



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## INDEX

NEMESIS project background

Results highlights summary.



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## NEMESIS (Novel Electride Material for Enhanced electrical propulsion Solutions)

CONSORTIUM



POLITÉCNICA



CONFIDENTIAL



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

## NEMESIS (Novel Electride Material for Enhanced electrical propulsion Solutions)

Exploring feasibility of a **new cathode technology** using **C12A7:e-** material as electron emitter for **transversal EP applications** for all neutralizers and thruster technologies requiring cathodes



POLITÉCNICA





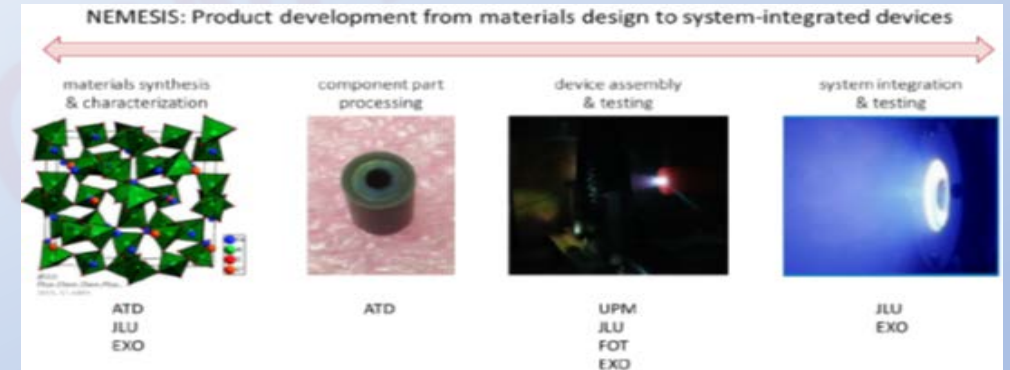
# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

## NEMESIS (Novel Electride Material for Enhanced electrical propulsion Solutions)

Exploring feasibility of a **new cathode technology** using **C12A7:e-** material as electron emitter for **transversal EP applications** for all neutralizers and thruster technologies requiring cathodes

The **Consortium** is covering the **full chain** of technology and product development of C12A7:e- electride based cathodes, **from the materials synthesis to EP system integration.**



POLITÉCNICA





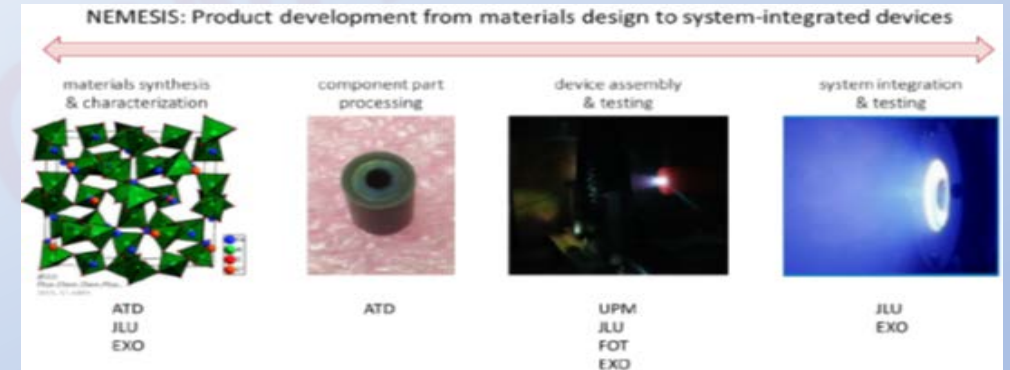
# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

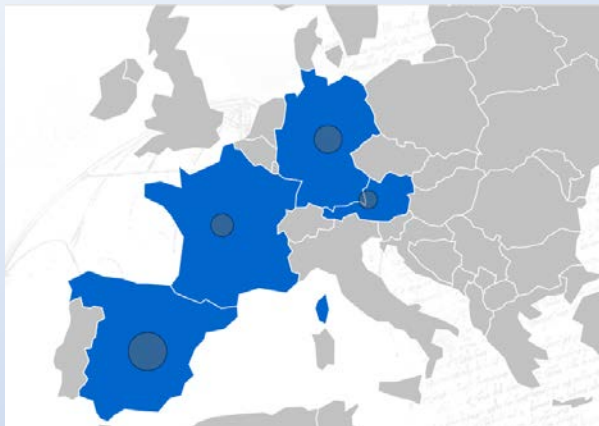
## NEMESIS (Novel Electride Material for Enhanced electrical propulsion Solutions)

Exploring feasibility of a **new cathode technology** using **C12A7:e-** material as electron emitter for **transversal EP applications** for all neutralizers and thruster technologies requiring cathodes

The **Consortium** is covering the **full chain** of technology and product development of C12A7:e- electride based cathodes, **from the materials synthesis to EP system integration.**



POLITÉCNICA



5 partners, 4 Countries, 2 Universities, 2 SMEs, 1 Research Center

ATD	Spain	SME
UPM	Spain	University
JLU	Germany	University
EXOTRAIL	France	SME
FOTEC	Austria	Research Center

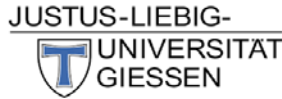


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- Deep research carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with HET thrusters, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours** in operation of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how** generated through project teams members and dissemination actions
- Three follow on **projects awarded** and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels

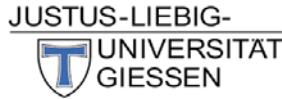


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with Xe, Ar, Kr, I, and NH<sub>3</sub>, coupled with HET thrusters, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours** in operation of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how** generated through project teams members and dissemination actions
- Three follow on projects awarded and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated experience of thousands of hours in operation of C12A7:e- based cathodes
- IP rights protected for key inventions, grouped into 2 patents for operative convenience
- Wide know how generated through project teams members and dissemination actions
- Three follow on projects awarded and 2 industrial collaboration agreements signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on projects awarded and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on projects awarded and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on projects awarded and 2 industrial collaboration agreements signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on **projects awarded** and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on **projects awarded** and 2 **industrial collaboration agreements** signed

**TRL4 achieved and technological understanding reached to proceed to qualify higher levels**



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- Deep research carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with HET thrusters, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours** in operation of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how** generated through project teams members and dissemination actions
- Three follow on **projects awarded** and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

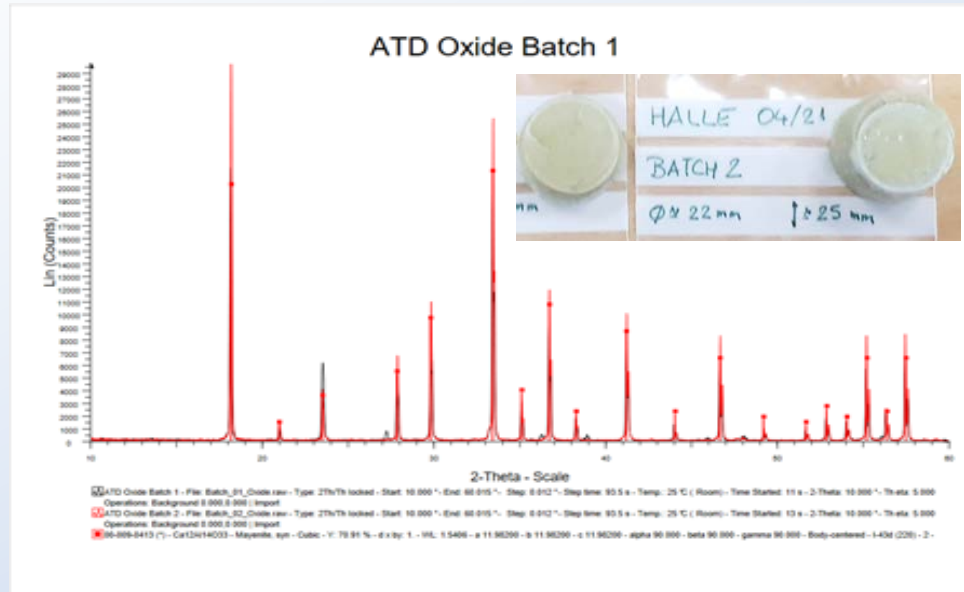
CONSORTIUM

High quality material locally produced from abundant precursors easy to store/operate

Achieved 100% purity in C12A7 ceramic synthesis



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

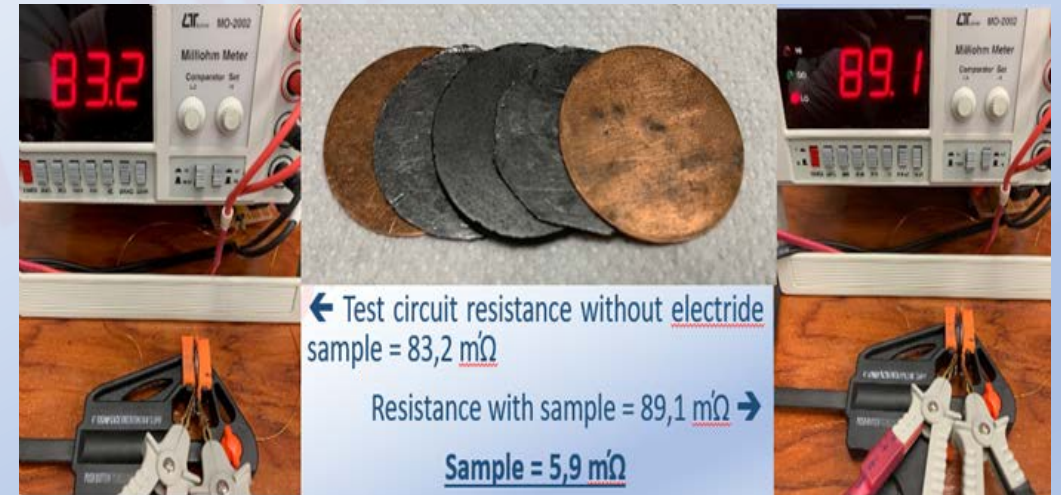
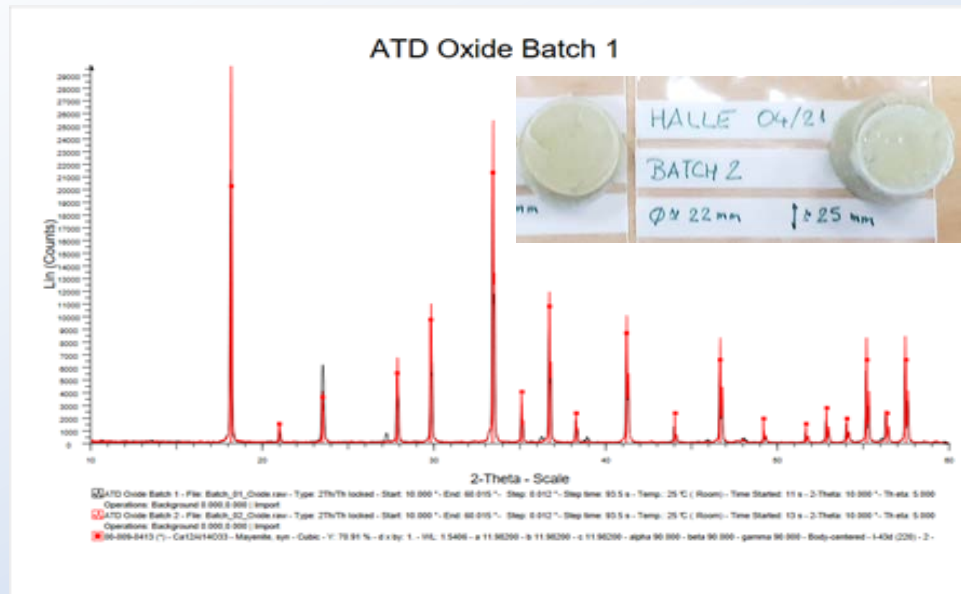
High quality material locally produced from abundant precursors easy to store/operate

Achieved **100% purity** in C12A7 ceramic synthesis

Very **high electron density** levels ( $> 10^{21} \text{ cm}^{-3}$ ) reached in transformation into C12A7:e-



POLITÉCNICA







# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

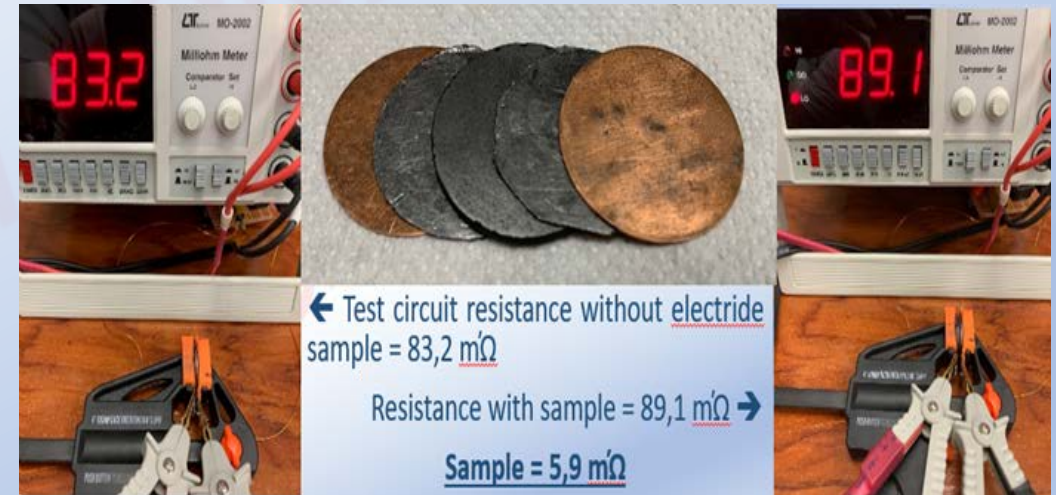
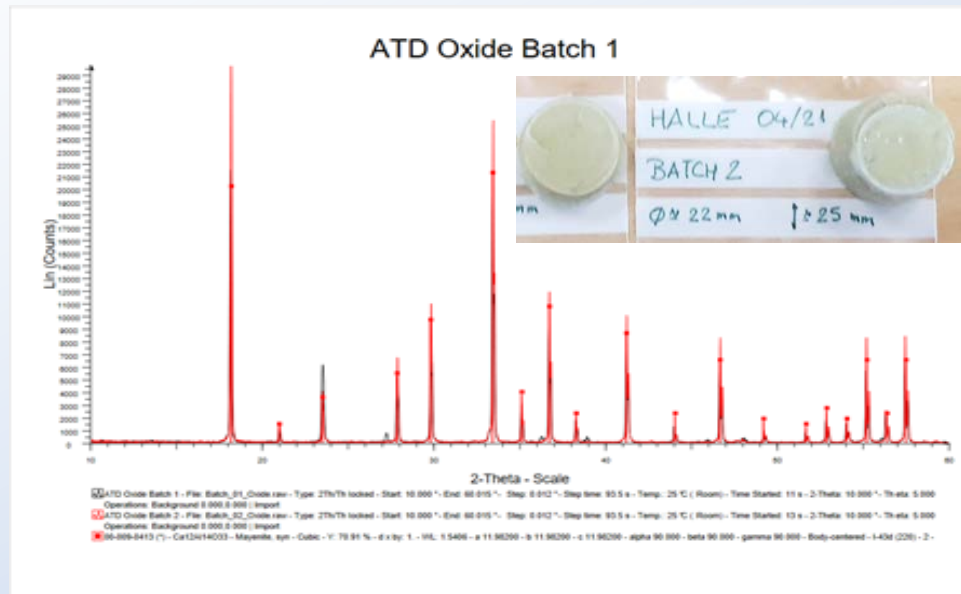
High quality material locally produced from abundant precursors easy to store/operate

Achieved 100% purity in C12A7 ceramic synthesis

Very high electron density levels ( $> 10^{21} \text{ cm}^{-3}$ ) reached in transformation into C12A7:e-



POLITÉCNICA



Multiple shapes and sizes in bulk or thin film depositions





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

**High quality material** locally produced from abundant precursors easy to store/operate

CONSORTIUM



POLITÉCNICA



CONFIDENTIAL

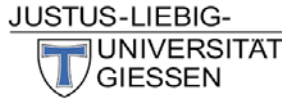


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



**High quality material** locally produced from abundant precursors easy to store/operate

**European non-dependance**

**Cost effective** local production within Europe from abundant unexpensive and **locally available** precursors

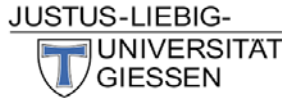


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



**High quality material** locally produced from abundant precursors easy to store/operate

**European non-dependance**

**Cost effective** local production within Europe from abundant unexpensive and **locally available** precursors

**Environment-friendly material**

**Non-toxic materials**, neither the electricle, nor the ceramic or precursors

**Water-free** production process



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



**High quality material** locally produced from abundant precursors easy to store/operate

**European non-dependance**

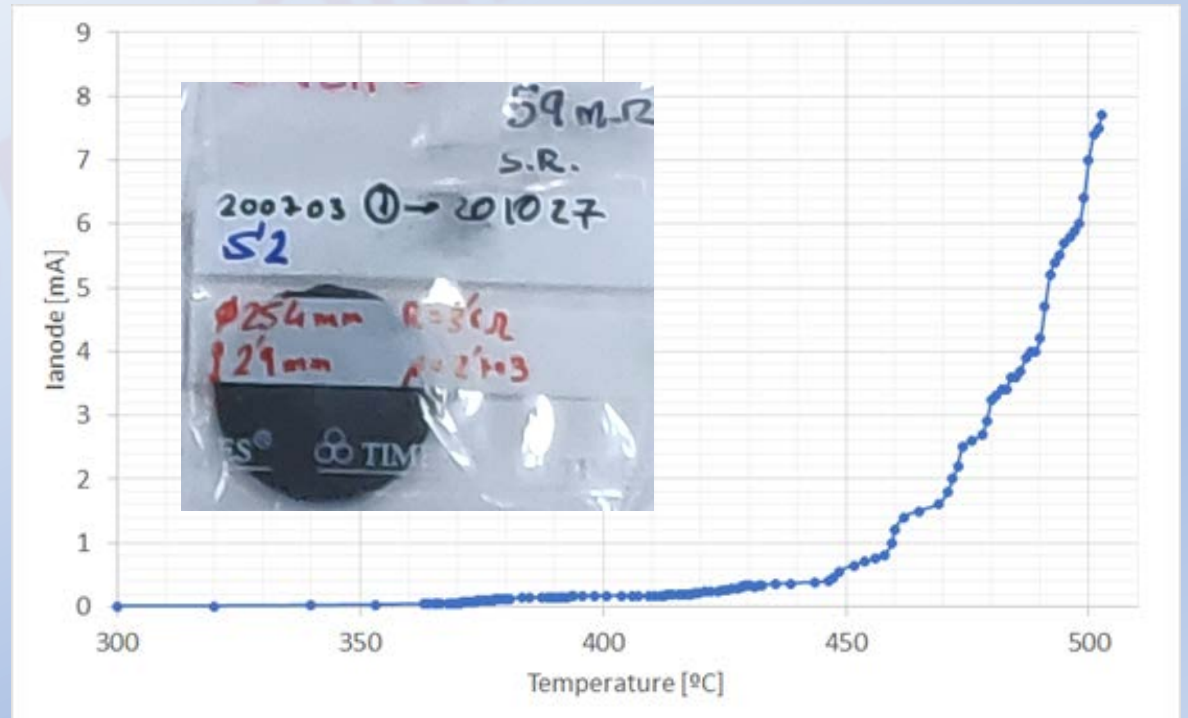
**Cost effective** local production within Europe from abundant unexpensive and **locally available** precursors

**Environment-friendly material**

**Non-toxic materials**, neither the electricle, nor the ceramic or precursors

**Water-free** production process

**Long-term stability** (> 2 years) with just a simple plastic bag storage





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with Xe, Ar, Kr, I, and NH<sub>3</sub>, coupled with HET thrusters, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours** in operation of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how** generated through project teams members and dissemination actions
- Three follow on projects awarded and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Deep research in material characterization and in derived key design rules



POLITÉCNICA



CONFIDENTIAL



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Deep research in material characterization** and in derived key design rules

**Extensive research** performed in electride material characterization, and LaB6 comparisons ...



POLITÉCNICA



CONFIDENTIAL





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Deep research in material characterization** and in derived key design rules

**Extensive research** performed in electride material characterization, and LaB6 comparisons ...

- Work function
- Thermionic emission curves
- Thermal conductivity
- Thermal emissivity coefficient
- Evaporation, melting, crystallization, and metals/isolators compatibility at high temperatures
- Electron mobility mechanisms modelling
- Mechanical parameters (micro-harness, elastic modulus, fracture toughness, fragility)
- Techniques for  $\text{cm}^{-3}$  electron concentration calculation (mass gain after oxidation, powder colour, electrical conductivity, XRD peaks shifts)
- Kinetic energy of emitted electrons
- Electrical conductivity & variation with temperature
- Heat capacity
- Operation under different atmospheres



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Deep research in material characterization** and in derived key design rules

**Extensive research** performed in electride material characterization, and LaB6 comparisons ...

- Work function
- Thermionic emission curves
- Thermal conductivity
- Thermal emissivity coefficient
- Evaporation, melting, crystallization, and metals/isolators compatibility at high temperatures
- Electron mobility mechanisms modelling
- Mechanical parameters (micro-harness, elastic modulus, fracture toughness, fragility)
- Techniques for  $\text{cm}^{-3}$  electron concentration calculation (mass gain after oxidation, powder colour, electrical conductivity, XRD peaks shifts)
- Kinetic energy of emitted electrons
- Electrical conductivity & variation with temperature
- Heat capacity
- Operation under different atmospheres

... which has allowed to overcome all the issues coming up during cathode's developments.



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Deep research in material characterization** and in derived key design rules

**Extensive research** performed in electride material characterization, and LaB6 comparisons ...

- Work function
- Thermionic emission curves
- Thermal conductivity
- Thermal emissivity coefficient
- Evaporation, melting, crystallization, and metals/isolators compatibility at high temperatures
- Electron mobility mechanisms modelling
- Mechanical parameters (micro-harness, elastic modulus, fracture toughness, fragility)
- Techniques for  $\text{cm}^{-3}$  electron concentration calculation (mass gain after oxidation, powder colour, electrical conductivity, XRD peaks shifts)
- Kinetic energy of emitted electrons
- Electrical conductivity & variation with temperature
- Heat capacity
- Operation under different atmospheres

... which has allowed to overcome all the issues coming up during cathode's developments.

Characterization results, R&D issues, and worked out solutions details can be found in the generated literature and also in project web site [www.nemesis-space.eu](http://www.nemesis-space.eu)



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Deep research in material characterization and in derived key design rules



POLITÉCNICA



CONFIDENTIAL



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Deep research in material characterization and in derived key design rules

One of the most complex issues to solve was the **emission barrier** effect and the **charge accumulation** caused by the **thin dielectric layer** present at material surface, which is randomly released as sparks, **causing instabilities and material damage.**



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

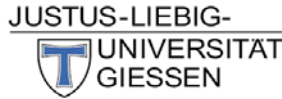
**Deep research in material characterization** and in derived key design rules

One of the most complex issues to solve was the **emission barrier** effect and the **charge accumulation** caused by the **thin dielectric layer** present at material surface, which is randomly released as sparks, **causing instabilities and material damage.**

**Charge coupling technique** using a pulsed operation mode was **verified** as the **solution** to such sparks and instabilities.



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

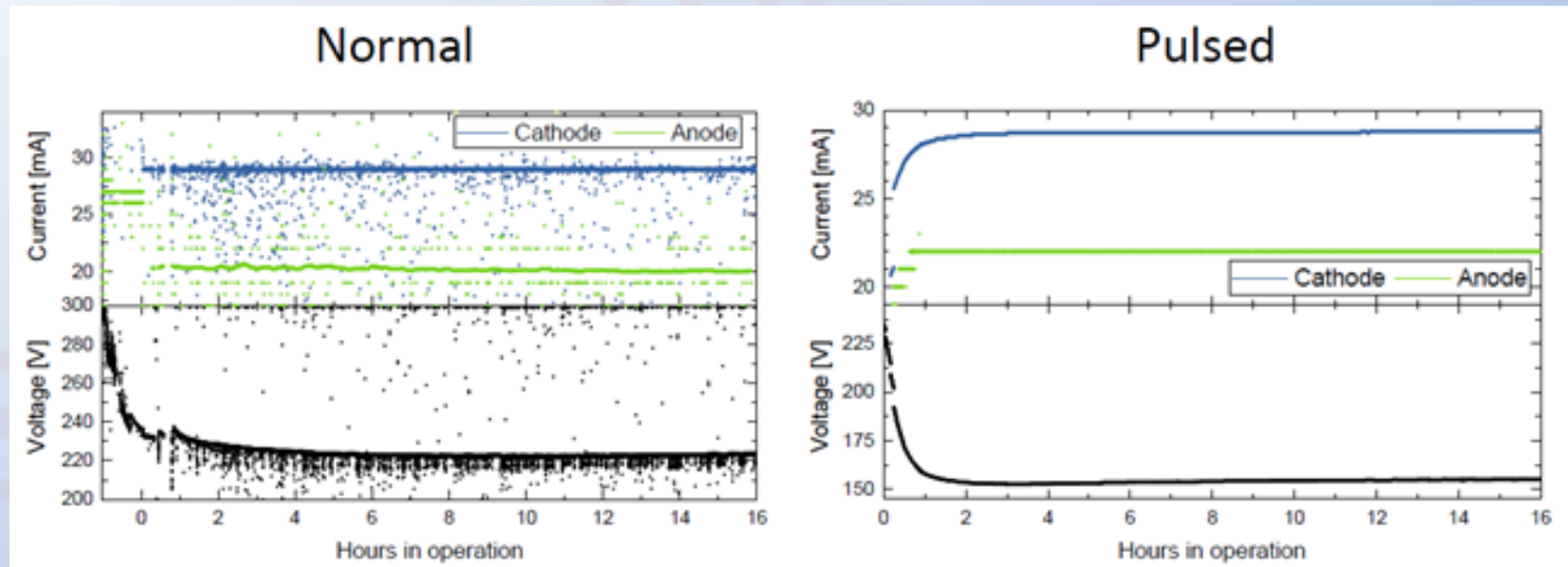
Deep research in material characterization and in derived key design rules

One of the most complex issues to solve was the **emission barrier** effect and the **charge accumulation** caused by the **thin dielectric layer** present at material surface, which is randomly released as sparks, causing **instabilities and material damage**.

Charge coupling technique using a pulsed operation mode was **verified** as the **solution** to such sparks and instabilities.



POLITÉCNICA



Performance test results without (left) and with (right) pulsed polarization mode



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Deep research in material characterization and in derived key design rules

In addition, pulsed operation mode provides **twice as much anode current**, and a slightly **better anode to cathode current ratio**.



POLITÉCNICA







# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

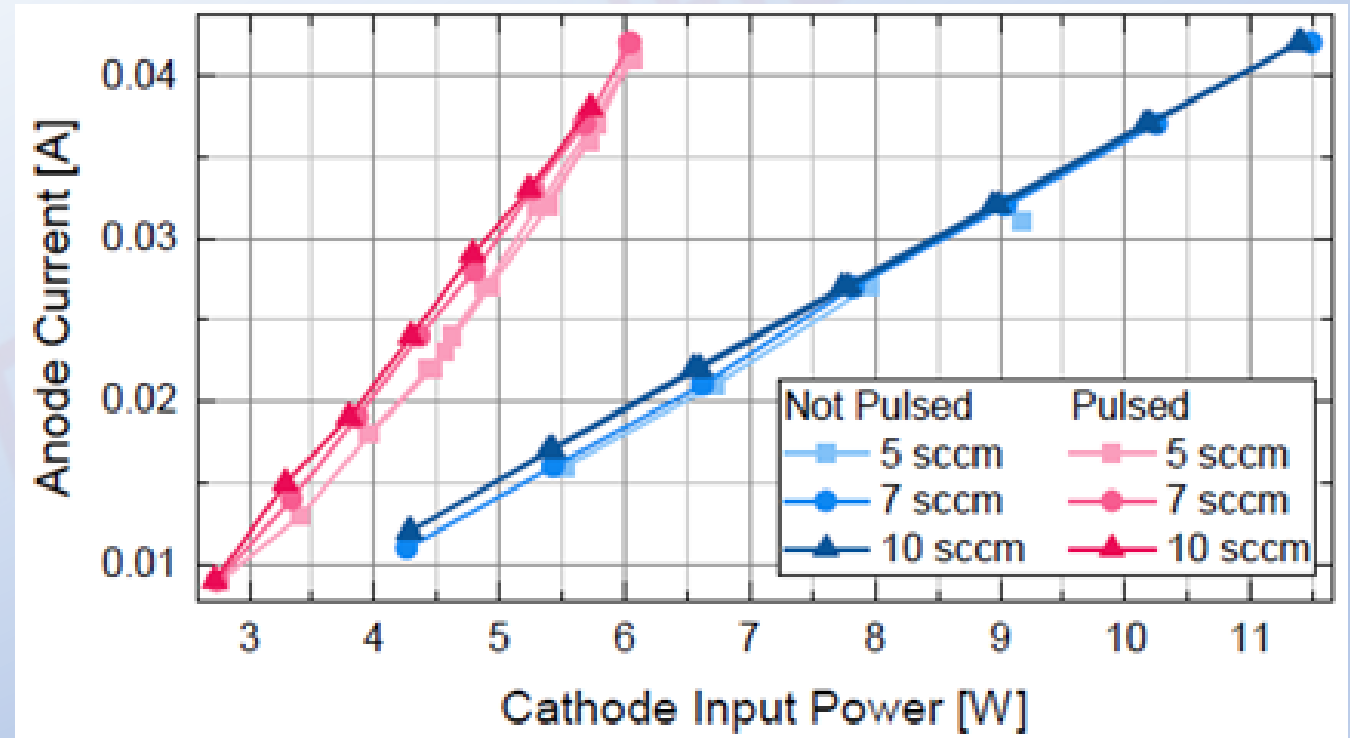
CONSORTIUM

Deep research in material characterization and in derived key design rules

In addition, pulsed operation mode provides **twice as much anode current**, and a slightly **better anode to cathode current ratio**.



POLITÉCNICA



I/V curves of pulsed (red) and not pulsed (blue) cathode polarization



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Deep research in material characterization and in derived key design rules



In addition, pulsed operation mode provides **twice as much anode current**, and a slightly **better anode to cathode current ratio**.

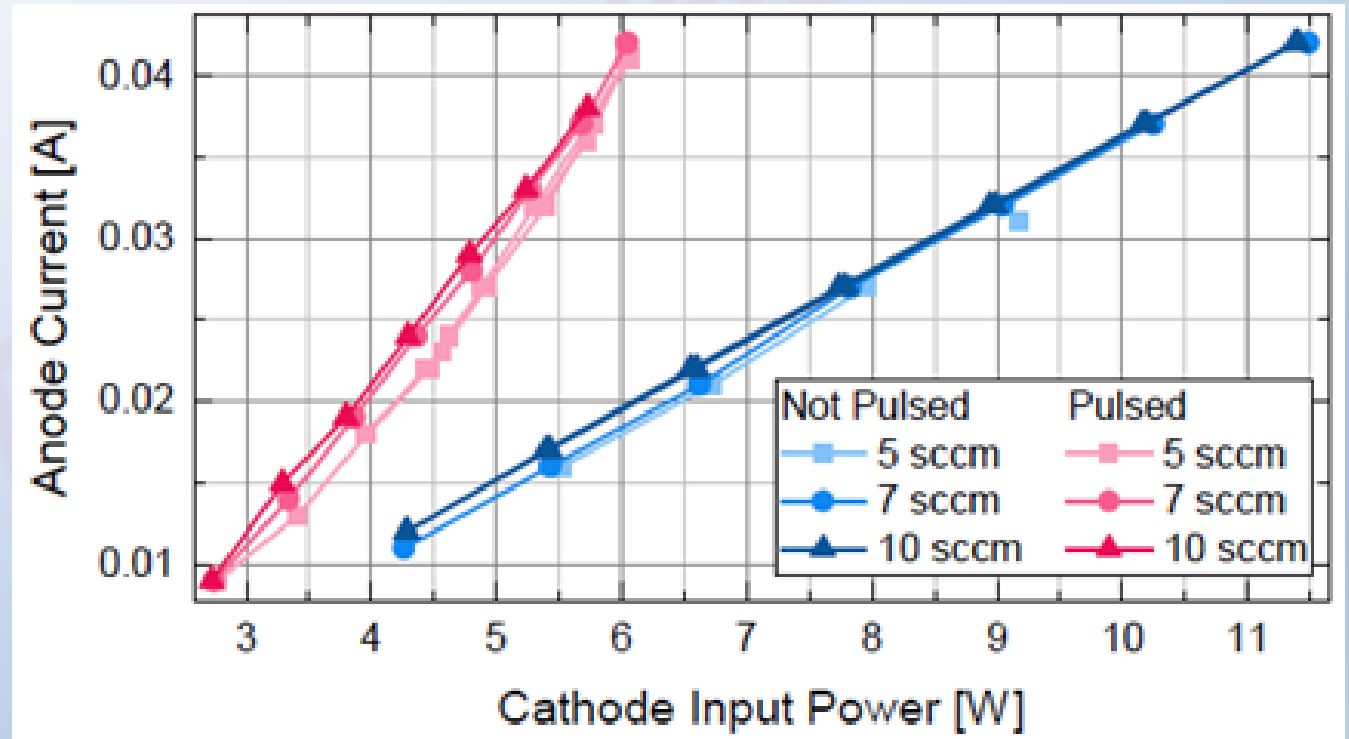


POLITÉCNICA



Patent for **pulsed operation mode** for C12A7:e- based cathodes has been **granted to ATD** (ES-2897523), and its worldwide extension is in progress.

- Patent licensing conditions can be requested through the contact section of NEMESIS project website



I/V curves of pulsed (red) and not pulsed (blue) cathode polarization



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



Deep research in material characterization and in derived key design rules

Material **fragility** and emitter **cracking** under thermal / electrical **shock conditions** was also an matter of concern and solution was developed by **deposition of emitting C12A7:e-** electrude material **on top of flexible unbreakable substrates** (carbon-cloth).

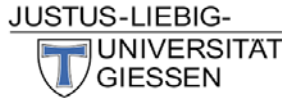


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

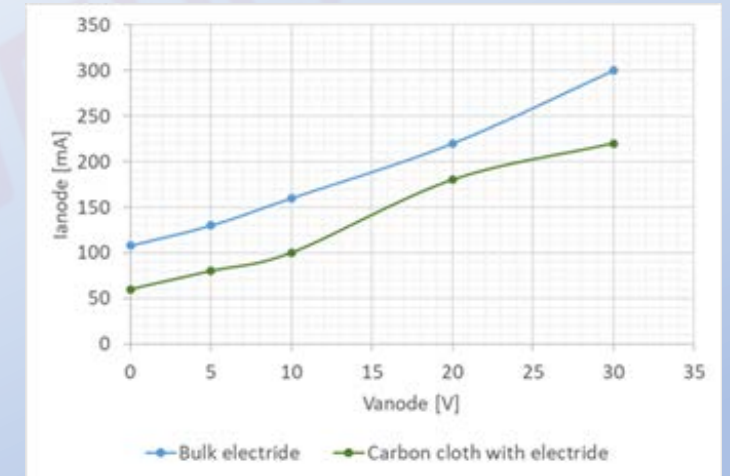


POLITÉCNICA



## Deep research in material characterization and in derived key design rules

Material **fragility** and emitter **cracking** under thermal / electrical **shock conditions** was also an matter of concern and solution was developed by **deposition of emitting C12A7:e- electride material on top of flexible unbreakable substrates** (carbon-cloth).



Current emission comparison between an electride bulk and a deposition on carbon cloth



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



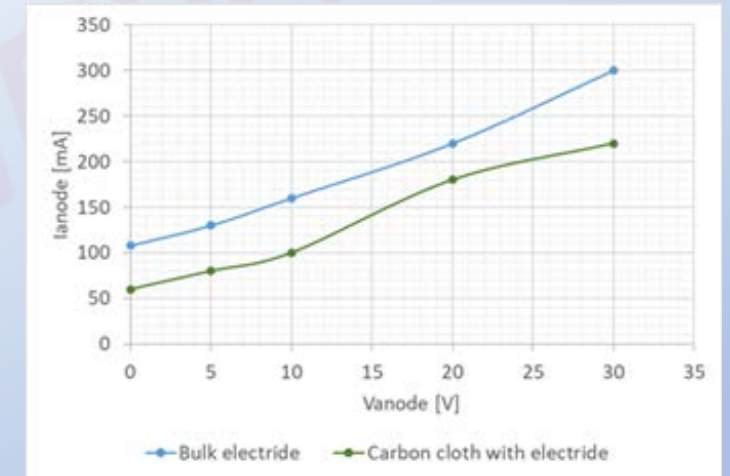
## Deep research in material characterization and in derived key design rules

Material **fragility** and emitter **cracking** under thermal / electrical **shock conditions** was also an matter of concern and solution was developed by **deposition of emitting C12A7:e- electrude material on top of flexible unbreakable substrates** (carbon-cloth).

Different **binders** are being tested to **improve the rigidity** of the carbon cloth-based cathode,

This **new cathode insert** will **support thermal shocks, vibrations, pressures, tensions**, and it is **inert** for a lot of **chemical** interactions keeping the emission properties comparable to bulk electrude samples.

**Patent** has already been presented for those processes and deposition techniques providing successful results.



Current emission comparison between an electrude bulk and a deposition on carbon cloth



Deposition with binder on carbon fiber (left) and carbon paper (right)



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated experience of thousands of hours in operation of C12A7:e- based cathodes
- IP rights protected for key inventions, grouped into 2 patents for operative convenience
- Wide know how generated through project teams members and dissemination actions
- Three follow on projects awarded and 2 industrial collaboration agreements signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels

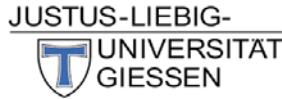


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

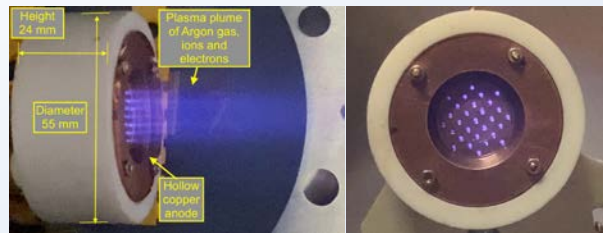


POLITÉCNICA



Several engineering model prototypes developed, successfully tested with Xe, Ar, Kr, I, and NH<sub>3</sub>, coupled with HET thrusters, and reaching high performance figures of merit.

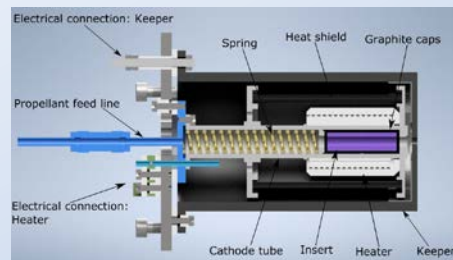
Different cathode architectures with several iterated versions each of them.



Side and front views of UPM HPD cathode prototype in operation



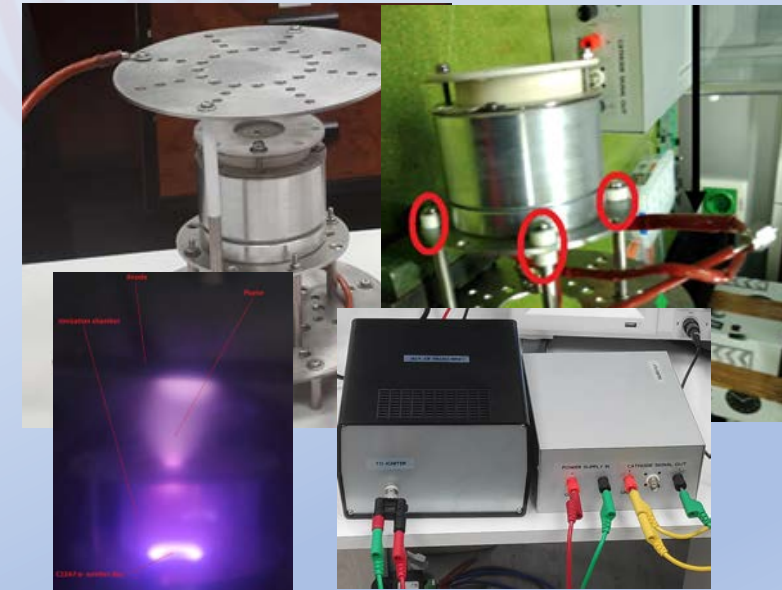
Heated planar insert cathode developed at JLU



JLU hollow cathode scheme



Exotrail heated and heater less hollow cathodes



ATD low power heater-less low temperature plasma discharge cathode prototypes version v16 (with igniter), v20, and v22 (with pulsed polarization generation box)



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

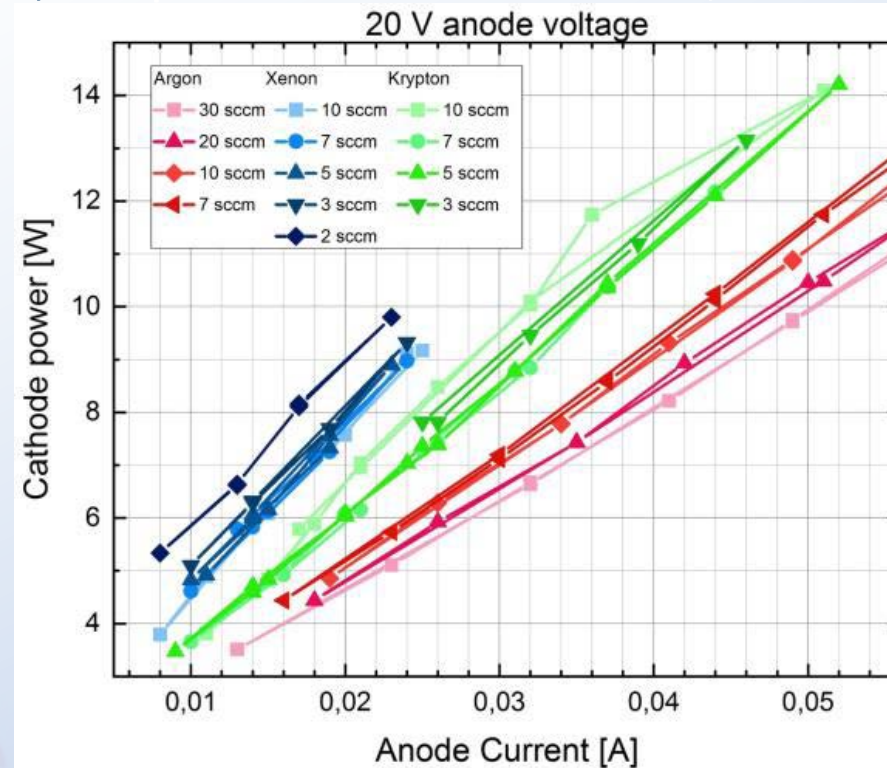
CONSORTIUM



POLITÉCNICA



Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH3**, coupled with HET thrusters, and reaching high performance figures of merit.



Performance tests of low power heater-less low temperature plasma discharge cathode operating with three noble gases





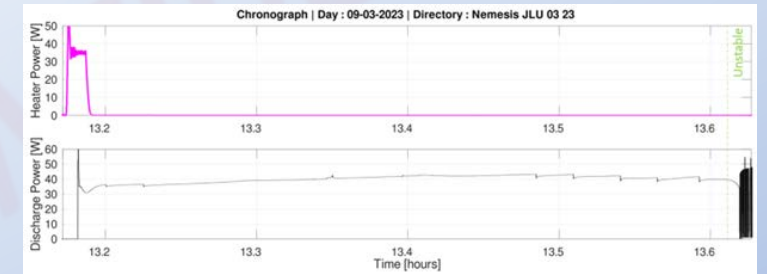
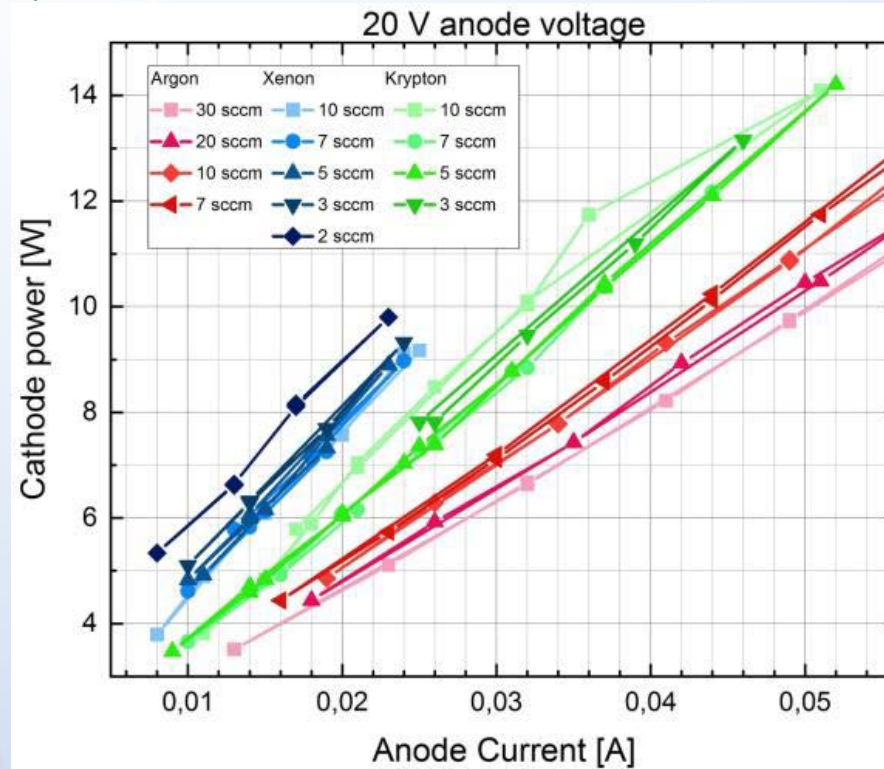
# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I,** and **NH3**, coupled with HET thrusters, and reaching high performance figures of merit.



POLITÉCNICA



Exotrail hollow cathode operated with I

Performance tests of low power heater-less low temperature plasma discharge cathode operating with three noble gases



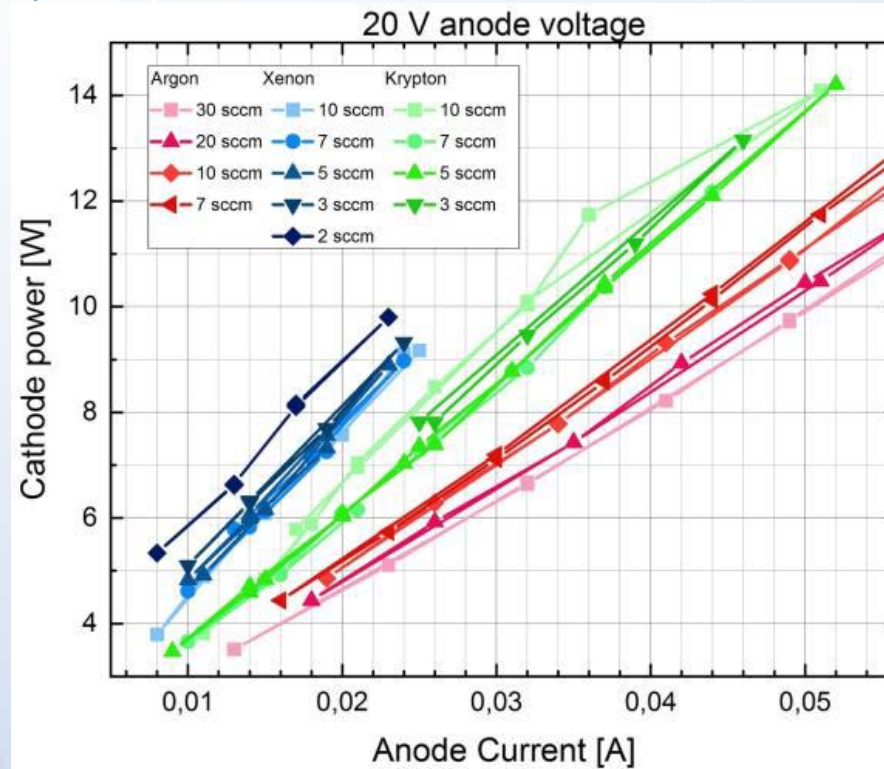
# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

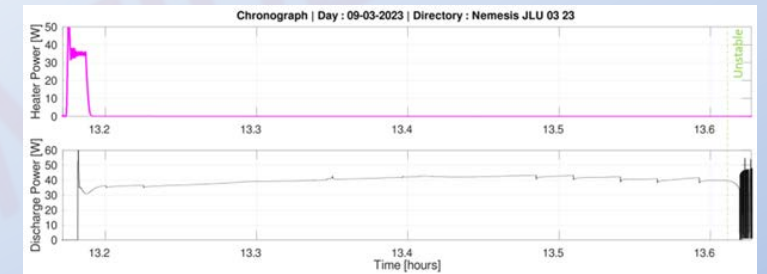
Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with HET thrusters, and reaching high performance figures of merit.



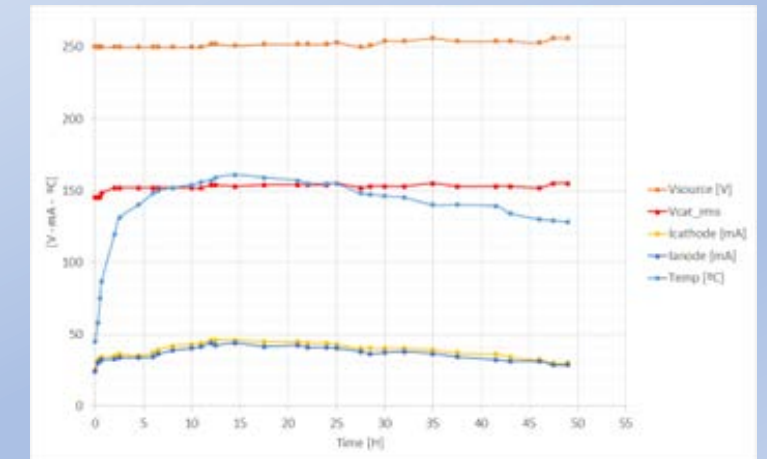
POLITÉCNICA



Performance tests of low power heater-less low temperature plasma discharge cathode operating with three noble gases



Exotrail hollow cathode operated with I



50 hour test of ATD cathode operated with NH<sub>3</sub>.



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching high performance figures of merit.



Exotrail hollow cathode coupled with EXOMG-Nano thruster (50 W HET)



Exotrail hollow cathode coupled with spaceware-micro thruster (150 W HET)

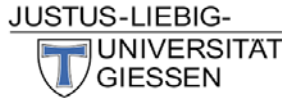


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

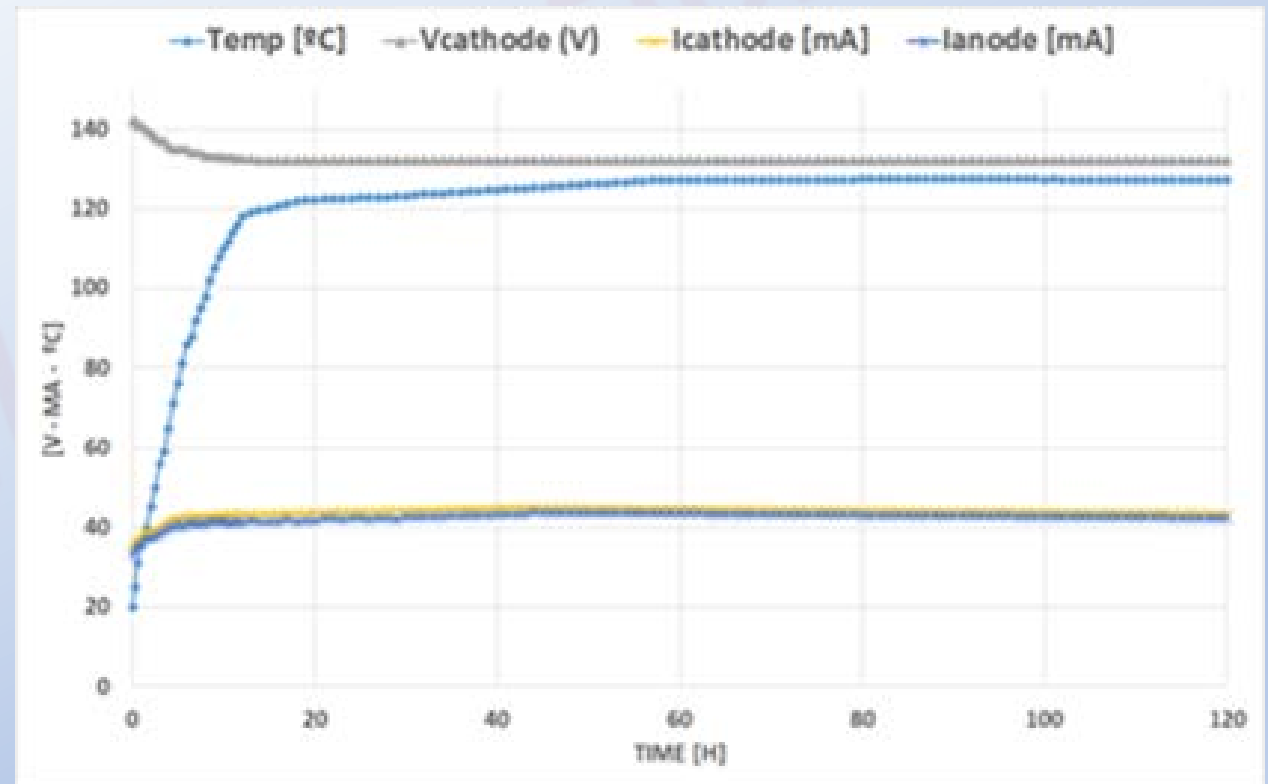


POLITÉCNICA



Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching high performance figures of merit.

Reaching performance ratios of **up to 10 mA/W**, and losses at keeper lower than 5% ( $I_{\text{anode}}/I_{\text{cathode}} > 95\%$ ).



120 h tests run of ATD cathode operating with Ar



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



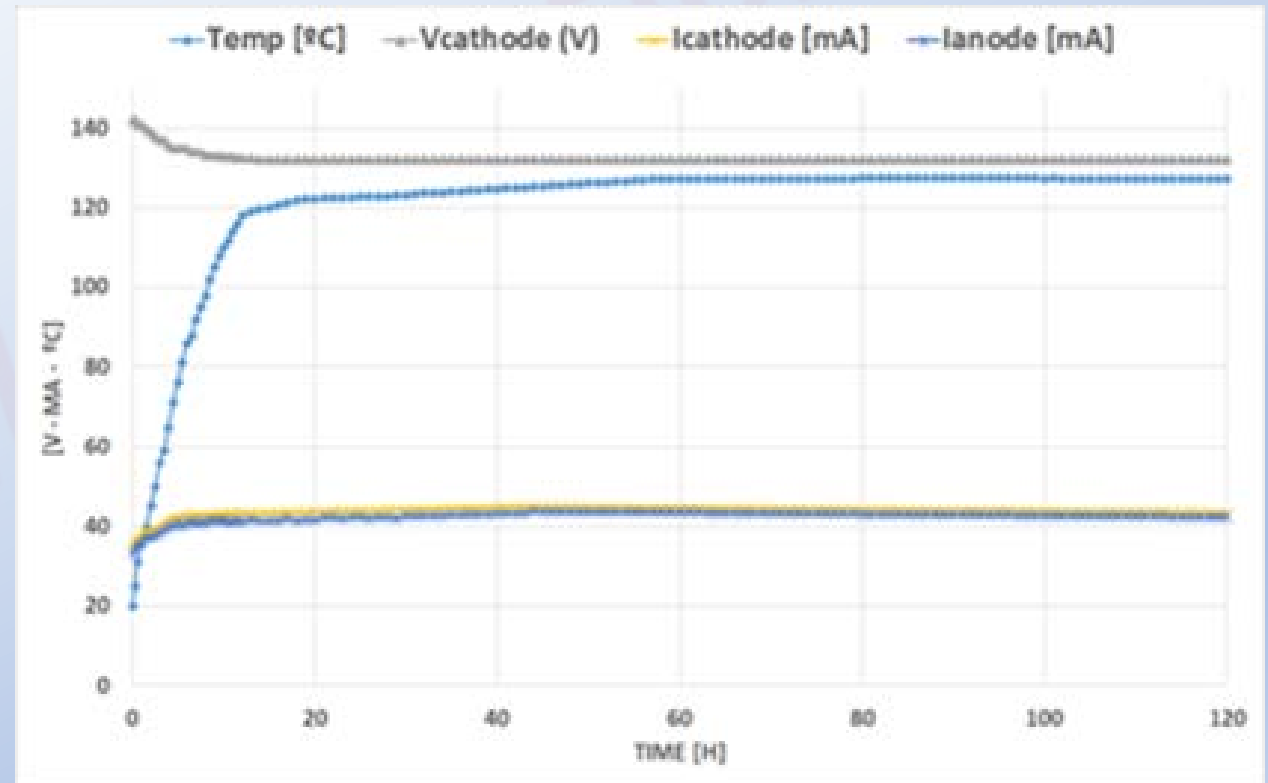
POLITÉCNICA



Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH3**, coupled with **HET thrusters**, and reaching high performance figures of merit.

Reaching performance ratios of **up to 10 mA/W**, and losses at keeper lower than 5% ( $I_{\text{anode}}/I_{\text{cathode}} > 95\%$ ).

Some of them operated with **powers below 1 W** in heater less configurations reaching operating temperatures **< 200 °C**



120 h tests run of ATD cathode operating with Ar



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA

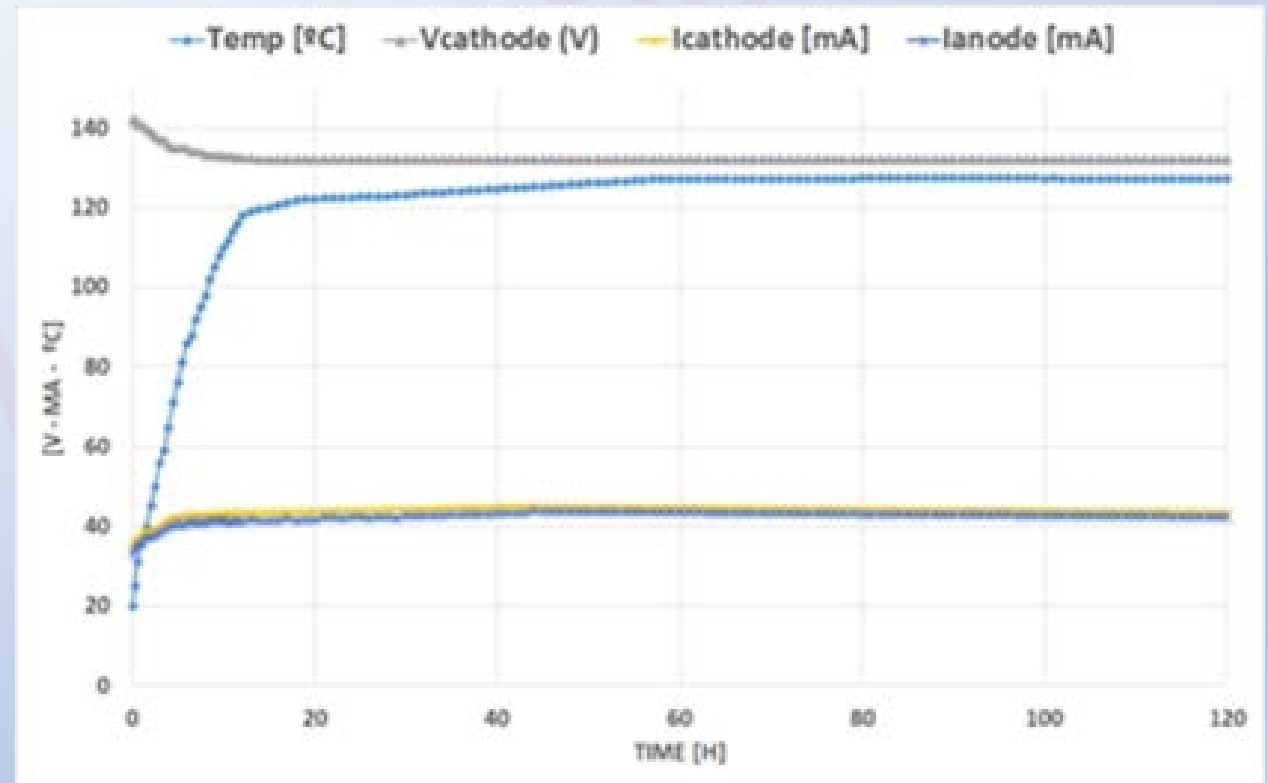


Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH3**, coupled with **HET thrusters**, and reaching high performance figures of merit.

Reaching performance ratios of **up to 10 mA/W**, and losses at keeper lower than 5% ( $I_{\text{anode}}/I_{\text{cathode}} > 95\%$ ).

Some of them operated with **powers below 1 W** in heater less configurations reaching operating temperatures **< 200 °C**

and providing **anode** extracted currents of some tenths of mA.



120 h tests run of ATD cathode operating with Ar



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on projects awarded and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels

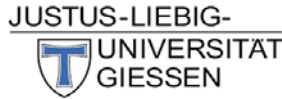


# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

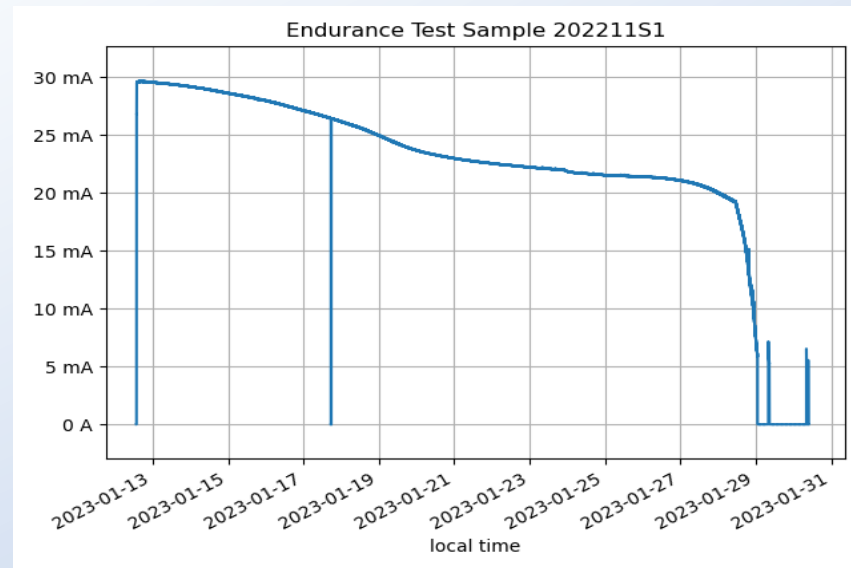


POLITÉCNICA



Cumulated experience of thousands of hours in operation of C12A7:e- based cathodes.

Over 1000 hours endurance tests performed on the ATD cathode at FOTEC in three runs, one reaching an uninterrupted average anode collected current of **25.38 mA (85% of 30 mA cathode current)** for 400 h



400 h tests run of ATD cathode operating with Ar





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

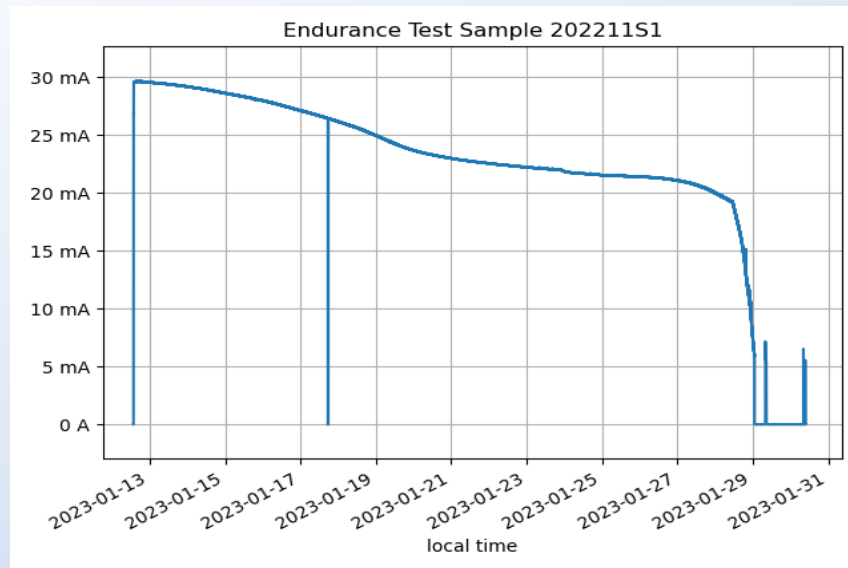


POLITÉCNICA



Cumulated experience of thousands of hours in operation of C12A7:e- based cathodes.

Over 1000 hours endurance tests performed on the ATD cathode at FOTEC in three runs, one reaching an uninterrupted average anode collected current of **25.38 mA (85% of 30 mA cathode current)** for 400 h with **less than 3 W cathode effective power** (240 V, 30 mA, 40% duty cycle), which represents a performance ratio of **8.5 mA/W** at an Argon flow rate of 0.25 mbar l/s.



400 h tests run of ATD cathode operating with Ar



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

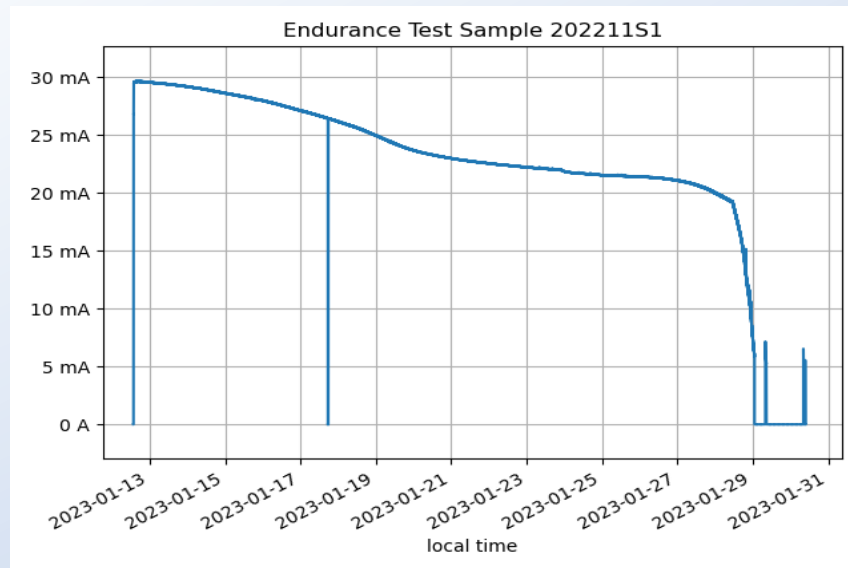


POLITÉCNICA



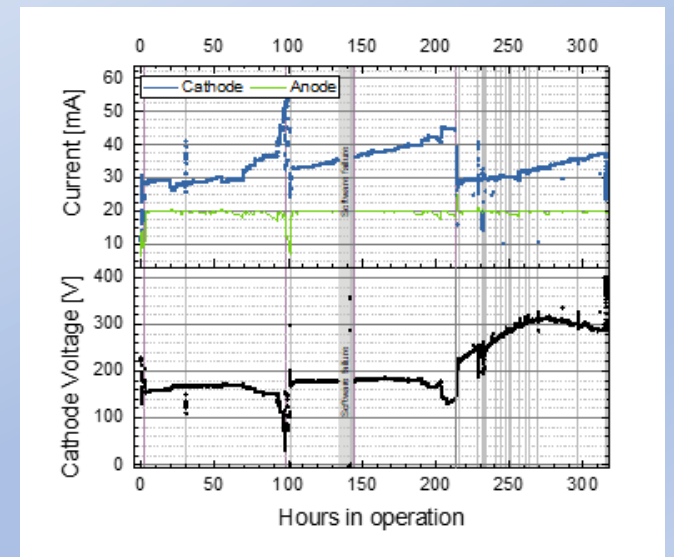
Cumulated experience of thousands of hours in operation of C12A7:e- based cathodes.

Over 1000 hours endurance tests performed on the ATD cathode at FOTEC in three runs, one reaching an uninterrupted average anode collected current of **25.38 mA (85% of 30 mA cathode current)** for 400 h with **less than 3 W cathode effective power** (240 V, 30 mA, 40% duty cycle), which represents a performance ratio of **8.5 mA/W** at an Argon flow rate of 0.25 mbar l/s.



400 h tests run of ATD cathode operating with Ar

Several endurance test runs performed also at JLU, one of them **over 300 h of uninterrupted operation with Kr.**



300 h tests run of ATD cathode operating with Kr



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on projects awarded and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**IP rights protected** for key inventions, grouped into 2 patents for operative convenience



8 inventions have been subject to IPR actions



POLITÉCNICA

45 claims grouped in two patents, one for mid-project and the other for end project inventions





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**IP rights protected** for key inventions, grouped into 2 patents for operative convenience

8 inventions have been subject to IPR actions

45 claims grouped in two patents, one for mid-project and the other for end project inventions



POLITÉCNICA



IPR protection actions	
Invention	Protection action
C12A7 oxide ceramic pure phase synthesis method	Industrial secret
Transformation process of C12A7 into C12A7:e- electrified with high electron density	
Cathode architecture elements for using C12A7:e- material as thermionic electron emitter	Patent P-202130777 <b>granted</b> (22 claims)
Pulsed polarization mode for operating C12A7:e- based electron emitting devices	
Techniques for electron concentration increase in synthesized C12A7:e- material	Patent <b>presented</b> (23 claims)
Several different cathode architectures using C12A7:e- as electron emitter	
Use of special substrates and deposition techniques for C12A7:e- material on these substrates	
C12A7:e- based cathodes for low temperature PEM/AEM hydrolyzers and fuel cells, and high temperature SOEC	



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on projects awarded and 2 industrial collaboration agreements signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Wide know how generated through project teams members and dissemination actions



Awareness generation within European space industry about this new cathode technology



POLITÉCNICA





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Wide know how generated** through project teams members and dissemination actions



**Awareness generation** within european space industry about this **new cathode technology**



POLITÉCNICA

24 presentations at 9 international Conferences / Workshops







# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Wide know how generated** through project teams members and dissemination actions



**Awareness generation** within european space industry about this **new cathode technology**



POLITÉCNICA

24 presentations at 9 international Conferences / Workshops

5 peer reviewed publications (see [www.nemesis.space.eu](http://www.nemesis.space.eu)) and 3 more under preparation:

- Performance of a C12A7:e- cold cathode based on charge coupling techniques
- Ramman spectroscopy characterization of C12A7:e-
- X-ray diffraction characterization of electride electron density





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Wide know how generated** through project teams members and dissemination actions



**Awareness generation** within european space industry about this **new cathode technology**



POLITÉCNICA

24 presentations at 9 international Conferences / Workshops

5 peer reviewed publications (see [www.nemesis.space.eu](http://www.nemesis.space.eu)) and 3 more under preparation:

- Performance of a C12A7:e- cold cathode based on charge coupling techniques
- Ramman spectroscopy characterization of C12A7:e-
- X-ray diffraction characterization of electride electron density



Additionally, a C12A7:e- workshop has been organized by JLU Giessen (04-05.10.2022), with the participation and presentations from academic and industrial entities.





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

**Wide know how generated** through project teams members and dissemination actions



**Awareness generation** within european space industry about this **new cathode technology**

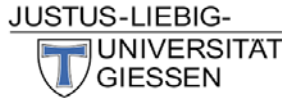


POLITÉCNICA

24 presentations at 9 international Conferences / Workshops

5 peer reviewed publications (see [www.nemesis.space.eu](http://www.nemesis.space.eu)) and 3 more under preparation:

- Performance of a C12A7:e- cold cathode based on charge coupling techniques
- Ramman spectroscopy characterization of C12A7:e-
- X-ray diffraction characterization of electride electron density



Additionally, a C12A7:e- workshop has been organized by JLU Giessen (04-05.10.2022), with the participation and presentations from academic and industrial entities.

And two PhD thesis based on NEMESIS project activities

- M. Reitemeyer (JLU Giessen) on C12A7
- D. Zschätzsch (JLU Giessen) on Hollow cathodes and iodine in space





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## Wide know how generated through project teams members and dissemination actions

CONFERENCES NEMESIS PROJECT		
Title	Author	Conference
NACES cathode: High performance cathode for electric propulsion devices based on C12A7:e electride novel material	A. Post, et alter	EPIC Workshop 2019, ESA-ESTEC 21-23.10.2019
Investigation of C12A7:e-under harsh conditions in relation to hollow cathode neutralizers	D. Zschätzsch, et alter.	8 <sup>th</sup> RGCEP, Kaliningrad 11-15.04.2021
High performance cathode based on C12A7:e- (electride) material for in space electric propulsion applications	J.F. Plaza, et alter	8 <sup>th</sup> RGCEP, Kaliningrad 11-15.04.2021
Compatibility of the electride C12A7:e- with alternative propellants and production of thin films	M. Reitemeyer, et alter	8 <sup>th</sup> RGCEP, Kaliningrad 11-15.04.2021
Key design and operation factors for high performance of C12A7:e- based cathodes	A. Post, et alter	11 <sup>th</sup> EASN Conference, On-line 1-3.05.2021
Performance comparison of LaB6 and C12A7:e- emitters for space electric propulsion cathodes	J. Toledo, et alter	11 <sup>th</sup> EASN Conference, On-line 1-3.05.2021
NEMESIS project progress status and achievements	A. Post, et alter	EPIC Workshop 2022, Cologne 4-6.04.2022
Novel approach to EP based on NH3 as propellant and on-board energy generation	J.F. Plaza et alter	EPIC Workshop 2022, Cologne 4-6.04.2022
A new heaterless plasma discharge (HPD) cathode	L. Conde, et alter	EPIC Workshop 2022, Cologne 4-6.04.2022
Physics and performance of the heaterless plasma discharge (HPD) cathode	L. Conde, et alter	COSPAR 2022, 16-24.04.2022 Athens
Performance analysis of several C12A7:e- based cathode devices with different design architectures and configuration	J. Toledo, et alter	8th SPC, Estoril 9-13.05.2022
Neutralizer design with flat C12A7:e- insert	M. Reitemeyer, et alter	8th SPC, Estoril 9-13.05.2022
Low power C12A7 hollow cathode characterization for small Hall thrusters	A. Guglielmi, et alter	37th IEPC, Boston 19-23.06.2022
C12A7:e- neutralizer operation with alternative propellants	M. Reitemeyer, et alter	37th IEPC, Boston 19-23.06.2022
Design and Operation of a Hollow Cathode with a C12A7:e- Insert in Comparison with a LaB6 Insert	D. Zschätzsch, et alter.	37th IEPC, Boston 19-23.06.2022
Comparison of C12A7 electride work function and surface composition by means of XPS, UPS and thermionic diode er	A. Gurciullo, et alter	37th IEPC, Boston 19-23.06.2022
Excellent performance of a C12A7:e- cold cathode based on charge coupling techniques	J.F. Plaza, et alter	37th IEPC, Boston 19-23.06.2022
Heaterless plasma discharge (HPD) cathode for electric propulsion applications	L. Conde, et alter	37th IEPC, Boston 19-23.06.2022
Neutralizers with planar C12A7:2e- inserts	M. Reitemeyer, et alter	C12A7:e- Workshop JLUUniversity, Giessen 04-05.10.2022
Development of a C12A7:2e- compatible hollow cathode neutralizer	D. Zschätzsch, et alter.	C12A7:e- Workshop JLUUniversity, Giessen 04-05.10.2022
Devices using C12A7:e- as electron emitter	A, Post et alter	C12A7:e- Workshop JLUUniversity, Giessen 04-05.10.2022
NEMESIS achievements: new cathode technology using C12A7:e- as electron emitter	A, Post et alter	12th EASN Inter. Conf., Barcelona 18-21.10.2022
Unbreakable, flexible and multipurpose cathode based on ceramic C12A7:e material deposited on special substrates	J.F. Plaza, et alter	12th EASN Inter. Conf., Barcelona 18-21.10.2022
NH3 fuelled space EP systems using C12A7:e- as electron emitter.	J.F. Plaza, et alter	12th EASN Inter. Conf., Barcelona 18-21.10.2022



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

Wide know how generated through project teams members and dissemination actions



POLITÉCNICA



## PEER REVIEWED ARTICLES NEMESIS PROJECT

Title	Author	Peer reviewed article
Ion thrusters for electric propulsion – scientific issues developing a niche technology into a game changer	K. Holste, et alt	
Key design and operation factors for high performance of C12A7:e- based cathodes	A. Post, et alt.	<a href="https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012092">https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012092</a>
Performance comparison of LaB6 and C12A7:e- emitters for space electric propulsion cathodes	J. Toledo, et alt.	<a href="https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012093">https://iopscience.iop.org/article/10.1088/1757-899X/1226/1/012093</a>
Identifying different electronic transport mechanisms in nanoporous inorganic electrides – a combined study using Hall measurements and electron paramagnetic resonance spectroscopy	J.K. Dinter, et alt.	Journal of Materials Chemistry
Ammonia fuelled space electric propulsion systems using C12A7:e- electride as electron emitter	J.F. Plaza, et alt.	Just accepted for publication in Journal of Physics: Conference Series



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

## CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on **projects awarded** and 2 **industrial collaboration agreements** signed

TRL4 achieved and technological understanding reached to proceed to qualify higher levels



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



Three follow on **projects awarded** and 2 **industrial collaboration** agreements signed

## 3 projects awarded financing

1. ATARI: Construction and test of C12A7:e- neutralizers in planar geometry.  
DLR funding.
2. ZEROeVTOL: Air transport decarbonization and autonomy increase for UAV vehicles.  
Next Generation funds managed by Spanish Administration.
3. HIDRAM: Green Hydrogen storage through Green Ammonia generation for naval transport and industries.  
Next Generation funds managed by Spanish Administration.



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM

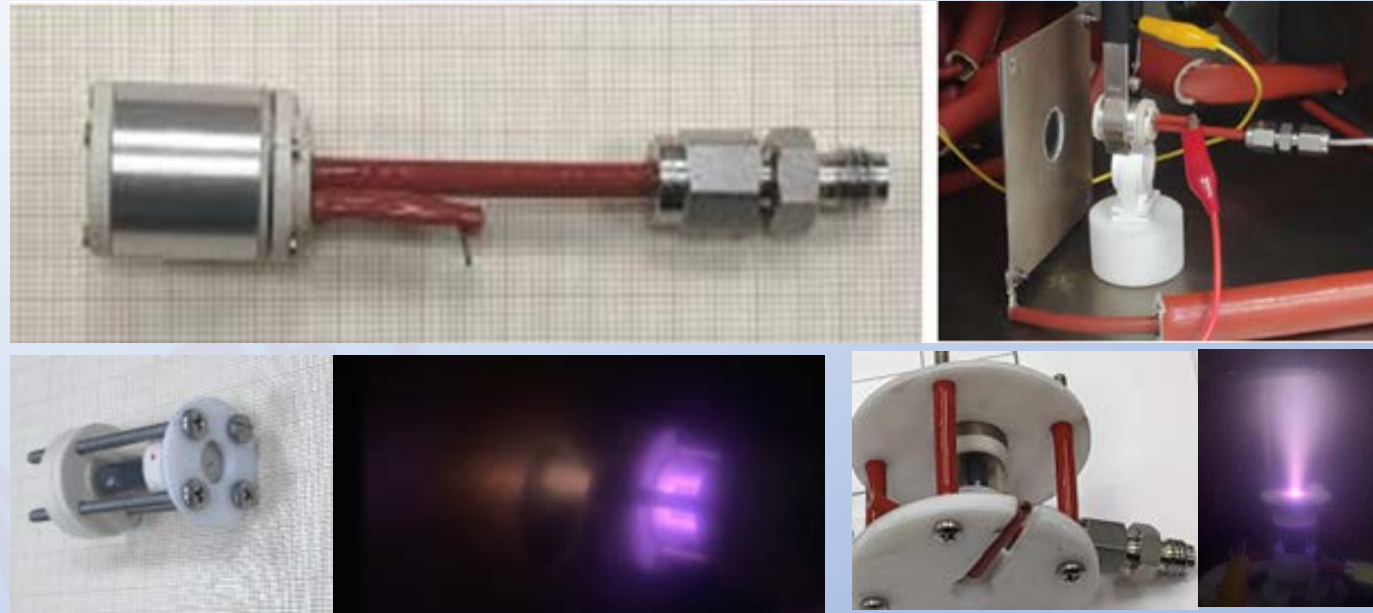


POLITÉCNICA



Three follow on **projects awarded** and 2 **industrial collaboration** agreements signed

Additionally, R&D on new configurations of C12A7:e- based cathodes is ongoing and will **continue beyond the NEMESIS project** thanks to the Collaboration Agreements signed with two European space industry companies.



New cathode design with ongoing development / test continuing beyond NEMESIS project





# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



## NEMESIS ACHIEVEMENTS HIGHLIGHTS SUMMARY

- **High quality material** locally produced from abundant precursors easy to store/operate
- **Deep research** carried out in **material characterization** and in derived key design rules
- Several engineering model prototypes developed, successfully tested with **Xe, Ar, Kr, I, and NH<sub>3</sub>**, coupled with **HET thrusters**, and reaching **high performance figures** of merit.
- Cumulated **experience of thousands of hours in operation** of C12A7:e- based cathodes
- **IP rights protected** for key inventions, grouped into 2 patents for operative convenience
- **Wide know how generated** through project teams members and dissemination actions
- Three follow on **projects awarded** and 2 **industrial collaboration agreements** signed

**TRL4 achieved and technological understanding reached to proceed to qualify higher levels**



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



**TRL4 achieved and technological understanding reached to proceed to qualify higher levels**

A new multi-propellant cathode technology has been matured up to TRL 4 for different designs and propellants in the NEMESIS project ...



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



**TRL4 achieved and technological understanding reached to proceed to qualify higher levels**

A new multi-propellant cathode technology has been matured up to TRL 4 for different designs and propellants in the NEMESIS project ...

... and is now ready to take over the place of old LaB<sub>6</sub> technology, and serve the European EP space industry providing and preserving its non-dependance.



# NEMESIS 2023 EPIC Workshop: NEMESIS project results summary

CONSORTIUM



POLITÉCNICA



THANK YOU

CONFIDENTIAL