ONGOING PRELIMINARY TEST CAMPAIGN OF A LOW-POWER CLASS APPT FOR MICROPROPULSION

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SPACE AND PLASMA PROPULSION RESEARCH GROUP (EP2)

MARTINLARA uc3m EP2 Aero Space

CONTENT

CONTENT

THE CHALLENGE

- NANOSATELLITE IN-ORBIT SPACE MISSION
- PLATFORM DESIGN
- RADIO ASTRONOMY AND EARTH OBSERVATION INSTRUMENTATION
- SPACE PHOTONICS
- **PLASMA MICROPROPULSION MODULE**

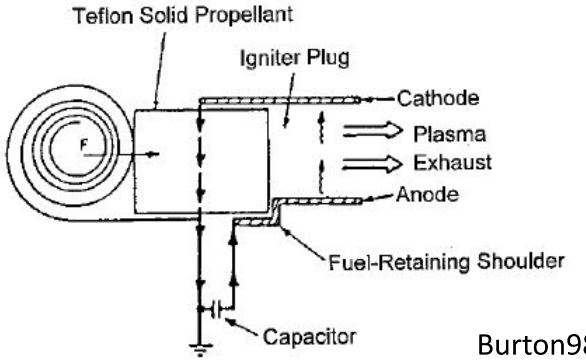
- **One of the EP2 Challenges**:

DEVELOPMENT OF AN ON-BOARD EP ENGINEERING MODULE FOR NANOSATELLITES :

- Isp=>500s | 10^5 firings | Ibit=10 uNs | <1kg | <= 1 CubeSat unit

- Simple structure (scalability; reliability).
- Low power consumption (<20W).
- Operational versatility

- First APPT Spanish proposal



Burton98

Fig. 1 Solid propellant PPT (schematic).

About PPT worldwide history:
- First EP thruster on a space flight (1960s).
- Successful heritage of about 50 years in **attitude-control** and **station-keeping, drag make-up** and **primary propulsion purposes**

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- DISCHARGE VISUAL ANALISIS
- VOLTAGE WAVEFORMS
- SINGLE LANGMUIR PROBES
- NEXT STEPS

EXPERIMENTAL CAMPAIGN

Final objectives:

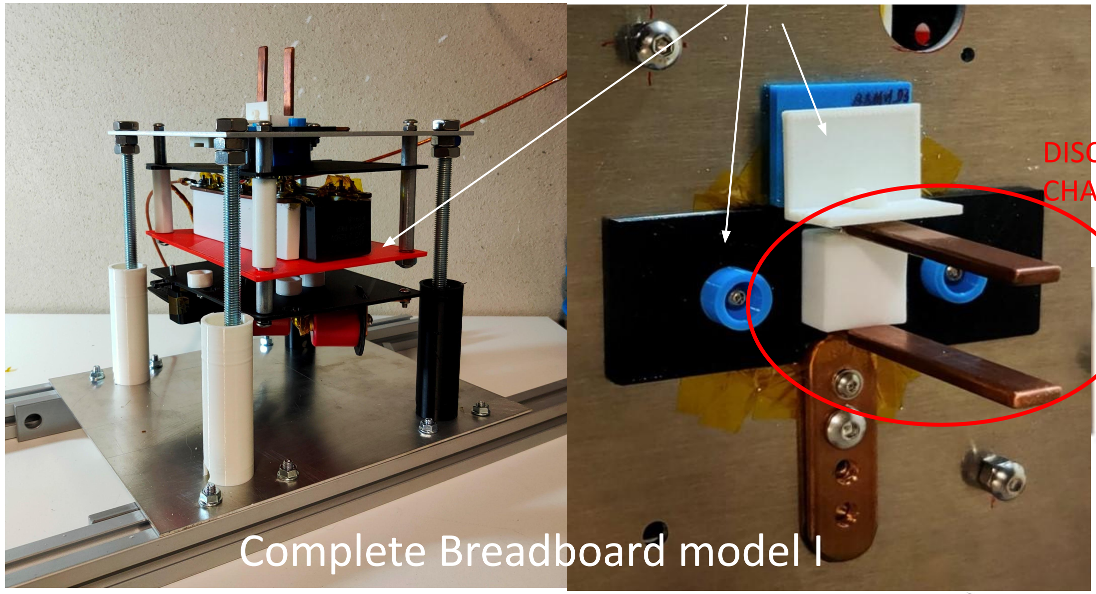
1. **Discharge characterization**
2. Understanding of the **physics**
3. Prototype **Optimization**

Critical starting considerations:

- CHANNEL GEOMETRY & SIZE
- MAIN ELECTRODE VOLTAGE
- MAIN CHANNEL W0/A RATIO
- TRIGGERING CONFIGURATION & CIRCUIT
- (INPUT POWER)
- **DIAGNOSTIC SELECTION**

Intermediate steps:

3Dprinted pieces to allow fast iteration



BBM 1*

Modular

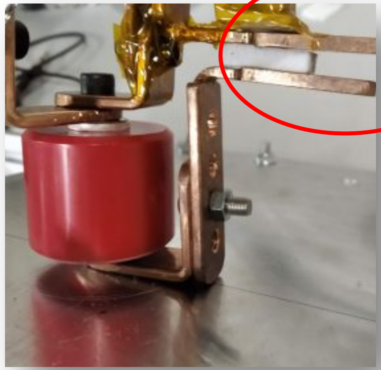
Versatile (geometry, electronics)

Easy to manufacture and assembly

Fast acceptance of modifications

Highly conservative in terms of insulation against electrical hazards

Nominal point also based on approximated scaling laws from existing parallel rail μAPPTs



Example of the **simplified models** operated in these preliminary tests.

Just the channel and the batteries are placed inside the vacuum chamber.

*) S. Barquero, M. Merino, J. Navarro. Design of an ablative pulsed plasma thruster for micropropulsion. Space Propulsion Conference 2020+1.

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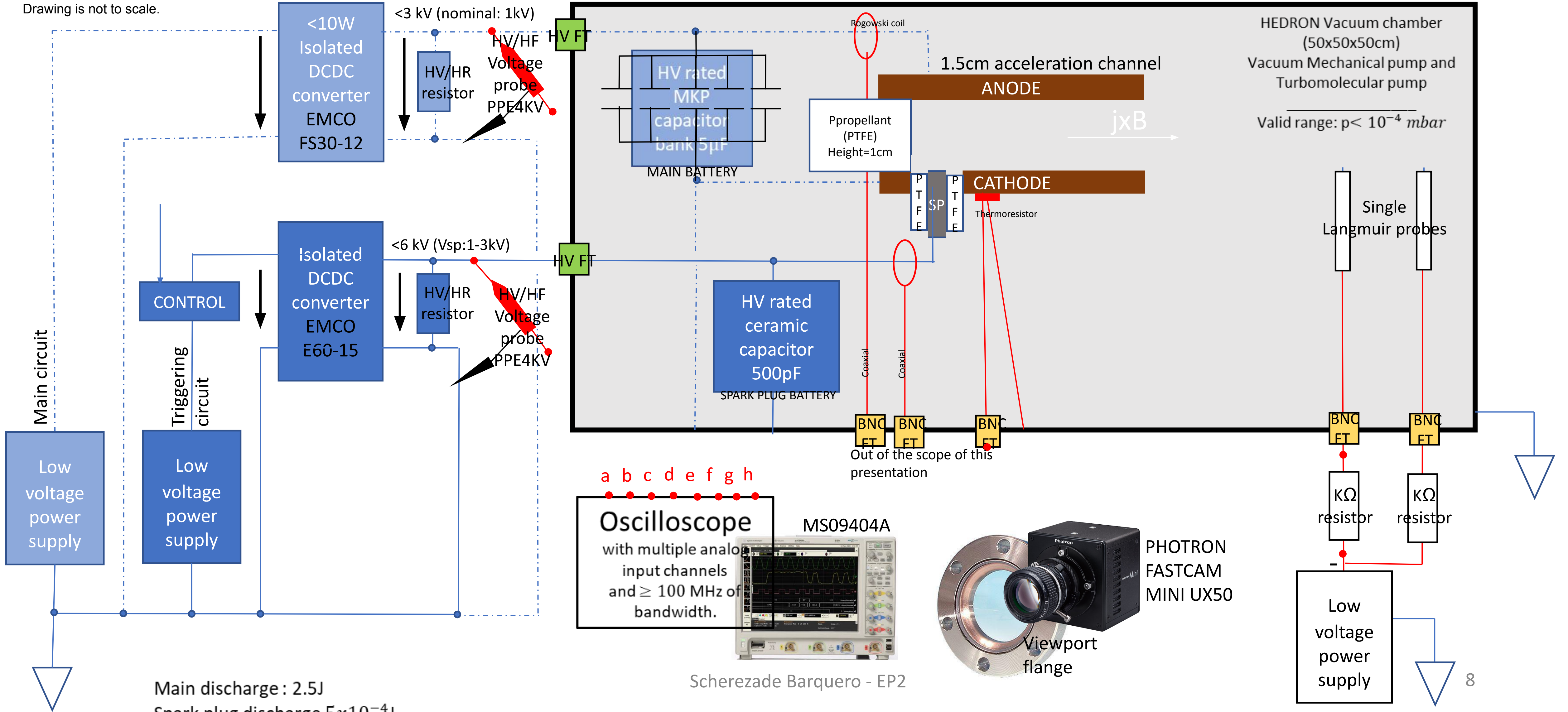
EXPERIMENTAL SETUP

Drawing is not to scale.



Main discharge : 2.5J

Spark plug discharge $5x10^{-4}$J

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DISCHARGE TRIGGERING

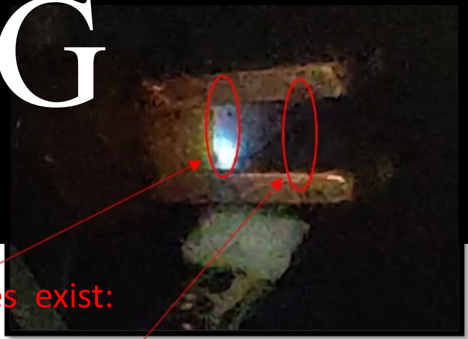
- Ignition in vacuum along an insulating surface (flashover) is **not a trivial task**.
  WE WANT THE PROPELLANT TO BE THE MAIN CONTRIBUTOR TO THE PLASMA GENERATED

- **kV + 1cm gap is not enough** electric field for a flashover
  AN EXTERNAL TRIGGERING MEANS IS REQUIRED TO RELEASE ENERGIZED ENOUGH FREE CHARGES

- Different triggering system have been manufactured and tested.
  THE MOST ROBUST ONE: **SMALL APPT WITH VACUUM**
  IGNITION VOLTAGE AROUND 1.5kV (1-3kV)

  >5000 FIRINGS WITHOUT SHORTCIRCUITING

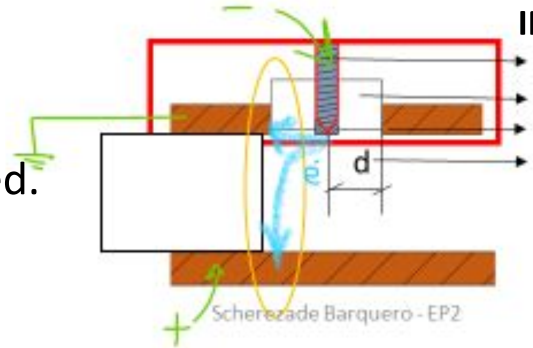
- Very complex topic, but it is a KEY ELEMENT FOR RELIABLE LIFETIME. Alternatives are needed.



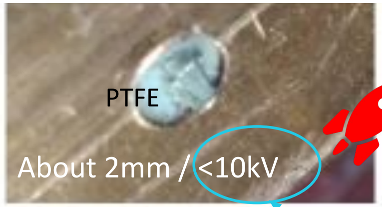
Different kind of discharges exist:

Metal-Insulator-Metal (MIM) gaps =Weakest path for vacuum discharges	**FLASHOVERS**
Metal-Vacuum-Metal (MVM) gaps	VACUUM METALLIC ARCS

- Different mechanisms
- Different Electric field demands for triggering
- Different plasma composition



INFLUENCE FACTORS:
- Electrode material and geometry (as the e- emitter)
- Spacer material and relative position / vacuum gaps
- Opposite electrode geometry
- Electrode-electrode gap



Some characteristics:
Erosion problem: Triggering demands are **highly sensitive (shot-to-shot variations)**
Contamination problem: Risk of short-circuits.
Uncertainness concerning the discharge location.

Because sometimes, probably when far from the thermal "favoring", a higher pulse is required to start the ignition.

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VISUAL INSPECTION I

PHOTOGRAPHY

- Reconstruction of a representative discharge sequence.

- Plasma evolves from the triggering seed towards the anode.

Main remarks after the observation of hundreds of photographs:

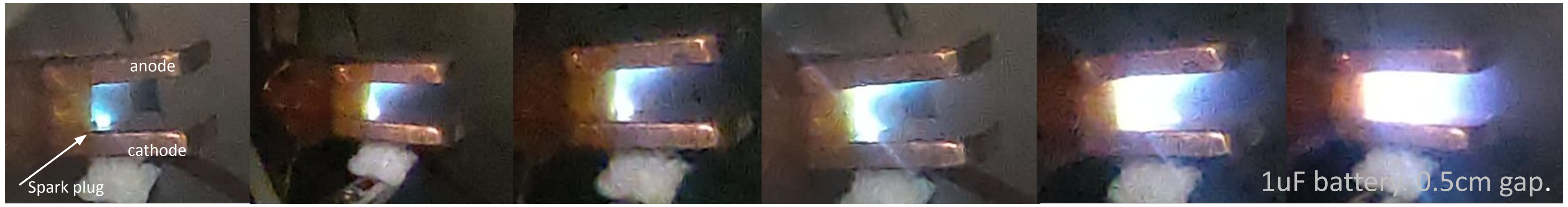
1) NONUNIFORM PLASMA DISTRIBUTION
   - Canting
   - Different “regimes” with dependence on the geometrical and electrical configuration: diffusive/sheets
   - efficiency?

2) PLASMA IS EJECTED

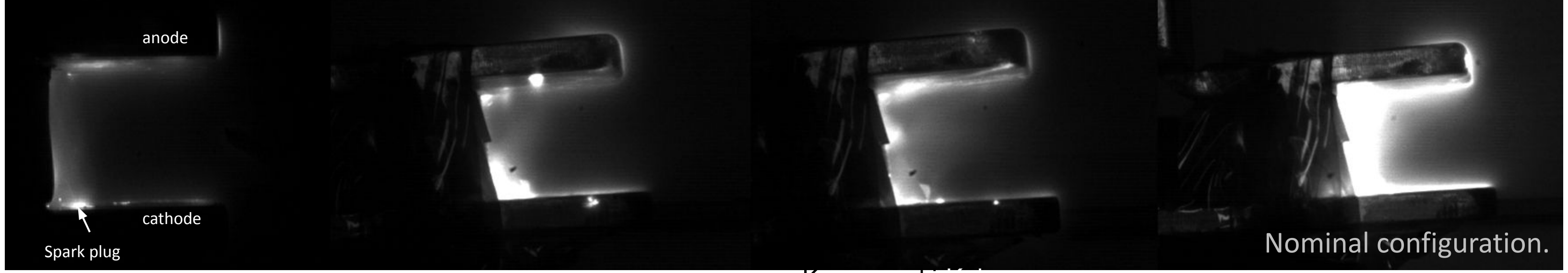
3) PROPELLANT IS CONSUMED

4) LIGHT/HOT POINTS
But be careful with reflections!

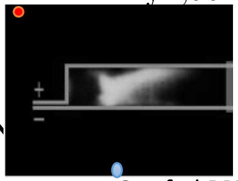
5) THE PLASMA BORDERS THE AN



BETTER CAMERA & BETTER POSITIONING OF THE CHANNEL.

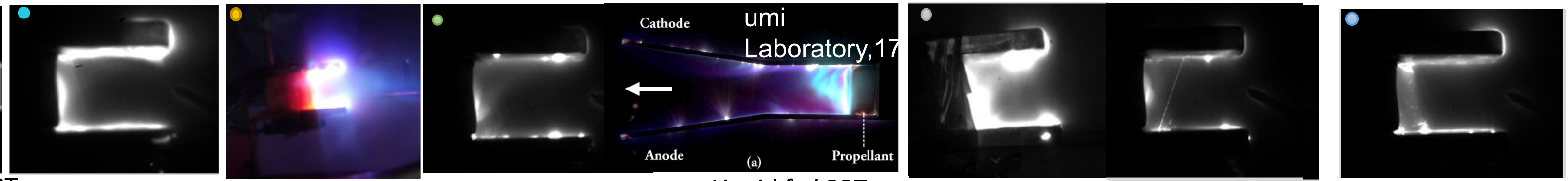


EPPDyL,99



Gas fed PPT

Komurasaki
umi
Laboratory,17

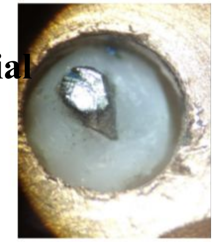


Liquid fed PPT

VISUAL INSPECTION II

SURFACE ANALYSIS

- SPARK PLUG



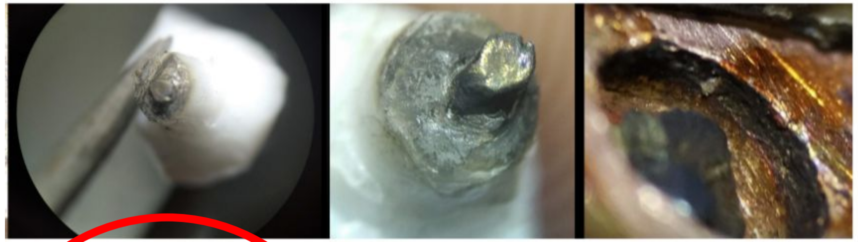
1. Conductive **charring and electrode material** deposition along the dielectric gap is a risk for short circuiting (experienced)
2. The **discharge cleans** the area around it.
3. Uncertainness about the amount of charring that comes from the SP discharge itself.

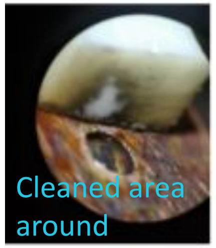
SP location

- ELECTRODES
  1. Hard erosion is not evident
  2. **Different plasma distribution patterns depending on the gap**
  3. Charring at the exit of the **anode's back** where the photographs showed plasma

- PROPELLANT
1. Erosion as **consumption** evidence
2. Conductive **charring accumulation**: risk of short circuit (not experienced)
3. Relation between the **Energy/Area ratio and the charring accumulation** requires a more detailed study (ongoing)

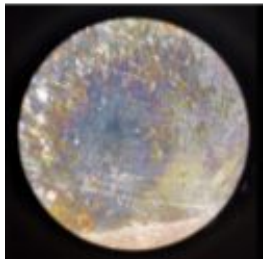
5000 SP firings



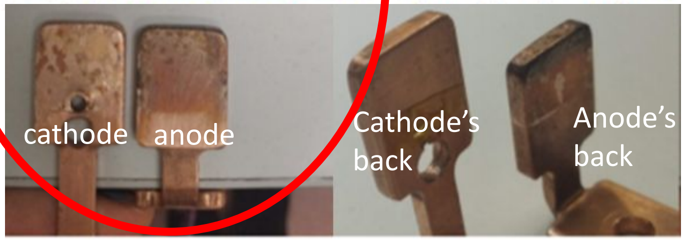


200 Main firings

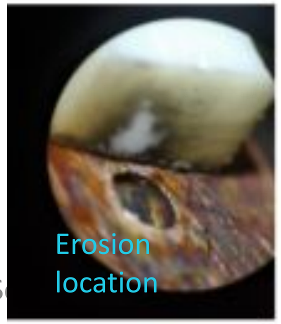
0.5cm gap

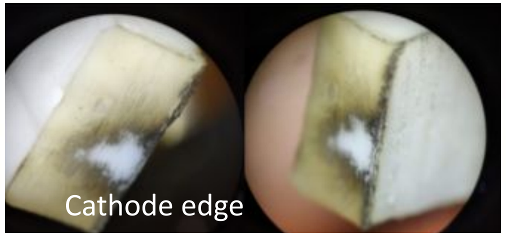


Anode's center (zoom)

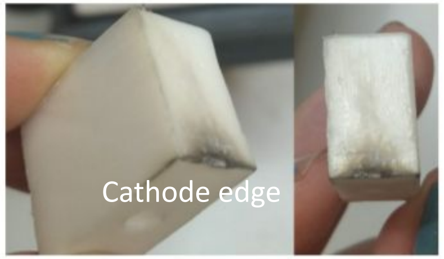


1.5cm gap





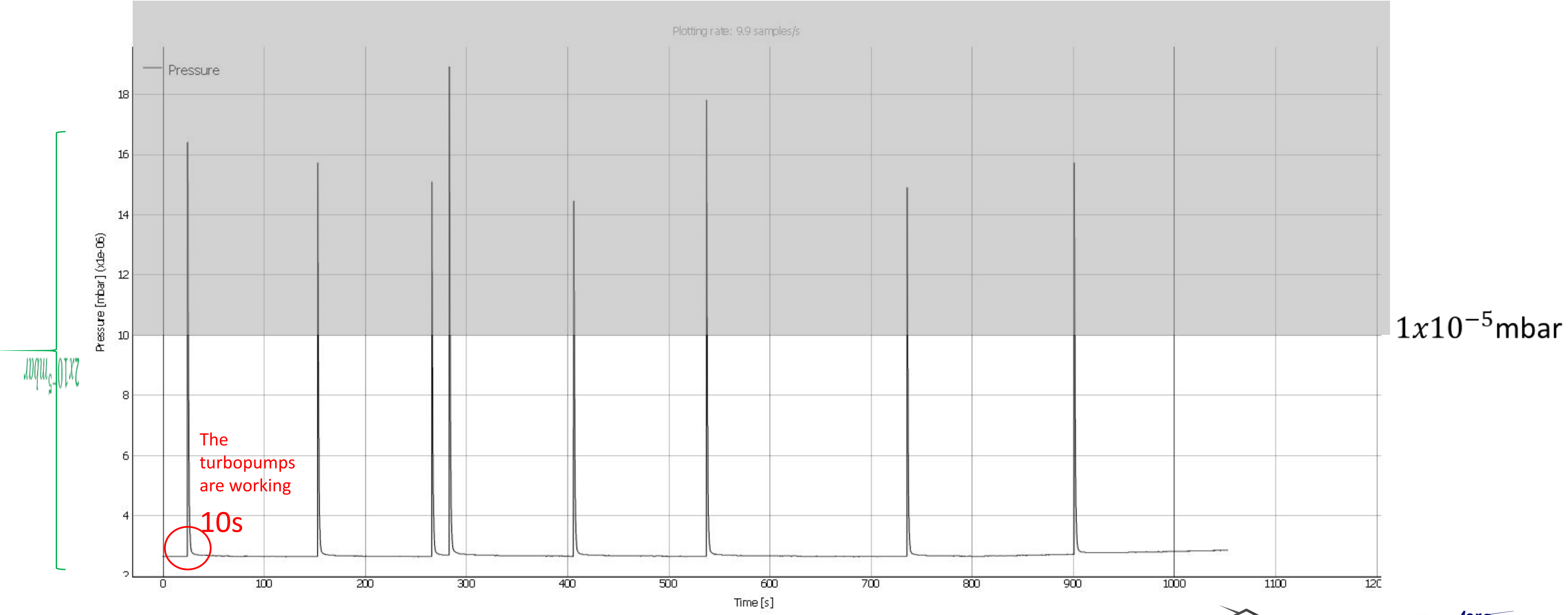
0.5cm gap



1.5cm gap

VACUUM CHAMBER PRESSURE VARIATION

BECAUSE OF THE MAIN DISCHARGE



This firing frequency is much larger than the characteristic operating one for APPTs (about 1Hz). This test was doing just with information purposes only.

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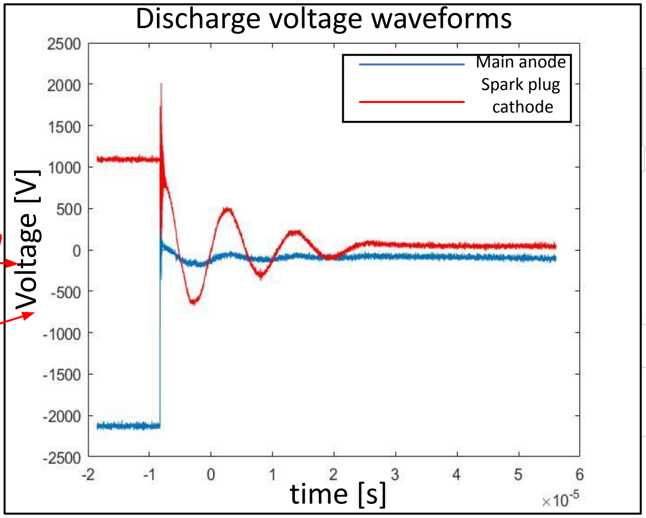
DISCHARGE VOLTAGE WAVEFORMS*

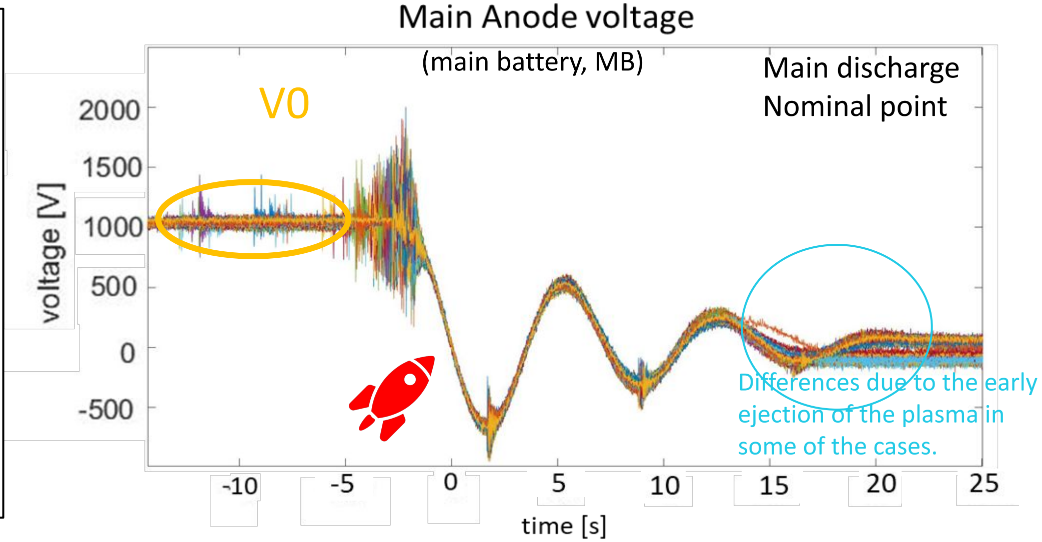
1. **Repeatability** verified for both discharges in terms of voltage waveforms (especially for the first discharge period in the case of the main one)
2. Very different **time scales**:

$$T_{MB} = T_{SP}x10^2$$

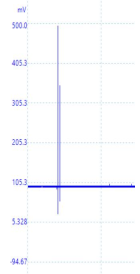
3. **Perturbation** on the main voltage due to the Spark plug discharge, and also, on the Spark plug discharged voltage induced by the energetic main discharge.

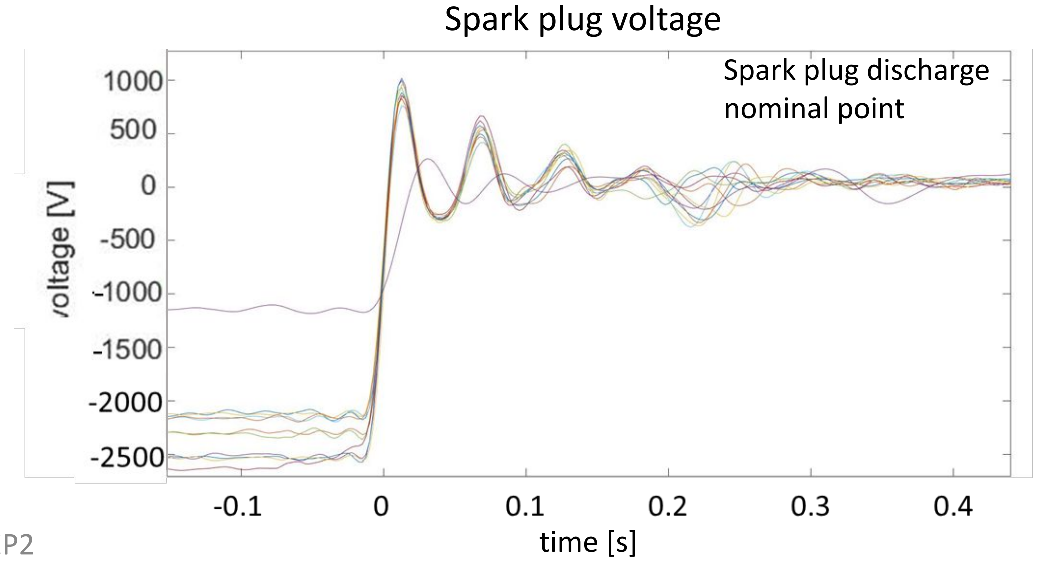
Other example





Perturbation on the thermoresistor circuit due to the APPT discharge





*) Thousands of main discharges analyzed, involving parameterization in terms of discharge energy, electrode voltage and channel gap.

SPARK PLUG VOLTAGE

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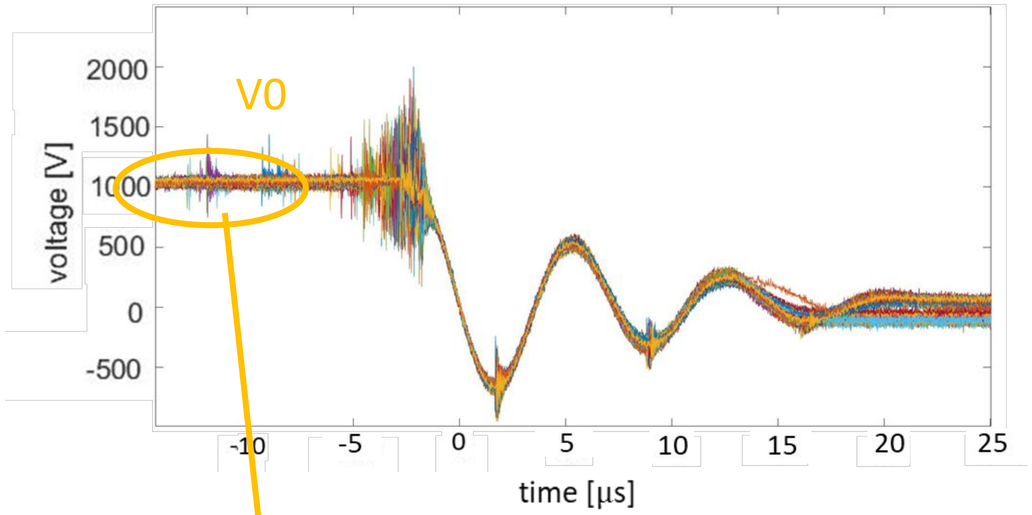
4. The **triggering voltage (V_{SP}) is for** this triggering circuit involving a battery (not for an inductive one where the voltage rising scale can be comparable to the discharge one), **out of our control, once** the SP geometry has been defined.

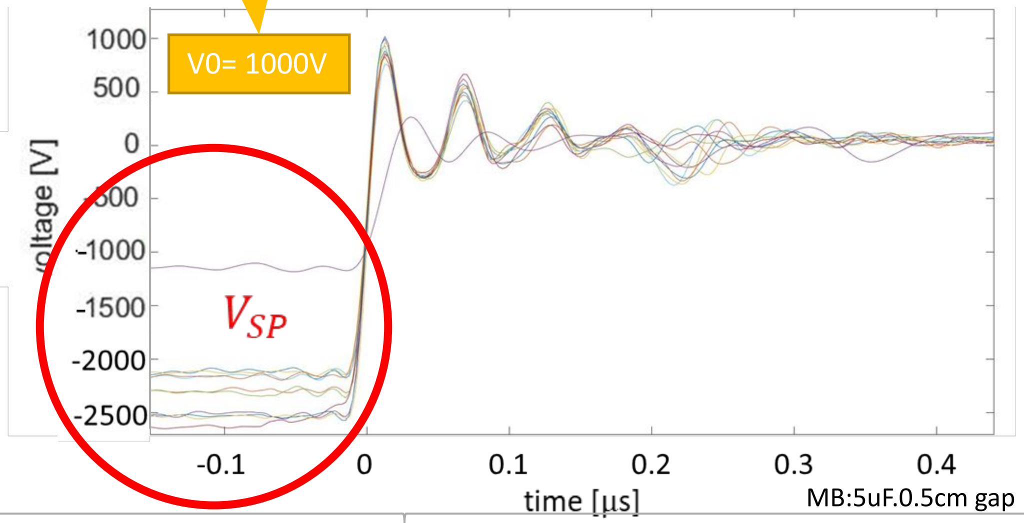
V_{SP} between 1-3kV

"Randomness": High sensitivity to microscale erosion.

Main Anode voltage



Spark plug voltage



MB:5uF.0.5cm gap

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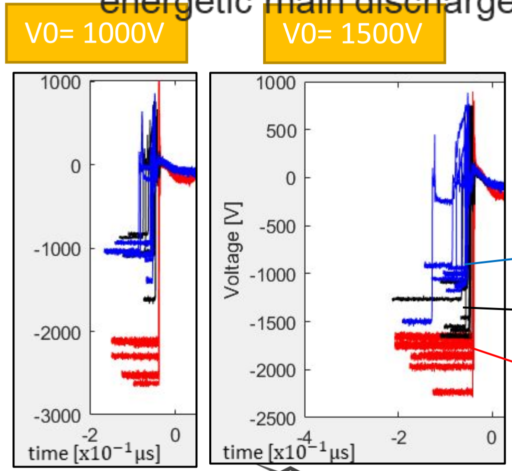
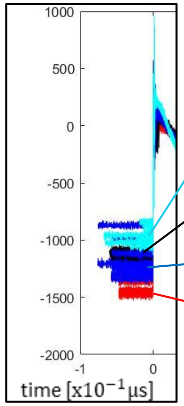


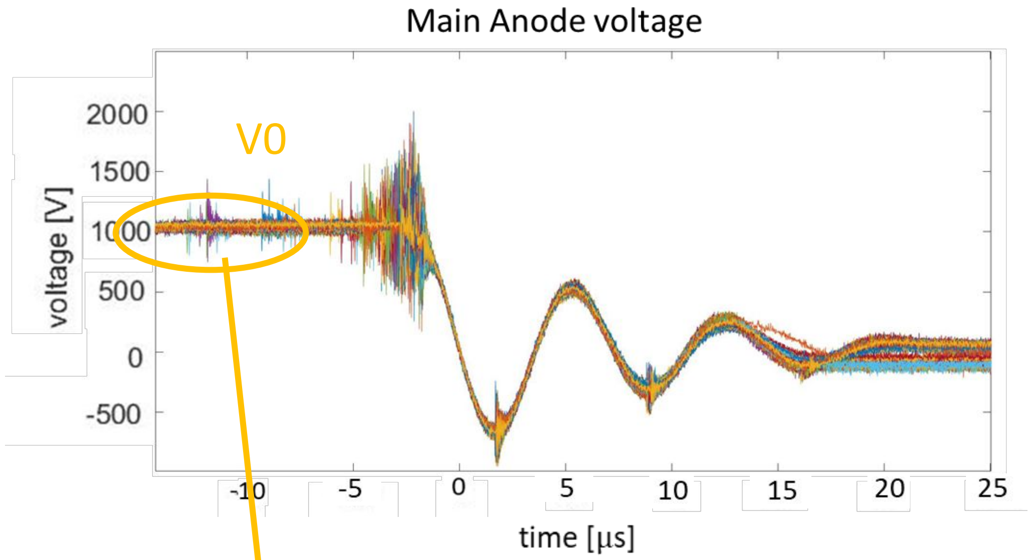
Channel height:
1.5cm
1cm
0.5cm

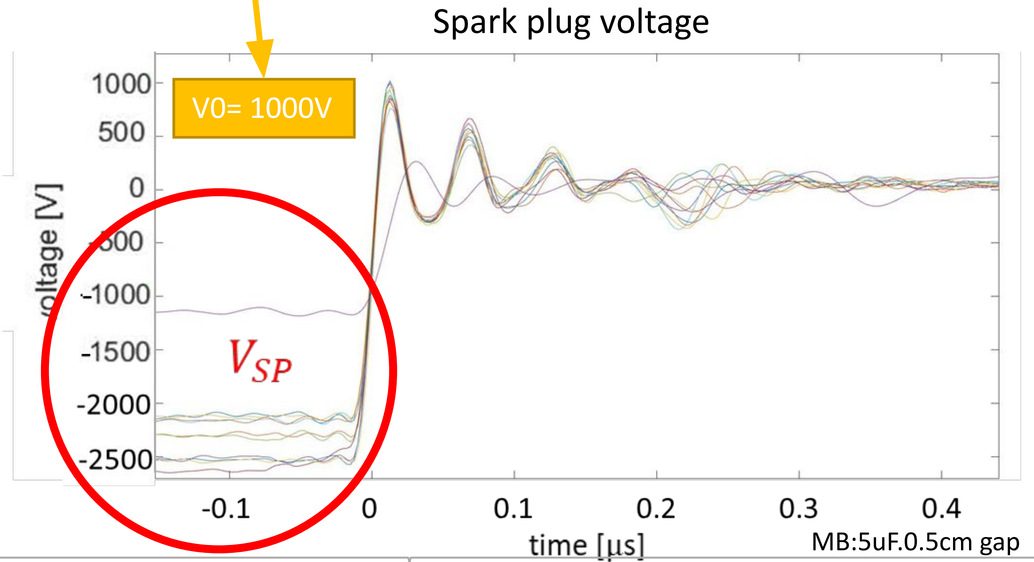
MB:5uF



V0:
2500V
2000V
1500V
500V

MB:3uF|0.5cm gap





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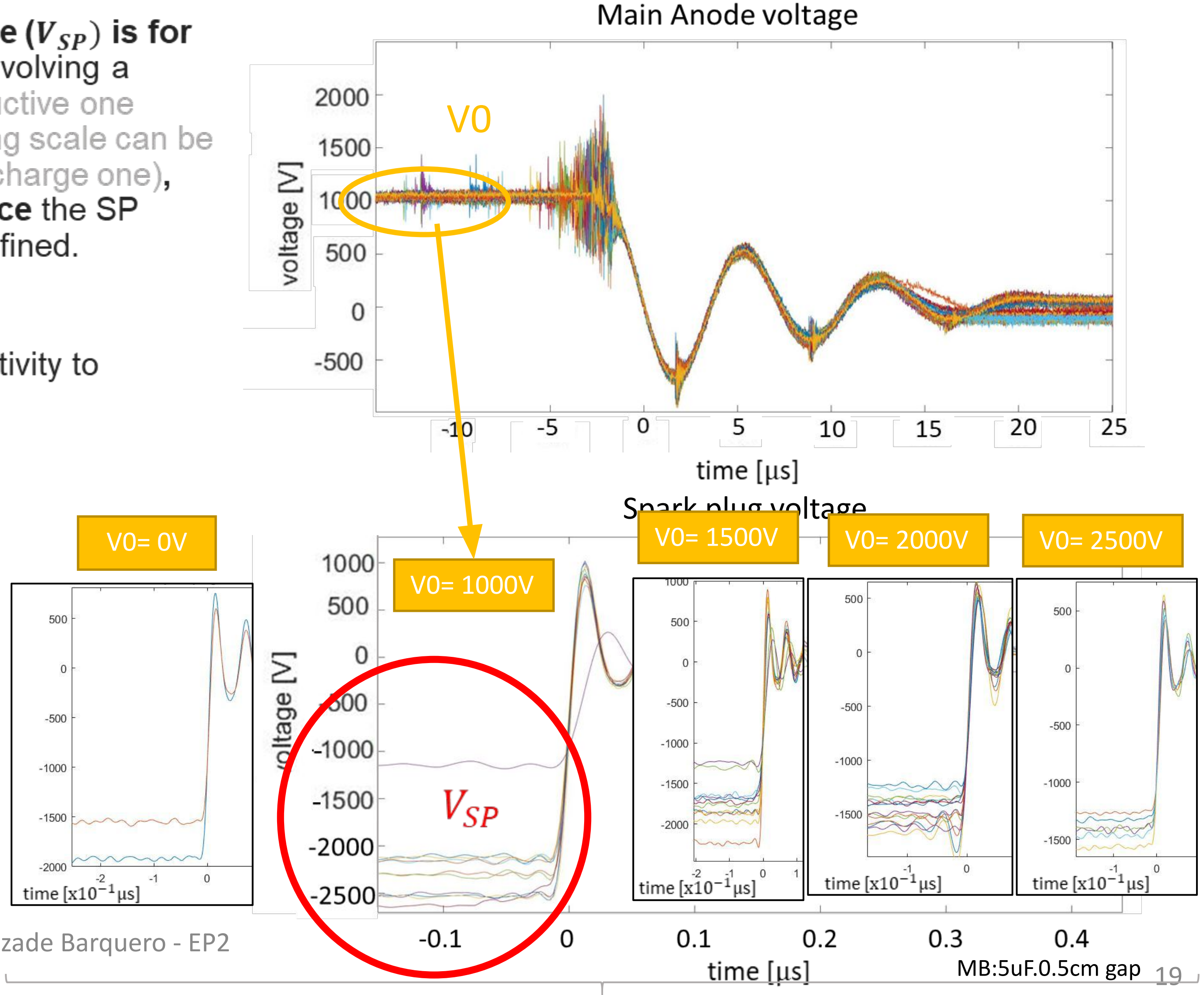
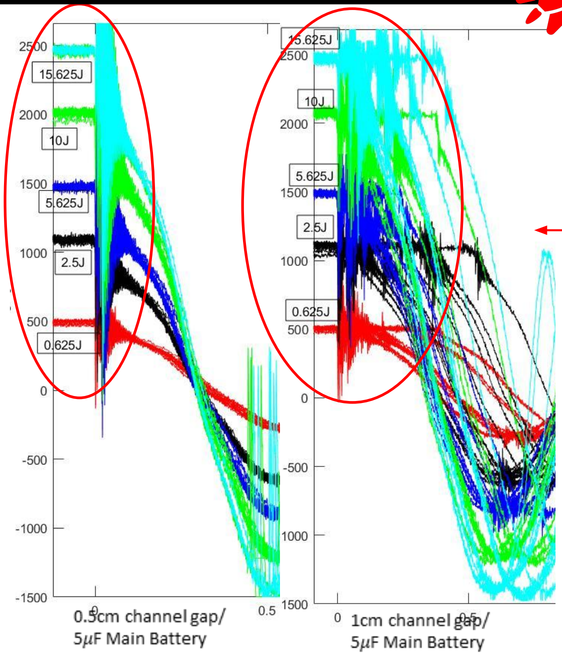
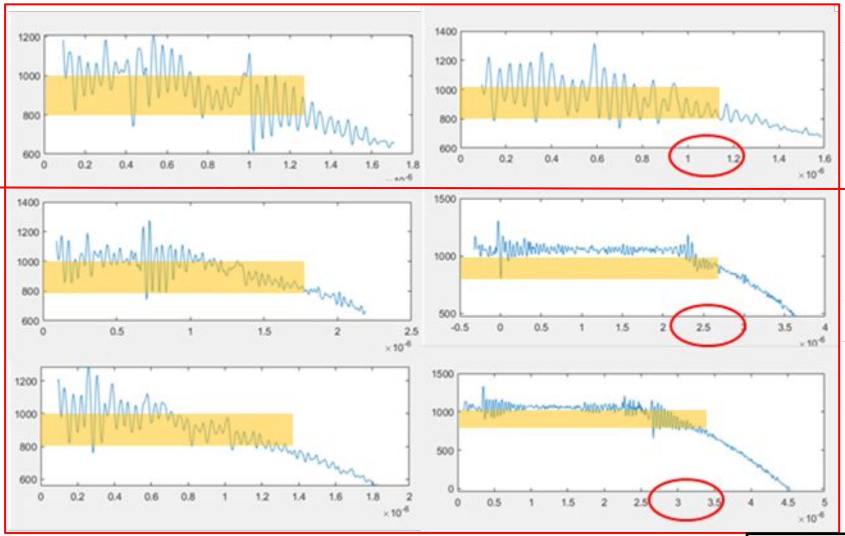
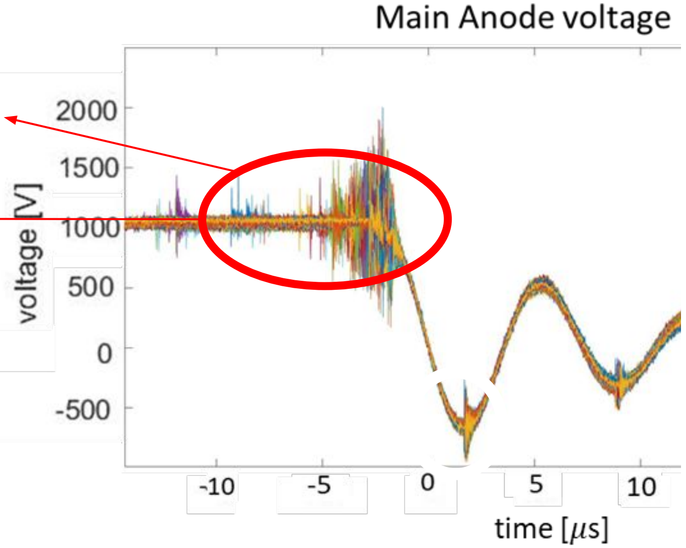


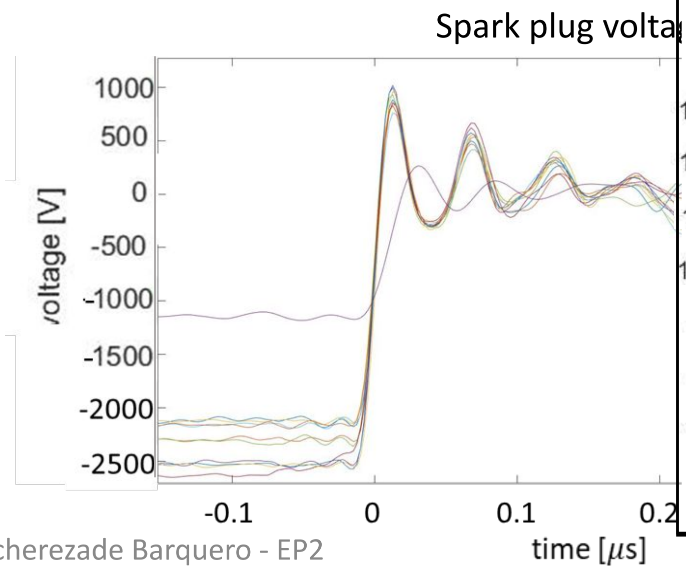
BREAKDOWN PROCESS

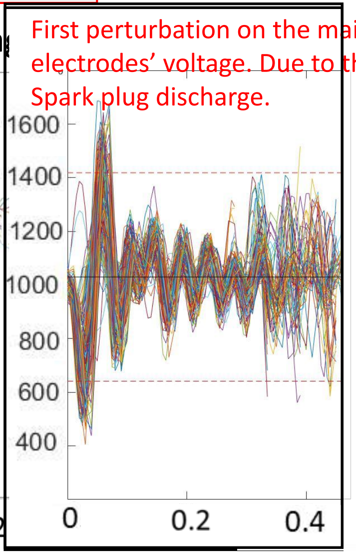
Main anode voltage from the initial time of the spark plug discharge up to the main gap breakdown initial time











5. **Transition time about 1-2us** but exceptions exist (the larger the gap is, the larger is the dispersion of the data)

Effective cross velocity $(10^4 m/s)$ for this transition is consistent with the reference electron thermal velocity $(10^5 m/s)$.

Different patterns, with evidence of noise coming from, probably, other discharges (e.g, non-desirable atmospheric discharges induced in the inside of the DC DC converters).

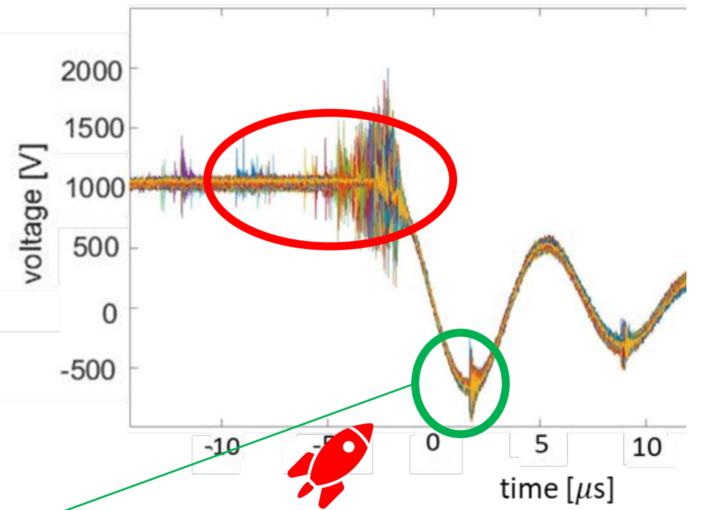
BREAKDOWN PROCESS

6. Often, **high frequency noise at the negative peaks** of the main discharge.

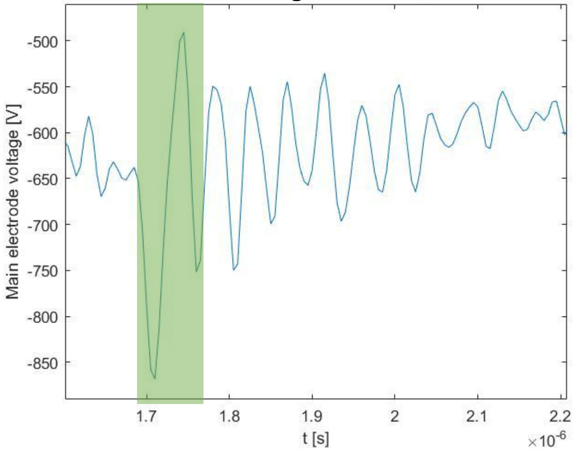
Same frequency than the SP discharge.

Existence of **secondary reignitions** could explain this, as first approach.

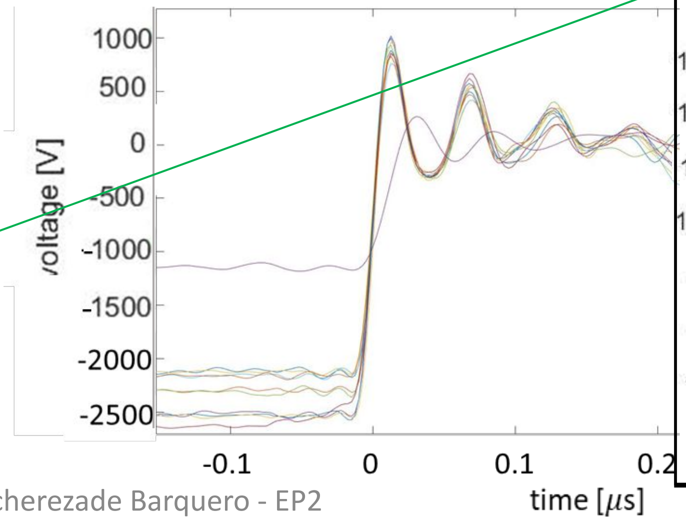
Main Anode voltage

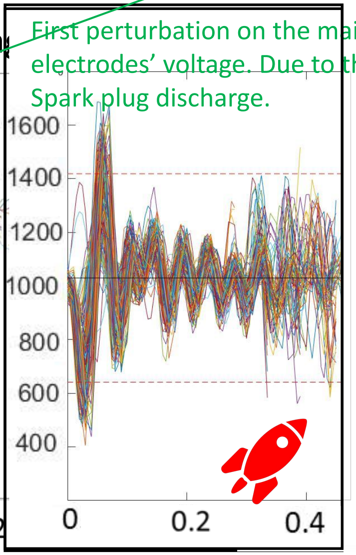


“Reignition”?

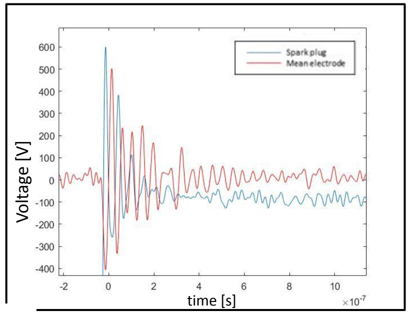


Spark plug volta





Spark plug discharge perturbation on a discharged main battery

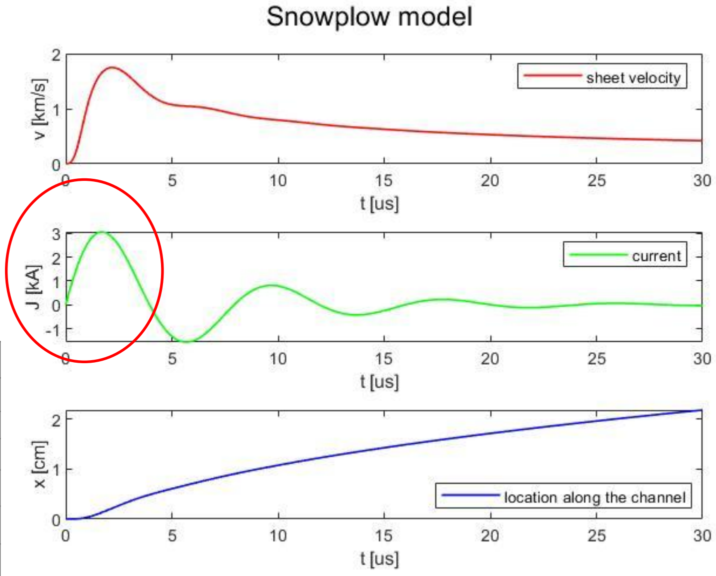


PERFORMANCE ESTIMATE
ELECTRICAL MODEL FITTING

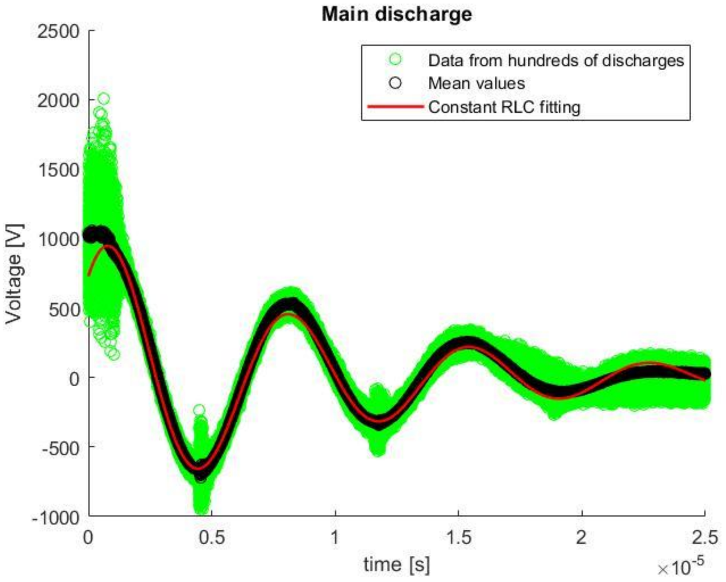
ELECTRICAL MODEL*
- Widely used
- Useful benchmark
- (Simplified) Plasma momentum equation + RLC circuit equation
- Plasma sheet assumption (as a mobile resistance with variable inductance)

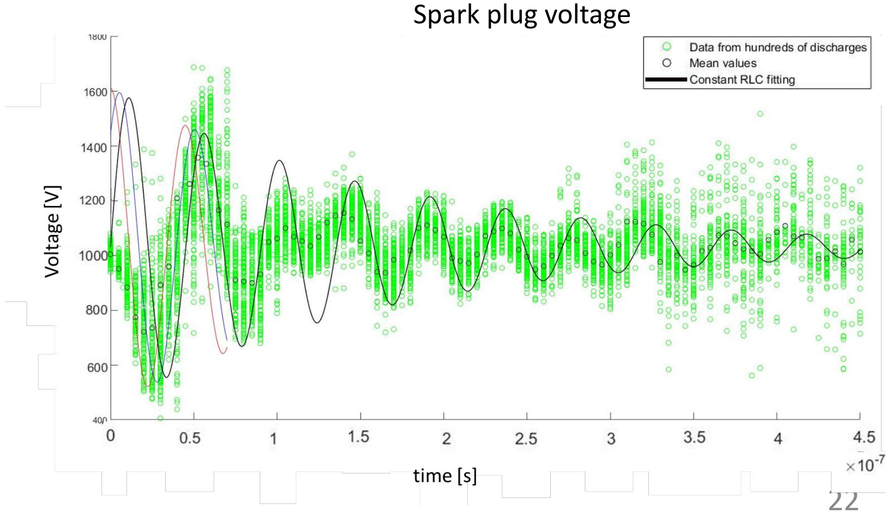
		Nominal case
Current peak	[kA]	~3
Ibit	[uNs]	~10
Isp	[s]	~200

Thruster	W0 [J]	W0/A [J/cm2]	V [V]	c [uF]	Isp [s]	Ibit [Ns]
LES-6 (B)	**<7 (1.85)**	<2.6	500-2000	0.66-6	**590 (300)**	**<90 (26)**
SMS (B)	**8.4**	1.15	-	-	**450**	**133**
EO-1 (B)	**<10 (8.5)**	0.88	-	-	**650**	**<100 (90)**
DAWSTAR (B)	**5.23**	2.27	500-2000	-	**483**	**56**
PPT-B20/ TMIT--X (B)	**2.3 -3.6 (3.38)**	(6.76)	1500	1-3	**(960)**	**(22)**
STSAT-2 (B)	**1.8**	-	>1500	1.6	**800**	**25**
PPTCUP (S)	**(1.7)**	(2-2.3)	<1500	2.4-3.2/ SP:333pF	**590**	**(29)**
BIT PPT (B)	-	-	<1500	(2)/ SP:0.18uF	-	-



Initial inductance $= 3x10^{-7}\ H$
Moving constant Resistance $= 1x10^{-1}\ \Omega$





*) R. G. Jahn. Physics of electric propulsion. New York: Dover Publications, 1968.

S. Barquero, M. Merino, J. Navarro. Design of an ablative pulsed plasma thruster for micropropulsion. Space Propulsion Conference 2020+1.

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MARTINLARA uc3m EP² Aero Space

- APPTs AND THE MARTINLARA PROJECT
- EXPERIMENTAL CAMPAIGN INTRODUCTION
- SETUP
- DISCHARGE TRIGGERING
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- VOLTAGE WAVEFORMS
- **SINGLE LANGMUIR PROBES**
- NEXT STEPS

SINGLE LANGMUIR PROBES

Floating and negatively biased (to collect positive ions for ToF)

VERY PRELIMINARY REMARKS:

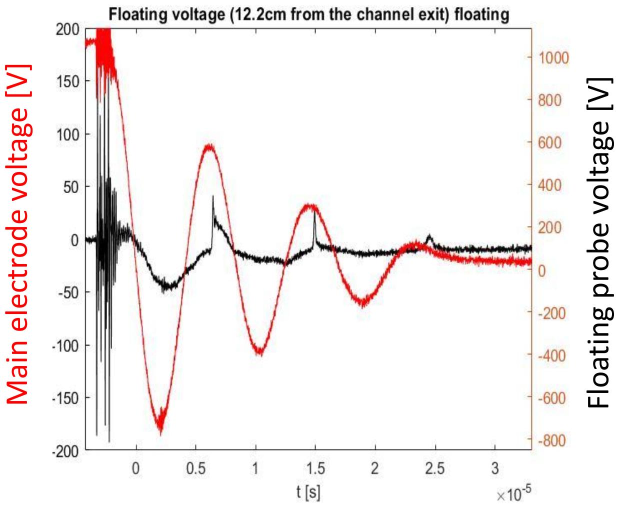
1. At least three voltage fluctuations are measured, BUT just (maybe) **two populations of ions** (from different (re)ignitions?)

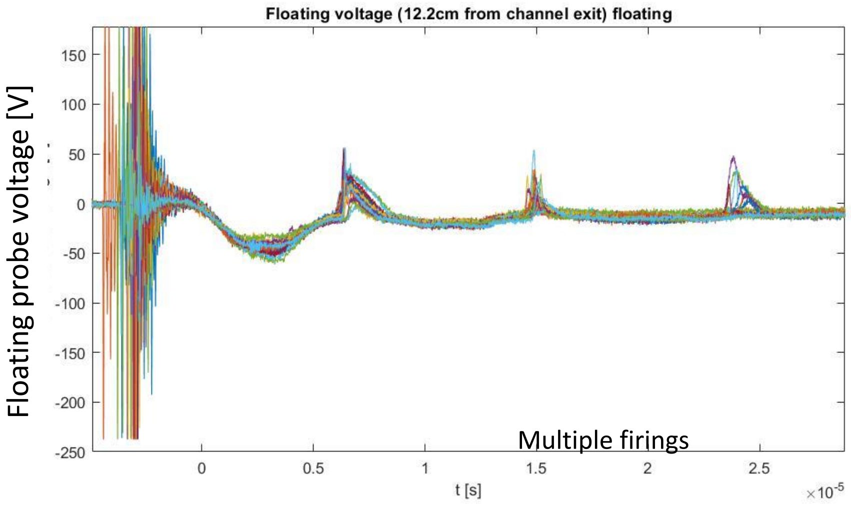
   In both cases, the data is apart from the noisy region.

2. **High repeatability of the peak positions** in the two types of tests for the respective regimes of interest

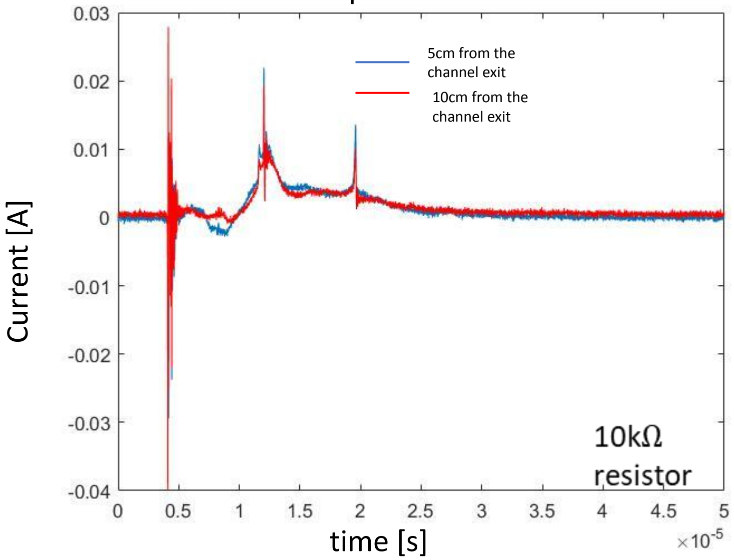
3. A **larger bias** favors positive ion collection (range tested: -30 to -200V), making the negative initial valley to reduce.

4. **USE LARGER DISTANCES BETWEEN PROBES!**
   The maximum distance tested between probes was about 10 cm but it is not enough to provide valid results (the delay time between probes is too short and can be comparable with the uncertainness). Hence, the **velocity results are wrong**, being at least one order of magnitude about the expected solution (i.e., around 10 km/s)





2 Biased probes at -70V



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- **NEXT STEPS**

NEXT STEPS

in the short time

- These results constitute a brief summary concerning a **necessary first approach** to the discharge basis, its measuring needs and the diagnostic execution.
- **Lesson learned** about how to refine the tests (including the setup) and open question list to focus on.
- **Electronics** must be also improved in order to provide a more robust but flexible design, especially in terms of control and ignition.

- A detailed **parametric analysis** must be developed exploring both electrical and geometry parameters. Already started in terms of energy, electrode voltage and electrode gap.
- **Metrics** concerning efficiency must be verified, and an improved nominal point, defined.

- **Photography synchronized** with the main discharge waveforms must be achieved.
- **Direct current measurements** (Rogowski coil) and the **Langmuir tests must be exploit** deeply (but improved) in order to provide consistent results.

- Our sight sets on **optical diagnostics** (as OES) in order to identify the plasma composition and distribution; another huge challenge.

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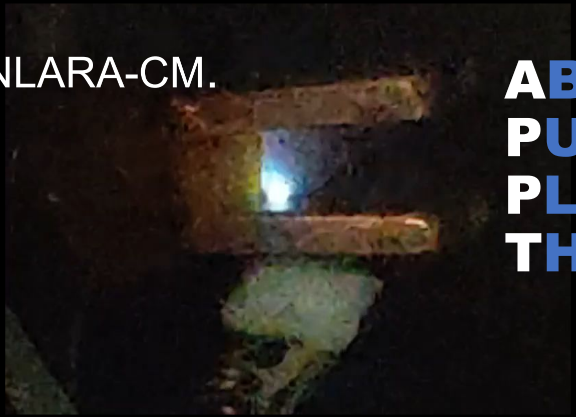

ABLATIVE
PULSED
PLASMA
THRUSTER

THANK YOU

ANY QUESTION?