Long-Term Testing and Evaluation of the Vacuum Arc Thruster System Using Multi-Element Cathodes

M.Kühn and J.Schein

Lab. for Plasma Technology

Universität der Bundeswehr München

M.Sc. Marvin Kühn

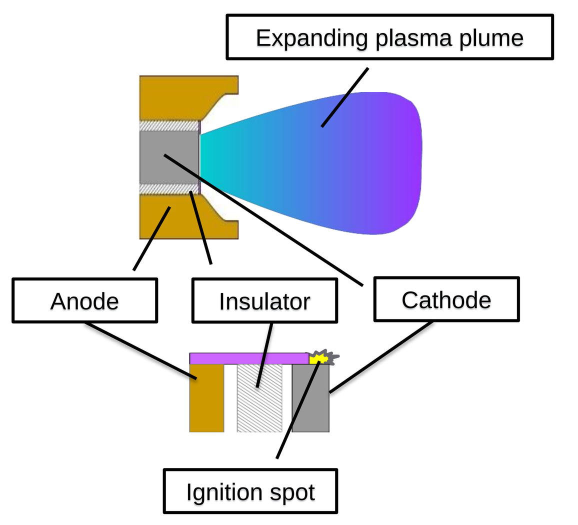
T: +49 (0) 89 6004-3527
E: marvin.kuehn@unibw.de

1. Introduction

- Small satellites need simple and reliable electric propulsion systems (1)
- Propulsion systems needs to be operated with limited space and energy resources
  - Vacuum arc thruster is a promising candidate (1,2,3,8)
  - Until now reliability of the VAT is from greater interest
  - Ignition mechanisms play a fundamental role (5,6)

Thruster ignition and operation principle:

I. Ignition initiation: "triggerless" flashover over a conductive layer between anode and cathode (4)
II. Micro plasma forms a conductive channel between anode and cathode
III. Conductive channel allows the formation of a vacuum arc
IV. Cathode material acts as "fuel" for plasma generation
V. Expanding plasma generates thrust
VI. Ion velocities dependent on cathode material



Desired cathode material properties:

- High specific impulse
- High self healing rate
- Low macro particle production rate
- Low average charge state
- Non toxic/radioactive

Both attributes are antagonists: High macro particles rates are responsible for regenerating the conductive layer but cause bad thrust efficiency due to their low velocity (~50-400 m/s) (7)

Advantages of the vacuum arc thruster:

- Easily scalable: → Cathode diameter
- Simple system → coaxial wire
- Solid metal fuel → high fuel density
- High ion velocities → high specific impulse without external acceleration systems
- Pulsed operation → low power needed
- "Triggerless" ignition can be used → voltages from 200 V (7,8,9)

Results from former experiments:

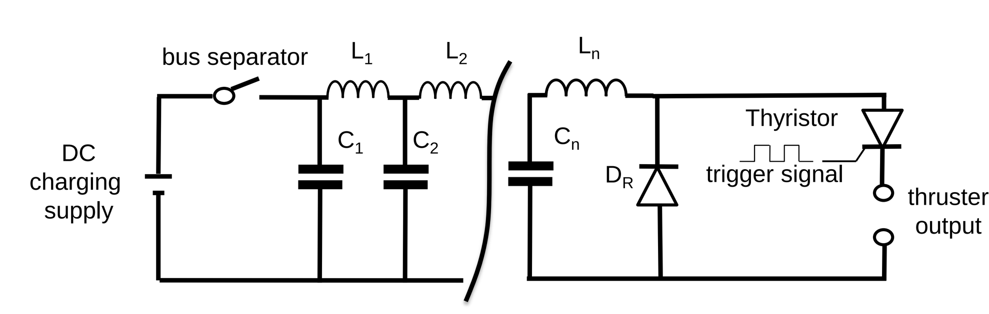
- Mo-cathodes showed high reliability with triggerless ignition
  → more than 1 million pulses
- Mo-cathodes can produce high ISP

Current questions:

- Could molybdenum be combined with another material that heals the conductive layer and increases the lifetime?
- Could tungsten, a material with high ISP but low reliability, be combined another material too?

2. Power Supply and Cathode Material

Pulse Forming Network Type E (PFN):



Energy stored in the PFN: $E = \frac{1}{2} * n * C * U^2$

Resulting Pulse length: $T = 2 * n * \sqrt{L * C}$

Characteristics of the PFN:

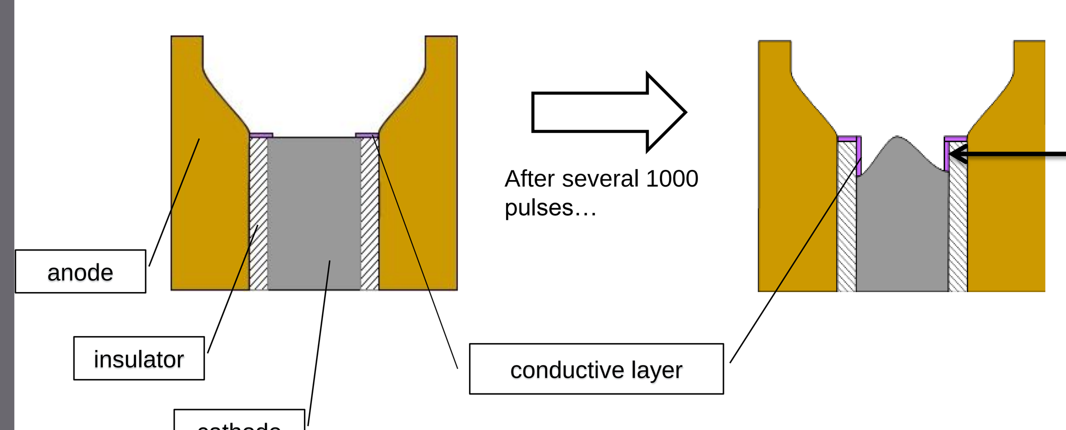
- Well shaped and reproducible current pulse
- Section control available → Thrust level control possible
- Reliable operation mode → commonly used for coating applications with several millions of ignition without degradation of components
- Maximum ignition voltage adjustable via loading voltage
- PFN can "un-fuse" a short circuit between anode and cathode → high current evaporation

Cathode materials selection:

- Proper choice of the cathode material can improve VAT performance and lifetime
- Until now it is unclear which material parameter(s) influence VAT's lifetime most
- Combination of multi-element cathode materials could improve thruster performance
  - High ISP materials for thrust generation → W or Mo
  - Materials with high macro-particle generation rate can help to regenerate the conductive layer → Cu or C
  - Arrangement of material can help to control cathode erosion

Cathode and conductive layer behavior and characteristics:

- Refractory materials could provide higher ISP but lower efficiency due to higher mean ion charge states
- Successful triggering via the conductive layer depends on:
  - The ignition current "path length" → insulator thickness
  - Re-coating potential of the thruster cathode material
  - Pulse length of the PFN → higher pulse lengths induce higher healing rate of the conductive layer
  - The maximum pulse energy for the initial ignition
  - Cathode erosion geometry → erosion at the outer parts of the cathode leads to an increased conductive layer path length



Available material combinations for 4mm diameter cathodes:

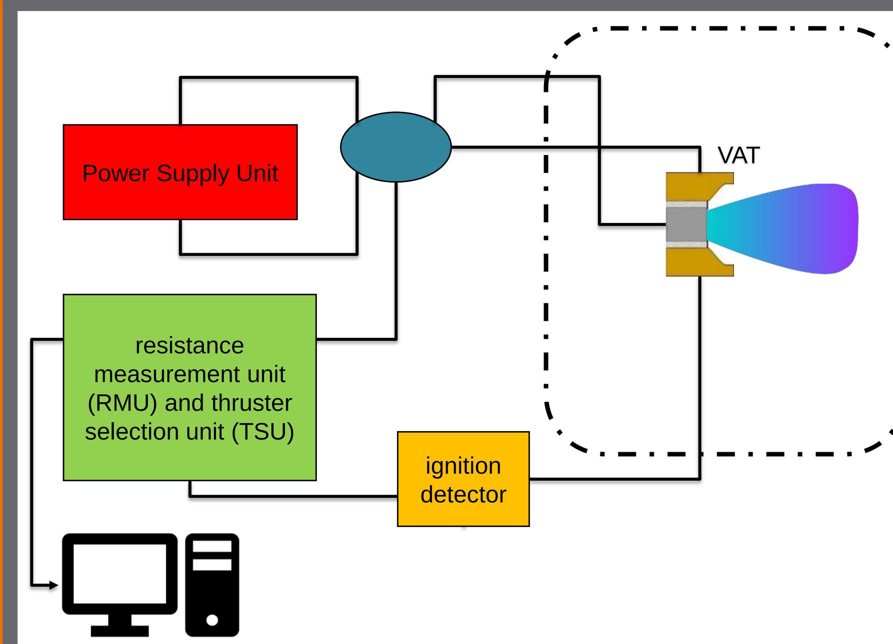
- Pure molybdenum
- Molybdenum with 2 mm carbon rod in the center
- Tungsten-Copper, sintered material with 20% copper and 80% tungsten

Possible cathode materials*

Material	Density [g/cm³]	Melting point [K]	Arc voltage [V]	Ion velocity [m/s]	Mean charge state	Electron Work Function [eV]	ISP [s] **
Molybdenum	10,28	2896	29,3	17400	3	4,16	1066
Tungsten-Copper (80/20)	15,00	Tungsten: 3695 Copper: 1357	Tungsten: 31,9 Copper: 23,4	Tungsten: 14300 Copper: 12800	Tungsten: 3 Copper: 2	Tungsten: 4,54 Copper: 4,39	Tungsten: 1078 Copper: 794
Carbon	3,4-5,3	Non existent	29,3	17300	1	4,81	859

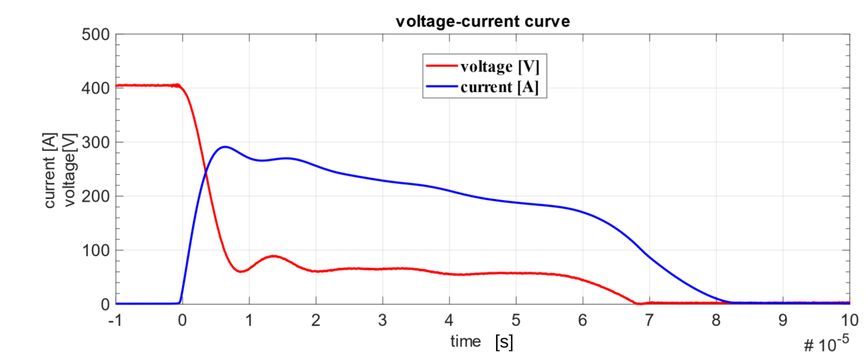
* Date was taken from (1)
**All predictions for ISP are for non enhanced VAT systems, ISP can change dramatically when using magnet fields or grids acceleration systems

3. Experimental Setup



PPU characteristics

PPU Type	Pulse Forming Network
Electric parameters	10 stages, 3,3µF & 3,3µH per stage
Loading Voltage	400V
Max Energy per pulse	2,64 J



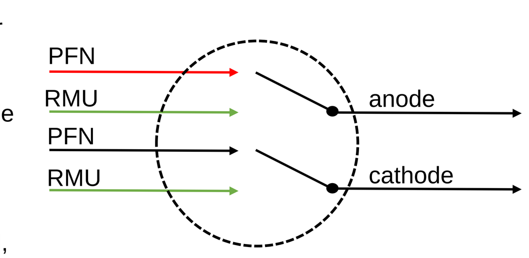
Measurement equipment

arc voltage probe	LeCroy, ADP305 differential probe
oscilloscope	LeCroy, HDO6104A
DC HV charging source	Heinzinger 400
current probe	LeCroy CP150

Resistance and pulse measurement :

- galvanic insulation via with high power relay (HPR)
- Highly detailed measurements possible up to one measurement per pulse possible
- 4 thruster for each material were used, measurements were averaged
- For each thruster conductive layer resistance measurement was performed each 200 pulses

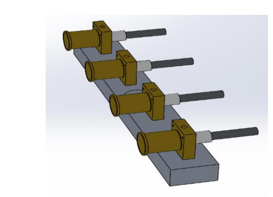
Galvanic insulation schematics:



Thruster Setup

Thruster geometry	Concentric arrangement, optional magnetic field applicable
Cathode	4mm rod, material: MoC, WCu,, 2mm carbon rod for MoC cathode
Anode	Brass
Insulator	Al_2O_3 , 6 x 4.0 mm diameter
Working pressure	2x10e-6 mbar
Initial resitance	1- 5kOhm

Single thruster

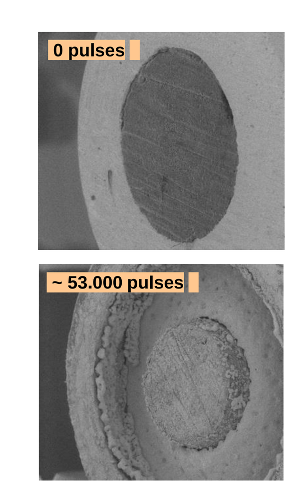


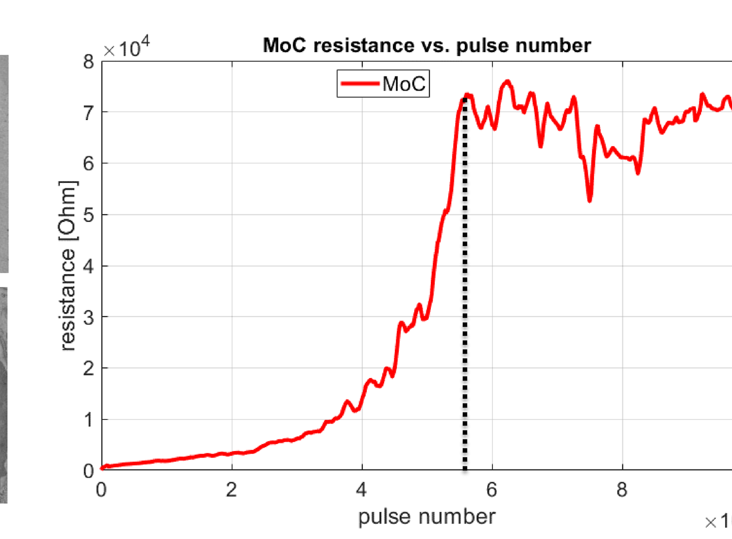
Quattro thrusters setup

4. Experimental Results

MoC cathode, 2mm C rod in the cathode center

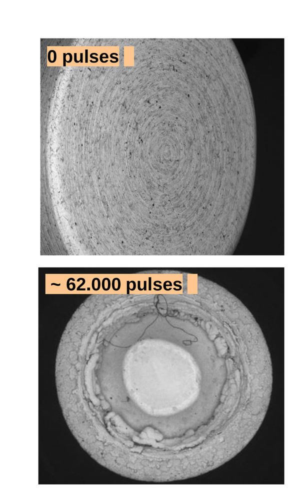
- Carbon core only slightly eroded on the edges
- Inner insulator surface coated with Mo, high surface tension leads to ablation
- Failure after ~55.000 pulses, after that point unregularly ignitions occurred (dotted line)
- No carbon found on the insulator (EDX measurement)
- Mo surface includes small craters
- Insulator front material composition and coating could not be measured due to thruster geometry

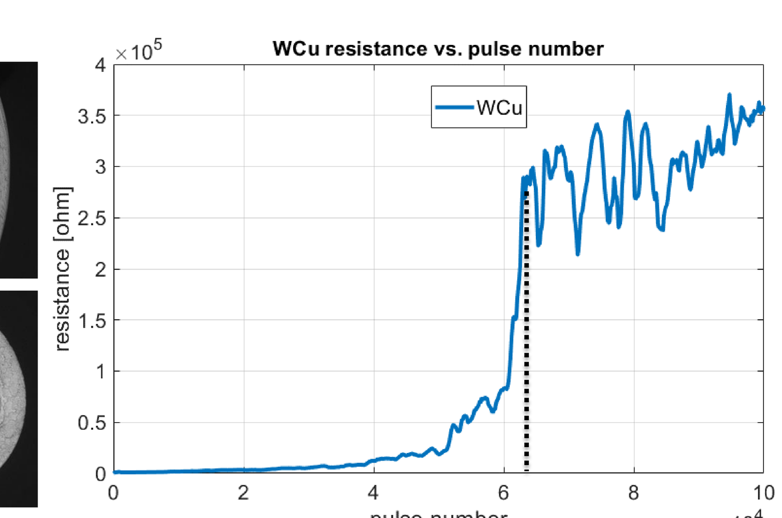




WCu (80/20) cathode

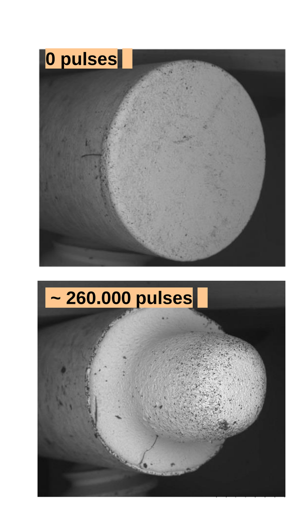
- Cathode outer regions eroded
- Inner insulator surface coated with W and Cu, high surface tension leads to ablation of the coating
- Failure after ~63.000 pulses, after that point unregularly ignitions occurred
- EDX measurements showed material composition on the insulator comparable to the cathode mixture of 80% tungsten and 20% copper
- Insulator front material composition and coating could not be measured due to thruster geometry

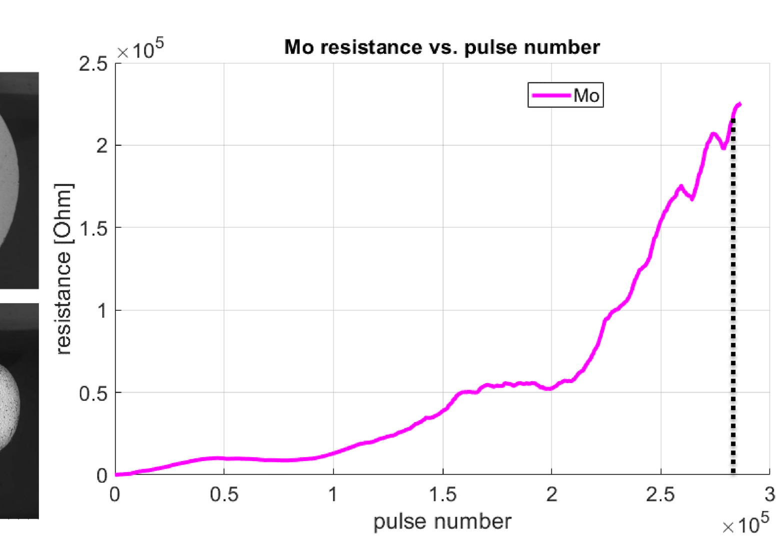


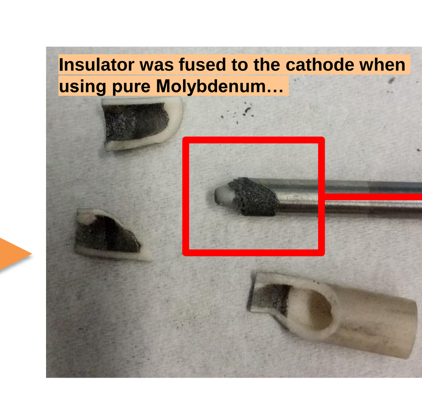


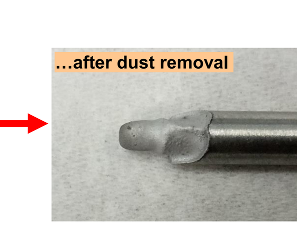
Mo cathode

- Cathode outer regions eroded
- Inner insulator surface coated with W and Cu, high surface tension leads to ablation of this coating in the front
- Failure after ~280.000 pulses, after that point unregularly ignitions occurred
- Better results than MoC and Wcu
- Insulator got destroyed when thrusters were dismounted
- Failure of one thruster by "clogging"
  - Thruster was "firing" but no plasma plume detectable
  - Cathode material was attached to the insulator inside and created barrier of "molybdenum-dust" → thruster failure









Results:

- Proper choice of the cathode material can improve VAT performance/lifetime
- Arrangement of cathode materials plays an important role
- Pure Mo cathodes work best compared to WCu and MoC cathodes
- Center regions of all cathode are not eroded
- Absolute failure resistance values vary for different materials

5. Discussion and Outlook

- Until now it is unclear which material parameter(s) influence VAT's lifetime most
- Center regions of the MoC cathode are not eroded
  → Carbon rod has much higher resistance compared to molybdenum rod, arc is not forced to attach at the carbon rod but the molybdenum
  → change of the geometry with carbon at the outside and Mo at the inside will be tested
- Instead of full material rod, tubes could be used
- Arc steering with magnetic field or geometries optimization are necessary for full material cathodes
- Resistance gradient over pulse number might give a better prediction for the thruster failure → comparison with thrust measurement is needed

6. Literature

(1) "A Theoretical Analysis of Vacuum Arc Thruster and Vacuum Arc Ion Thruster Performance", James E. Polk et al, IEEE Transactions On Plasma Science, VOL. 36, 2008
(2) "Development of Vacuum Arc Thrusters and Diagnostic Tools", M. Pietzka et al, 32nd IEPC, IEPC-2011-080,2011
(3) "Development and Characterization of a Propulsion System for CubeSats based on Vacuum Arc Thrusters", M. Pietzka, PhD thesis, 2016
(4) "Triggerless' triggering of vacuum arcs", A. Anders et al., J. Phys. D: Appl. Phys. 31 584, 1998
(5) "Low energy surface flashover for initiation of electric propulsion devices", Yunping Zhang et al, Plasma Res. Express 1, 2019
(6) "Lifetime of Vacuum Arc Triggering System Based on Surface Discharge", A.G. Nikolaev et al, 13th INTERNATIONAL CONFERENCE ON RADIATION PHYSICS AND CHEMISTRY OF INORGANIC MATERIALS (RPC-13), 2006
(7) "Cathodic Arcs - From Fractal Spots to Energetic Condensation", A. Anders, Springer – Science and Business, 2008
(8) "Pulsed Metallic-Plasma Generator", A. S. Gilmour et al, Proceedings of the IEEE VOL. 60, 1972
(9) "Efficient, compact power supply for repetitively pulsed, "triggerless" cathodic arcs", A. Anders et al, Review of Scientific Instruments 70, 4532, 1999