Karlsruher Institut für Technologie

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International Cryogenic Material Conference 2024
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Design and application of HTS magnet for magneto-hydro-dynamic plasma shielding in radio blackout and heat flux mitigation experiments

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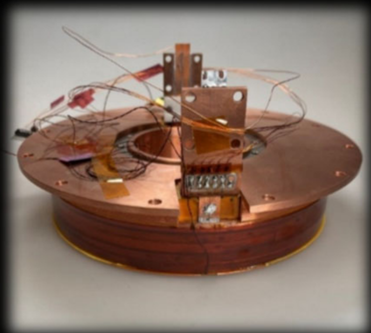
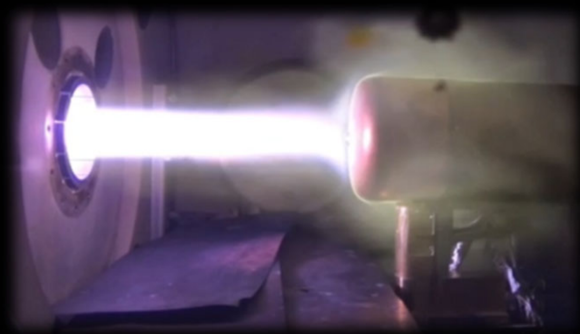
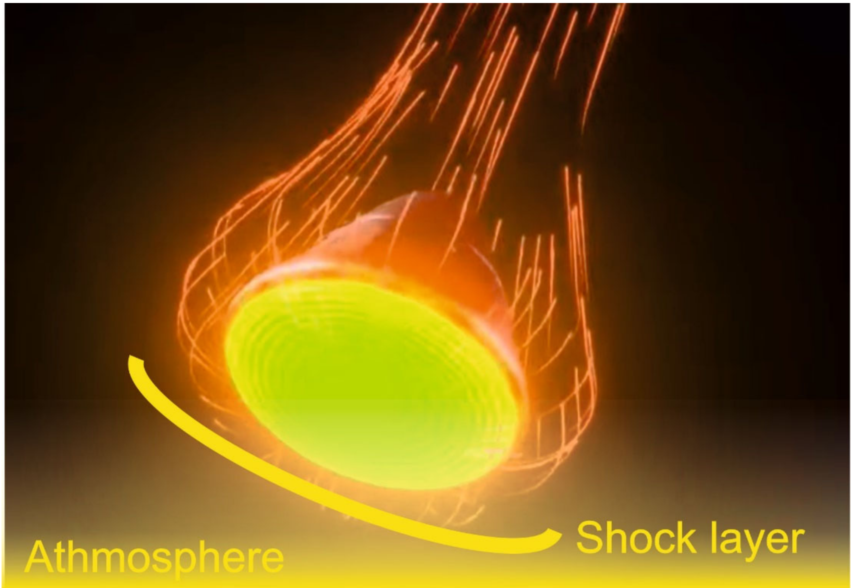




Reentry of Space vehicles: Heating

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

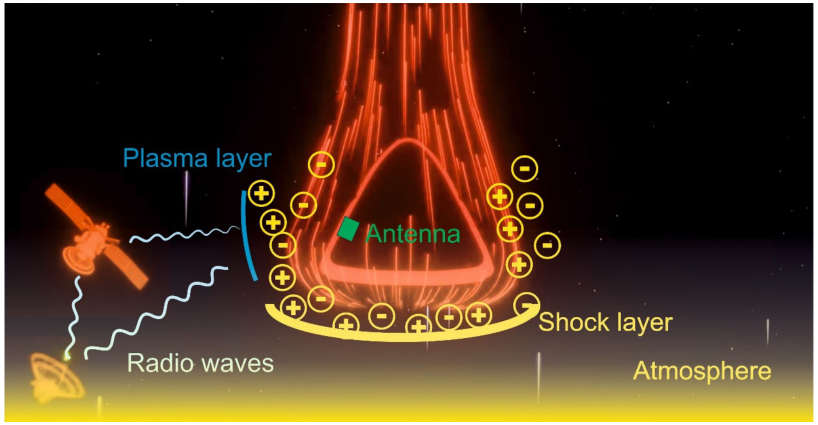
- **Missions and duration of blackout phases:**
  - Gemini 2: ~ 4 min.
  - Apollo: ~ 3 min.
  - Mars Pathfinder: ~ 30 sec.
  - Space Shuttles ~ 30 min.

- **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)

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

MEESST

Modelling:

KU Leuven (BE)
Project coordination
Code harmonization

University of Luxembourg (LU)
Radio blackout modelling

University of Southampton (UK)
Code harmonization

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:

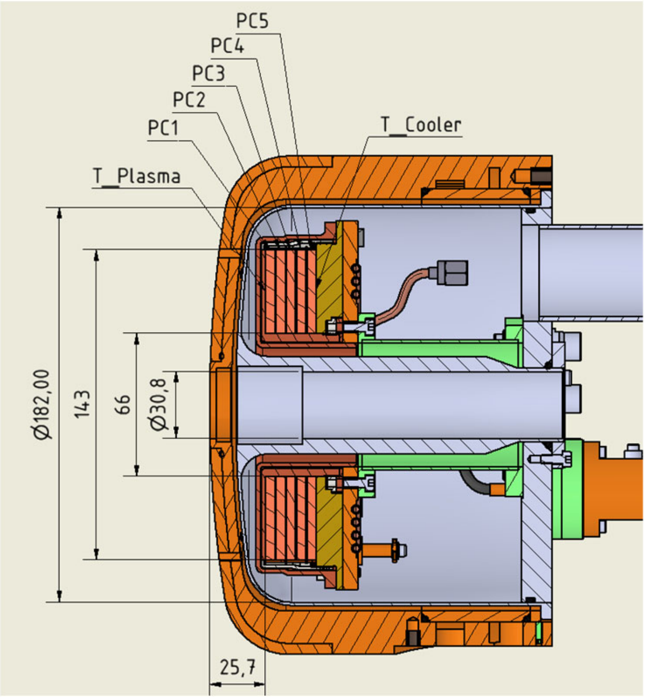
Von Karman Institute (BE)
Experimental radio blackout research

Institute of Space Systems (DE)
Experimental heat flux research
Code harmonization

Dissemination:

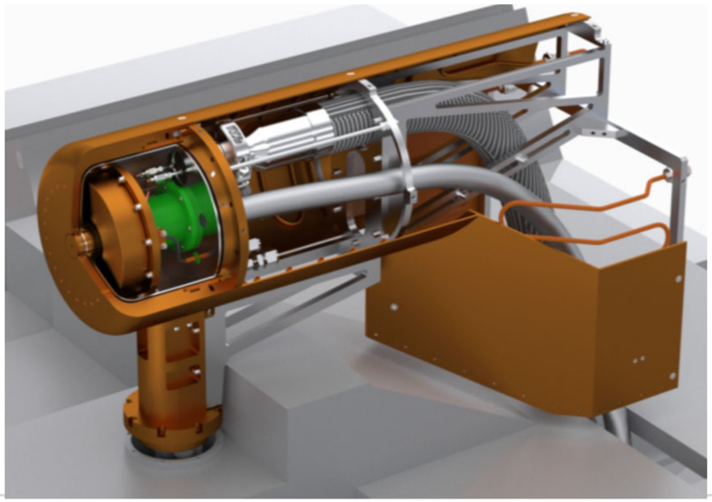
Neutron Star Systems
Project dissemination

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
- 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. upto ~ 10'000 °C)



More on MEESST-Cooling: M. Dalban-Canassy *et al.*, **Wed.-Or8-07**

The MEESST HTS Magnet

Robotic winding of MEESST magnet

- 5 pancakes, 4 mm wide REBCO-CC
- 10 soldered HTS-HTS joints

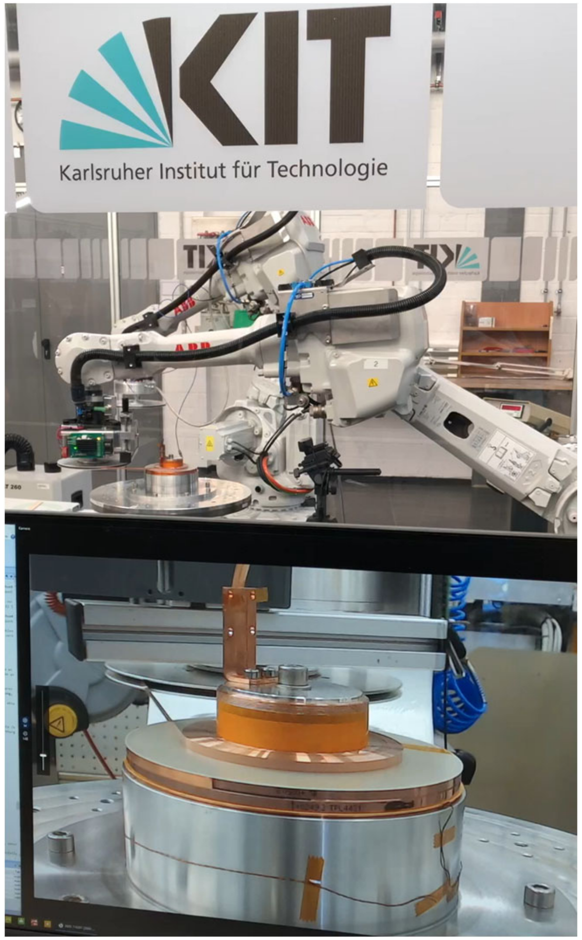
But:

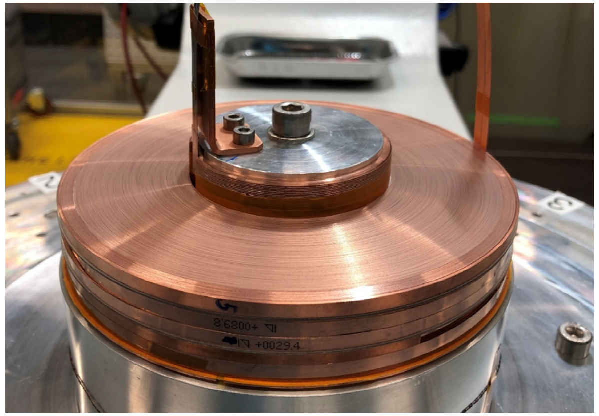
- Low winding density due to irregular shape of tapes
- Coil section in PC2-PC3 with high ohmic resistance

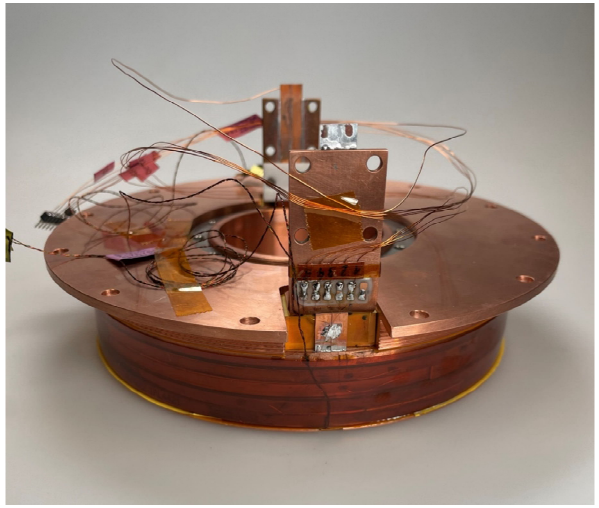
➢ Quench at ~ 62 A, far below expected I_c

→ 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

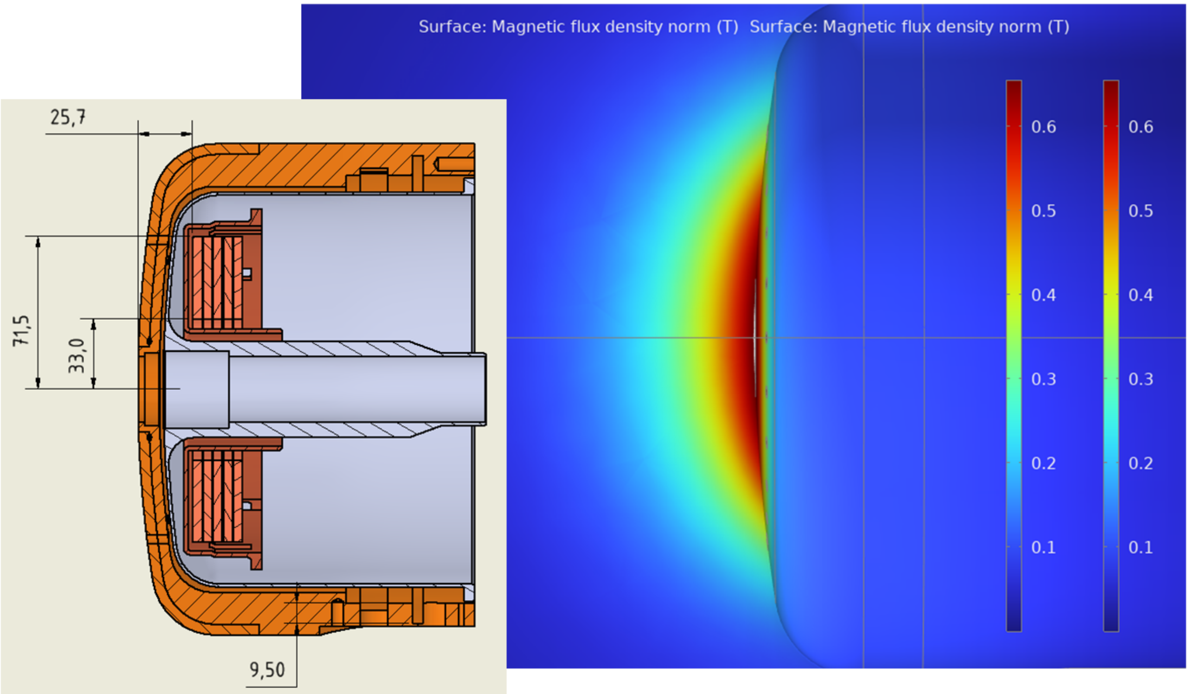


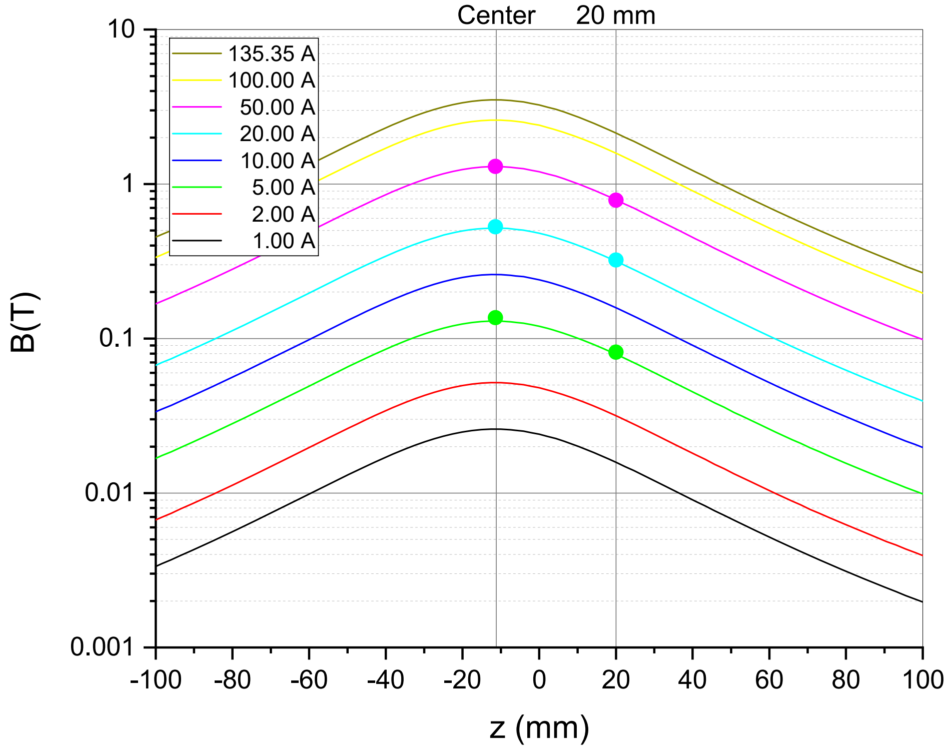




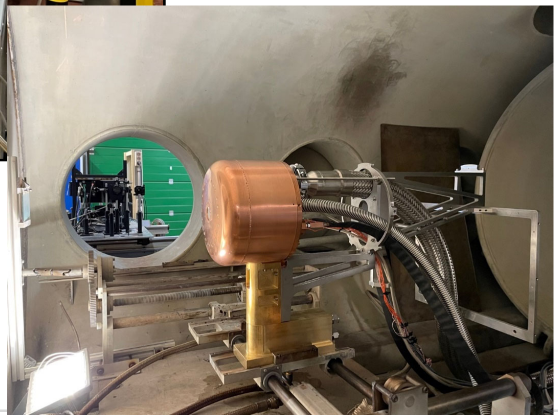
Magnetic field outside the probe at 50 A

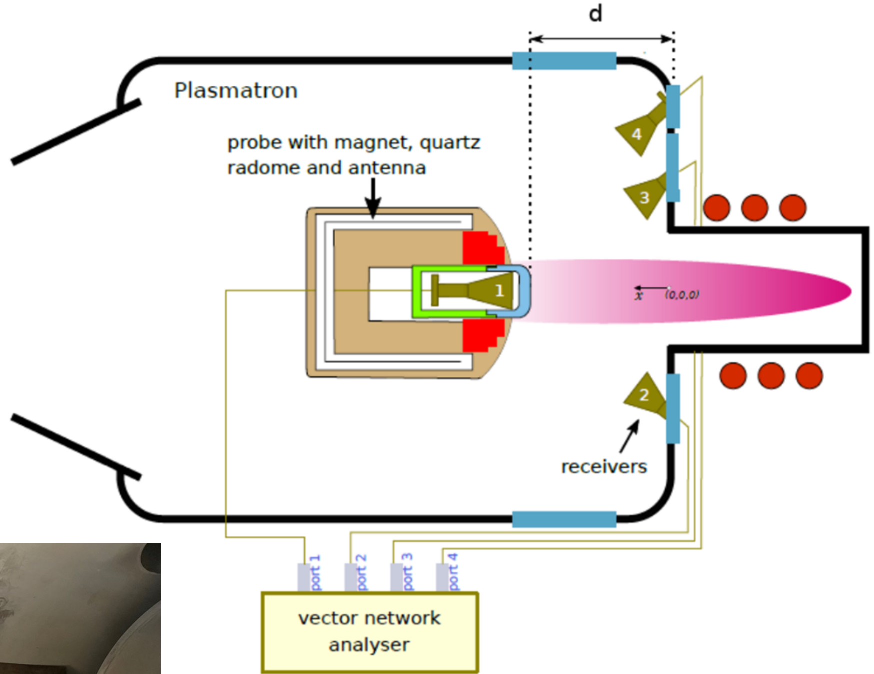
- Maximum field at probe surface ~ 655 mT, max. field at conductor: 2 T





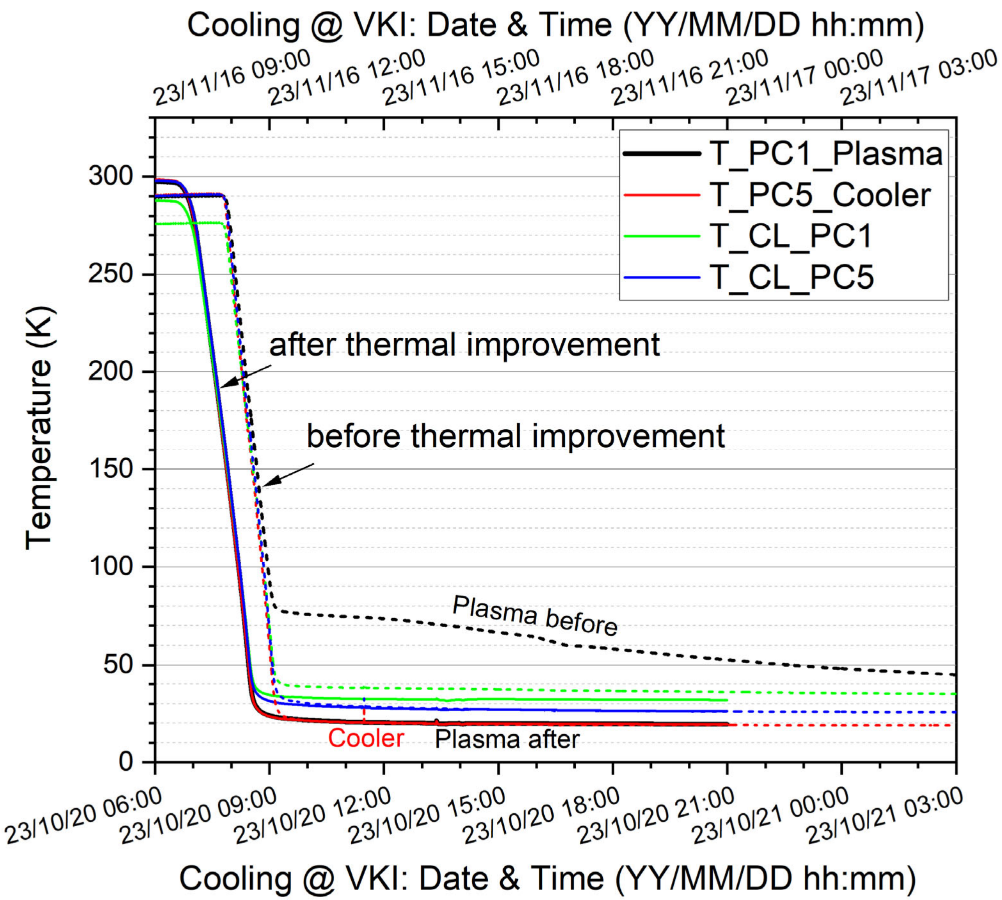
Radio Blackout Experiments at VKI



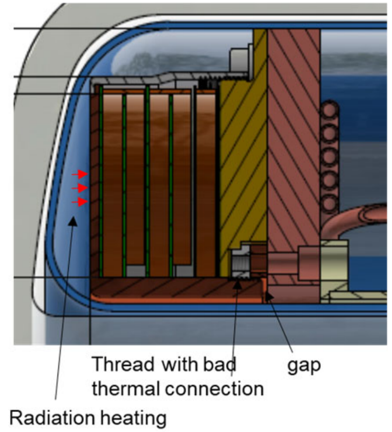


- Plasmas: Air & CO_2
- Static pressures (mbar): 50, 100, 110/120
- Electric Power: 100…300 kW
  - ➢ Particle density

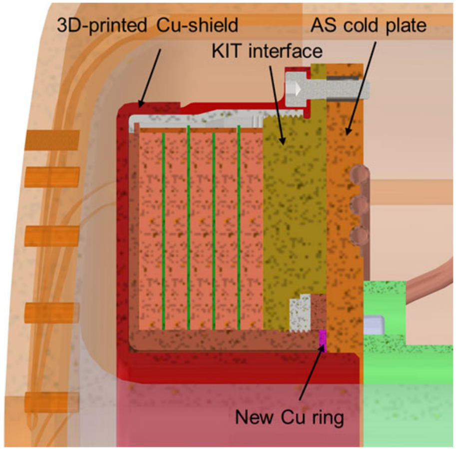
Magnet Temperatures



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

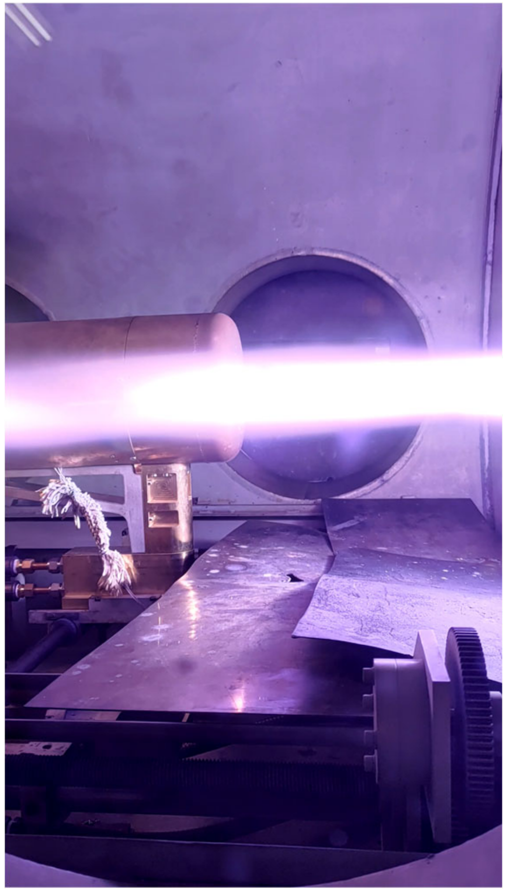


<u>Thermal improvement:</u>
Magnet temperatures at cooler and plasma side almost the same

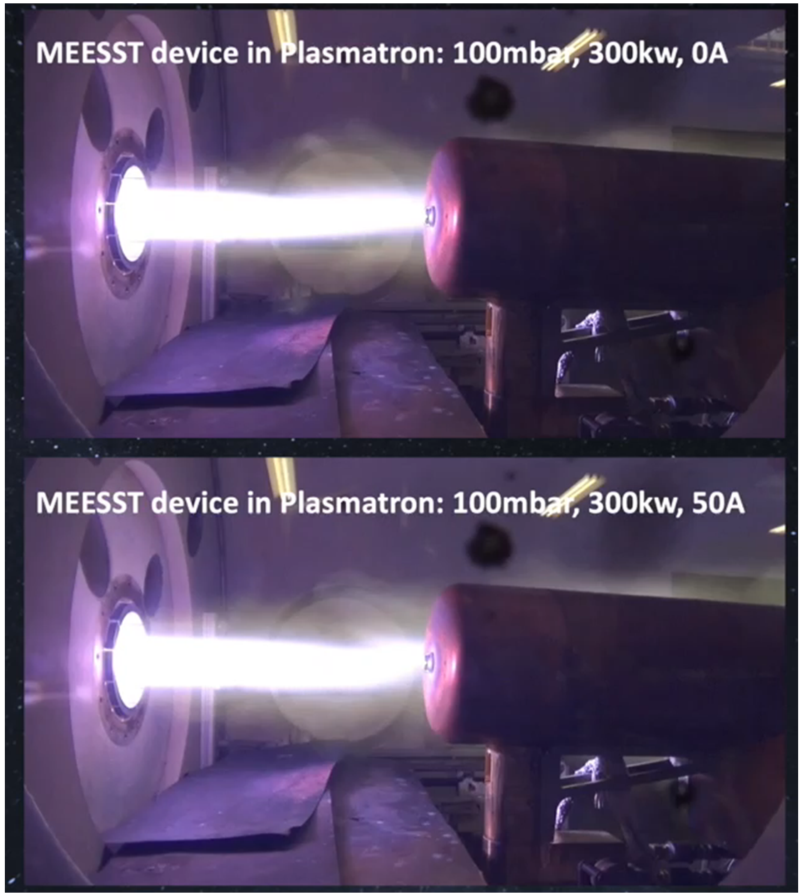


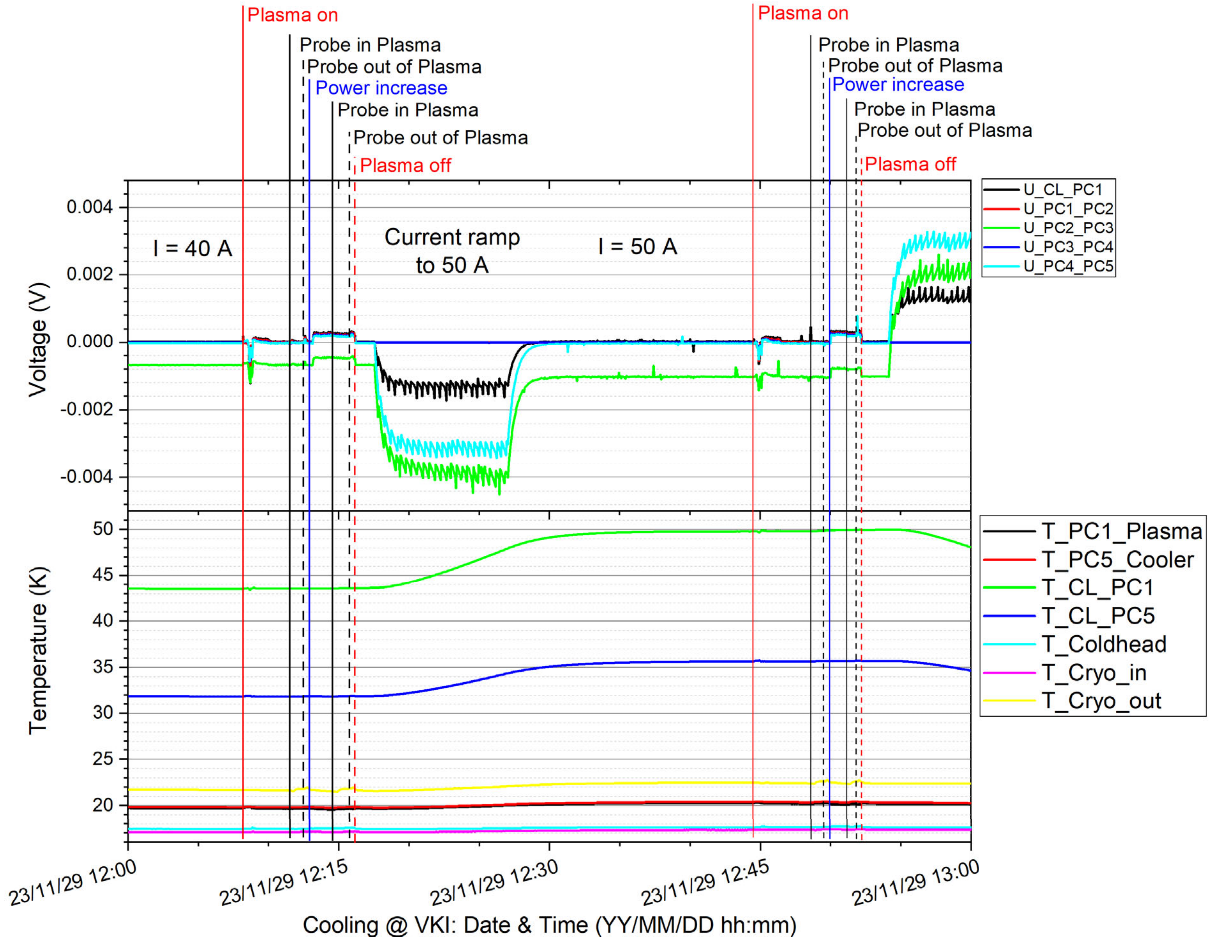
Sonja I. Schlachter *et al.*: „Design and application of HTS magnet for magneto-hydro-dynamic plasma shielding in radio blackout and heat flux mitigation experiments" (ICEC-ICMC 2024, Geneva)

Probe in Plama: Attention, it‘s hot …



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





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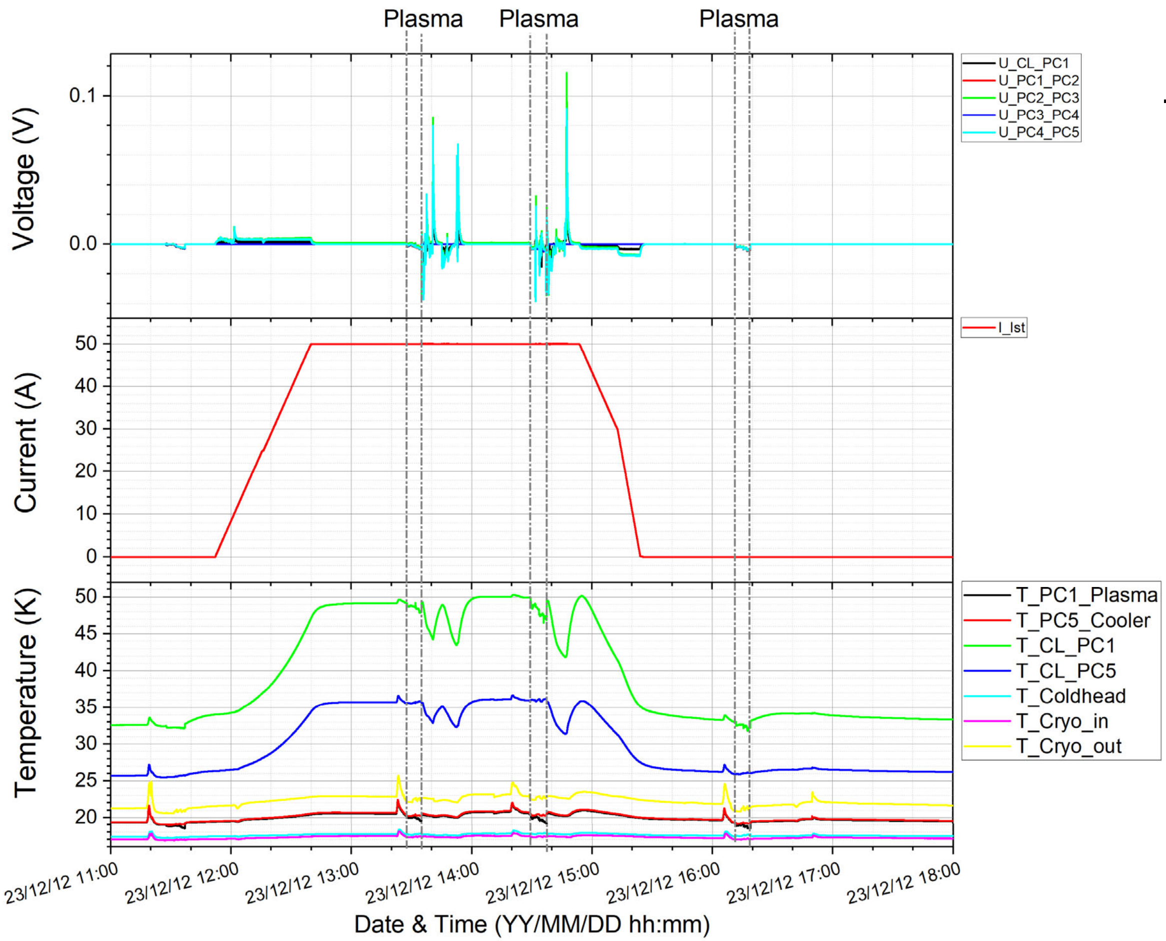
2023-12-12: Plasma Tests – Short at Current Leads



<u>Overview</u>

- 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

Radio Blackout Experiments

- Results still under evaluation
  - Only for some conditions small attenuation changes visible with applied magnetic field
  - Effects in Faraday rotation visible

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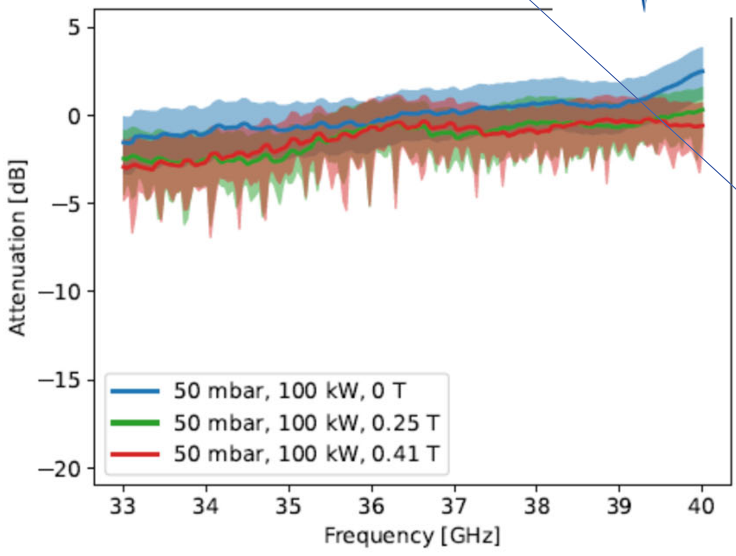
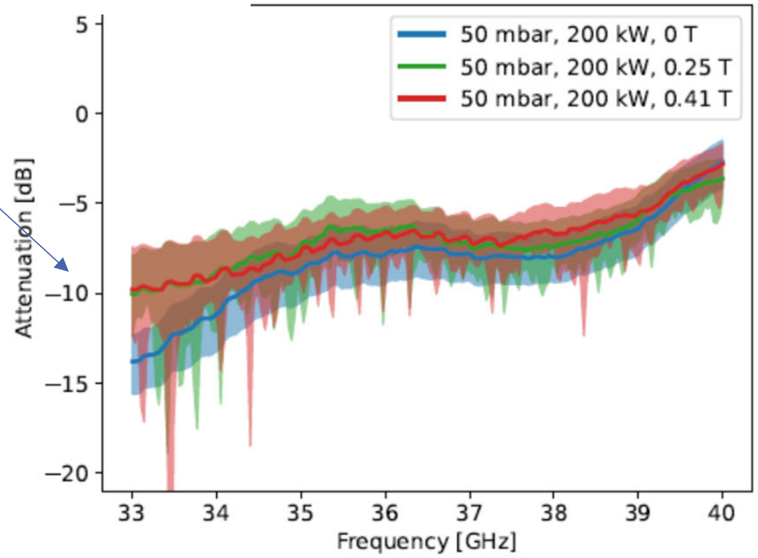
<u>Examples</u>:

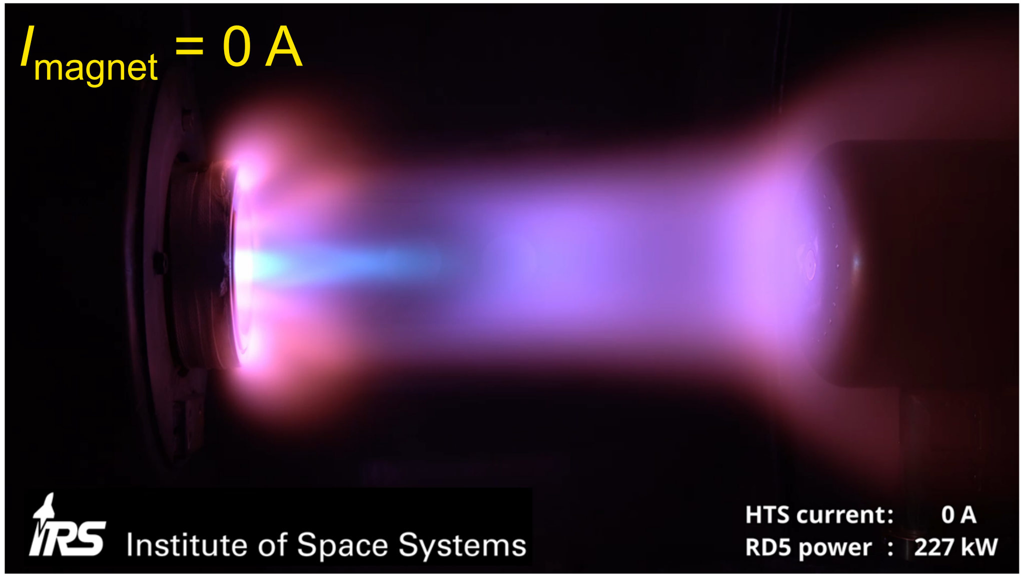


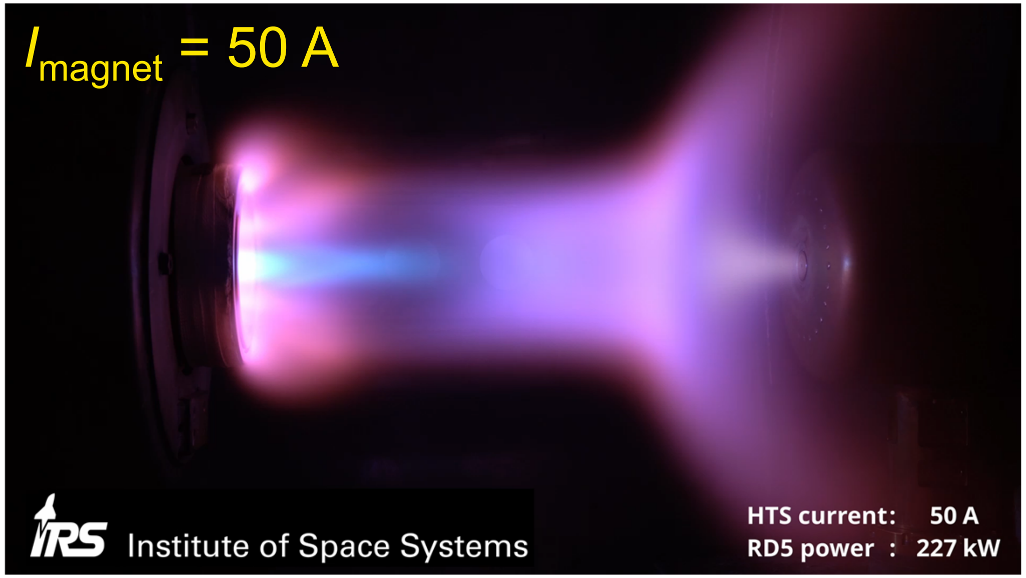
(b) S_{31}



(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:
  - Low winding density due to tape inhomogeneities, high number of resistive joints
  - 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.
  - Small effects of magnetic field in radio blackout experiments @ VKI
  - Shock layer pushed upstream in heat flux mitigation experiments @ IRS, however strong particle flux to magnet center visible with applied field

Acknowledgement

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