1LOr1A-03: Operation of an HTS magnet in heat flux and radio blackout mitigation experiments in plasma wind tunnels

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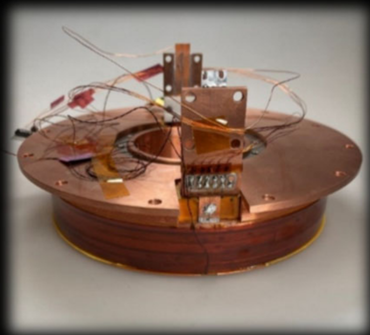

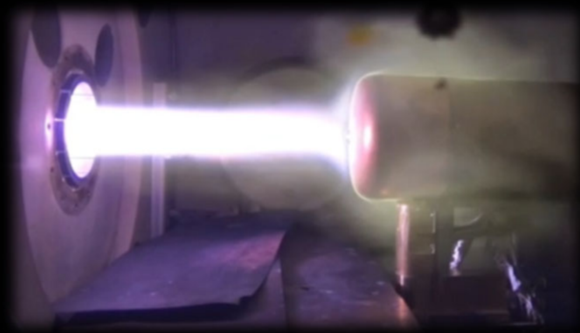

Reentry of Space Vehicles: Heating

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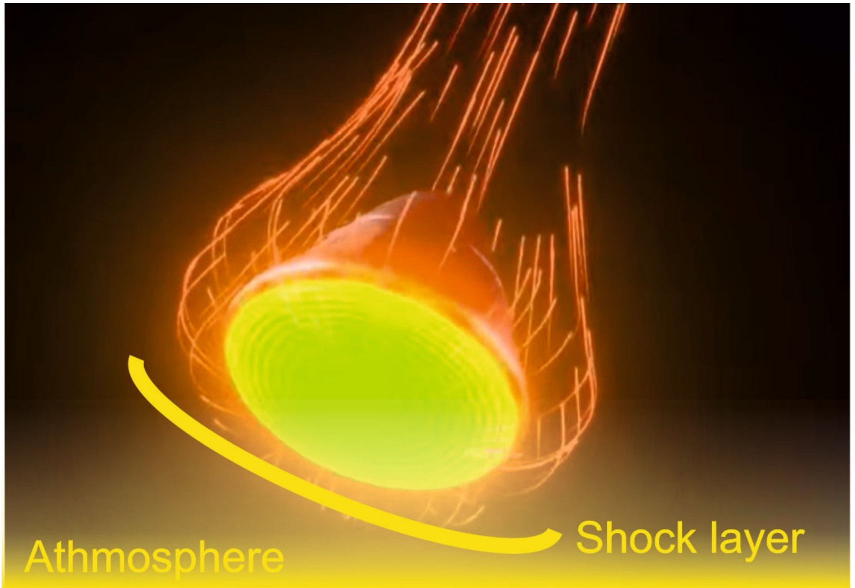
Problem during reentry at hypersonic speed:

- Compression of air at leading edge
  → Formation of hot shock layer
  → Radiation heating
- Convective heating from flow of hot gas past surface
- ➢ *T* exceeding 2000°C



State-of-the-Art Solutions

- Thermal protection systems (TPS), e.g.
  - Ultra High Temperature Ceramics
  - Insulators and Ultra High Thermal Conduction Materials
  - …

Reentry of Space vehicles: Radio Blackout

- **Problem:**
  - Hypersonic flow creates plasma layer around vehicle.
  - Dense plasma layer has high plasma frequency

    $f_e = \frac{\omega_e}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} > f_{radio}$

  → reflection of RF signals: 'Radio Blackout'

  → Loss of communication with ground stations, satellites, ...

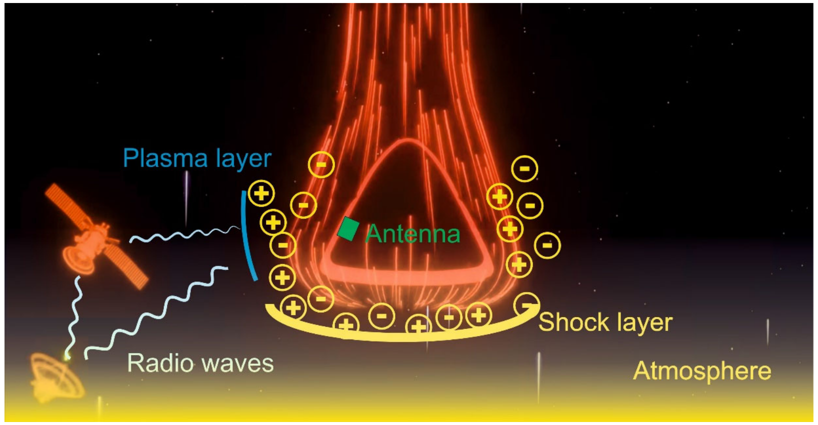
- **Missions and duration of blackout phases:**
  - Gemini 2: ~ 4 min.
  - Apollo: ~ 3 min.
  - Mars Pathfinder: ~ 30 sec.
  - Space Shuttles ~ 30 min.

- **Solutions (passive or active):**

  → Aerodynamic shaping (sharp edge not blunt)

  → Injection of quenchants to reduce ionization level

  → ….



Frequency [GHz]	Critical number density [m^{-3}]	Designation
0.30	1.12×10^{15}	Voice communication
1.55	2.99×10^{16}	GPS
1.68	3.52×10^{16}	L-band (data telemetry)
8.20	8.75×10^{17}	X-band
32.0	1.27×10^{19}	Ka-band

M. Kim and A. Gülhan, *Proceedings of 5th International Conference on Recent Advances in Space Technologies* - RAST2011, Istanbul, 2011, pp. 412-417, doi: 10.1109/RAST.2011.5966868.

Solving both Problems: “Magneto-Hydrodynamic Entry Systems for Space Transportation“ (MEESST)

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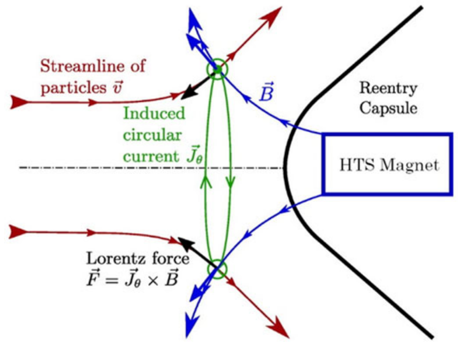
- EU-Funding: grant agreement No.899298
- Call/Topic: FET-Open Challenging Current Thinking
- Duration: 10/2020 – 09/2024 (incl. extension)
- Budget: 3.48 M€



A. Lani *et al., Journal of Space Safety Engineering* **10** (2023) 27–34

MEESST

Modelling:

KU Leuven (BE)
Project coordination
MHD & blackout modelling

University of Luxembourg (LU)
Radio blackout modelling

University of Southampton (UK)
MHD modelling

AEDS SARL (CH)
Radiative heat transfer modelling

HTS Magnet and Cryogenic System:

Theva Dünnschichttechnik (DE)
HTS tape design and production

Karlsruhe Institute of Technology (DE)
HTS Magnet design and production

Absolut System (FR)
Cryogenic system design and production

Plasma Experiments:

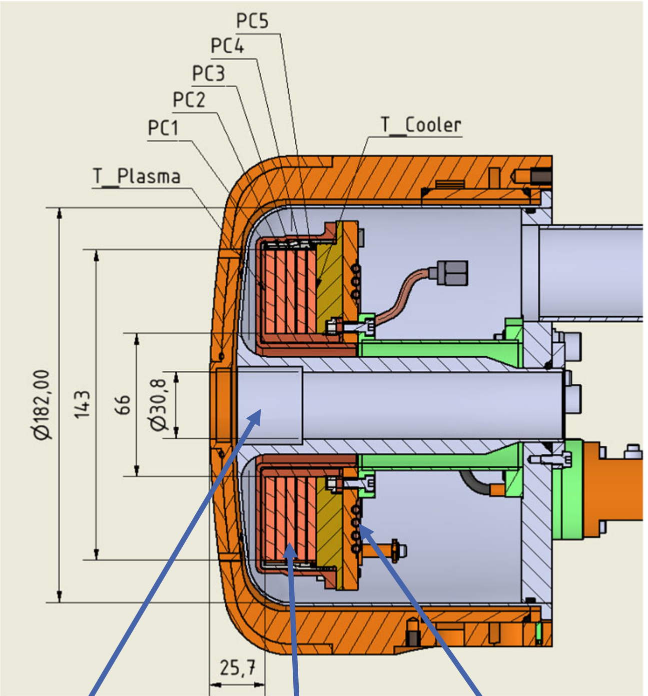
Von Karman Institute (BE)
Experimental radio blackout research

Institute of Space Systems (DE)
Experimental heat flux research
MHD modelling

Dissemination:

Neutron Star Systems
Project dissemination

MEESST: Magnet and Cryostat Design

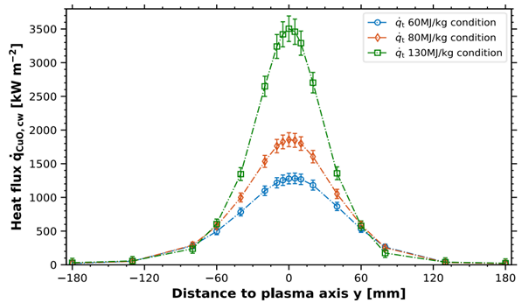


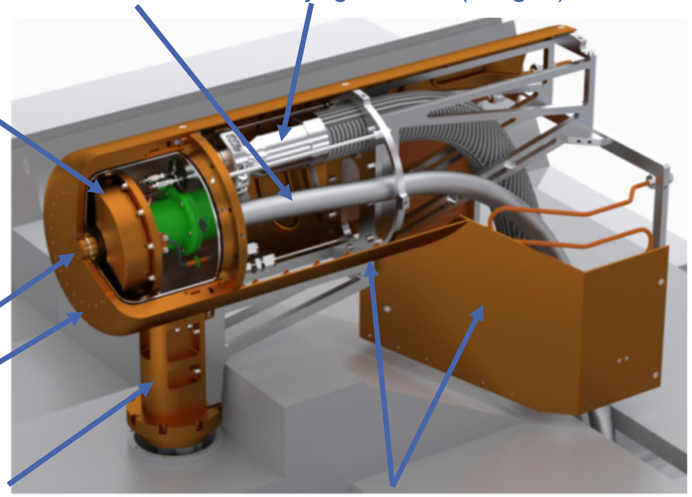
<u>MEESST Magnet</u>

- 5 pancakes, 4 mm wide REBCO-CC
- 10 soldered HTS-HTS joints
  - 2x CL to magnet
  - 2x inner connection of double pancakes
  - 2x outer connection of double pancakes
  - 4x tape-tape connection in pancake
- Design: Max. field in plasma @ $I = I_c$:
  ~ 2.2 ... 2.5 T

- Magnet conduction cooled (cold plate cooled by cryo-cooled He-gas)
  - ➢ Design Temperature: T_{Magnet} < 30 K
- Water cooling in shell
  - ➢ protection from hot plasma (Temp. up to ~ 10'000 °C)

<u>Heat flux profile from plasma jet</u>





S.I. Schlachter *et al. IOP Conf. Ser: Mat. Sci. and Eng.* **1302** (2024) 012021;
doi:10.1088/1757-899X/1302/1/012021

The MEESST HTS Magnet

Robotic winding @ KIT:
M. Dam et al. 1LOr1A-06

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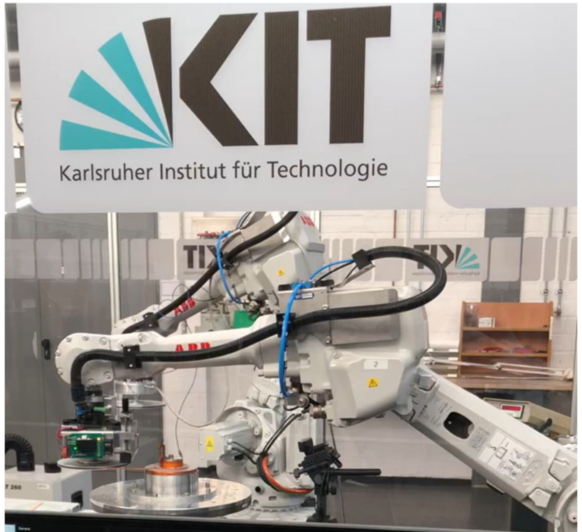
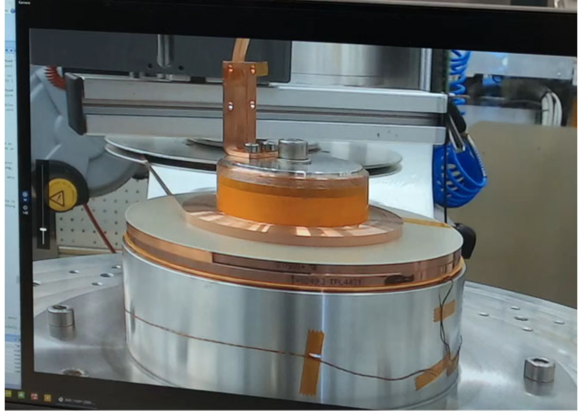
<u>Robotic winding of MEESST magnet @ KIT</u>
- 5 pancakes, 4 mm wide REBCO-CC
- 10 soldered HTS-HTS joints

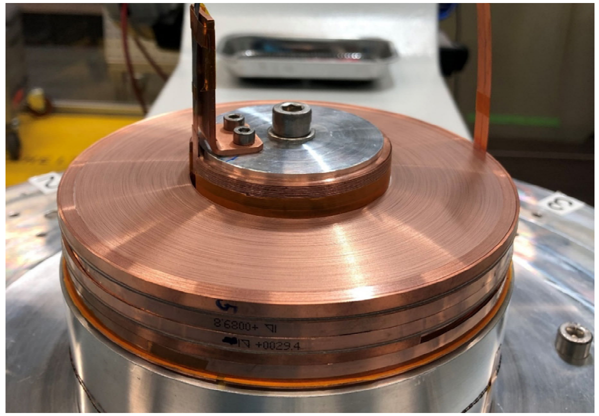
<u>But:</u>
- Low winding density due to irregular shape of tapes
- Coil section in PC2-PC3 with high ohmic resistance
- ➢ Quench at ~ 62 A, far below expected I_c

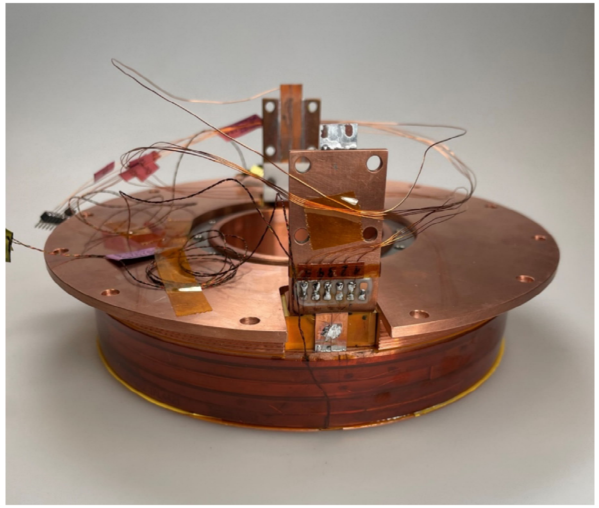
→ Run Experiments with maximum current of 50 A

S.I. Schlachter *et al. IOP Conf. Ser: Mat. Sci. and Eng.* **1302** (2024) 012021;
doi:10.1088/1757-899X/1302/1/012021



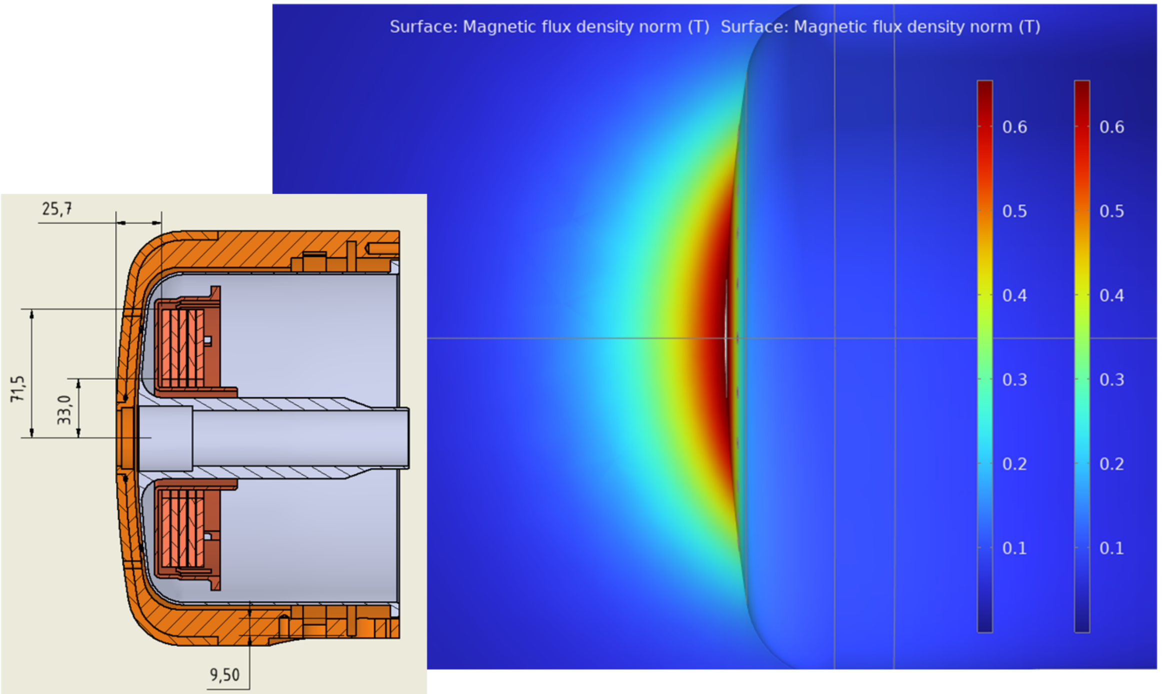


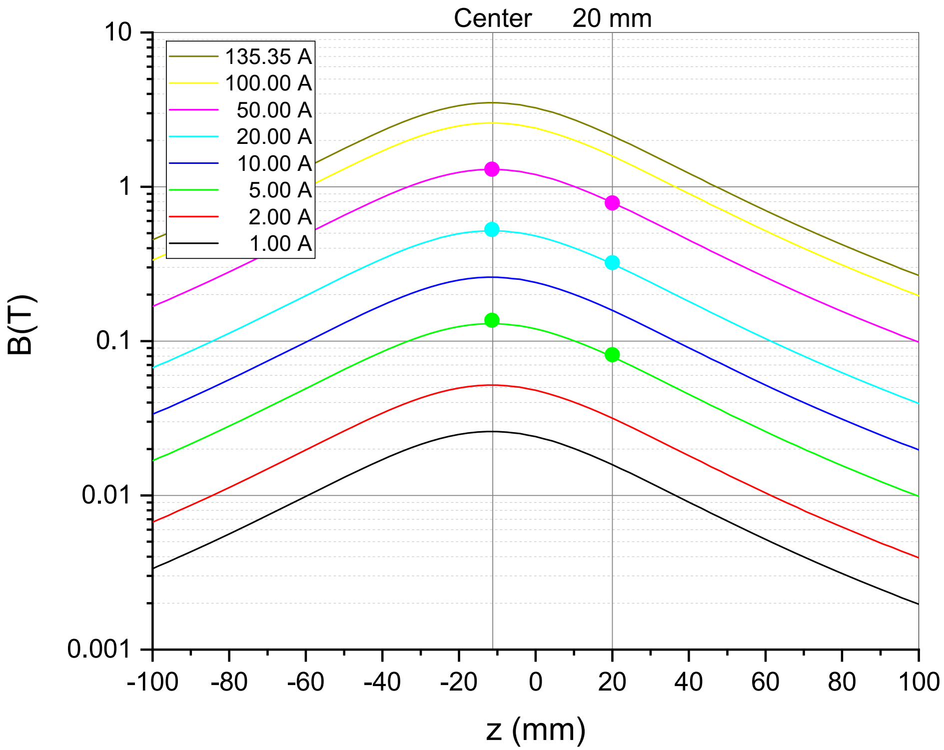




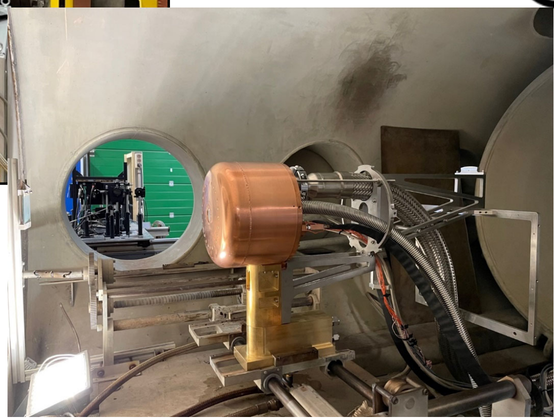
Magnetic field outside the probe at 50 A

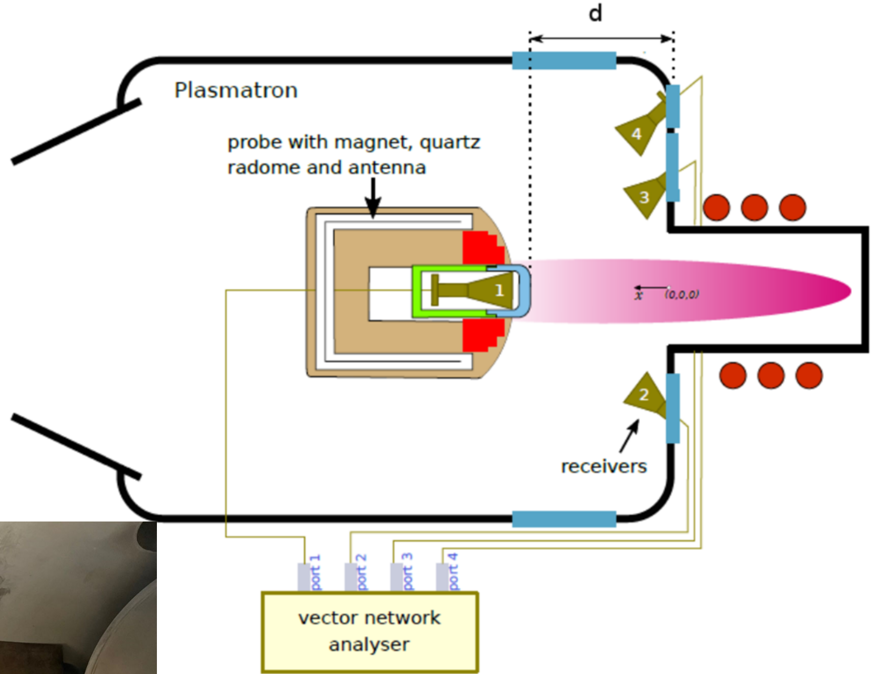
- Maximum field at probe surface ~ 655 mT, max. field at conductor: 2 T





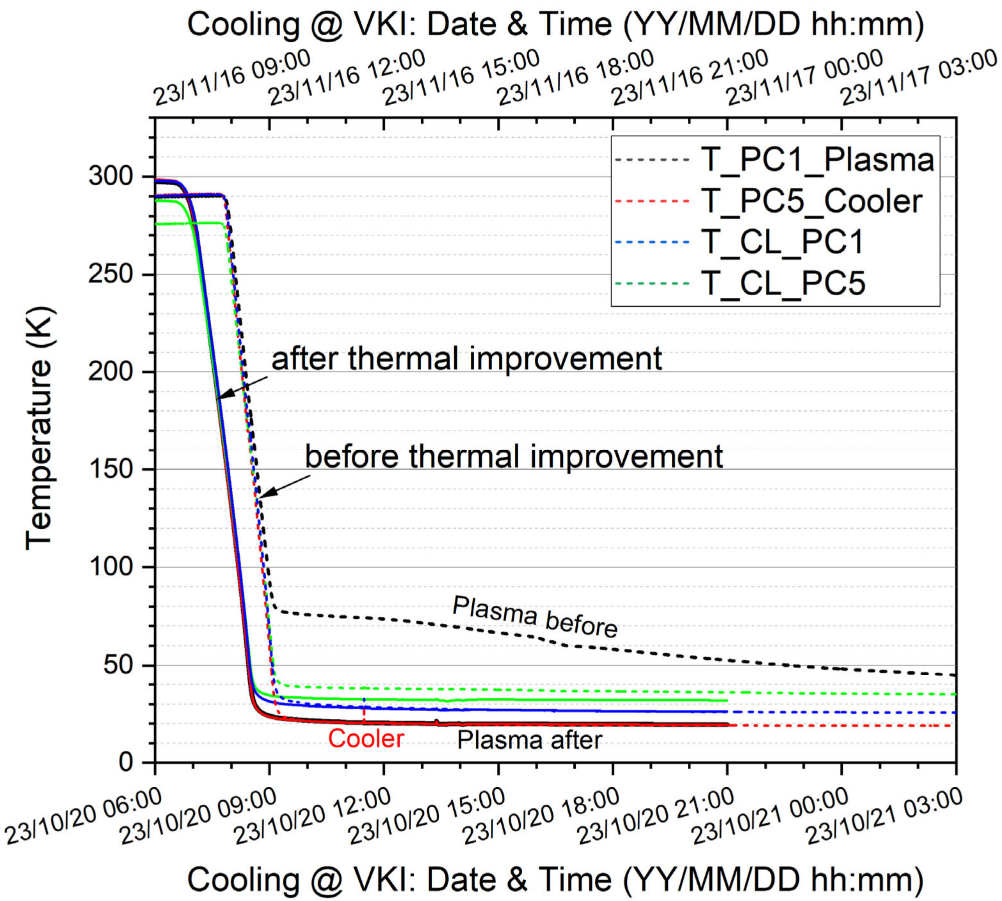
Radio Blackout Experiments at VKI



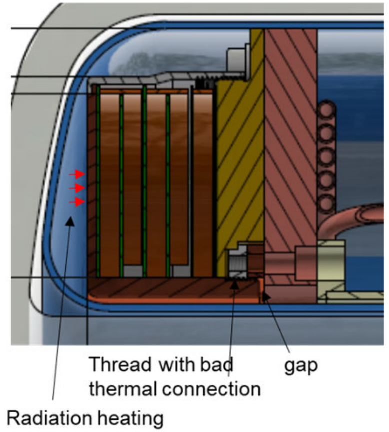


- Plasmas: Air & CO_2
- Static pressures (mbar): 50, 100, 110/120
- Electric Power: 100…300 kW
  - ➢ Particle density

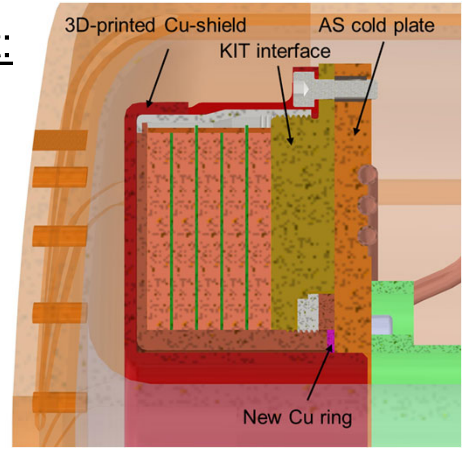
Magnet Temperatures



<u>First Test:</u>
Magnet temperature on plasma side much higher than on cooler side



<u>After thermal improvement:</u>
Magnet temperatures at cooler and plasma side almost the same



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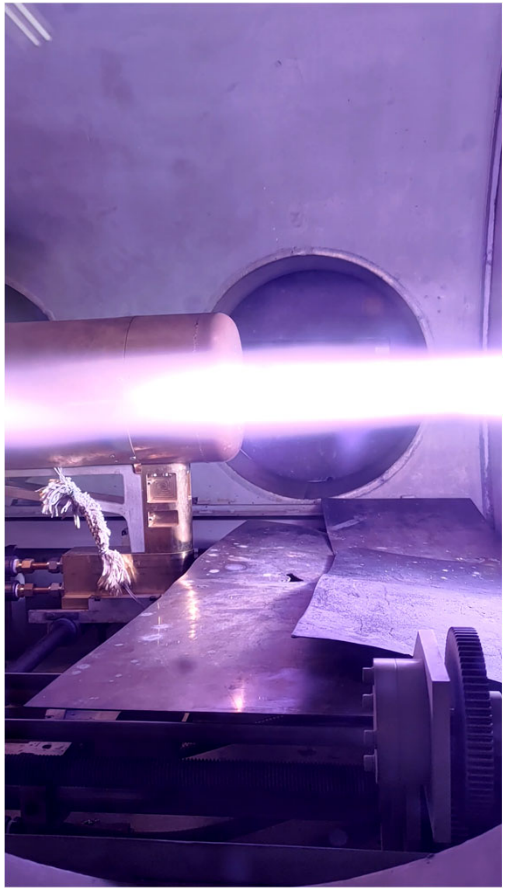
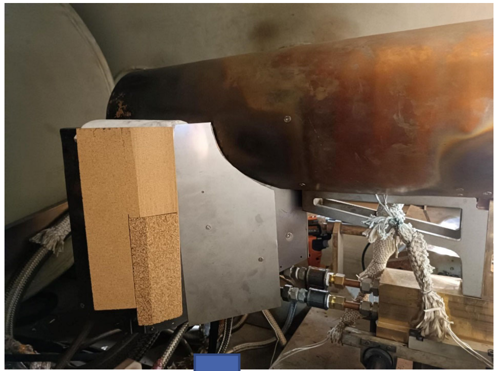
Probe in Plama: Attention, it‘s hot …





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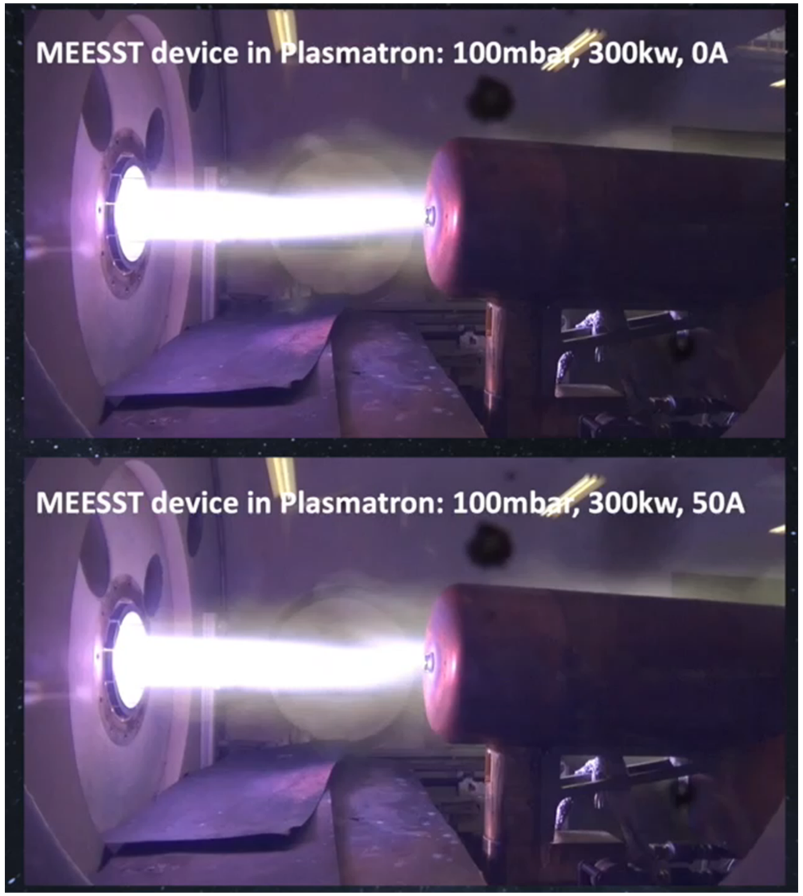
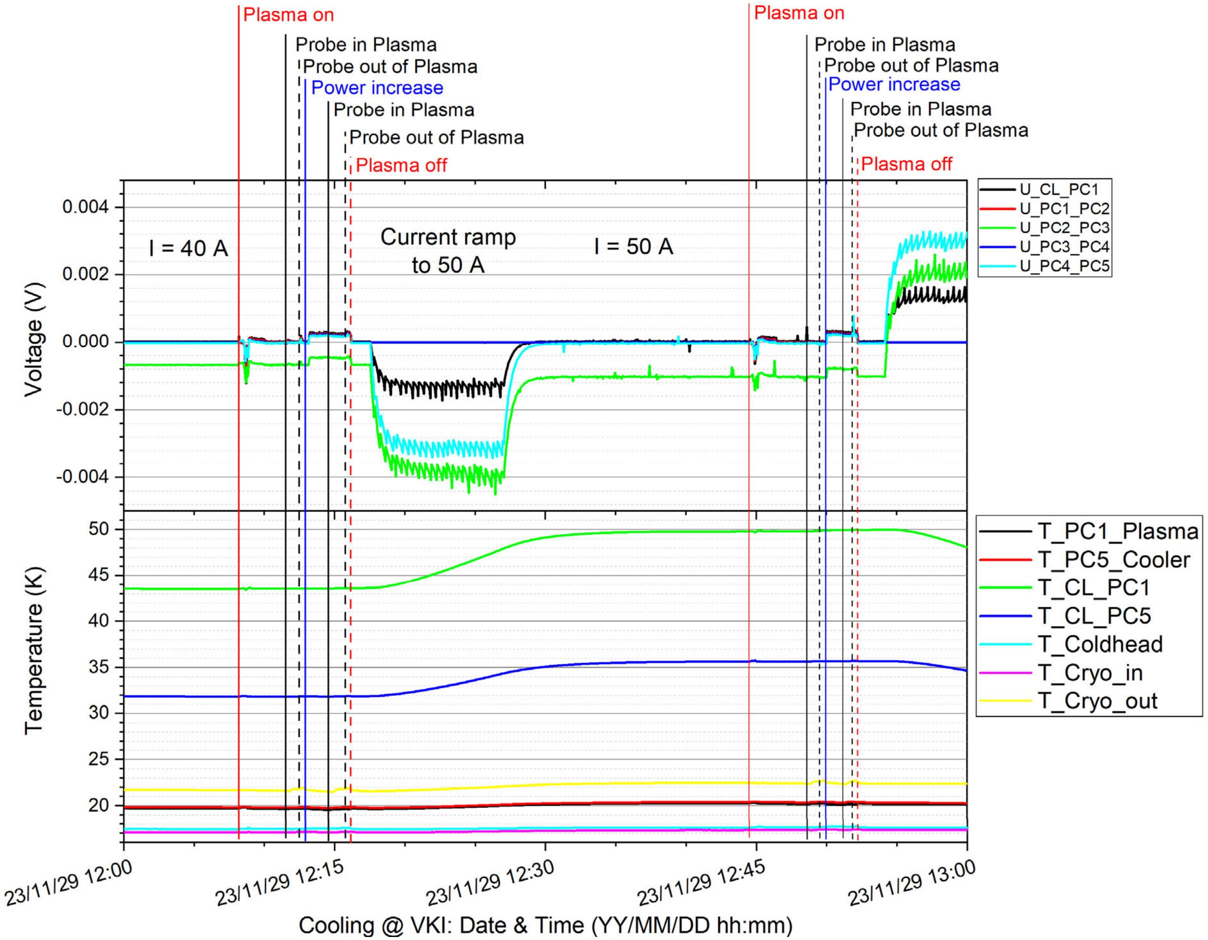
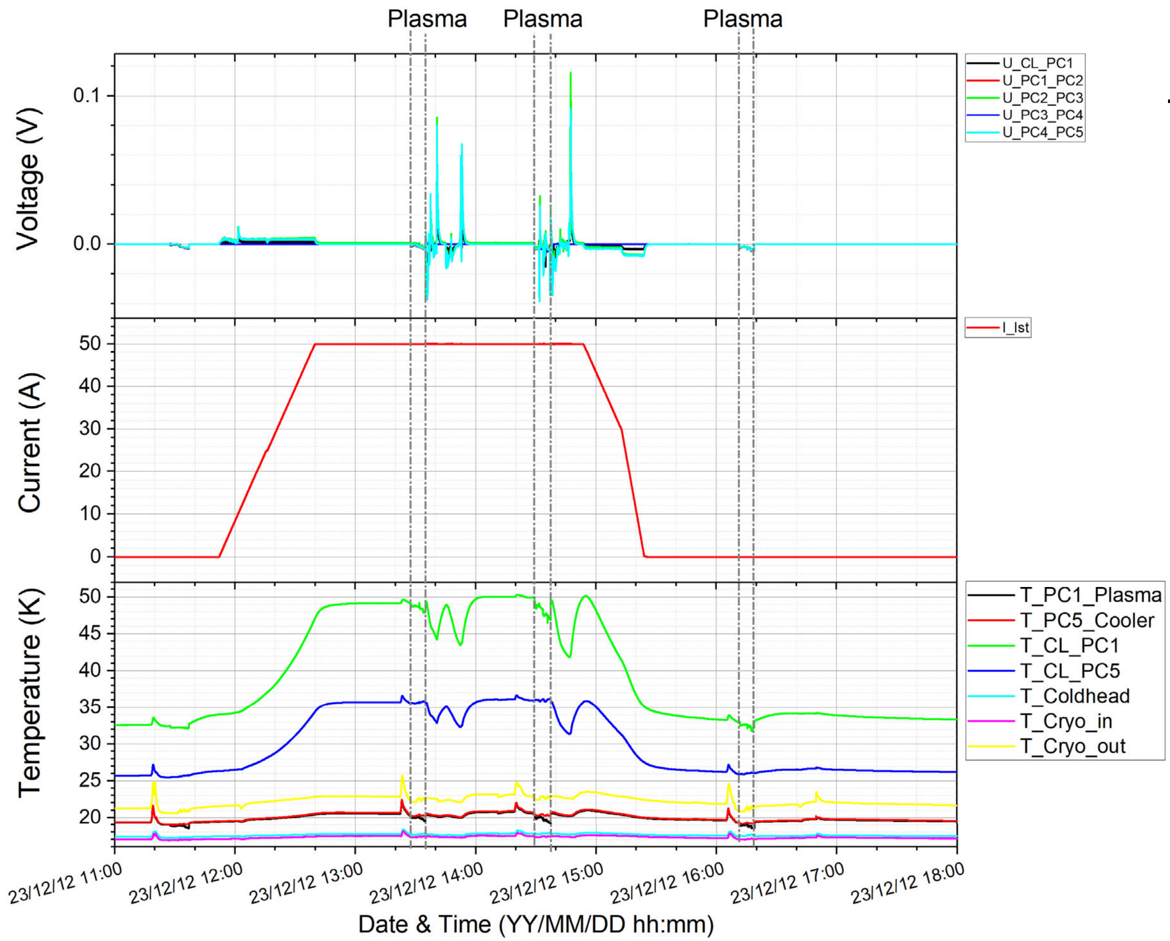
Nov. 28/29, 2023: Magnet test with plasma





2023-12-12: Plasma Tests – Short at Current Leads



Overview
- Ramping of magnet: 0→50 A, 0.02 A/s
- 2 Plasma tests @ 50 A
- Ramping down: 50 A→30 A, -0.02 A/s,
  30 → 0 A, -0.05A/s
- Plasma test @ 0A

- Strange signals in voltages and temperatures
  - ➢ Short @ Current Leads due to melted cable insulation

Sonja I. Schlachter *et al.*: „Operation of an HTS magnet in heat flux and radio blackout mitigation experiments in plasma wind tunnels" (ASC 2024, Salt Lake City, USA)

Radio Blackout Experiments

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- Results still under evaluation:
  - Effects in Faraday rotation visible
  - Only for some conditions small attenuation changes visible with applied magnetic field
    → unfavorable antenna position ?

<u>Examples test result</u>:

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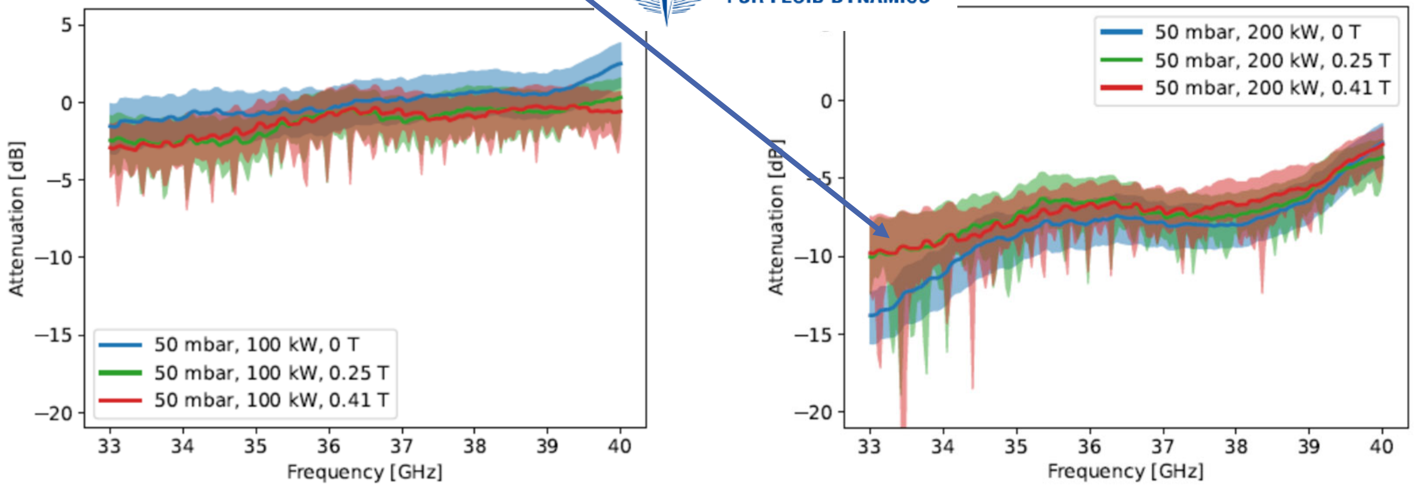
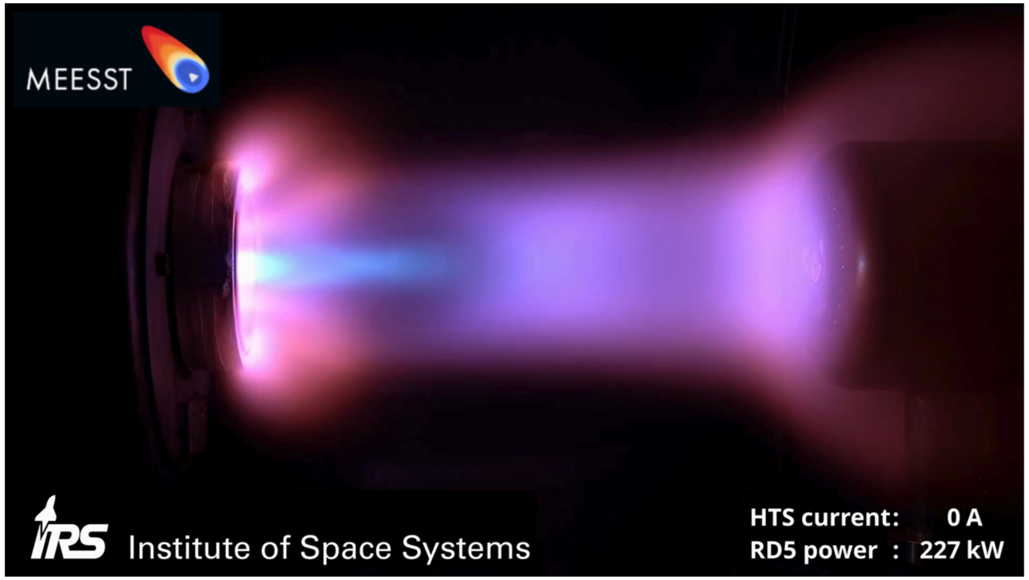


(b) S_{31} **(d)** S_{31}

Heat-Flux Mitigation Experiments at IRS



- Shock layer significantly pushed upstream and outwards the higher the magnet current
- At higher magnet current levels a cone-shaped structure emitting strong lines in the 500-650 nm range emerges in the stagnation region where the B-field lines are strongest axially
- Total heat flux on probe reduced (smaller temperature increase of cooling water)

Summary

- HTS magnet built for radio blackout and heat flux mitigation experiments at VKI (BE) and Stuttgart (Ger), respectively.
- Magnet:
  - Operation with maximum current of 50 A, i.e. ~ 0.66 T at probe surface, due to magnet section with high resistance.
- Experiments:
  - Safe magnet operation at VKI and IRS despite high plasma temperatures burning cables and Cu shield.
  - Radio blackout experiments @ VKI: small effects of magnetic field ↔ antenna position ?
  - Heat flux mitigation experiments @ IRS: shock layer pushed upstream with applied field, however strong particle flux to magnet center.

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