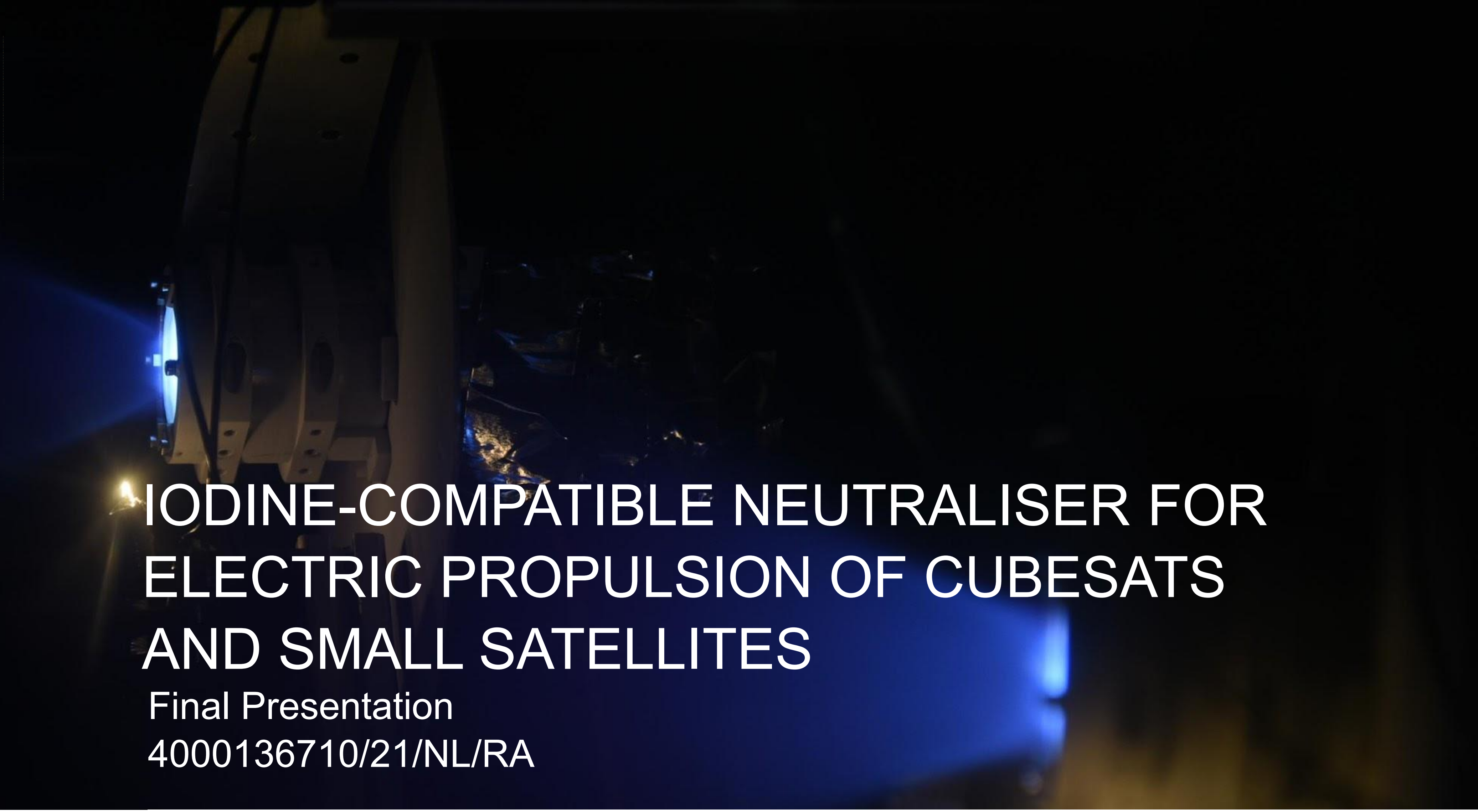

Laboratory for Enabling Technologies

IODINE-COMPATIBLE NEUTRALISER FOR ELECTRIC PROPULSION OF CUBESATS AND SMALL SATELLITES

Final Presentation

4000136710/21/NL/RA

DEFENCE AND SPACE

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LET
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Research on innovative propulsion systems

- usually ~4 PhD students and multiple master students researching for their thesis

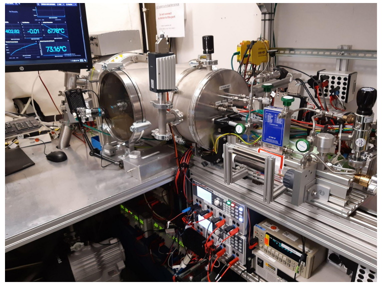
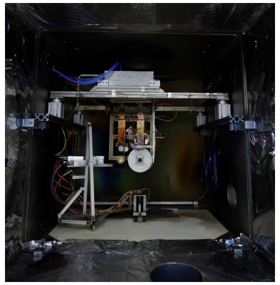
Range of vacuum facilities available

- Two laboratories with 5 test stands, up to 9000l
- Three vacuum chambers equipped to test with iodine

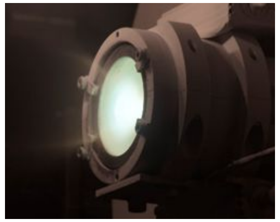
Portfolio

- 300 W thruster tested on Xenon, Krypton, Iodine, Argon, Water
- Development of a CubeSat propulsion unit with iodine
- Development of a kW-class thruster with iodine
- Development of noble gas hollow cathodes

➡ iodine compatible neutralizer is missing





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Iodine **co**mpatible **N**eutraliser (IcoN) for Electric Propulsion and Cubesats

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Key requirements:

- Iodine compatible cathode for a ~ 500 W propulsion system
- Design Lifetime > 1000 h
- Anode current: 1-1.5 A

Key success criteria:

- **100h endurance** test in spot mode using iodine as a propellant
- Total power **below 50 W** during **operation**
- Total power **below 150 W** during **ignition**
- Max. **1 mg/s** iodine consumption

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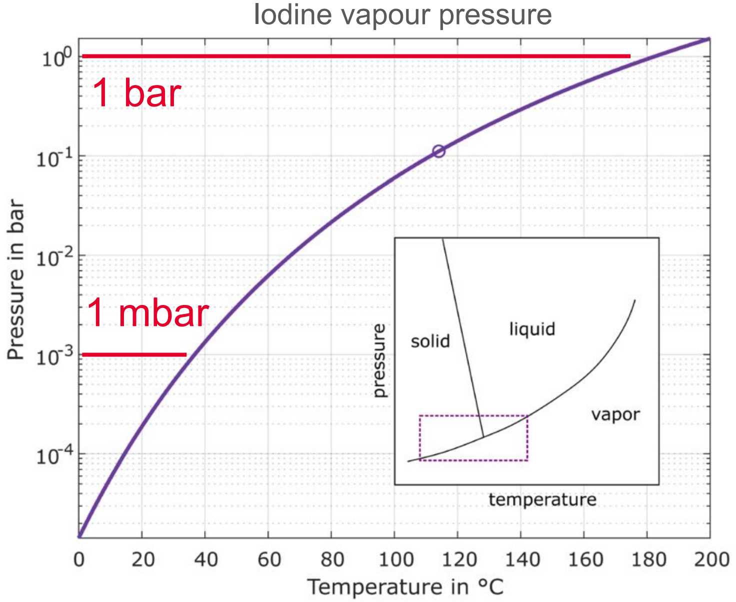
1. Introduction
2. **Literature Review**
3. Development and preliminary tests
4. IcoN CCN: Improvement of the iodine feed system
5. Test preparation and assembly
6. Test results
7. Post test analysis
8. Conclusion

Literature Review: Basics

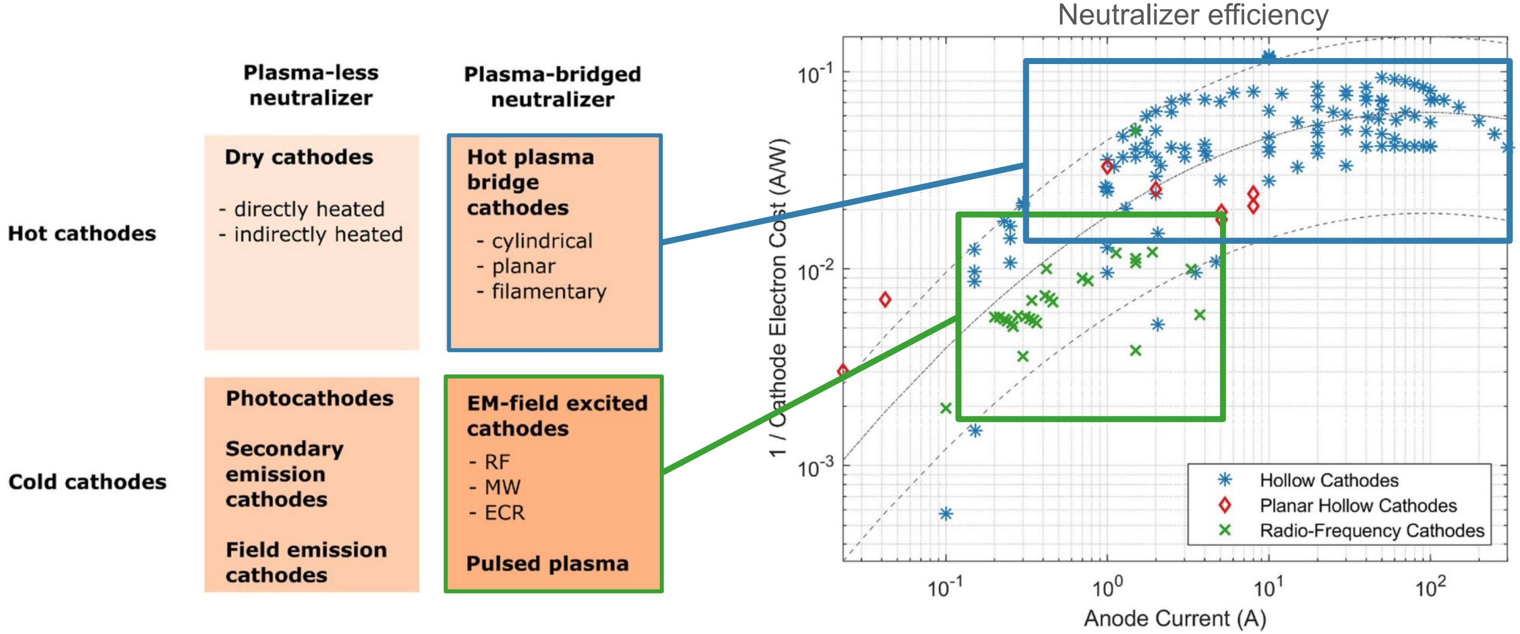
Iodine properties:

- 1 mbar to 1 bar at 20 - 200 °C
- **Solid**, high density storage
- High **mass**, **low ionization energy**
- However: **Very reactive**



Cathode types:

- Only **plasma-bridge neutralizer** fulfil requirements
- Only **hot** plasma bridge cathodes can deliver higher currents at **reasonable energies**



Source: Becke, P.S., Kottke, N.G., Vaupel, M. et al. Review on the current state of iodine compatible neutralizers. J Electr Propuls 3, 30 (2024). https://doi.org/10.1007/s44205-024-00093-y

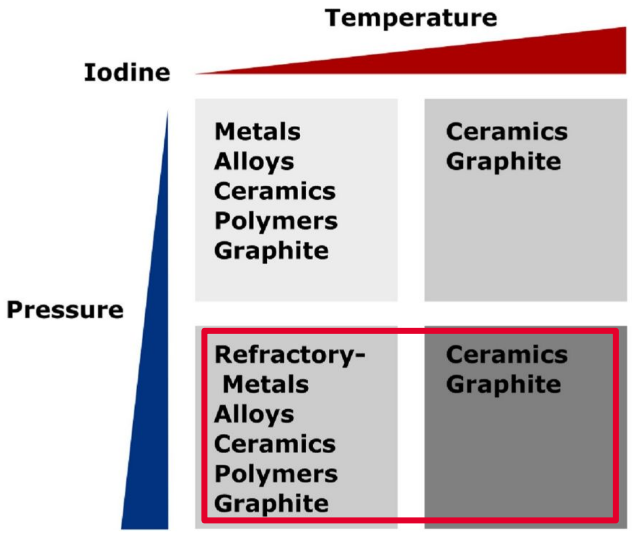
Literature Review: Material Compatibility

Structural materials:

- Iodine **compatibility** depends on the **environment**:

  ➡ **pressure** and **temperature**

- Ceramics and graphite survive worst conditions
- At lower temperatures refractory metals, Ni-alloys and polymers have acceptable performance



Hot Plasma Bridge Cathodes:

- Hollow/planar cathodes
- Require emitter to operate
- Only LaB_6 and C12A7 electride might be compatible with iodine according to literature

Emitter types

Metal based	**Pure metals** Tungsten Tantalum Rhenium	**Metal alloys** WL20 WC20 WTh20 WY20
Mixed	**Compounds** LaB6 C12A7:e- Cermet	**Dispenser** BaO SrO CaO Al2O3

Source: Becke, P.S., Kottke, N.G., Vaupel, M. et al. Review on the current state of iodine compatible neutralizers. J Electr Propuls 3, 30 (2024). https://doi.org/10.1007/s44205-024-00093-y

Literature Review: Iodine Cathode Tests

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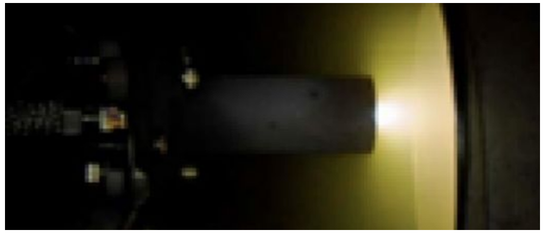
Testing Results from the literature:
- All emitter materials containing **metals** are **failing**:
  - WL20, BaO-Sc.-W, BCA
- Results for **LaB_6** were not published
- **C12A7 electride** has the **potential** to work, but tends to **melt**
- No further materials have been tested

- **RF neutralizers** up to 0.3 A have been tested

Damage to dispenser emitter

Cathode operating with iodine on C12A7 electride



Author	Emitter	Duration	Comment
Szabo (2012)	LaB_6	1h	Unknown result
Rand (2014)	C12A7:e-	20h	Emitter molten
Benavides (2018)	BCA	n.r.	Failure: Emitter depletion
Taillefer (2018)	BCA	n.r.	Failure: Emitter depletion
Thompson (2019)	BaO-Sc.-W	72h	Failure: Emitter depletion
Hua (2022)	C12A7:e-	0.5h	Emitter molten
Guglielmi (2022)	C12A7:e-	n.r.	Failure, reason unknown
Reitemeyer (2022)	C12A7:e-	2.75h	Success at low currents
Kottke (2023)	WL20	2.4h	Failure

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Source: Becke, P.S., Kottke, N.G., Vaupel, M. et al. Review on the current state of iodine compatible neutralizers. J Electr Propuls 3, 30 (2024). https://doi.org/10.1007/s44205-024-00093-y

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Design baseline

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Hot Planar Plasma Bridge Neutralizer v1

Based on Hollow Cathode legacy:

- Emitter materials: **LaB_6** and **C12A7** electride
- Cathode type: **Planar Hollow Cathode**
- Ignition: **Heater**
- Structural Materials: **Graphite, Ceramics, Refractory Metals, Stainless Steel**

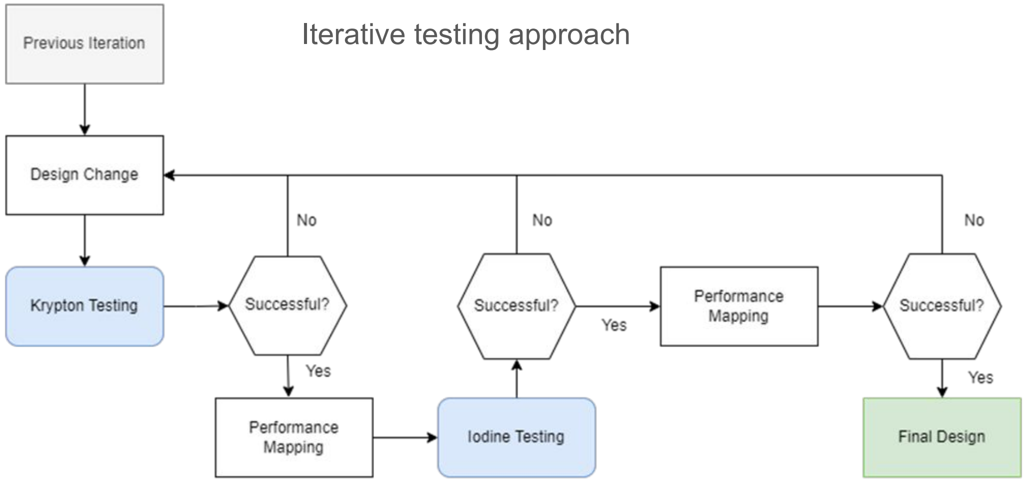
Design Philosophy: **Rapid Testing**

- Only a **few sources** in the literature exist
- Simulations are very complex, no useful design decisions
- Testing conditions are close to the limits of material parameters

➡ Design decisions from previous experimental data

➡ each failed test should contain new information to improve the design

Iterative testing approach



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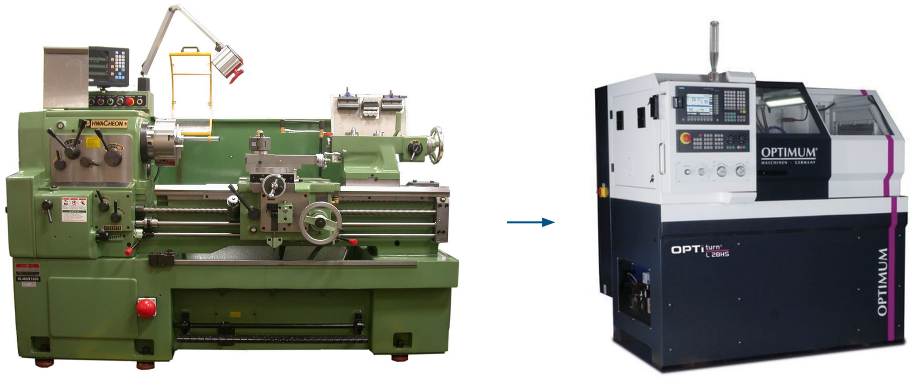
On-Site manufacturing enables rapid development

Overview of the Production Processes.

Lathing:

- Can be done by ourselves on the same day
- A CNC lathe has been procured and is used to machine small parts
- Extensive experience with cathode parts



Picture of a lathe and the CNC lathe.

Spot welding:

- Can be done by ourselves on the same day
- Extensive experience with cathode parts

Glueing:

- Insulating ceramic glue and conductive graphite glue
- Extensive experience with the process of glueing the cathode parts

Sintering:

- Production of the C12A7 emitter material is done by **Fraunhofer IKTS** in Dresden

Picture of a spot welder.

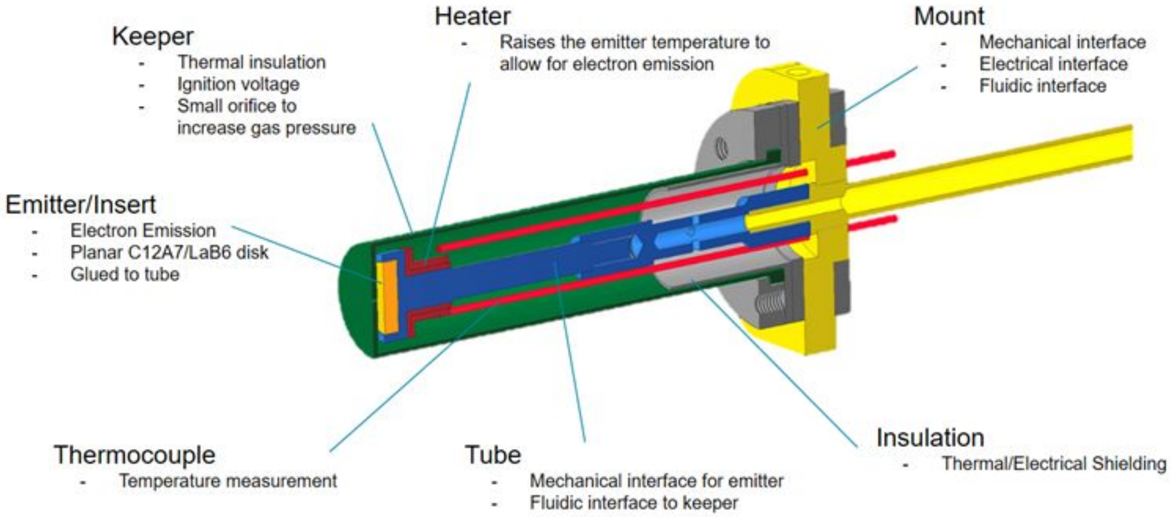
Design baseline

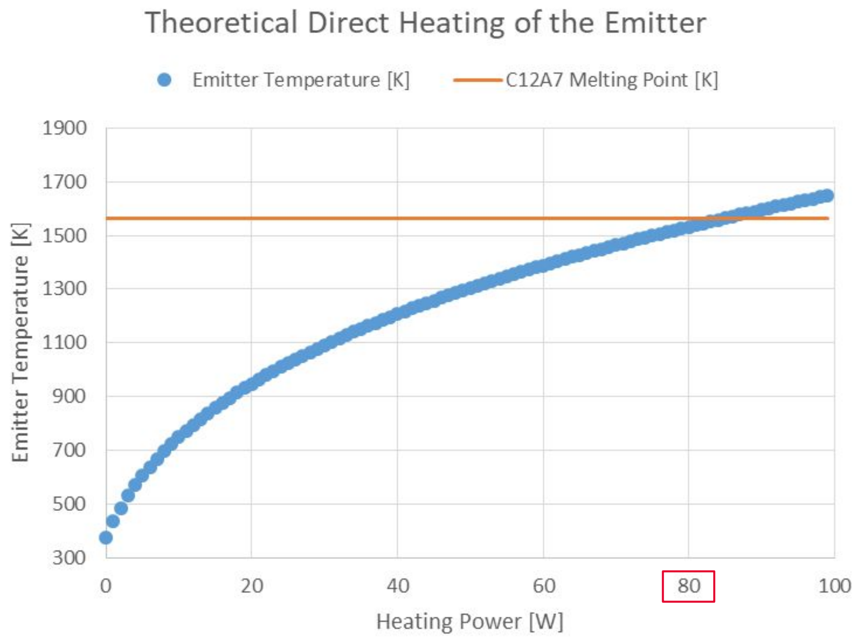
Laboratory for Enabling Technologies

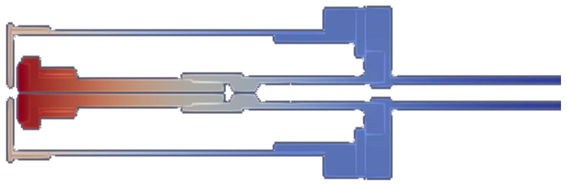
Hot Planar Plasma Bridge Neutralizer v1

First C12A7 electride prototype tested in our laboratory:

- Tests use krypton to characterize and improve the design
- Emitter is mounted with a clamp to the tube
- The noble gas is fed through holes in the mount
- Thermal simulations to define maximum heating power







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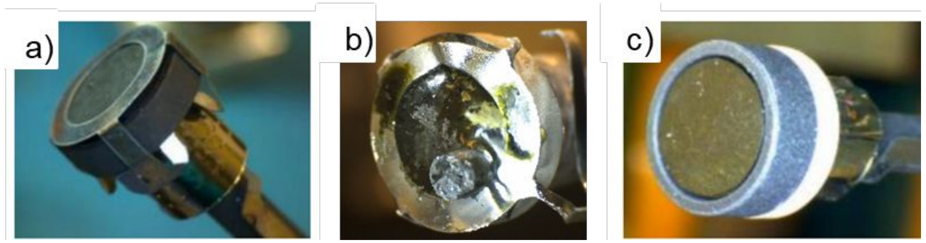
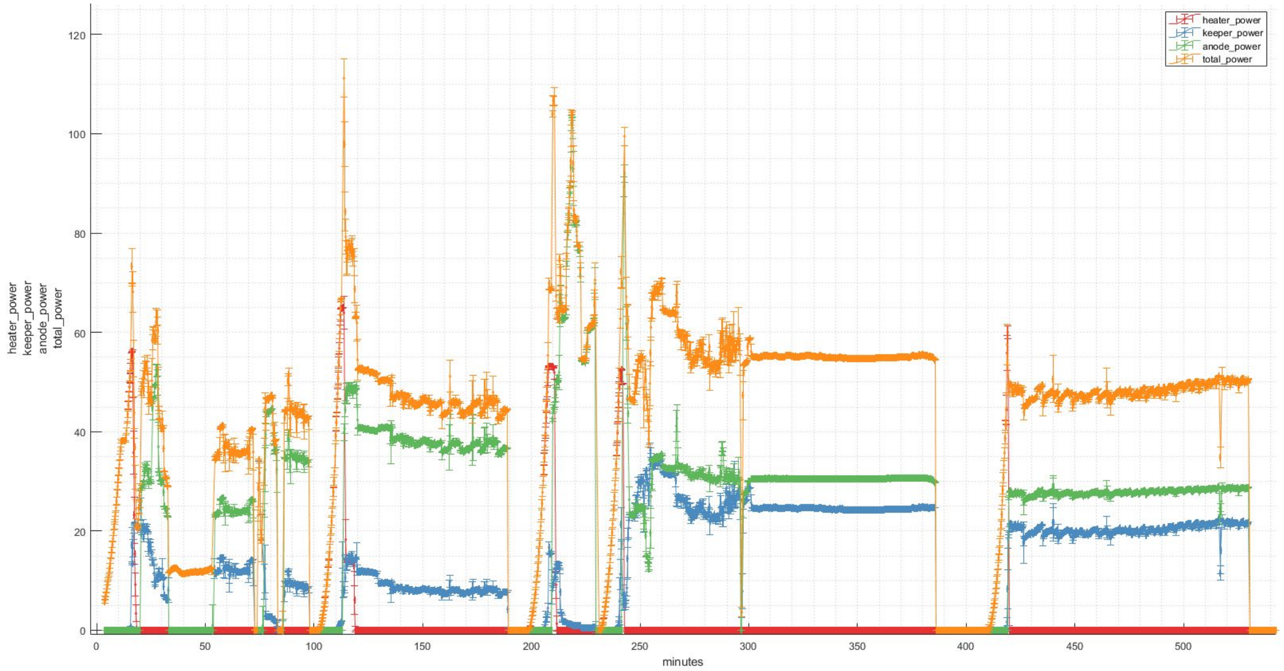
Testing of first cathode version with krypton

Hot Planar Plasma Bridge Neutralizer v1

- Ignition is hard to achieve, discharge is unstable
- Emitter is molten after test and refractory metal clamps are damaged (b)

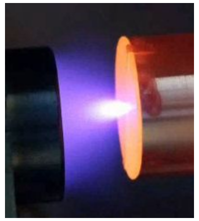
➡ Emitter is no longer clamped but glued with graphite glue (c)





Unstable

Stable



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Sudden Heater Failures: Thermal simulations

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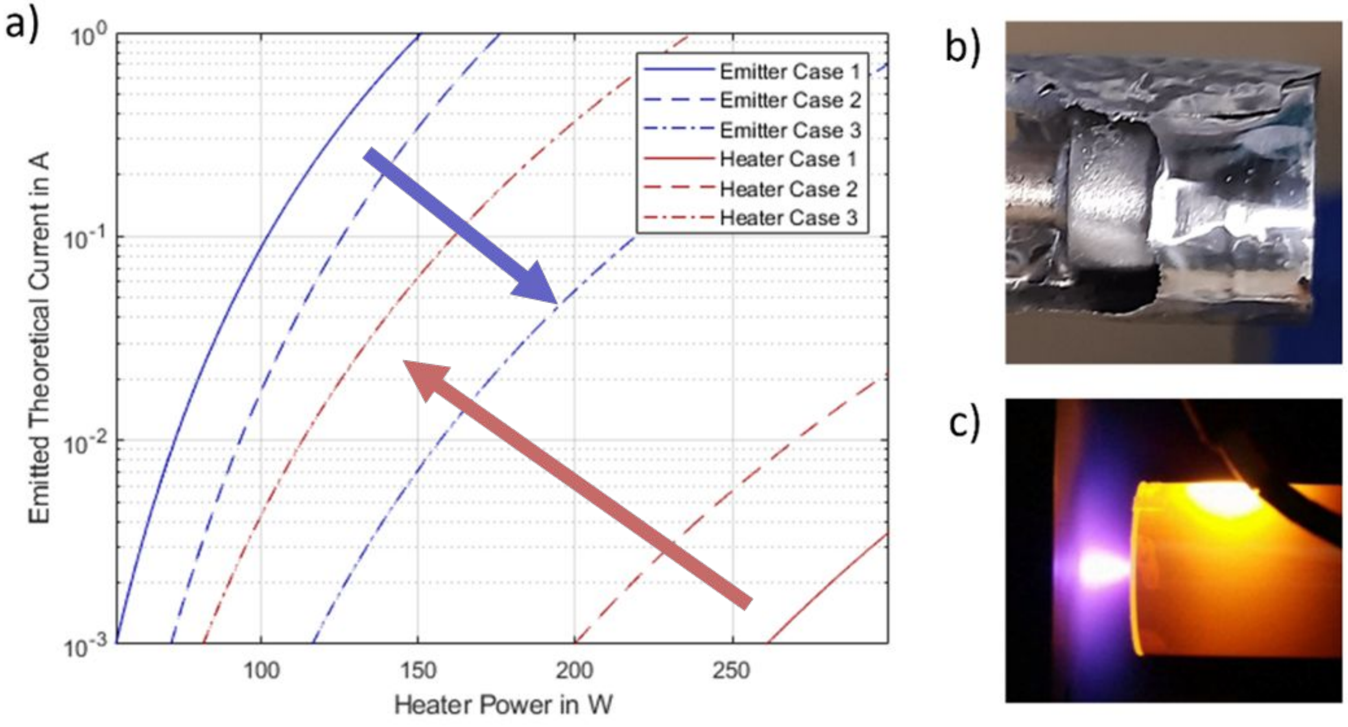
Ignition of the plasma to the heater

While using a heater in the planar cathode:

- Side of the cathode gets **hot** during discharge (c)
- **Molten insulation** found after test (b)
- **Thermal simulation** showed that it was possible the **discharge** actually started at the **heater** (a)

➡ Solution: Electrical insulation inside the keeper (except front)



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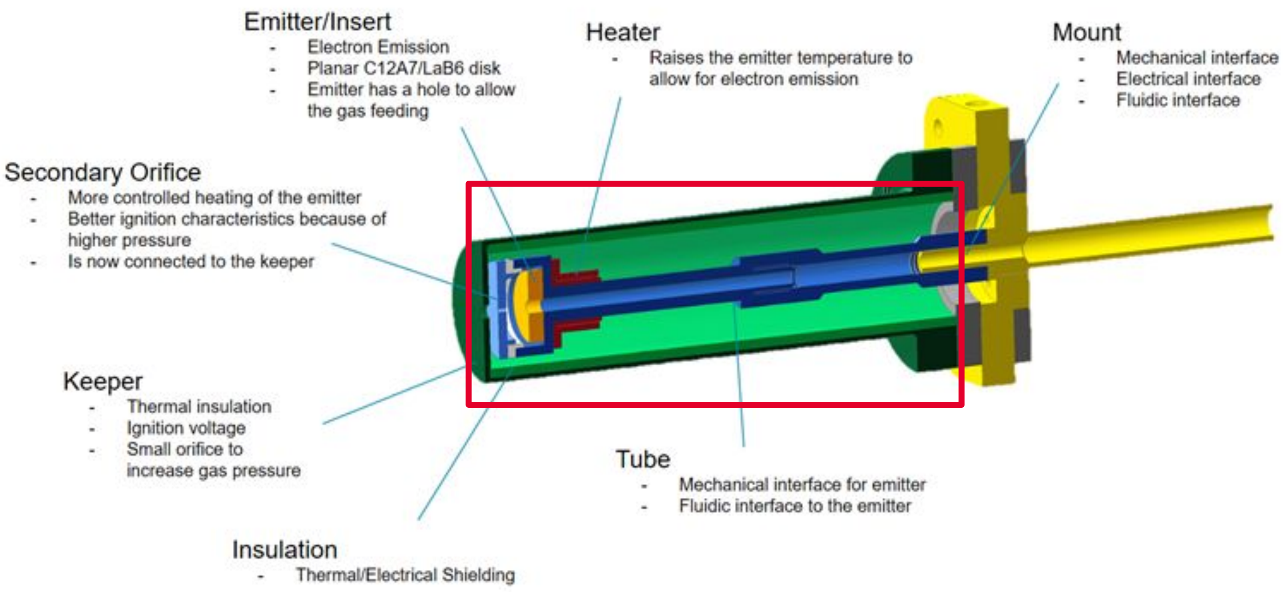
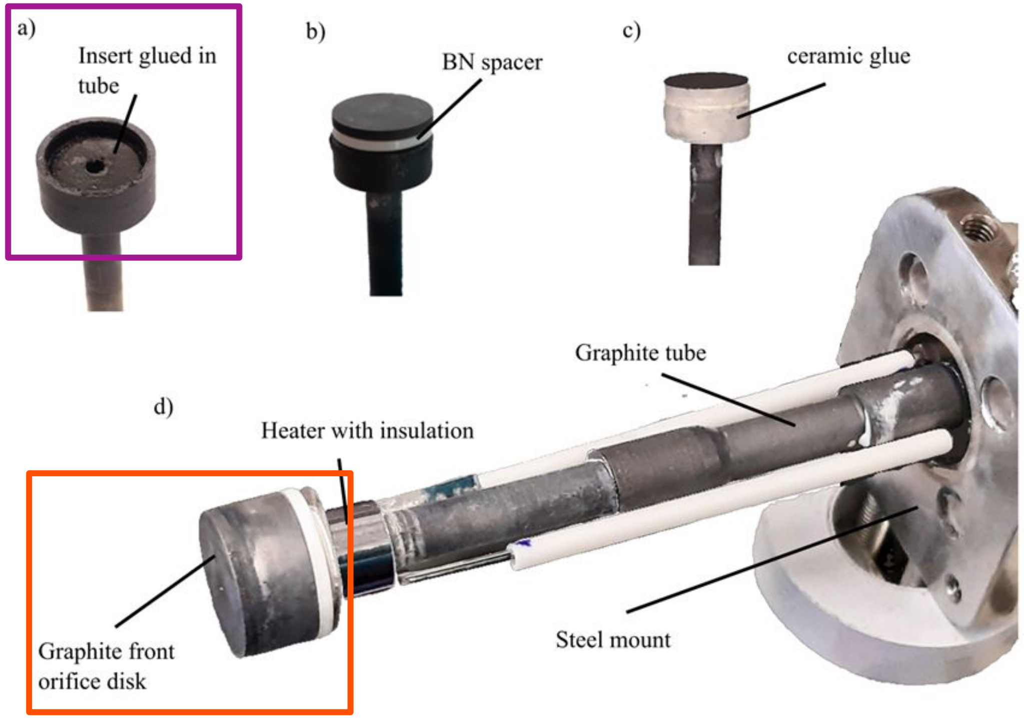
Planar cathode v2

Improvements of the design based on testing results

- Insulation inside keeper was added to prevent ignition to the heater
- A secondary orifice was added in front of the emitter to reduce thermal losses
- The emitter is glued inside the graphite tube





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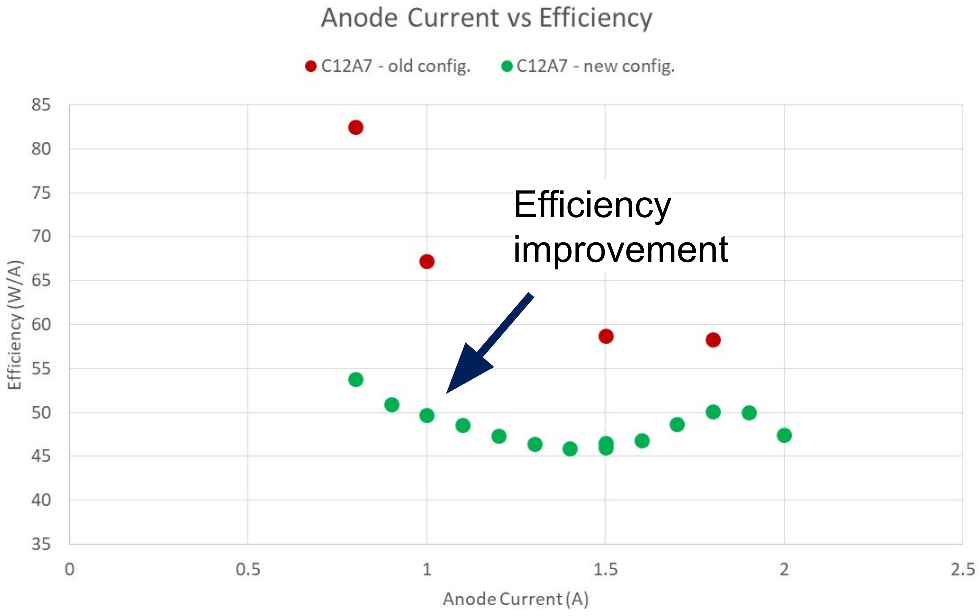
Further improvements

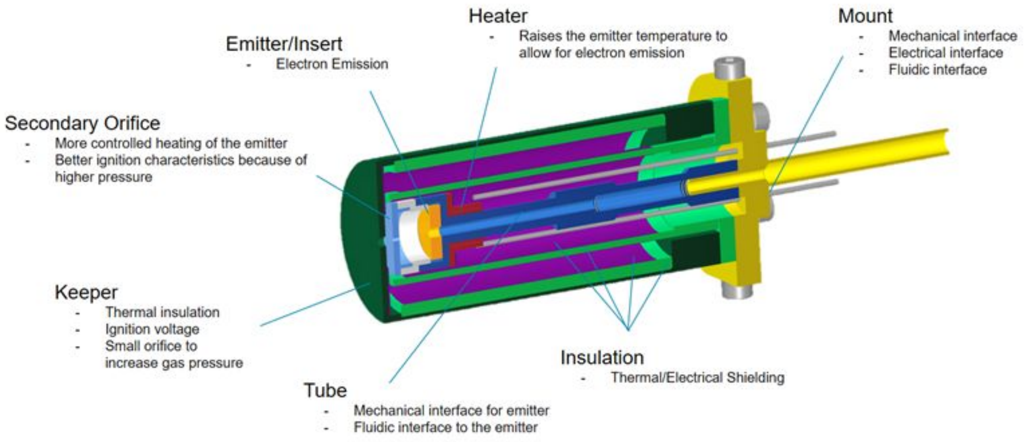
Testing of the Hot Planar Plasma Bridge Neutralizer v2

- **Ignition** works better
- **Less power** required to operate
- Emitter melting is prevented



Further improvements: Hot Planar Plasma Bridge Neutralizer v3

- Added **more insulation** to prevent thermal losses
- **Parameter studies** on orifice diameter and spacing
- Added **dual feeding**:
  Krypton and Iodine can be used simultaneously

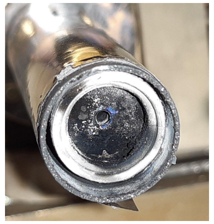


Preliminary Iodine Testing

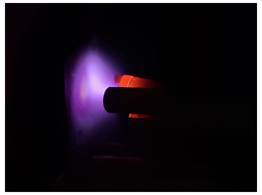
Testing of the Hot Planar Plasma Bridge Neutralizer v3

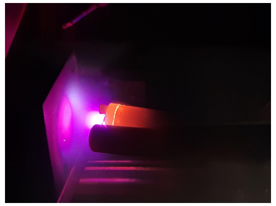
- **Ignition** with krypton
- **Transition** to iodine
- Different discharge parameters with iodine
- Tests ends after **15 minutes** because cathode front is blown-off
- Feeding **pressure run-away** suspected for failure

Before



After





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Feeding block

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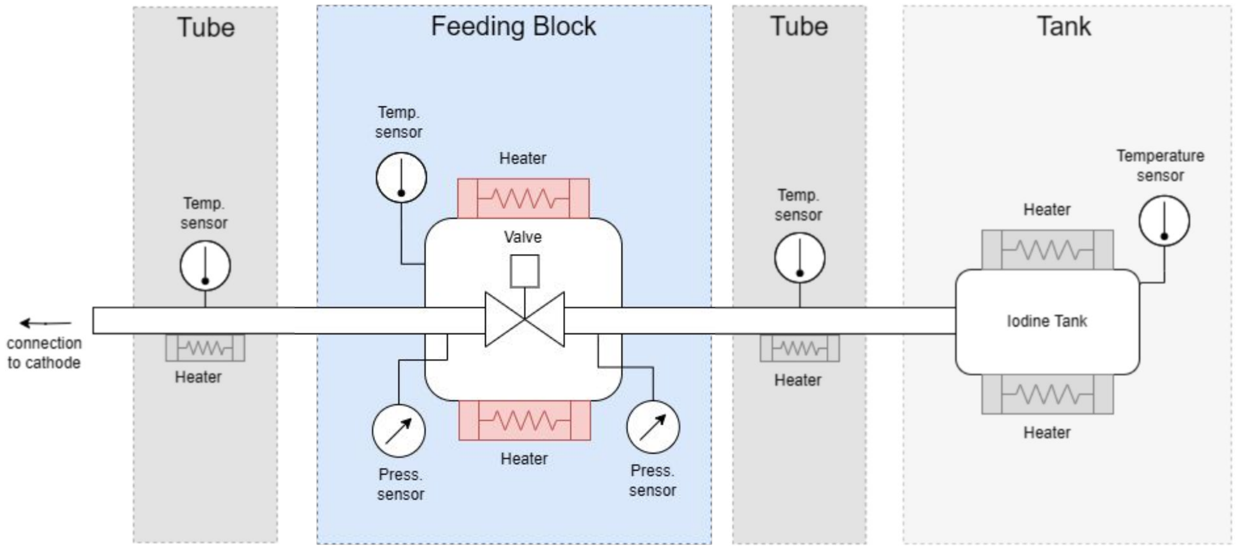
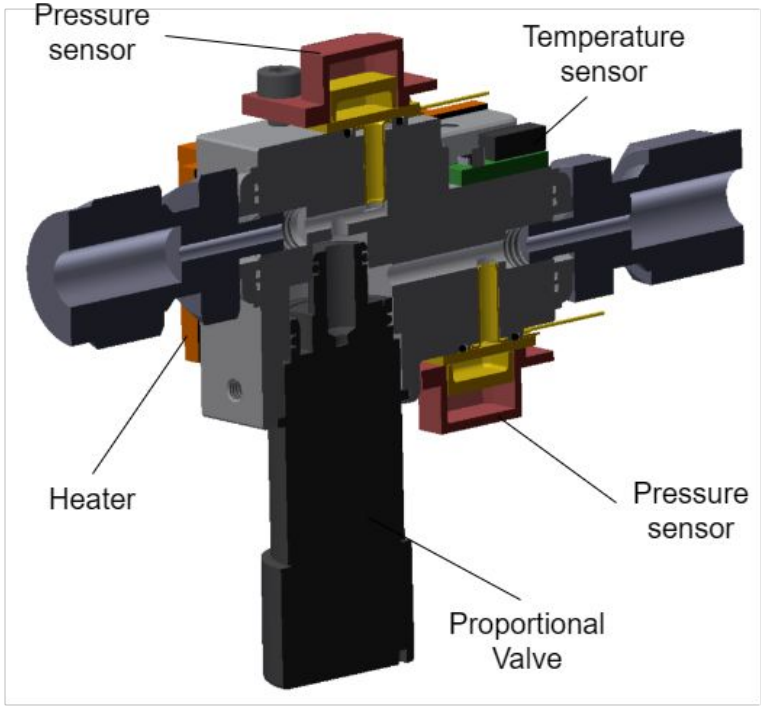
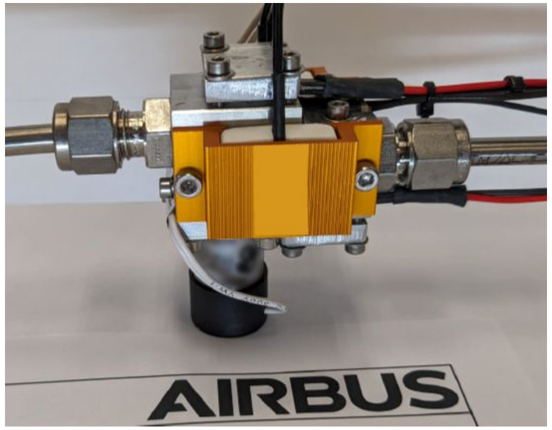
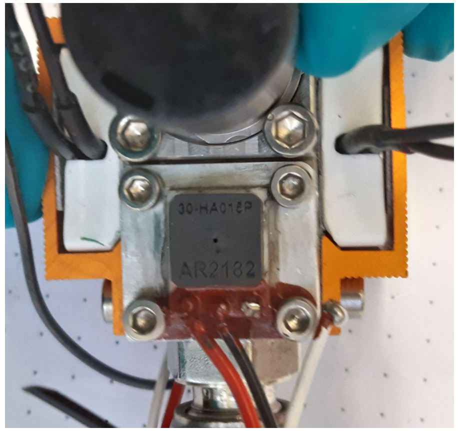
Redesign of the iodine feeding

- In the previous tests the flowrate could only be controlled by the tank temperature
  - Very slow reaction time
- A new feeding block was developed to control the iodine flow with a proportional valve









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Feeding block: Difficulties

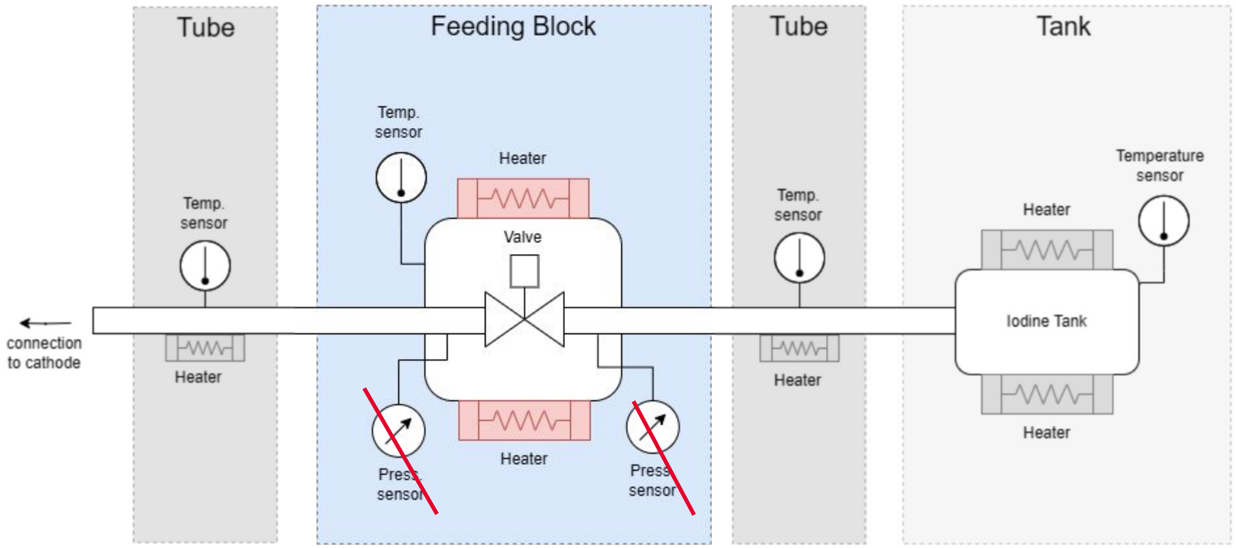
Detailed feeding design

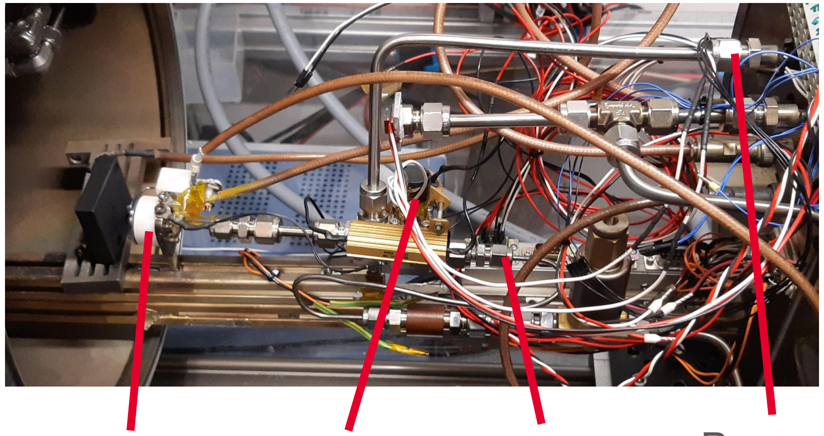
Problem:

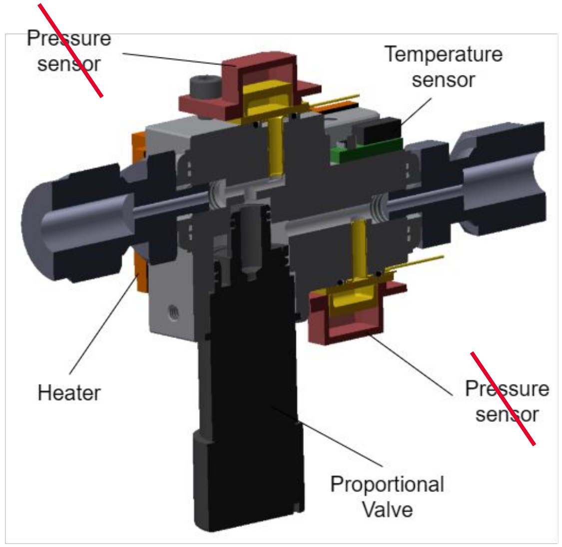
- Pressure sensor did not survive iodine environment

Solution:

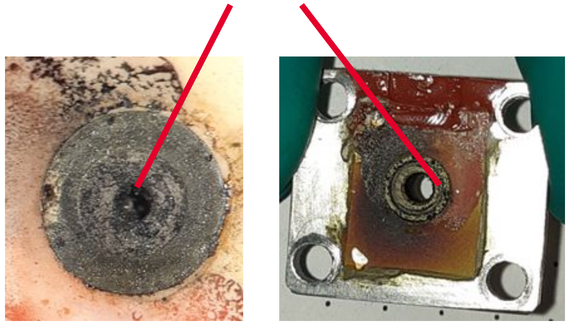
- Calibrate mass flow and valve performance with krypton







Corroded Membrane



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Feeding block: Measuring the performance of the prop. valve

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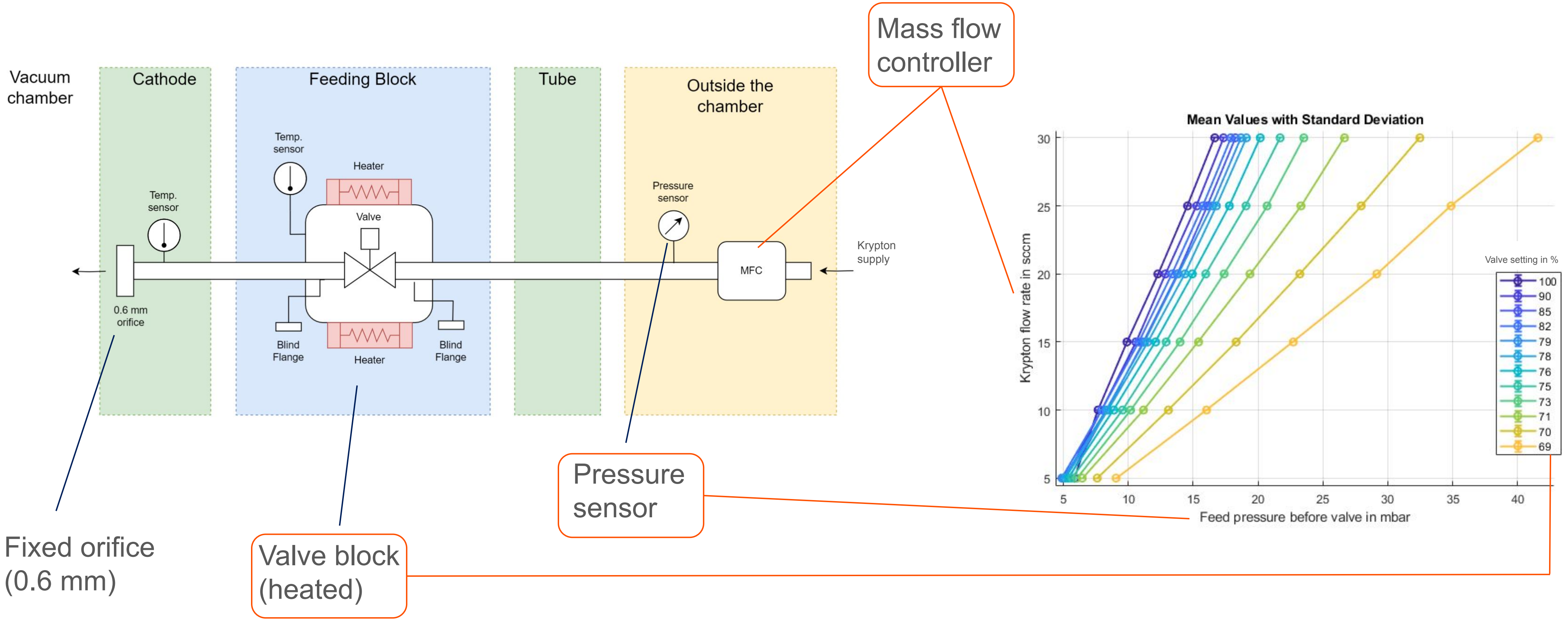
Measuring the ratio of pressure to mass flow for different valve settings



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Feeding block: Measuring the performance of the prop. valve

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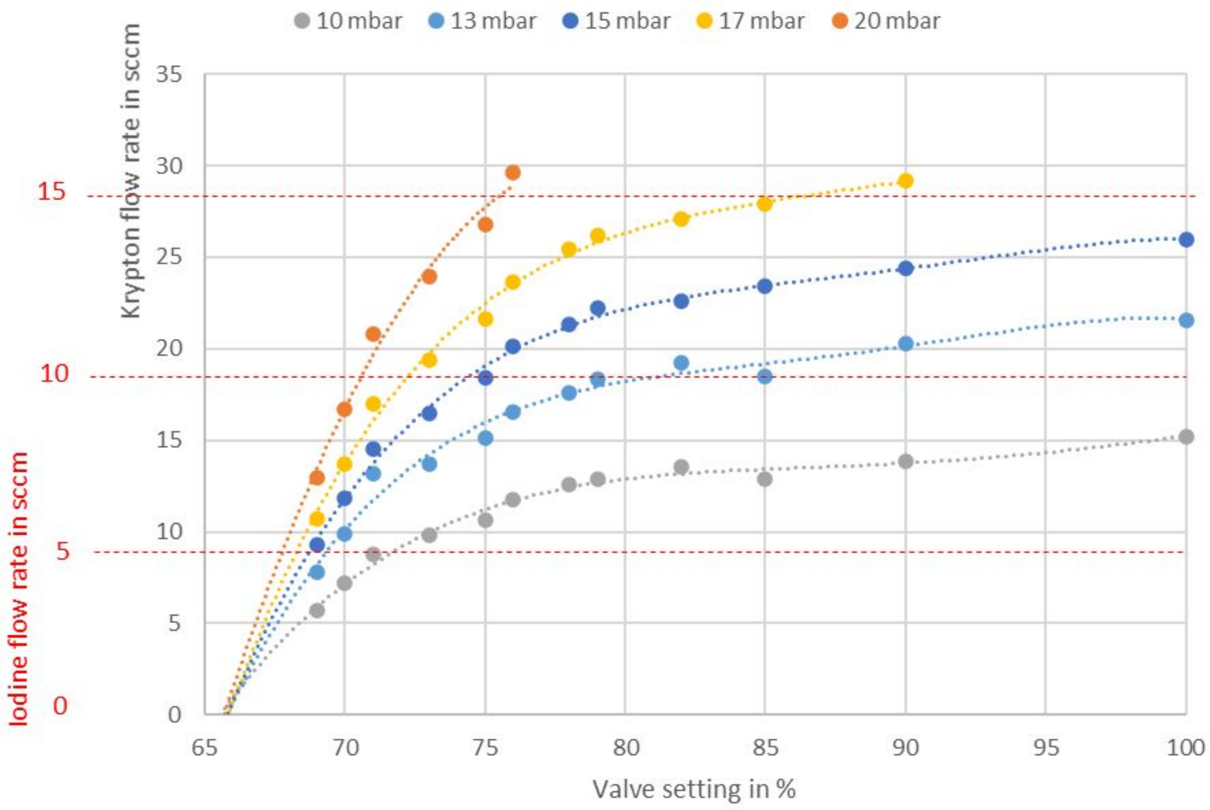
Calculating iodine performance

- Results allow to set a fixed iodine tank temperature (see below)
- Setting the flow rate can be done with the prop. valve
- Unknowns: Iodine might dissociate (I_2 -> 2I), doubling the pressure

Iodine flow rate	Iodine pressure	Iodine tank temperature
5 sccm	10 mbar	67.15 °C
10 sccm	13 mbar	71.36 °C
15 sccm	17 mbar	75.85 °C
20 sccm	20 mbar	78.67 °C



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Feeding block: Measuring the performance of the prop. valve

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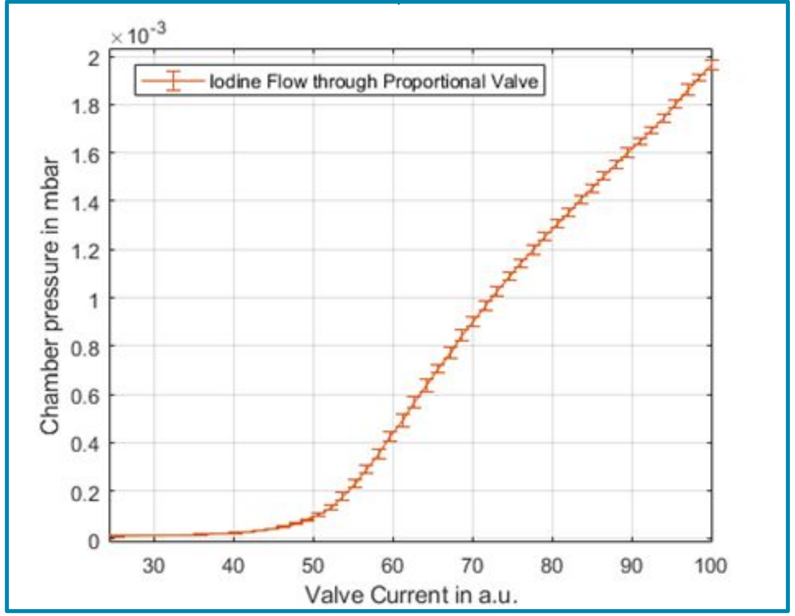
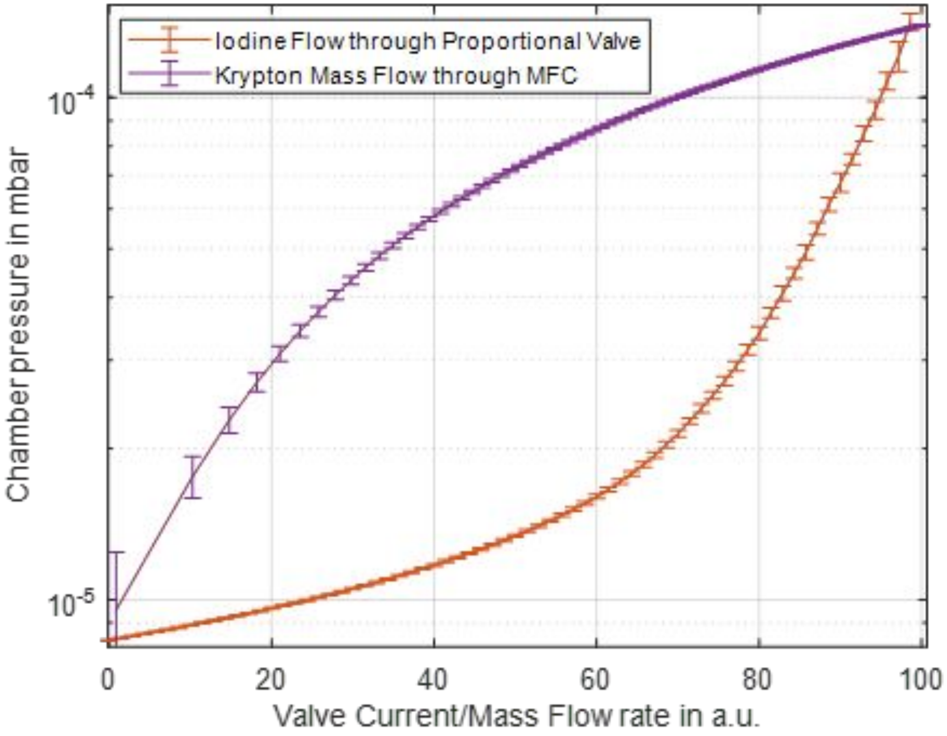
Measuring iodine performance

- Comparing the corrected chamber pressure:
  - krypton flow with a mass flow controller
  - Iodine flow with a proportional valve



- Same range of mass flow can be controlled:



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Testing facility

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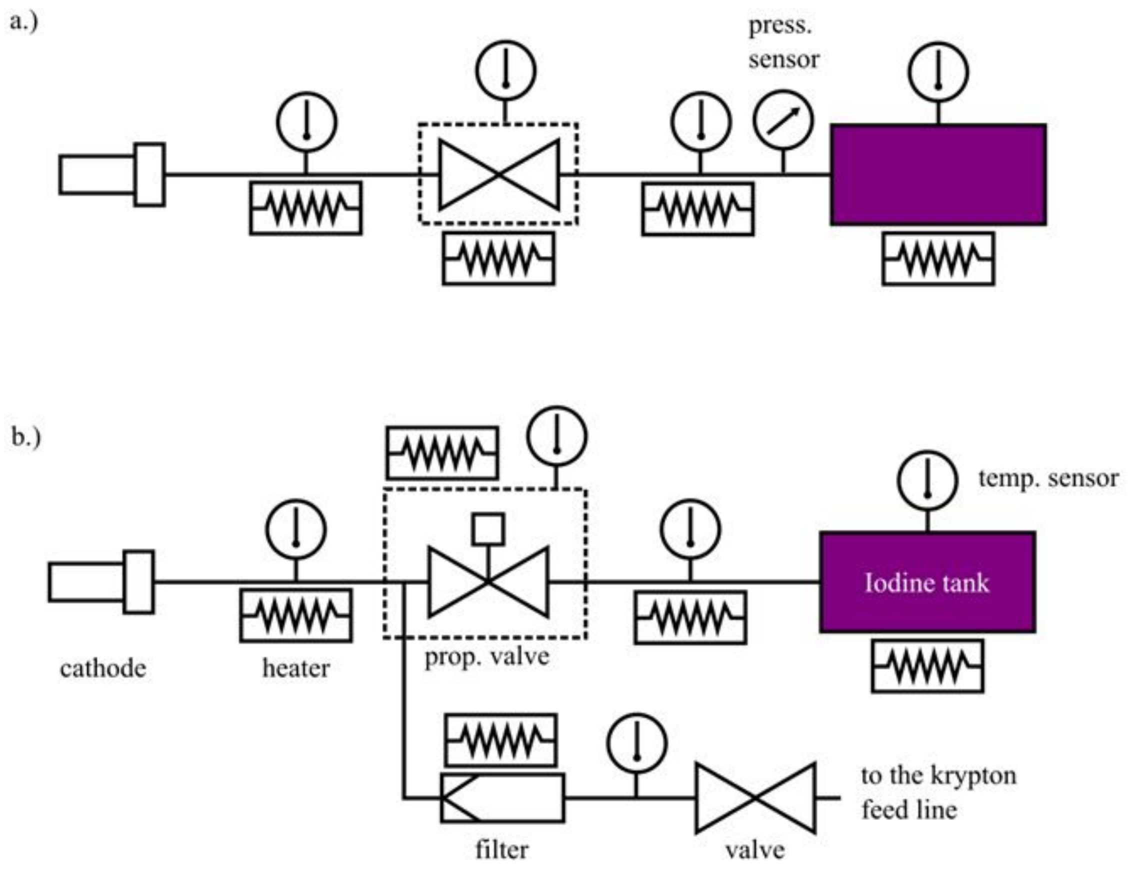
Feed system

- First cathode generations had a single feeding: krypton or iodine
- Later a dual feeding was introduced, allowing separate testing of krypton and iodine without venting
- Proportional valve for the iodine feeding was added later during the CCN
- The krypton feed system uses an oxygen filter to prevent the emitter from being poisoned



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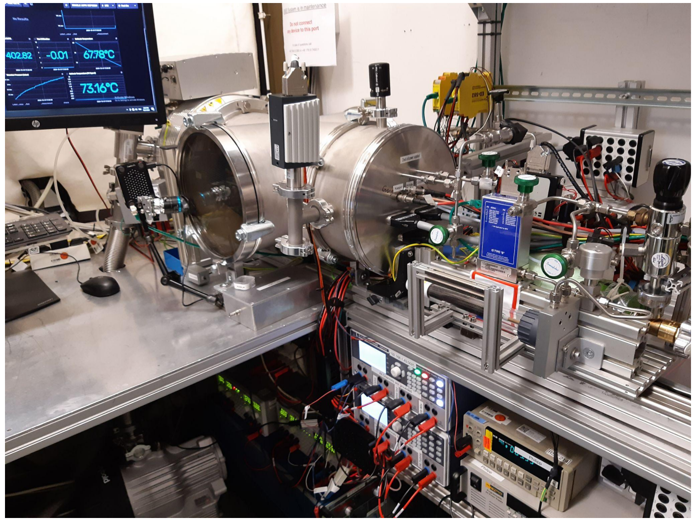
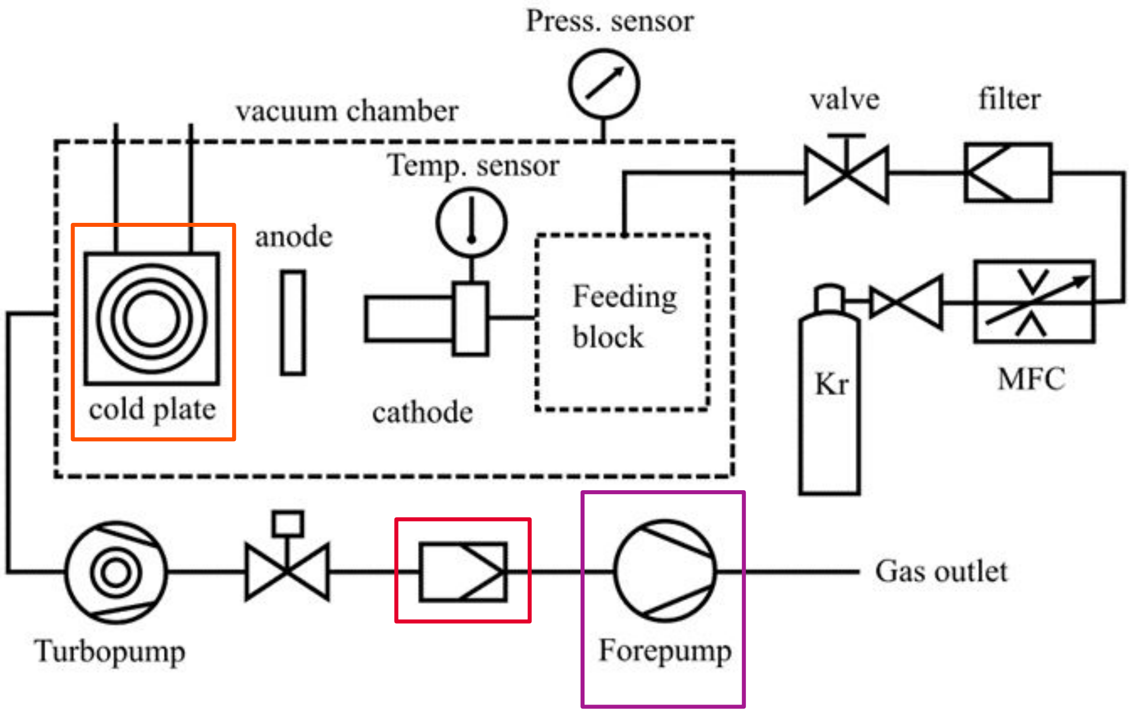
Testing facility

Pumping System

- Two-stage pumping system:
  - Turbomolecular pump
  - Forestage pump
- Testing had to be paused due to forestage pump failures during preliminary iodine tests

➡ A Ceramic filter, nitrogen purging and a cold plate were installed to solve this problem





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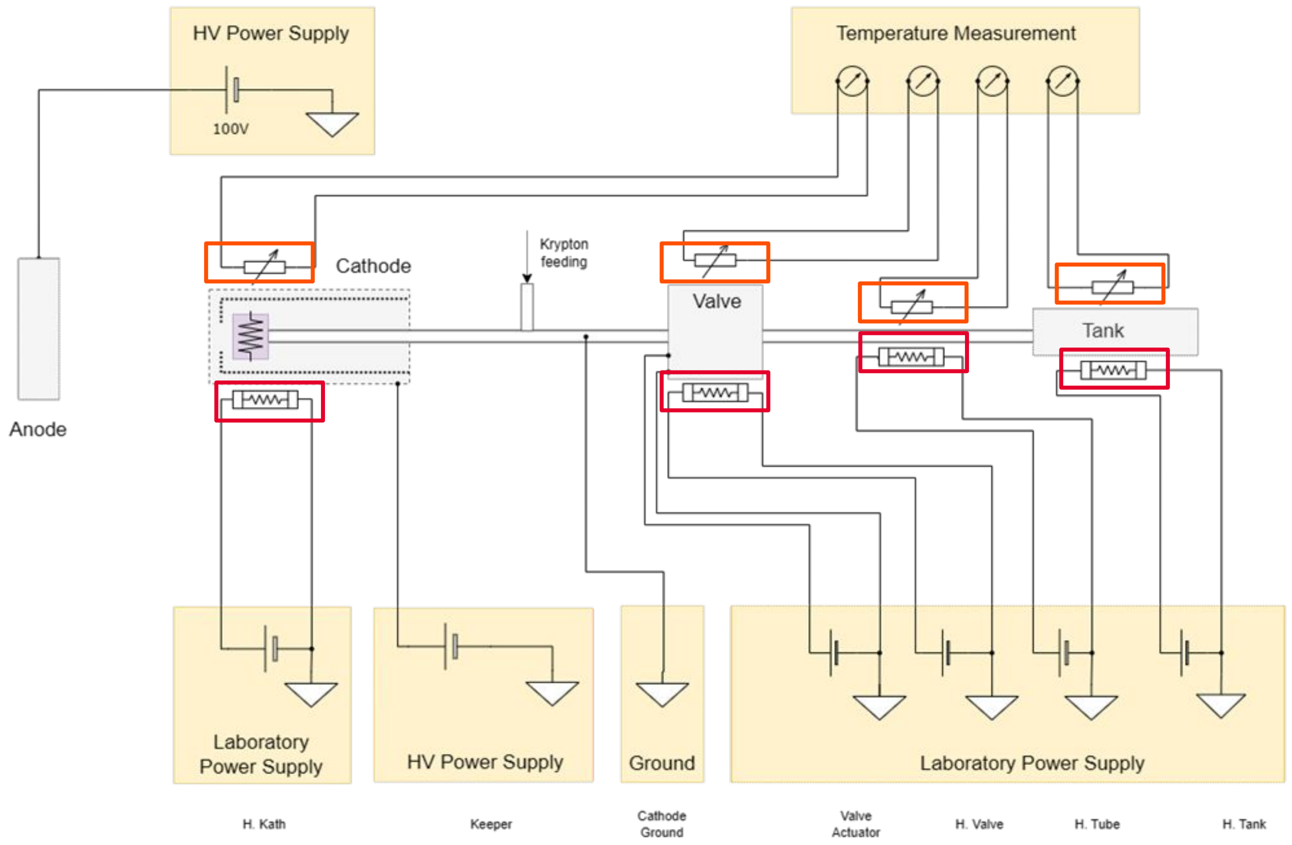
Testing facility

Electrical Setup

- Heaters and temperature sensors are placed along the tubing keep a temperature of 130° C to prevent iodine condensation
- To ignite the cathode, the keeper and the anode can be set to 500 V
- The cathode emitter is connected to ground

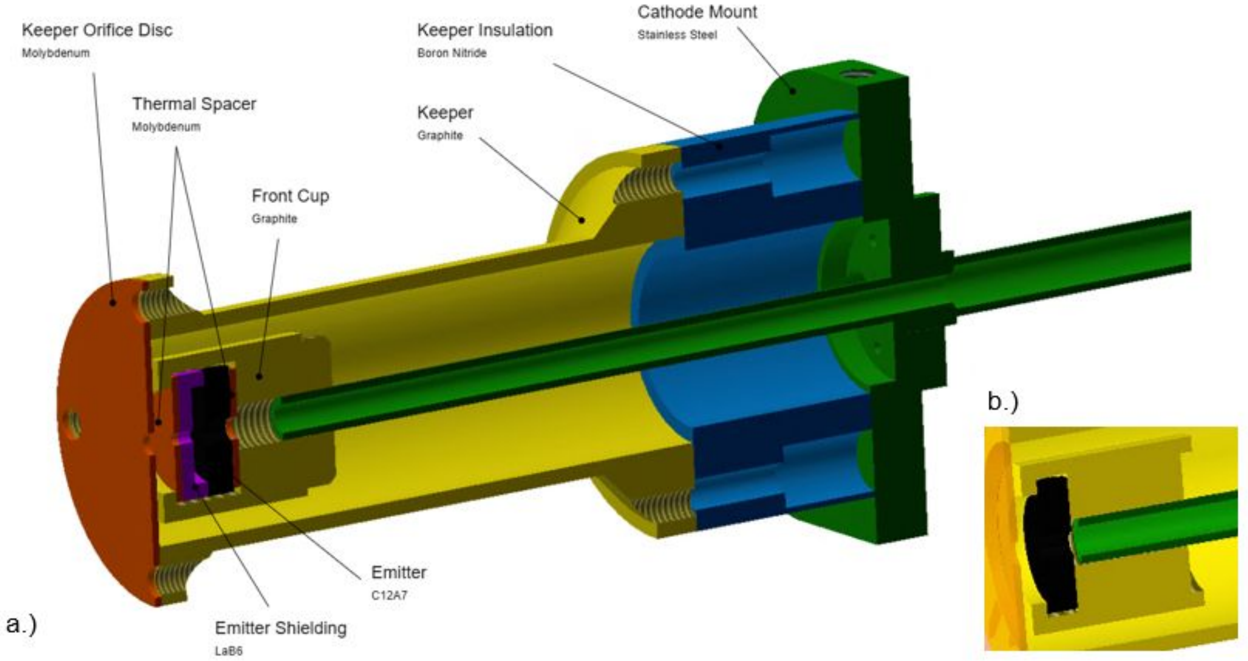
- During the extension, cathode heaterless ignition was tested and successfully implemented, removing issues with heater failure



Further cathode improvements during the extension

Hot Planar Plasma Bridge Neutralizer v4

- Two versions: With (a) and without (b) secondary orifice
- Heaterless ignition
- Emitter is mounted via a **screwable** graphite cup
- Three emitter materials have been tested in total:
  - C12A7 type A
  - C12A7 type B
  - LaB_6



Test preparation

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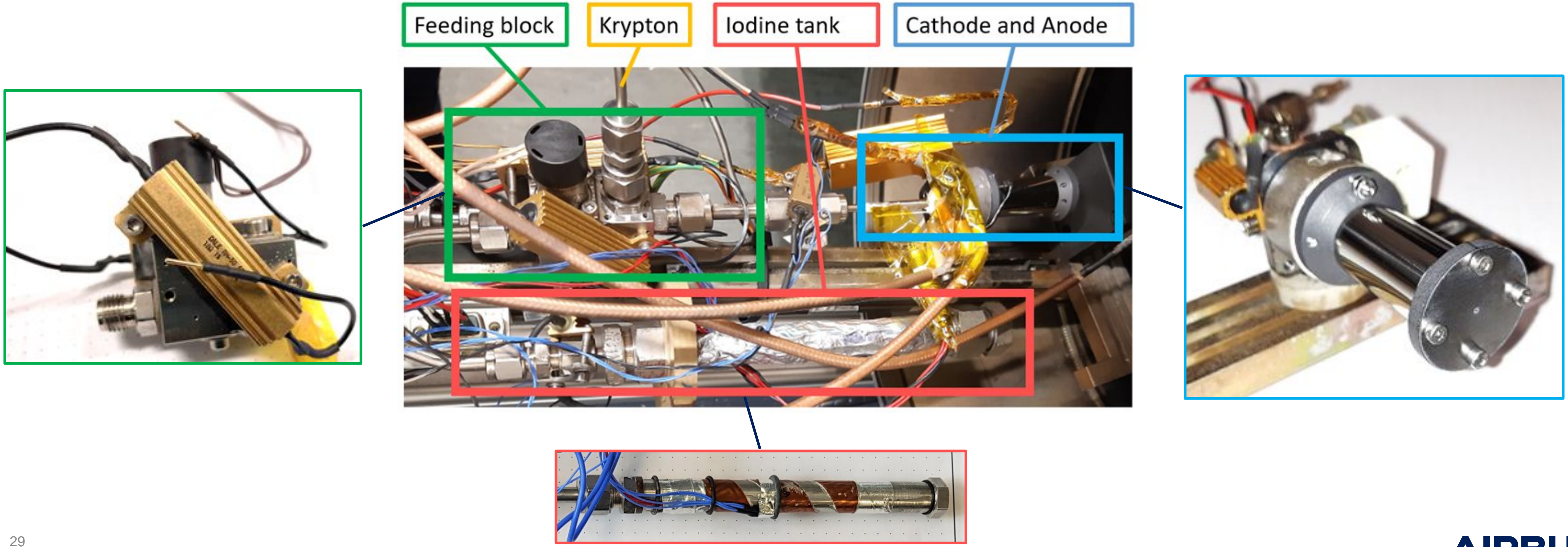
Cathode and feed system assembly

- All components are assembled and integrated in the test facility



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Preliminary Tests

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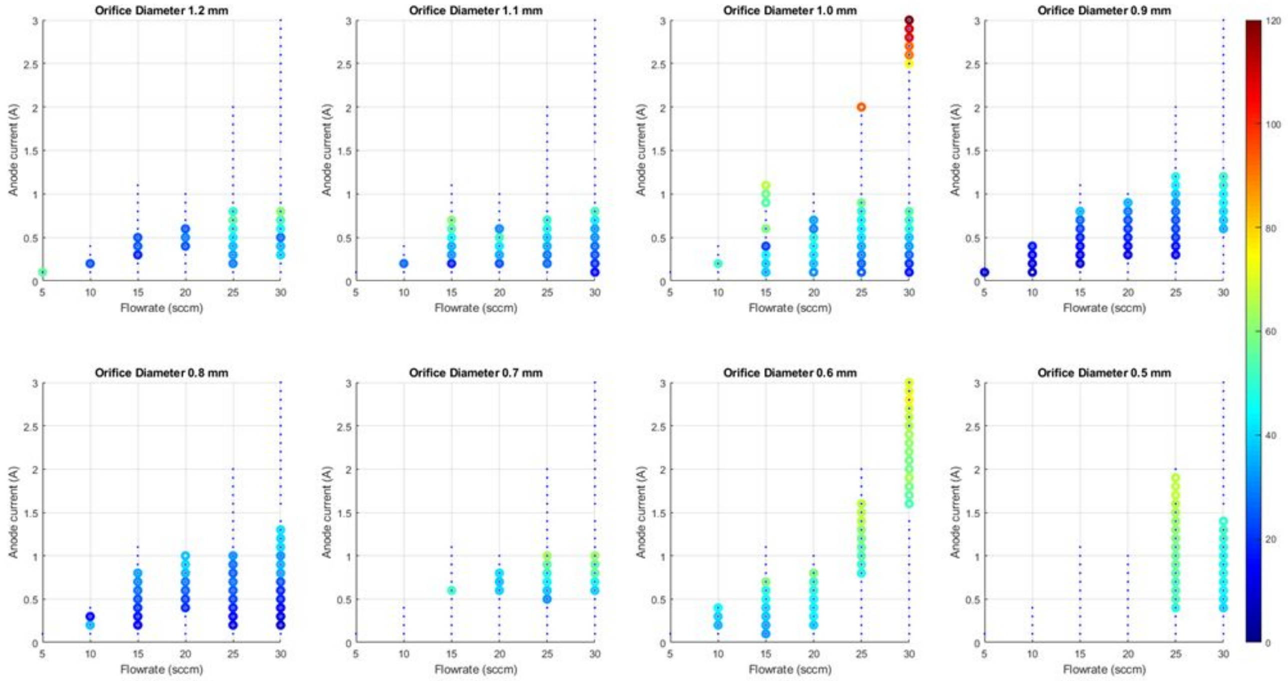
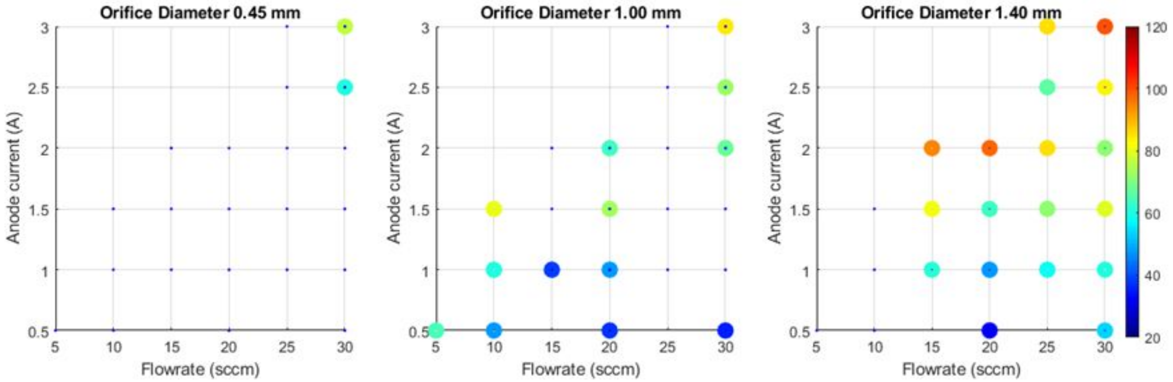
Characterisation of the performance of the planar cathode v4

- Cathode secondary orifice parameter study
- Parameter study of the keeper orifice





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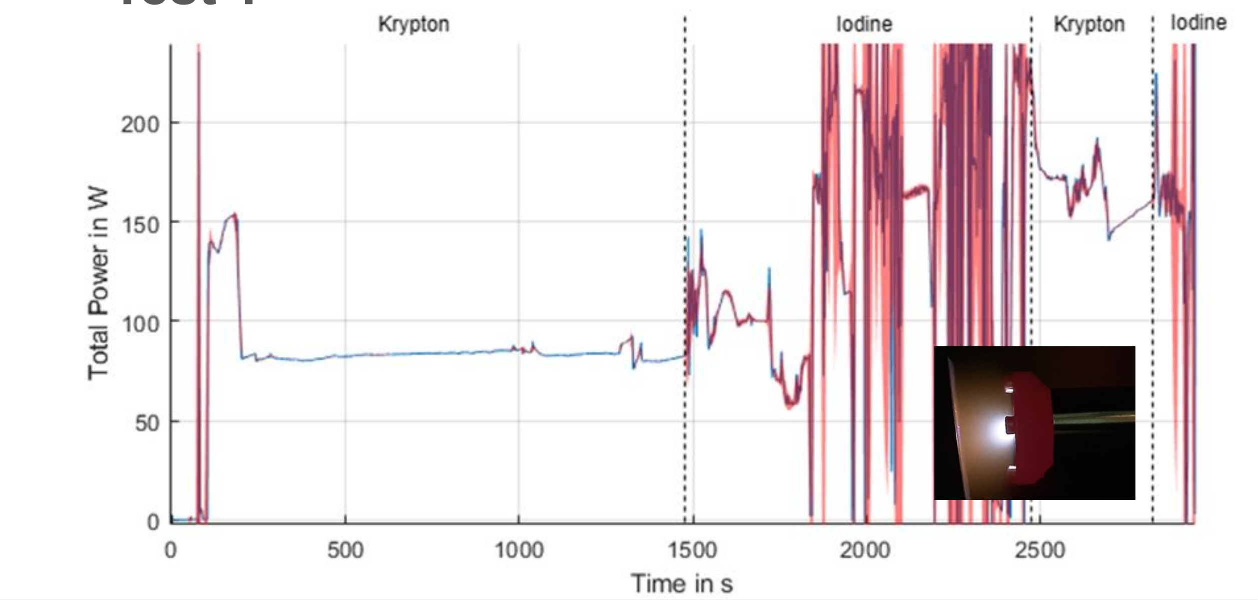
Final Tests: C12A7 type A

Iodine test with a C12A7 electride type A emitter

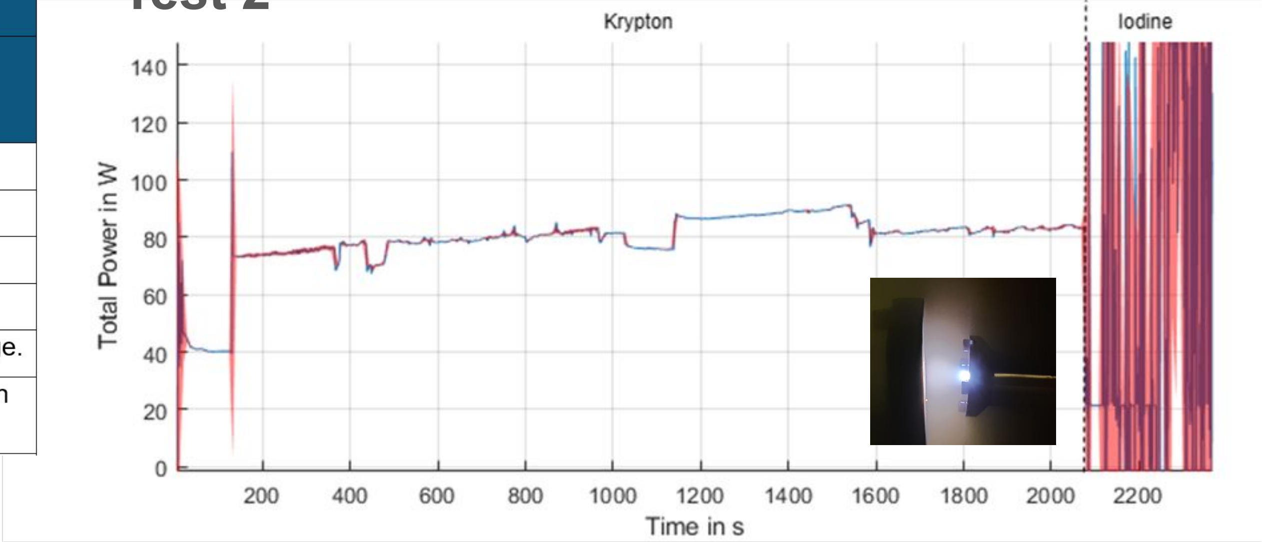
- Stable krypton discharge
- Becomes unstable, as soon as gas is switched to iodine
- Power necessary to operate with krypton has increased after iodine exposure or was not possible at all

Test	Emitter	Gas	Flow	Keeper		Anode		Duration in min	Comment
			in sccm or gr	Power in W	Current in A	Power in W	Current in A		
1	C12A7 Type A 1	Kr	30	20.3	1.2	153	3	25	Before iodine exposure.
		I	2	14.5	1.2	155	3	$\boxed{16}$	Iodine discharge.
		Kr	30	2.1	0.1	158	3	6	After iodine exposure.
2	C12A7 Type A 2	Kr	20	26.9	0.8	64	1.5	$\boxed{20}$	Before iodine exposure.
		I	3	118	0.5	21	3000	26	Unstable iodine discharge.
		Kr	-	-	-	-	-	-	No reignition with krypton possible.

Test 1



Test 2



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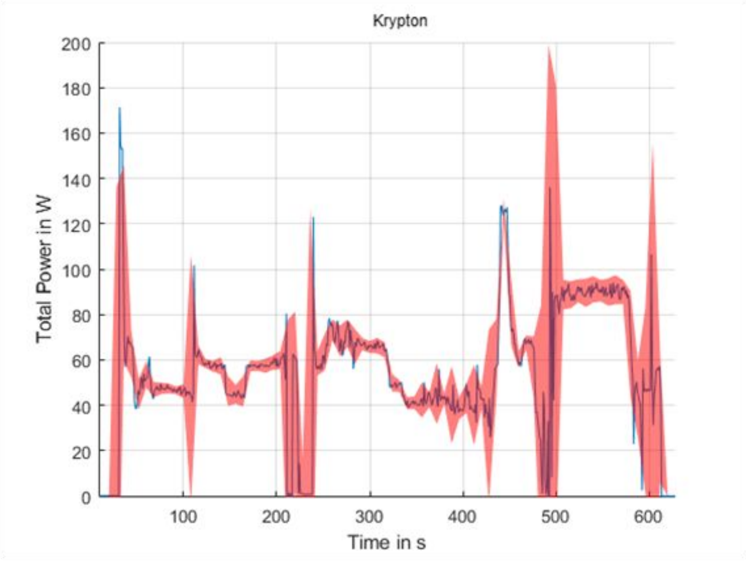
Final Tests: C12A7 type B

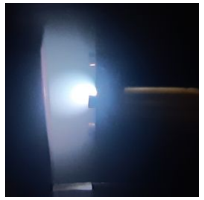
Iodine test with a C12A7 electride type B emitter

- No stable discharge, not even with krypton
- Is more stable with iodine than type A
- No reignition with krypton possible, as the keeper orifice was blocked by evaporated material

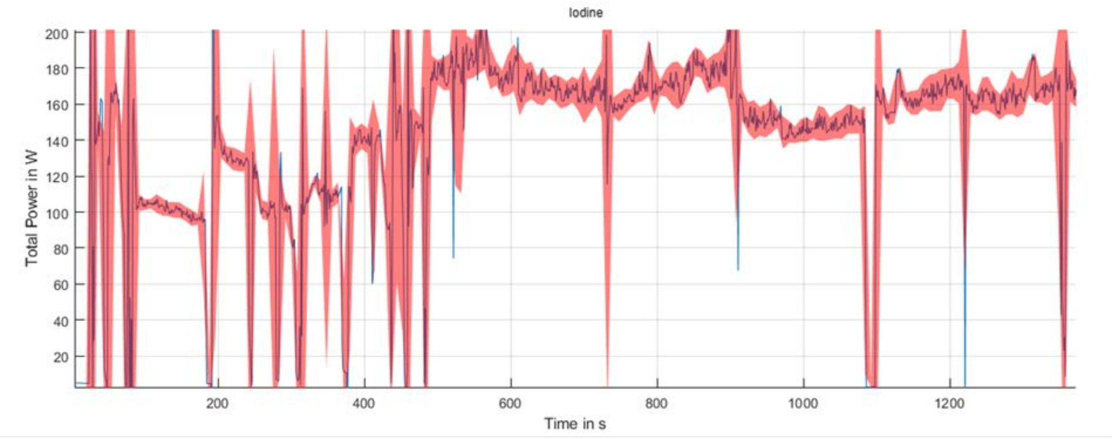
Test	Emitter	Gas	Flow	Keeper		Anode		Duration in min	Comment
			in sccm or gr	Power in W	Current in A	Power in W	Current in A		
3	C12A7 Type B 1	Kr	30	5	0.5	120	3000	9.5	Before iodine exposure.
		I	2.5	8	0.5	150	3000	22	Iodine discharge.
		Kr	-	-	-	-	-	-	No reignition with krypton possible.
4	C12A7 Type B 2	Kr	30	16	1200	100	3000	10	Before iodine exposure.
		I	4	21.5	1200	141	3000	18	Iodine discharge.
		Kr	-	-	-	-	-	-	No reignition with krypton possible.

Test 3 with krypton





Test 3 with iodine



Final Tests: LaB6

Iodine test with a LaB6 emitter

- Unstable after switching to iodine
- No reignition with krypton possible

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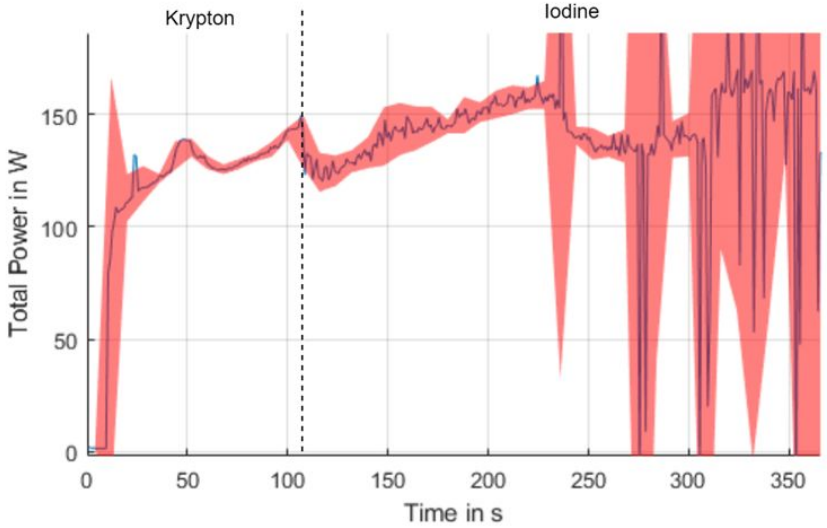
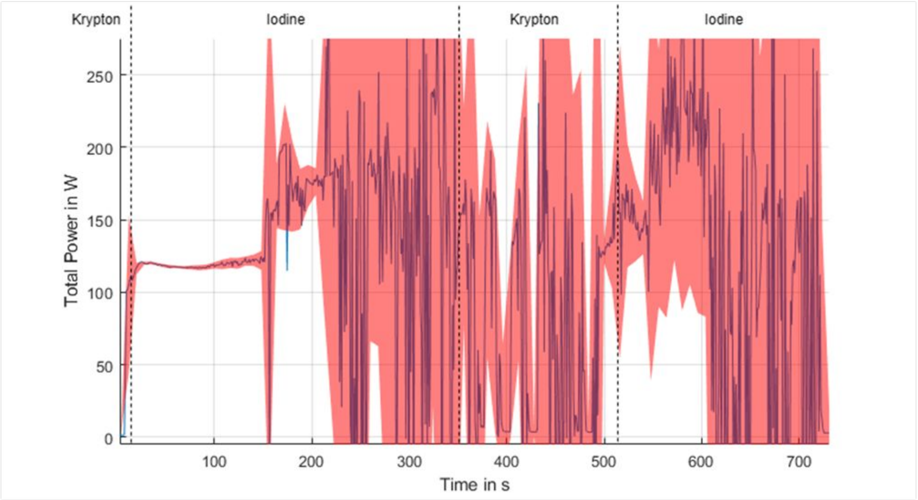
Test 5



Test 6



Test	Emitter	Gas	Flow	Keeper		Anode		Duration in min	Comment
			in sccm or gr	Power in W	Current in A	Power in W	Current in A		
5	LaB6 1	Kr	30	20	1200	115	3000	3	Before iodine exposure.
		I	2.5	25	1200	130	3000	23	Iodine discharge.
		Kr	30	268	1200	160	3000	1	After iodine exposure. No stable discharge.
6	LaB6 2	Kr	30	18	1200	100	3000	3	Before iodine exposure.
		I	1.5	27	1200	150	3000	9	Iodine discharge.
		Kr	30	20	1200	123	3000	1	After iodine exposure. No stable discharge.

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1. Introduction
2. Literature Review
3. Development and preliminary tests
4. IcoN CCN: Improvement of the iodine feed system
5. Test preparation and assembly
6. Test results

7. Post test analysis

8. Conclusion

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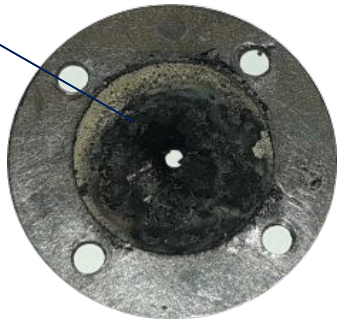
Post Test Analysis

Inspection after each iodine test

- C12A7:e- Type A:
  - Mostly stable in krypton discharge
  - Metallic + blackish residues after iodine test
- C12A7:e- Type B:
  - Already melting while using with krypton
  - Largely evaporates while operating with iodine
  - Evaporating emitter material blocks keeper orifice
- LaB_6:
  - Metallic coating after test with iodine
- Other:
  - Residues on keeper orifice
  - Evaporated emitter material blocking the keeper orifice



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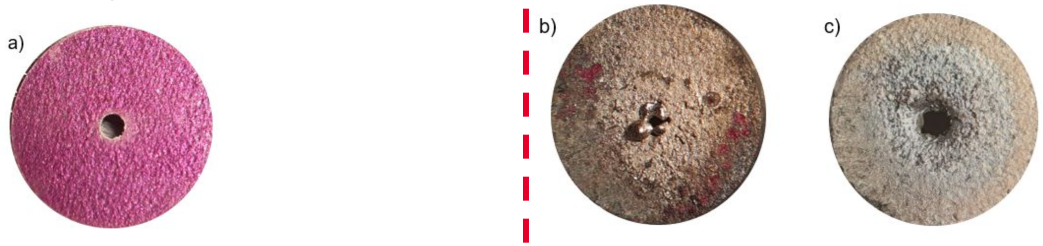
C12A7:e- Type A

Iodine

C12A7:e- Type B

LaB_6



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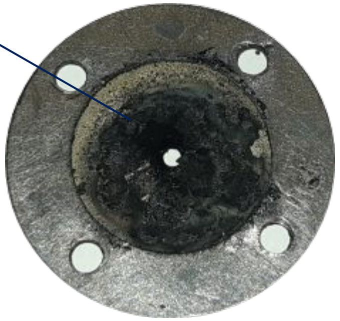

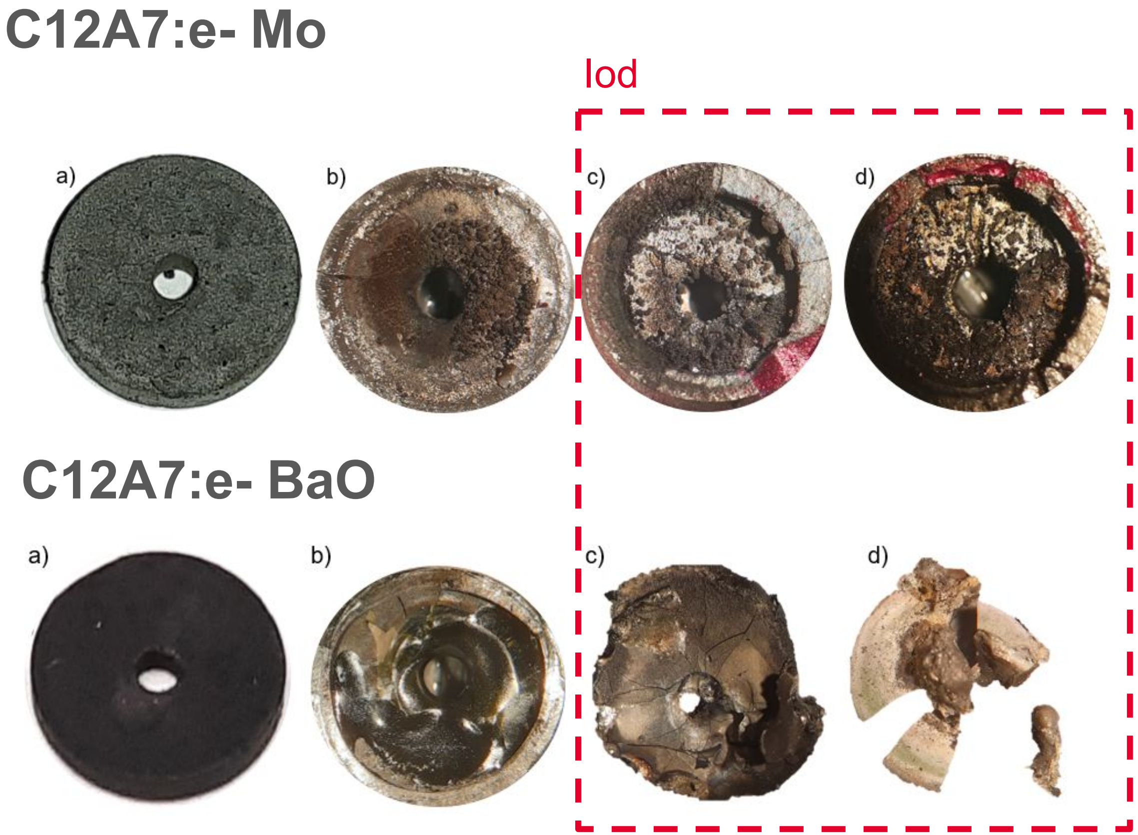

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Conclusion

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- **None** of the tested materials produced a **stable iodine discharge** of more than half an hour
- **None** of the **success criteria** were met

- Post-test analysis revealed that **all emitters have been coated** during the test
- **Significant damage through the iodine discharge** indicates that even if problems are reduced, the iodine discharge is **unlikely to last for the required thousands of hours**
- We have to conclude that with the currently known materials, **an iodine-fueled hot plasma-bridged cathode is not possible** to operate

- **Findings will be published** (peer-reviewed) to allow future researchers a reasoned approach to iodine electric propulsion

- However: Development of **iodine feeding** and **krypton planar C12A7:e- cathode** was **successful**

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Activity Overview

21 testing campaigns with **162 cathode** tests, including **30 tests** with **iodine**

113 manufactured components

3 forepumps and **1 turbopump** replacements

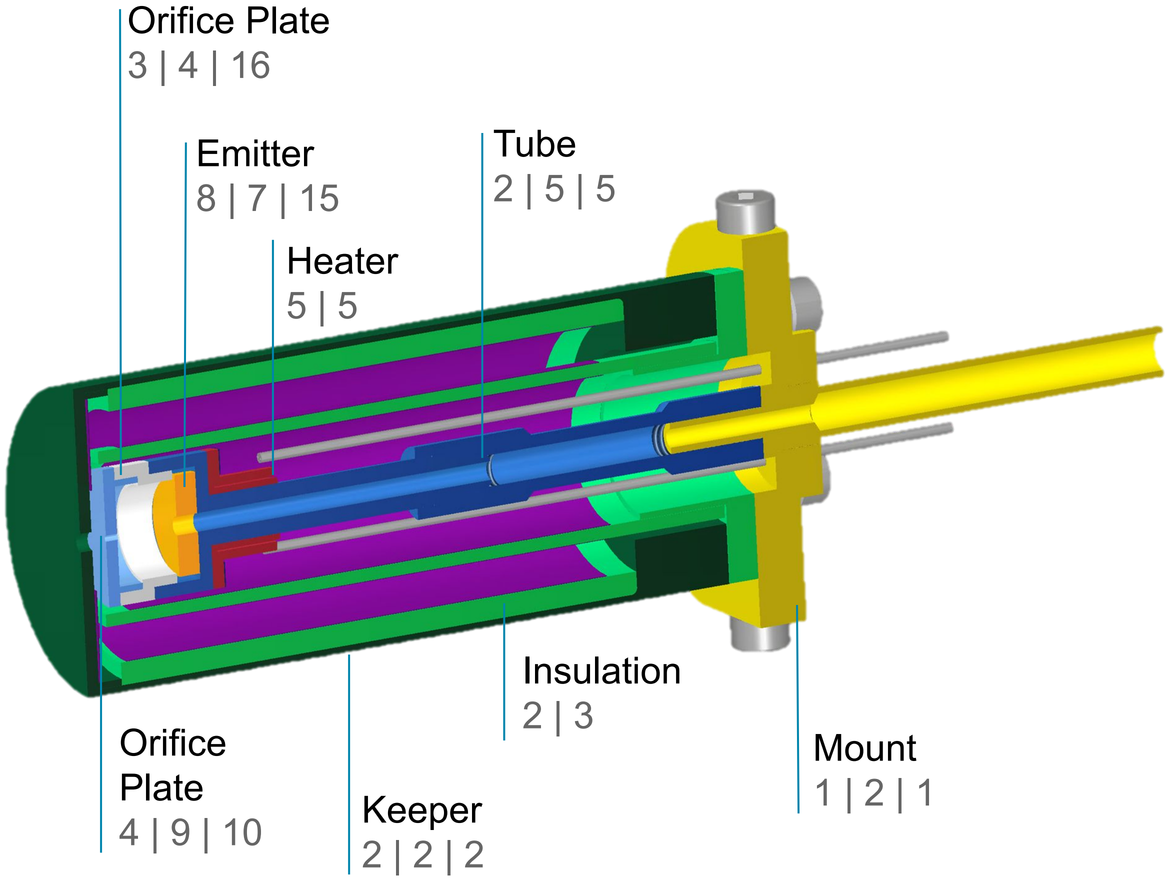
400l of krypton used

4 conference proceedings, including **1 best session**

1 published peer-reviewed review paper

1 paper being prepared for publication

Manufactured Part Type
Amount in 2022 | Amount in 2023 | Amount in 2024



Thank you for your attention

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