Analysis of current and X-ray signals for a vacuum high voltage holding experiment

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Megavolt ITER Injector and Concept Advancement

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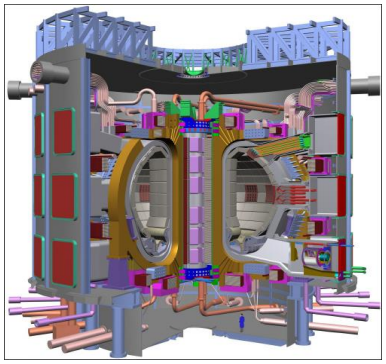
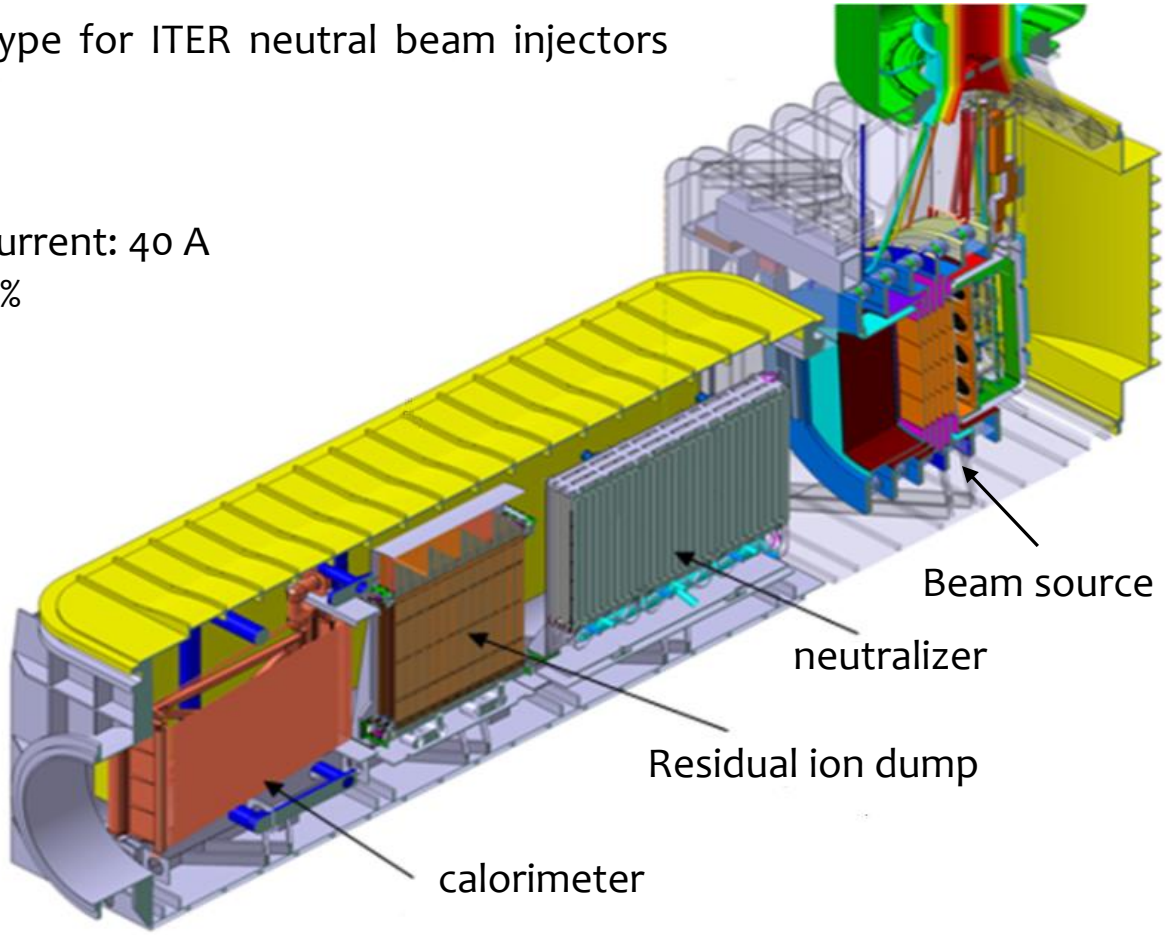
ITER is an international experimental facility (Cadarache, France) aiming to demonstrate the technological and scientific feasibility of **thermonuclear fusion** as an energy source. It requires additional heating by two **neutral beam injectors**.

MITICA is a full-scale prototype for ITER neutral beam injectors (Padova, Italy)

- Accelerating voltage: 1 MV
- Extracted and accelerated current: 40 A
- Neutralization efficiency: 60%
- Beam power: 17 MW
- Pulse length: 1 h
- Operating gas: H, D





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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)

High Voltage Padova Test Facility

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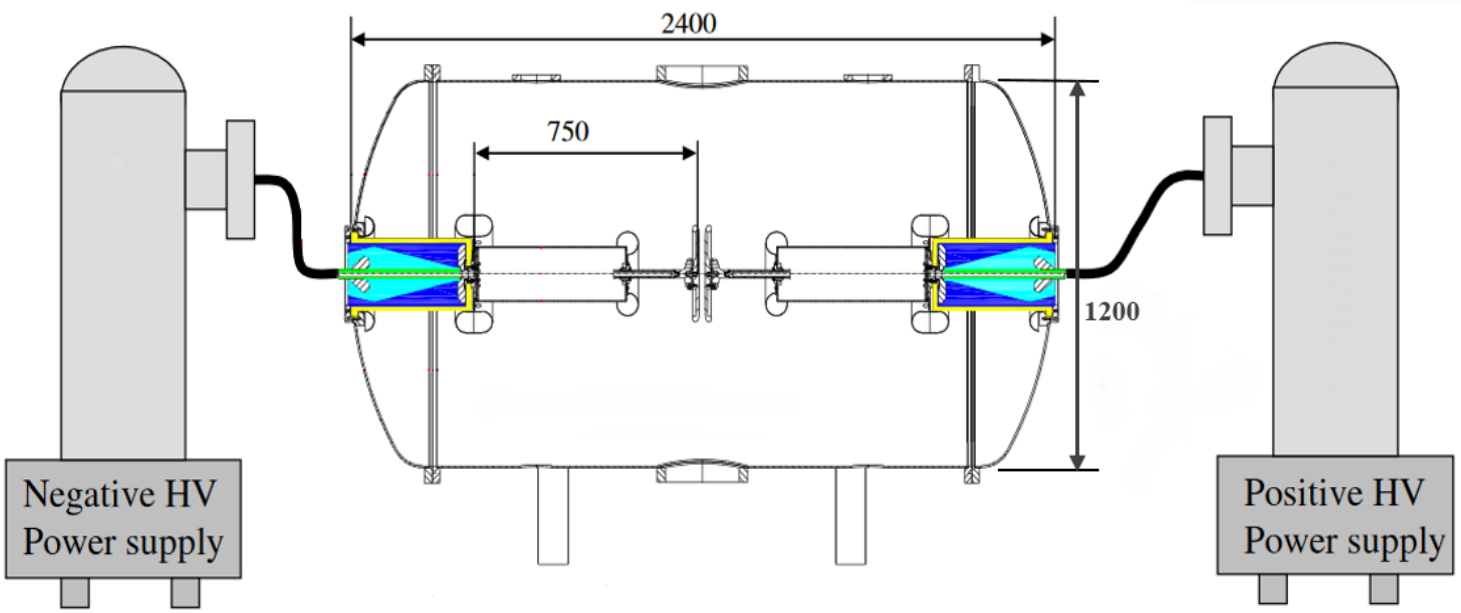
HVPTF aims:
- to support MITICA design and operation
- to test MITICA components (e.g. high voltage insulators)
- to investigate HV holding in large vacuum gaps as a physical phenomenon



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

Experimental setup: electrodes and voltage cycle

Negative electrode: Sphere AISI304 Ø=40 mm
Positive electrode: Plate AISI304 Ø=108 mm
Gap between the electrodes: 30 mm

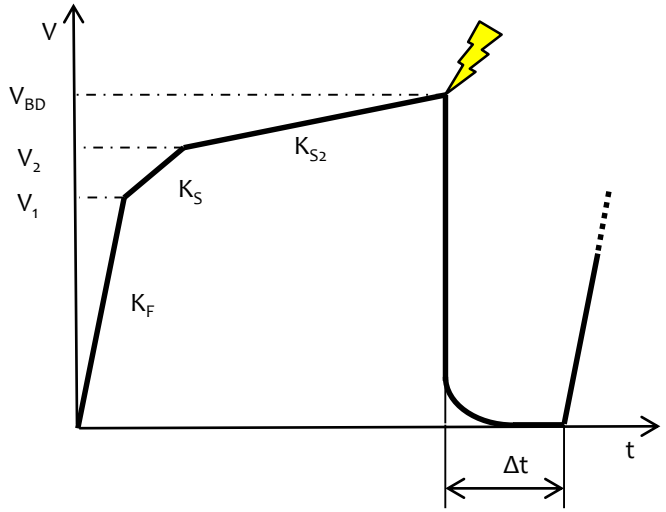
Electrodes treatment:

dry polishing using abrasive sheets
acetone cleaning
ultrasound washing

Voltage cycle:

Electrodes conditioning by means of automatic procedure, simmetrically operating on both power supplies:

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



Experimental setup: diagnostics

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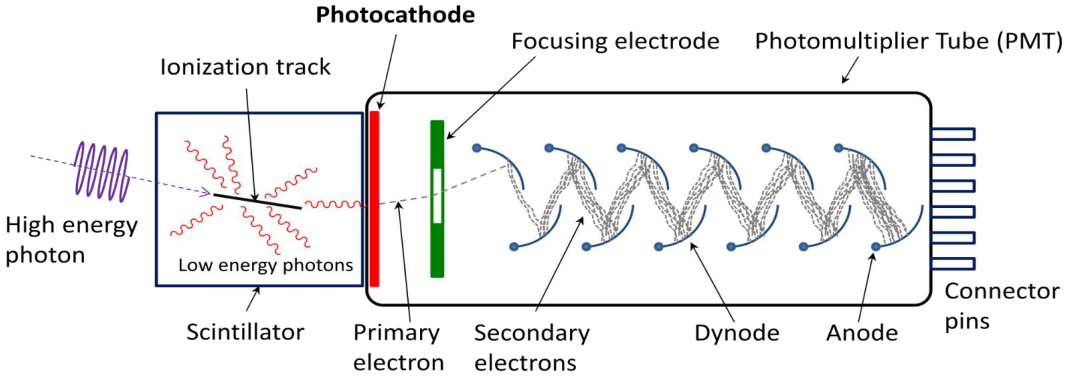
•Applied voltages, V_+ and V_-, electrode currents, I_+ and I_- and pressure signals are sampled together at 100 Hz.

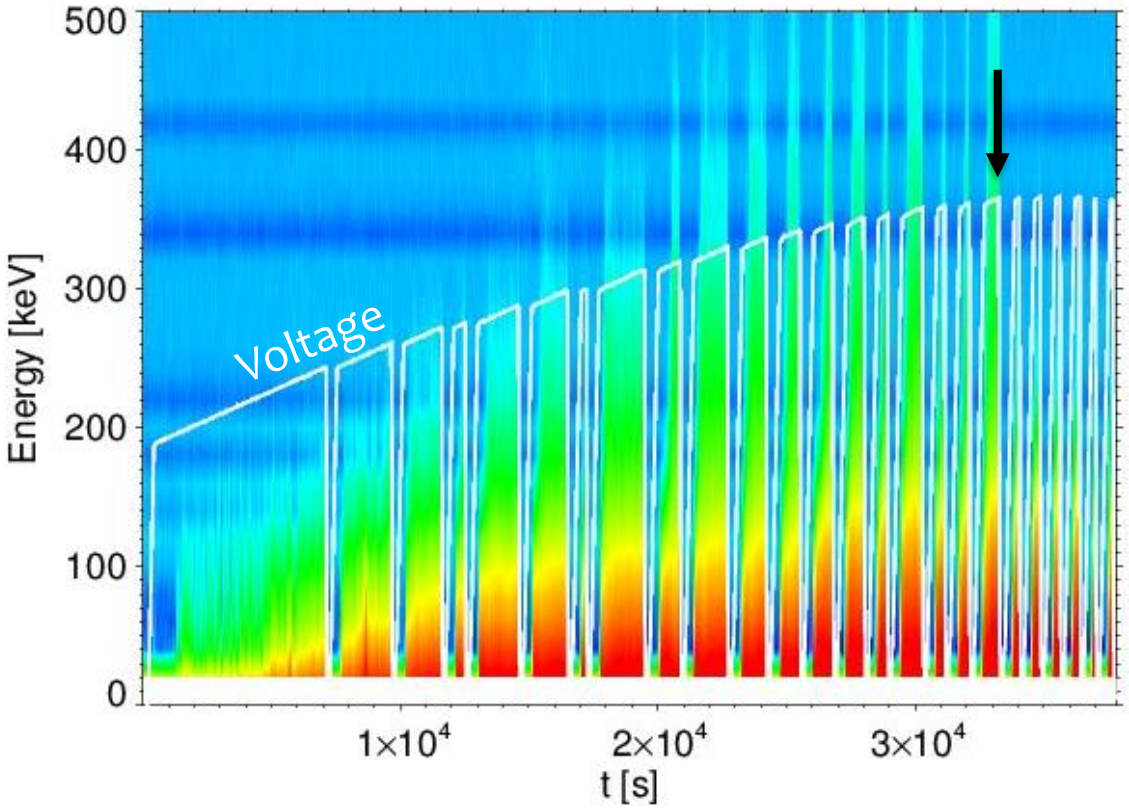
•A Residual Gas Analyzer (RGA), directly connected to the vacuum chamber, measures the composition of the gas desorbed from the internal surfaces.

•An Infra-Red Camera is devoted to monitor the temperature inside the vessel. Thermal sensitivity: 0.03°C; each frame is recorded at 50 Hz.

•X-rays emitted by accelerated electrons are measured by a EJ-228 organic scintillator in polyvinyl toluene (PVT). It is positioned outside the vacuum chamber, at 1 meter far from a glass window and connected to a multichannel digitizer, recording energy and time of each single photon detected up to a maximum rate of 350 kHz.



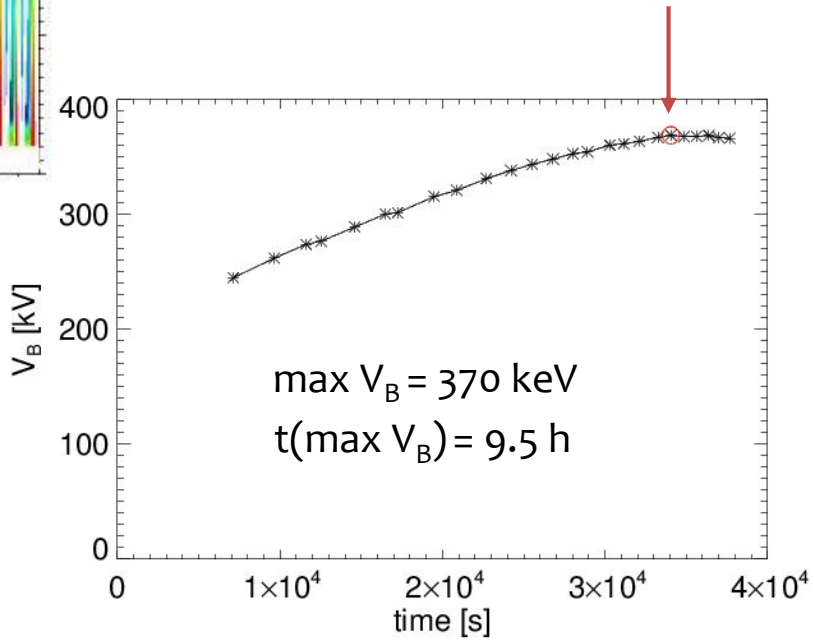
X-rays energy spectrum



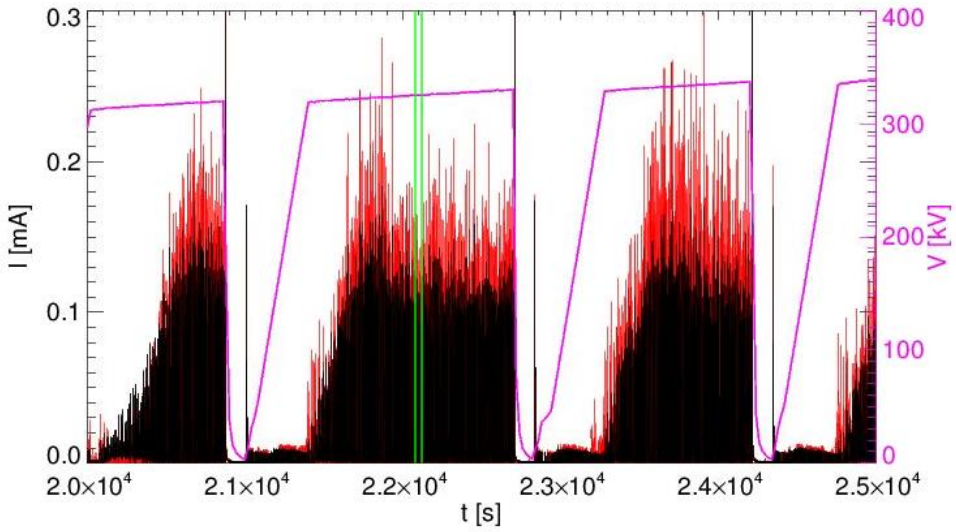
X-rays energy spectrum during a conditioning session

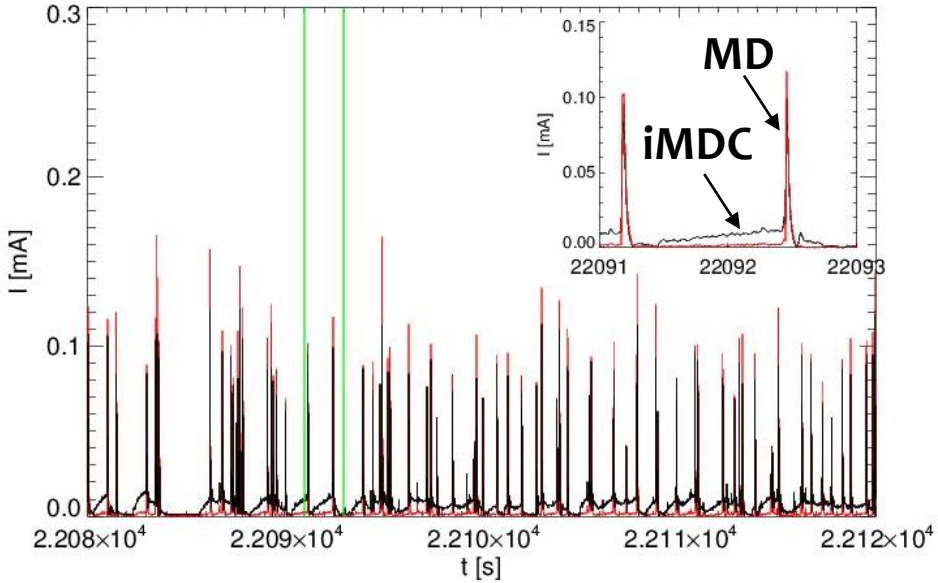
(it is a sum of Compton spectra).

No high energy X-rays after the maximum voltage value is achieved.



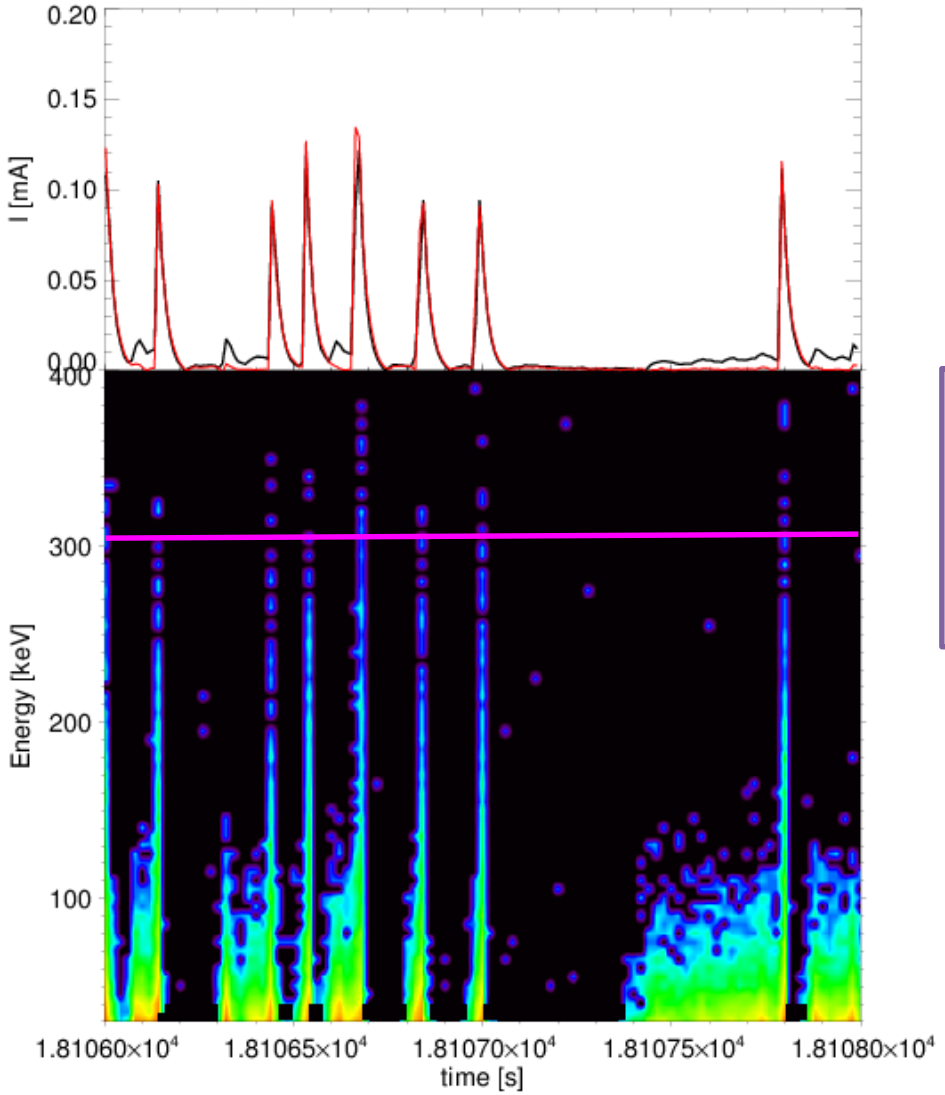
The current signals





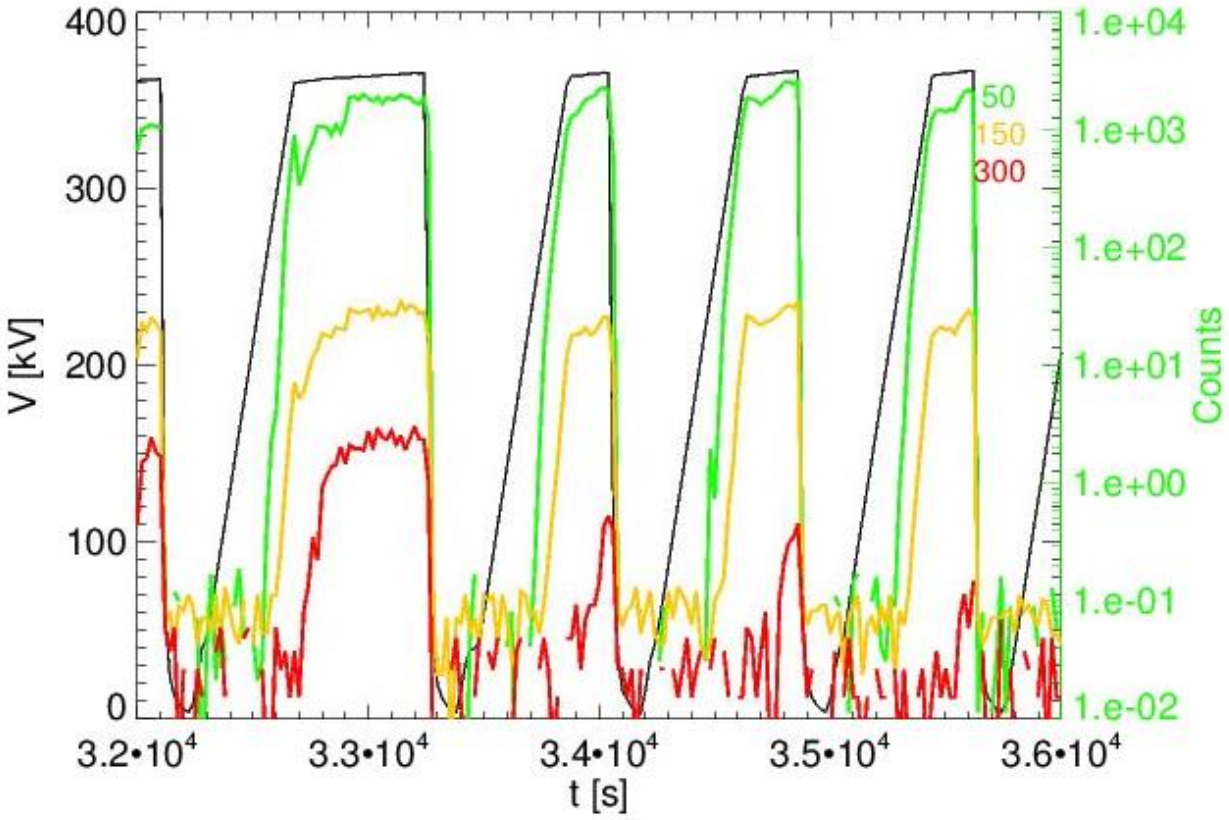
- I_+ and I_- both exhibit the occurrence of spikes or **microdischarges (MD):** this interation mainly involves electrodes.
- I_- signal measures an almost continuous current of about 0.01 mA, not simmetrically corresponded by I_+, named **inter-MD Current (iMDC).** The cathode interacts with the vessel.

Experimental observations: I and X correlation



There is a clear relation between I_- current and X-ray signals: MD are associated to **high energy** (full energy) events.

Experimental observations: high energy X-rays



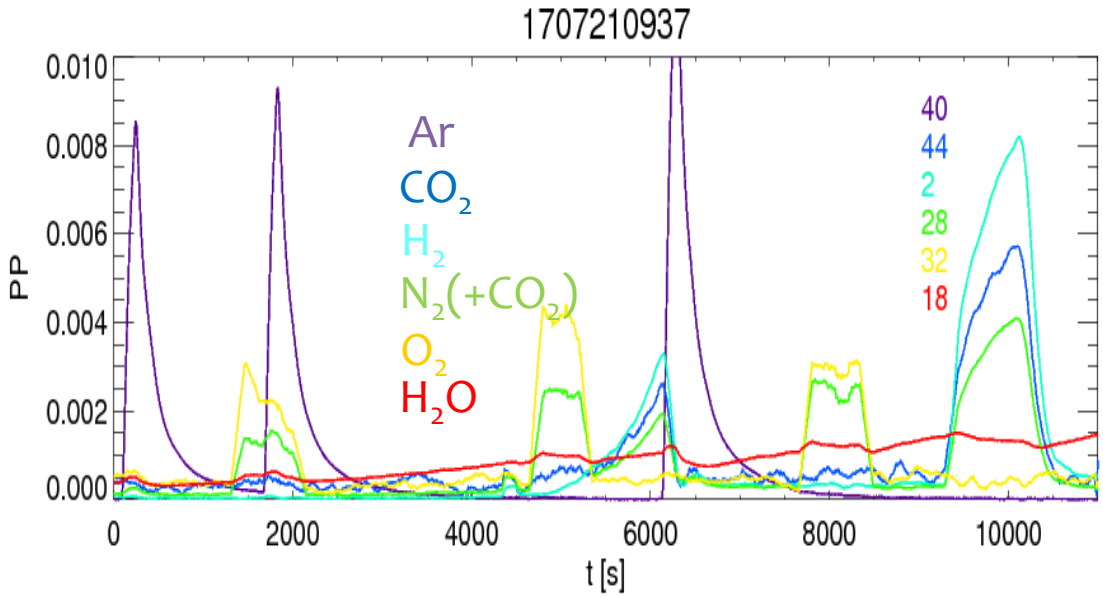
E_1=50 keV

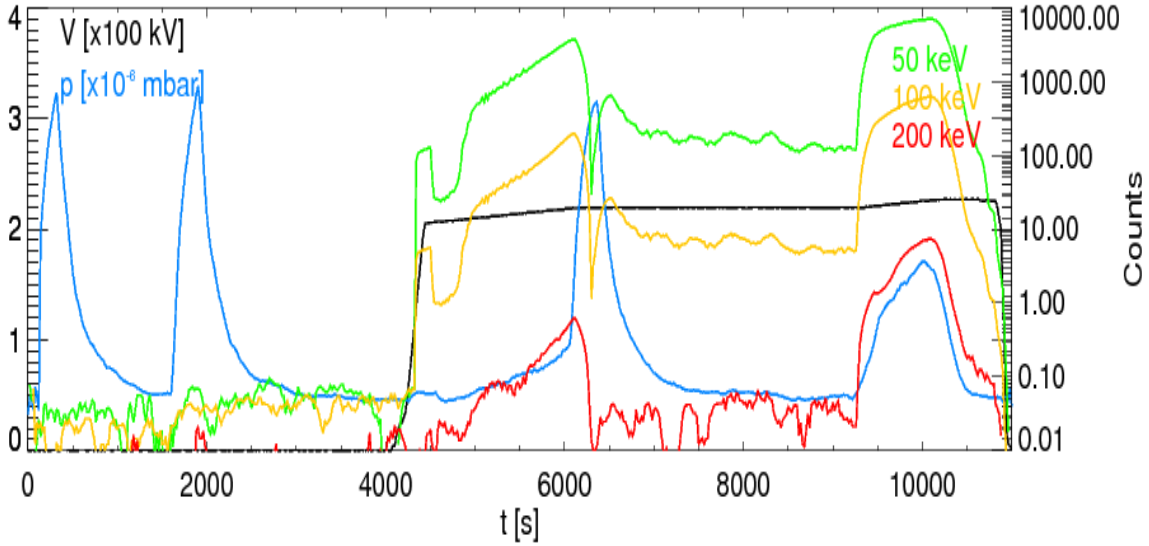
E_2=150 keV

E_3=300 keV

High energy X-rays occurr when the voltage overcomes the previous breakdown value.

Experimental observations: gas emission





The emission of H2 and CO2 is measured in correspondence of the **high energy** X-rays detection.

W.T. Diamond, Journal of Vacuum Science & Technology A **16**, 720 (1998)

Experimental observations

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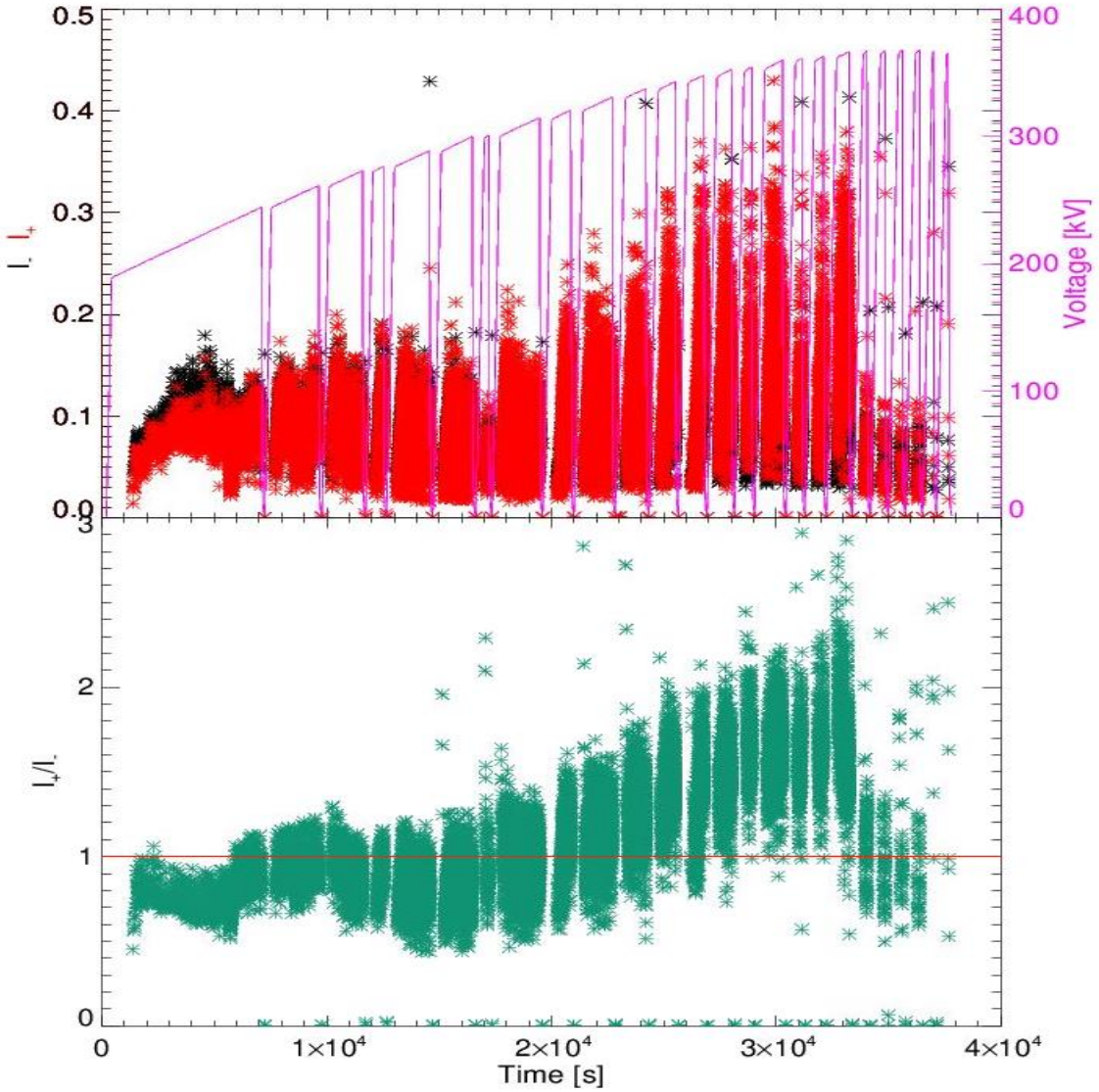
- There is a clear relation between I_- current and X-ray signals: **MicroDischarges** are associated to **high energy** (full energy) events.
- **High energy** X-rays occurr when the voltage overcomes the previous breakdown value.
- The emission of Hydrogen and Carbon dioxide is measured in correspondence of the **high energy** X-rays detection.

MD realize the conditioning of the electrodes

Microdischarges



Cathode current

Anode current

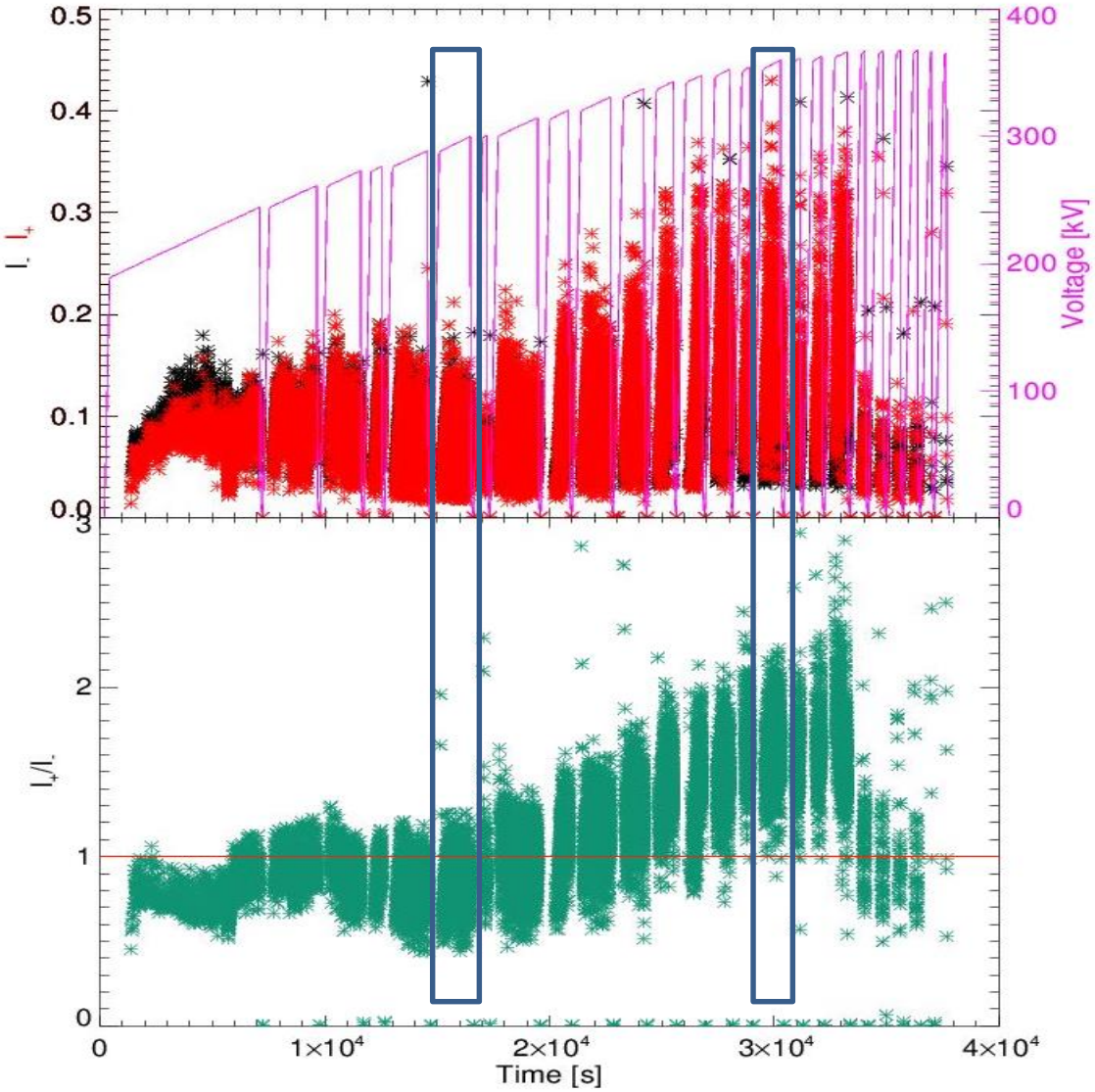
$$R = \frac{I_+}{I_-}$$

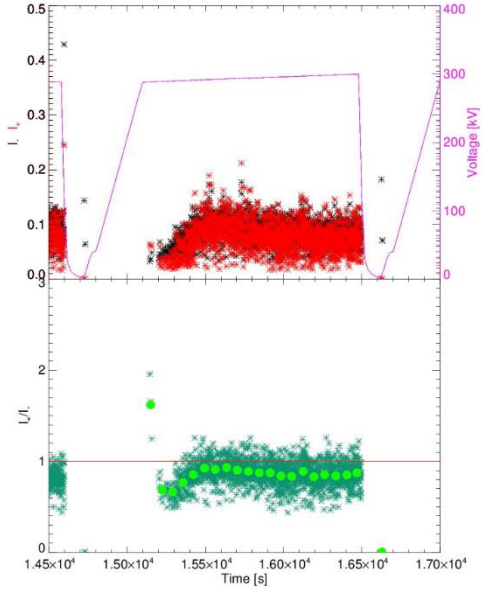
1st phase: $R \leq 1, I_- \geq I_+$

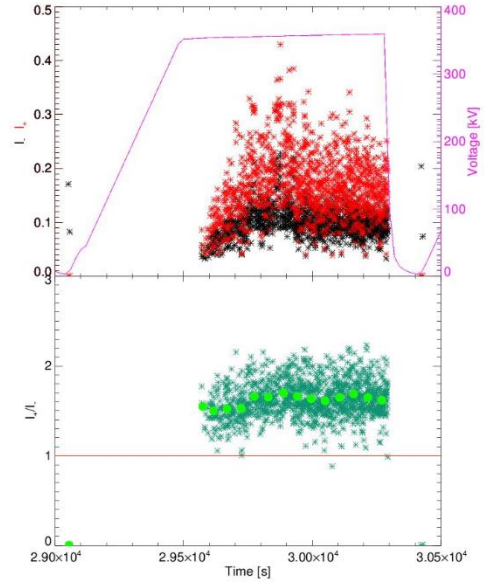
2nd phase: $R > 1, I_- < I_+$

3rd phase: $R = 1, I_- = I_+$

Microdischarges







Experimental observation

Idea

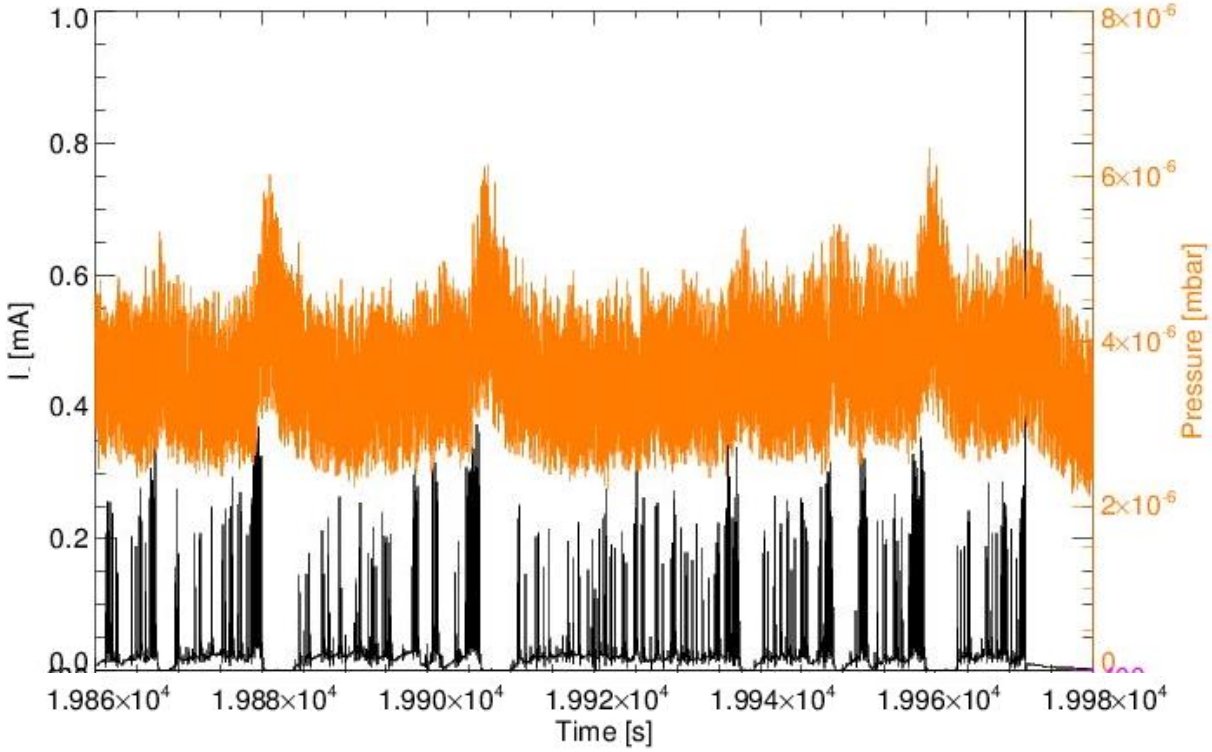
MD are triggered by electrons from the cathode

Electrons impact on the anode generates gas emission

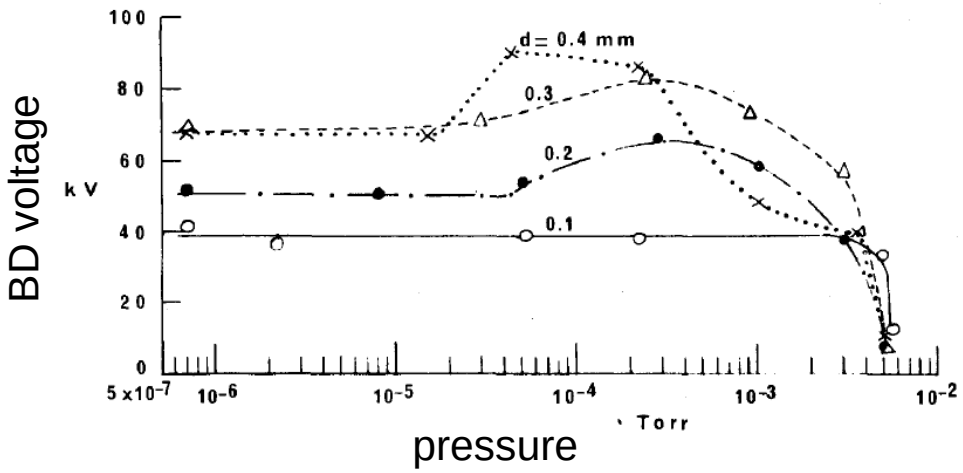
Experimental observations

we measure full-energy X-rays;

Pressure increases just after MD + H_2 and CO_2 associated to high-energy X

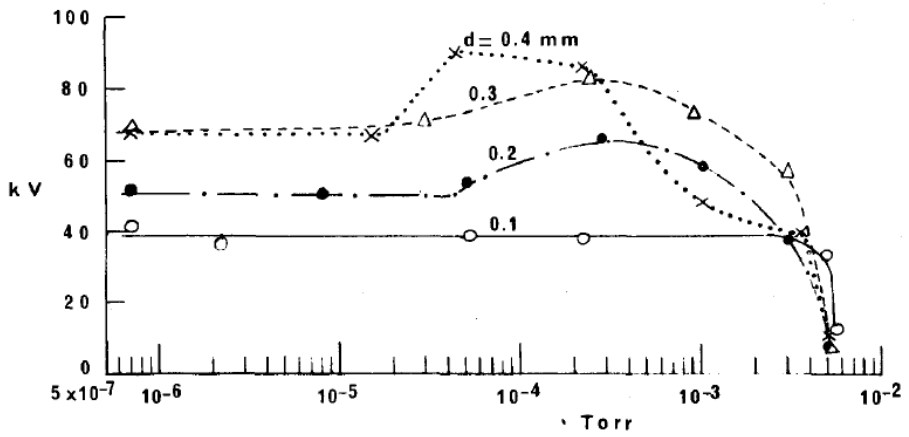


Pressure effect



R. Hackam and G. R. Govinda Raju,
Journal of Applied Physics **45**, 4784 (1974)

Pressure effect



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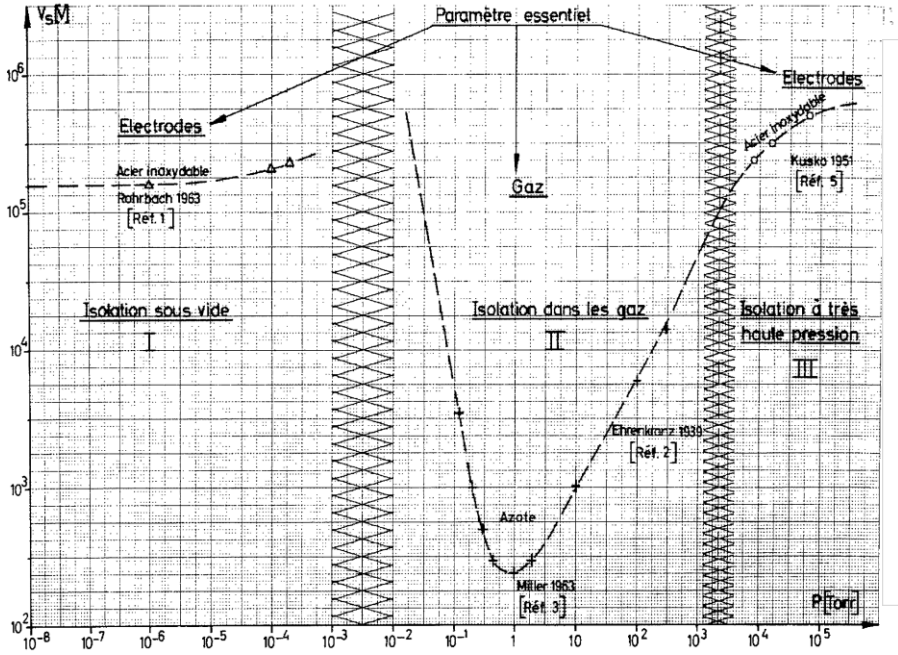
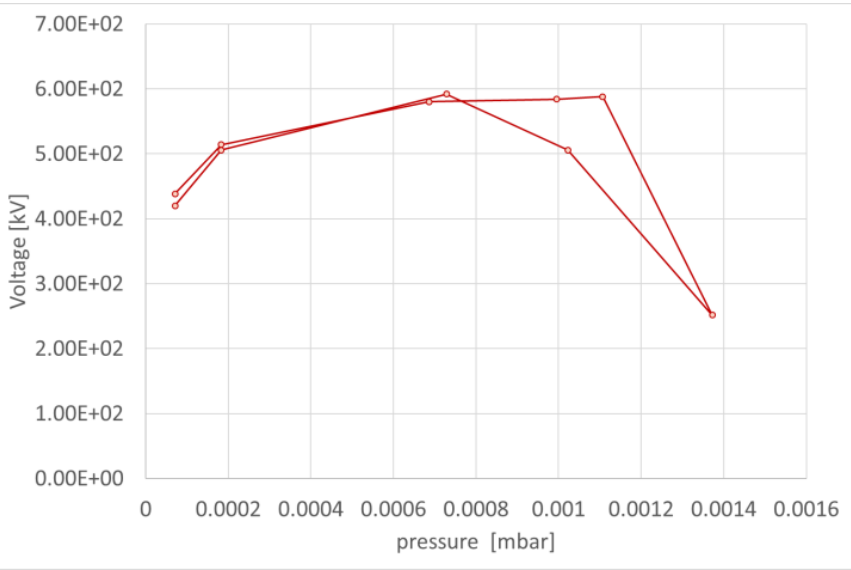


Fig. 1 Tension disruptive en fonction de la pression en champ homogène (écartement 1 cm).



Local pressure effect?

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Idea

MD are triggered by electrons from the cathode

Electrons impact generates gas emission

Emitted gas causes a *local pressure effect*

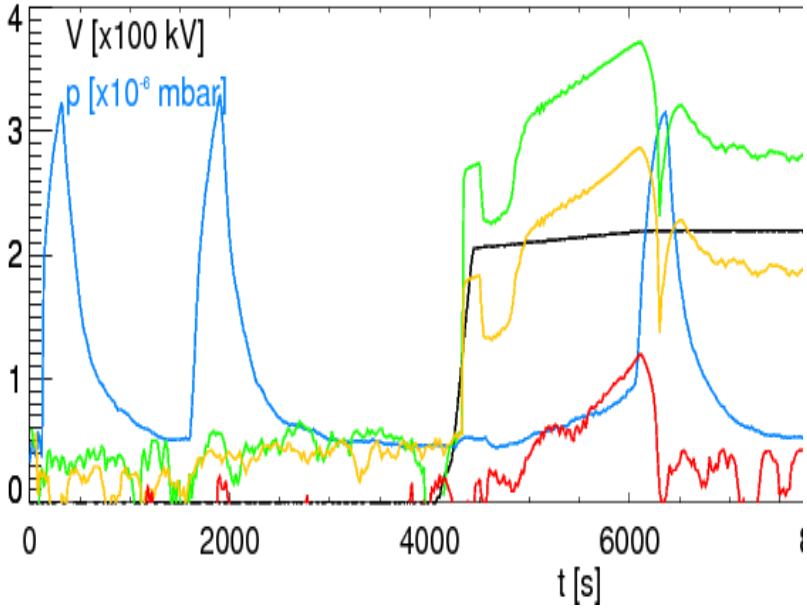
Experimental observations

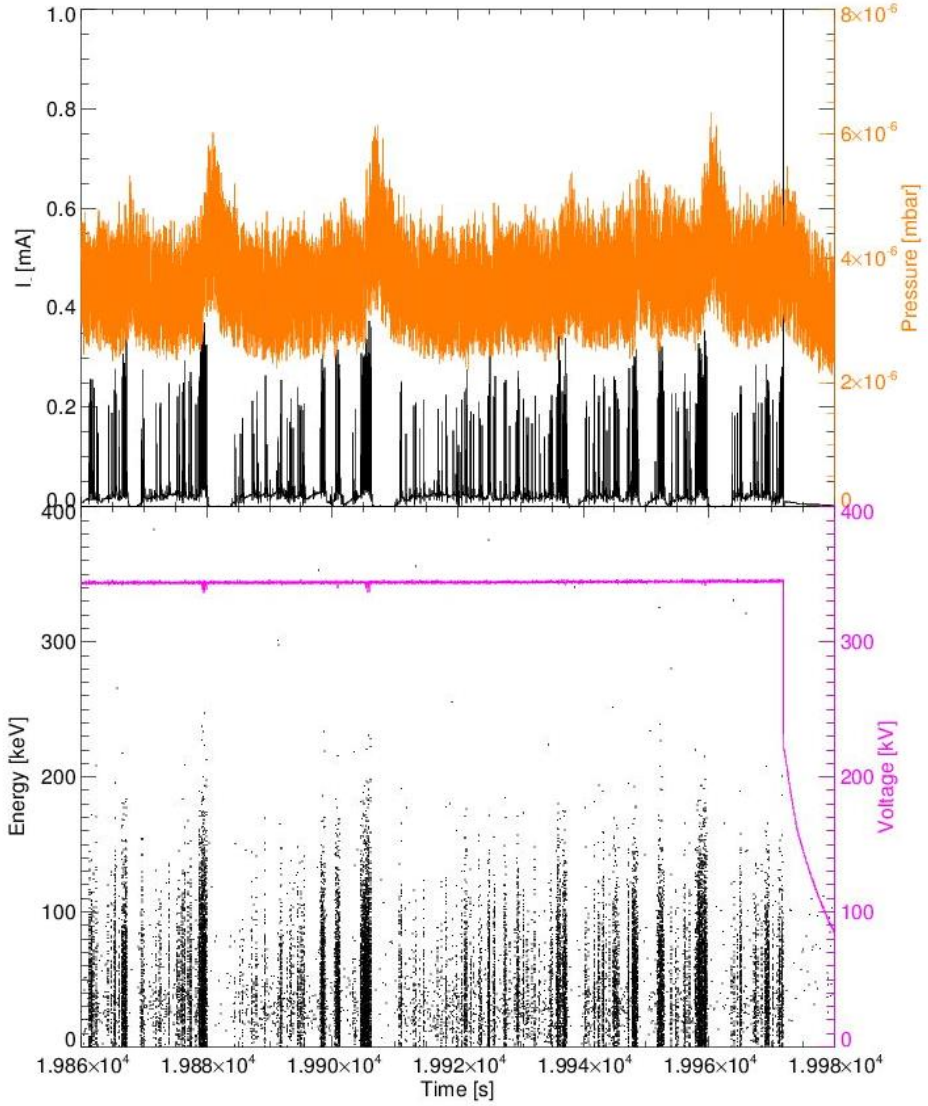
we measure full-energy X-rays;

Pressure increases just after MD + H_2 and CO_2 associated to high-energy X

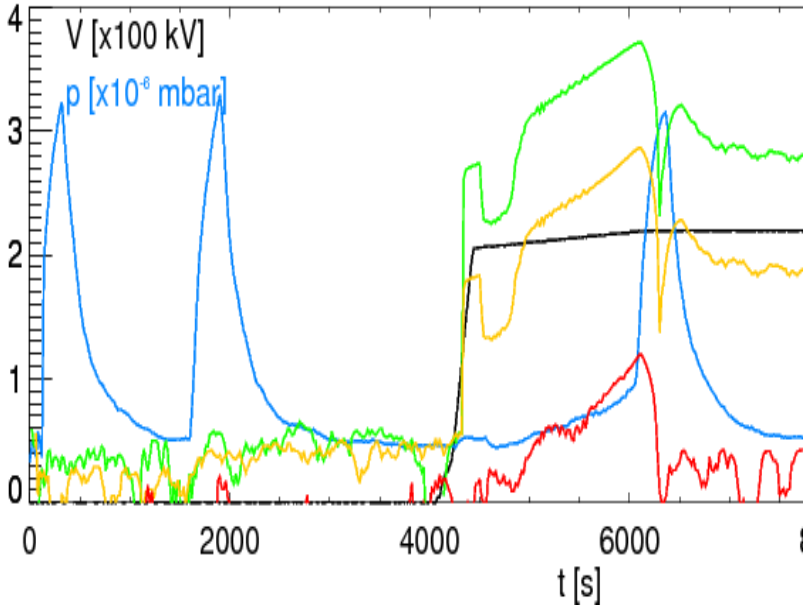
X-rays are inhibited for some time after the spike

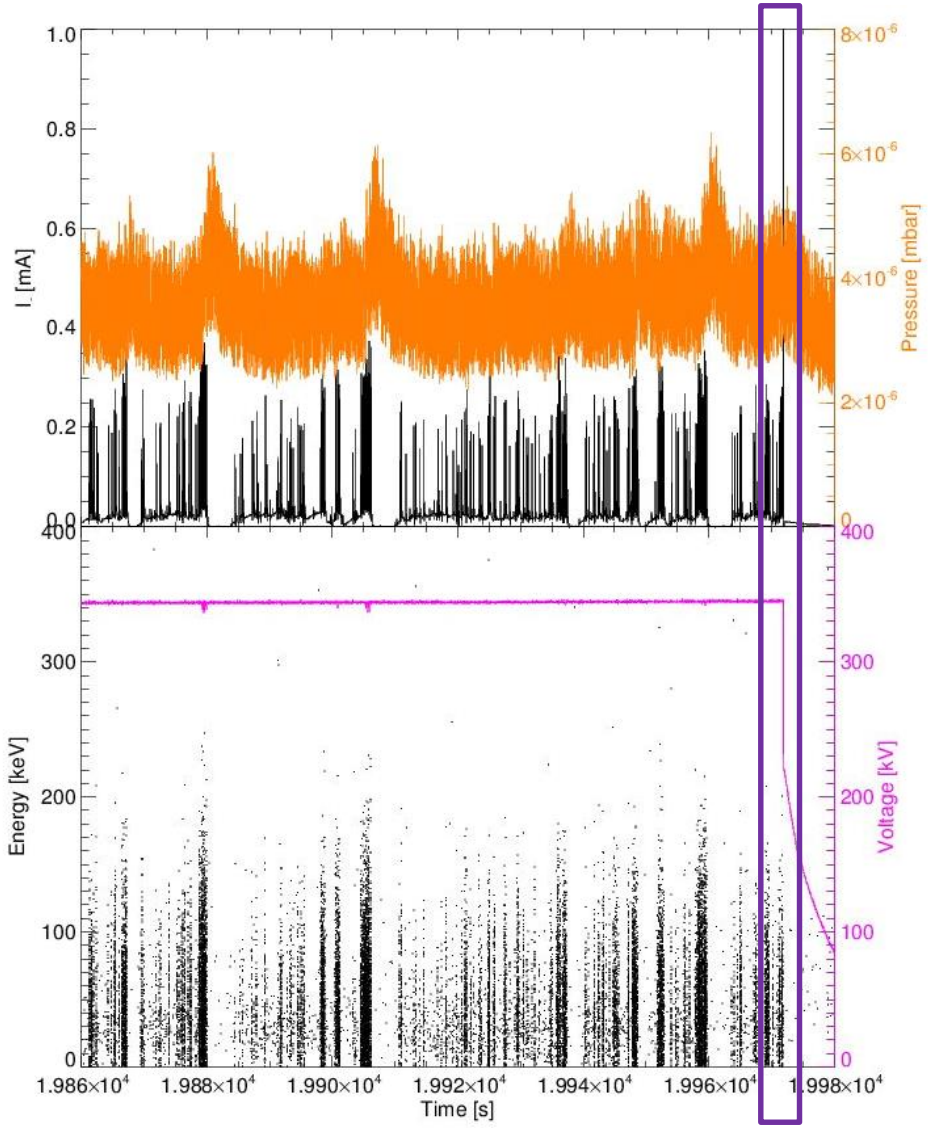
Local pressure effect?



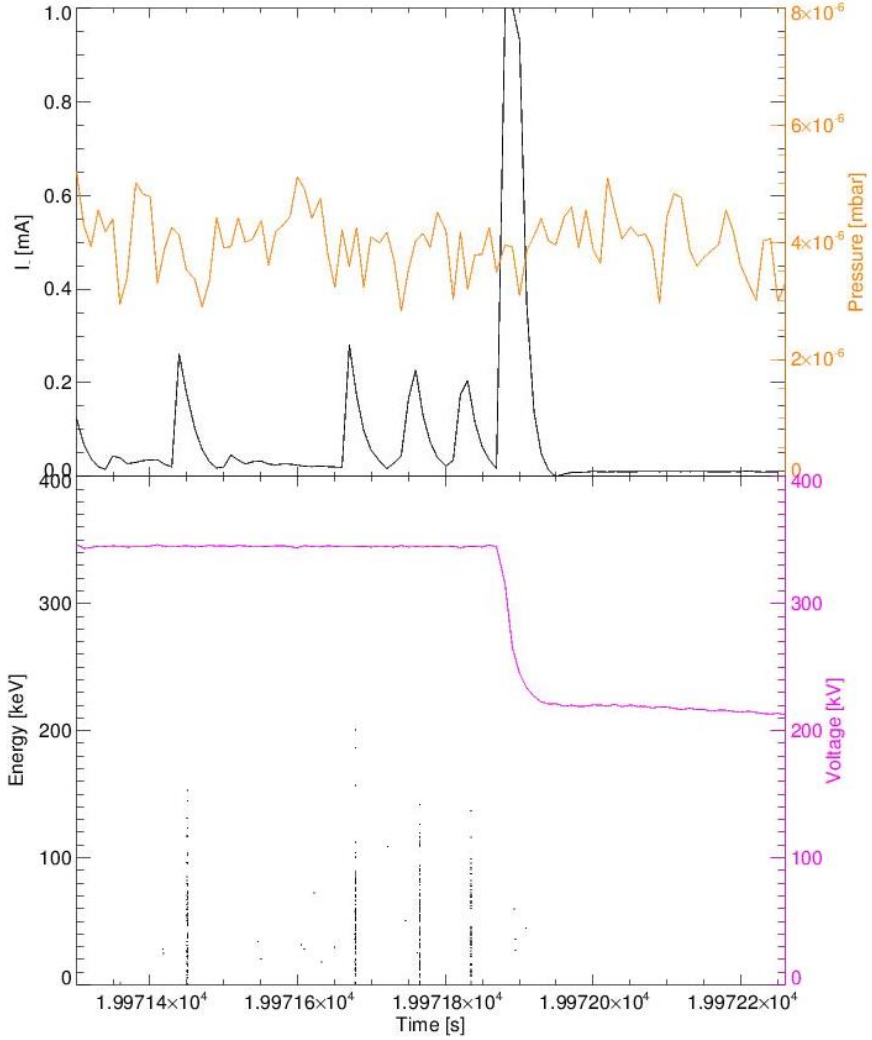


Local pressure effect?





Local pressure effect?



No X-rays observed in correspondence of BreakDown events.

Summary and conclusions

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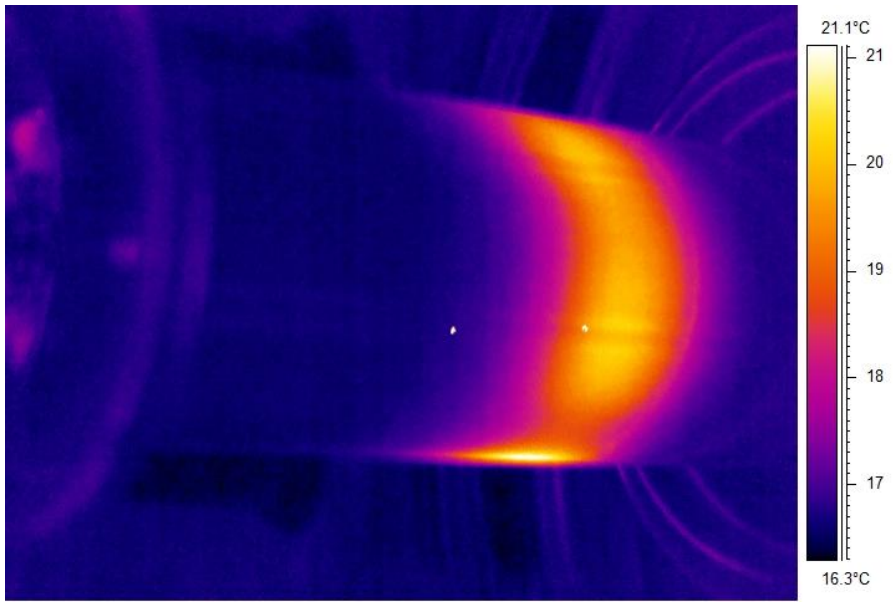
- HVPTF is an experimental device with the aim to investigate the voltage holding in vacuum in support of MITICA accelerator and as a physical phenomenon.
- A clear relation between the cathode current and X-rays measurement: MD are associated to high energy events, iMDC produces half energy X-rays.
- Different conditioning regimes are recognized during the experimental session and within the voltage cycles, in terms of different contributions of current collected by the two electrodes.
- Gas emission (Hydrogen and Carbon dioxide) is measured in correspondence of the high energy X-rays detection.
- Gas emission could generate a local pressure effect, inhibiting MD occurring for few tens of milliseconds.

Thank you for the attention

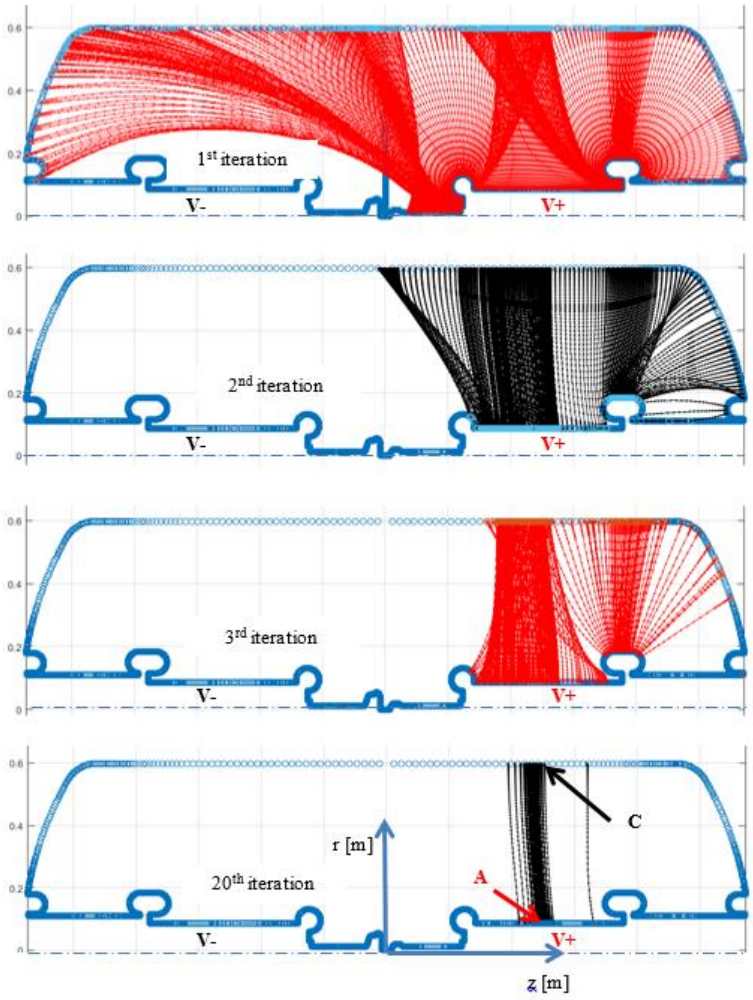
Iron and Chromium from the stainless steel anodic support



IR camera picture of the stainless steel (cantilever) arm connected to the positive power supply and supporting the planar electrode

Vessel inner wall : two circumferential stains are progressively appeared during the execution of the high voltage tests

N. Pilan et al. “Evidences of accumulation points in cascade regenerative phenomena observed in high voltage dc devices insulated by vacuum“ submitted to *New Journal of Physics*.



The trajectories of positive charged particles, uniformly distributed on the anodic surfaces, have been integrated considering the an axialsimmetric electrostatic field map.
The trajectory stops when a charged particle hit an electrode, than the sign of the charge is changed and a new trajectory is integrated. The process has been repeated up to a condition characterized by a stationary mutual-exchange of trajectories. In this geometry, twenty iterations are necessary to converge toward the final configuration.

M. Cavenago et al, "Cascades of Secondary Particles in High Voltage Accelerators", Comsol, Stockholm (2010).

X-ray diagnostics: the instrument

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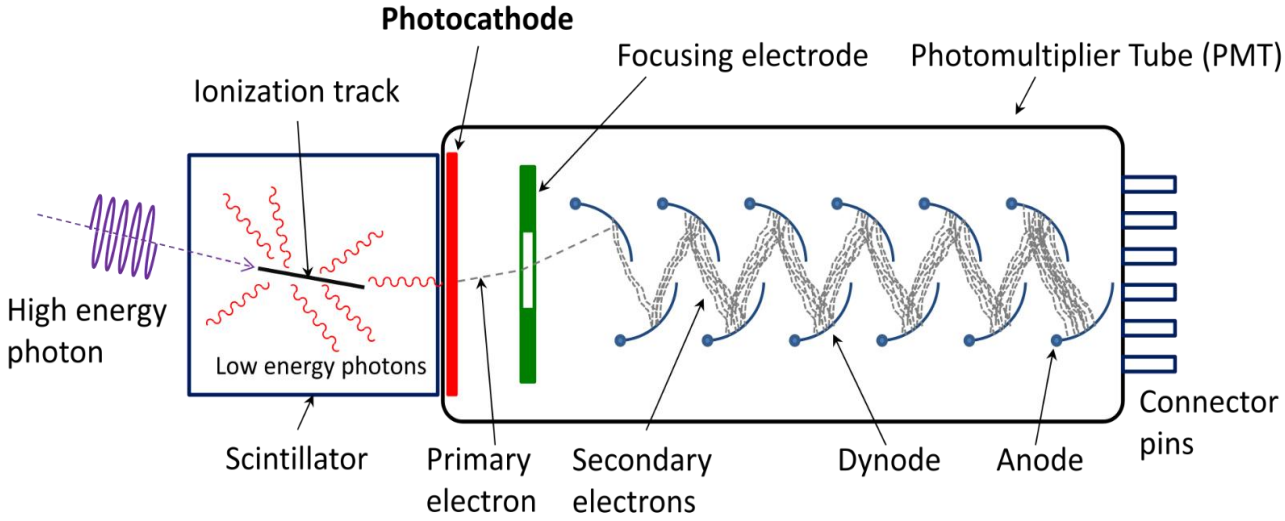
X-rays are emitted by accelerated electrons during experimental sessions: we study their energy spectrum in time, single events are distinguished.



EJ-228 plastic scintillator detector:
- intended for very fast timing applications;
- in air, 1 m from a glass window DN 100 (5 mm thick);
- connected to a CAEN DT5720B multichannel digitizer;
- Energy and time of each single photon detected is recorded up to 350 kHz.

X-ray diagnostics: energy spectrum calibration

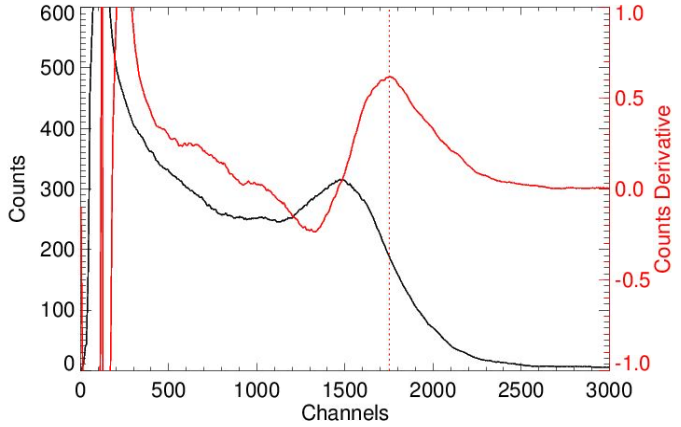
X-ray energy in this range in organic scintillators is mainly converted to scintillator light via single Compton scattering: the energy distribution is continuous, due to the different scattering angles, till the maximum value, named **Compton edge:**

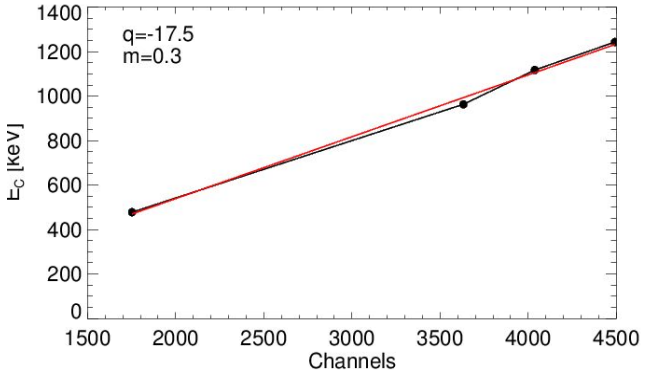
$$E_C = \frac{2E^2}{m_e c^2 + E}$$ where E is the incident photon energy

Radioactive sources used as known photons emitters:

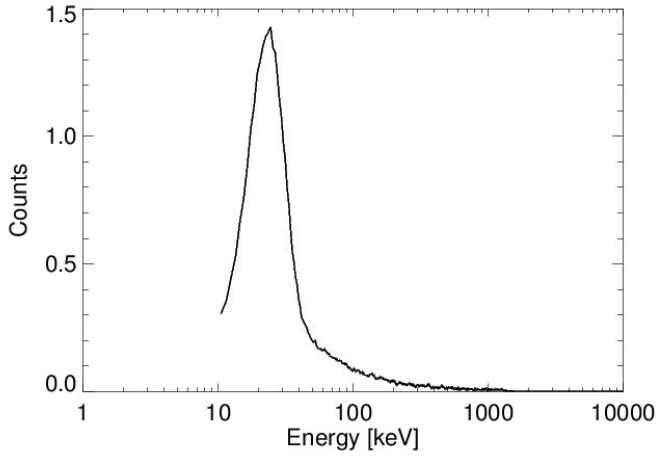
- $^{40}K \rightarrow E = 1461$ keV
- $^{60}Co \rightarrow E = 1173$ keV, 1332 keV
- $^{137}Cs \rightarrow E = 662$ keV

$$E\ (keV) = E\ (ch) \cdot m$$



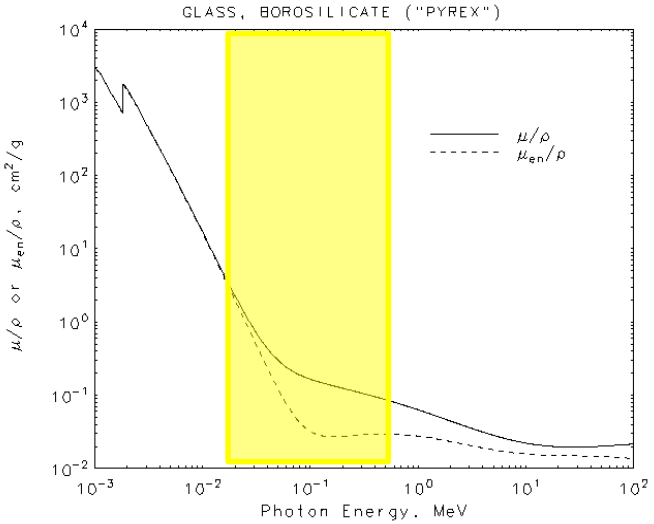


X-ray diagnostics: background and attenuation



Background radiation is subtracted to the measured energy spectrum

X-rays measurement is affected by the possibility to interact with the molecules of the vessel window and of the scintillator plastic:



$$\Gamma = \Gamma_0 e^{-\mu x}$$

Attenuation coefficient

Glass: x_g=5 mm, PVT: x_p=60 mm

$$\Gamma_0 = \Gamma_m / \{e^{-\mu_g x_g}[1 - e^{-\mu_p x_p}]\}$$

National Institute of Standards and Technology (NIST)

X-rays energy spectrum

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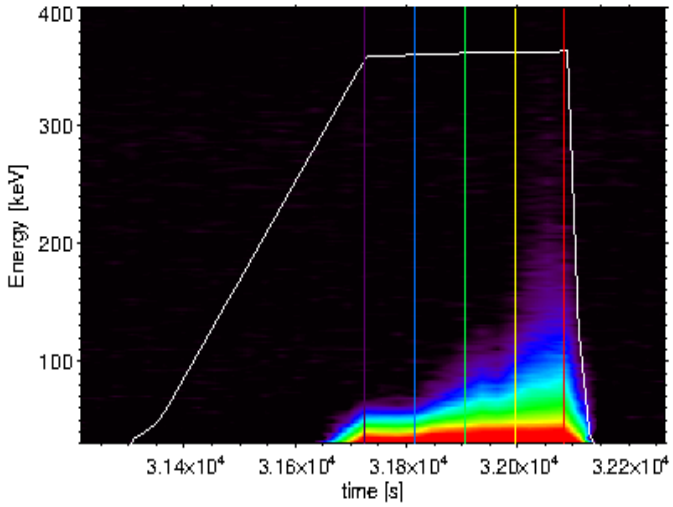
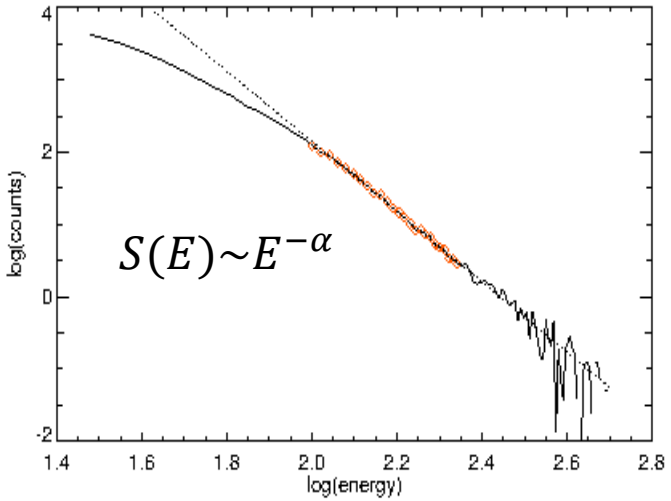
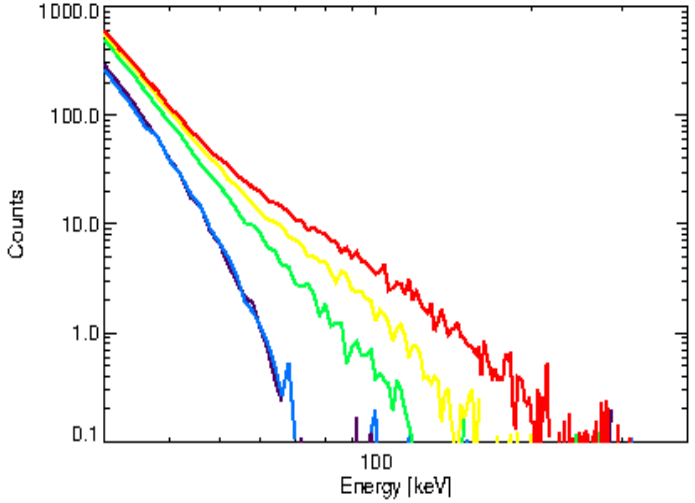
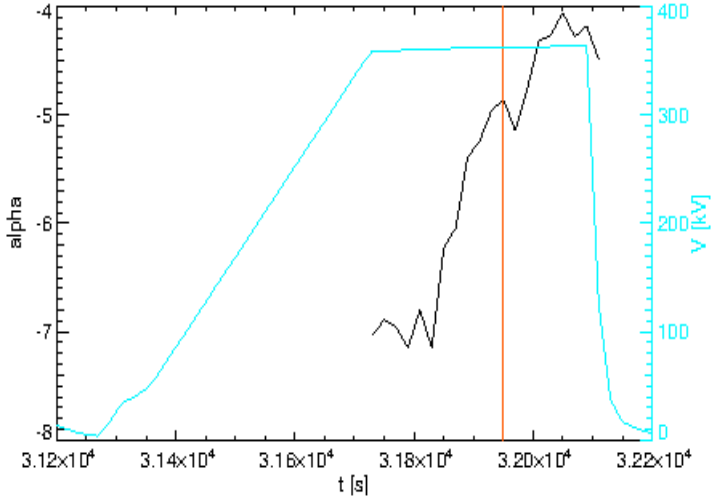
X-rays spectrum evolves within a voltage cycle

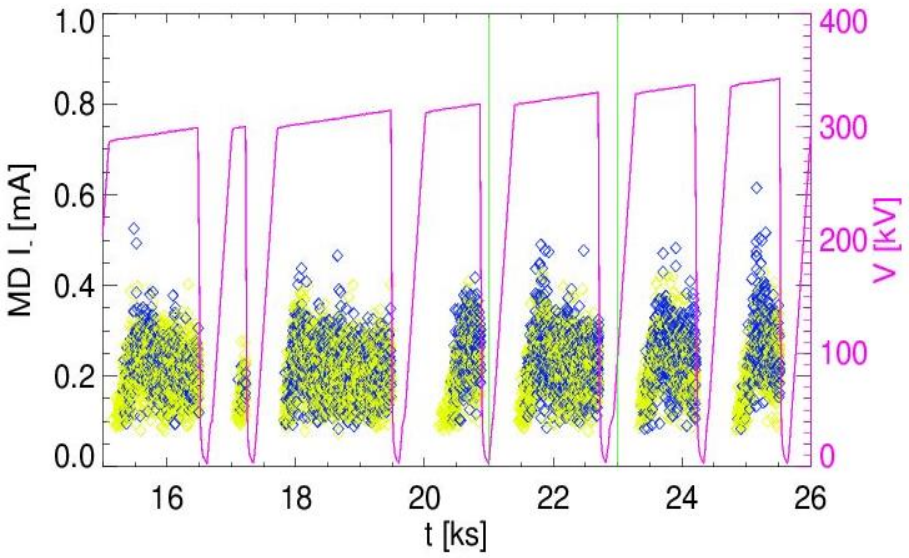


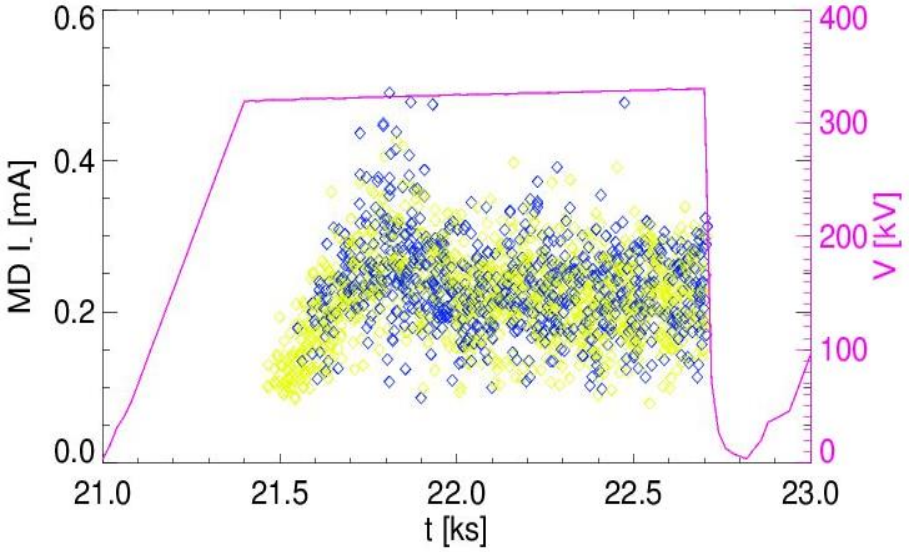


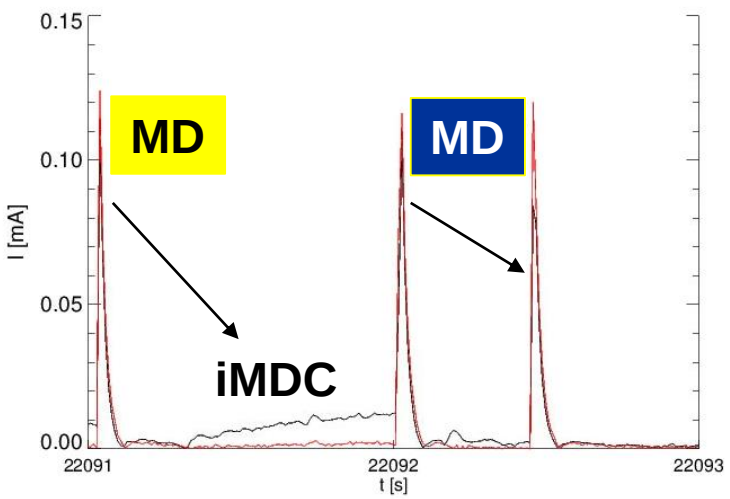




The current signals

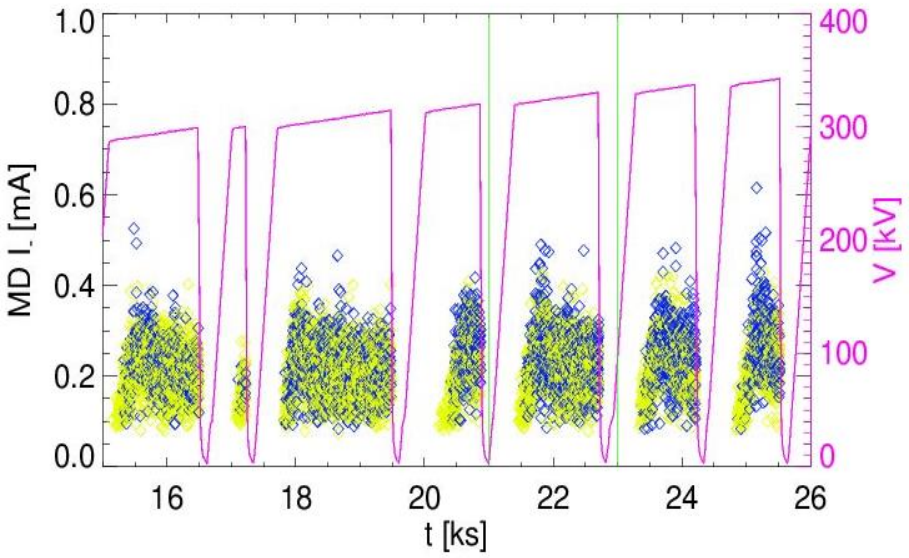


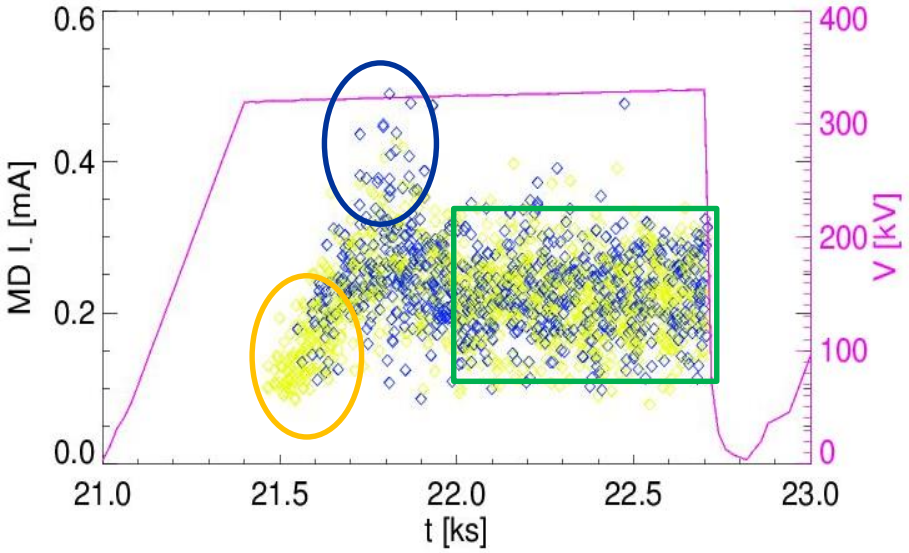


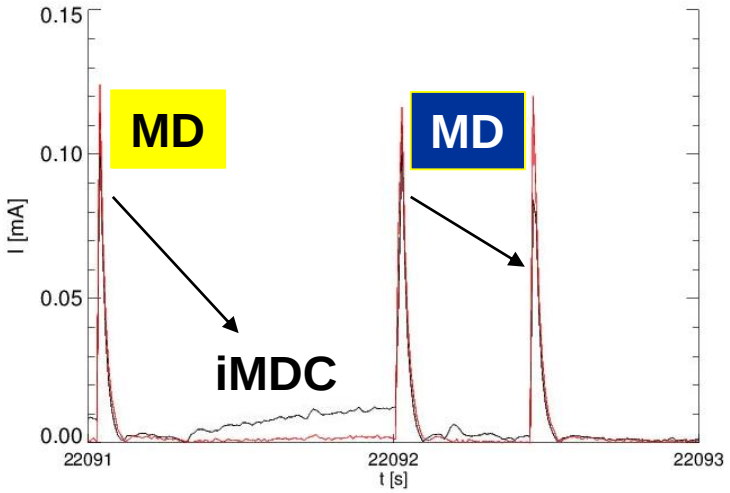


- MD followed by a non-zero iMDC
- MD followed by another MD

The current signals



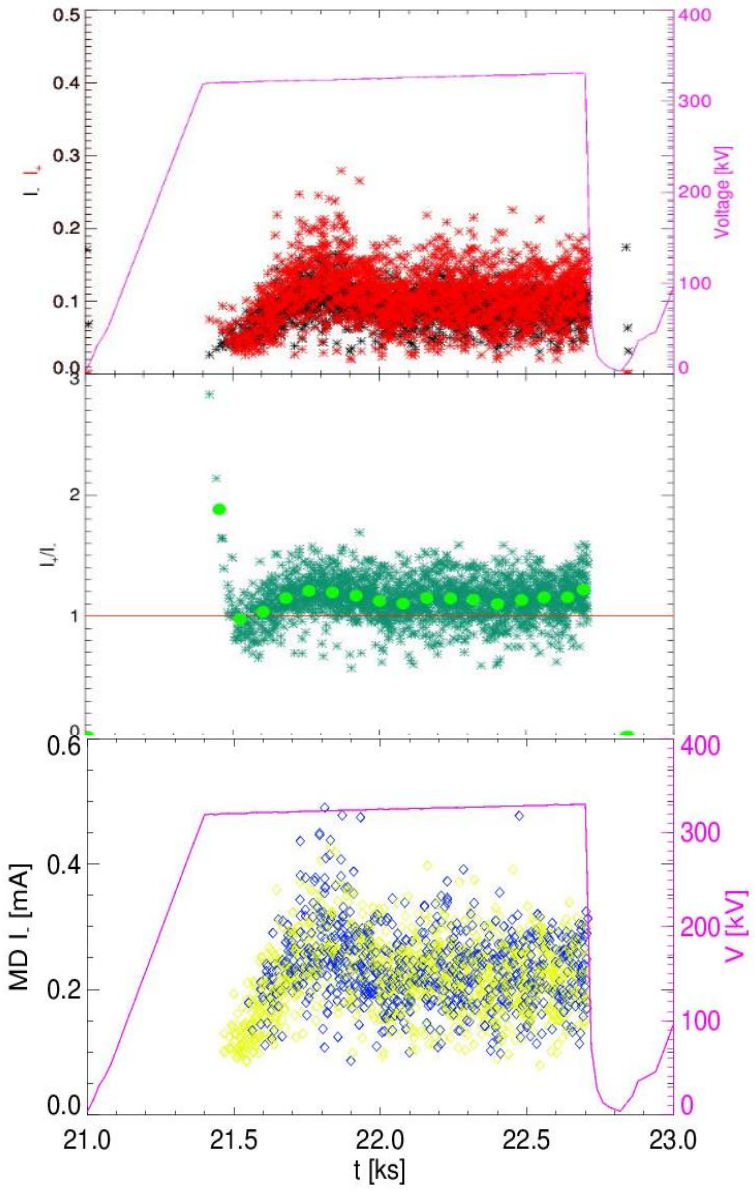




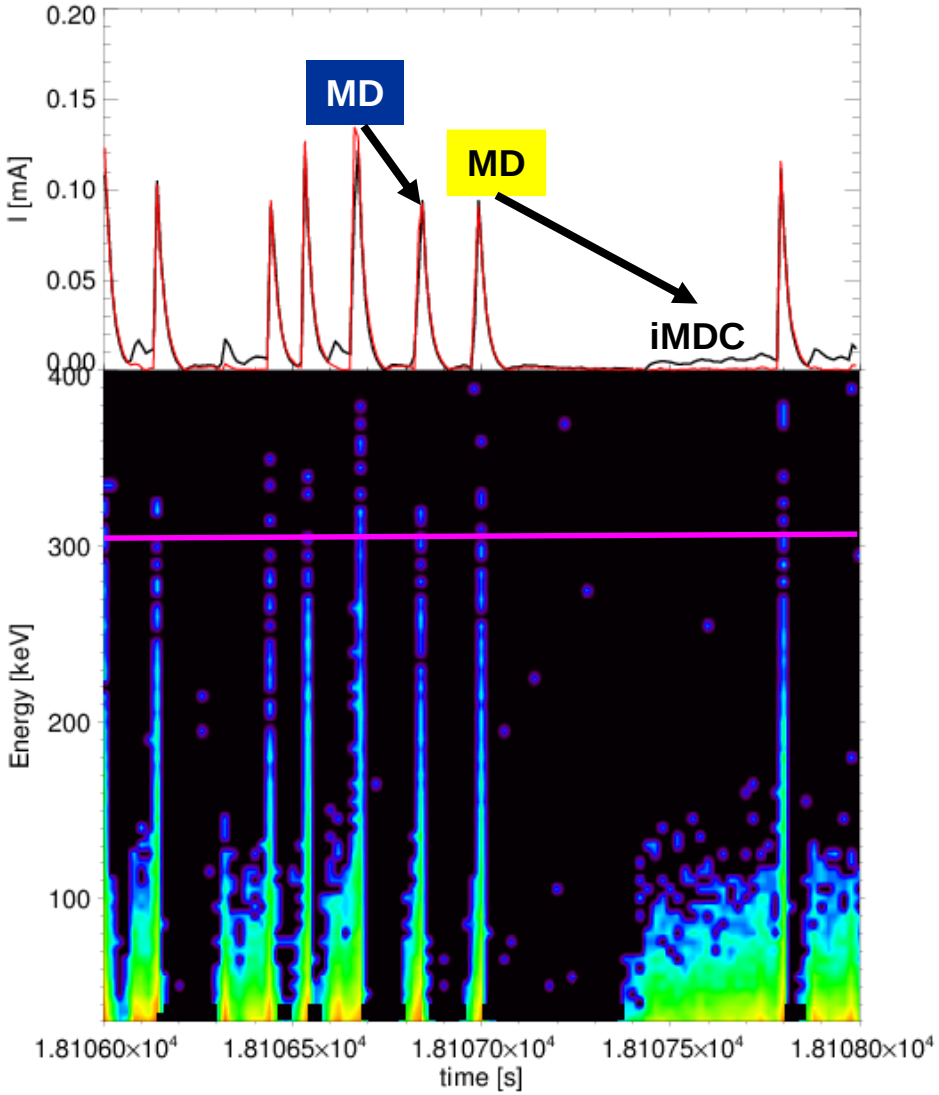
- MD followed by a non-zero iMDC
- MD followed by another MD

<u>For each voltage cycle</u>:

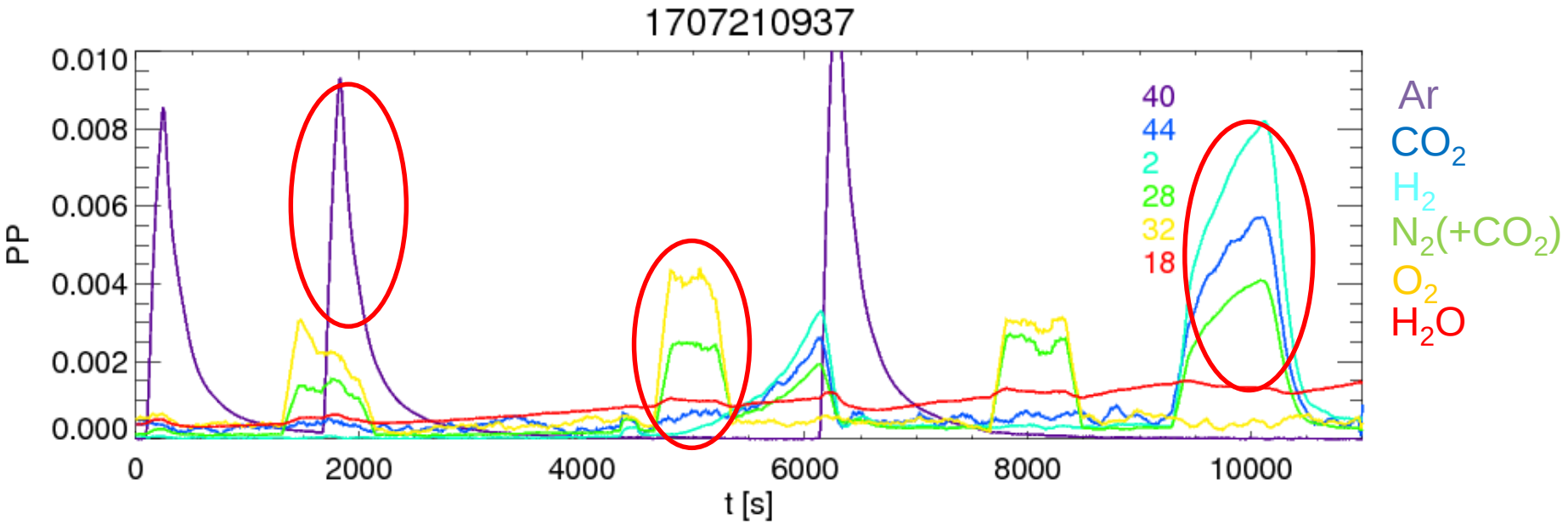
- small-current MD followed by iMDC accumulate in correspondence to the initial conditioning phase
- Intensive high current MD are seen at the end of this first initial phase;
- two types of events are almost evenly distributed.


I_ I_
Voltage [kV]
I_/I_
MD I_ [mA]
V [kV]
t [ks]

I and X correlation



RGA: different gas populations

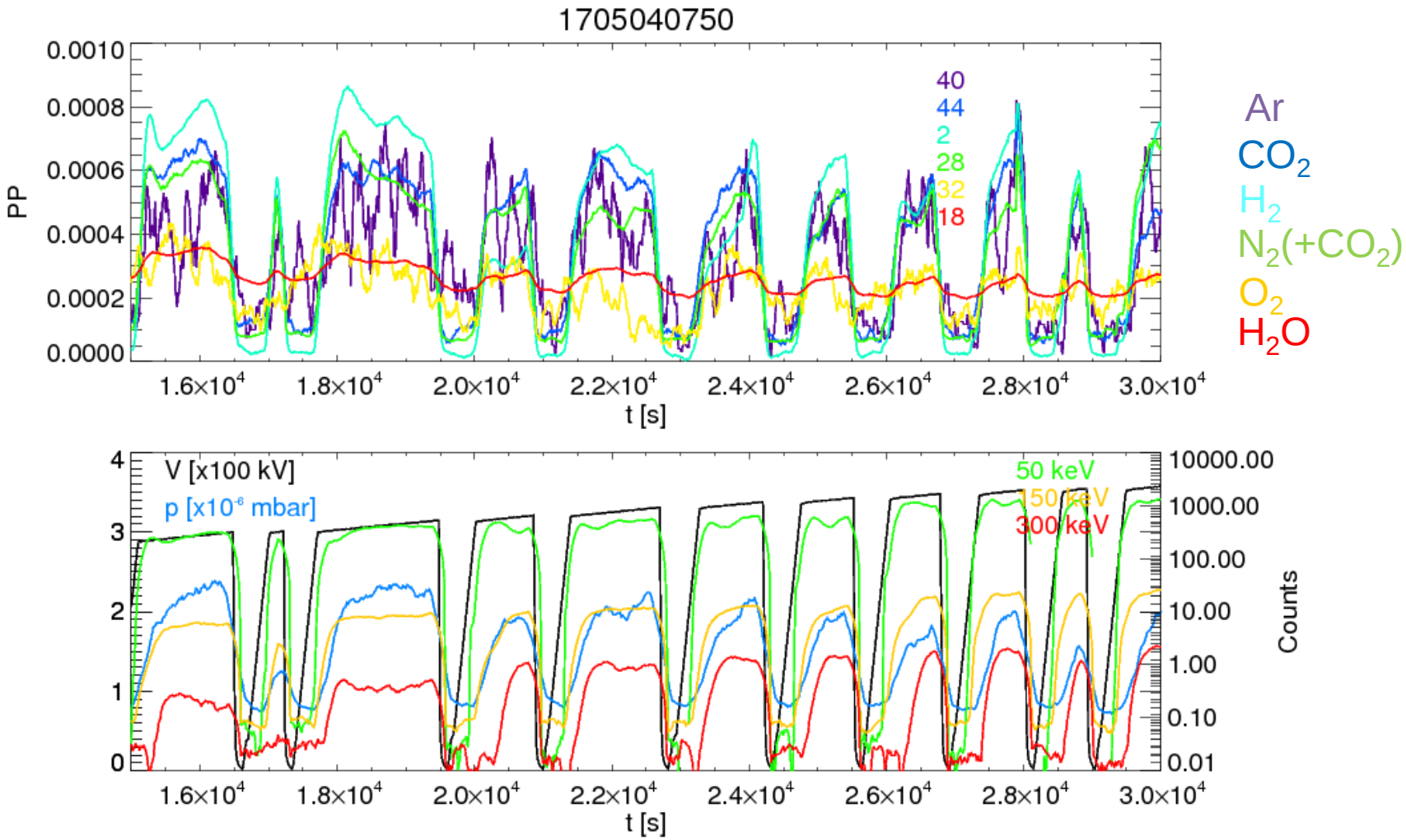


Negative electrode connected to the vacuum vessel (0 V)

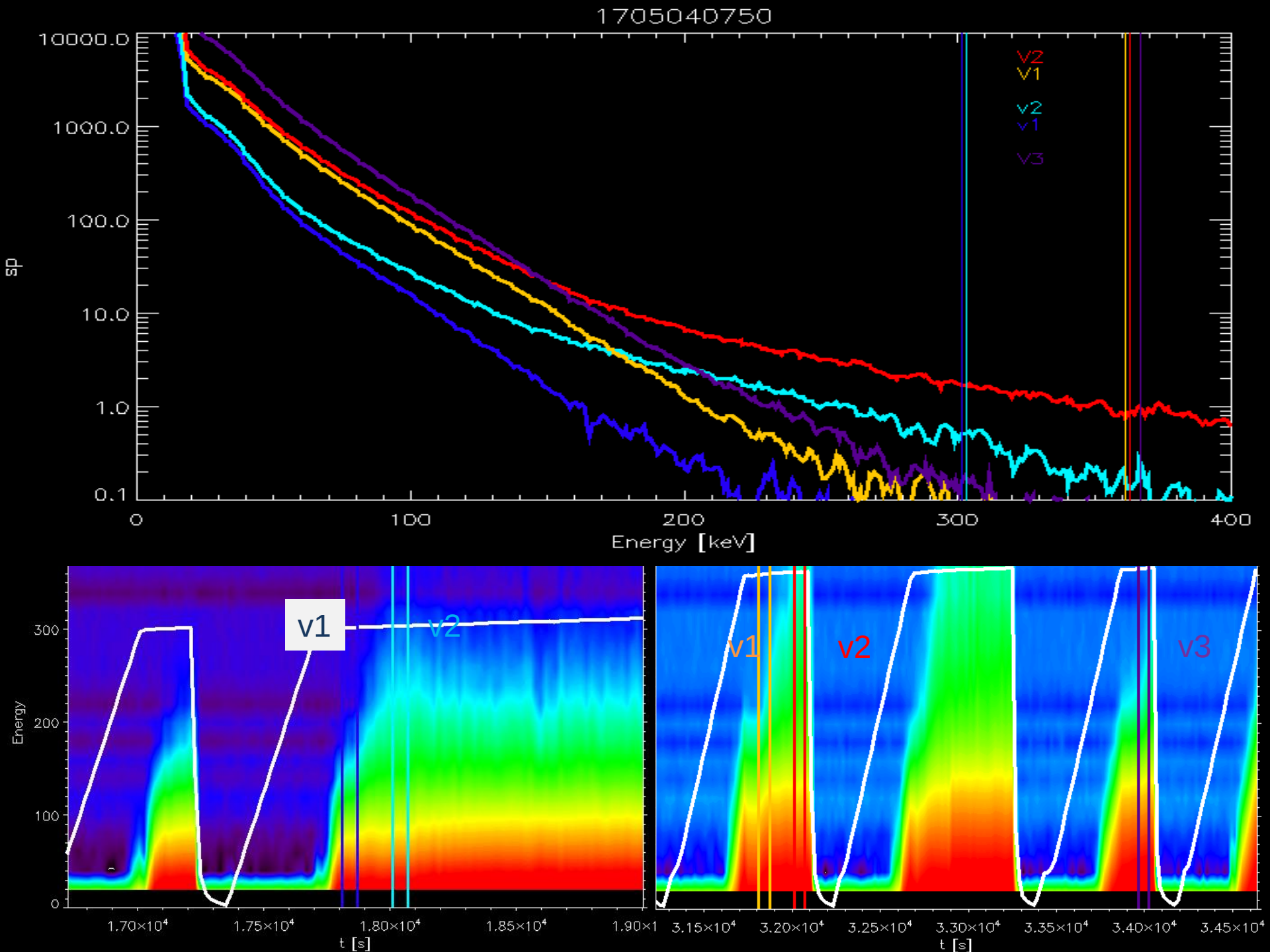
4 different gas populations:

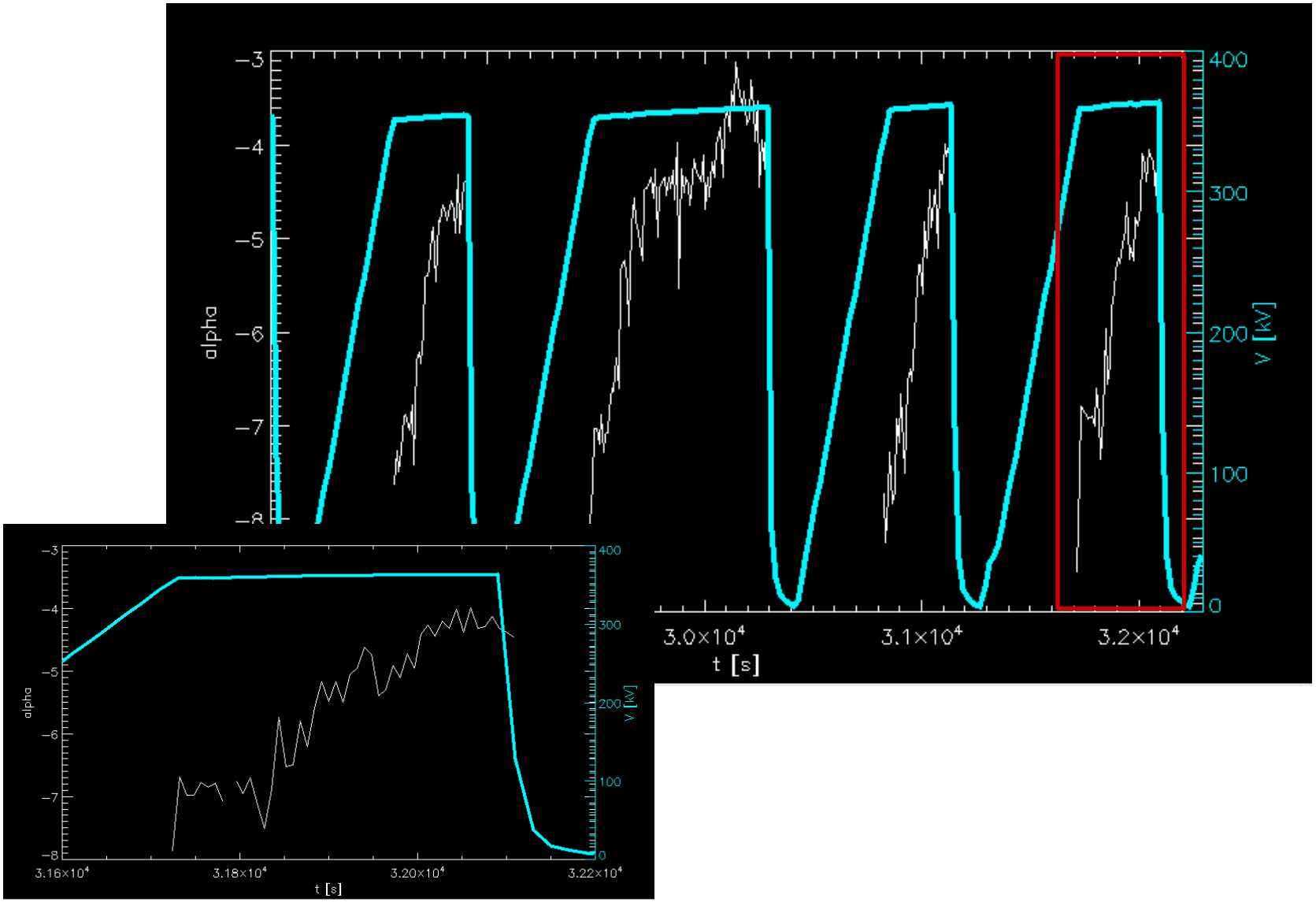
- Argon (40) injection
- Air leaks: O_2 (32), N_2 (28)
- Emission of H_2 (2), CO_2 (44), CO_2(+N2?) (28) in correspondence to high energy X-rays.
- H_2O (18) slightly increases in time

RGA: different gas populations



- Emission of H_2 (2), CO_2 (44), CO_2(+N2?) (28) in correspondence to high energy X-rays
- H_2O (18) slightly decreases in time


1705040750
10000.0
1000.0
100.0
10.0
1.0
0.1
sp
0
100
200
300
400
Energy [keV]
V2
V1
v2
v1
V3
v1
v2
Energy
300
200
100
0
1.70×10⁴
1.75×10⁴
1.80×10⁴
1.85×10⁴
1.90×1
t [s]
v1
v2
v3
3.15×10⁴
3.20×10⁴
3.25×10⁴
3.30×10⁴
3.35×10⁴
3.40×10⁴
3.45×10⁴
t [s]


alpha
V [kV]
t [s]
3.0×10⁴
3.1×10⁴
3.2×10⁴
3.16×10⁴
3.18×10⁴
3.20×10⁴
3.22×10⁴