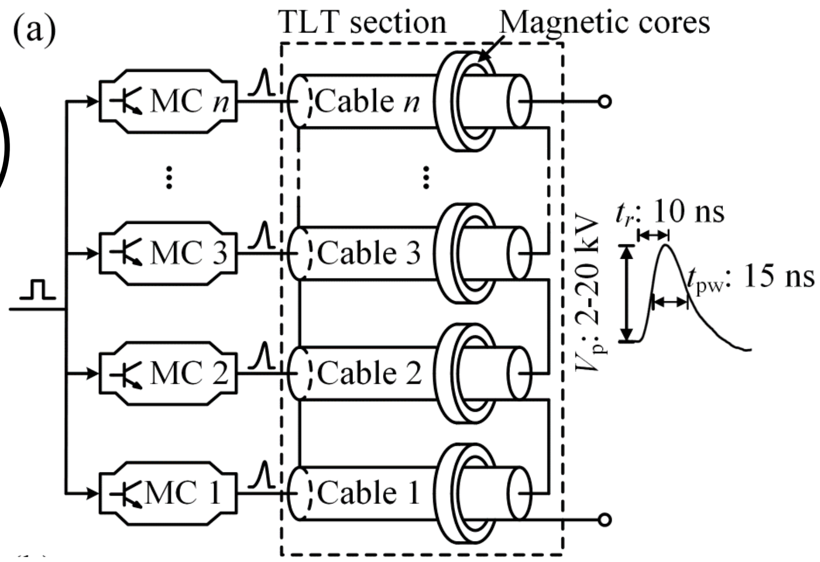
After a few number of voltage pulses (10-100)

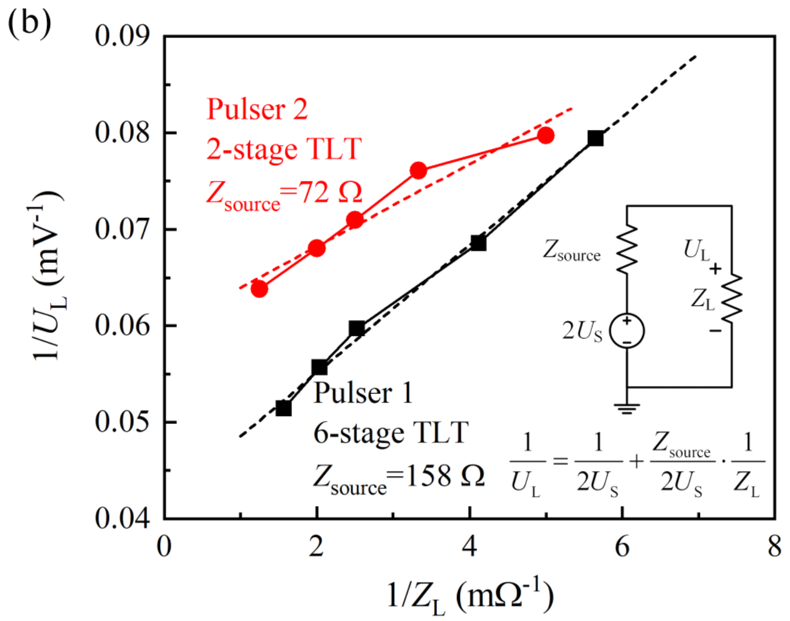
High-speed camera
PRF: 2 kHz

Repetitive nanosecond pulse power supply

Avalanche transistor Marx circuits + Transmission line transformer (power combining)







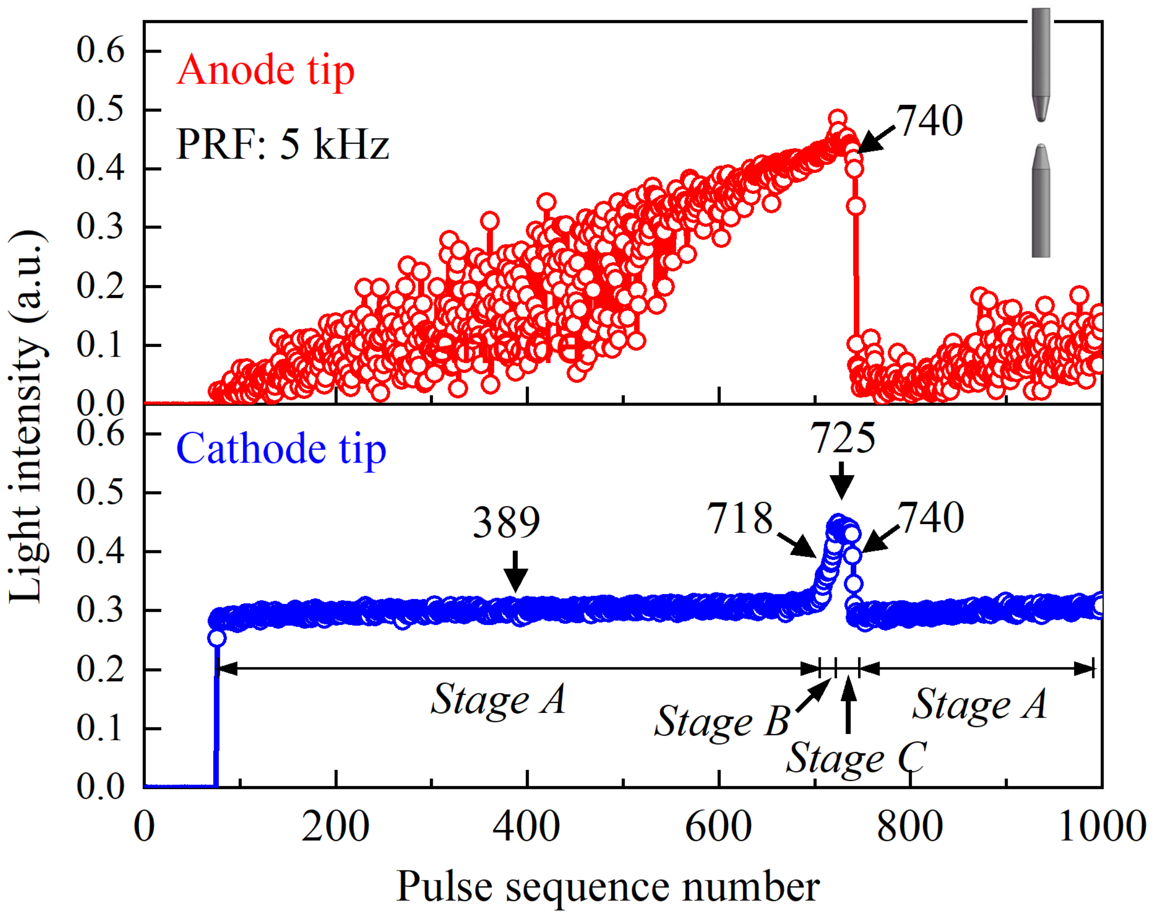
Output specifications of two pulse suppliers

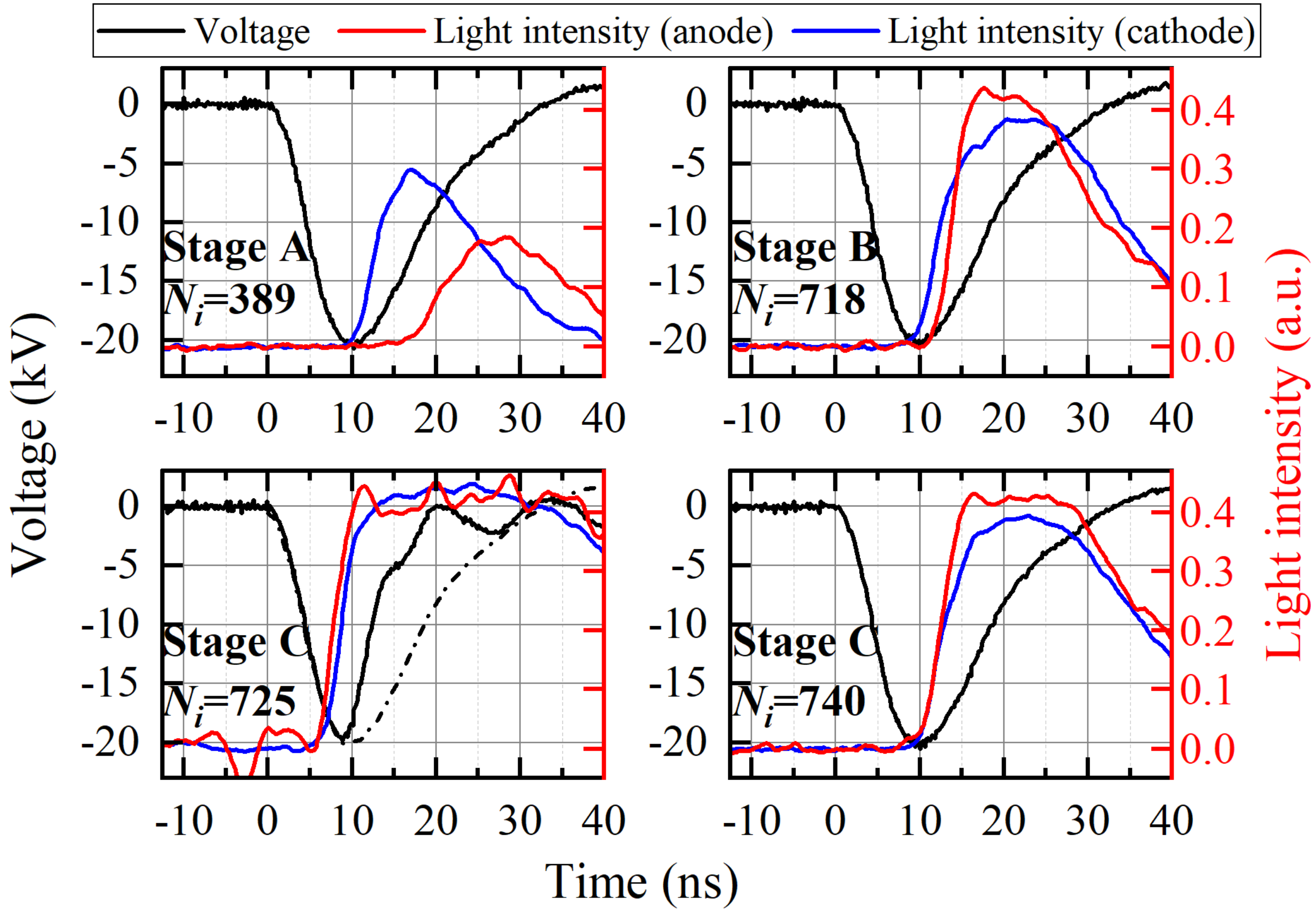
Power supply	Amplitude /kV	Rise time/ns	Pulse width/ns	Output impedance/Ω	Energy storage/mJ
Pulser 1	20	10	14	158	6.48
Pulser 2	15.3	11	17	72	6.18

[1] Li J, Zhao Z, et al 2017 RSI **88** 033507 [2] Li J, Zhao Z, et al 2017 RSI **88** 093514

NRP discharge behaviors: needle-needle structure

Periodical discharge regime transition (5 kHz)—electrical features

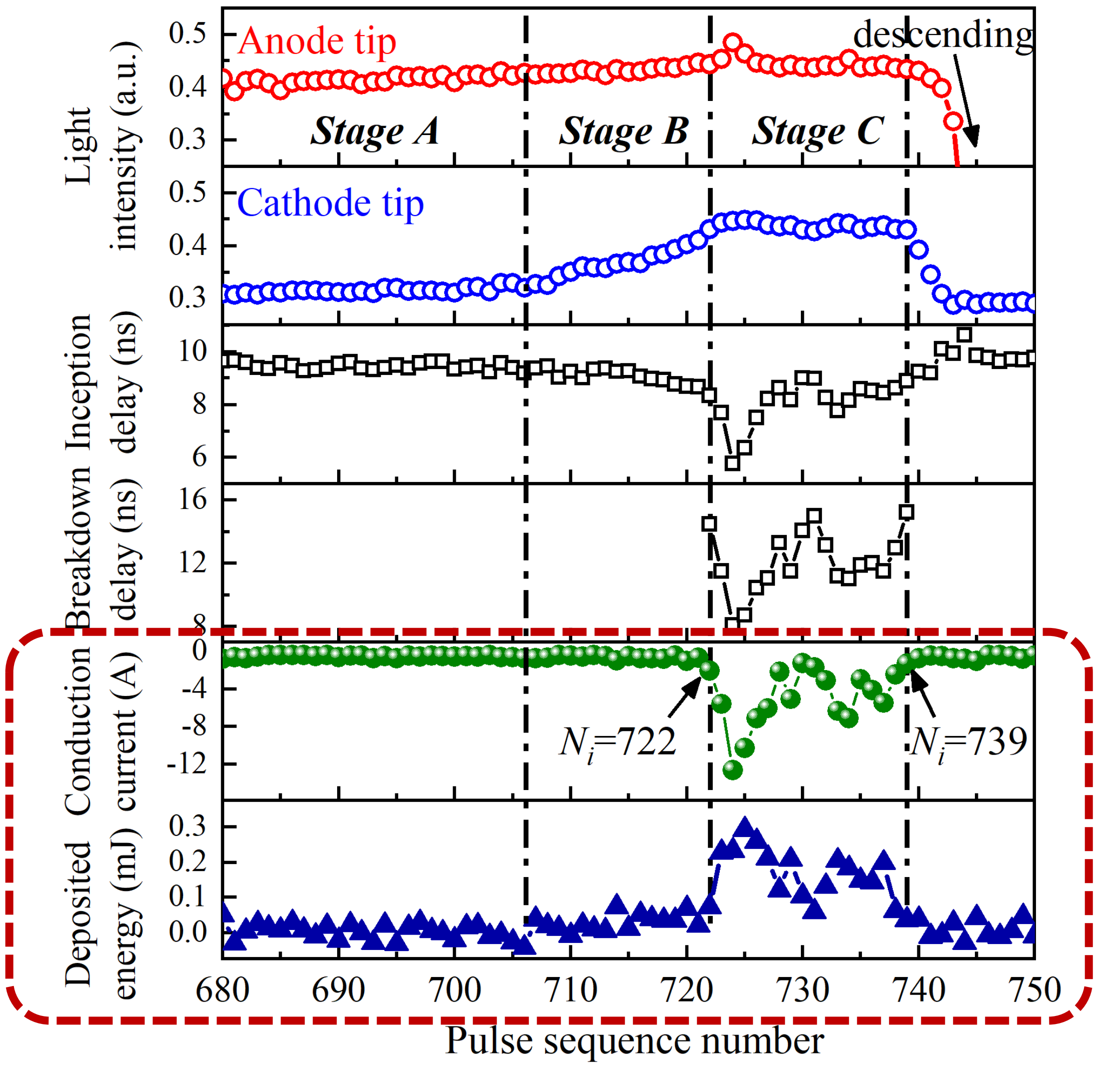


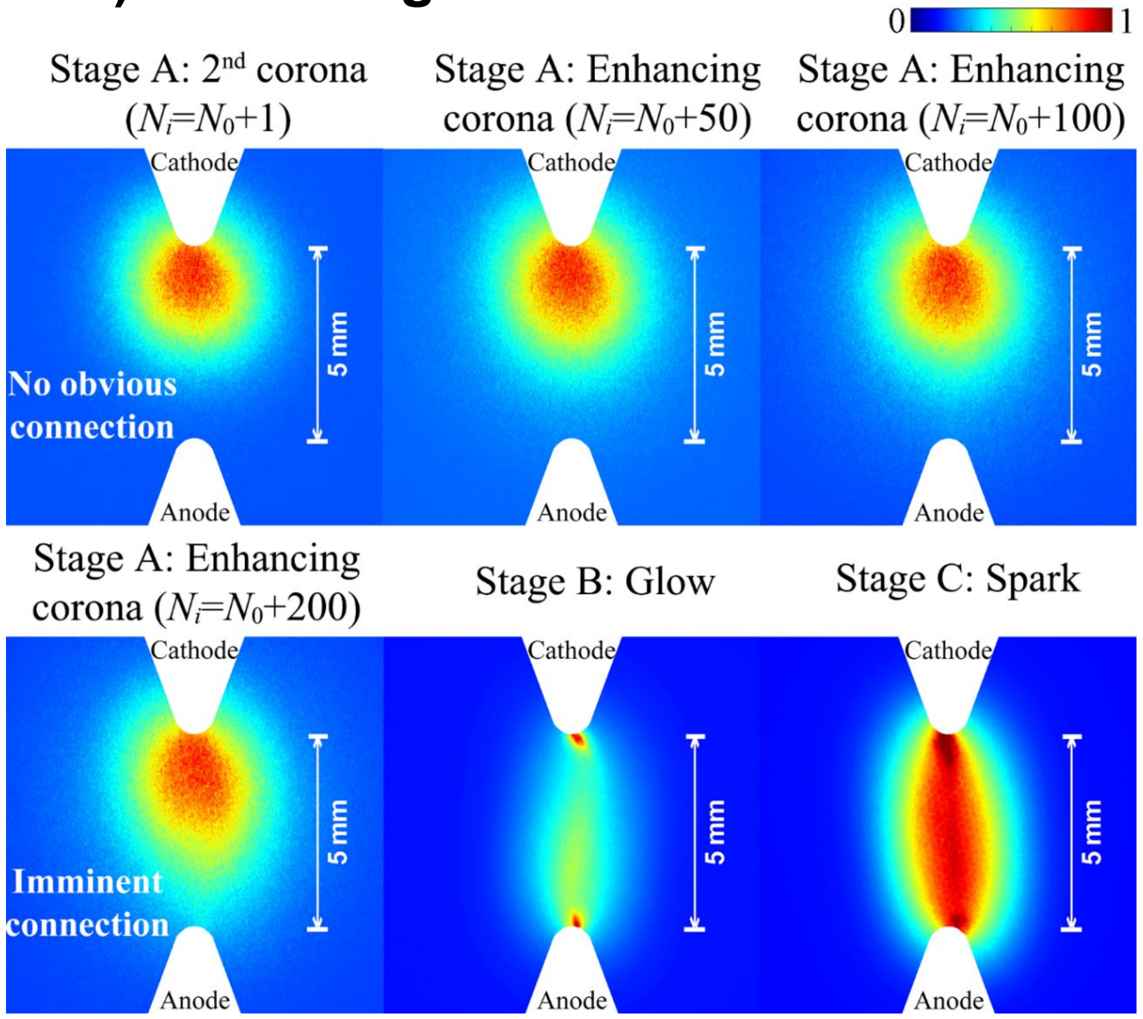


Pulser 1 (20 kV), needle-needle, r/d=500 μm/5 mm, 0.1 MPa N_2

NRP discharge behaviors: needle-needle structure(cont.)

Periodical discharge regime transition (5 kHz)—discharge channels





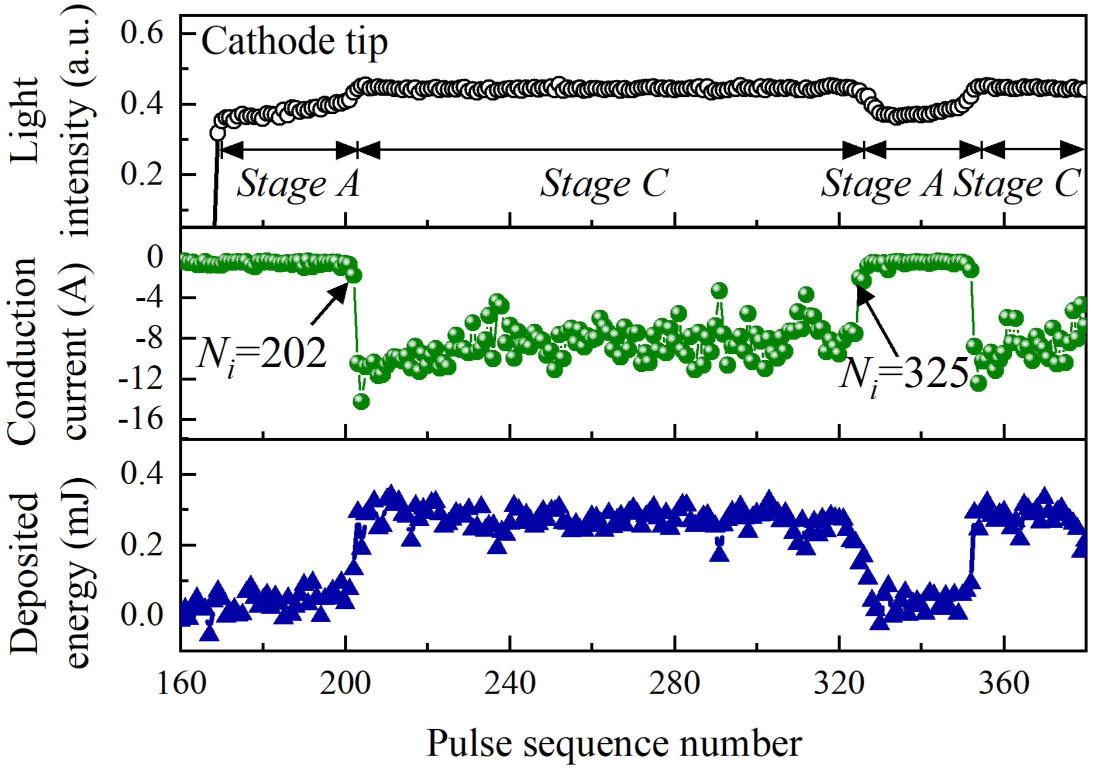
Deposited energy: 0.02 mJ   0.3 mJ

NRP discharge behaviors: needle-plane structure

Periodical discharge regime transitions in needle-plane structure (negative pulse)

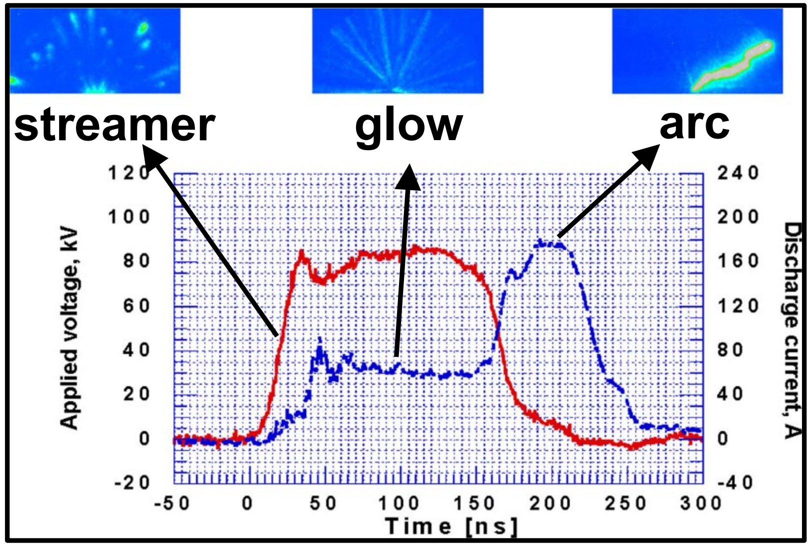
- **Spark regime** could be sustained under **much more voltage pulses**
- **Longer duration length** of corona stage
- No clearly distinguishable “glow” discharge stage

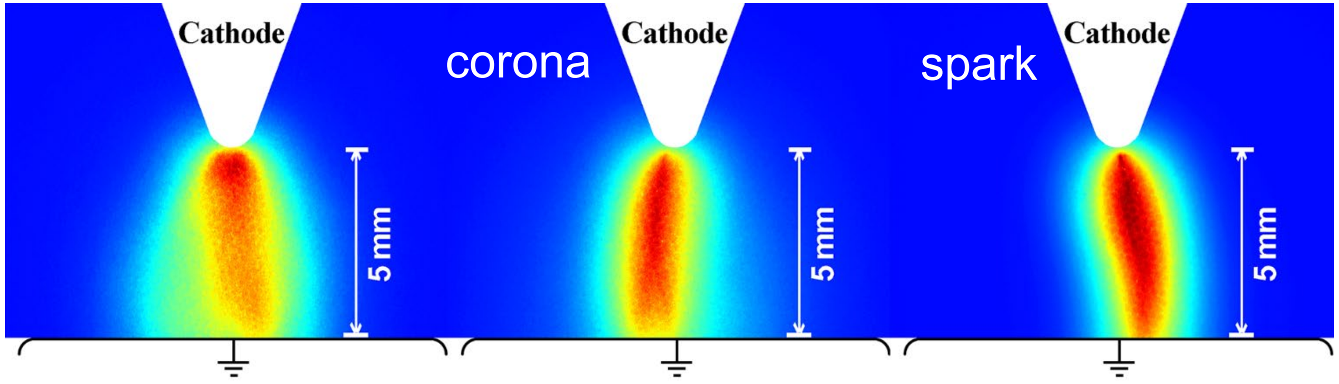
Wang DY et al. PSST. 2020 (29) 023001



~200 ns duration

~15 ns duration

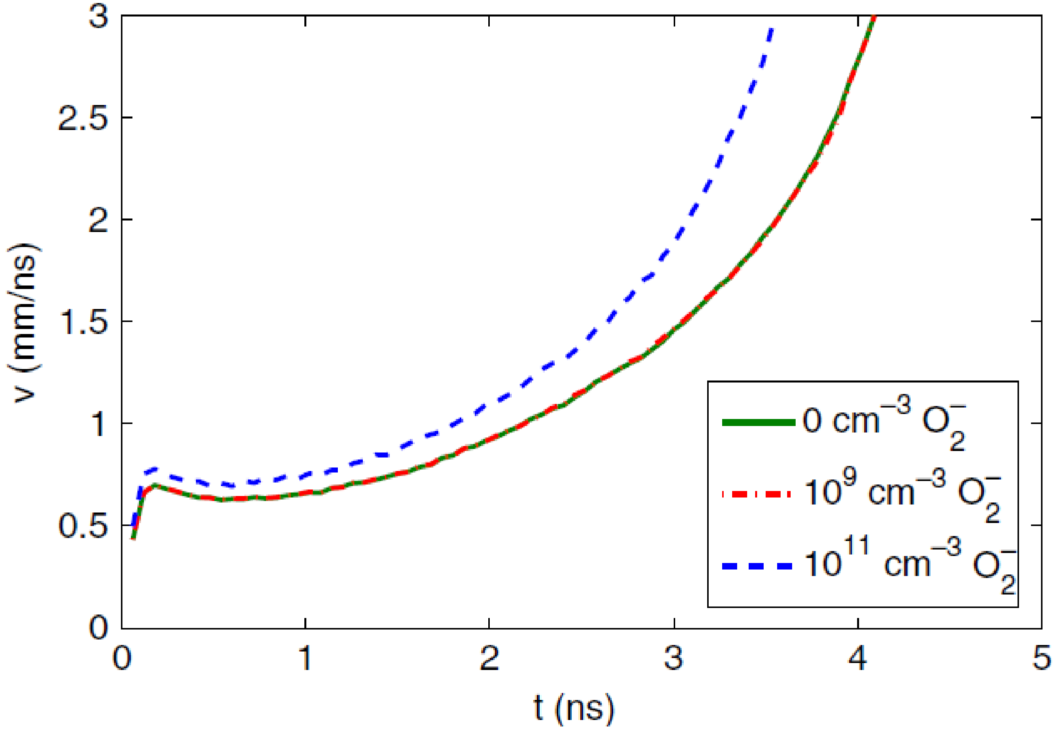




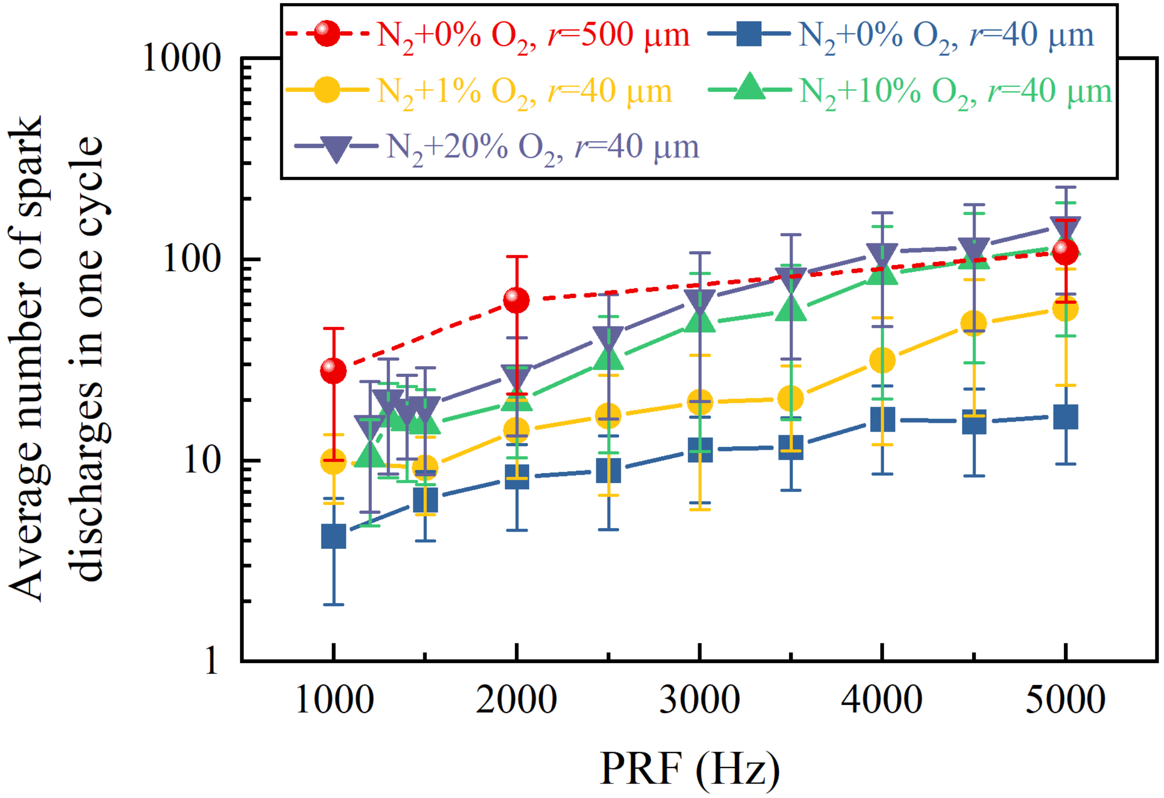
NRP discharge behaviors: effect of O_2 concentration

Effect of O_2 addition on discharge regime transition (negative pulse)

- Macroscopic changes: higher breakdown voltage, higher propagation velocity, branching features
- Microscopic mechanisms: electron attachment, photo-ionization, heating efficiency
- For discharge regime transition: longer spark regime, periodical transitions still exist



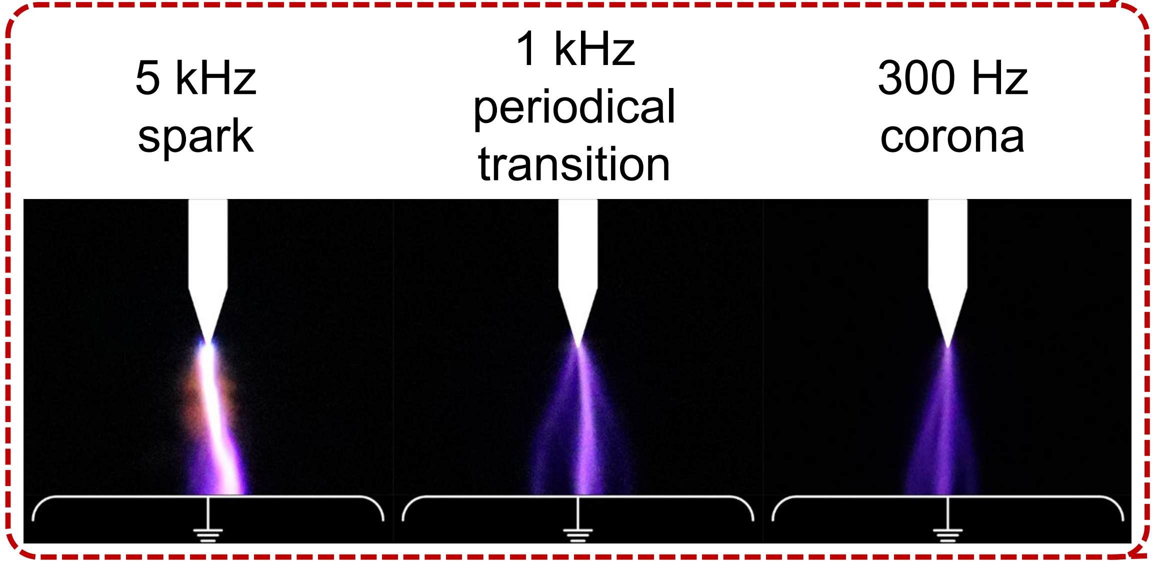
Wormeester et al. JPD. 2010 (43) 505201

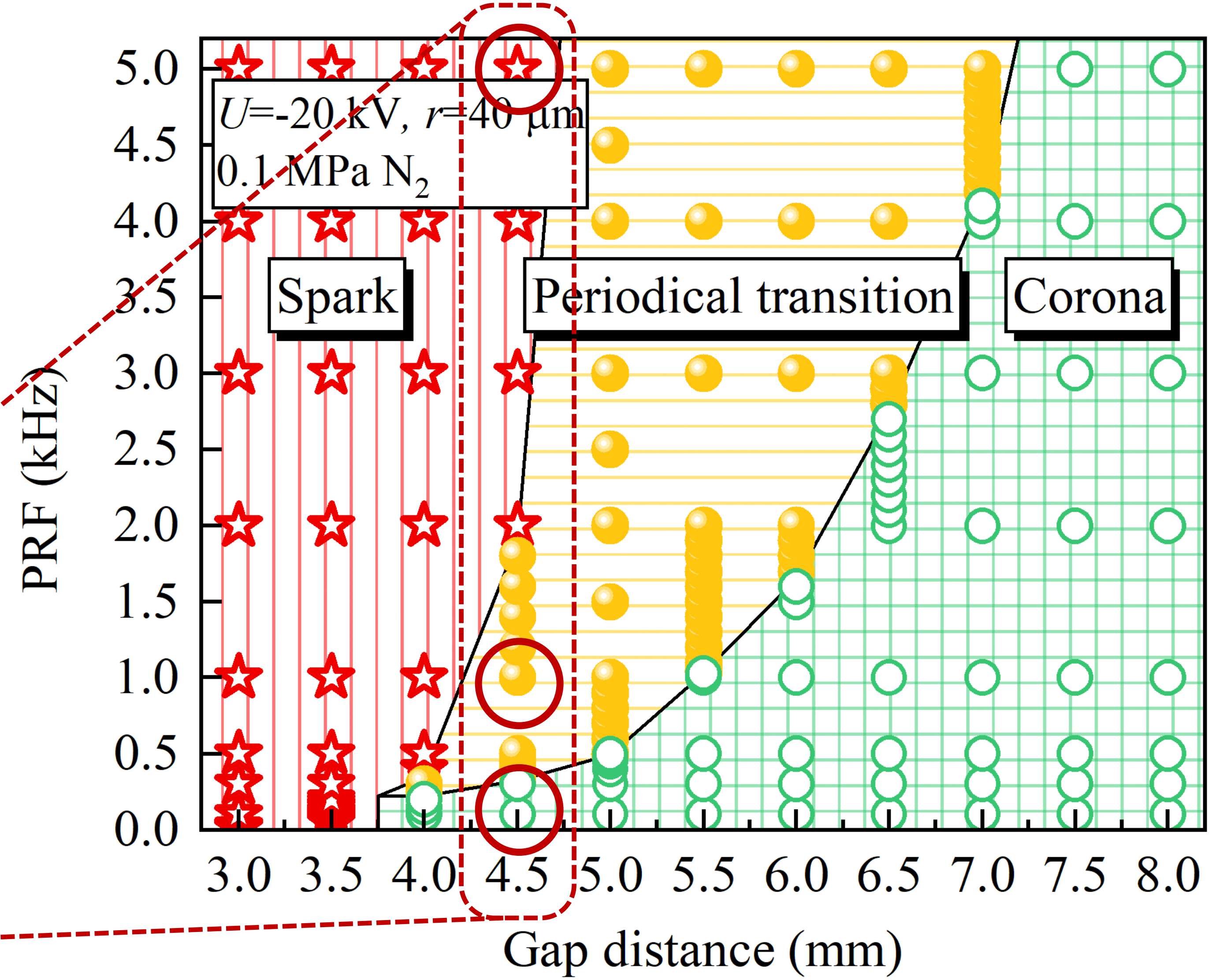


NRP discharge behaviors: parameter dependences

Existences of periodical transitions

- Short gap: only spark once ignited
- Long gap: only corona without spark
- Moderate gap and PRF: periodical transition



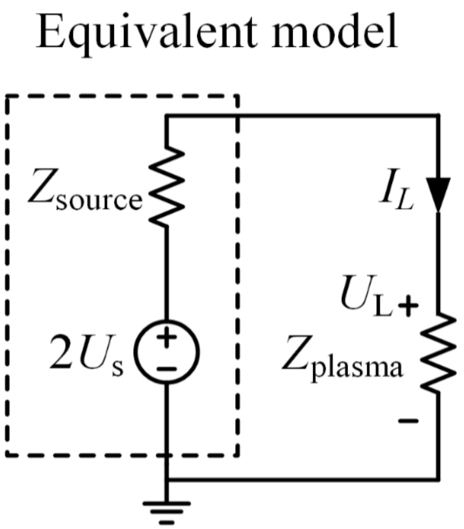


Periodical discharge regime transition mechanisms (1/3)

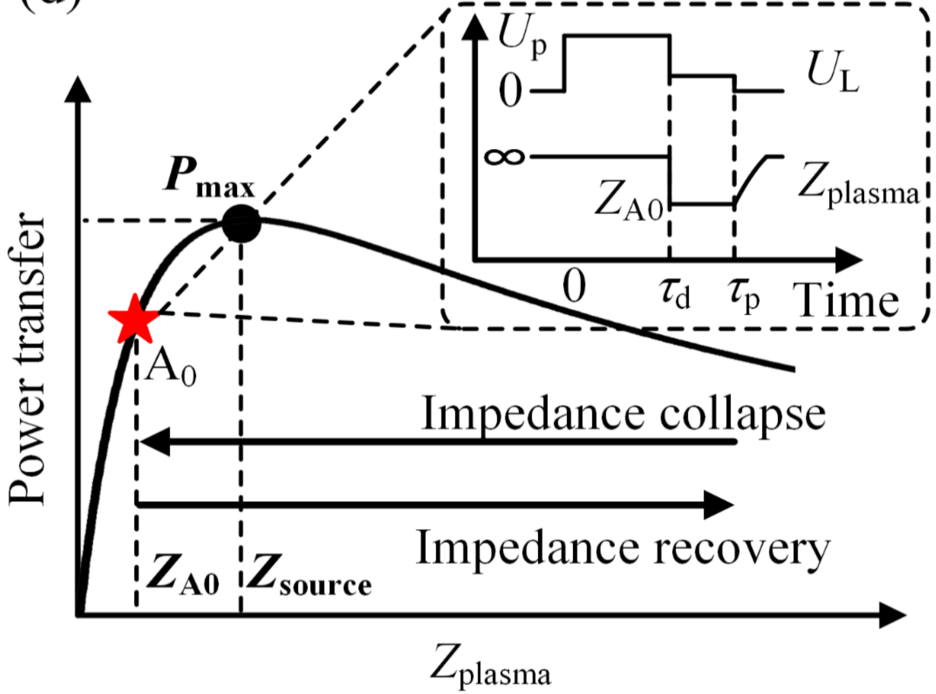
Plasma-source coupling

- Thevenin's equivalent circuit + Equivalent operation point (EOP)
- Movement of EOP during the discharge regime transition (“memory effect”)

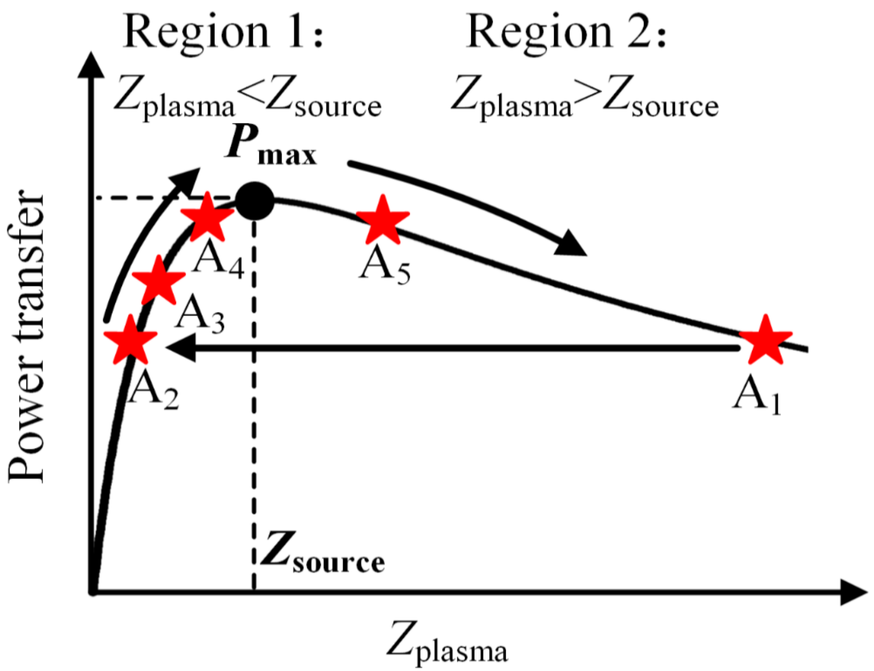
(c)



(d)



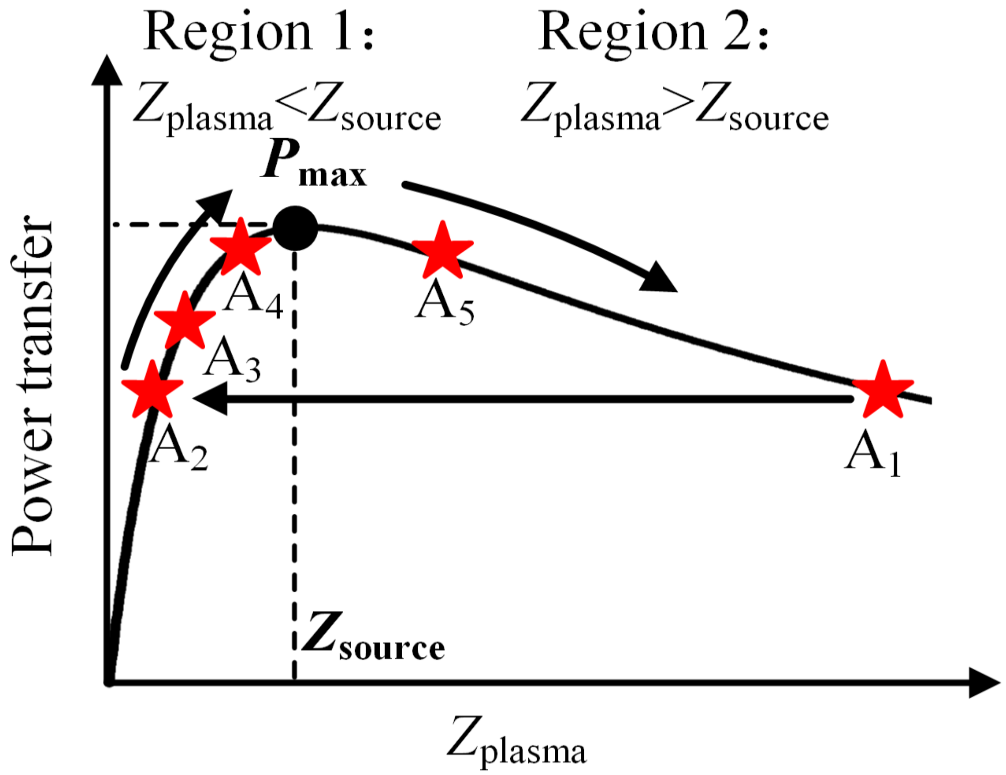
(e)



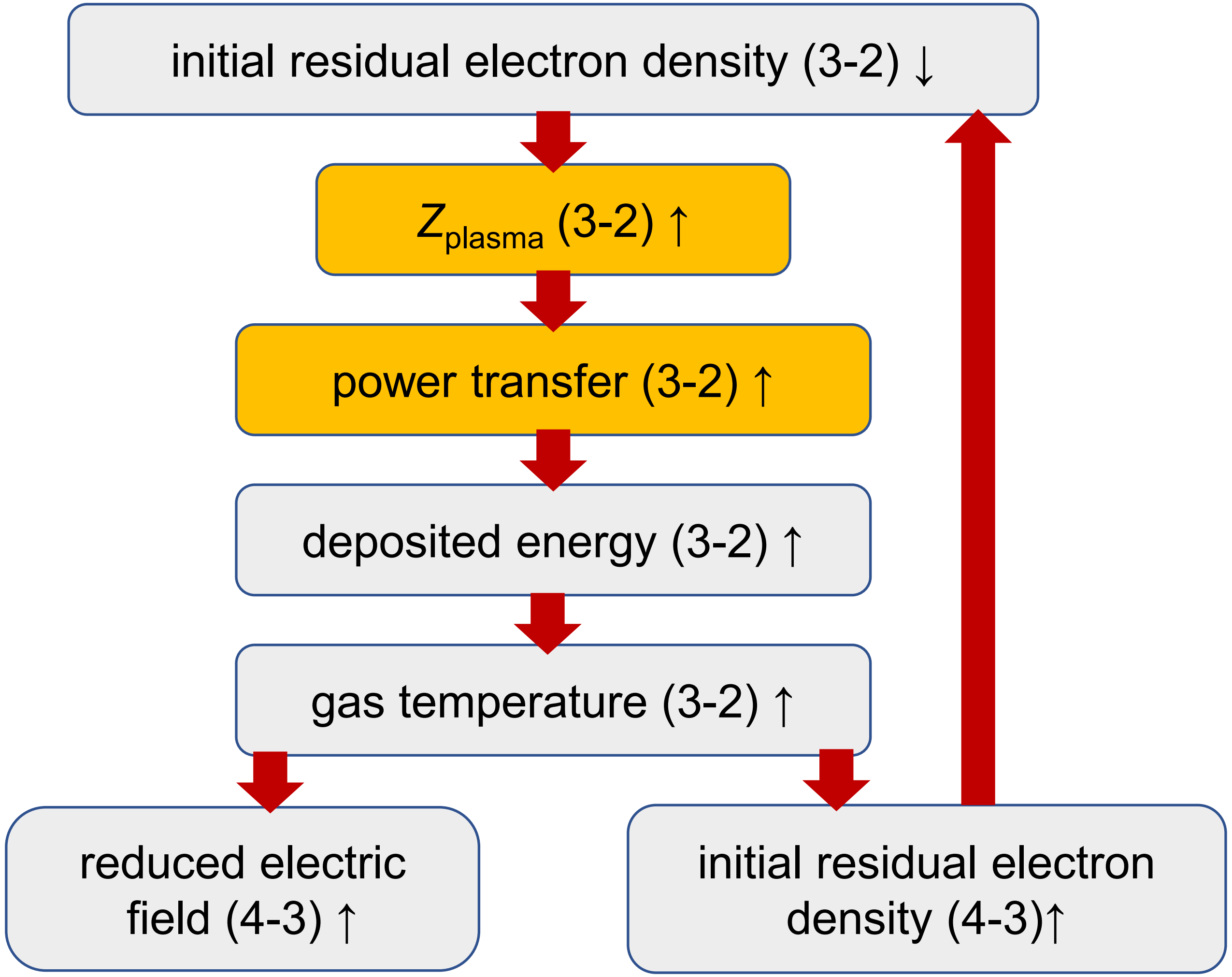
Periodical discharge regime transition mechanisms (2/3)

Plasma-source coupling (cont.)

- Multiple feedback mechanisms
- Effect of residual conductivity
- Average deposited energy per unit distance



Feedback mechanism (among successive spark events)



initial residual electron density (3-2) ↓

Z_{plasma} (3-2) ↑

power transfer (3-2) ↑

deposited energy (3-2) ↑

gas temperature (3-2) ↑

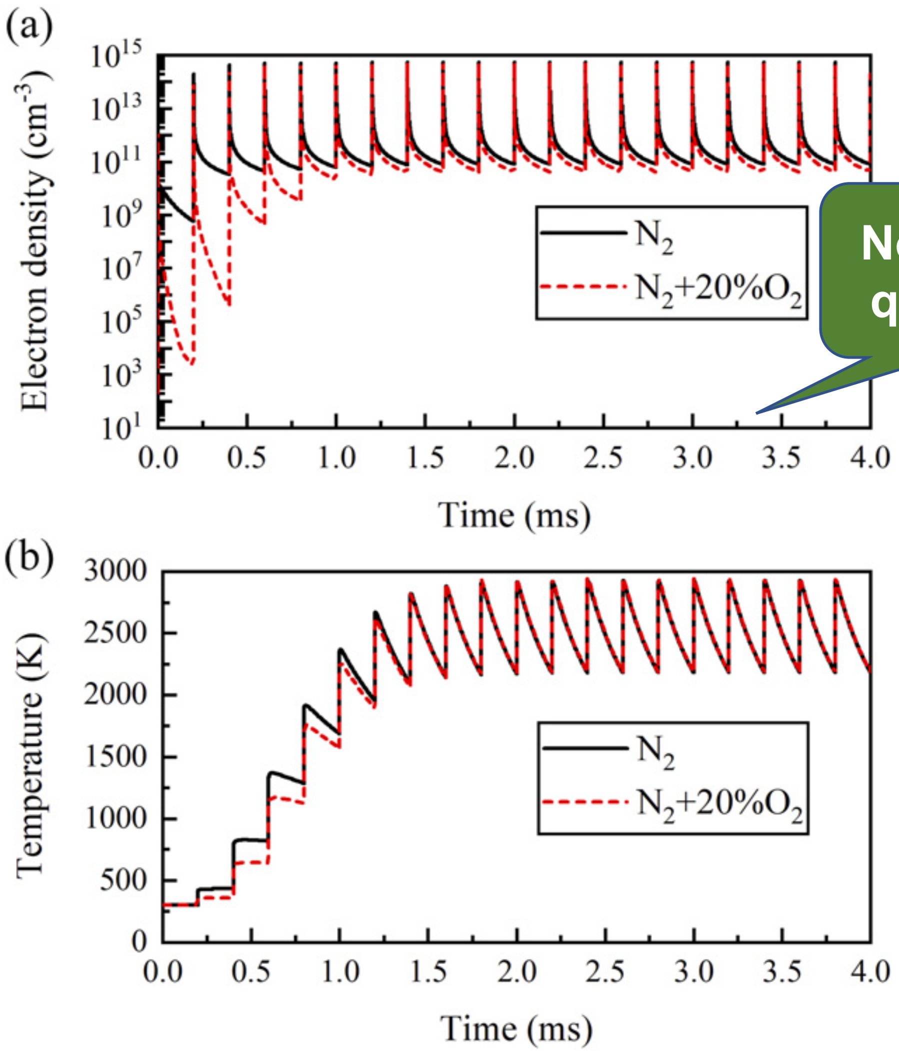
reduced electric field (4-3) ↑

initial residual electron density (4-3)↑

Zhao Z et al 2022 PSST **31** 045005

Periodical discharge regime transition mechanisms (3/3)

Simple modelling with ZDPlasKin



No spark quench!

Stability indicator based on enthalpy balance

$$\Gamma_{\mathrm{eq}} = \frac{\Delta H_{\mathrm{input}}}{\Delta H_{\mathrm{relaxation}}} = \frac{f_{\mathrm{rep}}\eta\int_{\tau_{\mathrm{d}}}^{\tau_{\mathrm{p}}} I_{\mathrm{d}}E\,\mathrm{d}t}{4\pi\lambda_{\mathrm{avg}}T_{\mathrm{axis}}}\left(\frac{r_{\mathrm{T}}}{r_{\mathrm{ch}}}\right)^2$$

$$\leqslant \frac{f_{\mathrm{rep}}W_{\mathrm{max}}}{d}\,\frac{\eta}{4\pi\lambda_{\mathrm{avg}}T_{\mathrm{axis}}}\left(\frac{r_{\mathrm{T}}}{r_{\mathrm{ch}}}\right)^2 \propto \frac{W_{\mathrm{max}}}{d\cdot 1/f_{\mathrm{rep}}}$$

$$W_{\mathrm{max}} = P_{\mathrm{max}}(\tau_{\mathrm{p}}-\tau_{\mathrm{d}}) = \frac{{U_{\mathrm{s}}}^2}{Z_{\mathrm{source}}}(\tau_{\mathrm{p}}-\tau_{\mathrm{d}}),$$

Based on Naidis G V 2008 *JPD* **41** 234017

Γ_{eq} is estimated as 0.085 to 0.32 at 5 kHz
(channel temperature is 1000-2000 K ?)

More instability mechanisms are required to be revealed!

Q1.Applicability of discharge mechanisms

Whether this peculiar transition pattern could only occur under the specific TLT pulser **or is prevalent** under other pulsers (commercially available FID pulser)?

Q2.Implicit straight streamer channel before quench

Streamer discharge evolutions that may lead to spark quenches have not been revealed.

Q3.Effect of additional gas flow

The enhanced residual ***charge transport*** and the ***heat removal*** would inevitably affect the discharge regime and transitions.

Outline

01 Background

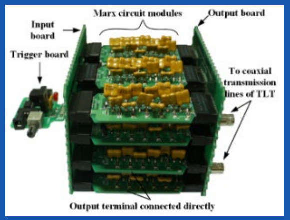
02 Discharge instability coupled with pulsed power supply

03 Discharge instability affected by gas flow

04 Concluding remarks

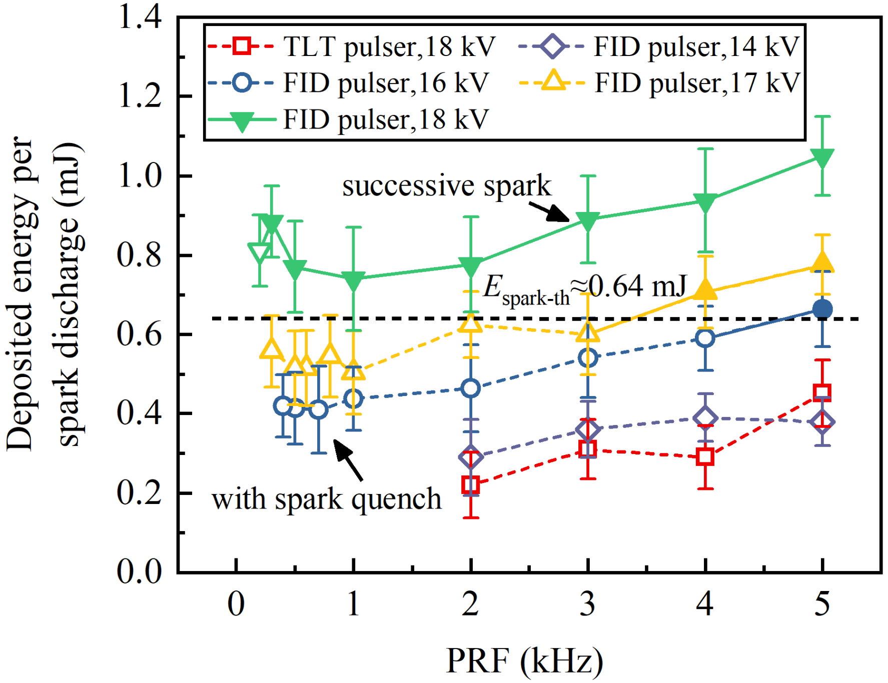
Comparisons of discharge regimes under two pulsers

Home-made TLT pulser

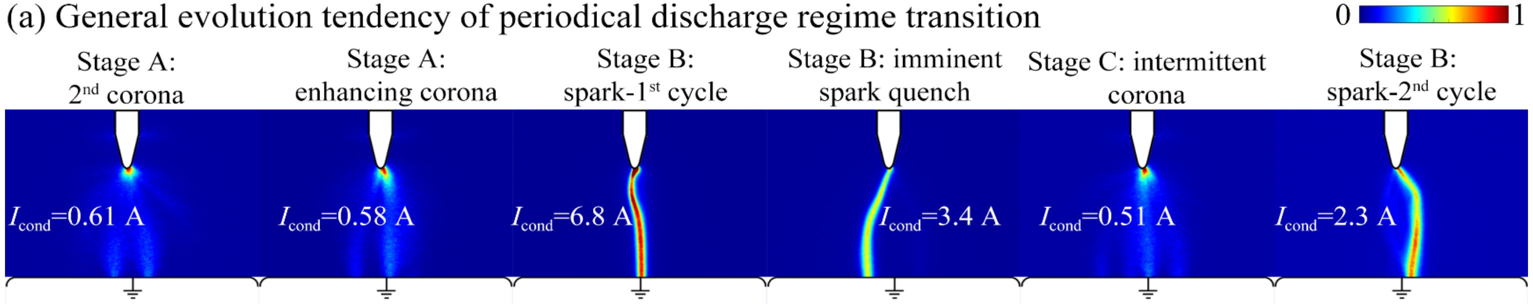


Commercially available: FID

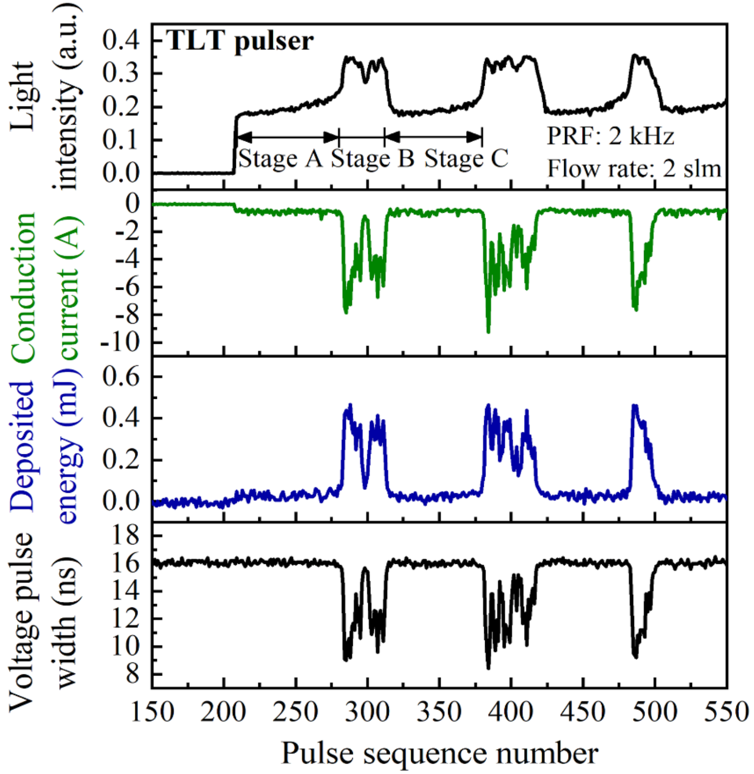
A minimum deposited energy per spark is required for successive sparks!



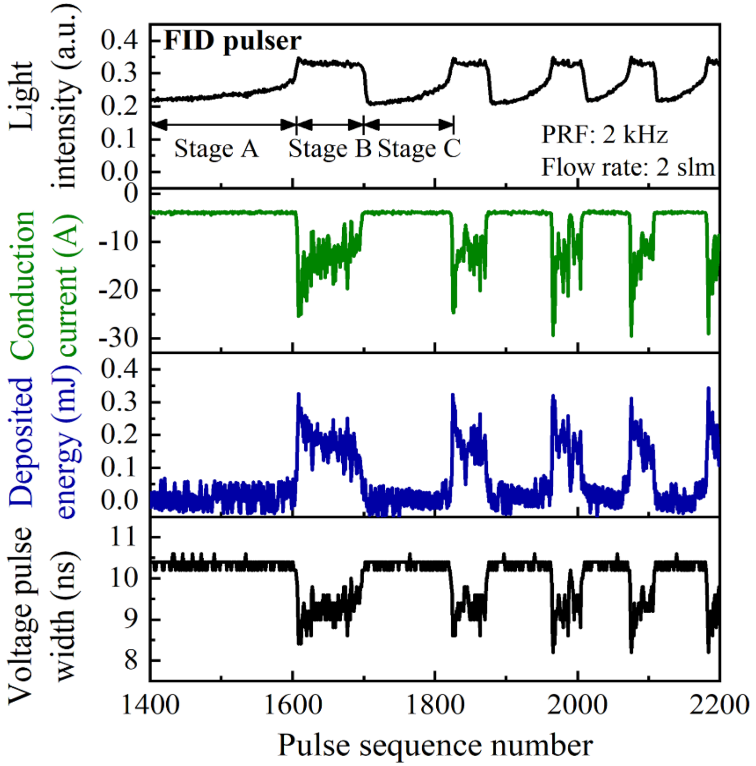
(a) General evolution tendency of periodical discharge regime transition



(b) Regime transitions under TLT pulser (18 kV)



(c) Regime transitions under FID pulser (14 kV)



Effects of the gas flow: 1. gas flow rate

Periodical discharge regime transition

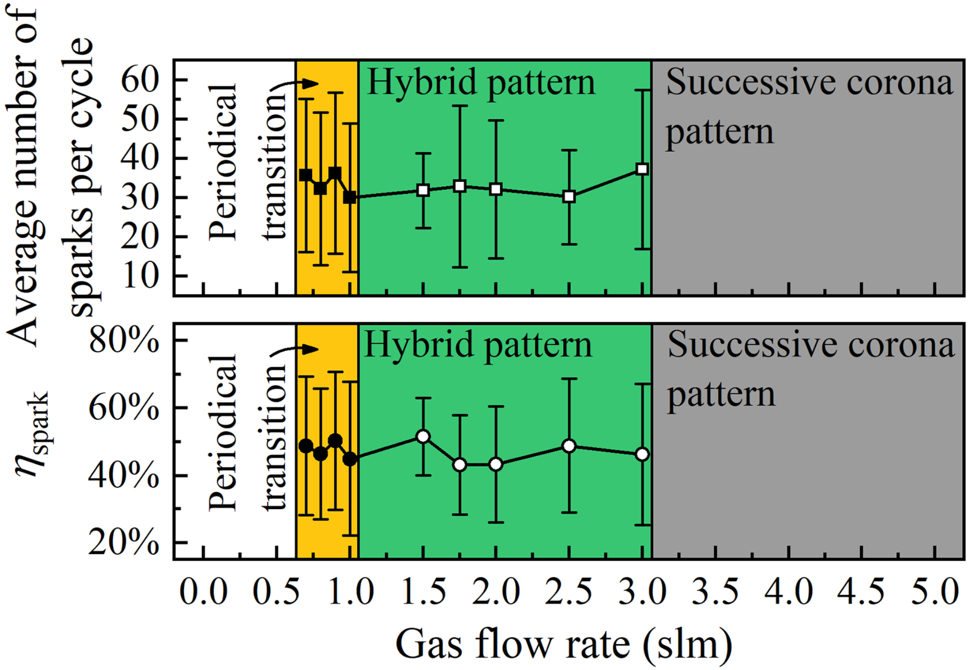
↓

Hybrid pattern

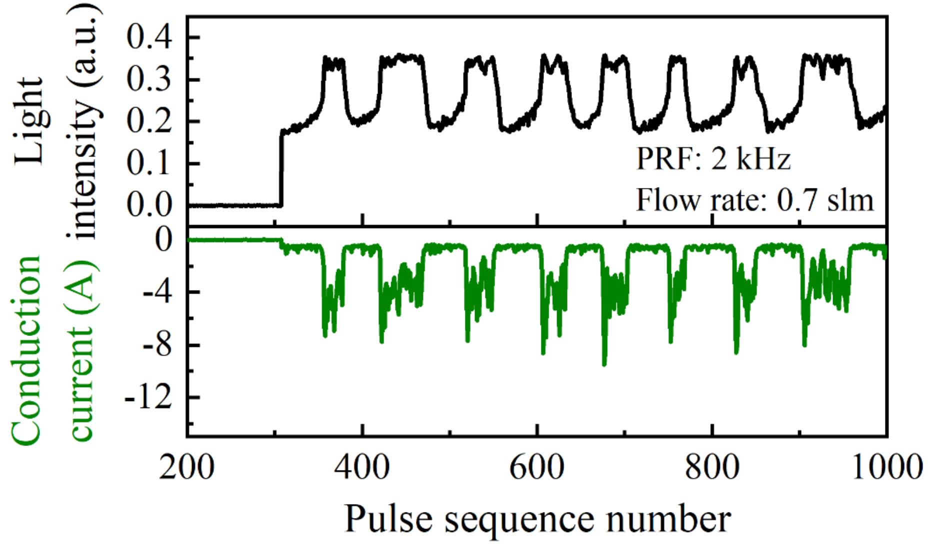
↓

Successive corona pattern

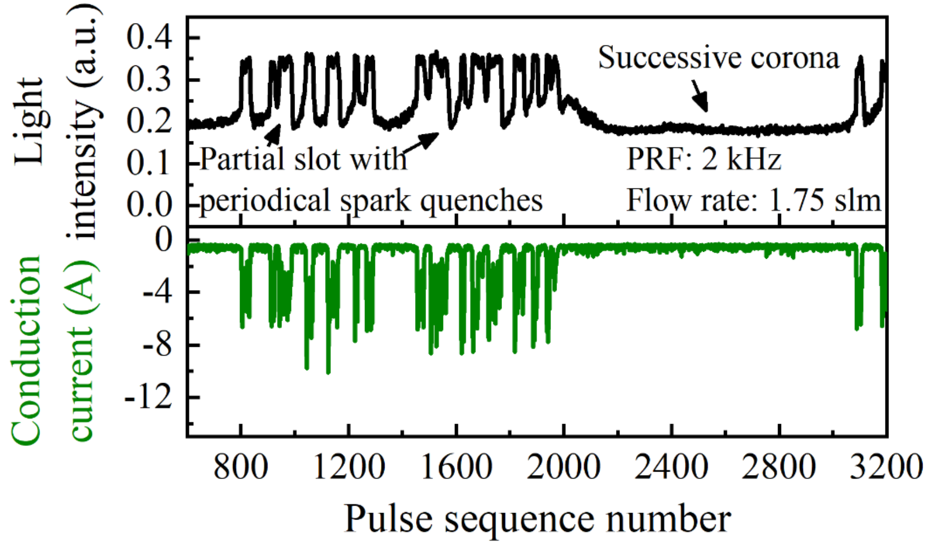
(a) Transition parameters v.s. gas flow rate



(b) Periodical regime transition

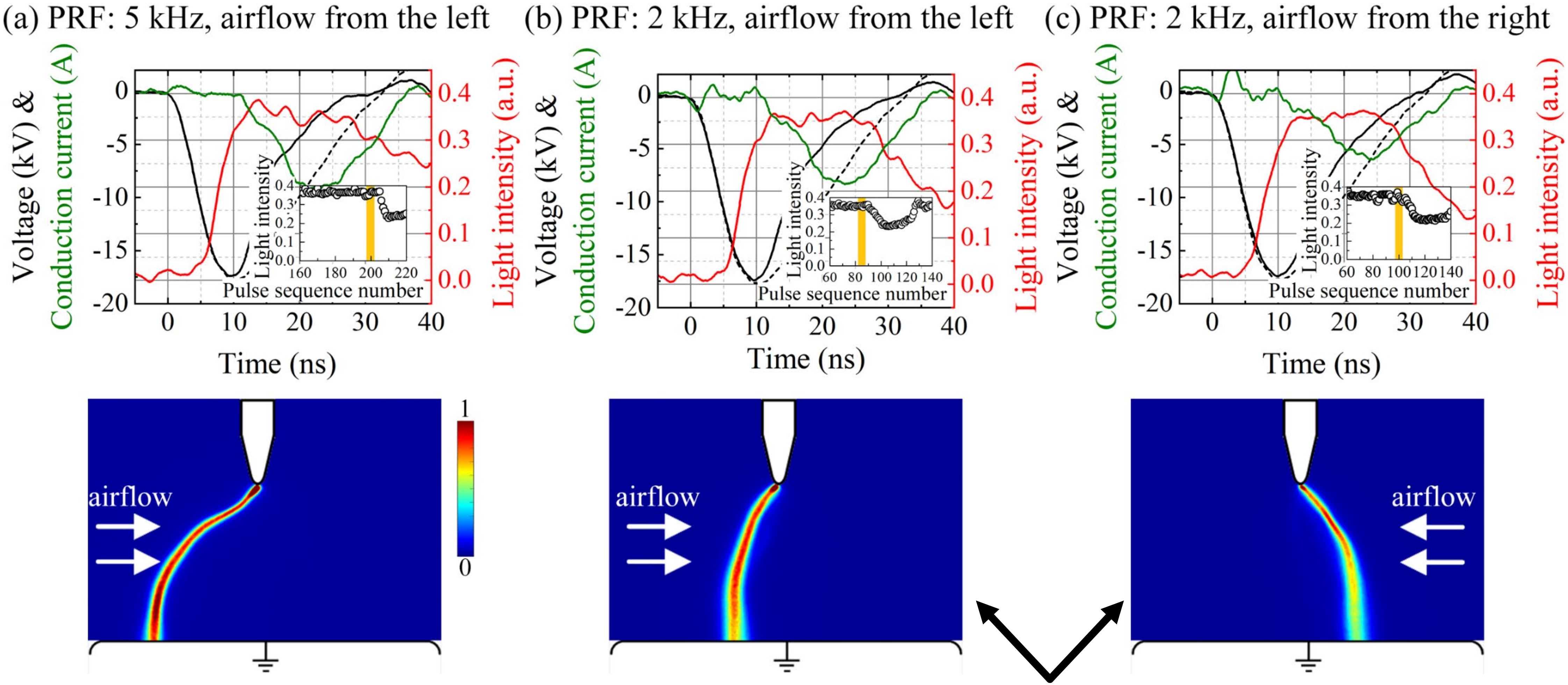


(c) Hybrid pattern



Effects of the gas flow: 2. gas flow direction

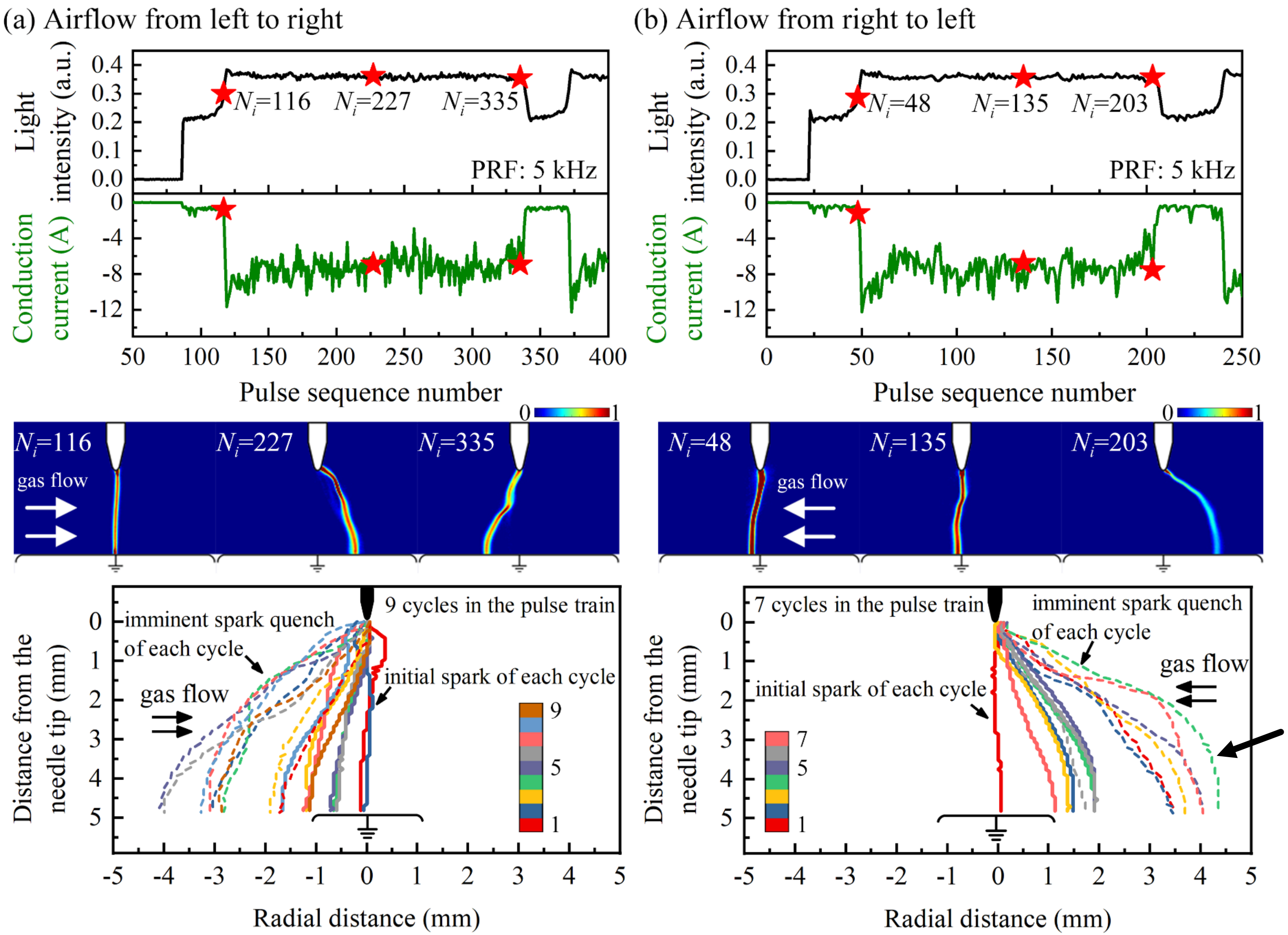
Abnormal channel bending preference: the spark prefers to bend upstream prior to the its quench rather than downstream where high-density residuals are present.



(a) PRF: 5 kHz, airflow from the left (b) PRF: 2 kHz, airflow from the left (c) PRF: 2 kHz, airflow from the right

Abnormal channel bending preference

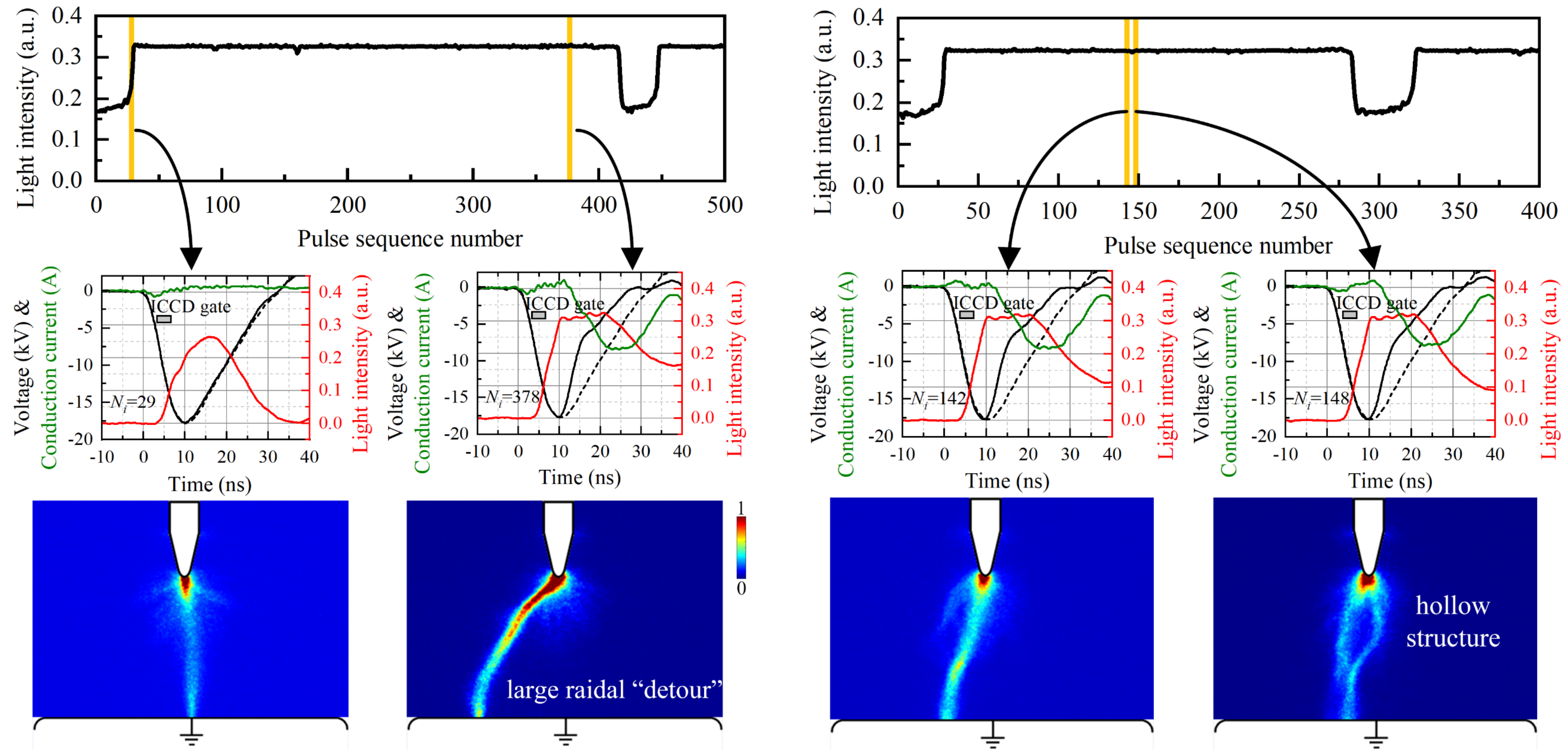
Effects of the gas flow: 2. gas flow direction (cont.)



Every spark inception and quench from high-speed camera

Effects of the gas flow: 2. gas flow direction (cont.)

Streamer channel already bends before the spark quench: double frame feature (DIF)



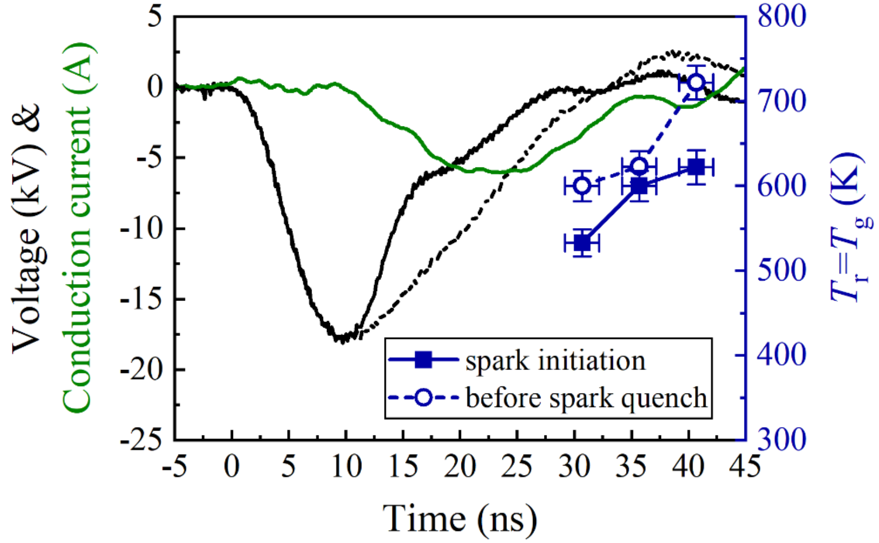
(a) PRF: 5 kHz, prior to spark formation and spark quench

(b) PRF: 5 kHz, at the middle of spark stage

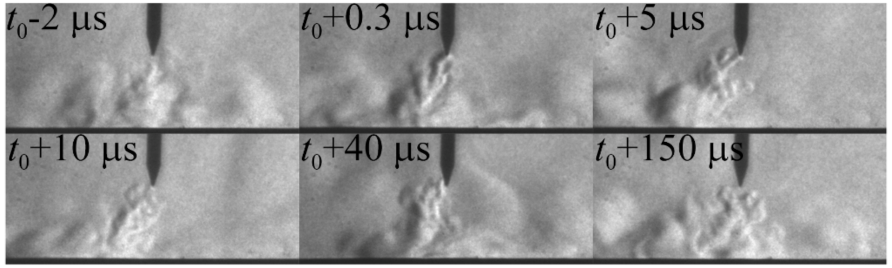
Streamer dynamics before NRP spark quench

$$\frac{\eta_R(T)W_{total}f}{\pi d} = \alpha\lambda_0(T - T_0)$$

(a) Evolutions of gas temperature during the spark



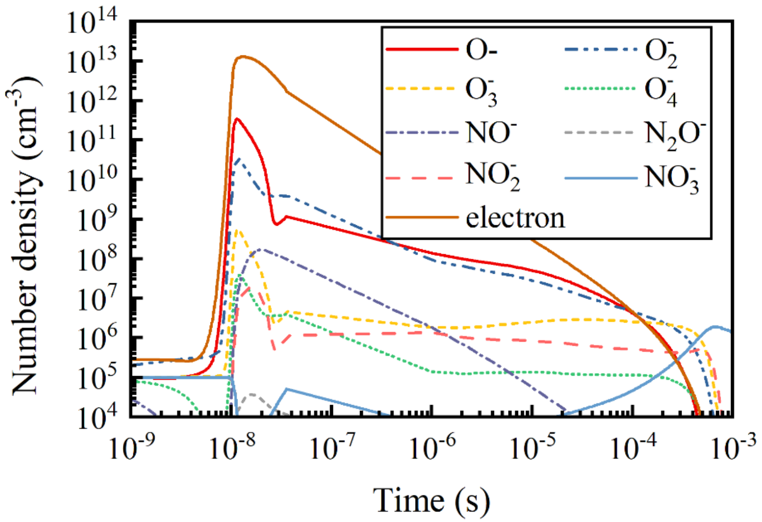
(b) Schlieren images before and after spark discharge

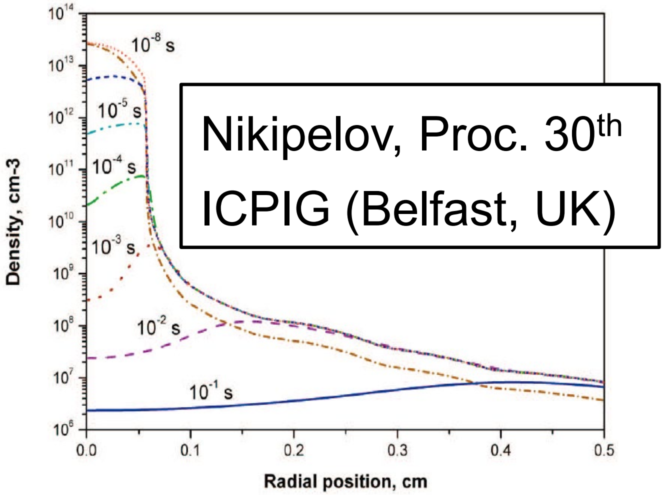


Question1: why would the spark channel abnormally bend upstream rather downstream?

- Higher concentrations of residual negative ions at the upstream side
- Negative ions with higher electron bound energies would be formed and accumulated at the downstream side

(c) Evolutions of negative charge carriers



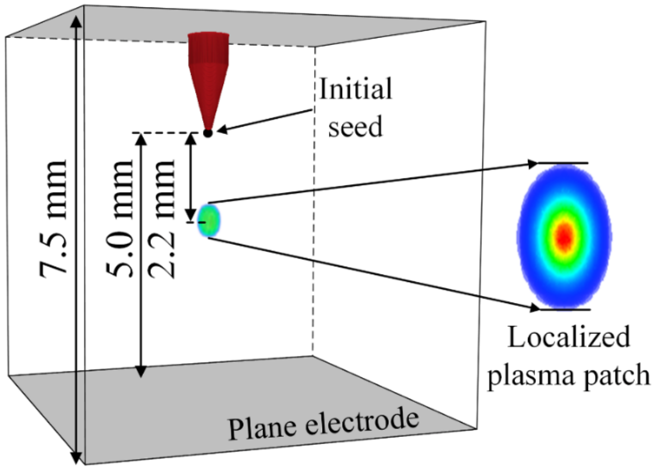


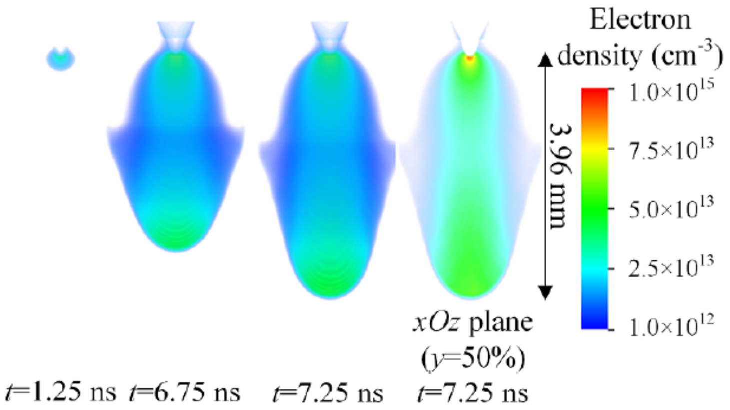
Nikipelov, Proc. 30th ICPIG (Belfast, UK)

Streamer dynamics before NRP spark quench (cont.)

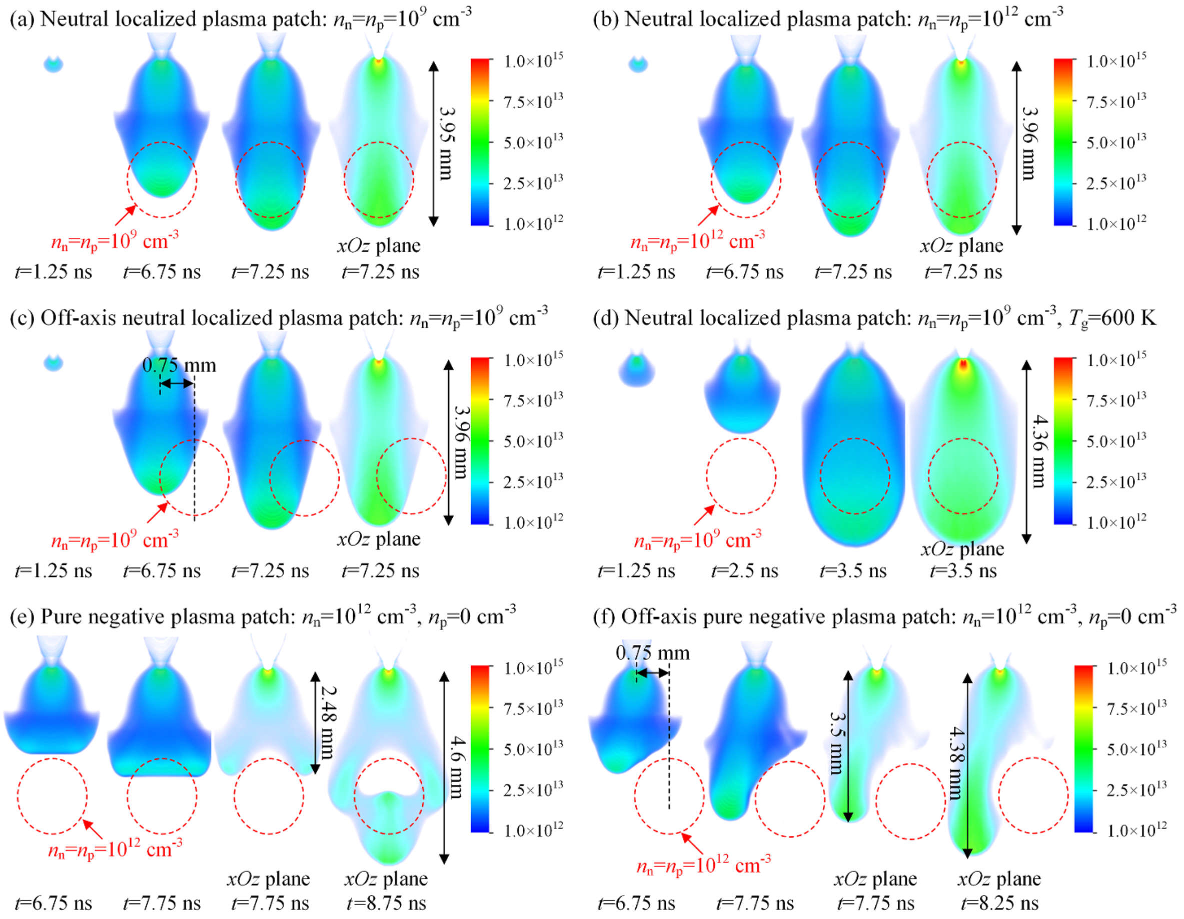
Question2: Are residual space charges responsible for the following streamer detour?

3D simulations of streamer propagation with different plasma patches





Afivo-streamer 3D



- Neutral localized plasma patch may be not responsible for the streamer “detour (still questionable!)

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Concluding remarks

- Discharge instabilities exist in ~15 ns NRP streamer discharge, although discharge stochastics have been greatly weakened by residuals.
- Two fundamental discharge instability mechanisms: residual charge transport/energy relaxation (plasma modulation and scale-up).
- Evolutions of residual charges and strong coupling with pulsed power supply are important for NRP streamer instability development.

Related recent publications

1. **Zhao Z**, Li C, Guo Y, et al. Streamer dynamics and periodical discharge regime transitions under repetitive nanosecond pulses with airflow[J]. ***Plasma Sources Science and Technology***, ***2023***, 32 (1): 015002.
2. **Zhao Z**, Li C, Zheng X, et al. Periodical discharge regime transitions under long-term repetitive nanosecond pulses[J]. ***Plasma Sources Science and Technology***, ***2022***, 31 (4): 045005.
3. **Zhao Z**, Huang Z, Zheng X, et al. Evolutions of repetitively pulsed positive streamer discharge in electronegative gas mixtures at high pressure[J]. ***Plasma Sources Science and Technology***, ***2022***, 31 (7): 075006.
4. **Zhao Z**, Li J. Repetitively pulsed gas discharges: memory effect and discharge mode transition[J]. ***High Voltage***, ***2020***, 5 (5): 569-582.
5. **Zhao Z**, Huang DD, Wang YN, et al. Volume and surface memory effects on evolution of streamer dynamics along gas/solid interface in high-pressure nitrogen under long-term repetitive nanosecond pulses[J]. ***Plasma Sources Science and Technology***, ***2020***, 29 (1): 015016.

- Funding support from the National Natural Science Foundation of China (52107164, 52077168), the Fundamental Research Funds for the Central Universities (xzy012021015), and the China Postdoctoral Science Foundation (2021M702568).
- The authors acknowledge Dr. Yifei Zhu for fruitful discussions and simulations by Mr. Yulin Guo.

Thanks for your attention!

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