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CONSORZIO RFX
Ricerca Formazione Innovazione

X-RAY MICRO-DISCHARGES FINE DYNAMICS IN A VACUUM HIGH VOLTAGE EXPERIMENT

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Outline

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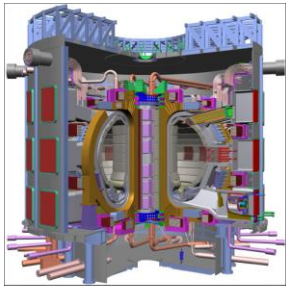
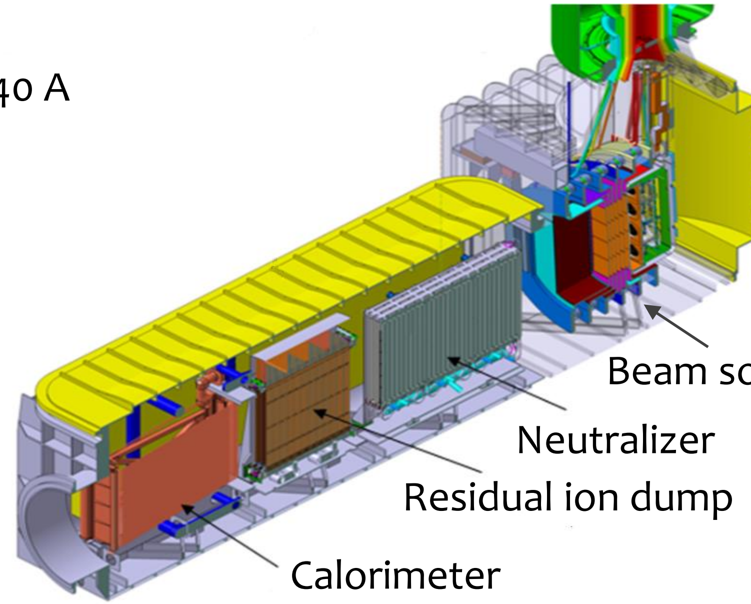
- Experimental Setup
- Experimental observations
  - Micro Discharges - MD
  - X fine dynamics of MD
- Tentative Interpretation
  - X fine dynamics of MS
  - I fine dynamics of MD
  - Anode-Cathode current imbalance
- Microdischarges time distribution
- Improvements
- Summary and conclusions

INTRODUCTION & MOTIVATION



MITICA (**M**egavolt **IT**ER **I**njector and **C**oncept **A**dvancement) is the full-scale prototype for ITER NBI (Neutral Beam Injectors), located in Padova, Italy)

- Accelerating voltage: 1 MV
- Extracted and accelerated current: 40 A
- Beam power: 17 MW



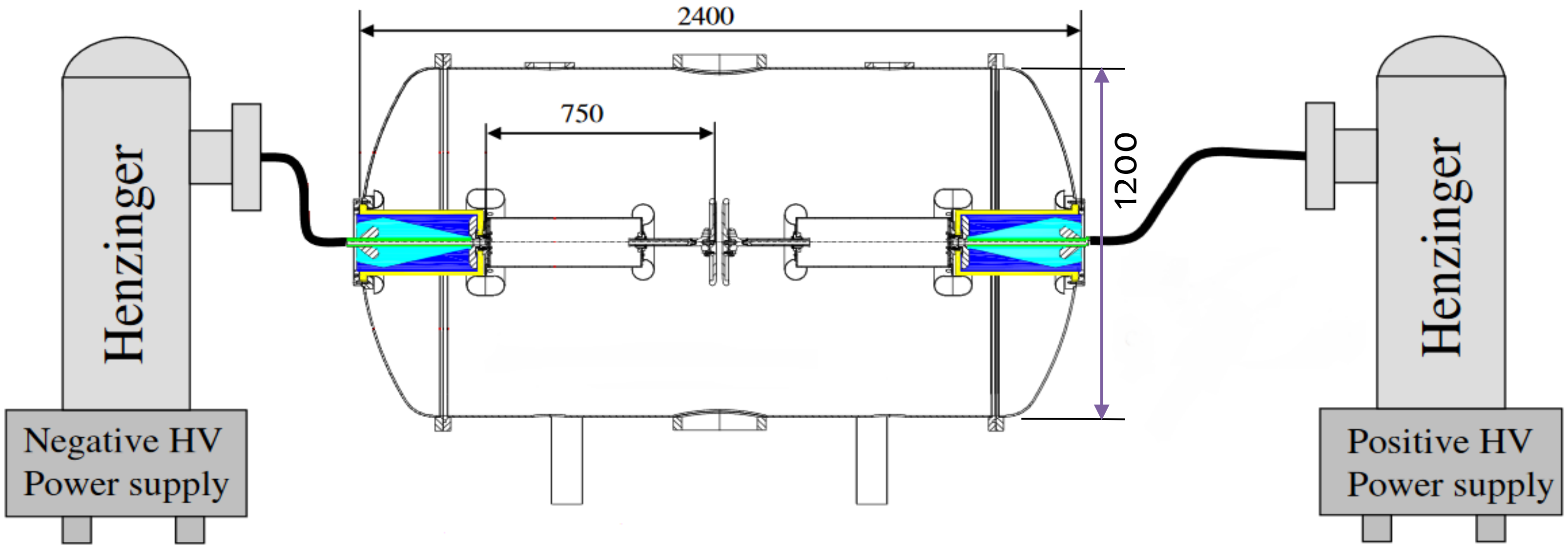
Still Open Issue:

Voltage holding capability in the gap between the Ion Source and the Vessel in MITICA (conditioning pressure of 10^{-5} Pa, typical gap of 1 m)

- Voltage conditioning is characterized by very frequent current bursts, associated to pressure increase and enhanced Xray emission.
- These current burst are considered in all respect breakdown precursors.
- Understanding its dynamic is fundamental to find the way for a **reliable, single gap, 1 MV voltage holding**

EXPERIMENTAL SETUP

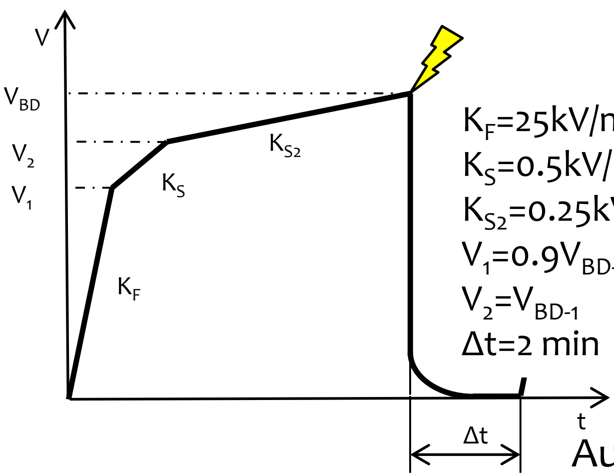
Related R&D are done at **HVPTF**, the **H**igh **V**oltage **P**adova **T**est **F**acility



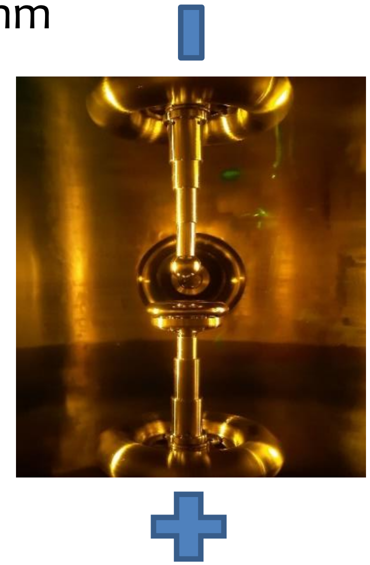
- Stainless steel vacuum chamber (2.4 m, Ø=1.2 m)
- 2 Cockcroft-Walton power supplies (+400kV, -400kV, 1mA dc)
- Vacuum pressure around 4.10^{-7} mbar
- Electrodes gap 0-250 mm

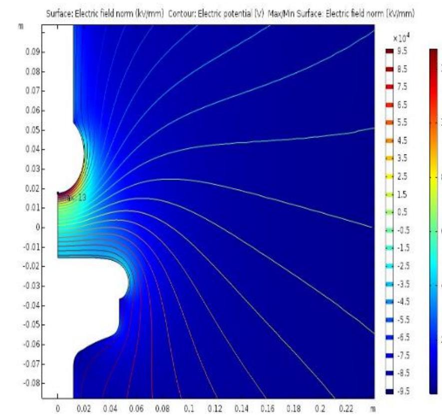
EXPERIMENTAL SETUP

Negative electrode:	Sphere AISI304 Ø=40 mm
Positive electrode:	Plate AISI304 Ø=108 mm
Electrodes gap:	30-33 mm
E_K @ 400 kV:	26 MV/m



K_F=25kV/min
K_S=0.5kV/min
K_{S2}=0.25kV/min
$V_1=0.9V_{BD-1}$
$V_2=V_{BD-1}$
Δt=2 min





Automatic Voltage Conditioning. The **Voltage Cycle** is simmetrically applied on the two power supplies.

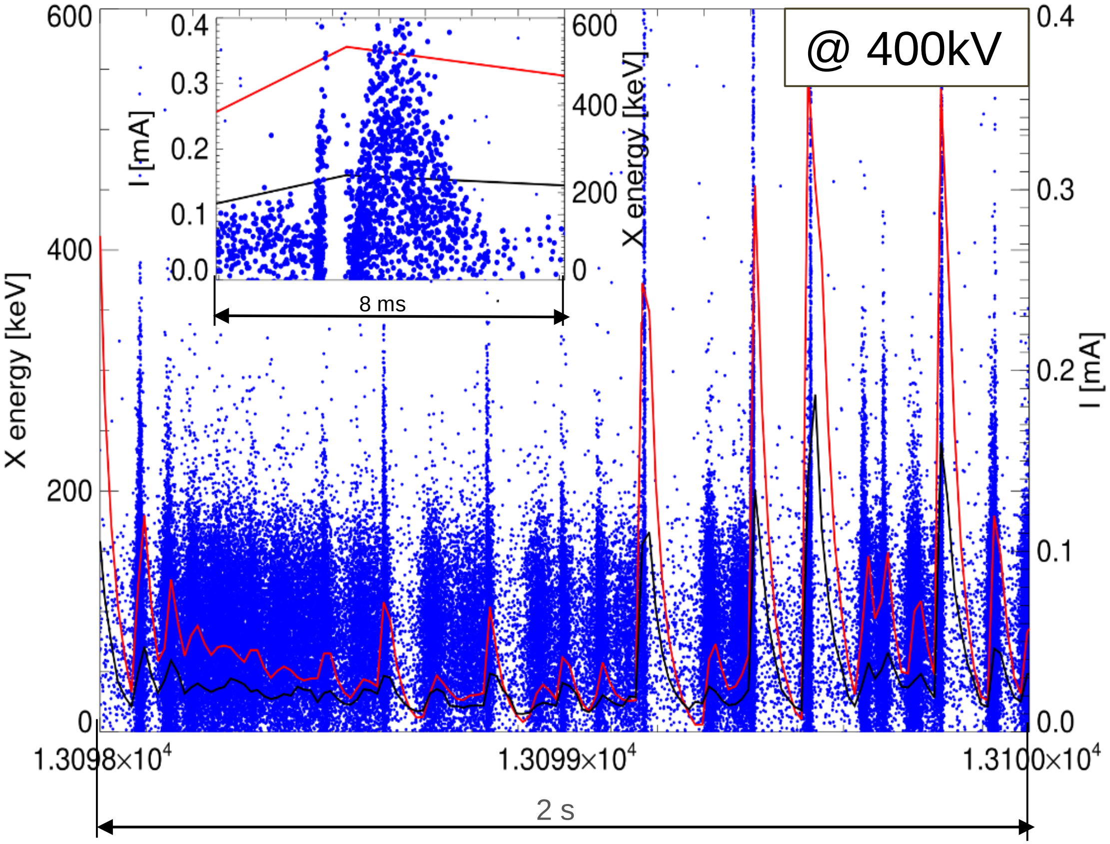
Diagnostics

• Power supply **voltages** V_+ and V_-	sampling rate 100 Hz
• Power Supply **currents,** I_+ and I_-	sampling rate 100 Hz
• **pressure**	sampling rate 100 Hz
• **X-rays energy spectra**	sampling rate > 10 MHz

X-Ray measurement are based on Lutetium–Yttrium OxyorthoSilicate (**LYSO**) crystal (4mm x 4mm x 20 mm).

- High average Z (66) and high density (5 g/cm^3) .
- Scintillator pulses decay time is ~40 ns)
- Energy resolution less than 9% (at 662 keV).

EXPERIMENTAL OBSERVATION - MicroDischarges



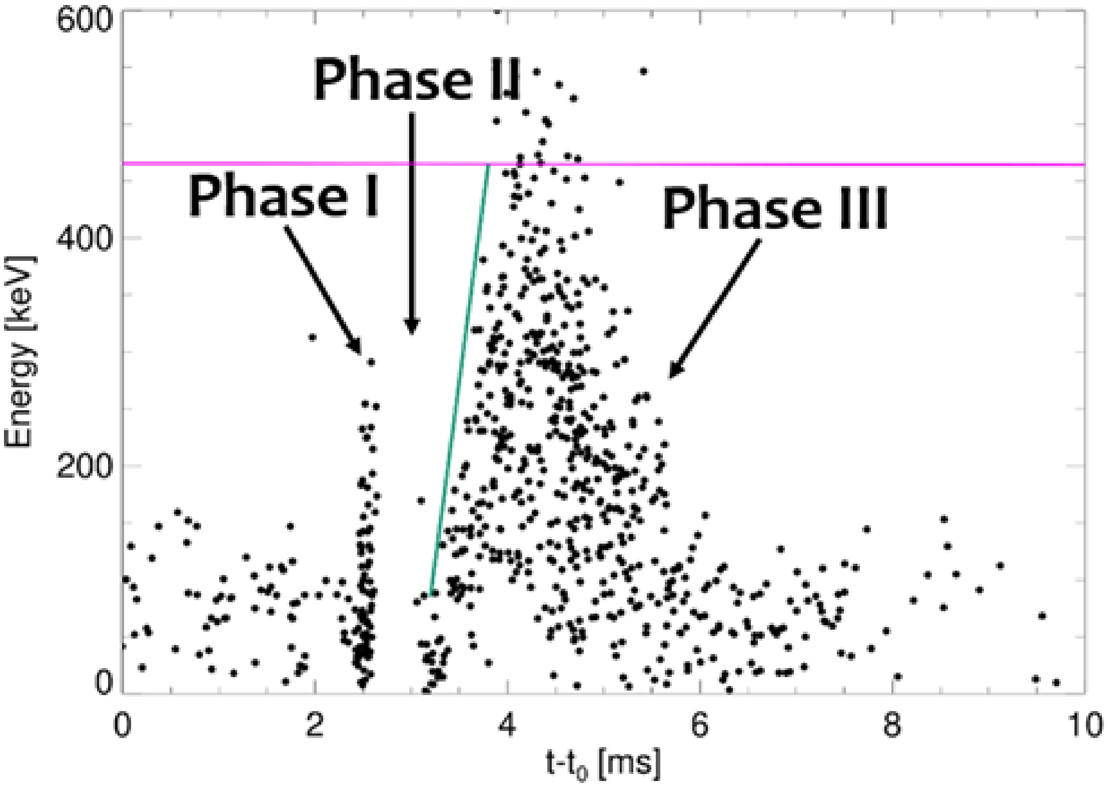
- I_+ and I_- both exhibit the occurrence of spikes or **MicroDischarges (MD)**.
- The majority of X-ray events have half energy. **MD** are associated to **full energy spectra** (the voltage difference is about 400 kV) → MD involves both the electrodes.
- MD anode current increases during the conditioning process with respect to the cathode current → **MD currents asymmetry.**
- The **MD fine dynamics** changes during the conditioning process: from 1 to 3 phases observed by X detectors.

I_K → cathode current
I_A → anode current

$$\text{Asymmetry } R_{exp} = \frac{Q_A}{Q_K}$$

We focus on the X spectra measurement, to explain current asymmetry and MD fine dynamics.

EXPERIMENTAL OBSERVATION – X fine dynamics of MD

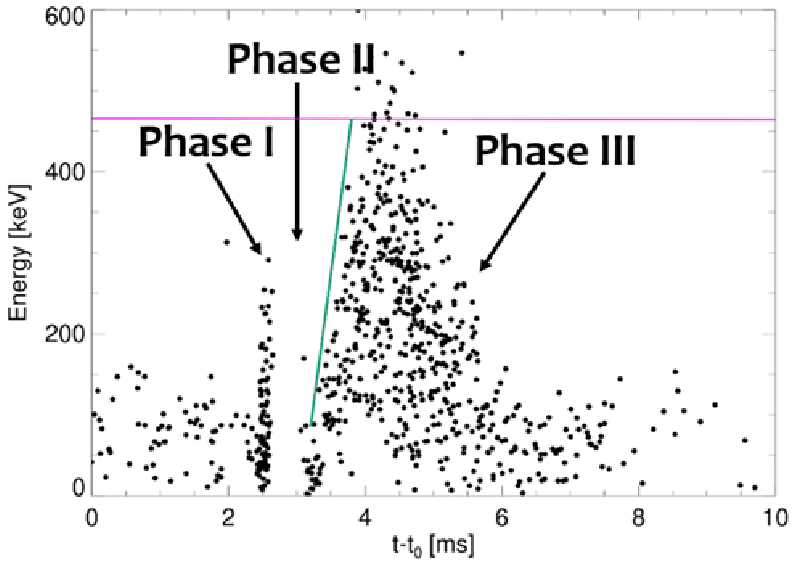


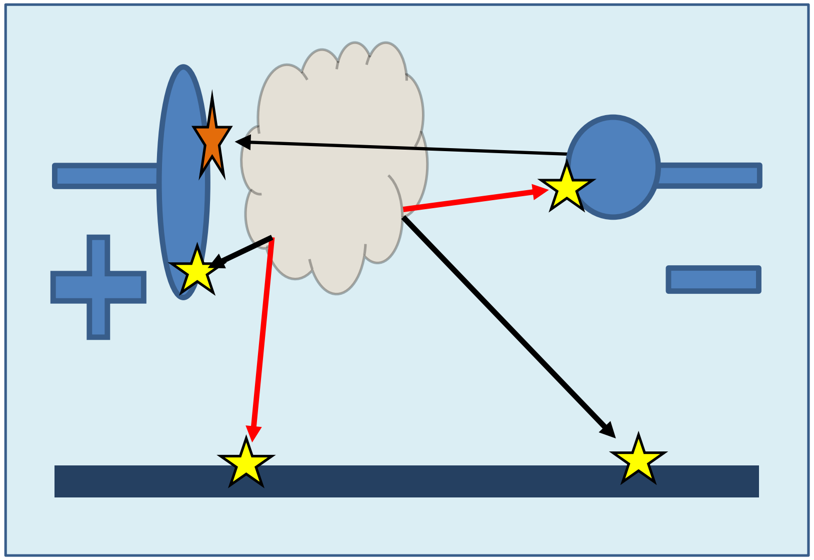
PHASE I: X-rays of different energies are generated, up to the maximum value provided by the accelerating voltage (Δt = 0.1 - 0.2 ms)

PHASE II: X events are very rarefied (Δt = 0.4 - 0.5 ms)

PHASE III: a strong X-rays production is measured (Δt = 3 - 4 ms).

TENTATIVE INTERPRETATION– X fine dynamics of MD





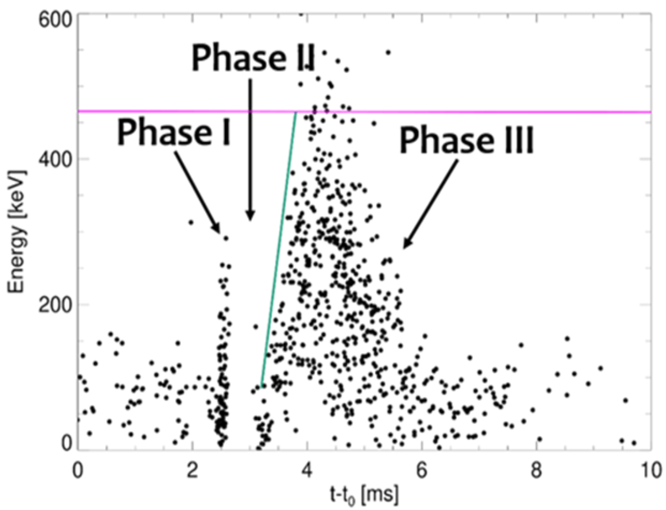
PHASE I: *X-rays generated by the primary electrons emitted by the cathode hitting the anode;*

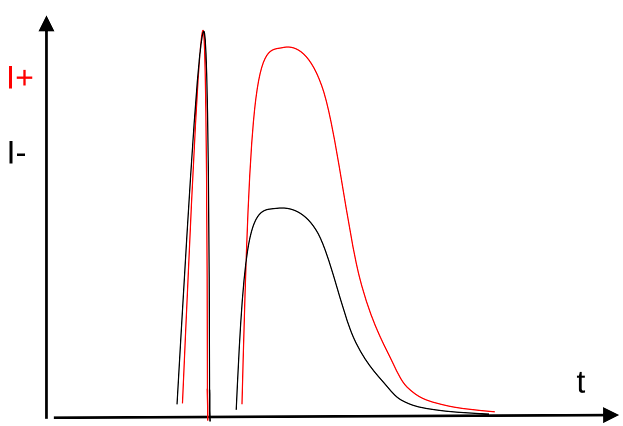
PHASE II: *primary electrons hitting the anode cause gas desorption. (H_2 and CO_2 emission was measured in correspondence of MD events). A gas bubble expands and ionizes: X-rays emission disappears, likely due to:*

- *Voltage drop across the gap*
- *interaction of electrons with gas*

PHASE III: *X-rays are generated by the electrons produced by the ionized gas and by secondary electrons, hitting the chamber, the electrodes and their metallic supports.*

TENTATIVE INTERPRETATION – I fine dynamic of MD





Due to the insufficient sampling rate, the fine dynamic of the currents can be inferred only from the X ray measurement.

- Phase I current is sustained by the primary electrons from cathode to anode, generated by the BD of the oxide layer (BIRD model) → symmetric current.

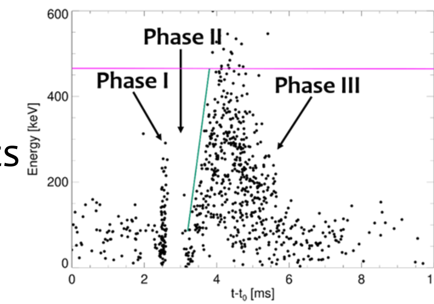
- The Phase I current has discharged the stray capacitances, then the electron current disappears, no longer sustained by the voltage (and/or electron current is present but the presence of gas prevents electrons to produce X)

- Phase III current is produced by the recovery of the V_{gap} that ionizes the (expanding) gas bubble. The slope shown by X energy could be associated either to the expansion of the gas bubble or to the dV_{gap}/dt. The current is then sustained by ions and electrons from the ionized gas and by the secondary electrons produced at the cathode and at the vessel → source of current asymmetry.

TENTATIVE INTERPRETATION – A-K Current Imbalance

- Current imbalance is measured in terms of electric charge $R_{exp} = \frac{\int i_A dt}{\int i_K dt} = \frac{Q_A}{Q_K}$. It has been observed that such imbalance increases with the conditioning from unity to 2.0

- The current imbalance comes only from processes associated to the ionization of the gas desorbed from the anode, as the first peak of current is sustained by K→A primary electrons. To compare the experiment with a zero-order («toy model») evaluation of such processes, we have to make the following assumptions.



1. $Q_{e-I} \propto X_I$ Total electron charge of Phase I proportional to X_I counts
2. $Q_{e-III} \propto X_{III}$ Total electron charge of Phase IIII proportional to X_{III} counts
3. $\frac{X_I}{X_{III}} = k = 15\% \rightarrow Q_{e-I} = k \cdot Q_{e-III}$
4. $Q_{A-I} = Q_{K-I} = Q_{e-I}$
5. $Q_{e-III} = Q_{V-e-III} + Q_{A-e-III}$ Total electron charge hitting the Vessel and the Anode
6. Ionized gas ions and electrons flow to the electrodes and the vessel in symmetric way (KIF=0.5).

- Under these assumption, during phase III the total charge collected by the anode Q_{A-III} and cathode Q_{K-III} can be evaluated, given the values of the ion-electron Yield Y_{i-e}, electron-electron Yield Y_{e-e} and the share of the secondary electrons produced by the gas ions hitting the cathode between the Anode and the Vessel

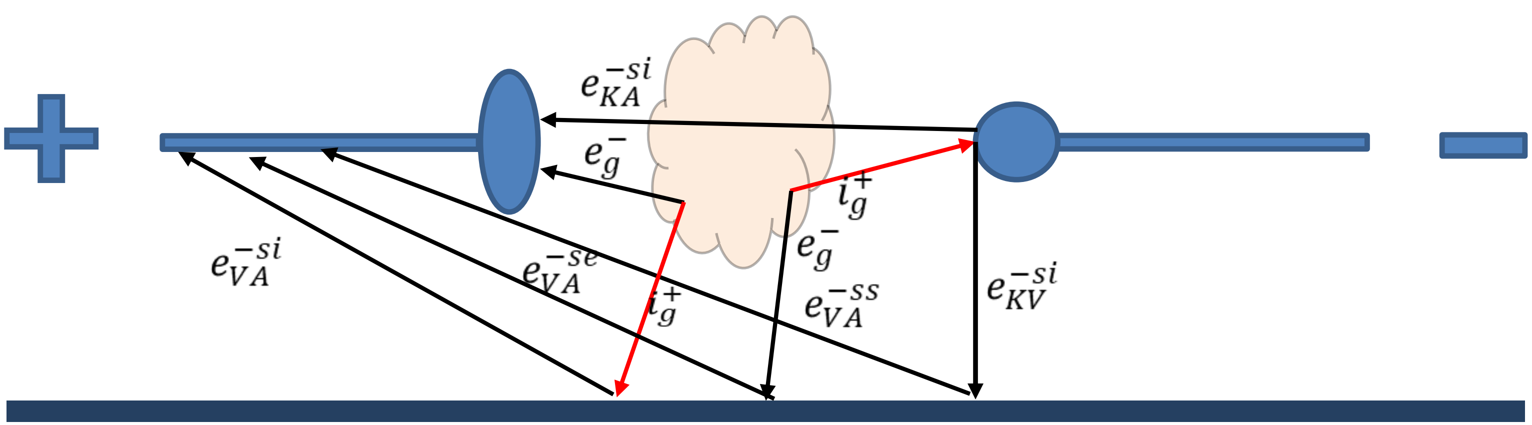
- The Current (charge) imbalance is then calculated as $R_{mod} = \frac{Q_{A-I}+Q_{A-III}}{Q_{K-I}+Q_{K-III}}$

TENTATIVE INTERPRETATION – A-K Current Imbalance

The toy model starts from the $i_g^+$and e_g^- generated by the desorbed gas ionizaton, taking into account the following interactions and processes:

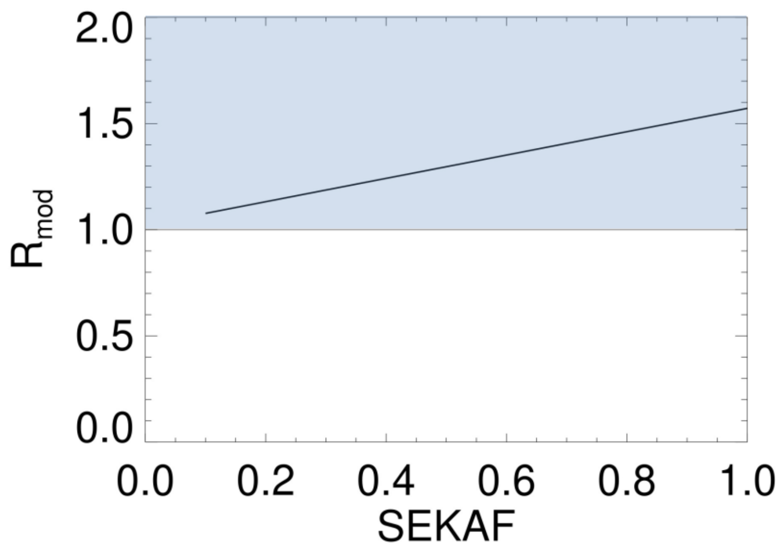
- i_g^+ fly to K
  - generate SEs flying to A e_{KA}^{-si} Y$_{i\text{-}e}$=2.5
  - generate SEs flying to V e_{KV}^{-si} Y$_{i\text{-}e}$=2.5
    - generate SEs flying to A e_{VA}^{-ss} Y$_{e\text{-}e}$=0.1
- i_g^+ fly to V
  - generate SEs flying to A e_{VA}^{-si} Y$_{i\text{-}e}$=2.5
- e_g^- fly to A
  - no generation of flying SEs
- e_g^- fly to V
  - generate of SEs flying to A e_{VA}^{-se} Y$_{e\text{-}e}$=0.1

} SEKAF=[0.1 – 1.0]

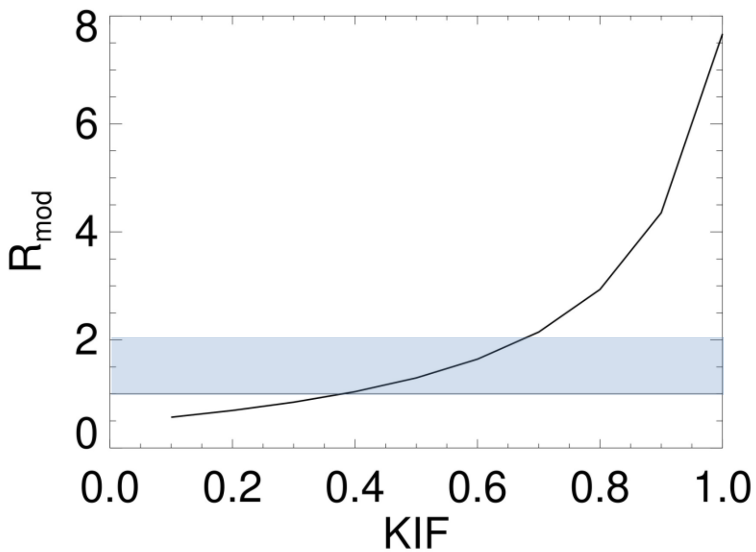


TENTATIVE INTERPRETATION – A-K Current Imbalance

- The current imbalance R_{mod} poorly depend on the value of the yields and linearly depend of the value of SEKAF. $R_{mod} > 1$ always.



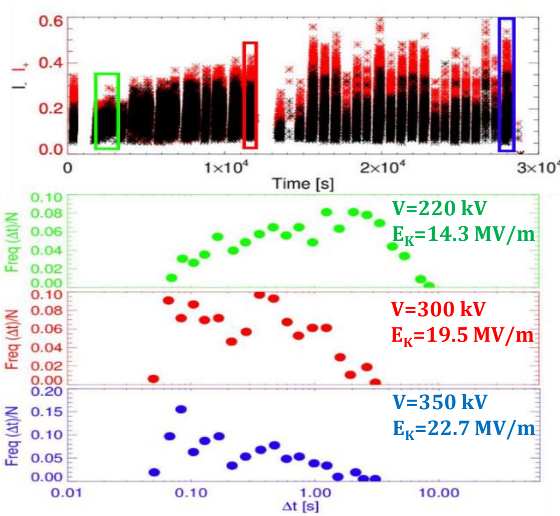
- The current imbalance strongly depend on the symmetric flow of gas ions and electrons: can produce current imbalance even in favour of the cathode ($R_{mod} < 1$)

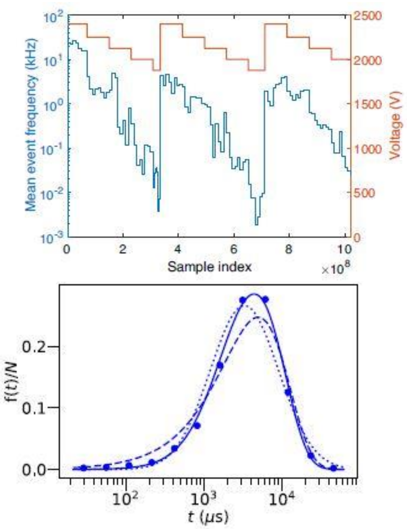


MICRODISCHARGES TIME DISTRIBUTION

Suggestion by Andreas: to analyse the MDs time distribution and to compare the findings in the framework of the MDDF model

*E. Z. Engelberg, "Dark current spikes as an indicator of mobile dislocation dynamics under intense dc electric fields", PHYSICAL REVIEW ACCELERATORS AND BEAMS 23, 123501 (2020)





Similarities

- Δt decrease with voltage

Differences

- Often two peaks can be identified
- Time intervals differ of 3 order of magnitude
- E_k lower than $E_{activation}$ (20-30 MV/m)

The mechanism of CSs generation seems different CS induced by mobile dislocation dynamics.

IMPROVEMENTS

Diagnostics

- Use of ACCT current transformer to measure burst current with <1μA resolution BW 1 MHz (Bergoz). *In progress*
- Increase of the sampling rate to 1 kHz. *Implemented*
- Full synchronization of all signals (in particular Current and X). *In progress.*
- Reduction of the EMI affecting the X measurement during CB.
- Spatial identification of X source (Collimator) with the use additional LYSO-Based detectors. *Implemented.*
- Use of Gas Electron Multiplier (GEM) based dectector for Soft X-ray. *Implemented*
- Validation of the circuit model.
- Charge generation model (Comsol). *In progress.*
- Further investigation on Microdischarges statistics

SUMMARY AND CONCLUSIONS

- During voltage conditioning, current asymmetry and a Micro-Discharge fine dynamics are observed. From the X measurements, the micro-discharge process evolves in three phases:

  I) cathode emits electrons hitting the anode (BIRD? MDDF?).
  II) gas is emitted by the anode and ionized.
  III) ionized particles and secondary electrons hit electrodes, their supports and vacuum chamber.

- Phase III accounts for asymmetry. A toy model of the charges collected by anode and cathode suggests that the asymmetry between the currents is related to the fraction of the secondary electrons produced by the gas ions hitting the Cathode.

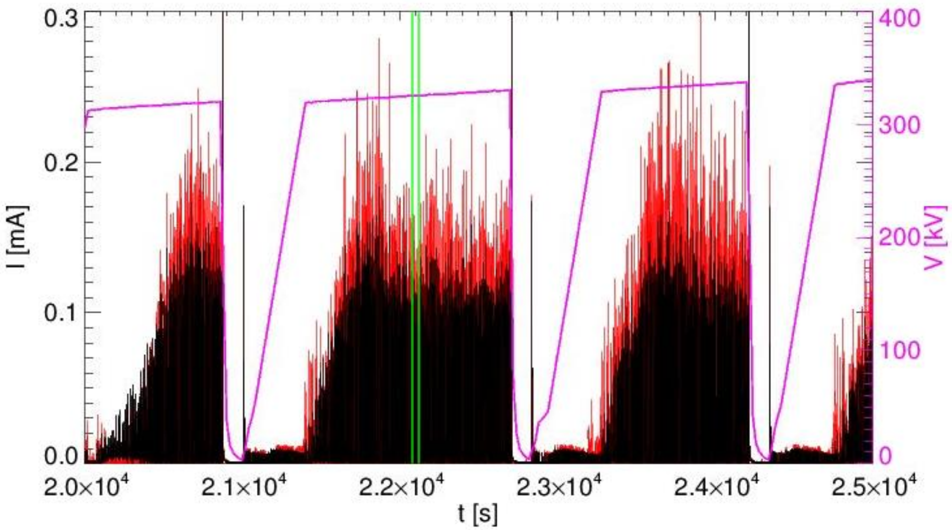
- A comparison made with a MD statistical analysis made on the framework of the MDDF theory, indicates that in our case the Current Spike initiation mechanism is different.

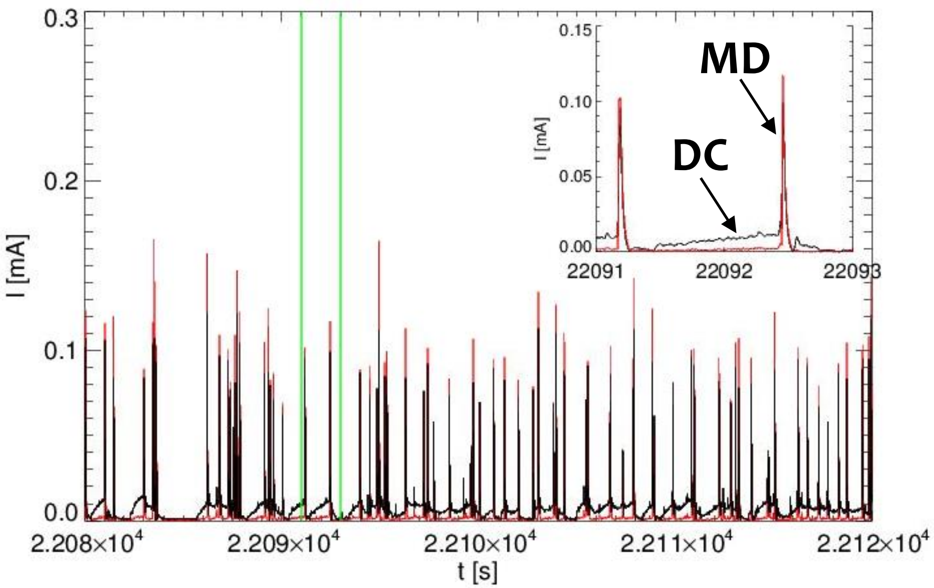
- Some modifications of the system are required in order to focus the analysis on the physical phenomena strictly involving the electrodes.

THANK YOU FOR THE ATTENTION

Back up slides

The current signals

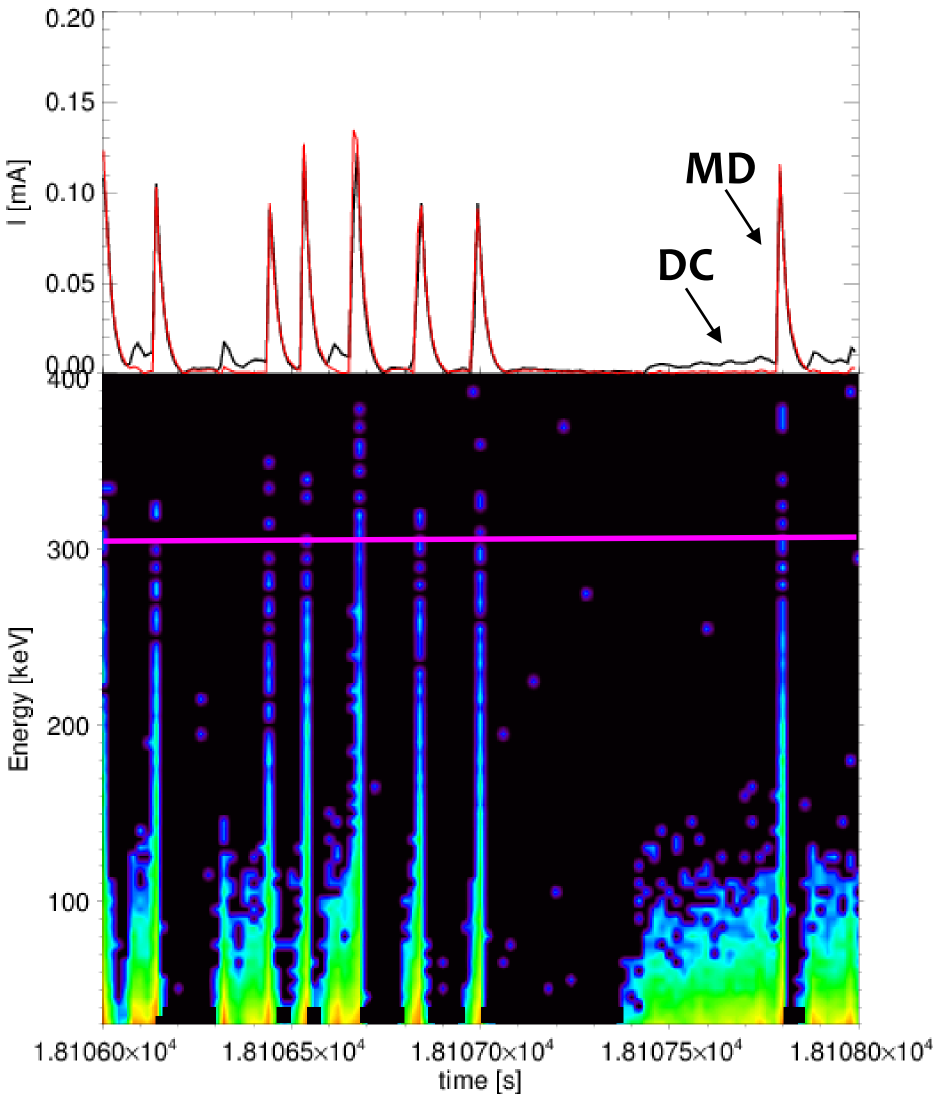




I_- → current on negative electrode
I_+ → current on positive electrode

- I_+ and I_- both exhibit the occurrence of spikes or **MicroDischarges (MD):** this interation mainly involves electrodes.
- I_- signal measures an almost continuous current, named **Direct Current (DC),** of about 0.01 mA: the cathode interacts with the vessel.

X-rays

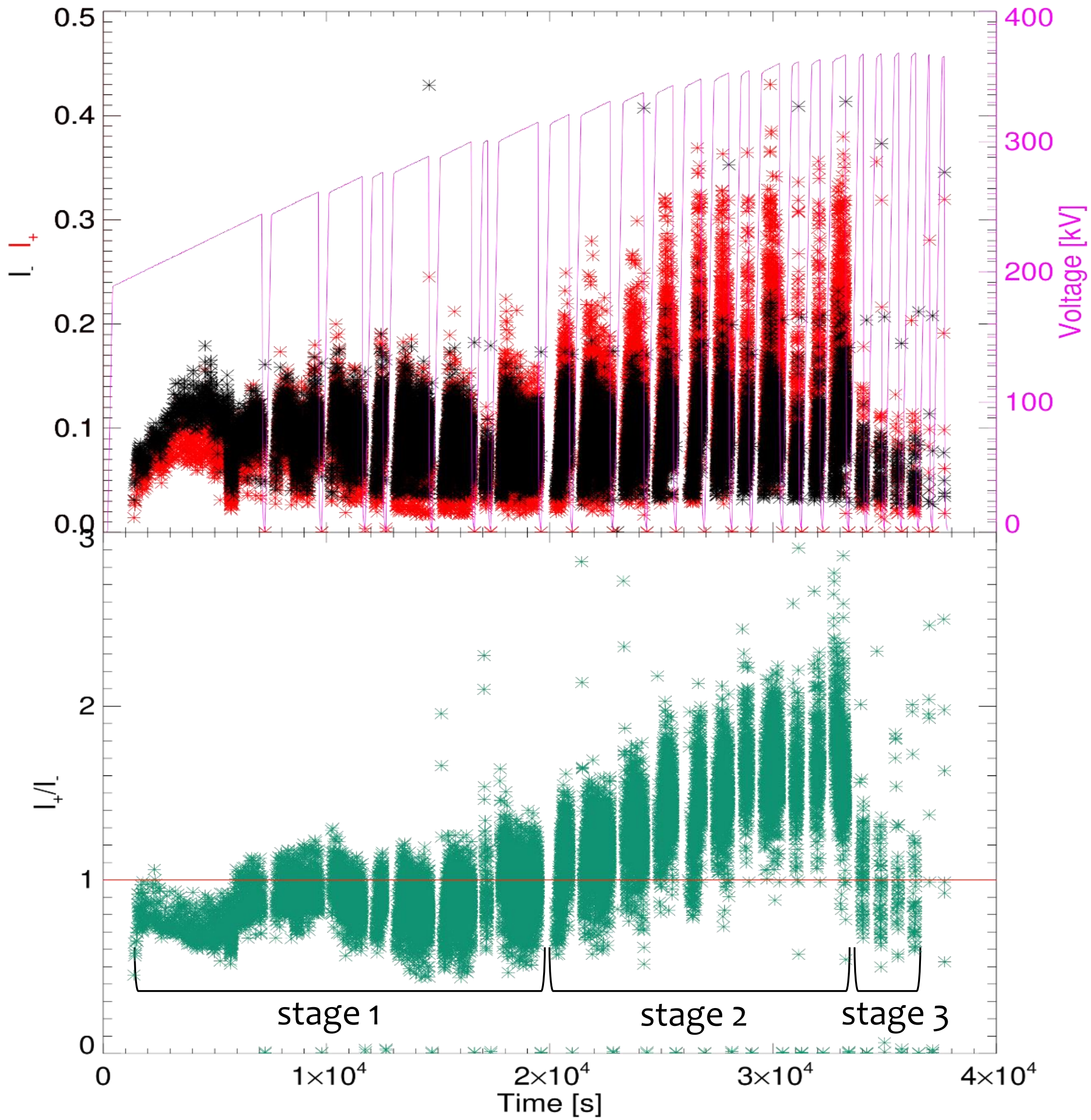


There is a clear relation between I_{-} current and X-ray signals:

- MD are associated to **high energy** (full energy) events → from the electrodes.
- DC is due to electrons from the cathode to the vessel (half energy)

We will focus on MD phenomenon

Microdischarges



Cathode current

Anode current

R parameter $\mathbf{R} = \frac{\mathbf{I}_+}{\mathbf{I}_-}$

During the conditioning process

Stage 1: $R \leq 1, I_- \geq I_+$

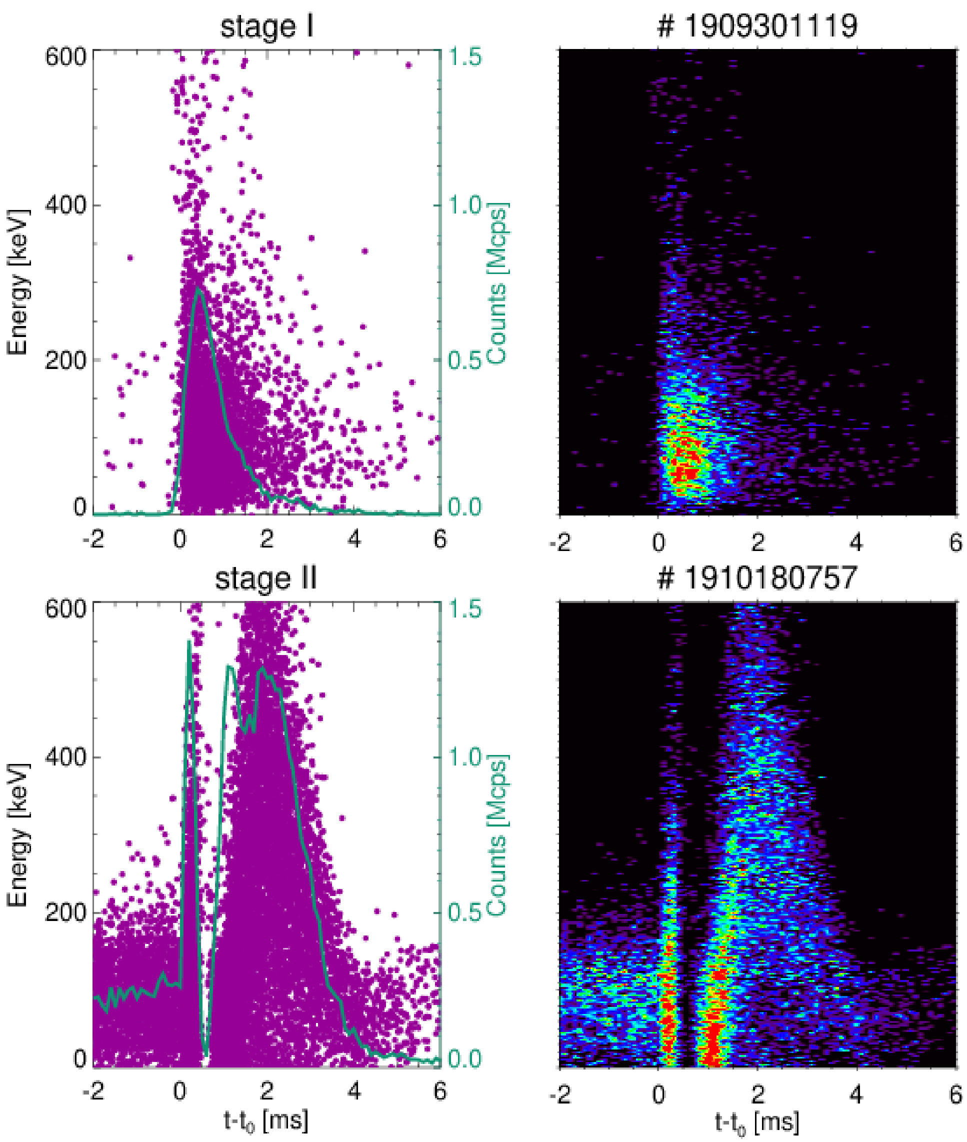
Stage 2: $R > 1, I_- < I_+$

Stage 3: $R = 1, I_- = I_+$

At stage 2, I_+ increases with respect to I_- → WHY?

$1 < R < 1.8$

X-rays measurements during the conditioning



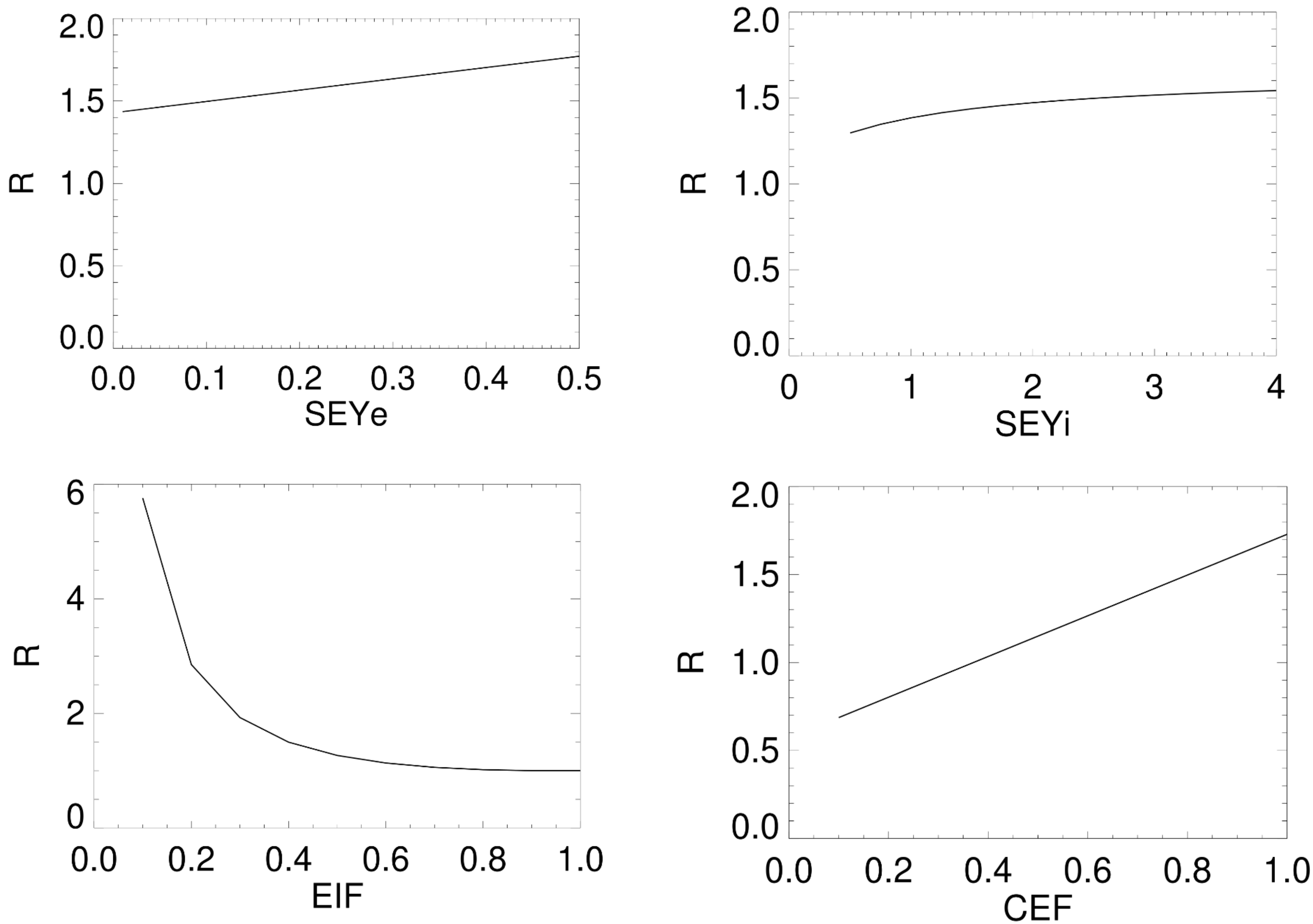
Stage I: high energy X-rays produced by the primary electrons are observed, followed by those produced from secondary electrons emission.

Stage II: the 3 phases can be distinguished → high energy electrons extract a (growing) gas amount from the anode.

We wonder if the two experimental observations (i.e. the modification of the MD fine dynamics and the anode current increase during the electrodes conditioning) are related.

Tentative interpretation: the R parameter

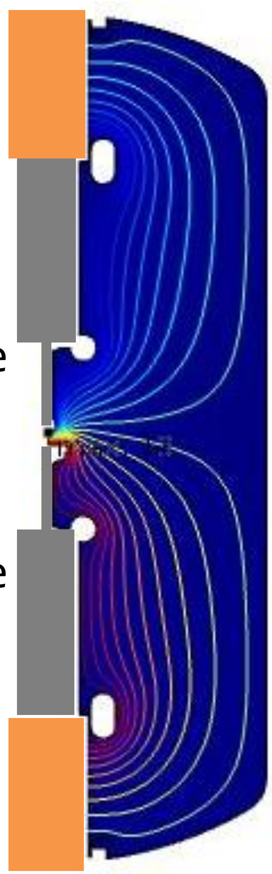
$$R = \frac{I_+}{I_-}$$

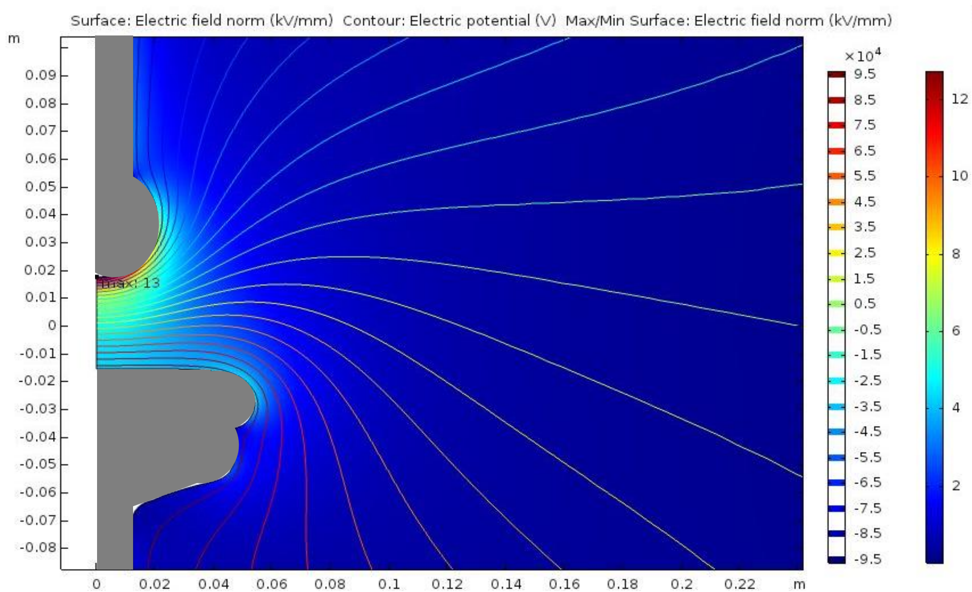


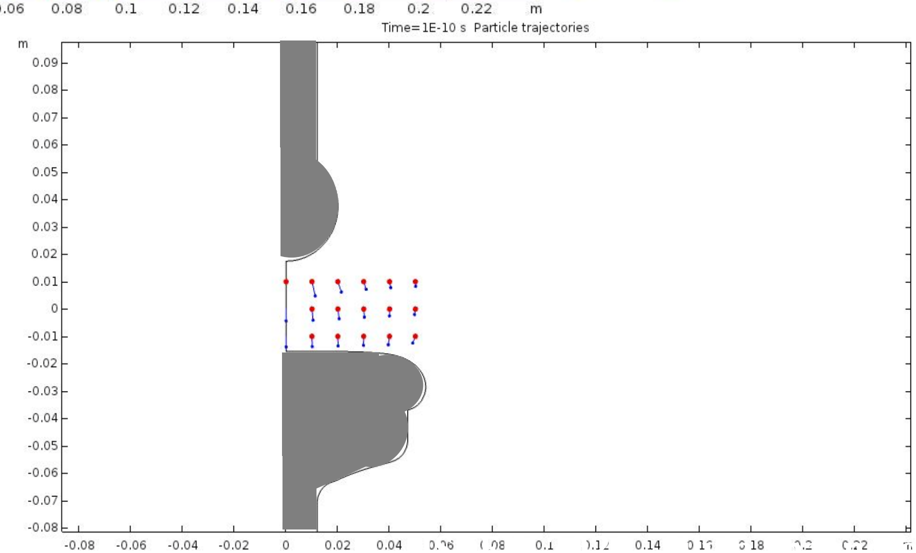
Tentative interpretation by simulation

Negative electrode

Positive electrode

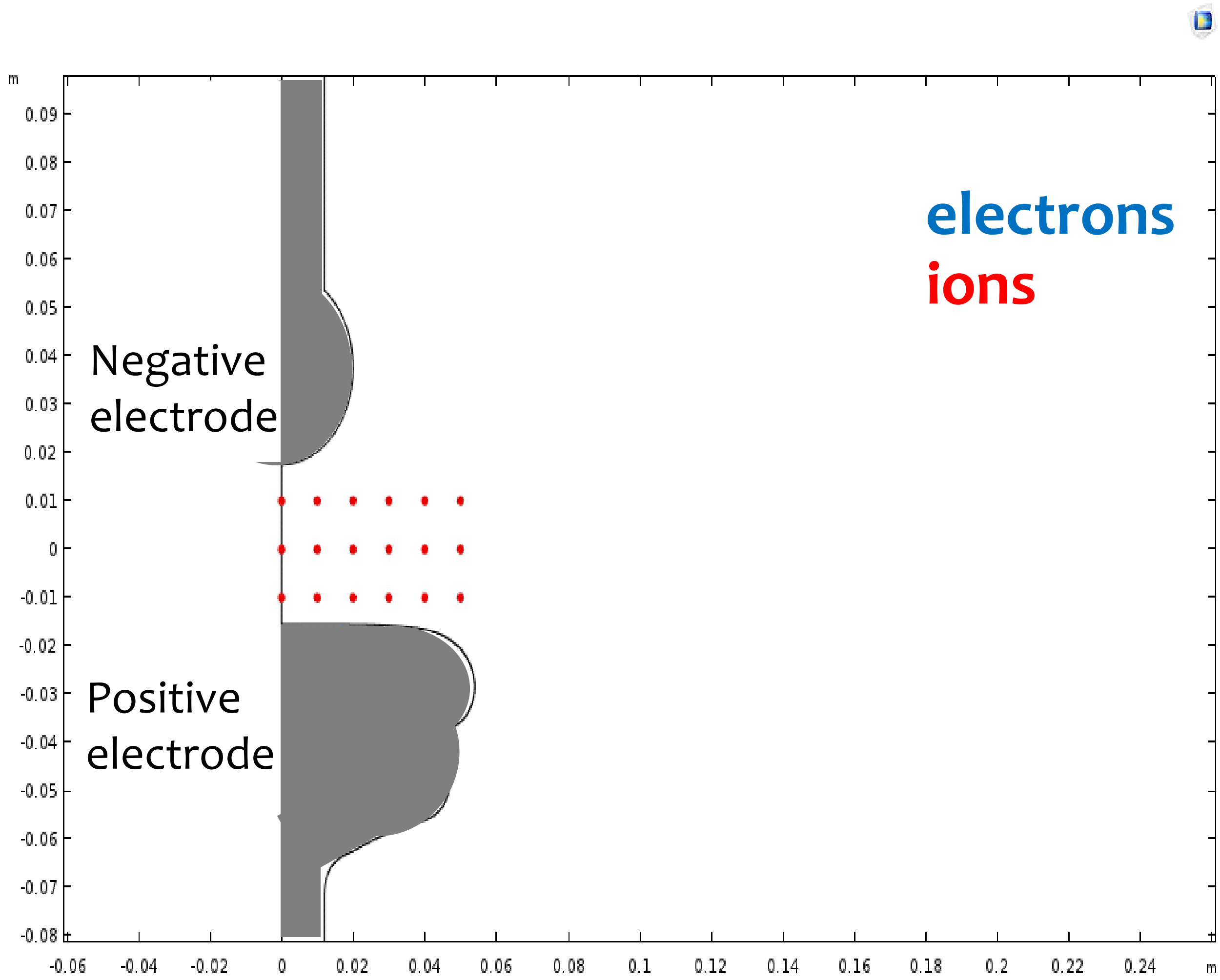


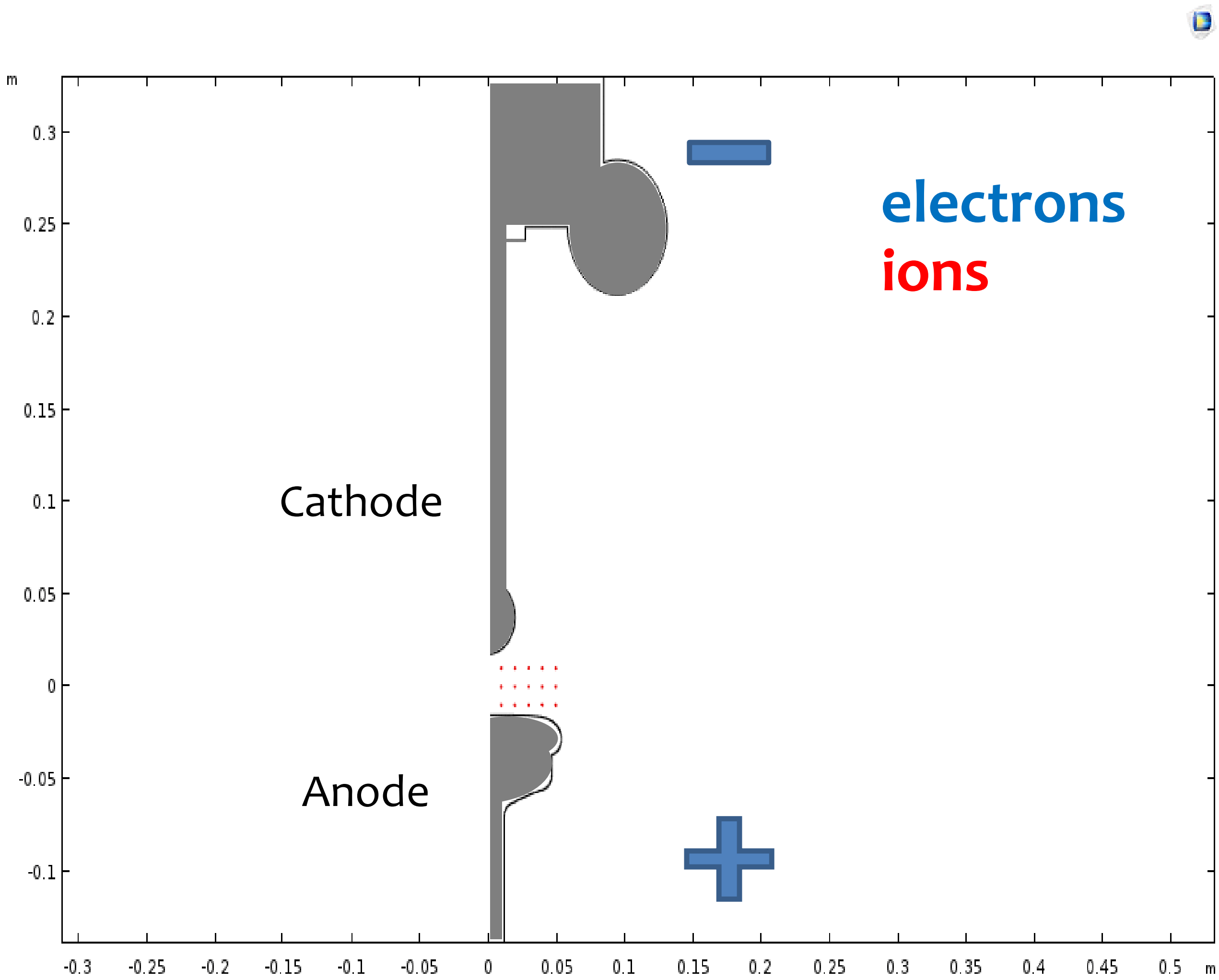




- Axisymmetric geometry of the chamber
- Electrode = electrode itself + its metallic support
- Ion/electron pairs matrix between the electrodes (v=0), miming the ionized gas

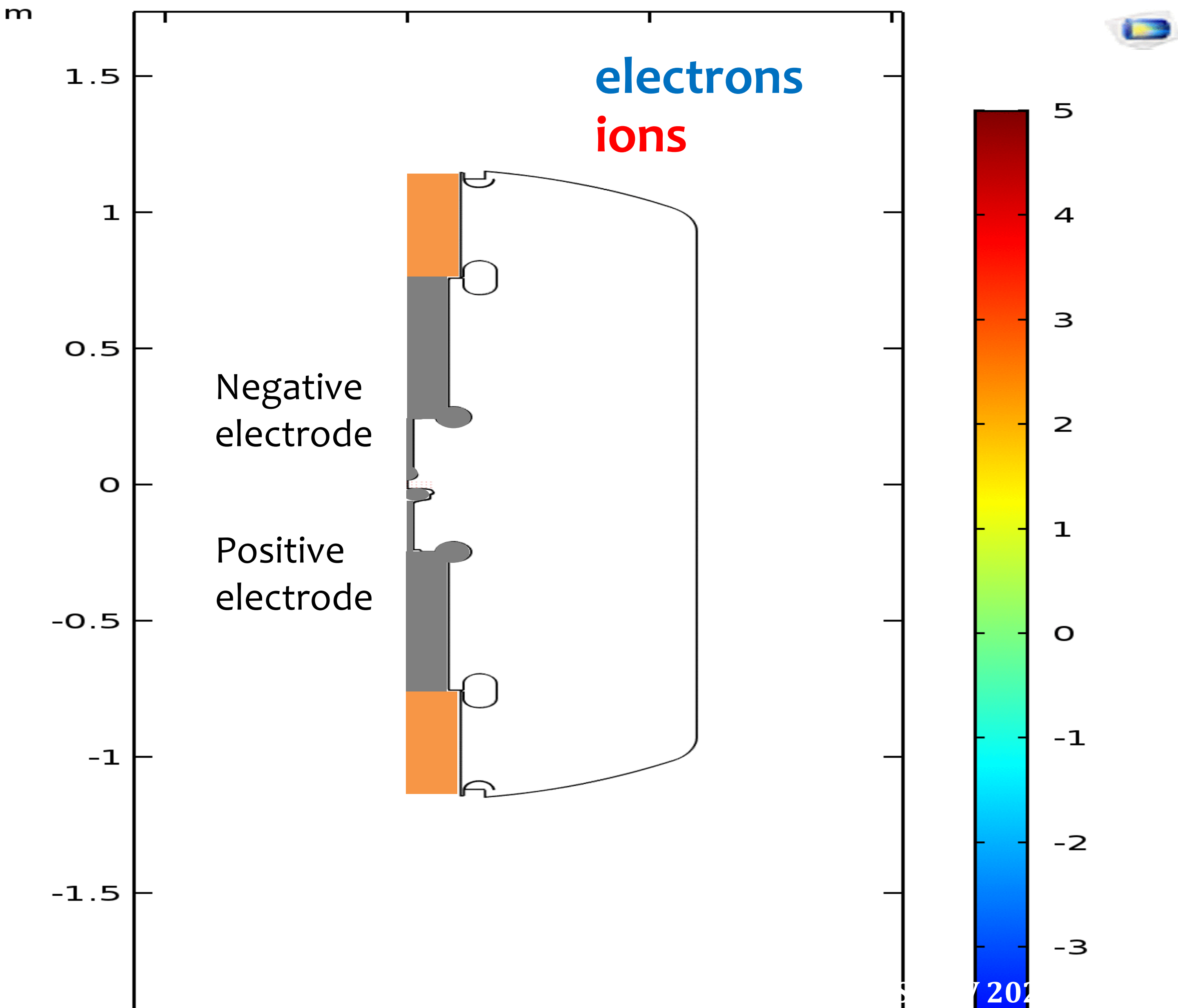
Tentative interpretation by simulation





m
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
m
Cathode
Anode
electrons
ions

Tentative interpretation by simulation



Tentative interpretation by simulation