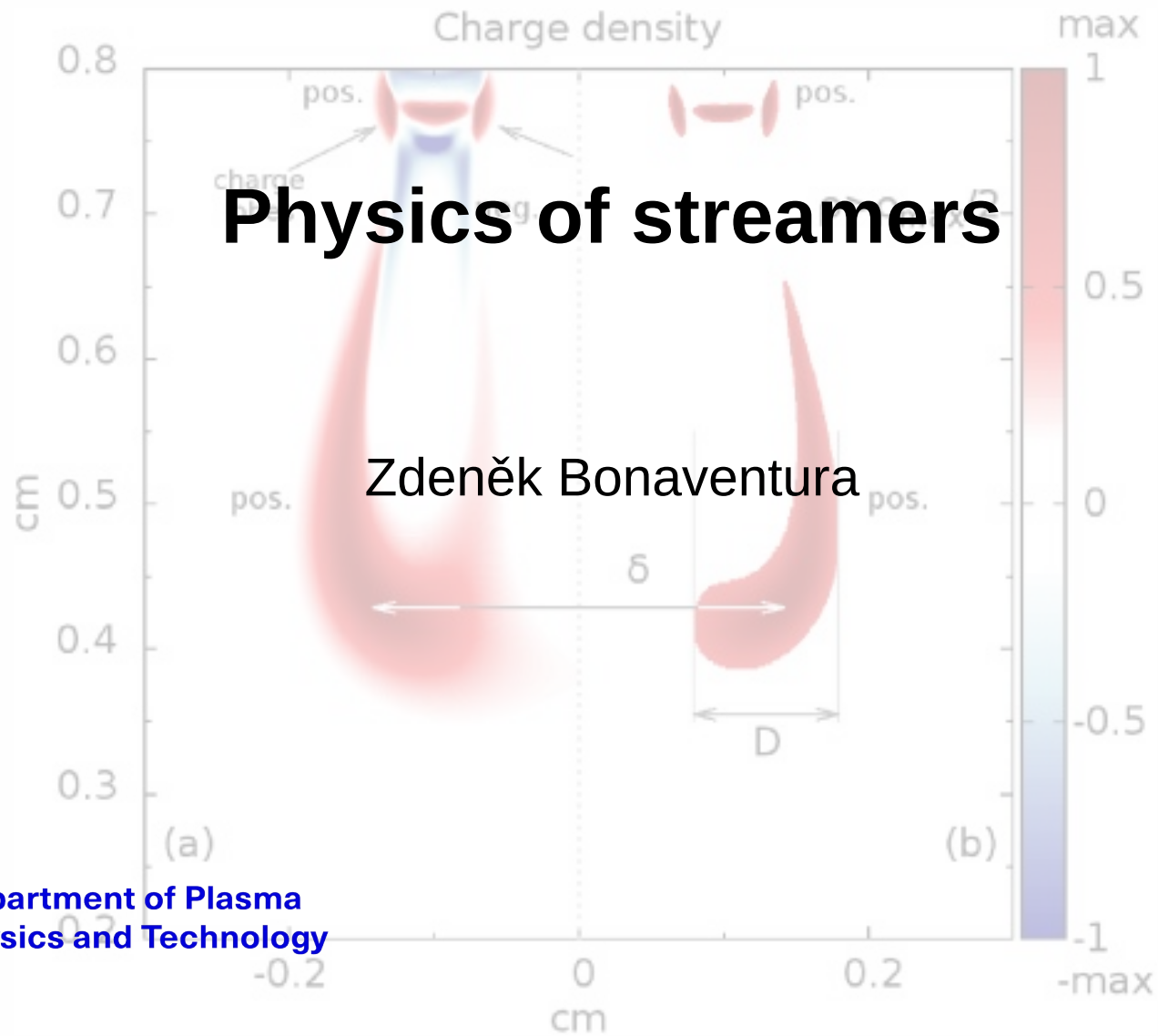


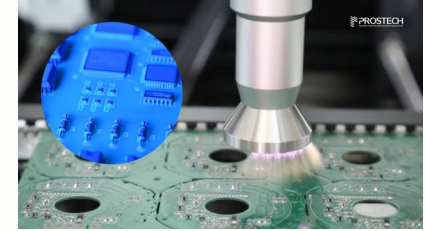
Physics of streamers

Zdeněk Bonaventura



Transient electric discharges

(strongly biased timeline)



TEDs: Almost as long as Earth existed..

Production of nitric acid by an electric spark in air
Cavendish H 1785 Experiments on air Phil. Trans. 75 372–84

Streamer Theory

TLS

Plasma roadmap
I Adamovich et al 2022
J. Phys. D: Appl. Phys. 55 373001

Today

4Gya

1785

1900 1924

1940

1960s

1980s 1990

Volcanic lightning → origin of life?

Avalanche theory

Ionization + self consistent E
Davies

Streamer simulation studies
Morrow/Lowke

**Runaway electrons
& TLS (prediction)**



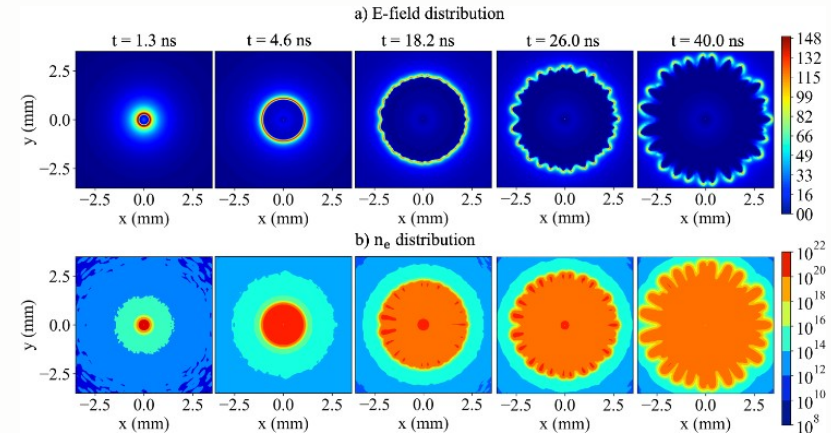
Eyjafjallajökull eruption april 17 2010 Credits:Marco Fulle

A Production of Amino Acids Under Possible Primitive Earth Conditions

Stanley L. Miller^{1, 2}
G. H. Jones Chemical Laboratory,
University of Chicago, Chicago, Illinois
Science. 117 (3046): 528–9.



Stephen Hummel

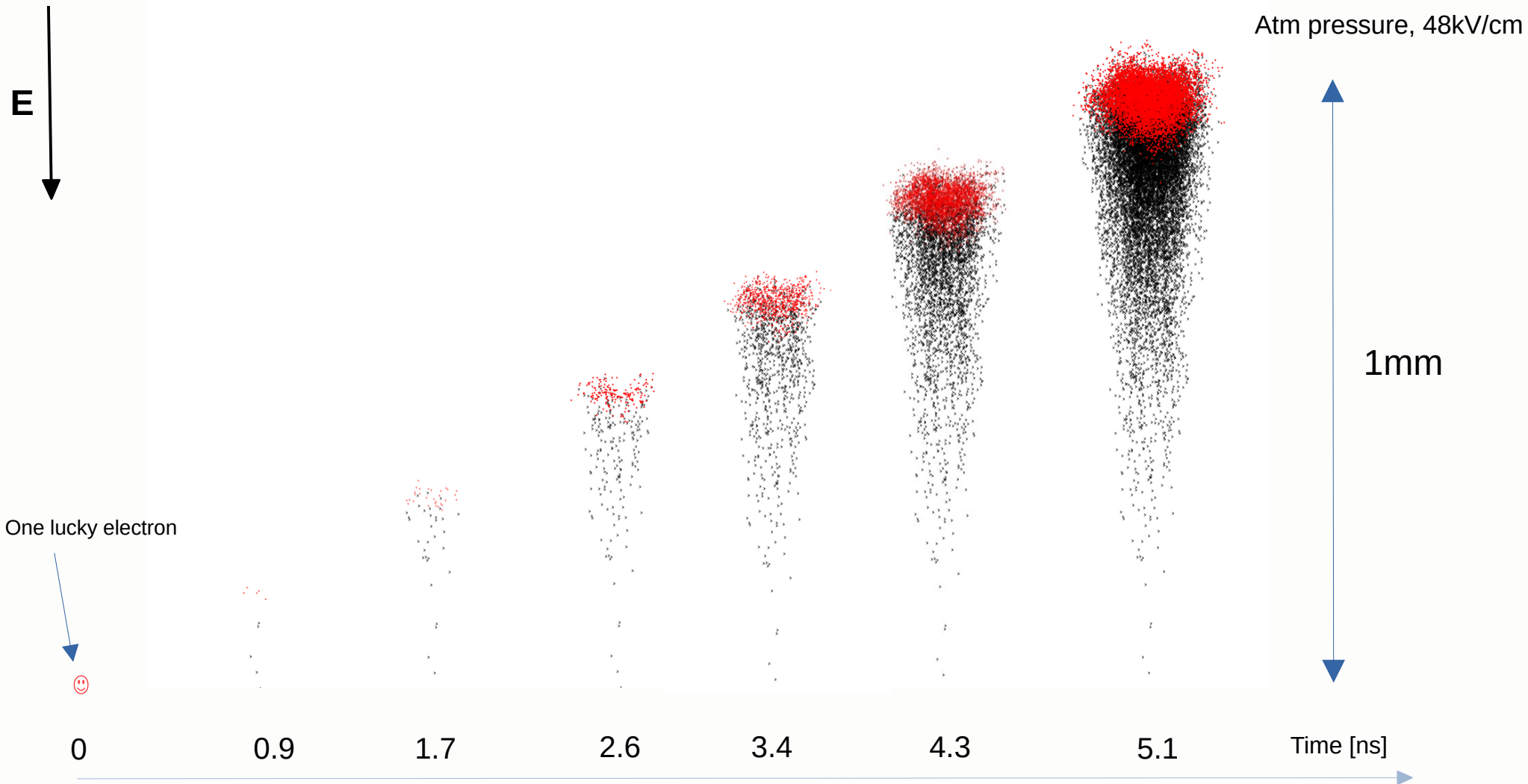


Antoine Herrmann et al 2025 Plasma Sources Sci. Technol. 34 015004



One lucky electron





E



0

0.9

1.7

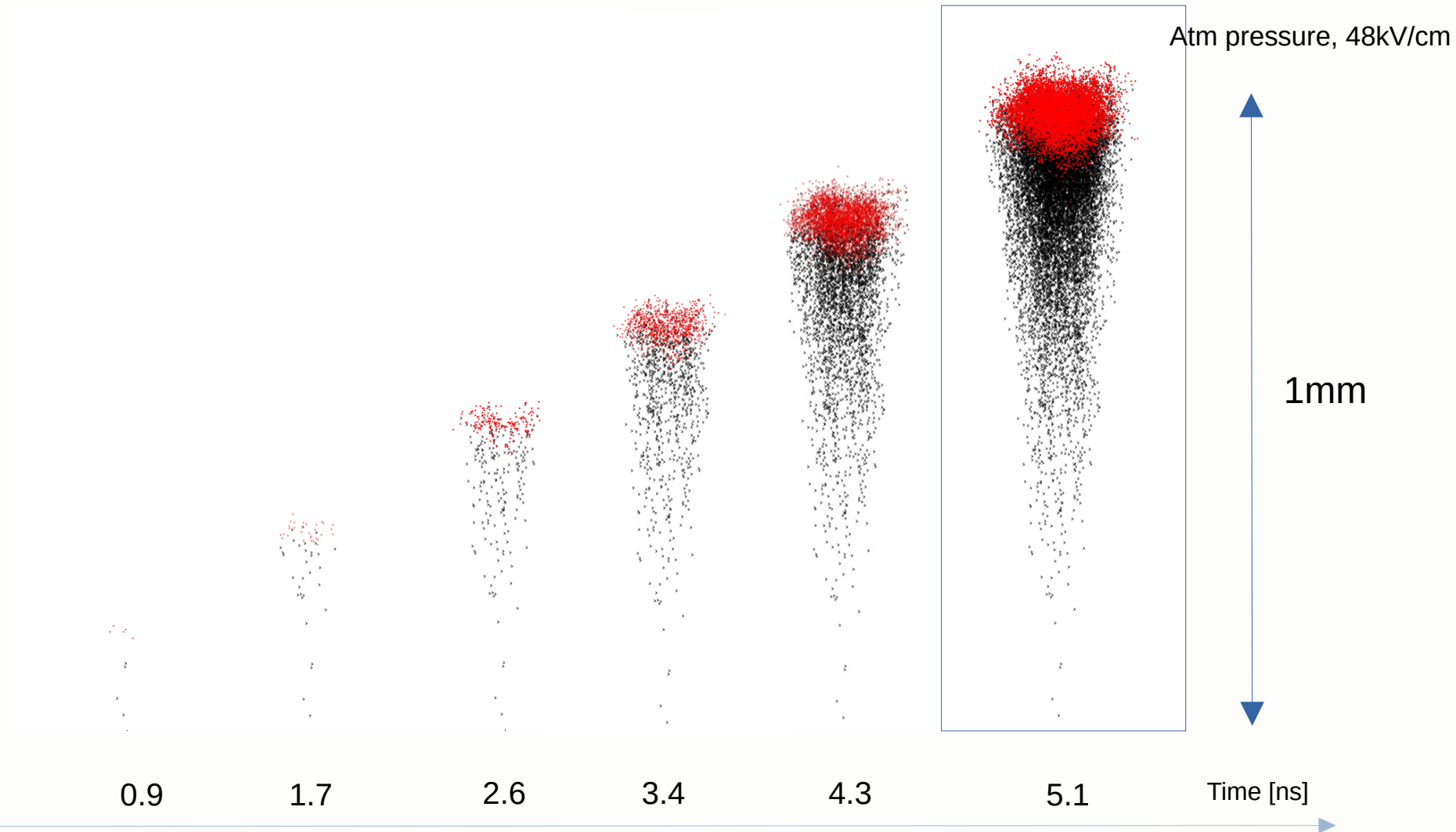
2.6

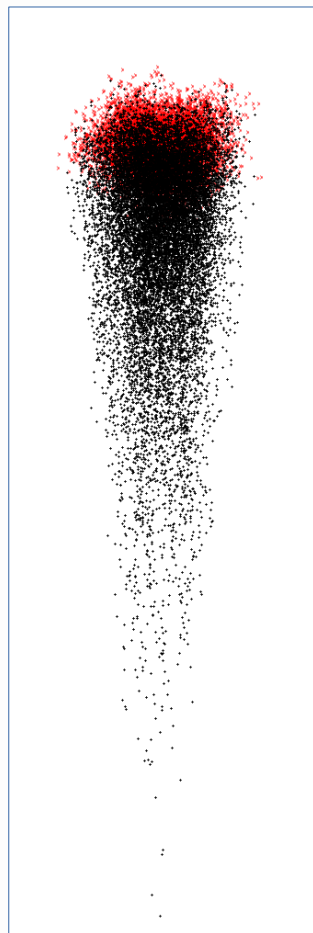
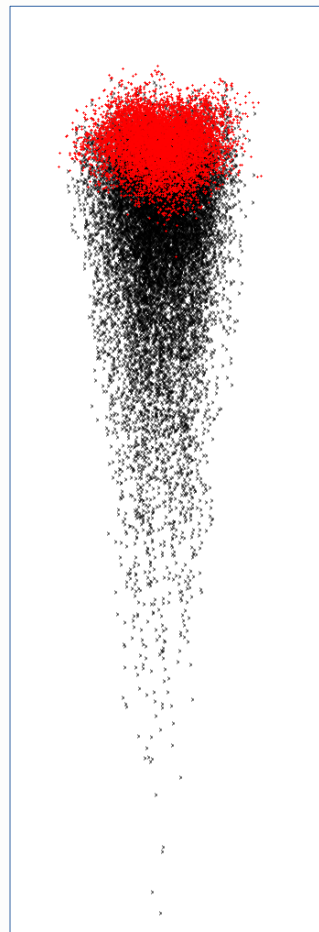
3.4

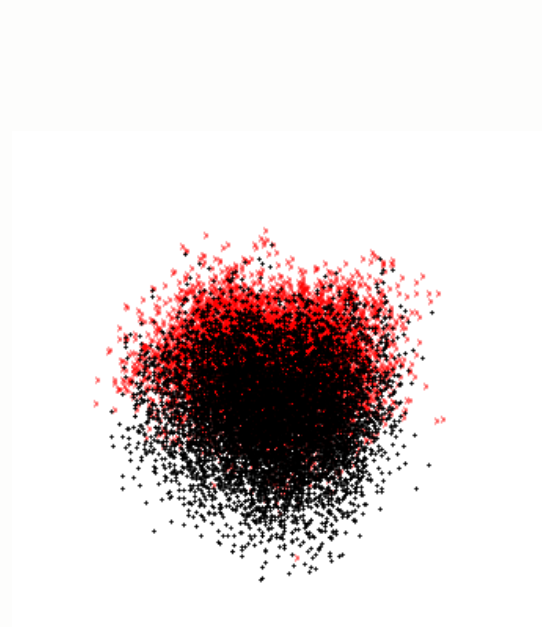
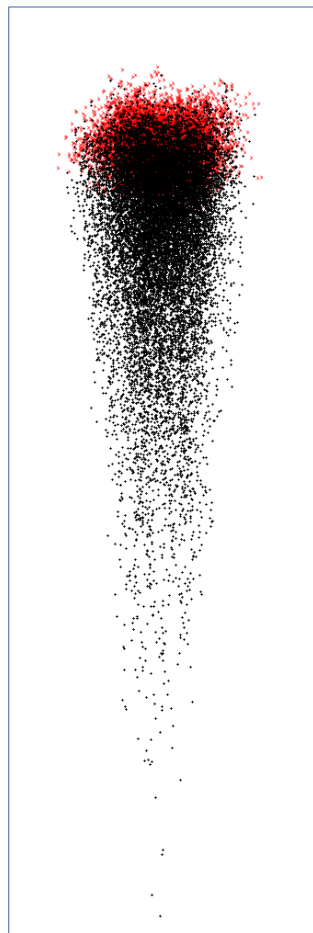
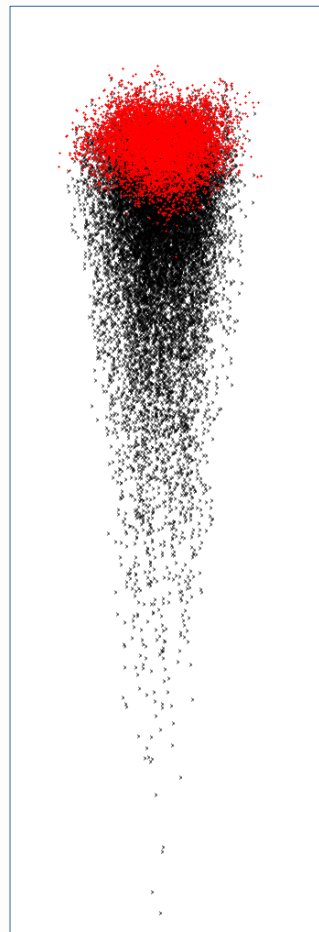
4.3

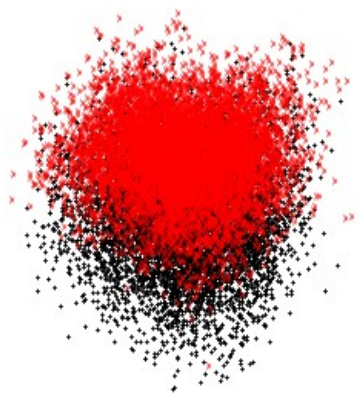
5.1

Time [ns]

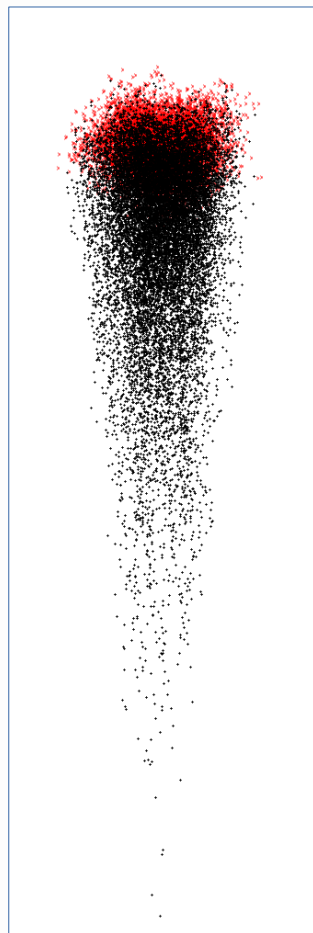
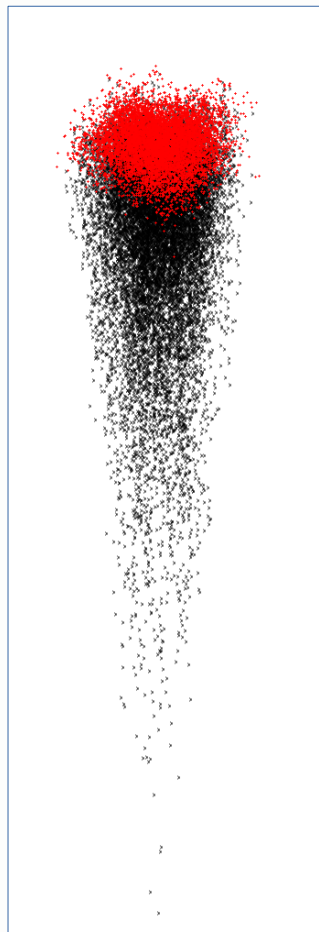






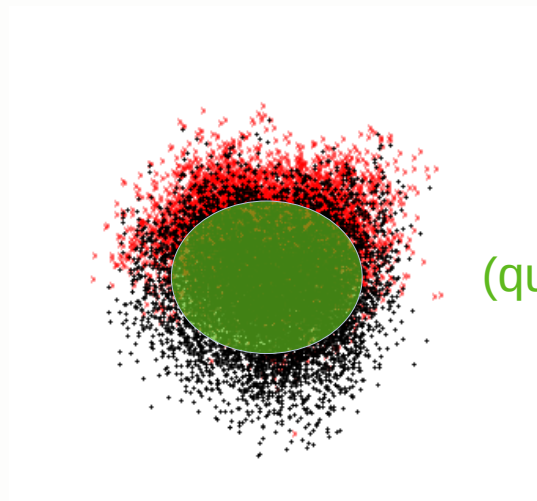


Positive 'space' charge



Negative 'space' charge

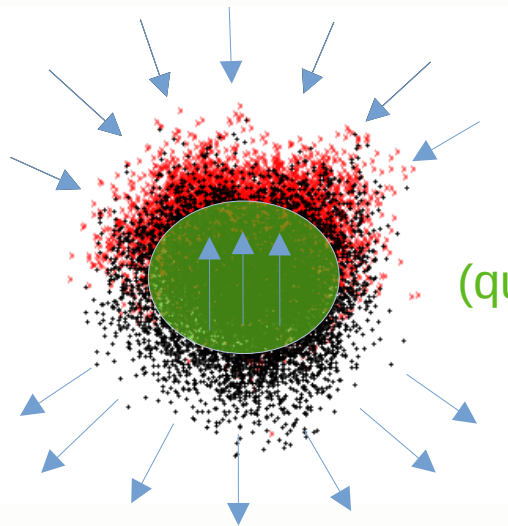




(quasi) neutral zone



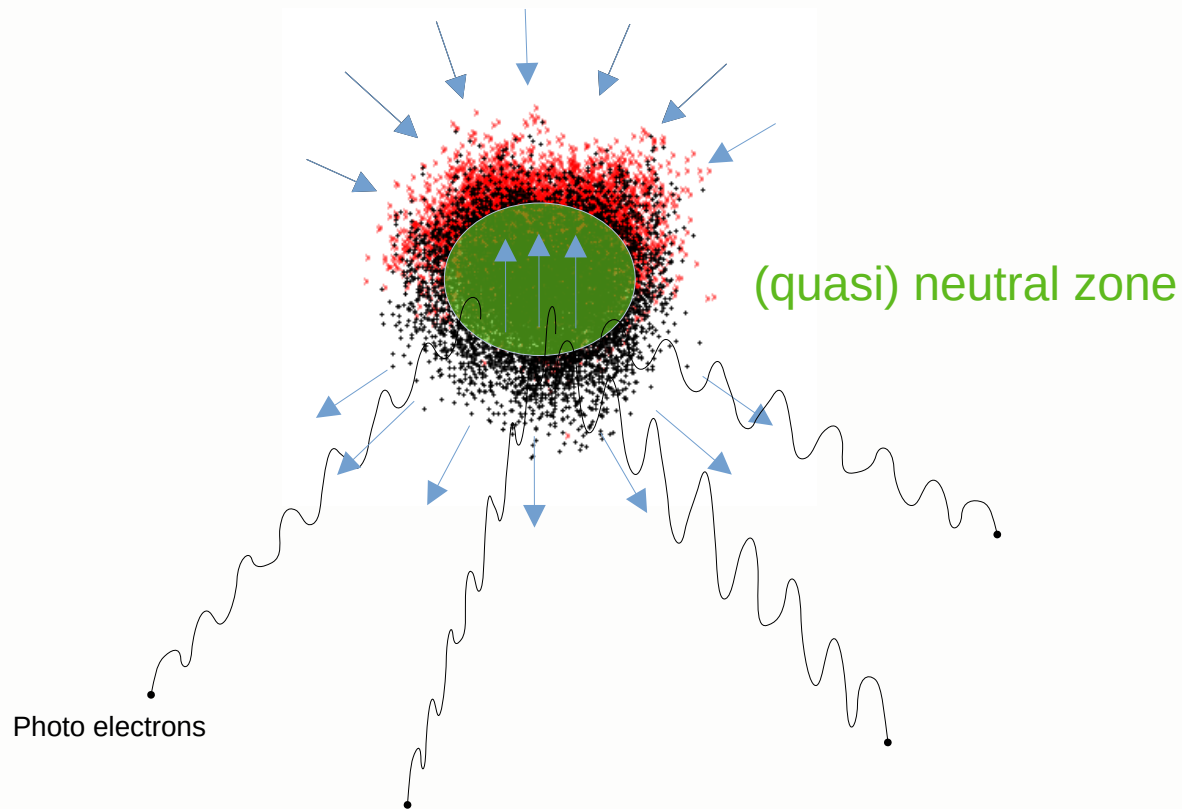
Space charge electric field

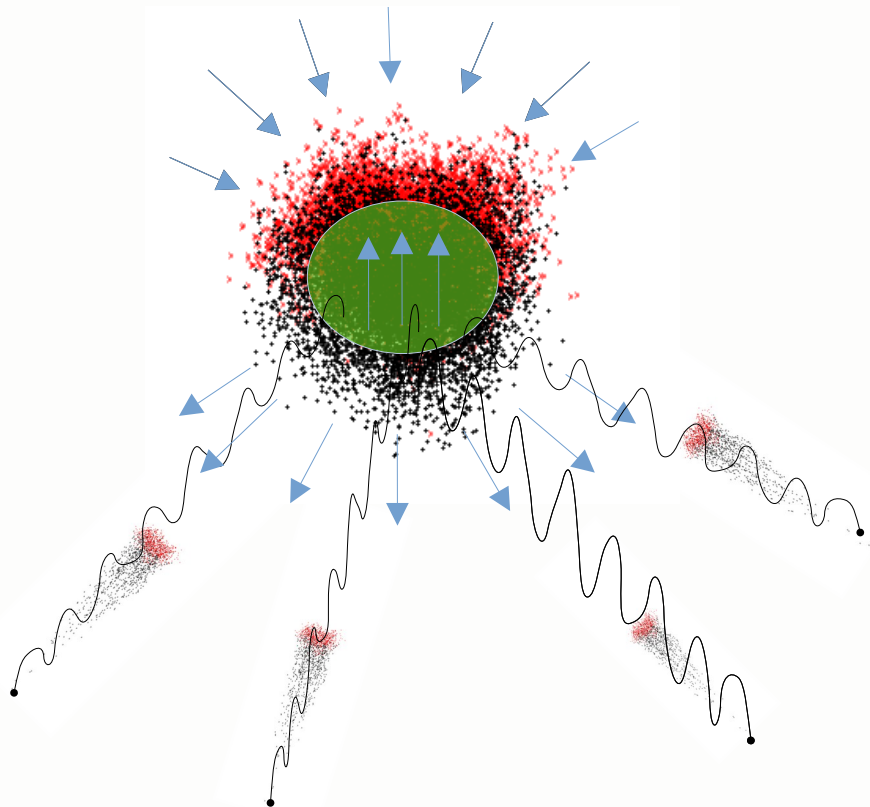


(quasi) neutral zone

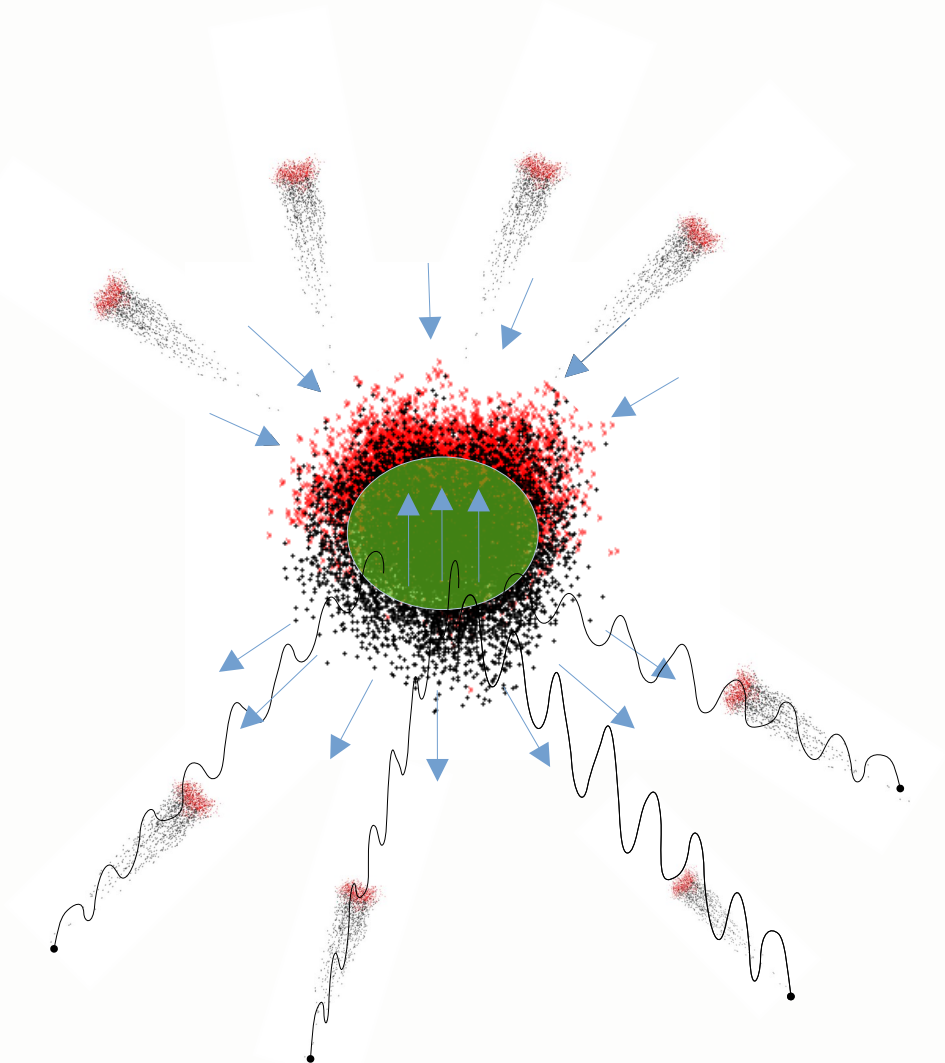


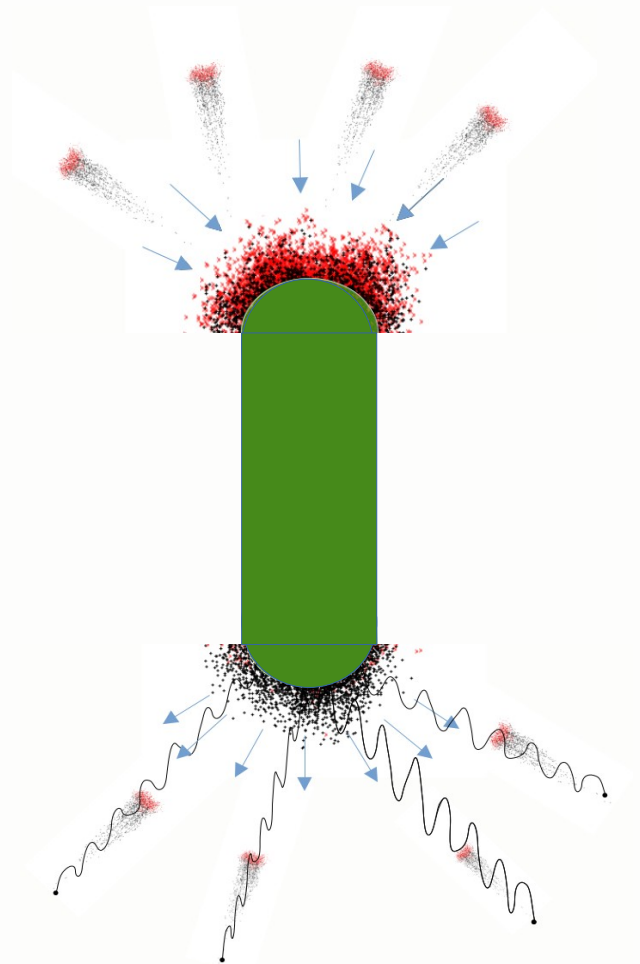
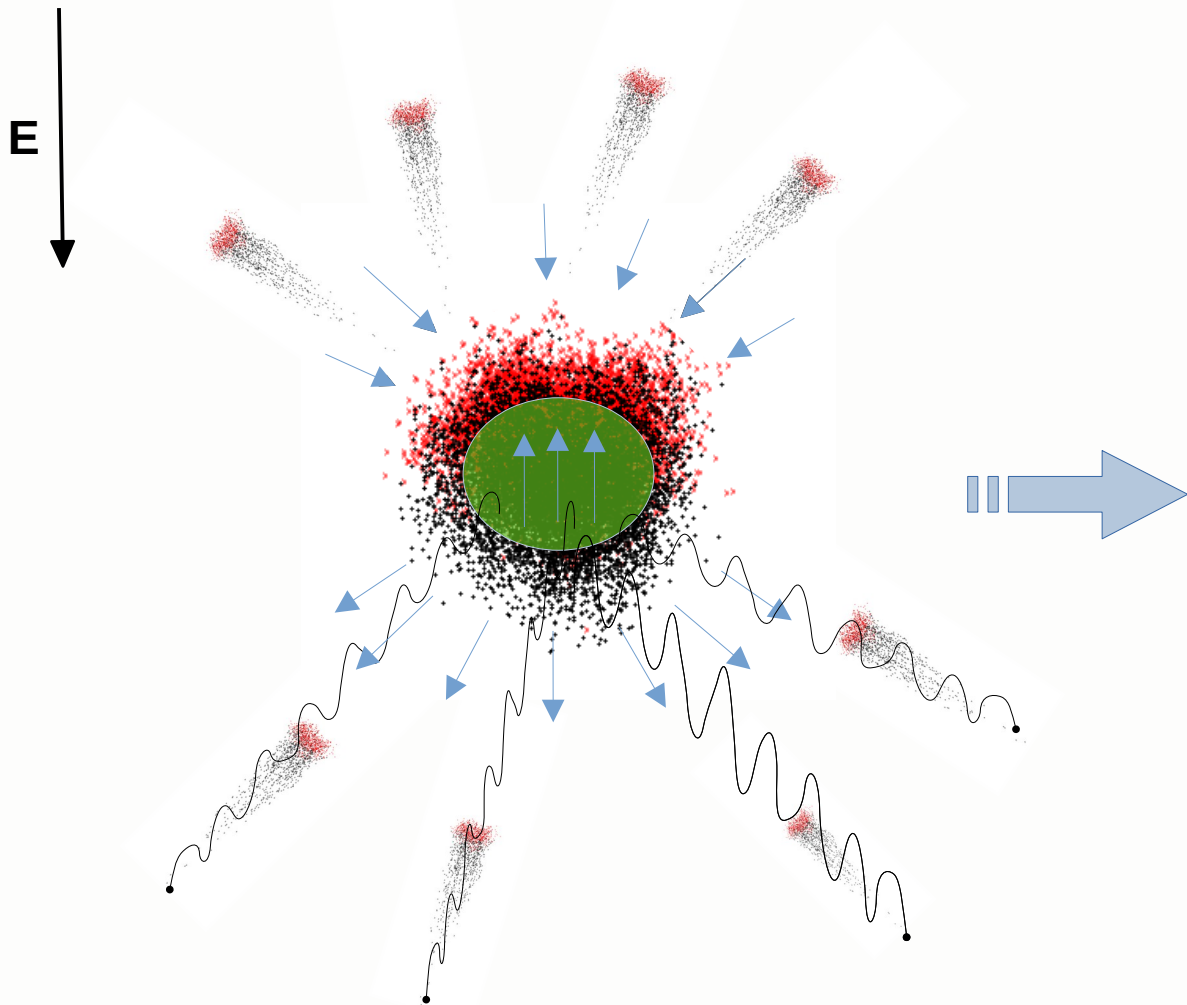
Space charge electric field



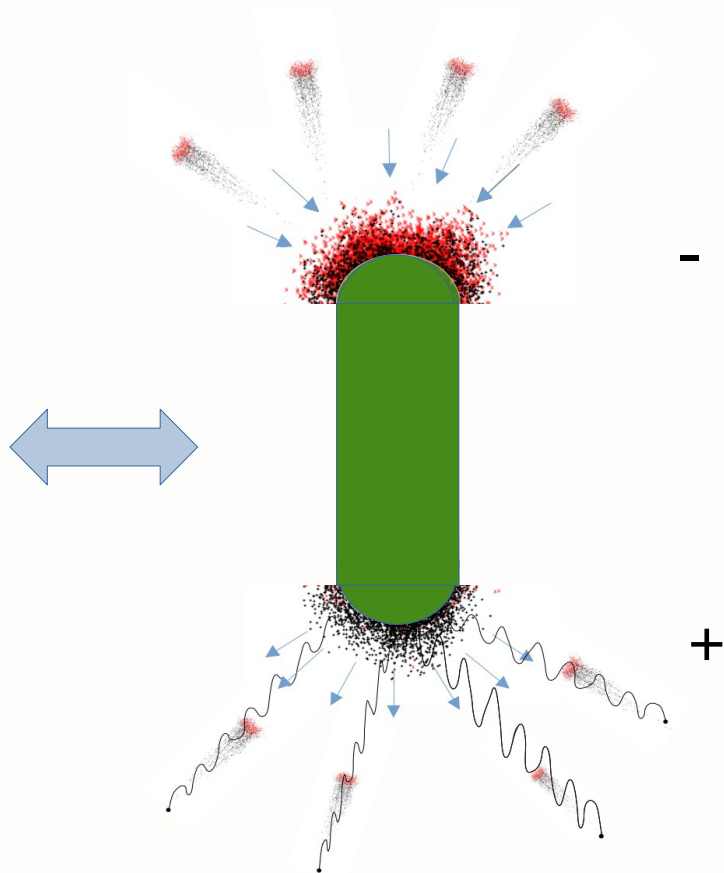
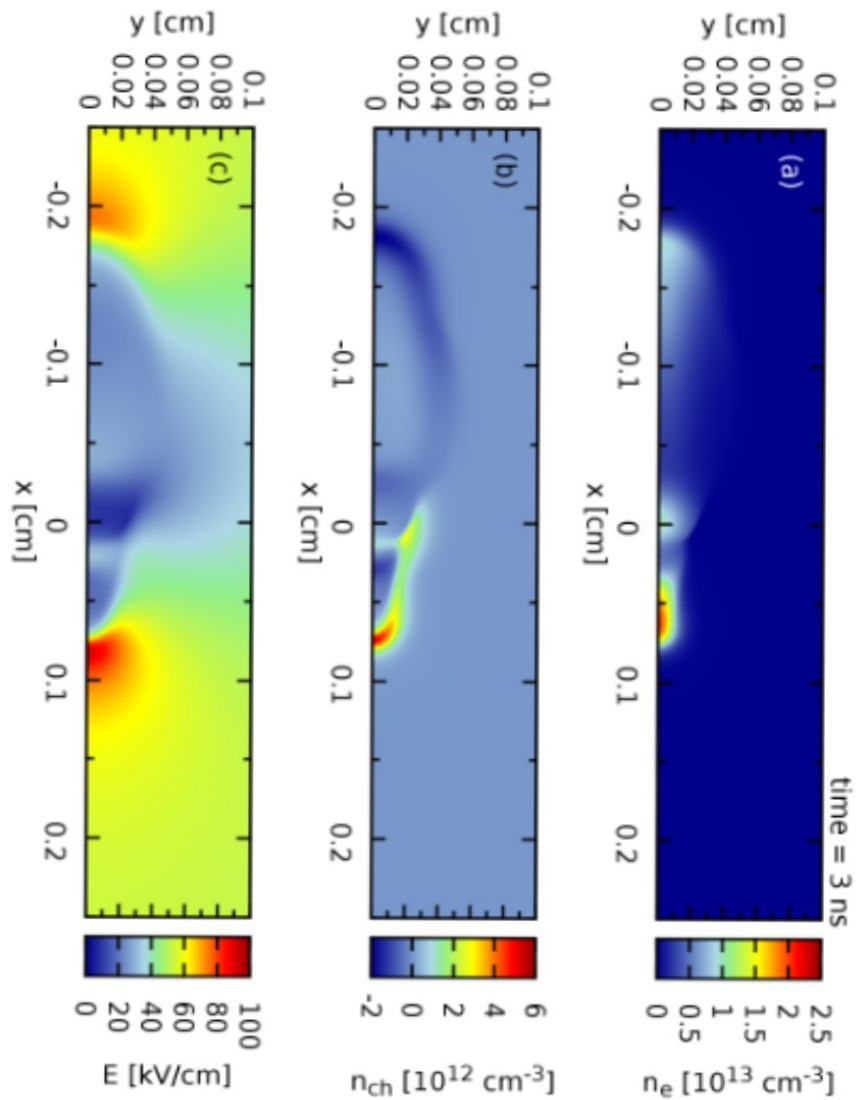


E





'Double headed' streamer



Basic feedback loop for streamer propagation



Free electrons present
(seed electrons / background ionization / photoionization)

$$n_e > 0$$



Electron transport in electric fields

(drift + diffusion)

$$\mathbf{\Gamma}_e = -\mu_e n_e \mathbf{E} - D_e \nabla n_e$$



Impact ionization in high field

(local electron multiplication)

$$S_i \sim \alpha(E) \mu_e E n_e$$



Charge separation and space charge

(electrons and ions redistribute)

$$\rho = e(n_i - n_e)$$



Electric field redistribution / enhancement

$$\nabla \cdot \mathbf{E} = \rho / \epsilon_0$$



Basic set of streamer equations

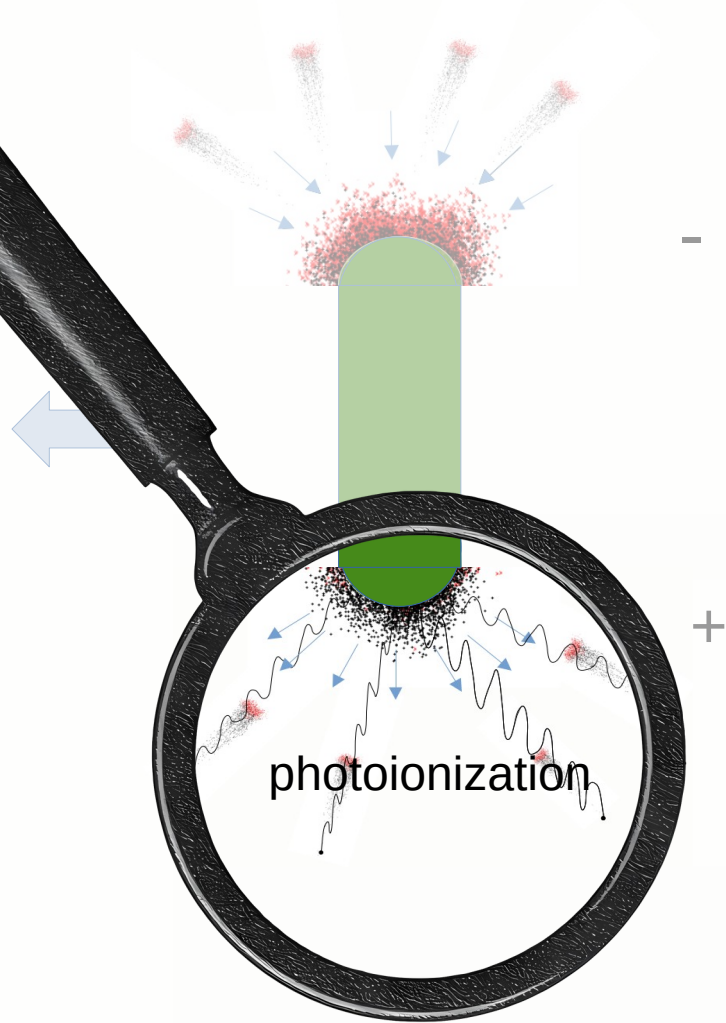
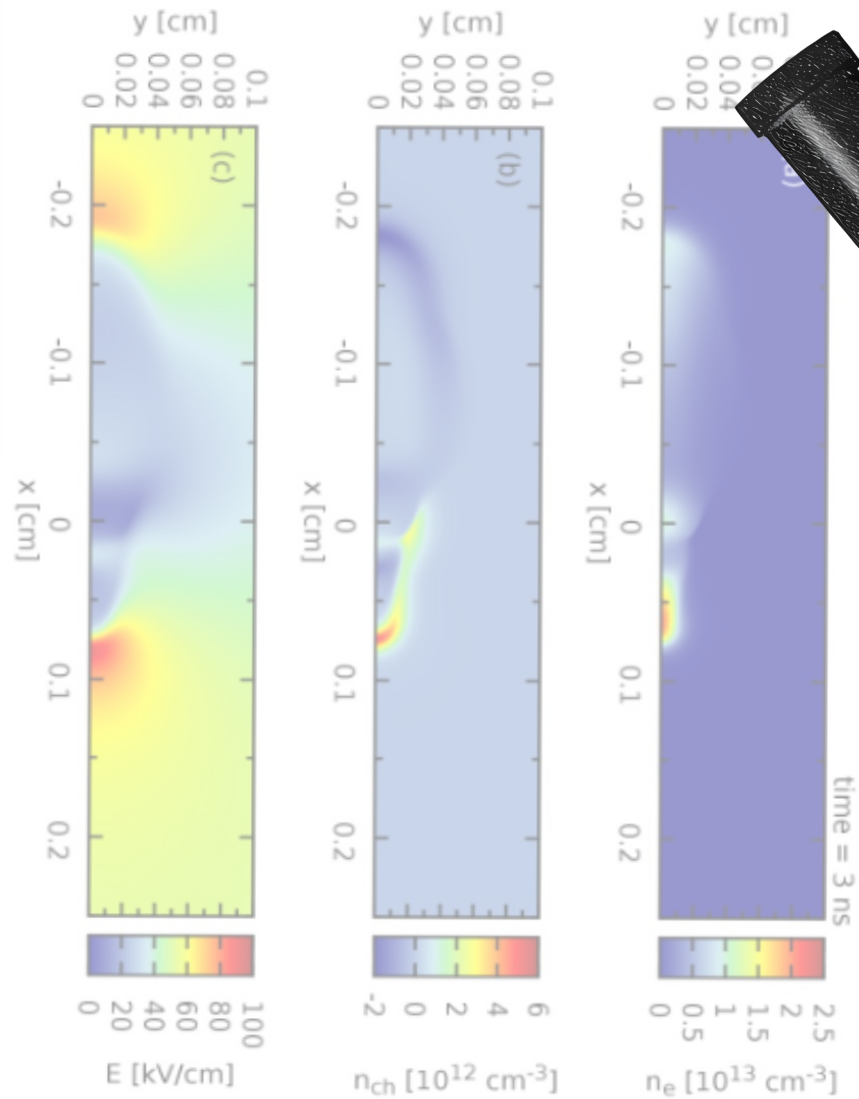
Electrons: $\frac{\partial n_e}{\partial t} + \nabla \cdot (-\mu_e n_e \mathbf{E} - D_e \nabla n_e) = S_{\text{ion}} - S_{\text{att}} + S_{\text{ph}}$

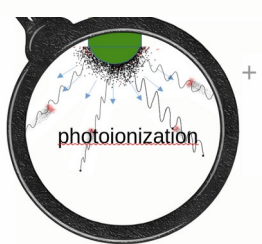
Pos. ions: $\frac{\partial n_i}{\partial t} = S_{\text{ion}} + S_{\text{ph}}$

Neg. ions: $\frac{\partial n_-}{\partial t} = S_{\text{att}}$

Electric field: $\nabla^2 \phi = -\frac{e(n_i - n_e - n_-)}{\epsilon_0} \quad \mathbf{E} = -\nabla \phi$

'Double headed' streamer

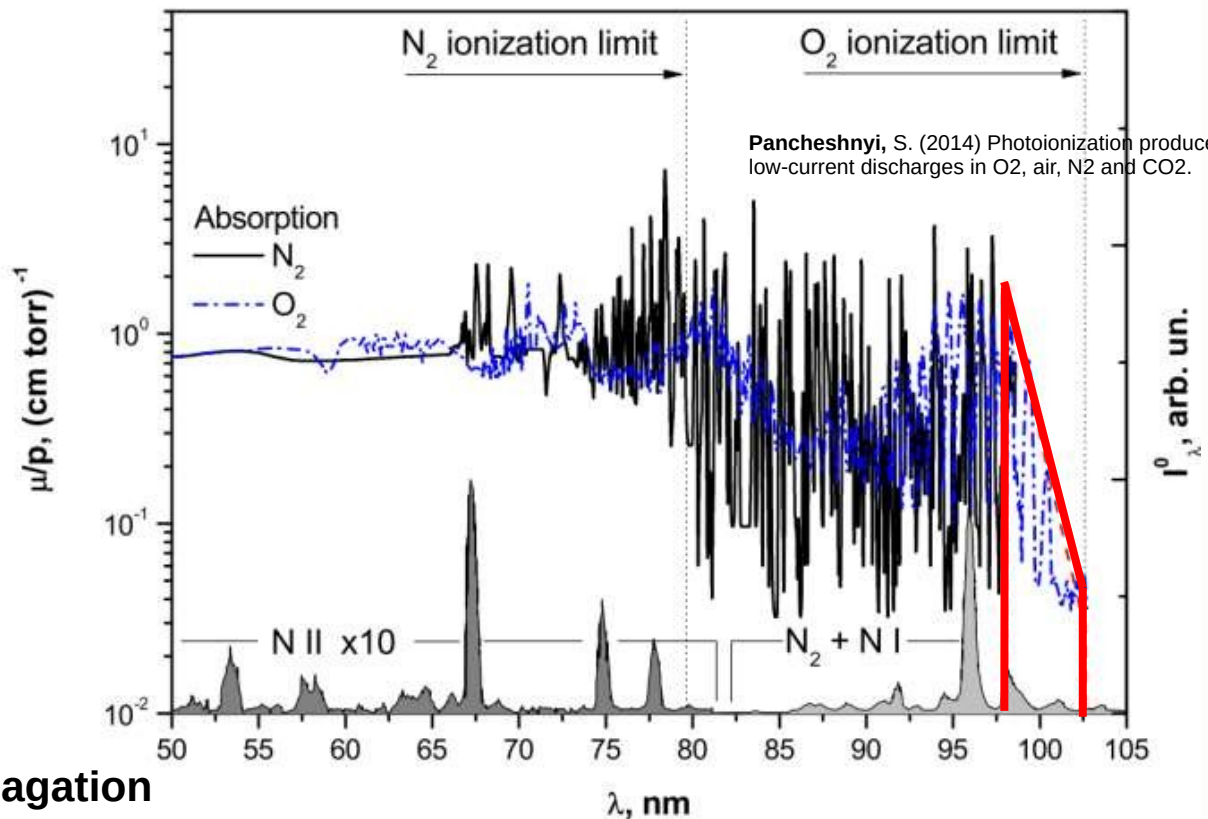
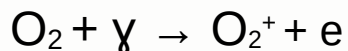
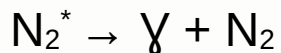
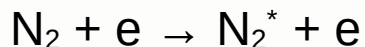




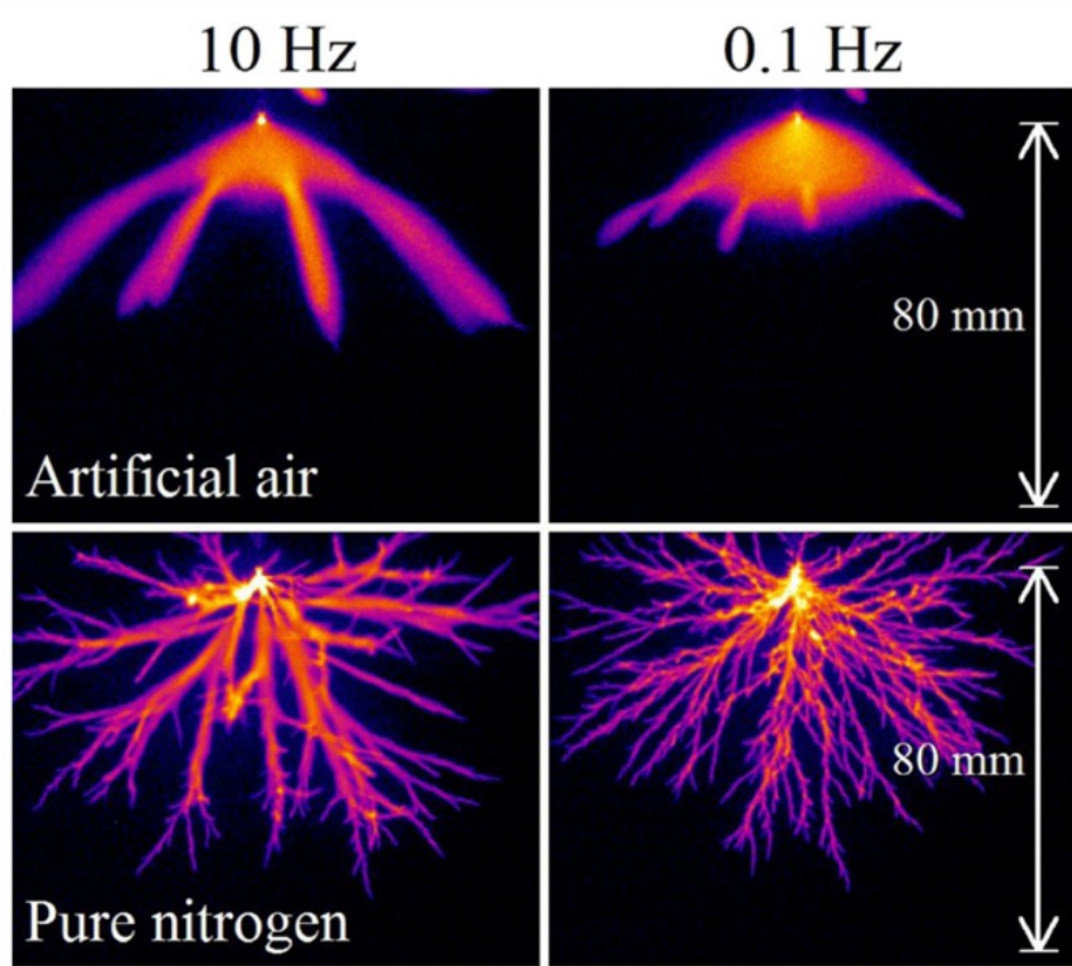
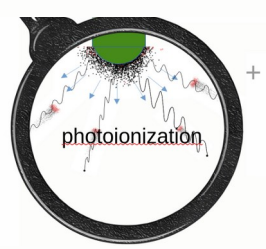
Photoionization window

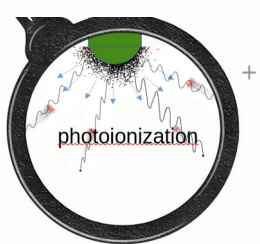
- O₂ ionization threshold of 12.1 eV
- N₂ absorbs strongly above 12.65 eV

Zheleznyak, M. B. et al. (1982).
Photoionization of nitrogen
and oxygen mixtures by radiation from a
gas discharge.

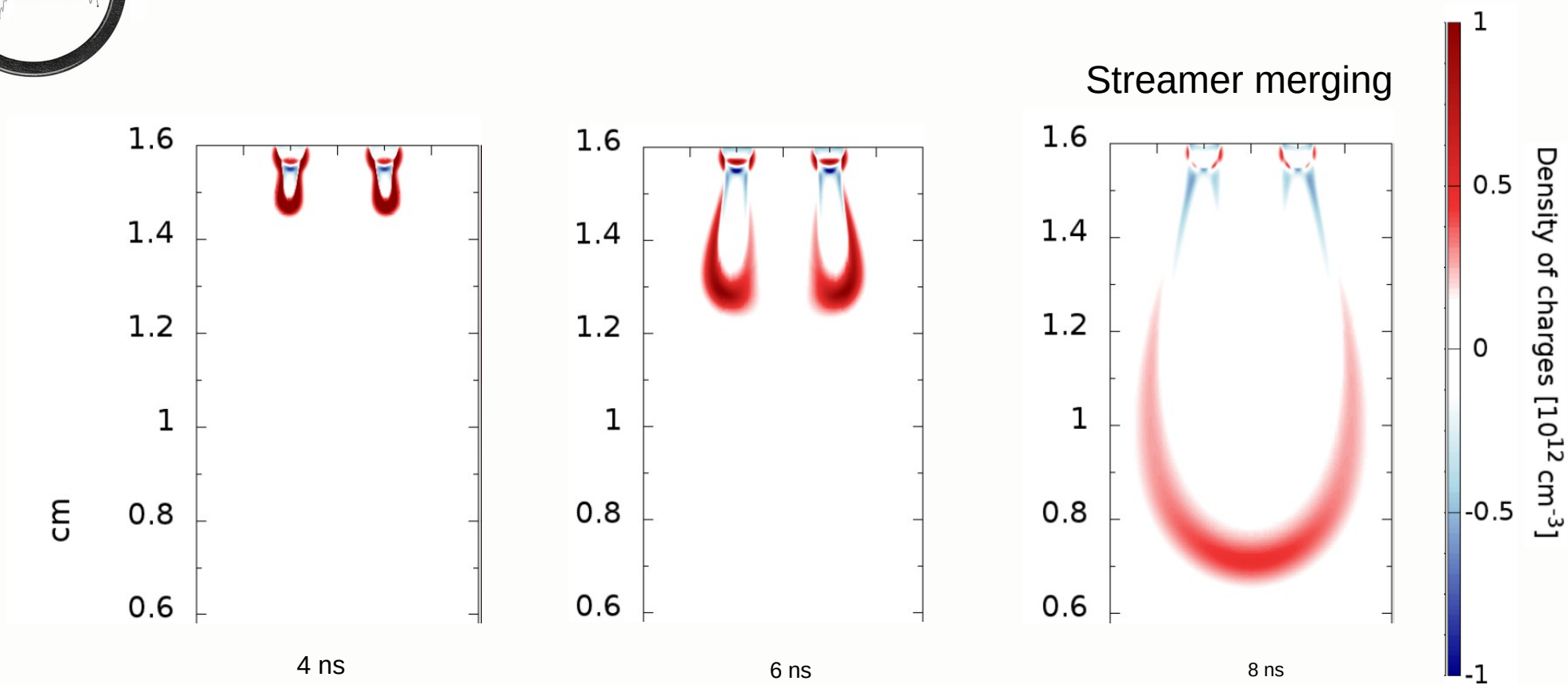


**Photoionization supports propagation
of positive streamers in Air**



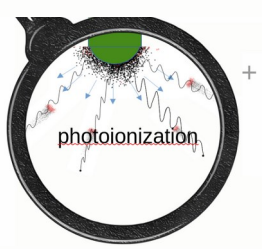


Interaction of two positive streamers



[Derivation of a merging condition for two interacting streamers in air](#)
 Z Bonaventura, M Duarte, A Bourdon, M Massot, PSST 21 (5), 052001, 2012.

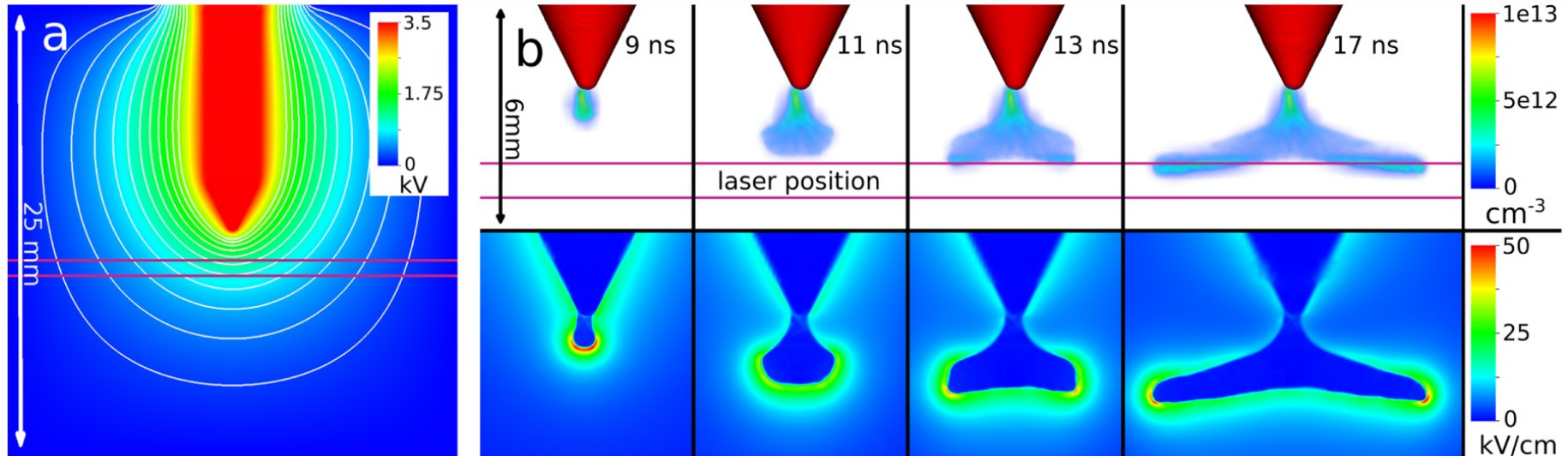
[A numerical strategy to discretize and solve the Poisson equation on dynamically adapted multiresolution grids for time-dependent streamer discharge simulations](#)
 M Duarte, Z Bonaventura, M Massot, A Bourdon J. Comp. Phys. 289, 129-148, 2015.



Guiding of streamers using laser induced ionization

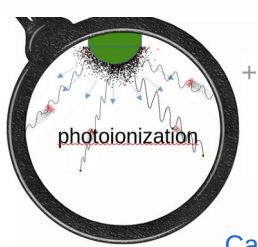
$\text{N}_2 + 10 \text{ ppm O}_2$

S Nijdam et al 2016 Plasma Sources Sci. Technol. 25 044001



Laser pulse: 1–2 mJ per pulse, wavelength of 248 nm, pulse length of 20 ns.

Laser guiding does not work in air $\Rightarrow$ photoionization is rather efficient source of electrons

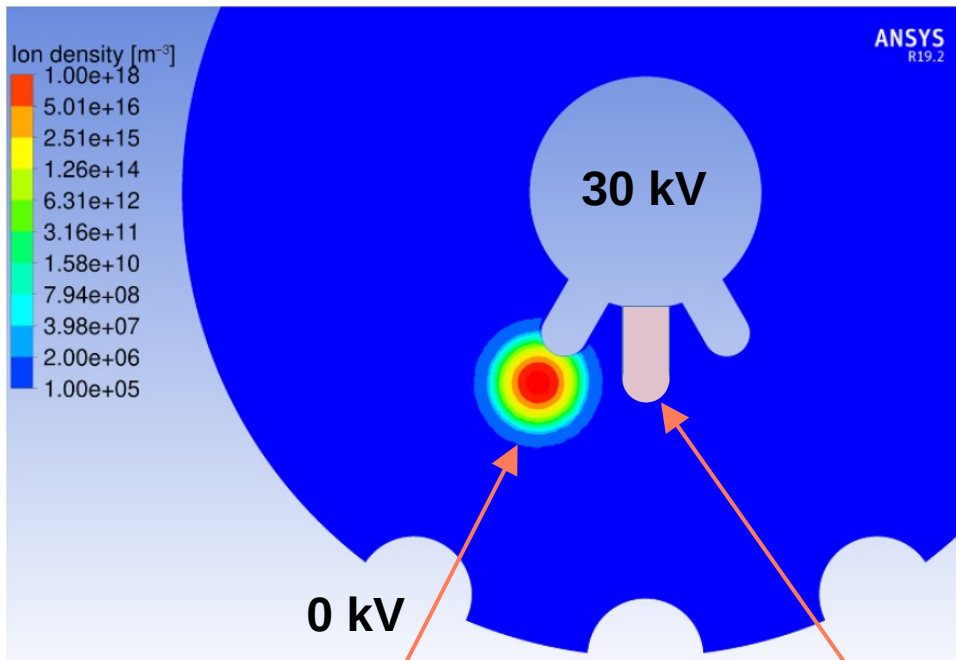


Capturing photoionization shadows in air streamer simulations

Eddington approx. of RTE vs Discrete Ordinates Method

Capturing photoionization shadows in streamer simulations using the discrete ordinates method

J Tungli, M Horký, S Kadlec, Z Bonaventura, Plasma Sources Science and Technology 32 (10), 105009, 2023.



Eddington approximation:

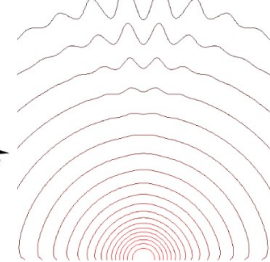
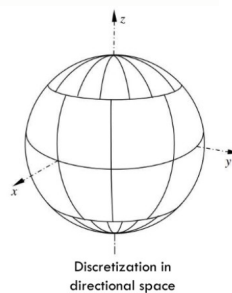
$$\left(\nabla^2 - 3(\lambda_j p_{O_2})^2\right)(\xi \Psi_{j,0}) = -3\lambda_j p_{O_2} \frac{q\zeta}{c} S_i$$

$$S_{ph}(\mathbf{r}) = \sum_j S_{ph,j} = p_{O_2} c \sum_j A_j \xi \Psi_{j,0}(\mathbf{r}),$$

Bourdon A, Pasko V P, Liu N Y, Célestin S, Ségur P and Marode E 2007 *Plasma Sources Sci. Technol.* **16** 656–78

Discrete Ordinate method:

- Divide directional space to $N_\theta \times N_\phi$ divisions (ordinates).
- For each direction solve direction-independent RTE.
- The incident radiation is given by a weighted sum of directed intensities.



$$N_\theta \times N_\phi = 12 \times 12$$

Dielectrics

Low preionization

$$n_0 = 10^5 - 10^9 \text{ m}^{-3}$$

$$A = 10^{18} \text{ m}^{-3}$$

$$y_0 = 4.6 \text{ mm}$$

$$y_0 = 8.1 \text{ mm}$$

$$\sigma = 4 \text{ mm}$$

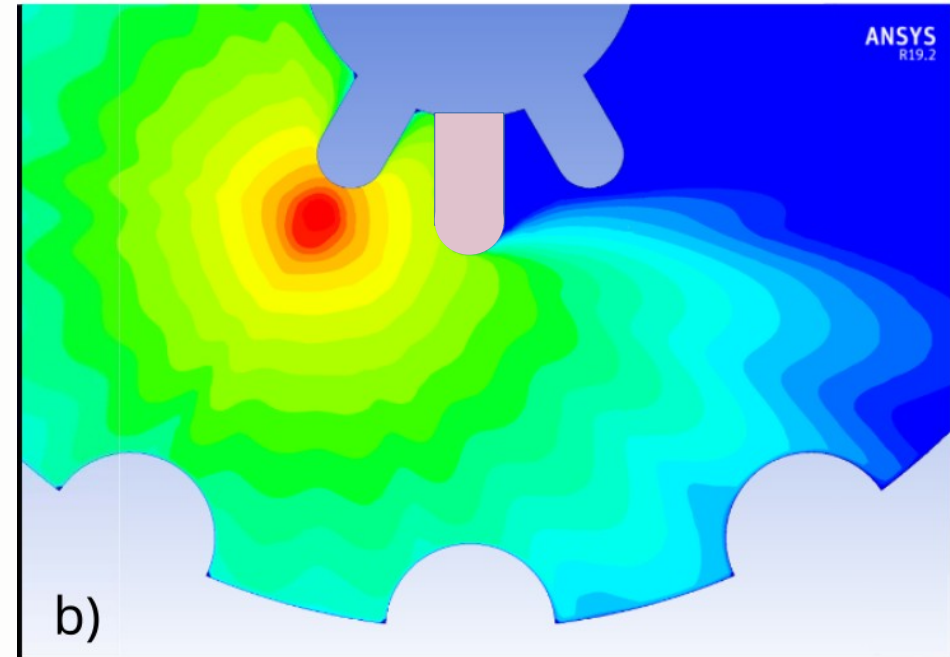
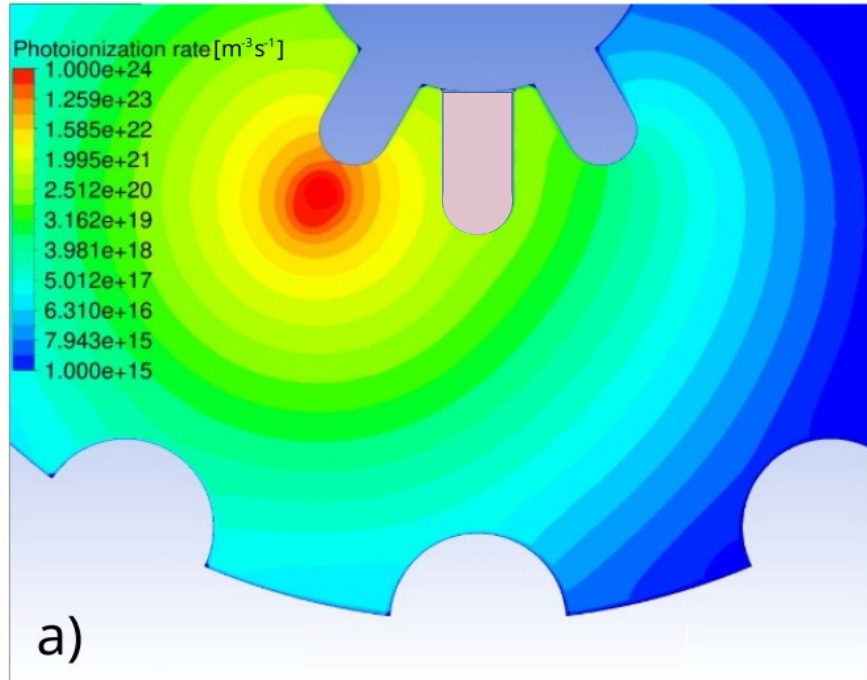
$$n_{e,i}(t=0) = n_0 + Ae^{-\frac{(x-x_0)^2 + (y-y_0)^2}{\sigma^2}}$$

Shadow effects on the photoionization source

$$n_0 = 10^5 \text{ m}^{-3}$$

Eddington model

Discrete Ordinates



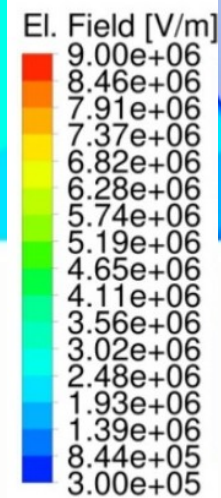
Q: Does the shadow leads to the **time delay** in **forming** of the **secondary streamer**???

6.8 ns
Primary streamer

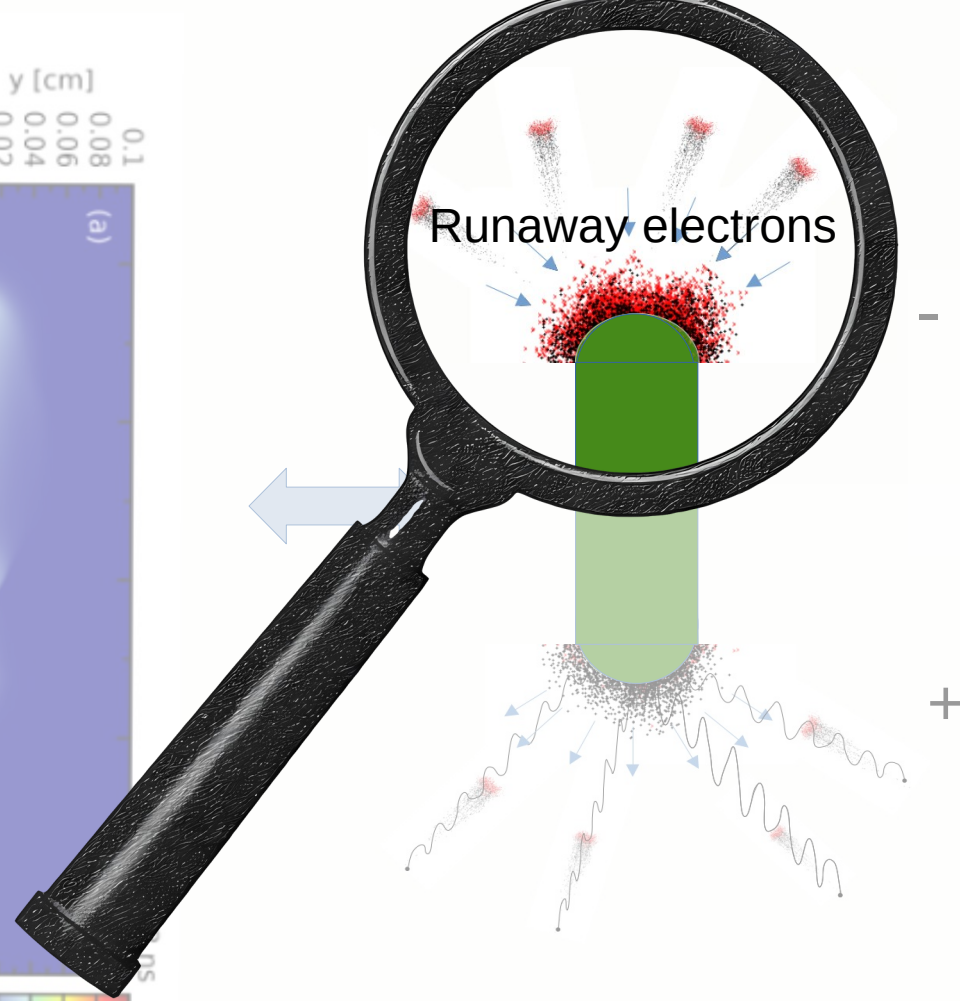
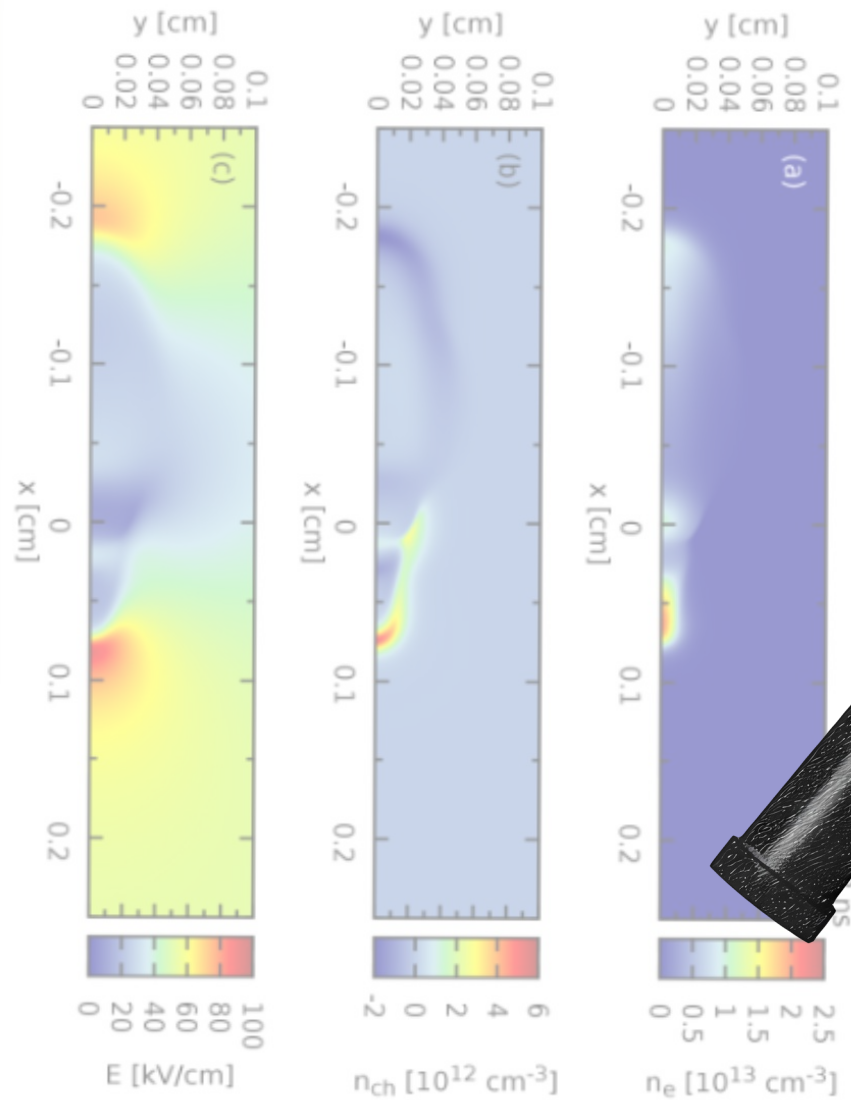
14 ns
Secondary streamer

Eddington

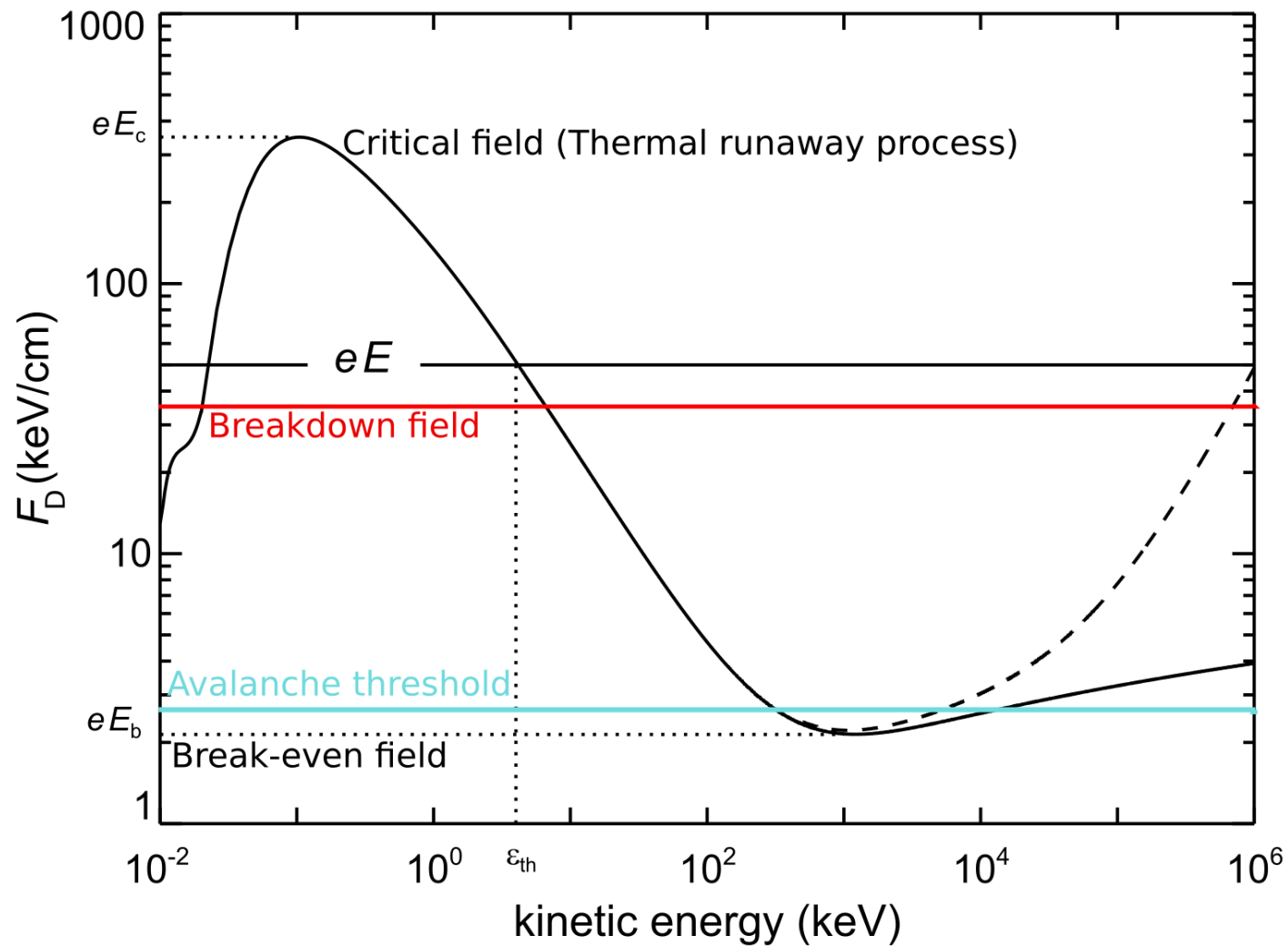
Discrete Ordinates



'Double headed' streamer

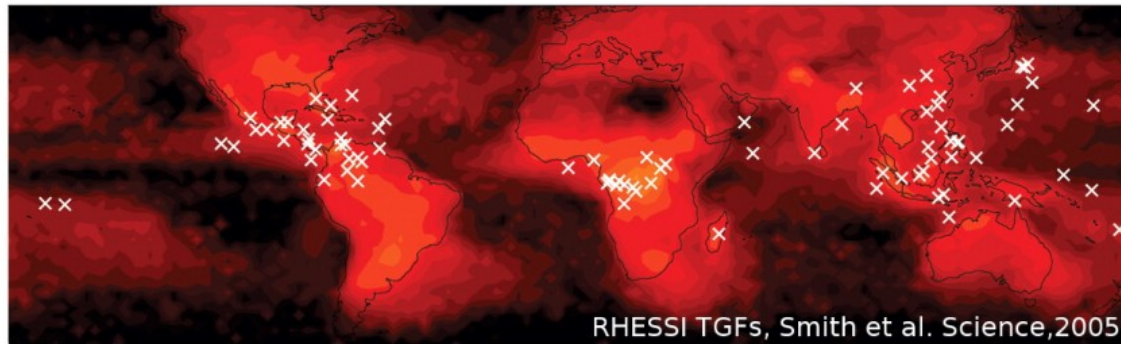
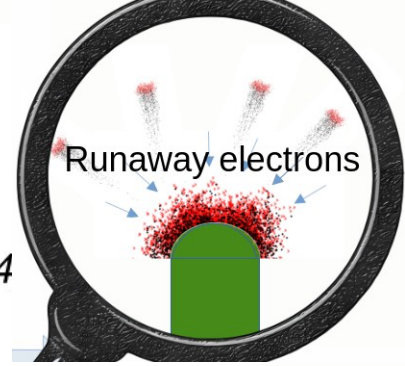


Thermal runaway process

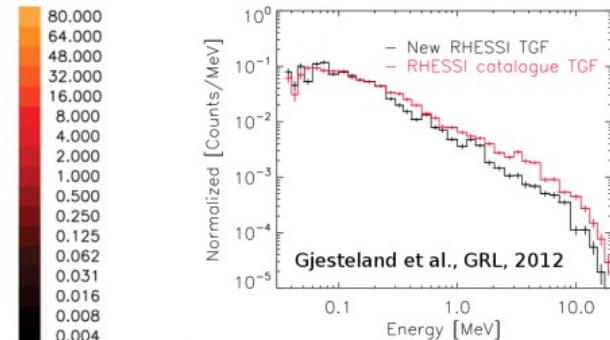


Runaways electrons and TGFs

- C.T.R. Wilson 1925: Runaway electrons (**RE**), bremsstrahlung.
- Terrestrial gamma-ray flashes (**TGFs**): *Fishman et al., Science 264 (1994)*
BATSE: 76 detections of **TGFs** in 9 years.
RHESSI: >500 detections (2004–2006).
- Possibly >50 **TGFs** per day (>3M lightning events).
- Source altitude < 20 km, energy of photons up to 20 MeV.
- **Accepted scenario**: bremsstrahlung of runaway electrons.

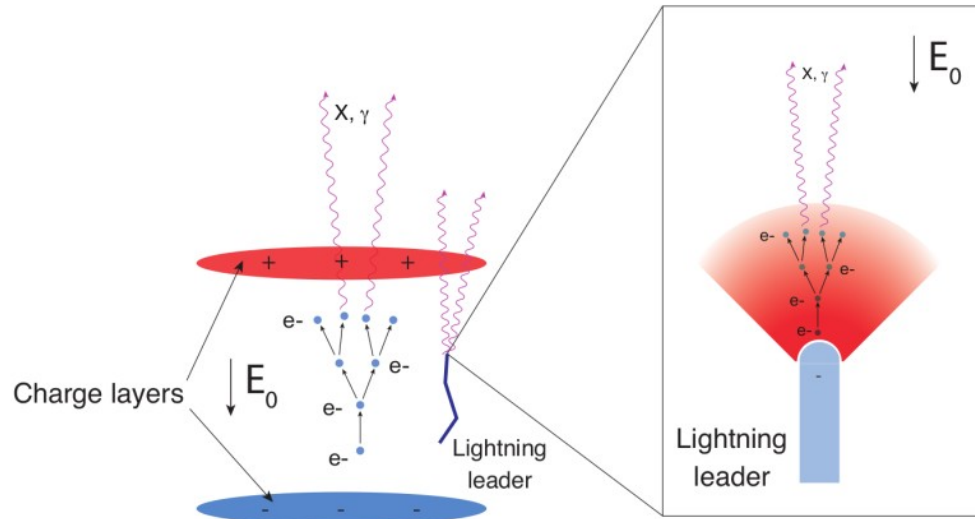
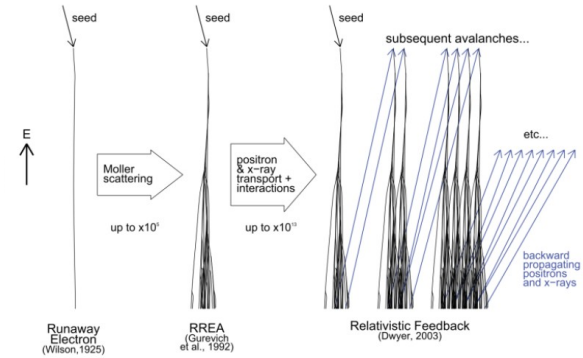


RHESSI TGFs, Smith et al. Science, 2005

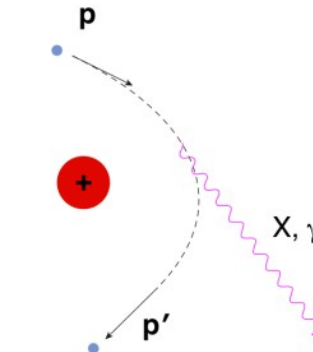


Two theories to explain TGFs

- Relativistic Runaway Electron Avalanche + Feedback (e.g., Dwyer)
 - high energy seed electron needed.
- Thermal runaway process (e.g., Moss 2006, Chanrion 2008, 2014, Li 2012, Celestin 2011)
 - **acceleration of electrons in streamer fields** (tens of kV).
 - further acceleration in the field of leaders (tens of MV).



Credits: S.Celestin

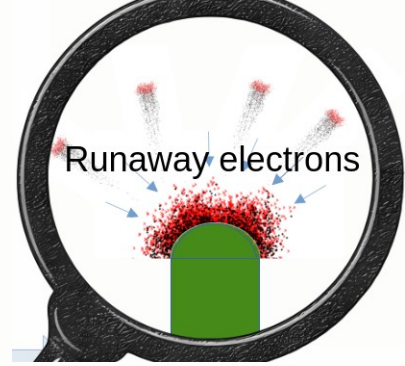


Bremsstrahlung emission process.

Needed: 10^{17} runaway electrons, $>1\text{MeV}$, (Dwyer, GRL, 2003).

Is the thermal runaway process from streamers able to provide enough of RE??

How RE effect negative streamer propagation?

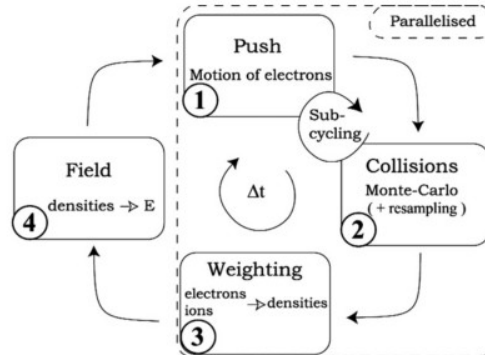


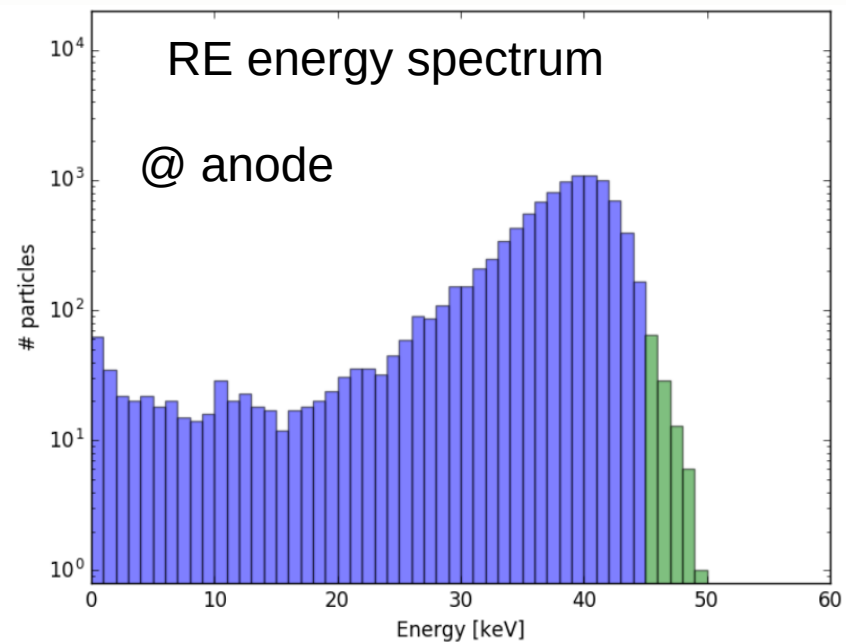
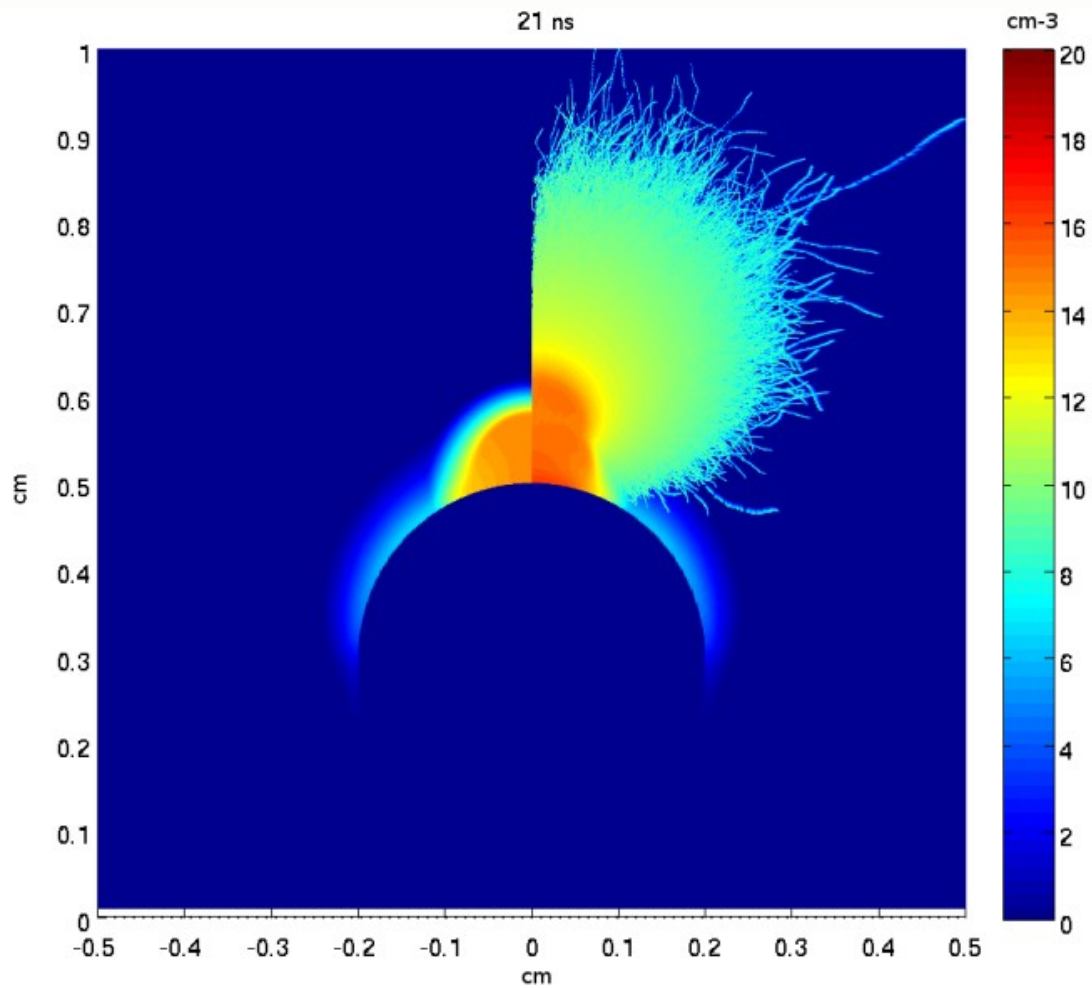
A beam-bulk approach proposed by Belenguer and Boeuf for RF discharge (Phys. Rev. A, 1990).

- 2 models for 2 electron groups divided in the energy space:
- **Low energy electrons** (< 100 eV): fluid **Drift-Diffusion** code

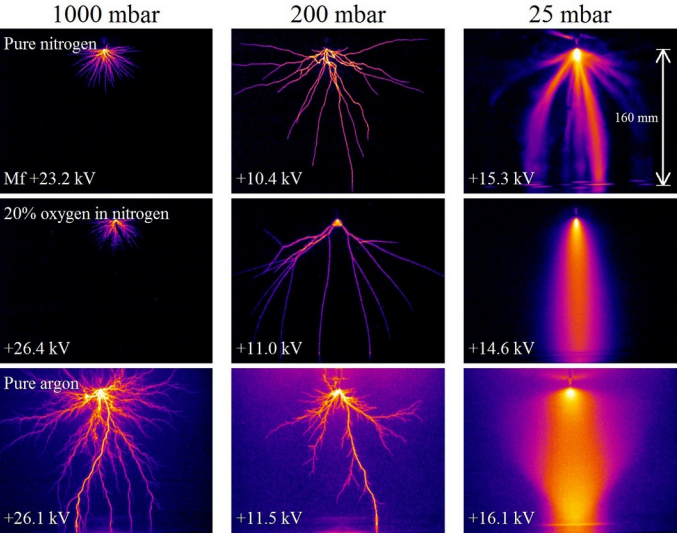
$$\begin{aligned}\partial_t n_e + \nabla \cdot (n_e \mathbf{v}_e) - \nabla \cdot (D_e \nabla n_e) &= n_e \alpha |\mathbf{v}_e| - n_e \eta |\mathbf{v}_e|, \\ \partial_t n_p &= n_e \alpha |\mathbf{v}_e|, \\ \partial_t n_n &= n_e \eta |\mathbf{v}_e|,\end{aligned}\tag{1}$$

- **High-energy electrons: PIC-MCC** code (Chanrion, JCP, 2008) with RBEB electron impact ionization model (Celestin, Pasko 2010)



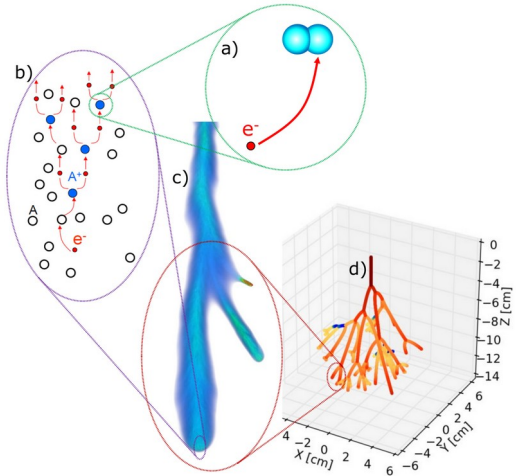


Conclusion and Challenges



Sander Nijdam et al 2020 Plasma Sources Sci. Technol. 29 103001

Gas mixtures/pressures



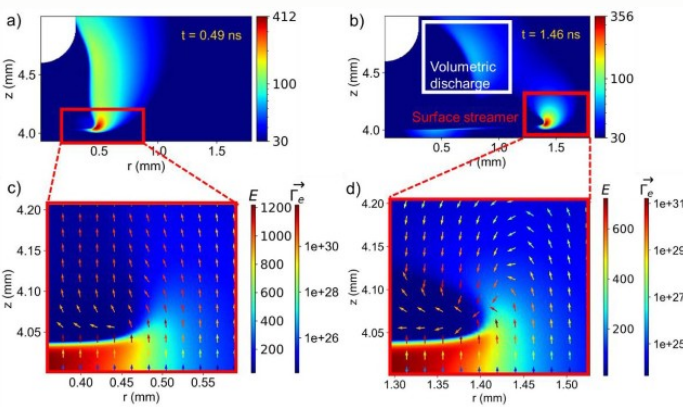
Sander Nijdam et al 2020 Plasma Sources Sci. Technol. 29 103001

Multiscale nature



Credits: Milan Šimek

Fast HV pulsed break down in water



Antoine Herrmann et al 2024 Plasma Sources Sci. Technol. 33 025022

Streamer surface interaction

Streamer to spark on water

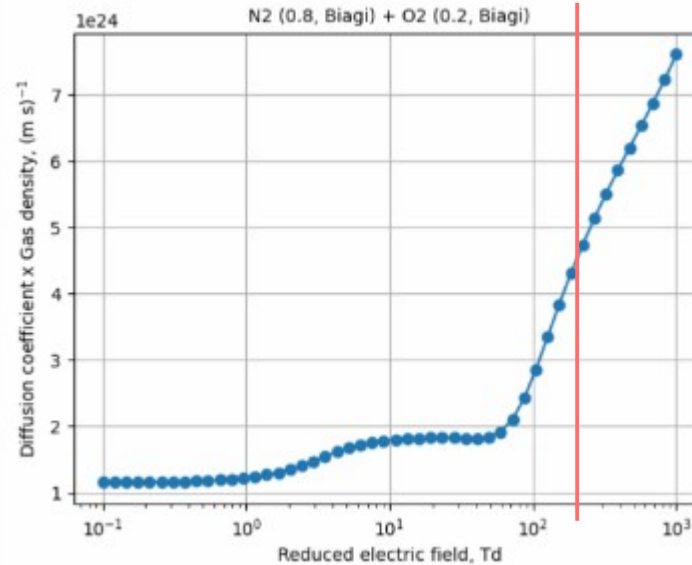
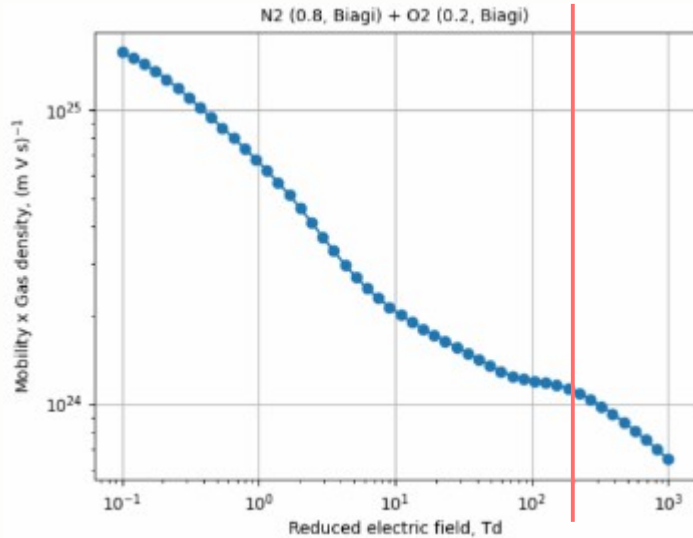


Credits: Milan Šimek

Discussion

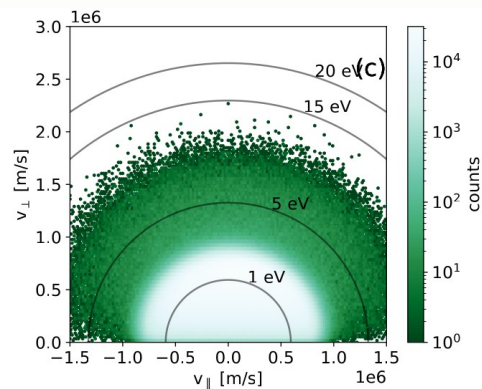
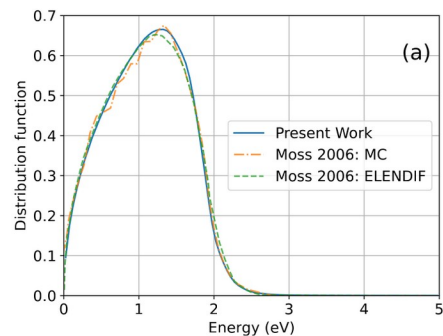
CDP Q1:

The document shows several results for the mobility and diffusion coefficients (figures 1.3, pg. 11) obtained from the solutions to the electron Boltzmann equation using Bolsig+ (which means under the usual two-term approximation) up to a value of the reduced electric field of 1000 Td. Isn't this upper value too large to use a Boltzmann solver based on the two-term approximation?

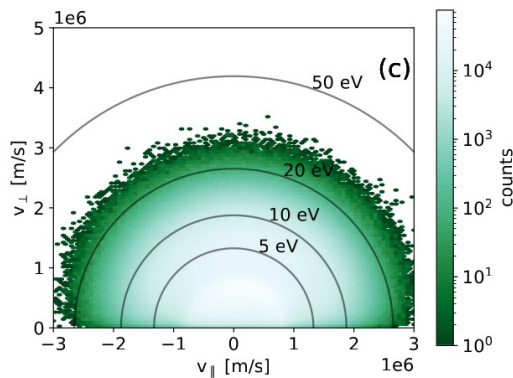
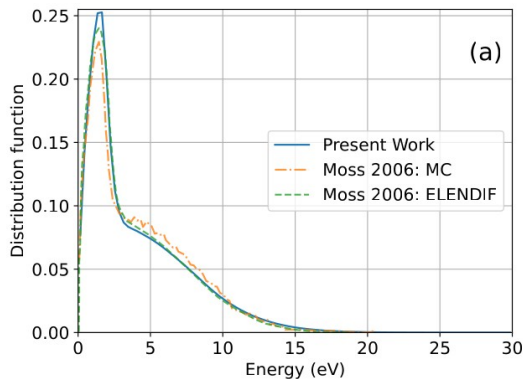


Yet, it is too high!

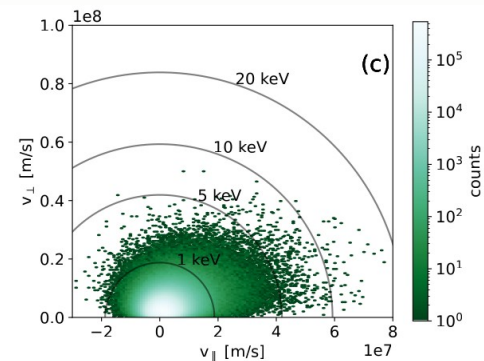
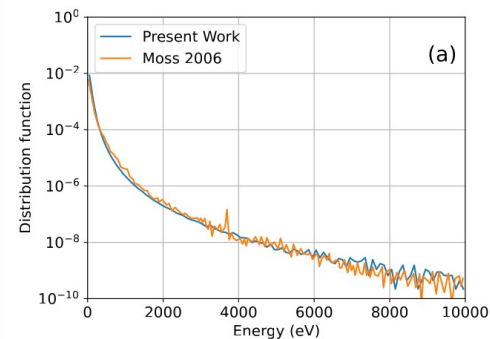
CDP Q1:



0.3 Ek (9.6 kV/cm) ~ 25 Td



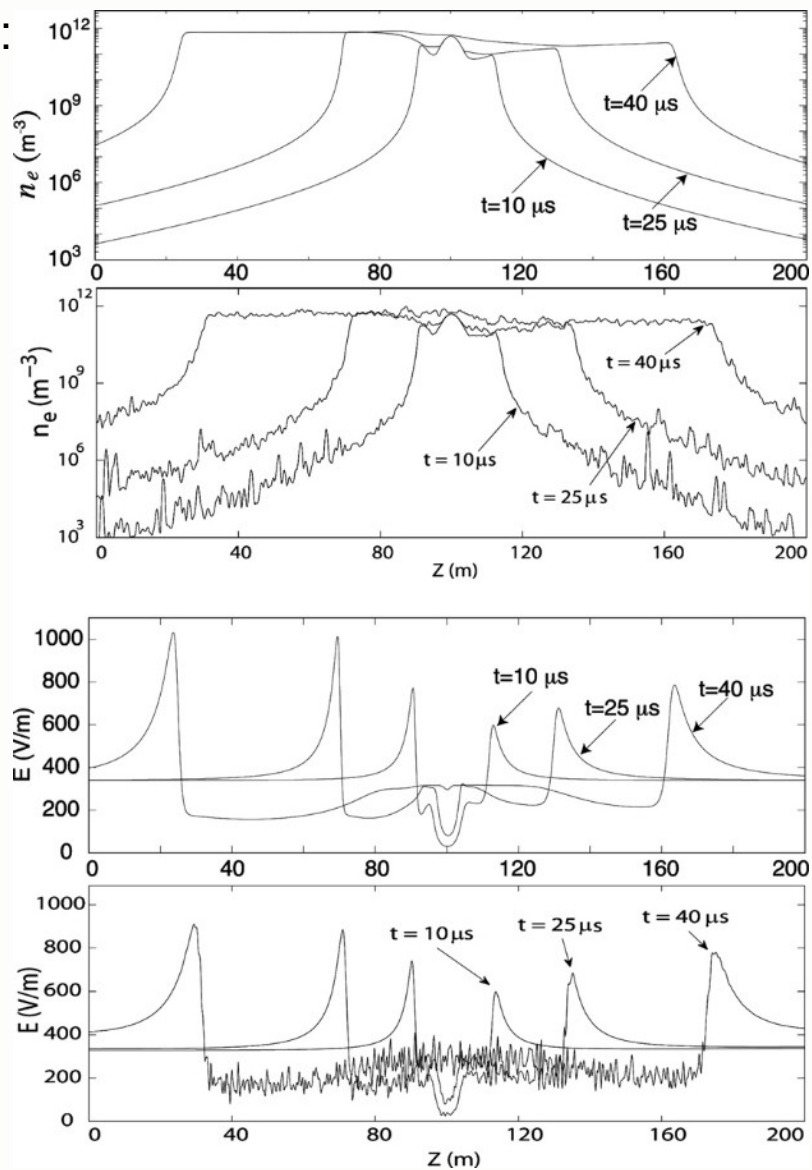
38 kV/cm ~ 143 Td



640 kV/cm ~ 2388 Td

Streamer head ~ 200 - 800 Td...

CDP Q1:



Available online at www.sciencedirect.com

ScienceDirect

Journal of Computational Physics 227 (2008) 7222–7245

JOURNAL OF
COMPUTATIONAL
PHYSICS

www.elsevier.com/locate/jcp

A PIC-MCC code for simulation of streamer propagation in air

O. Chanrion*, T. Neubert

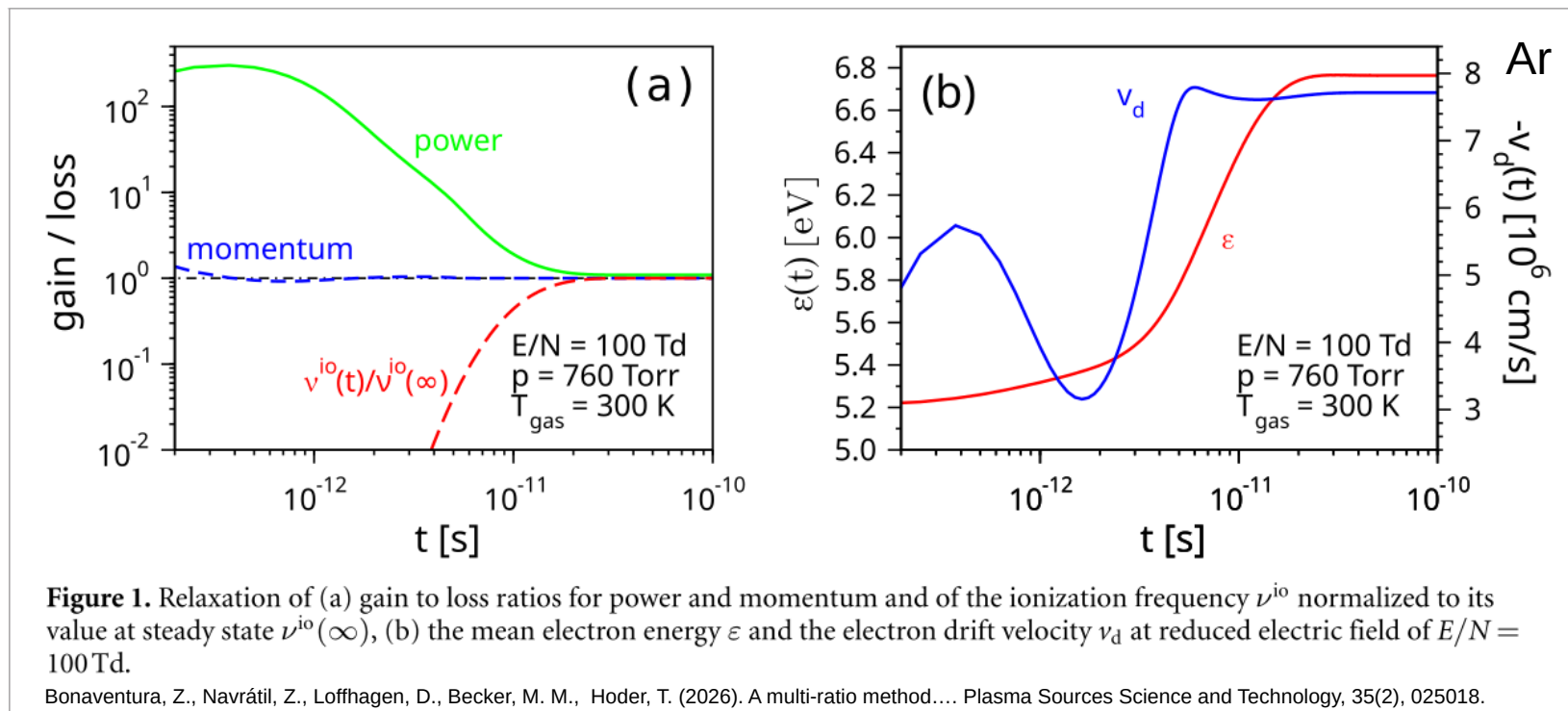
DTU Space, National Space Institute, Technical University of Denmark, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark

Received 24 March 2007; received in revised form 8 April 2008; accepted 8 April 2008

Available online 30 April 2008

CDP Q2:

These values (and others) are obtained by considering the stationary solutions of the electron Boltzmann equation. How far does this hold for times shorter than ~ 1 nanosecond?



Relaxation analysis is performed using the 8-term solution of the time-dependent spatially homogeneous electron Boltzmann equation.

Loffhagen D 2022 Multiterm and non-local electron Boltzmann equation Plasma Modeling (2nd edn) 2053-2563 (IOP Publishing) p 3–1 to 3–28

CDP Q3:

How do you handle, in general, the value of the gas temperature in your models? How reliable is the assumption of a constant value? For instance, if the gas temperature is found to be 500 K instead of 300 K, for a given pressure, this would imply a different gas number density N . How may this impact your calculations, namely in what concerns E/N ?

no influence on the results presented in this section. To take into account the fact that the discharge occurs at atmospheric pressure in preheated air at $T = 1000$ K, we have simply changed the value of the total density $N = N_0 T_0 / T$, where $N_0 = 2.45 \times 10^{25} \text{ m}^{-3}$ is the air neutral density at ground pressure and ambient temperature ($T_0 = 300$ K). This decrease in the total density by a factor of 3 increases by the same factor the local reduced electric field E/N and then has a direct impact on transport parameters and reaction rates in air which are assumed to be functions of E/N .

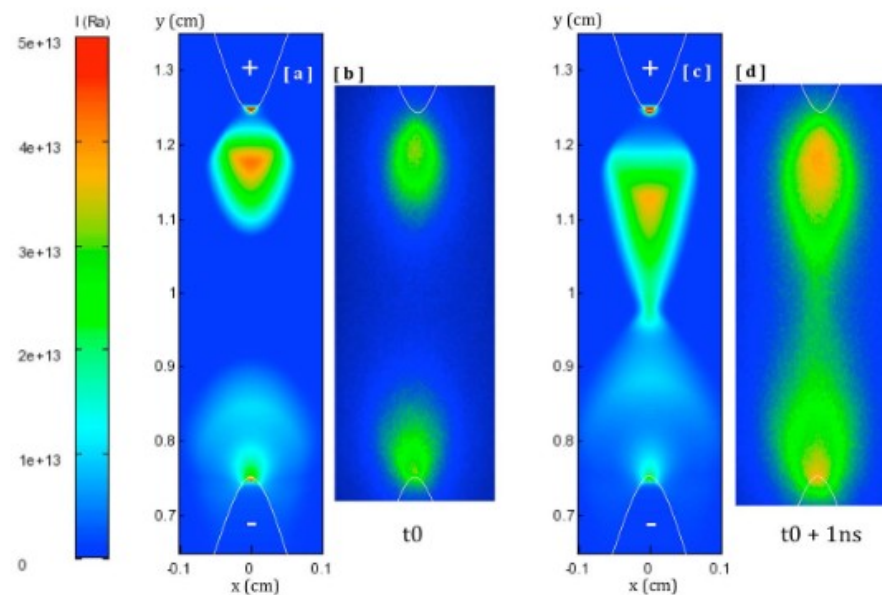
The use of the ghost fluid method for Poisson's equation to simulate streamer propagation in point-to-plane and point-to-point geometries

Sebastien Celestin^{1,4}, Zdenek Bonaventura^{1,2}, Barbar Zeghondy¹, Anne Bourdon¹ and Pierre Ségur³

¹ Ecole Centrale Paris, EM2C, UPR CNRS 288, Grande voie des vignes, 92295 Châtenay-Malabry Cedex, France

² Department of Physical Electronics, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

³ Université de Toulouse, LAPLACE, UMR CNRS 5213, INPT, UPS, 118 route de Narbonne, 31062 Toulouse Cedex 9, France



F Tholin et al. IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 39, NO. 11, NOVEMBER 2011

MJ Q1:

Transition to Spark: Are there any future plans in your group to simulate the complex transition phase where a streamer evolves into a fully developed spark?

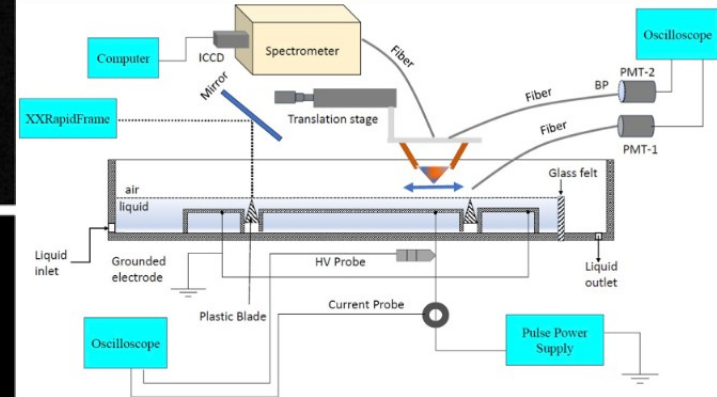
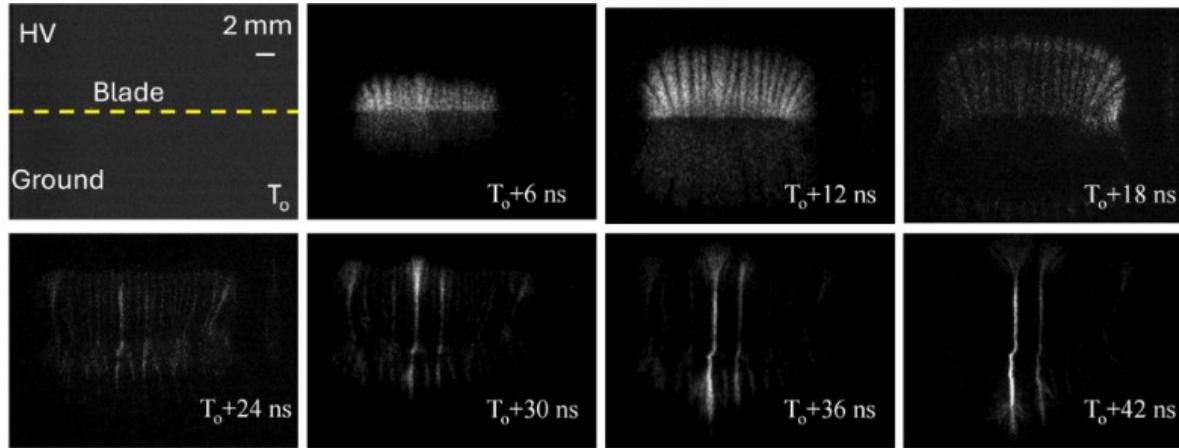
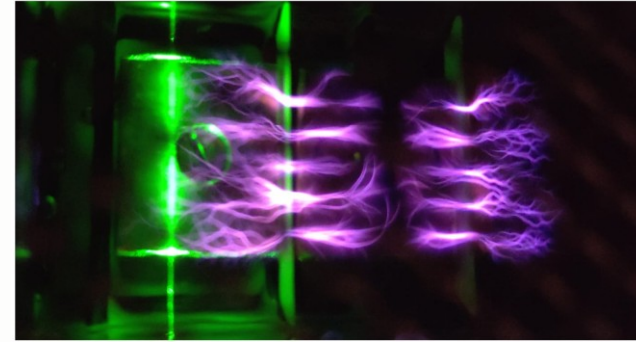
GA26-21439S (1/2026-12/2028)

Investigation of processes occurring in non-equilibrium plasma on interfaces between two phases with different permittivity and conductivity

MUNI: (B.Palúch, K.Farkaš, Zbona)

IPP Prague: (P. Hoffer, J.Fujera, P. Bilek, V. Prukner, M.Simek)

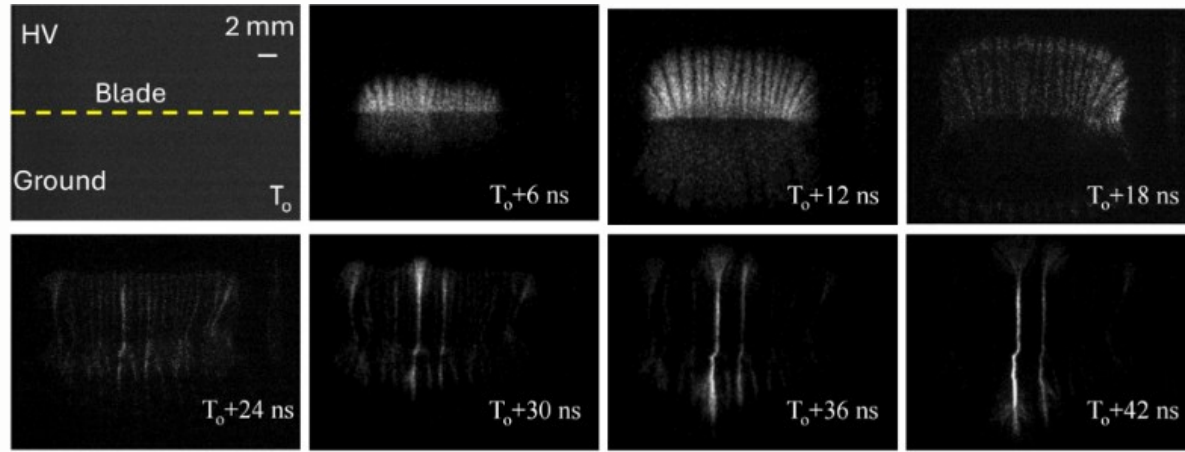
+ collab: MFF UK (M. Fehling [deal.ii FEM library])



MJ Q2:

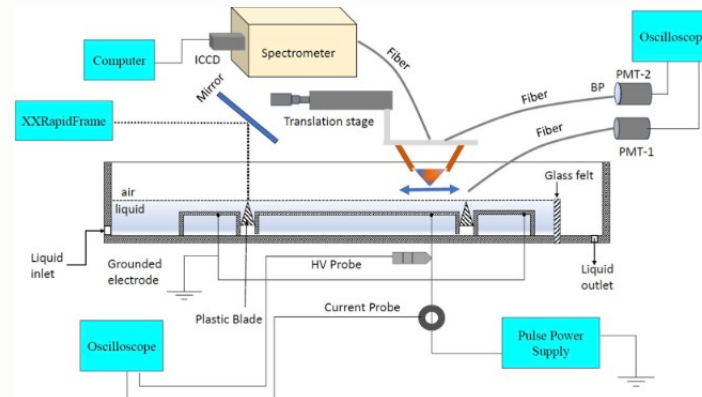
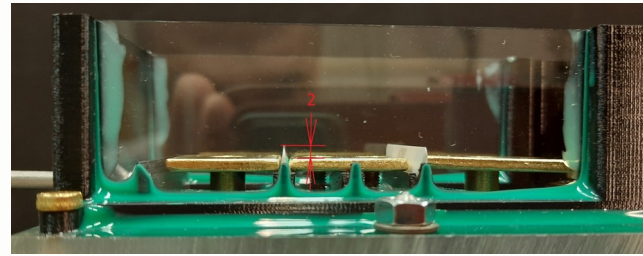
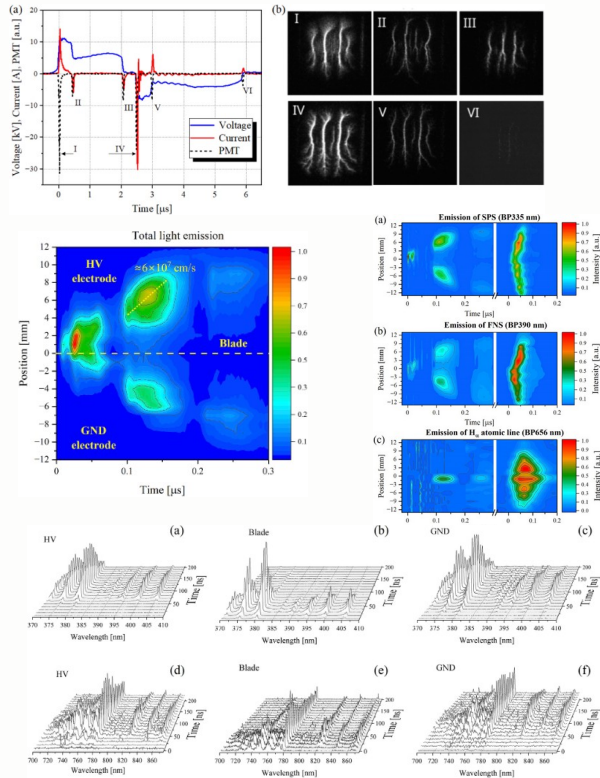
Future Modeling Challenges: What do you consider to be the single greatest theoretical or computational challenge in the upcoming era of streamer modeling?

Inception → multi streamer interaction → transition to spark
on water surface



MJ Q3:

Experimental Validation: What specific experiments should experimental physicists focus on next to best assist in validating the results obtained from your computational models?



CC Q1

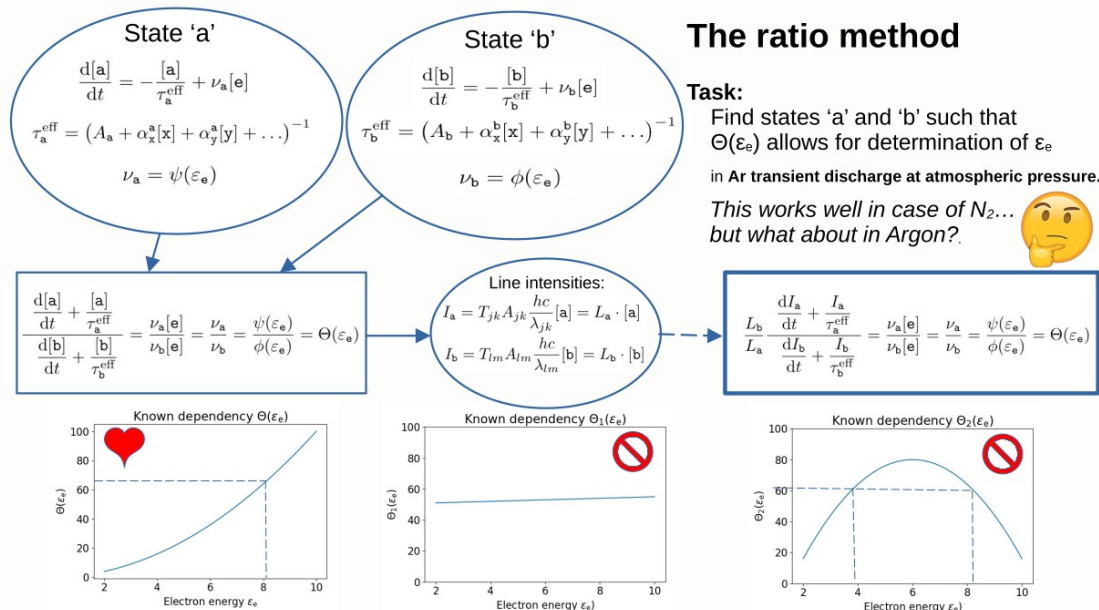
Which physical processes are currently the largest source of uncertainty in streamer simulations?

What is the quantity of interest?

Streamer formation and propagation is well understood...

- electron cross section data, attachment, recombination: especially in gas mixtures (Air+ {H₂, H₂O, CO₂....})
- model assumptions and limitations: photoionization, quasi-stationary assumptions, stochastic processes..
- boundary conditions: (!discharge in contact with boundary!) secondary emission, photo-emission coefficients, etc.
- model limitations at boundaries: **cathode streamer interaction**, ...

What do Dr. Bonaventura consider to be the most significant scientific contribution of his work to the understanding of streamer discharges?



Zdeněk Bonaventura, Anne Bourdon, Sebastien Celestin, and Victor P Pasko. Electric field determination in streamer discharges in air at atmospheric pressure. *Plasma Sources Science and Technology*, 20(3):035012, 2011. doi: 10.1088/0963-0252/20/3/035012.

Petr Bílek, Adam Obrusník, Tomáš Hoder, Milan Šimek, and **Zdeněk Bonaventura**. Electric field determination in air plasmas from intensity ratio of nitrogen spectral bands: II. Reduction of the uncertainty and state-of-the-art model. *Plasma Sources Science and Technology*, 27(8):085012, 2018. doi: 10.1088/1361-6595/aad666.

Adam Obrusník, Petr Bílek, Tomáš Hoder, Milan Šimek, and **Zdeněk Bonaventura**. Electric field determination in air plasmas from intensity ratio of nitrogen spectral bands: I. Sensitivity analysis and uncertainty quantification of dominant processes. *Plasma Sources Science and Technology*, 27(8):085013, 2018. doi: 10.1088/1361-6595/aad663.

Plasma Sources Sci. Technol. 35 (2026) 025018 <https://doi.org/10.1088/1361-6595/ae413d>

Plasma Sources Science and Technology

PAPER

A multi-ratio method for determination of the electric field from 2p states in transient argon discharges at atmospheric pressure

Zdeněk Bonaventura^{1,*} , Zdeněk Navrátil¹ , Detlef Loffhagen² , Markus M Becker² and Tomáš Hoder¹

¹ Department of Plasma Physics And Technology, Masaryk University, Brno, Czech Republic

² Leibniz Institute for Plasma Science and Technology, Greifswald, Germany

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E-mail: zbona@physics.muni.cz

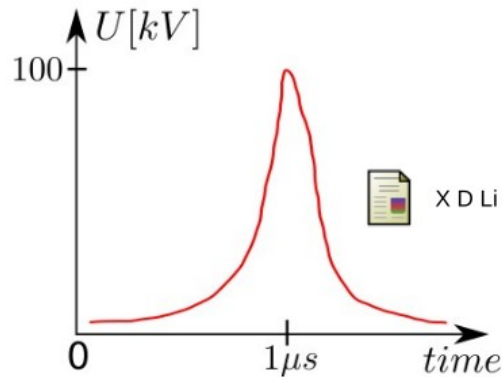
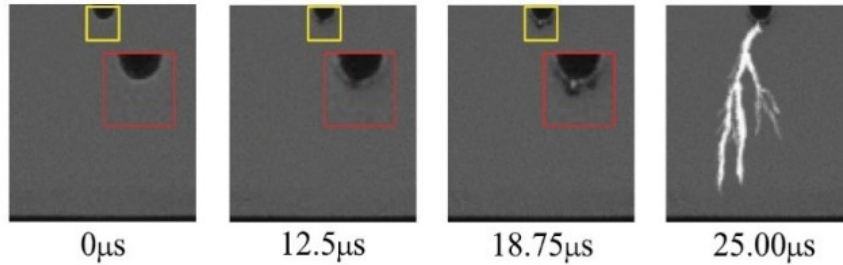
Keywords: electric field, metastable density, diagnostics, method, argon plasma, spectroscopy

Backup slides: Electron multiplication in nanovoids.

Mechanisms of discharge generation in liquid water

Bubble-driven breakdown

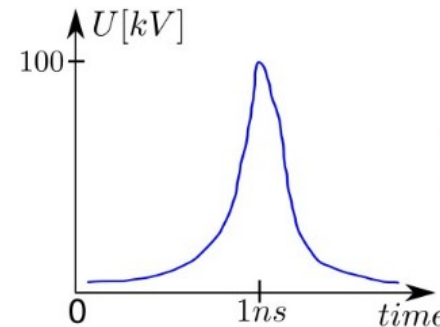
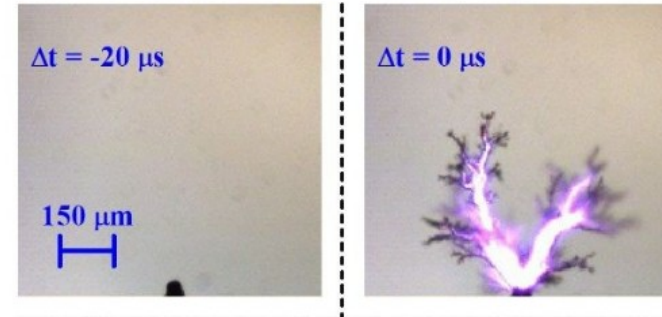
- Long rise-time of high voltage waveform
- Mechanism: Joule heating creates vapor bubbles, where the discharge is initiated.



X D Li et al 2017 J. Phys. D: Appl. Phys. 50 255301

Direct breakdown

- ns rise-time of high voltage waveform
- Joule heating is impossible on such a short timescale
- Mechanism: electrostriction, field ionization ????

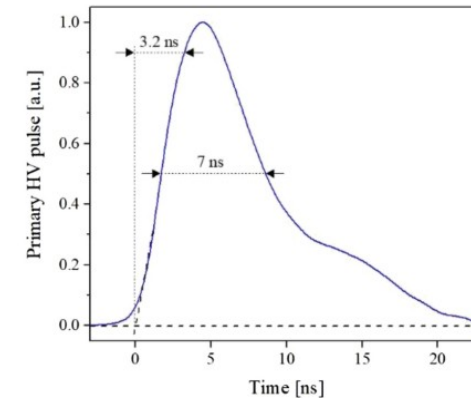
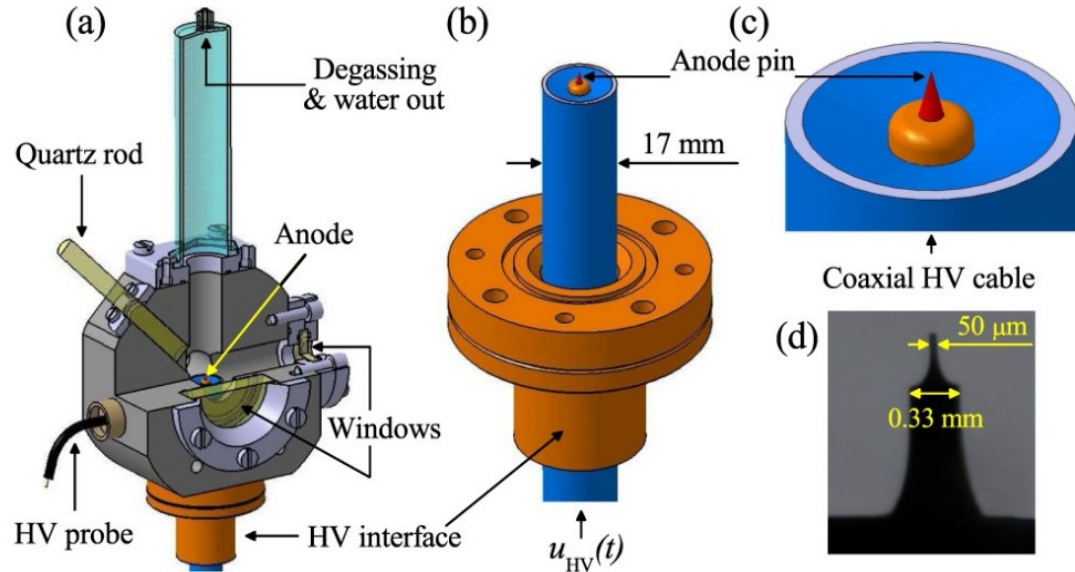


Petr Hoffer et al 2022 Plasma Sources Sci. Technol. 31 015005

Experimental Campaign (IPP Prague)

Reactor needle-to-chamber wall geometry, the discharge generated by nanosecond pulsed HV power supply (FID Technology GmbH).

Credits: Milan Šimek

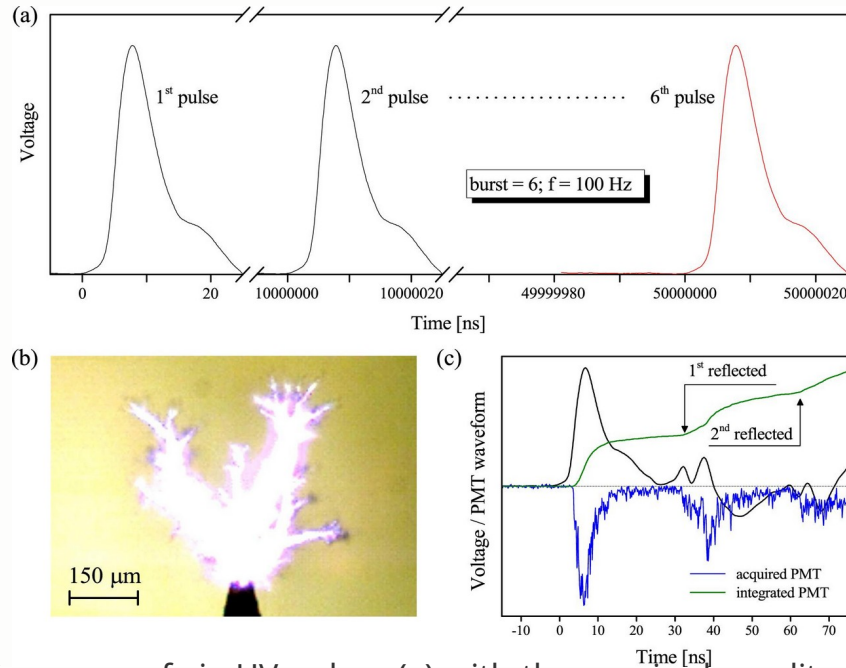


 M Šimek et al Plasma Sources Sci. Technol. 29 (2020) 064001

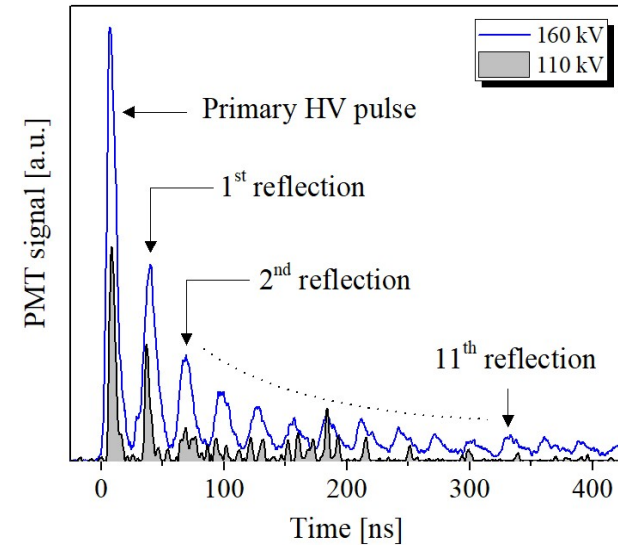
1. **High-speed framing**
2. **Picosecond shadowgraphy**
3. Mach-Zehnder interferometry
4. Four-channel ICCD imaging
5. **Optical emission spectroscopy**

HV pulses

Single HV pulse - single HV burst - periodic HV



Sequence of six HV pulses (a) with the required amplitude is produced at a specific repetition frequency ($f = 100$ Hz). Each HV pulse causes a specific discharge event (b) composed of the primary discharge pulse followed with several discharges due to the reflected HV pulses visualized through the discharge-induced emission revealed by the PMT (c).

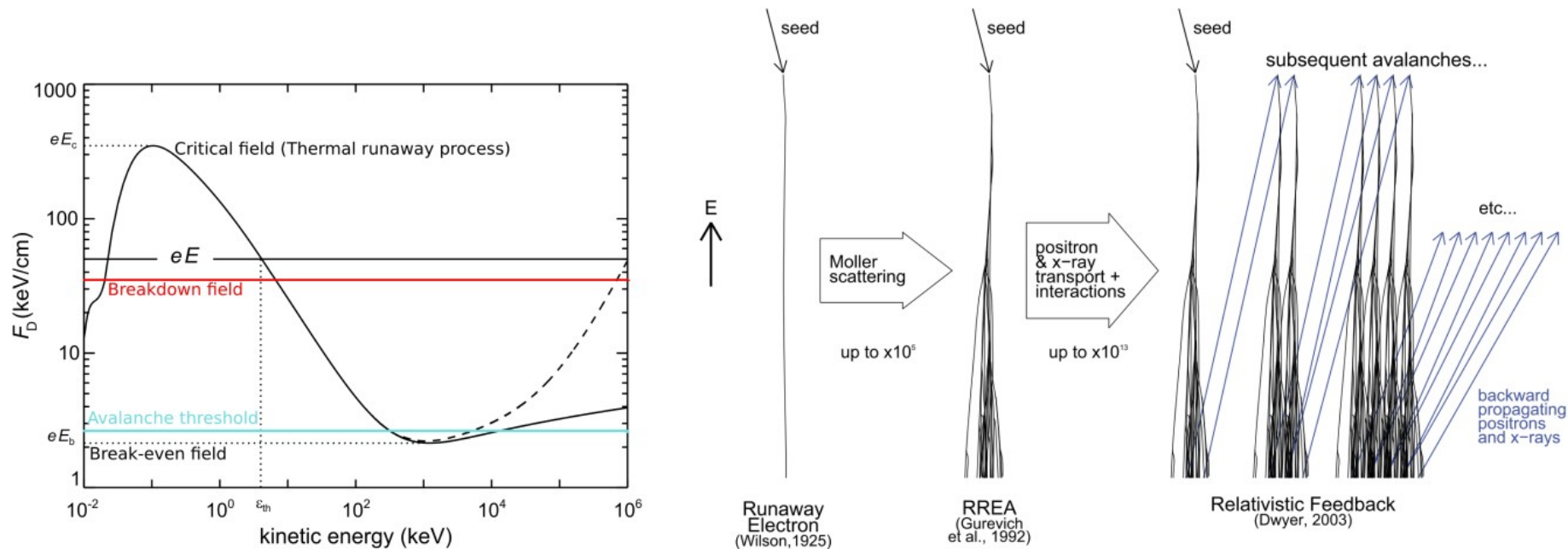


PIE waveforms characterizing pulsed HV discharge in DI water composed of the primary discharge event followed by a succession of gradually fading events caused by reflections of HV waveforms on the unmatched load. PIE registered by the ultrafast PMT and plotted for two different amplitudes of the primary HV pulse (anode side) of 110 kV and 160 kV.



Runaway electrons

- Dynamic friction force (Rate of energy loss): $\frac{\partial p}{\partial t} = eE - F$.
- Runaway electrons in air: Wilson 1925.
- Relativistic Runaway Electron Avalanche (**RREA**): Gurevich 1992;
- Relativistic feedback: Dwyer 2003 (Avalanche threshold $E_{th} = 2.84 \times 10^5$ V/m)

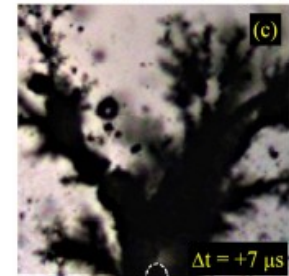
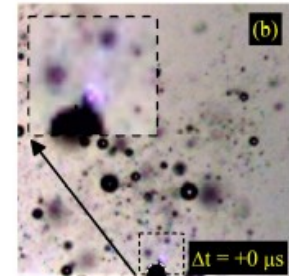
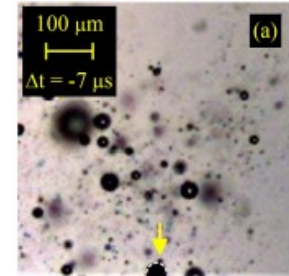
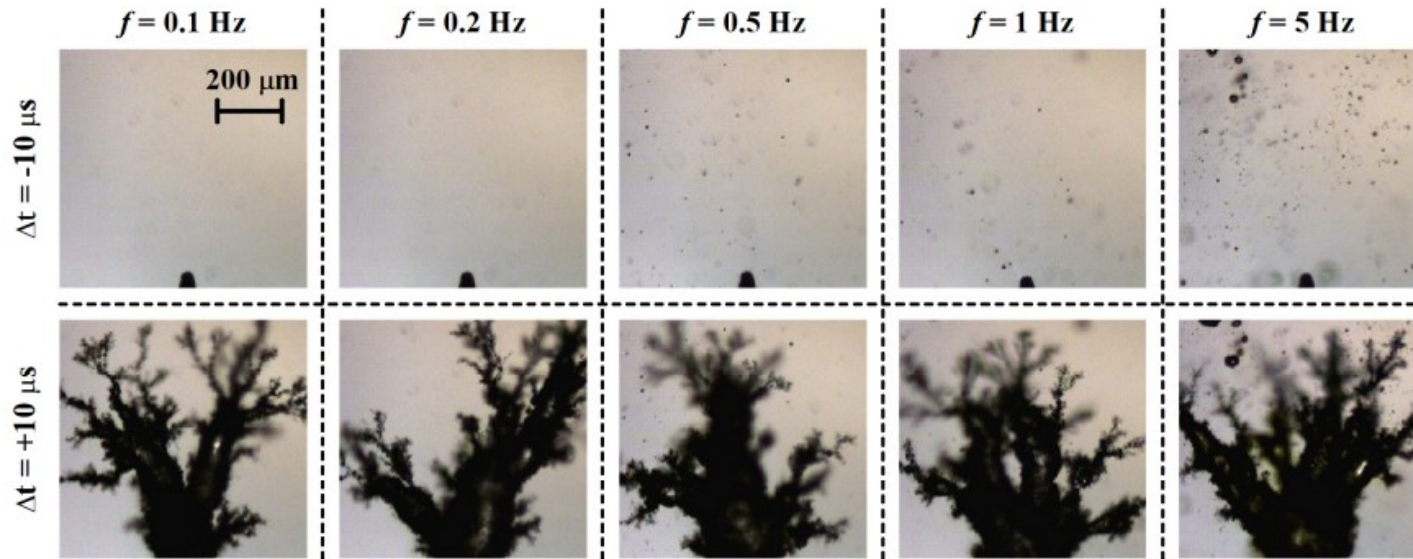


(Fig. source: Dwyer et al., Space Sci Rev, 2012.)

Hi-speed framing

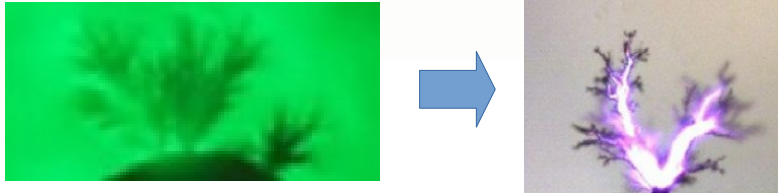
Key insights:

Microbubbles (non-condensable gases, H_2 / O_2) may perturb the anode area, and therefore the initial phase of the discharge



Picosecond shadowgraphy

Key insights:

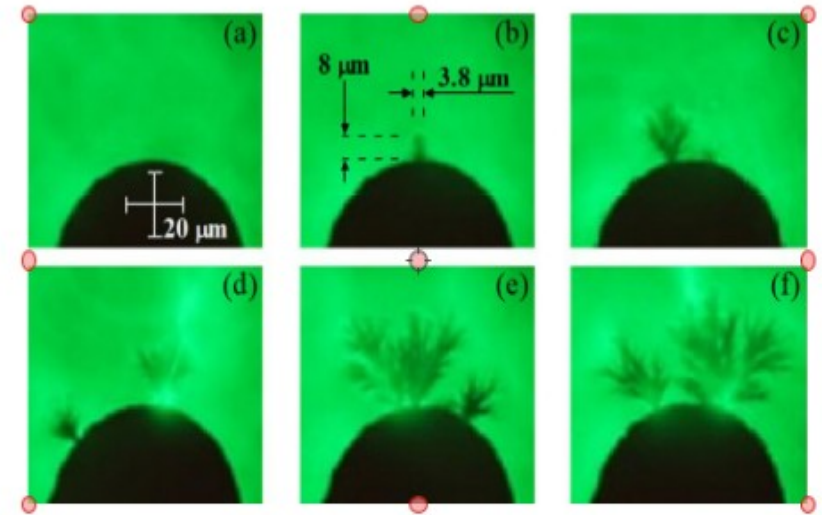


The discharge develops through a sequence of the **dark** and **luminous** phases.

The dark filaments start occurring with a delay of $\sim 3\text{--}4$ ns after the onset of the HV pulse and subsequently expand at velocity of $\sim 1 \times 10^5\text{--}2 \times 10^5$ ms $^{-1}$.

The luminous discharge phase is delayed by $\sim 600\text{--}800$ ps with respect to the onset of the initial dark filament structures.

M Simek et al Plasma Sources Sci. Technol. 29 (2020) 064001

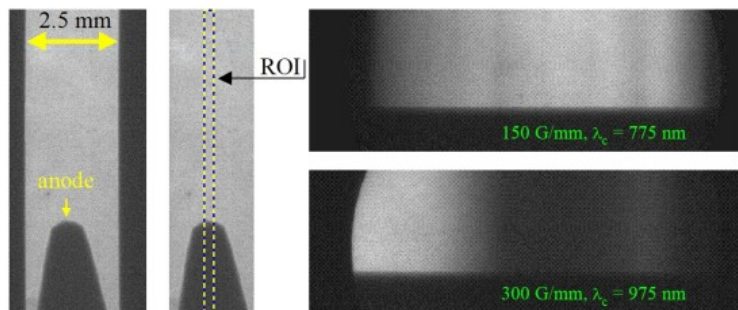
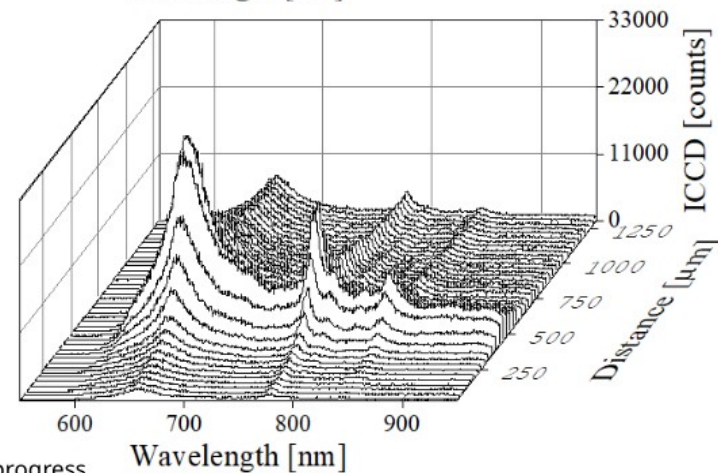
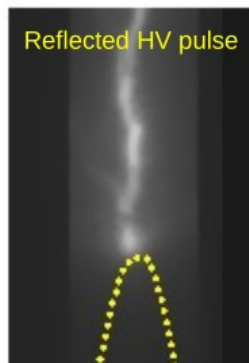
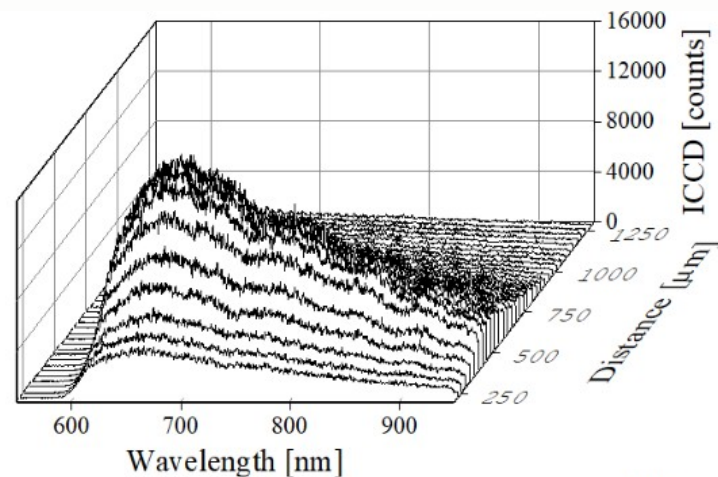
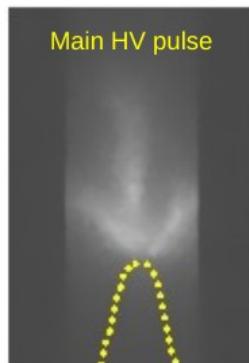
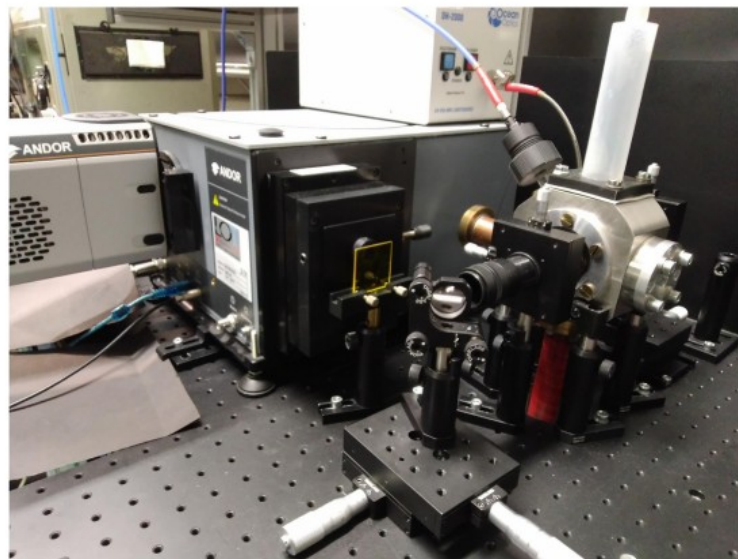


Sequence of shadowgraphic images captured with exposure of 1 s during the main HV pulse for various HV onset-laser pulse delays for a paraboloid-like anode stressed with HV pulse of 130 kV. Probing laser pulse delayed by (a) 2.8, (b) 3.3, (c) 3.5, (d) 3.6, (e) 3.7 and (f) 3.8 ns with respect to the HV pulse onset.

Credits: Milan Šimek



Optical emission spectroscopy



M. Simek et al 2023 manuscript in progress

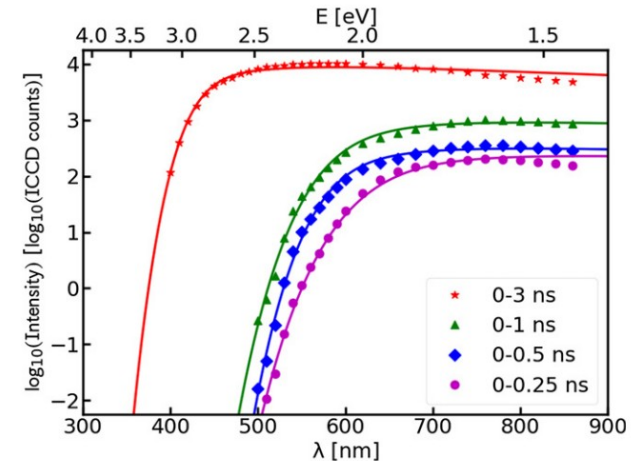
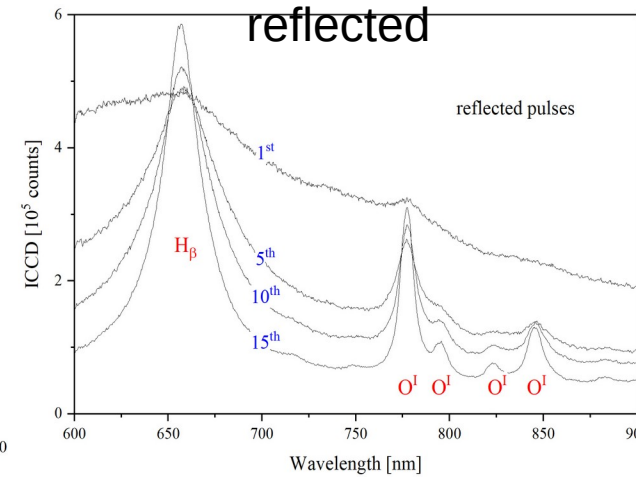
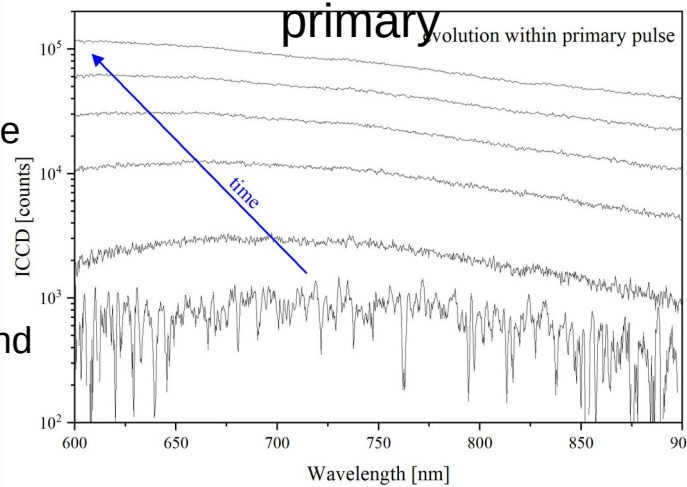
Credits: Milan Šimek

Optical emission spectroscopy

Key insights:

- Exclusive spectrometric fingerprints characterizing 'direct' breakdown seem to be the bound-free and free-free transitions (no atomic H/O lines).
- Atomic H/O lines emerge during **reflected pulses** and line-shape seems to only depend on the distance from the anode tip.
- Working hypothesis: Electron–neutral bremsstrahlung radiation seems to be a good candidate to explain the shape of initial emission continua.

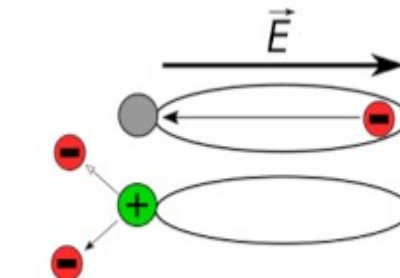
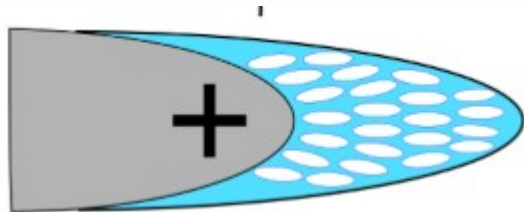
$$\varepsilon_{\text{ff}}^{\text{en}} = \frac{\sqrt{\pi}}{2} C_{\text{en}} \frac{n_e n_n}{\lambda^2} \times \int_{\frac{hc}{\lambda}}^{\infty} Q_{\text{en}}^m \left(1 - \frac{hc}{2\lambda E} \right) \sqrt{1 - \frac{hc}{\lambda E}} E^{\frac{3}{2}} f(E) dE,$$



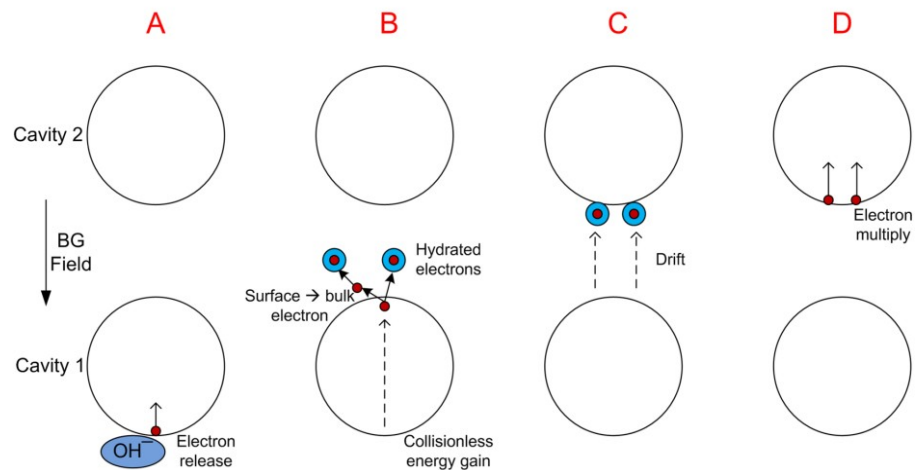
Nanosecond discharge initiation mechanism

[Seepersaad 2013, J.Phys.D.: Appl. Phys. ; Shneider 2016, IOP PPS]

- Strong and inhomogeneous electric fields: **electrostriction**
- Fast rise of applied voltage: liquid has no time to move to compensate
- **Cavitation** appears if neg. pressure exceeds about -30 MPa.
- Low density regions: free space for acceleration of electrons.
- **Accelerated electrons ionize water molecules**



Cavitation with isotropic pressure

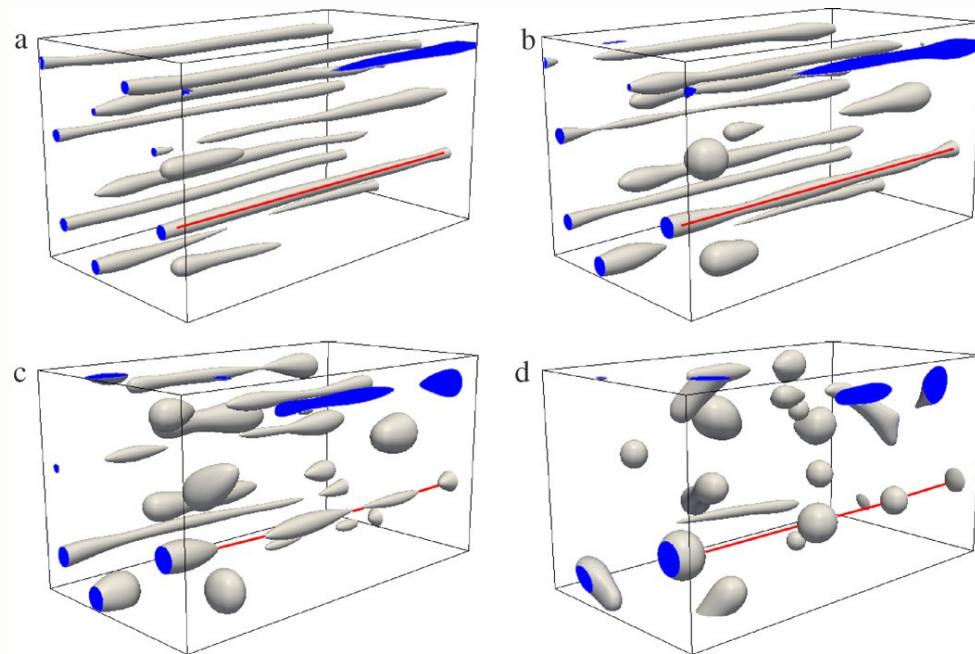


$$\frac{dn_c}{dt} = \Gamma(t) = \frac{3}{4\pi R_c^3} \frac{k_B T}{2\pi\hbar} \exp\left(-\frac{4\pi\sigma R_c^2}{3k_B T}\right),$$

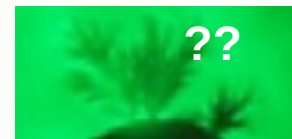
$$\frac{d}{dt} \left[R^3 \left(\frac{dR}{dt} \right) \right] = \frac{2}{\rho} R^2 \frac{dR}{dt} \left[\frac{3}{4} (\alpha - 1) \epsilon_0 \epsilon E^2 - \frac{2k_\sigma \sigma}{R} - p_h \right]$$

X. Zhang, M. Shneider, J. Appl. Phys. 129, 103302 (2021)
 X. Zhang, M. Shneider, Phys. Fluids 34, 101704 (2022)
 M. Shneider, M. Pekker, Journal of Applied Physics 117, 224902 (2015)

Cavitation in anisotropic force field (anisotropic instability)



$$\mathbf{F} = -\frac{E^2}{8\pi} \nabla \epsilon + \frac{1}{8\pi} \nabla \left[E^2 \rho \left(\frac{\partial \epsilon}{\partial \rho} \right)_T \right]$$



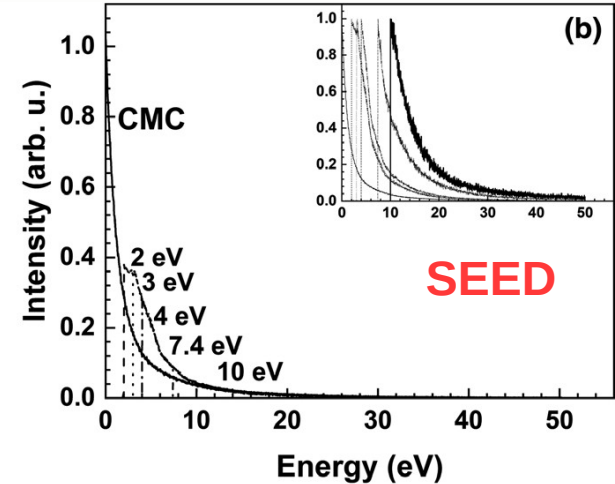
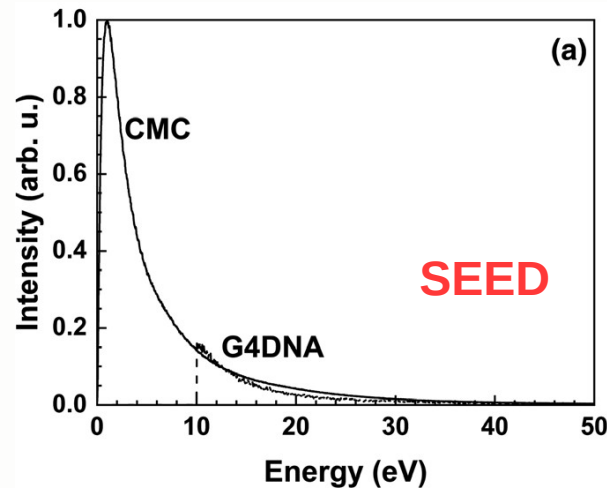
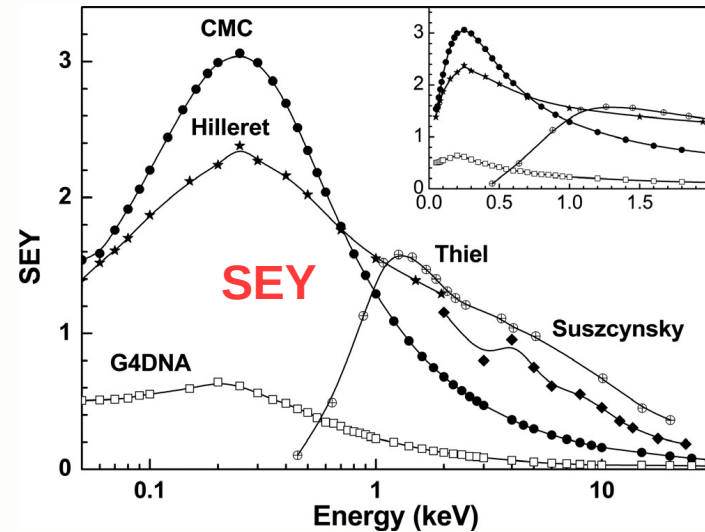
A Kupershtokh, D. Medvedev, PHYSICAL REVIEW E 74, 021505, 2006.
 A.L. Kupershtokh:
 Computers and Mathematics with Applications 67 (2014) 340–349.

Simulating of electron propagation and interactions in liquid water



geant4-dna.org

- toolkit for the simulation of the interaction of particles with matter
- low-energy electron transport in liquid water ($< 10\text{keV}$).
- “Sub-excitation” ($< 7.4\text{ eV}$) electrons cannot contribute to ionization, instant thermalizaion (**limitation:** dielectric function model)

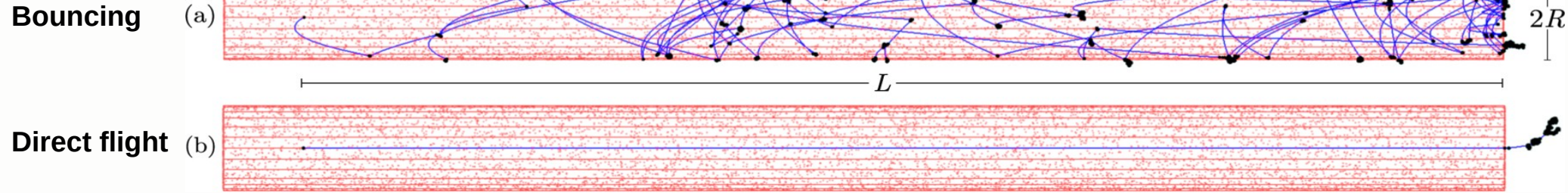


Credits: Mehnaz et al. Med. Phys. 47 (2), 2020

SEY: similar in shape to experimental, **but** GEANT4-DNA **underestimates**

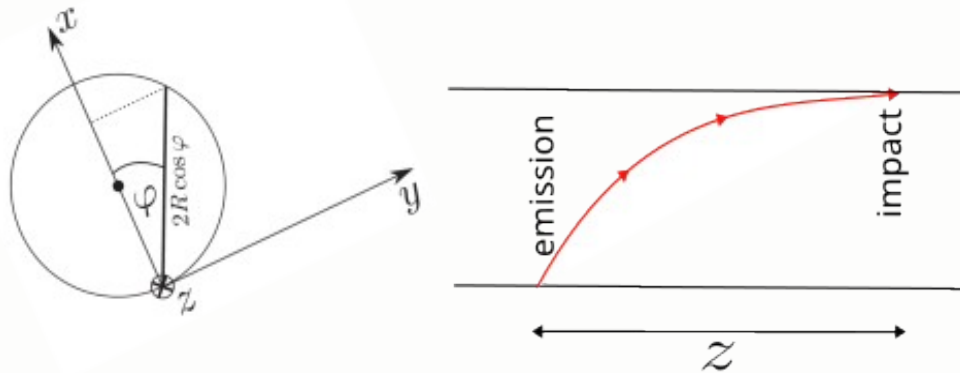
SE **E**nergy **D**istribution: validated against other CMC trajectory model, (Geant4-dna cut-off).

Electron propagation scenarios:



Q: What is the efficiency for electron multiplication?

Electron trajectory (inside of the cavity)



Impact Z-coordinate:

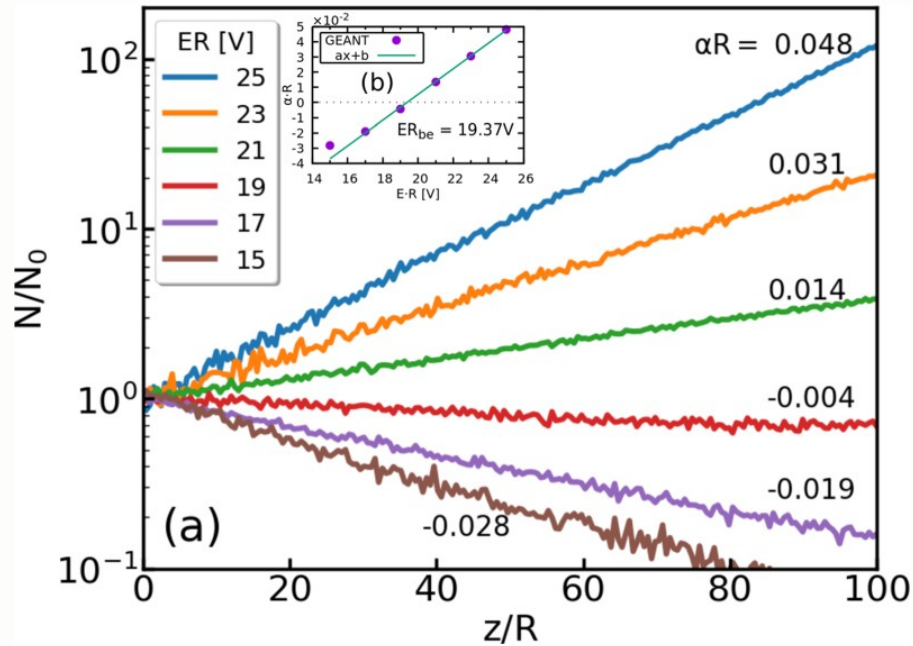
$$\frac{z}{R} = v_{\parallel} \left(\frac{t_{\text{fl}}}{R} \right) + \frac{q}{2m_e} (E \cdot R) \left(\frac{t_{\text{fl}}}{R} \right)^2,$$

Time of flight:

$$\frac{t_{\text{fl}}}{R} = \frac{2 \cos \varphi}{v_{\perp}} = \frac{2v_{\perp x}}{v_{\perp}^2}$$

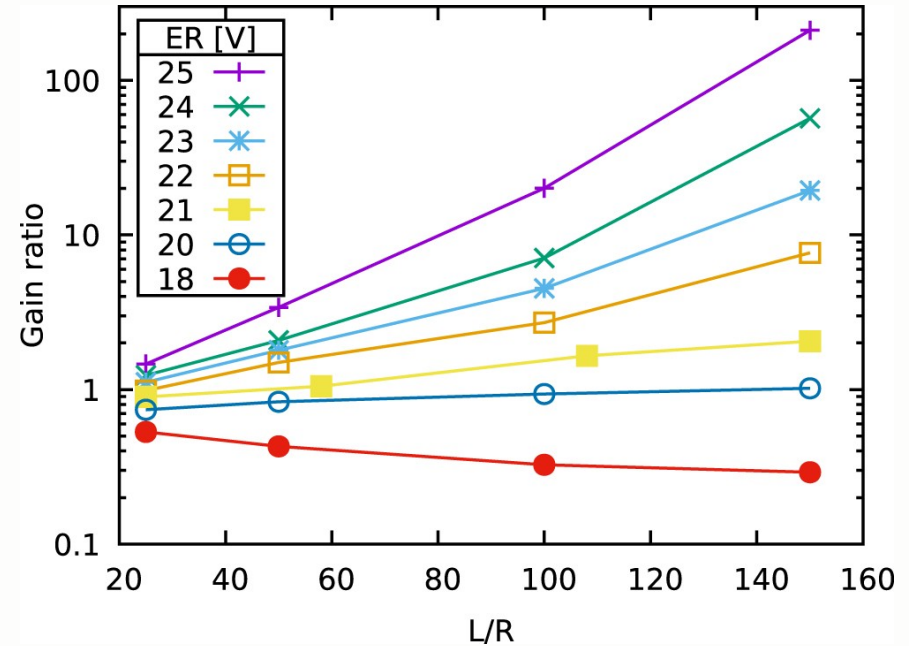
Bouncing vs Direct flight

e-fold multiplication (depletion)



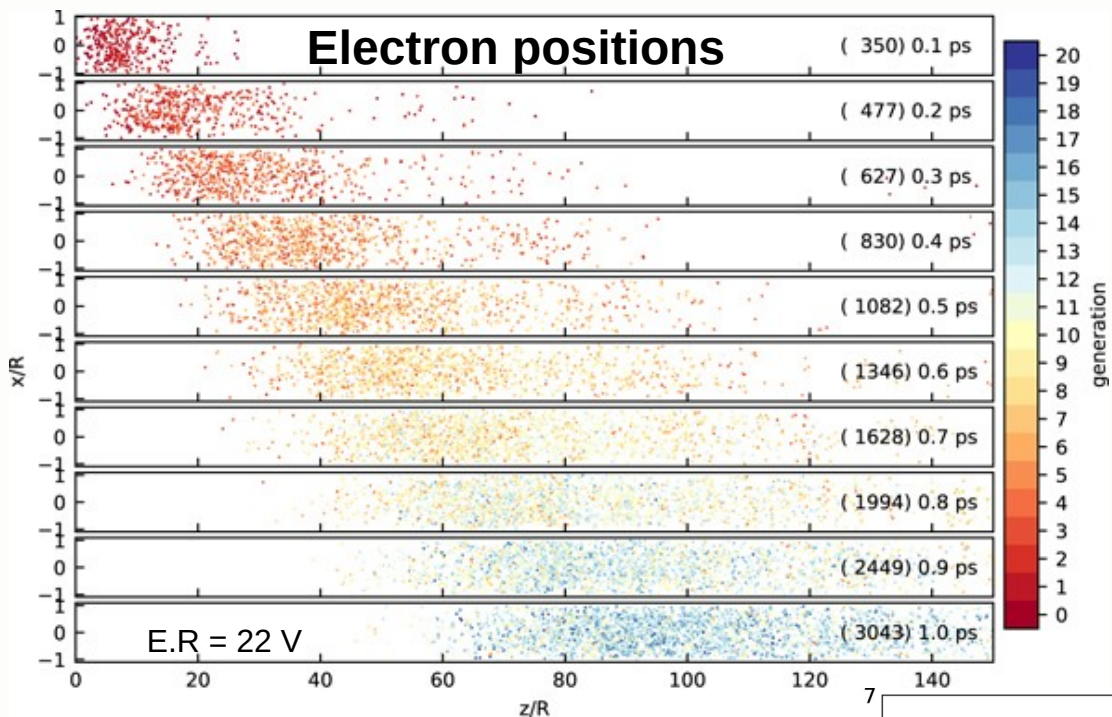
Break even $ER \sim 20$ V

Gain: Bouncing / Direct flight

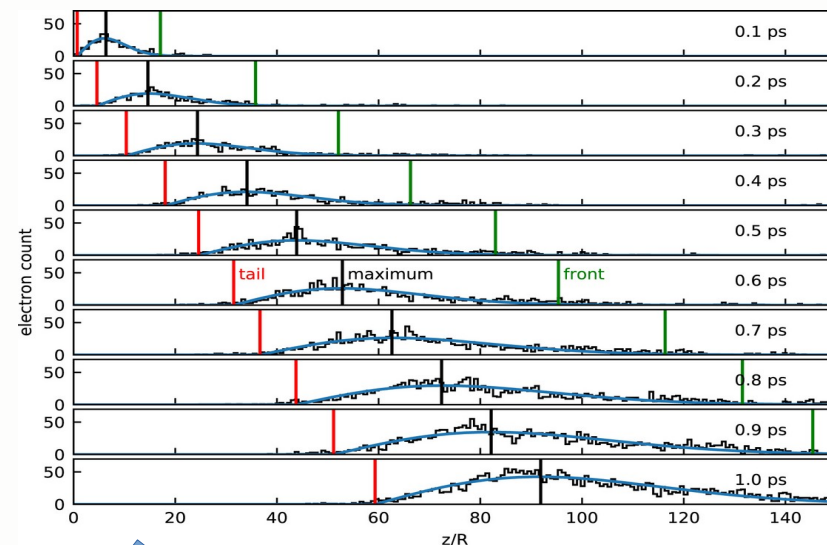


Bouncing more efficient!
(in multiplying conditions)

IC: N_0 electrons injected isotropically @ 7.4 eV (from cylinder inner surface (cloak) at $z=0$)



$$f(\xi) = \begin{cases} A(\xi - \xi_0) \exp(-(\xi - \xi_0)^2 / (2\sigma^2)) & \text{for } \xi > \xi_0, \\ 0 & \text{for } \xi \leq \xi_0, \end{cases}$$



Avalanche characteristics:

- velocity of propagation
- Multiplication timescale

