Karlsruhe Institute of Technology

CSE European Cryogenic Days 28./29. March 2023

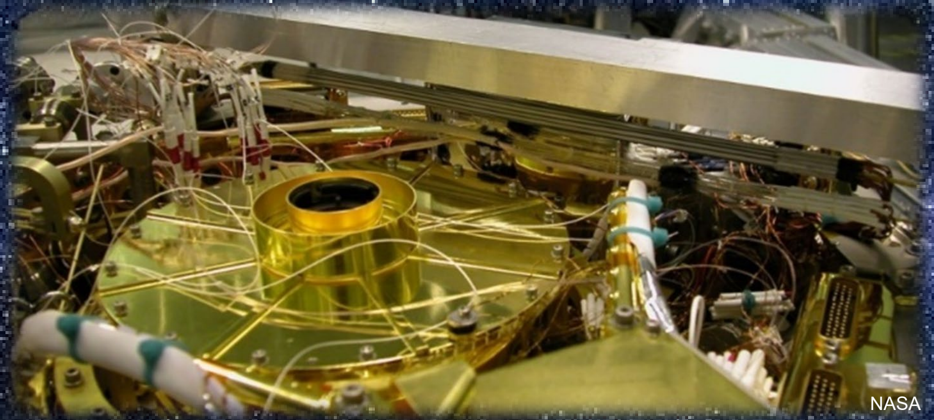
FAIR GSI HEPTech

Cryogenics in Superconductor Applications in Space

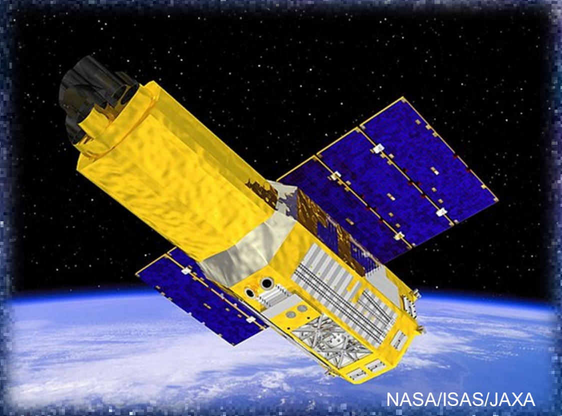
S.I. Schlachter

Karlsruhe Institute of Technology, Institute for Technical Physics,
Hermann-von Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen

NASA/ISAS/JAXA



NASA



NASA/ISAS/JAXA

Superconductor Applications in Space

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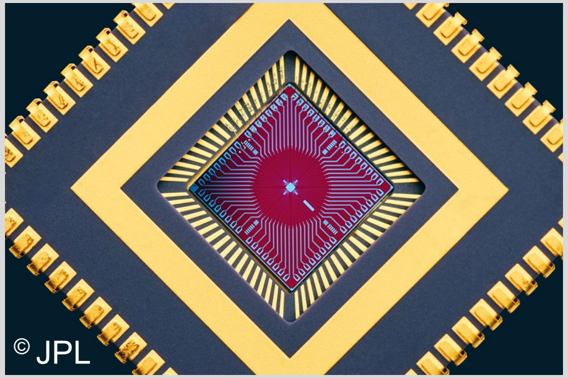
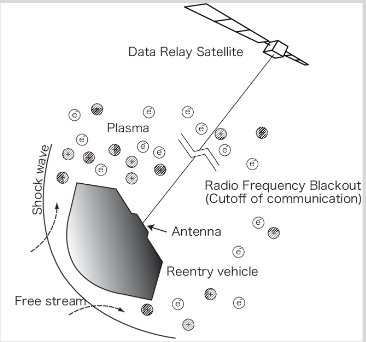
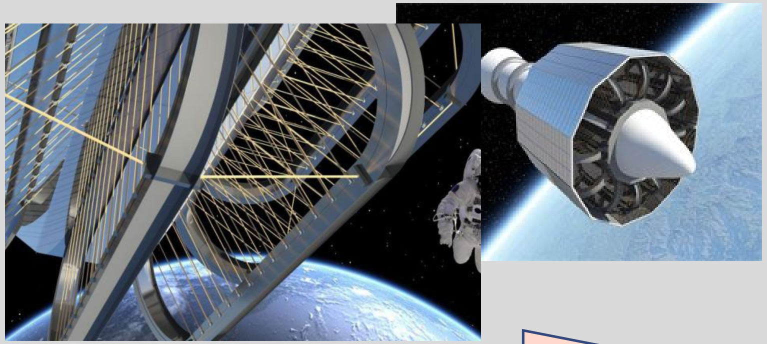
Superconducting Electronis



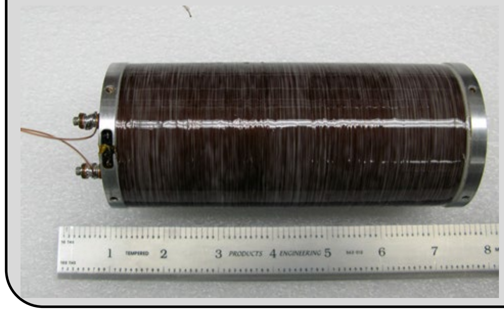
Magnetic Shielding (re-entry, radio blackout, mars missions)

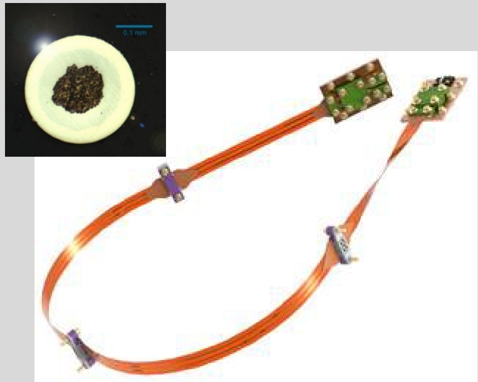




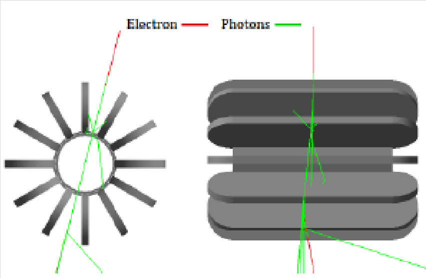
Today → ***Future***

ADR Magnets and Current Leads

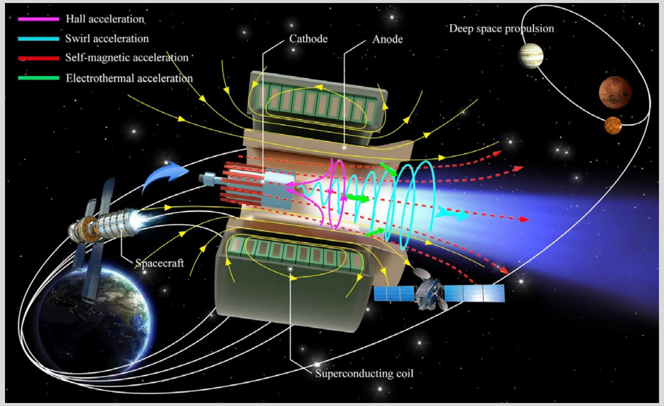




Particle Detectors

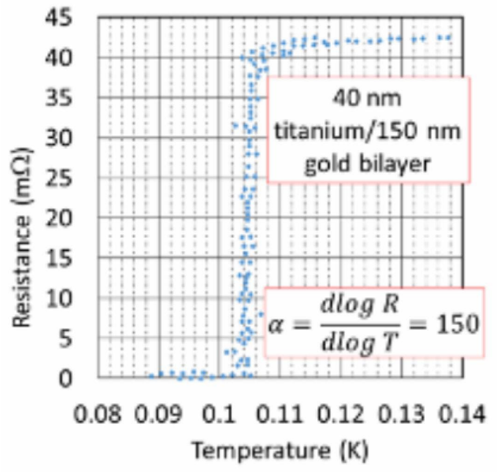


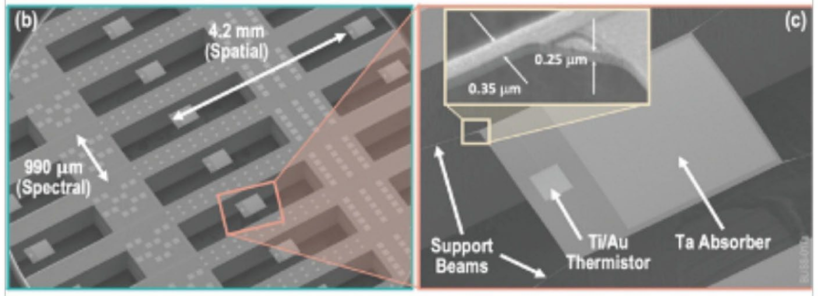
Magneto-Plasma-Dynamic Propulsion

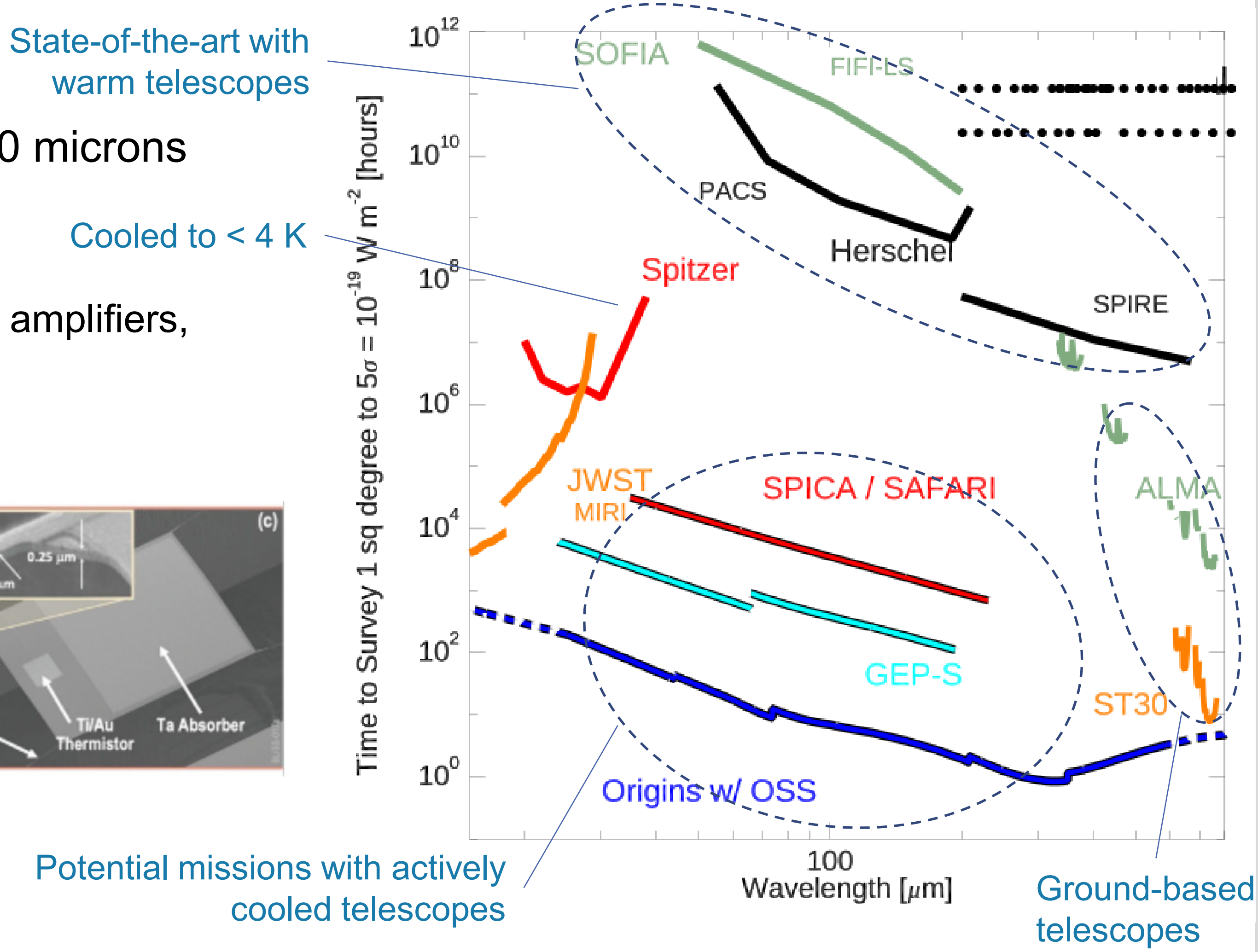


Far-Infrared (Far-IR) Detectors: Superconductivity Enables New Astrophysical Discoveries

- Study of the birth and infancy of galaxies
- far-IR: light with wavelengths between 20 to 500 microns
- far-IR detector has to be cooled to **below 1 K**
  - No semi-conductor electronics
  - Superconducting electronics, e.g. SQUID current amplifiers, radifrequency and microwave resonators
  - TES-sensed bolometers







Source:
https://science.nasa.gov/technology/technology-highlights/far-infrared-detectors-superconductivity-enables-new-astrophysical-discoveries

Superconductors in Space: Why do we need to cool?

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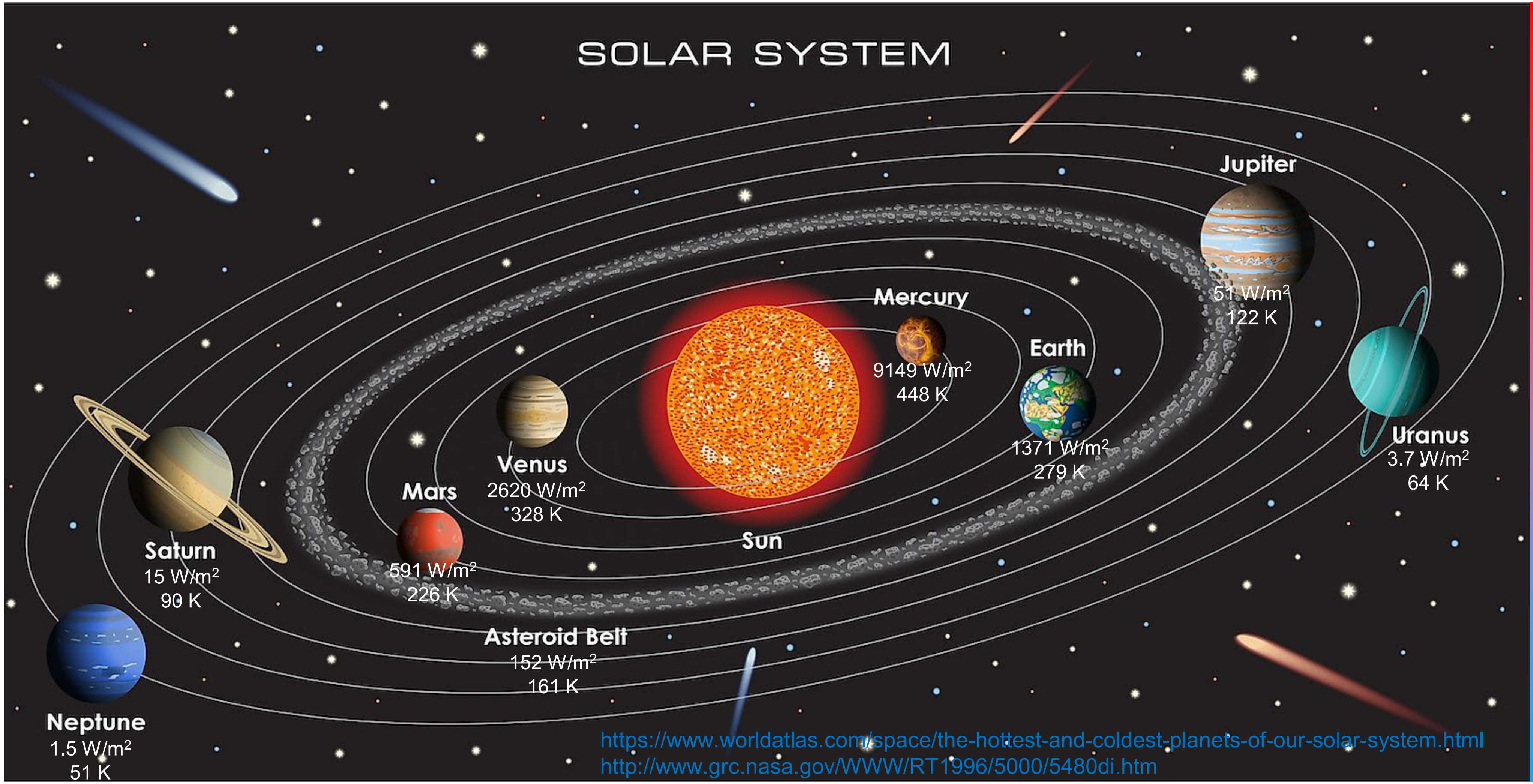

Solar System:

$T = 277\ \text{K} \cdot (1\text{AU}/R)^{1/2}$

AU=average dist. earth-sun

But: Temperature strongly depends on sun / shadow, distance from planets

Deep interstellar space:

2.73 K: Cosmic Microwave Background

Challenges for Space Cryogenics and Applications

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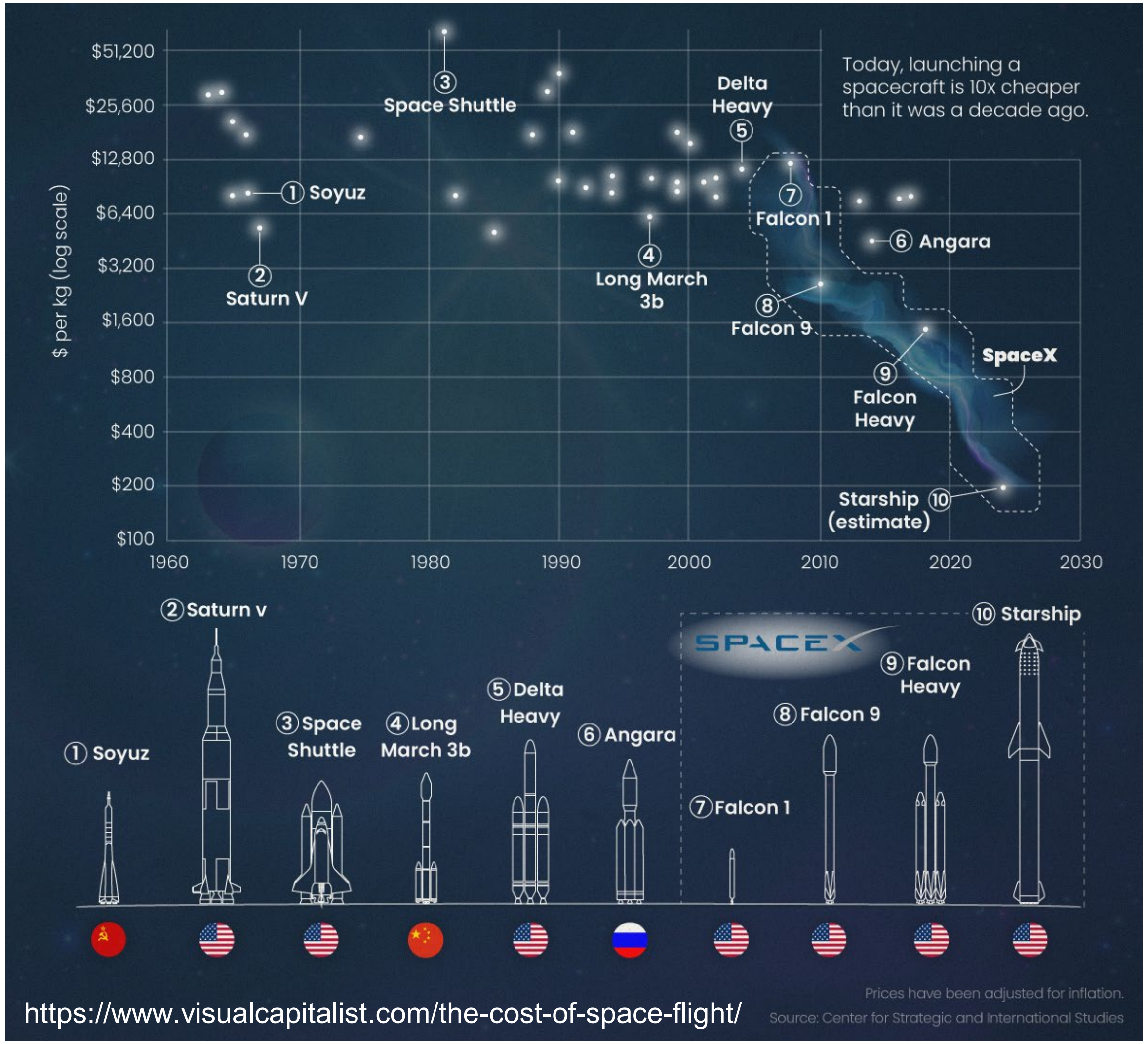
- Weight → Cost
- Limited electric Power
  - Solar panels, radioisotope thermoelectric generators (RTGs)
- No possibility for maintenance
  - Long-term durability
  - Determines lifetime
- Zero gravity
- Space Qualification
  - Mechanical robustness (Vibrations during launch)
  - Low outgasing materials (vacuum applications)
  - Qualified processes
  - …



Space Cooling Chain

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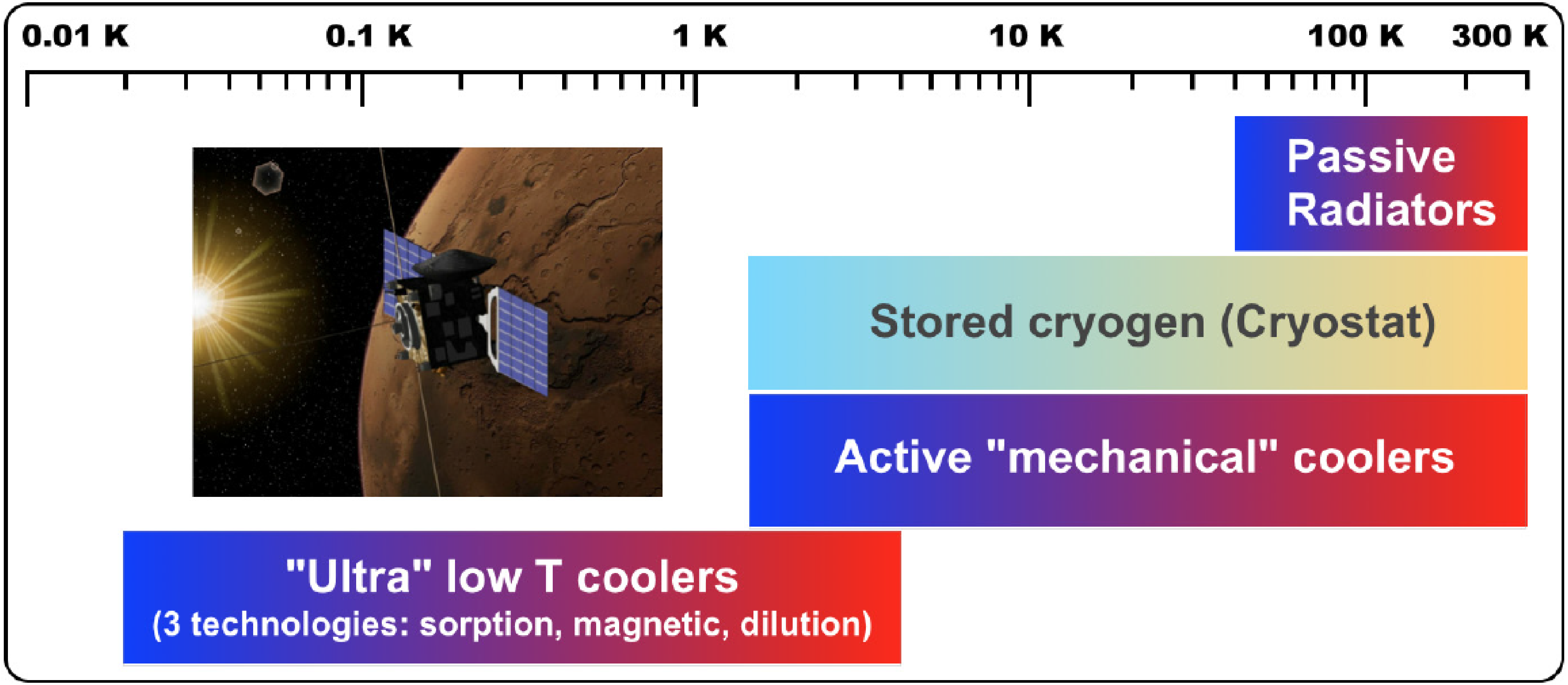
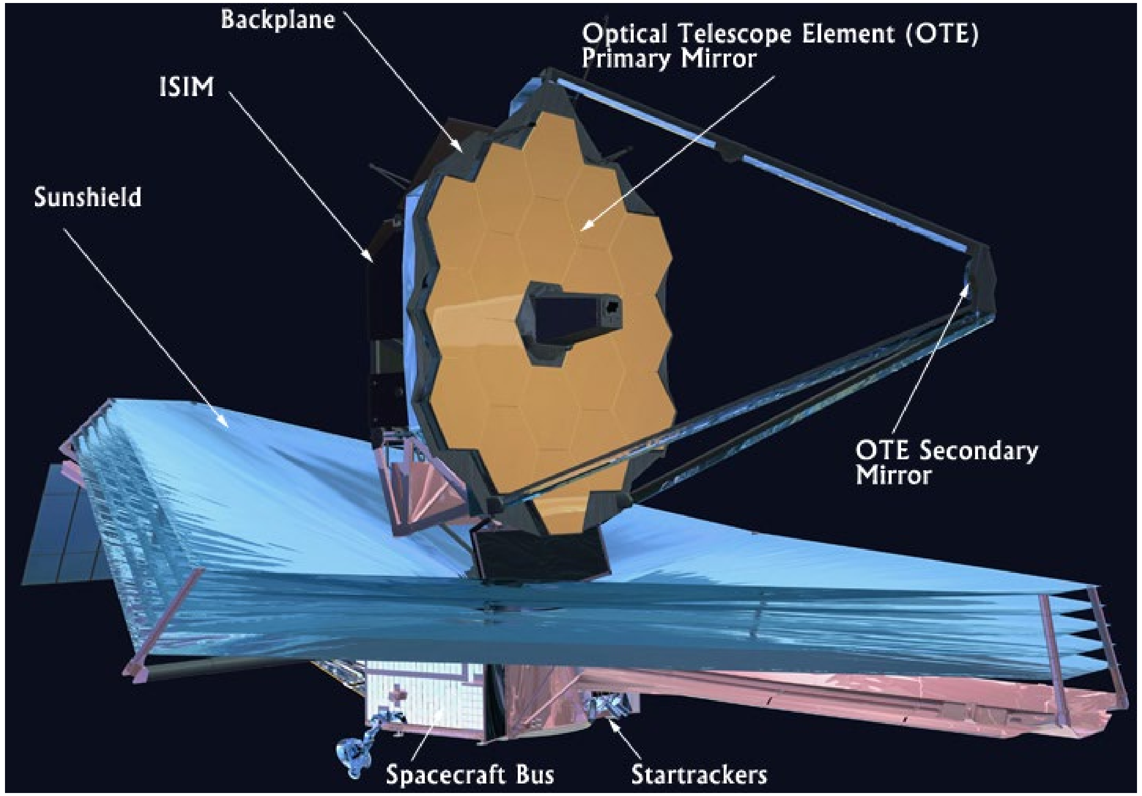


L. Duband, „*Space cryocooler developments*", Physics Procedia 67 (2015) 1 – 10

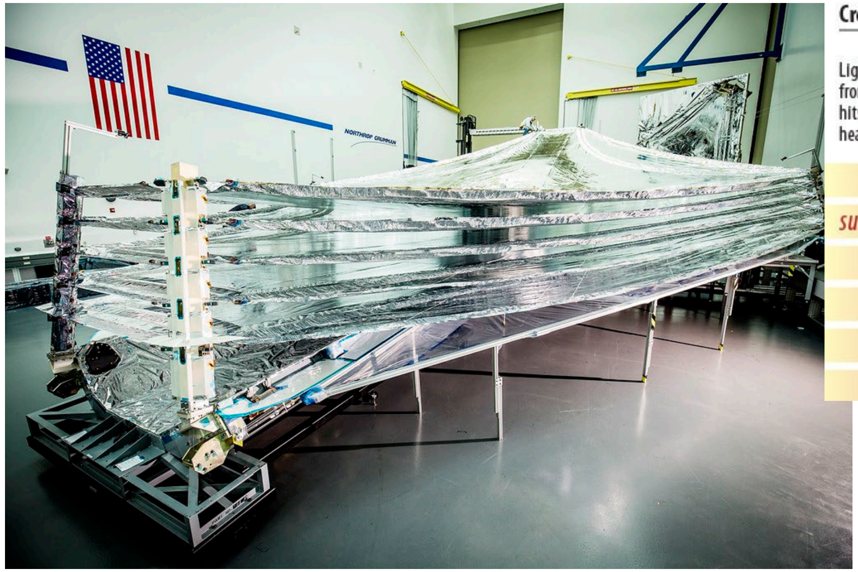
Passive Radiators:

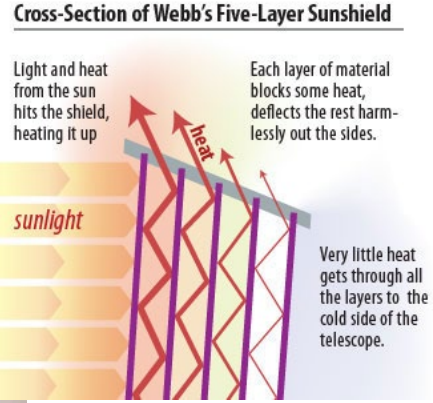
Radiator panels: lightweight, long lifetime

Example: James Webb Space Telescope



https://webb.nasa.gov/content/observatory/sunshield.html





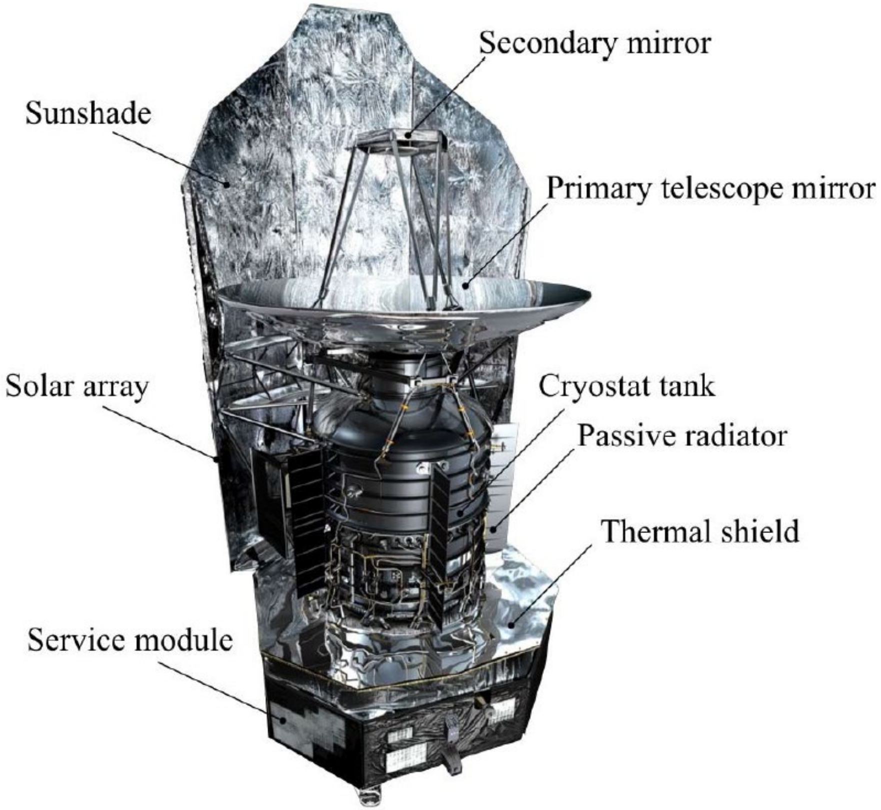
Protect telescope from external sources of light and heat (Sun, Earth, and Moon) as well as from heat emitted by the observatory itself.

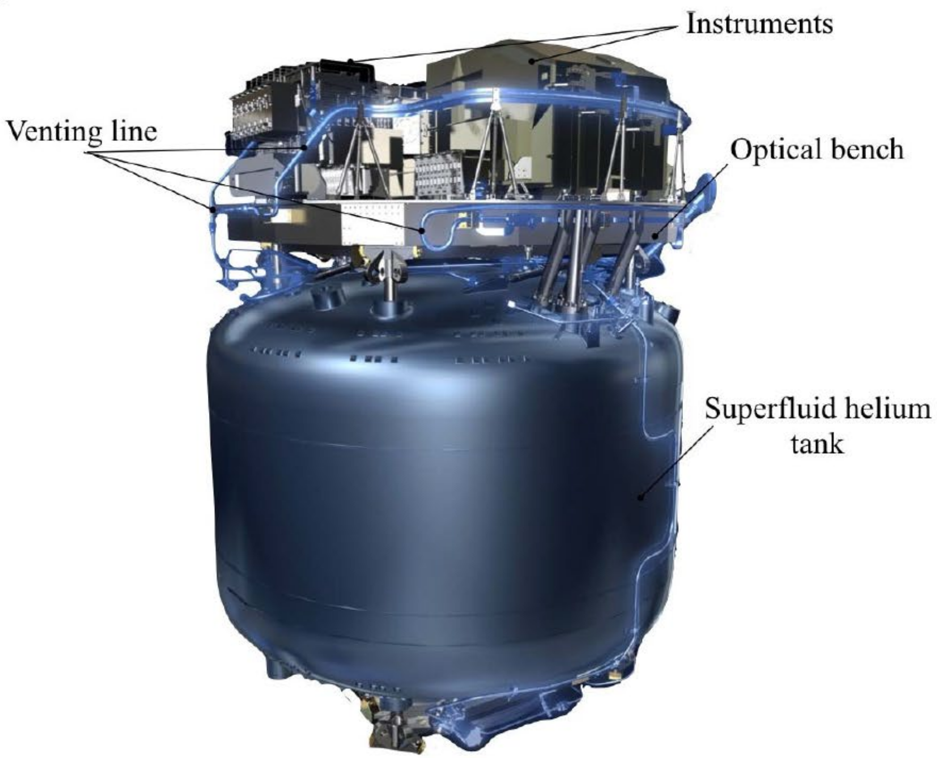
- ➢ Modeled max. temp. at outermost layer: 383 K
- ➢ Modeled minimum cold side temperature: 36 K

Liquid / Solid Cryogens in Space

Liquid or solid cryogens, excellent T-stability, no vibrations, *but:* high launch mass, limited lifetime

Example: HERSCHEL (Superfluid helium tank contains about 2360 liters of He II., launched in 2009)





L. Duband et al., Cryocoolers 16, edited by S.D. Miller and R.G. Ross, Jr., International Crocooler Conference, Inc., Boulder, CO, 2011

Mechanical Coolers
Temperature range down to 10-15 K

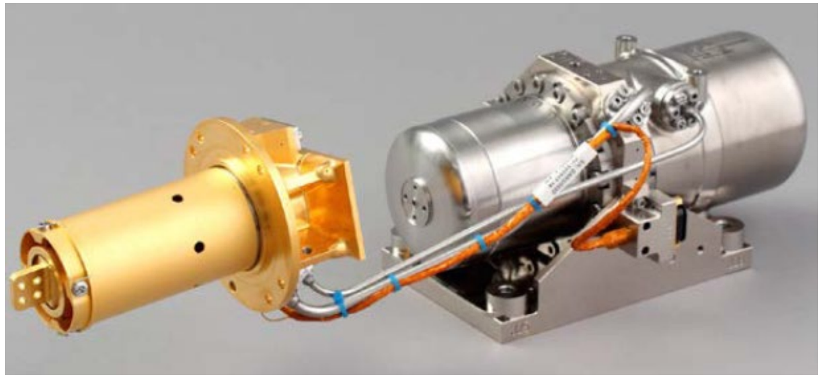
Challenges:

- Power consumption (el. power provided by solar panels or radioisotope thermoelectric generators)
- Reliability for long time periods without maintenance
- Vibration

Types:

- Stirling Coolers
- Pulse Tube Coolers

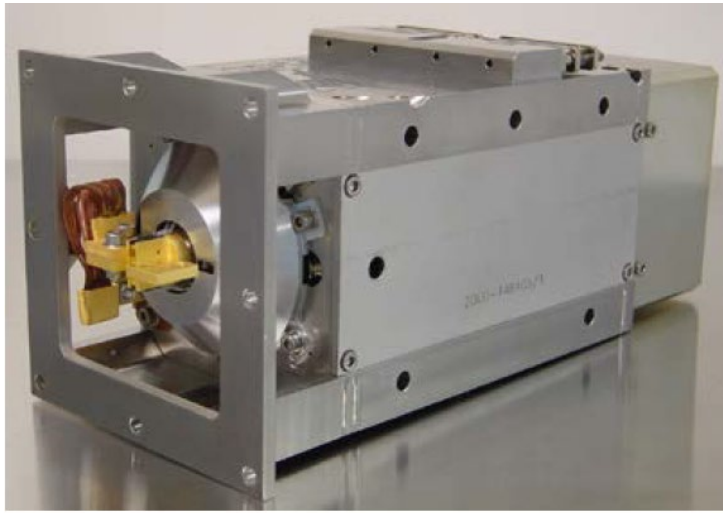
Hybrid J-T, Stirling and Pulse Tube Cooling for Temperatures down to 4 K



Large pulse tube cooler (LPTC) developed conjointly by CEA-SBT, Thales and Air Liquide for Meteosat third generation (MTG) and the CSO program

Sub-Kelvin Cooling

300 mK helium sorption cooler
(HERSCHEL)



robust, simple and lightweight,
but T > 200 mK, recycling necessary

100 mK dilution cooler
(PLANCK)

Continuous, T ≥ 50 mK
But: lifetime limited (open cycle)

50 mK ADR
(ASTRO-H / HITOMI)

High thermodynamic efficiency,
low temperatures,
but heavy, magnetic field issues

→ Combinations of coolers for optimization, e.g. sorption cooler + ADR

L. Duband, "*Space cryocooler developments*", Physics Procedia 67 (2015) 1 – 10

Cooling System of Soft X-Ray Spectrometer (SXS) on HITOMI satellite to cool detector array to 50 mK

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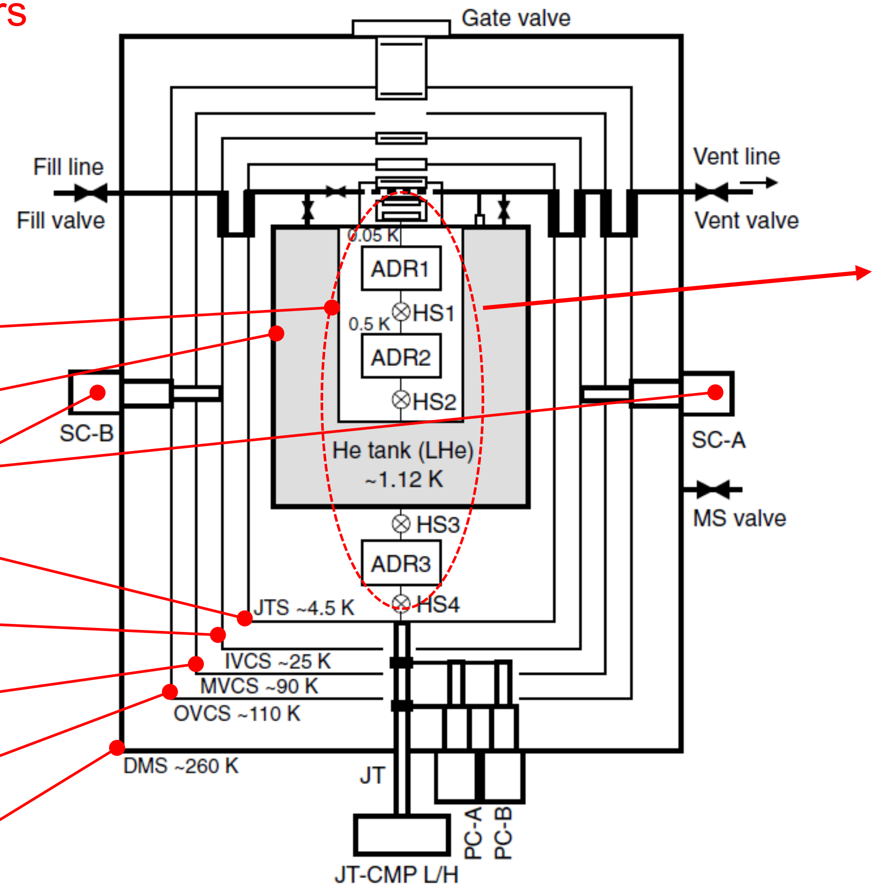
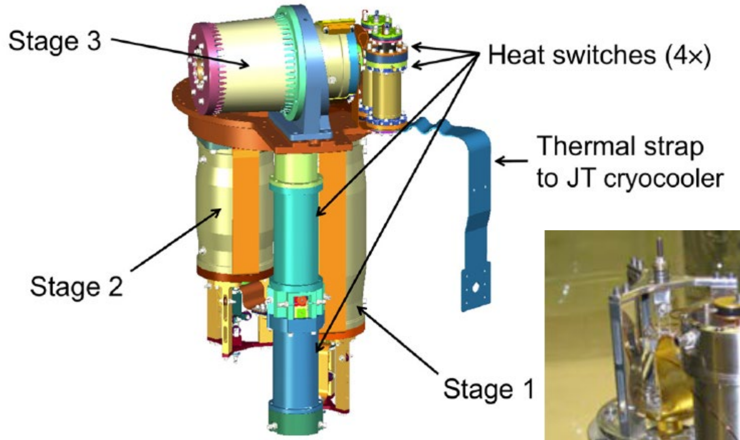
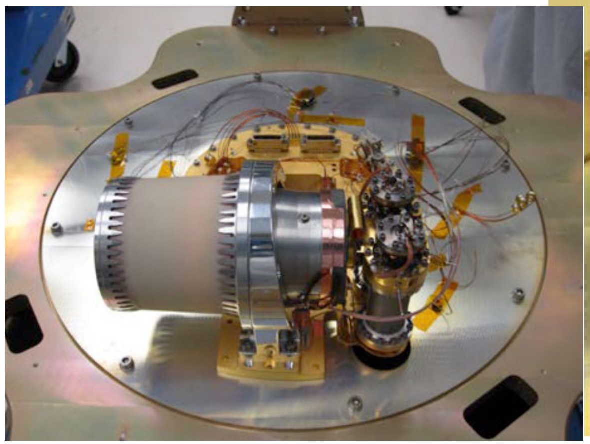
Projected LHe lifetime: > 3years

Operation possible when He depleted → ADR3







R. Fujimoto *et al.*, *Performance of the helium dewar and the cryocoolers of the Hitomi soft x-ray spectrometer*, Journal of Astronomical Telescopes, Instruments, and Systems 4(1), 011208 (Jan–Mar 2018)

P.J. Shirron et al., "*Design and on-orbit operation of the soft x-ray spectrometer adiabatic demagnetization refrigerator on the Hitomi observatory*", Journal of Astronomical Telescopes, Instruments, and Systems 4(2), 021403 (2018)

SXS: Heat flow diagram in orbit

Dewar Main Shell (DMS)

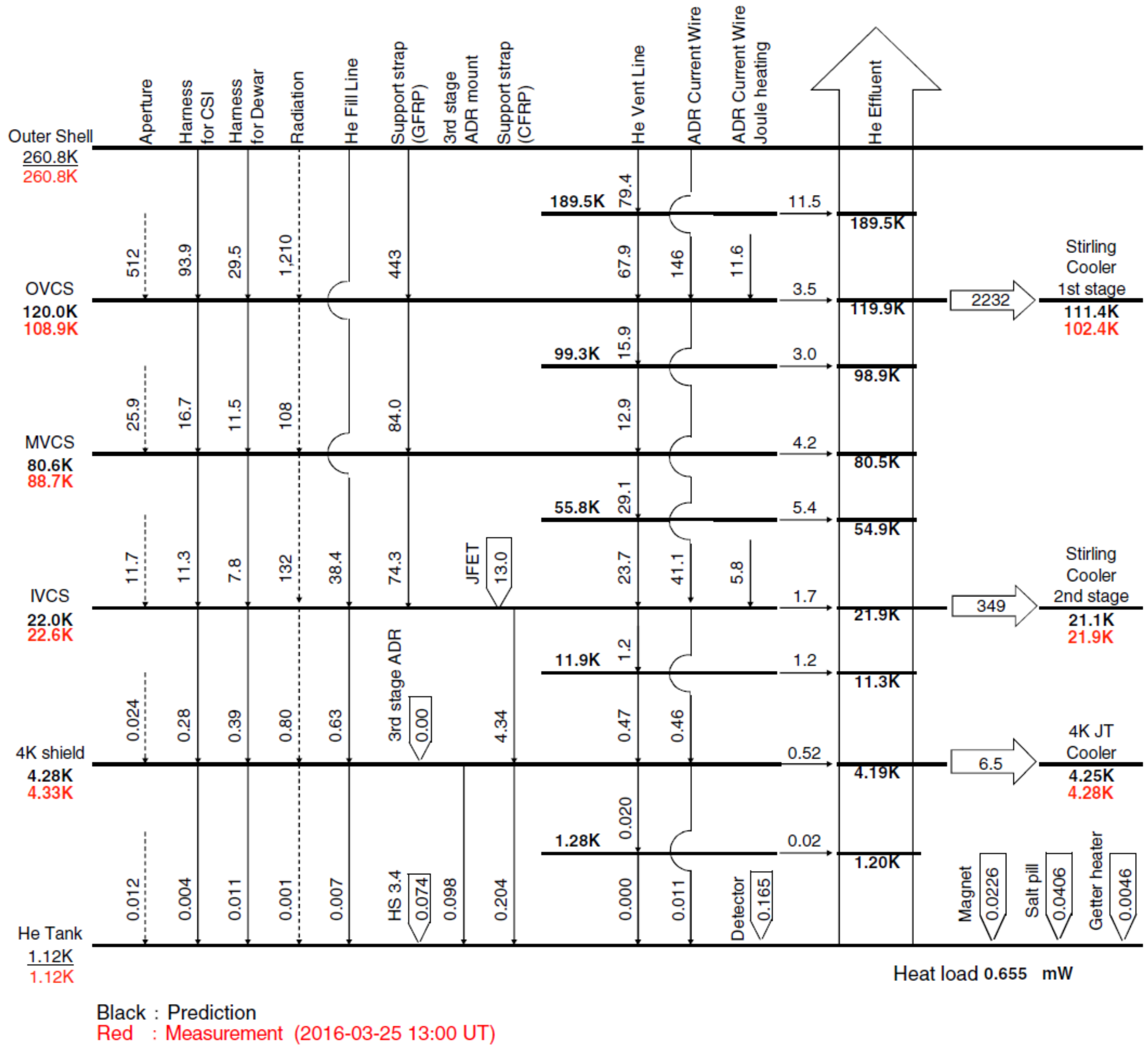
Outer vapor-cooled shield (OVCS)

Middle vapor-cooled shield (MVCS)

Inner vapor-cooled shield (IVCS)

Joule Thompson stage (JTS)

LHe tank (> 30 L)

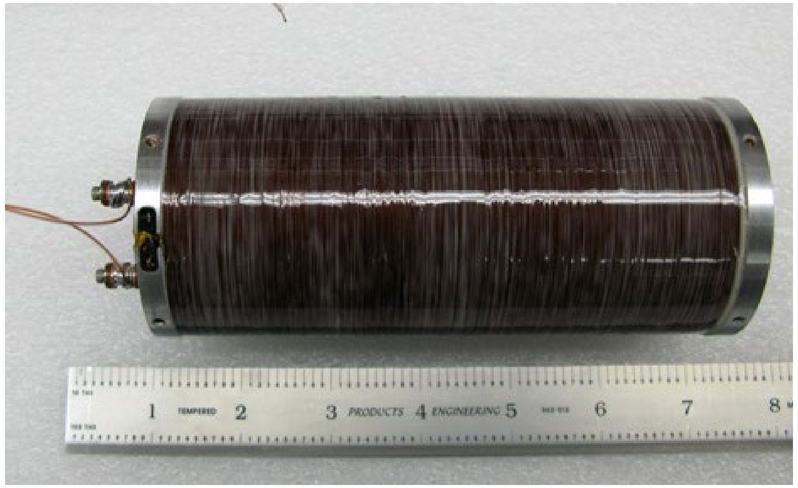


Superconducting ADR Magnets

Low currents, high winding numbers
→ thin conductors required, usually NbTi – higher *T* possible by using Nb_3Sn

Hitomi lower stage NbTi ADR magnet

- Insulated NbTi wire, Ø=0.1 mm
- Total Mass: 1.14 kg
- Magnetic field: 2 T
- Magnet current: 2A



P. Shirron *et al*,. „ADR design for the Soft X-ray Spectrometer instrument on the Astro-H mission“, Cryogenics 50 (2010) 494–499

Lightweight Nb_3Sn ADR Magnet for higher operating temperature

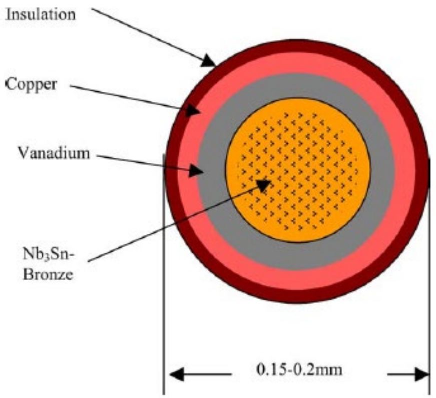
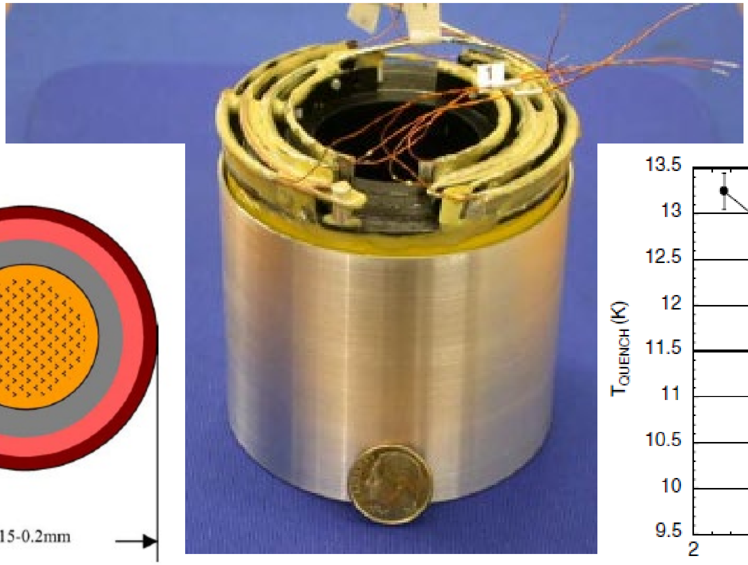
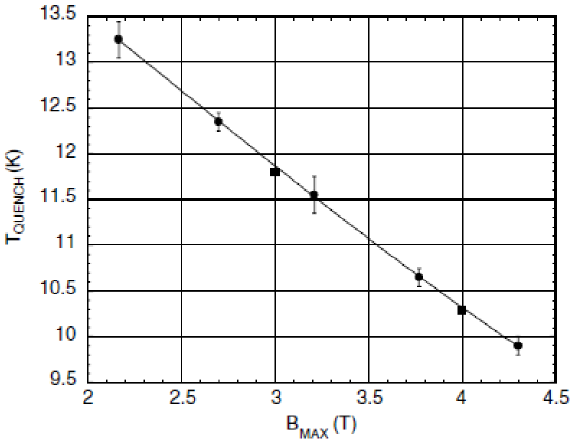


Fig. 1. Basic components of a reinforced Nb_3Sn wire.



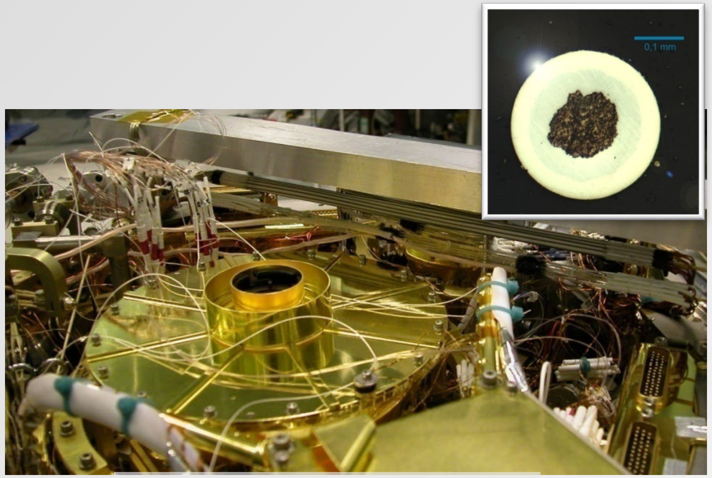


S. Pourrahimi et al., *Manufacturing of lightweight low-current Nb3Sn ADR magnets operating at 10 K,* Cryogenics 46 (2006) 191–195
J. Tuttle et al., *A lightweight low-current 10 K magnet for space-flight ADRs,* Cryogenics 46 (2006) 196–200

Superconducting Current Leads

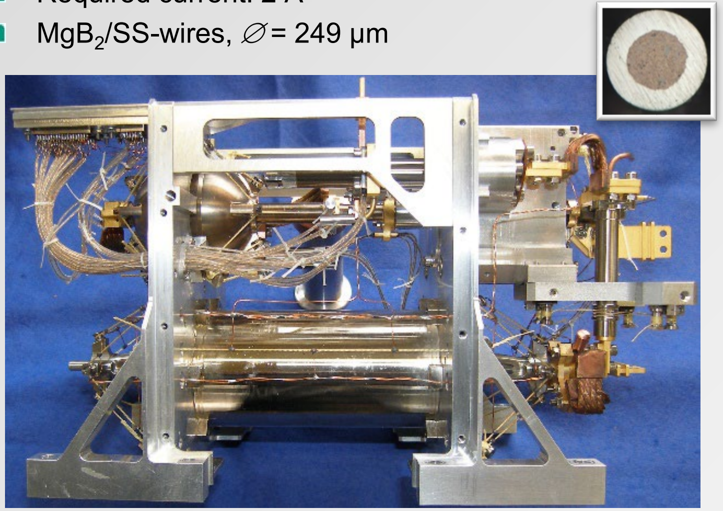
Cooling detectors to T < 100 mK with ADRs: low current magnets with B = 2-3 T, high winding numbers

XRS-2 Instrument on Satellite „Suzaku“
- CLs for ADR magnet and valves
- MgB_2/Fe/SS-wires, ∅ = 310 µm
- Required currents:
  - Magnet Leads: I = 2 A @ 17 K
  - Valve Leads: I =1 A @ 17 K



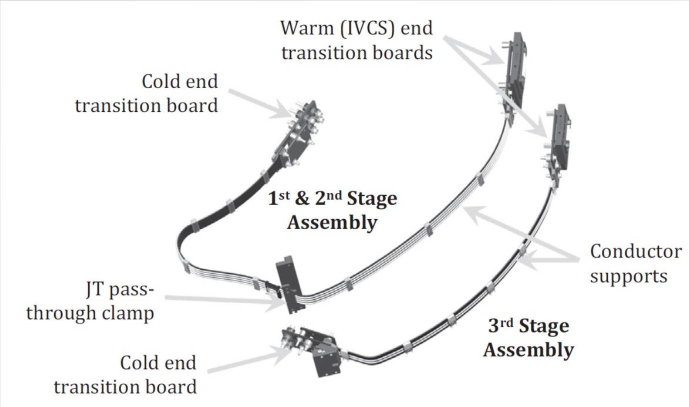
Courtesy of J.S. Panek, NASA

Engineering model of ADR/sorption cooler for SPICA / SAFARI instrument
- CL for ADR magnet
- T = 4.9 K - 20 K
- Required current: 2 A
- MgB_2/SS-wires, ∅ = 249 µm



J.-M. Duval *et al.*, IOP Conf. Series: Materials Science and Engineering 101 (2015) 012010 doi:10.1088/1757-899X/101/1/012010

Hitomi / XRSM high-temperature-superconductor lead assemblies
- CL for 3-stage ADR magnets
- Warm end: IVCS: T_{max} = 28 K - 62 K
- Cold end 1.2 K (1st and 2nd stage), 4.5 K (3rd stage)
- Nominal current: 2 A, Max. current: 5 A
- REBCO Tapes, 1 mm width



E.R. Canavan *et al.*, Cryogenics 64 (2014) 194–200

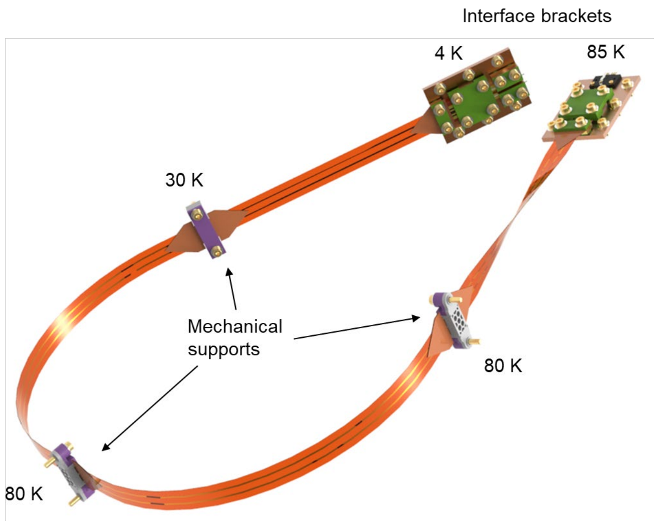
KIT / NASA — KIT / CEA: MgB_2 (T_c ~ 39 K)

NASA: REBCO (T_c ~ 89 - 93 K)

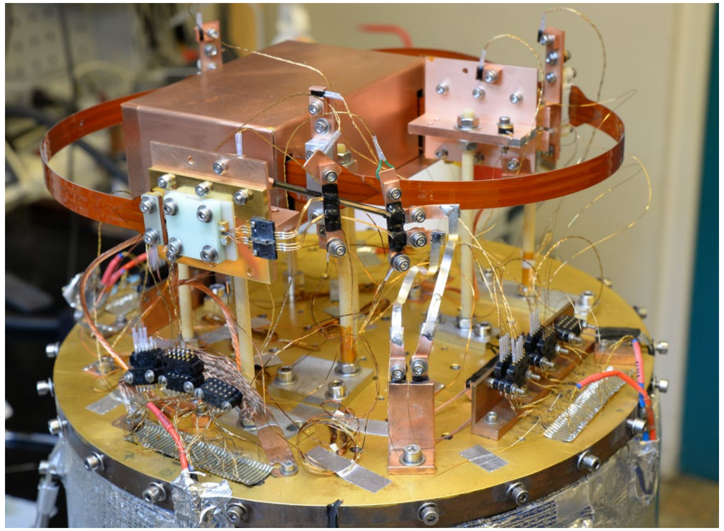
ESA HTS Harness Engineering Model

- Current leads for ADR magnet, nominal Current: *I* = 2 A
- Laser-cut REBCO HTS tapes, 1 mm width
- High warm-end temperature: 85 K || Cold end temperature: 4 K
- Maximum heat load at cold end: 1 mW
- 3-axis flexibility (minimum bending radius 5 cm) but: high mechanical stability
- Mechanical supports @ 30 K and 80 K with 25 cm distance between supports

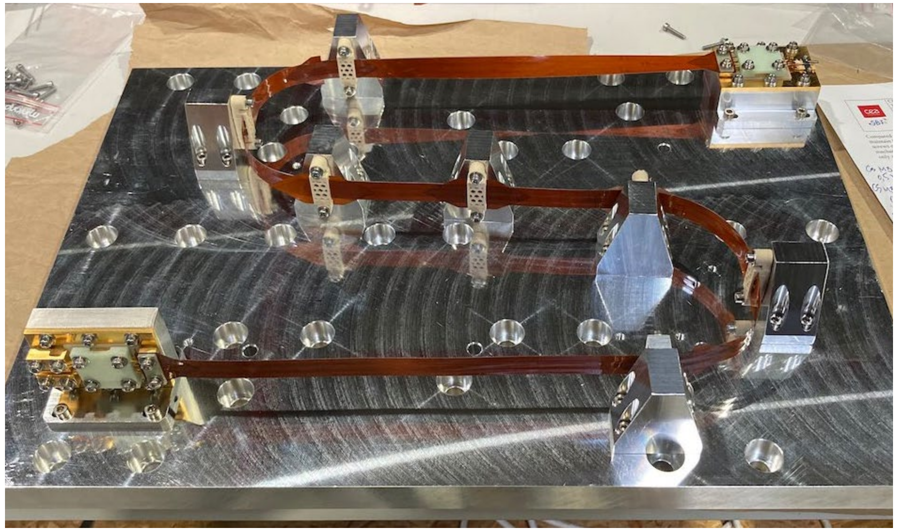
CAD model of Harness



Thermal testing @ CEA-DSBT



Setup for mechanical tests (sine, random, shock)

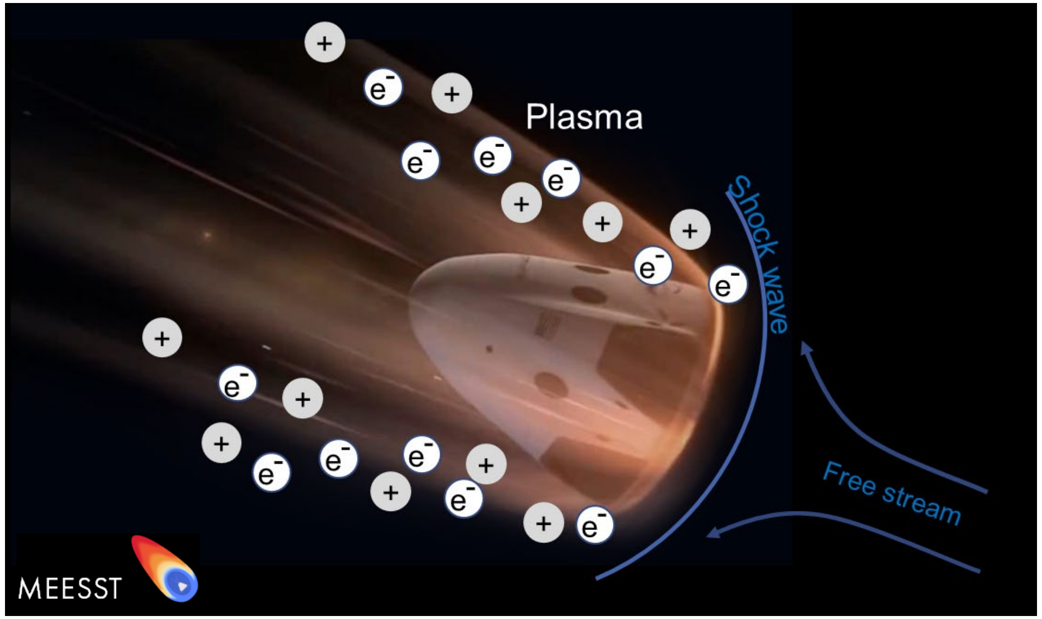


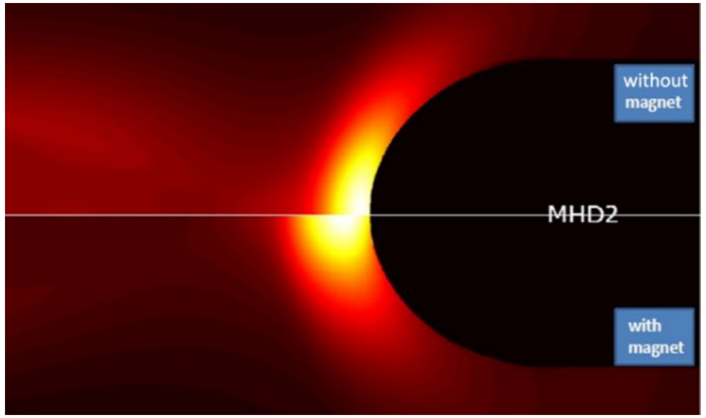
Future Superconductor Space Applications:

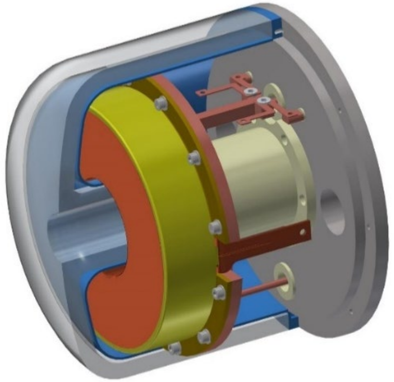
Image credit: NASA, ESA, CSA, and STScI

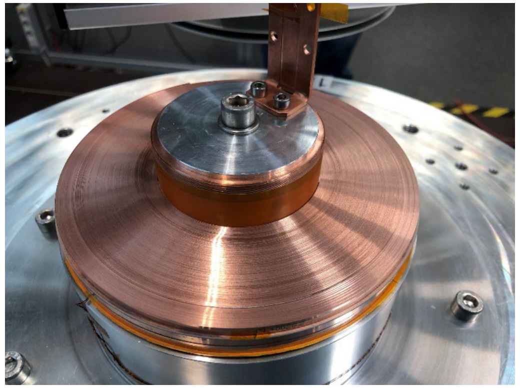
Magnetic Plasma Shielding: Heat flux or Radio Blackout Mitigation

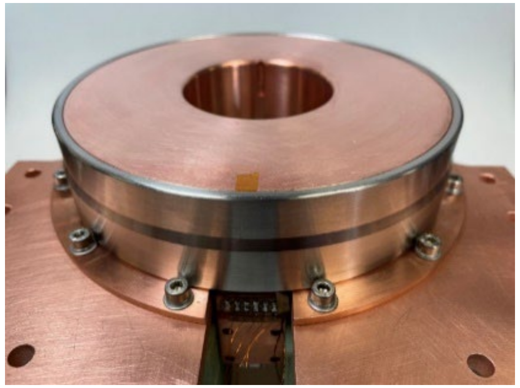
- EU-Project MEESST:
  „MHD Enhanced Entry System for Space Transportation“
  - Conduction cooled REBCO HTS magnet, T_{op} = 30 K
  - Ground experiments in arc-heated wind tunnels
    - IRS: heat flux mitigation
    - VKI: radiao blackout mitigation







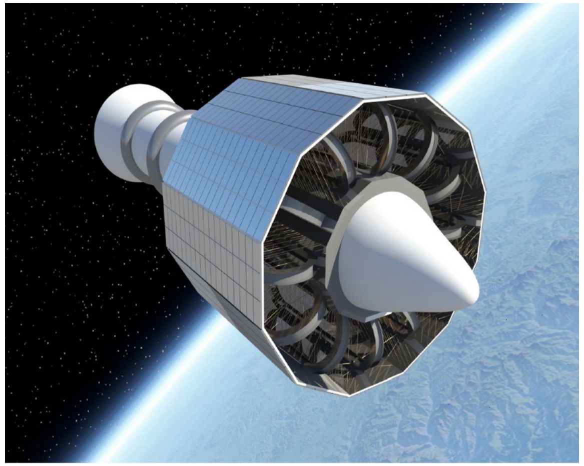


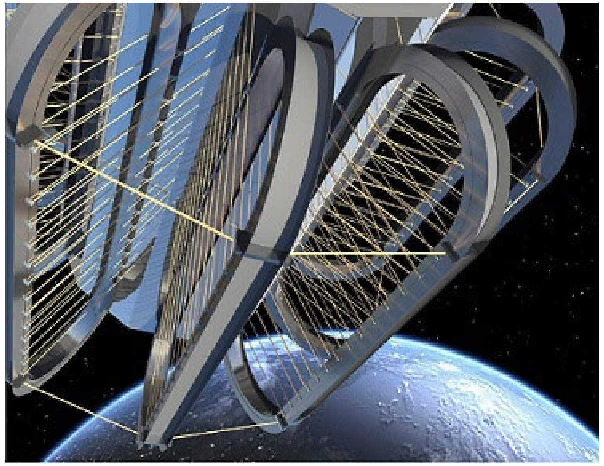


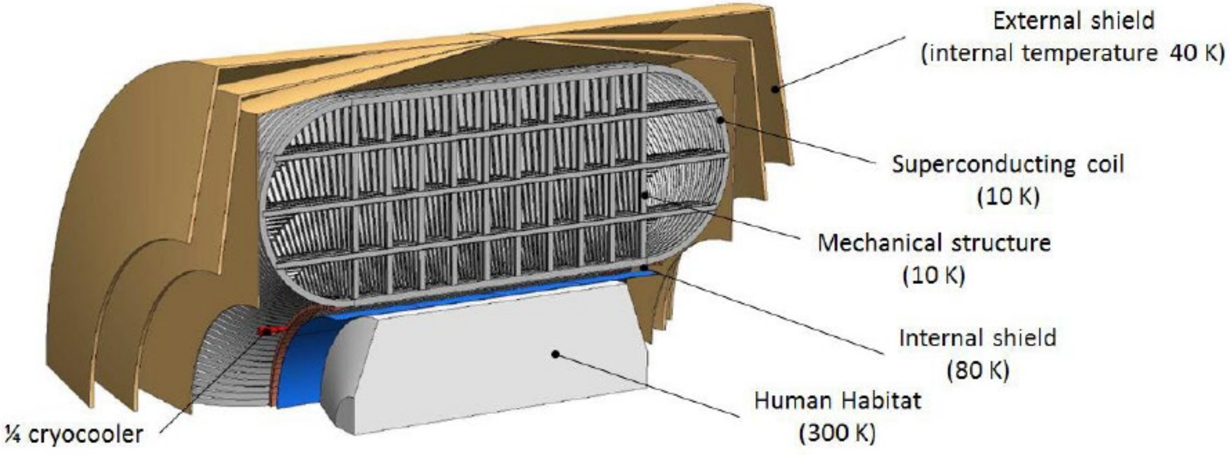
Magnetic Shielding during Mars Missions

EU-Project SR2S (01/2013 – 12/2015): Space Radiation Superconductive Shield

- Prevent long-time exposure to galactic cosmic rays and solar energetic particles during manned Mars missions
- Cooling of MgB_2 magnets @ 10 K:
  - passive cooling system, using a V-groove sunshield
  - pulse tube cryocoolers







https://ec.europa.eu/newsroom/horizon2020/items/20890

Romain Bruce and Bertrand Baudouy / Physics Procedia 67 (2015) 264 – 269

Magneto Plasma Dynamic Thrusters

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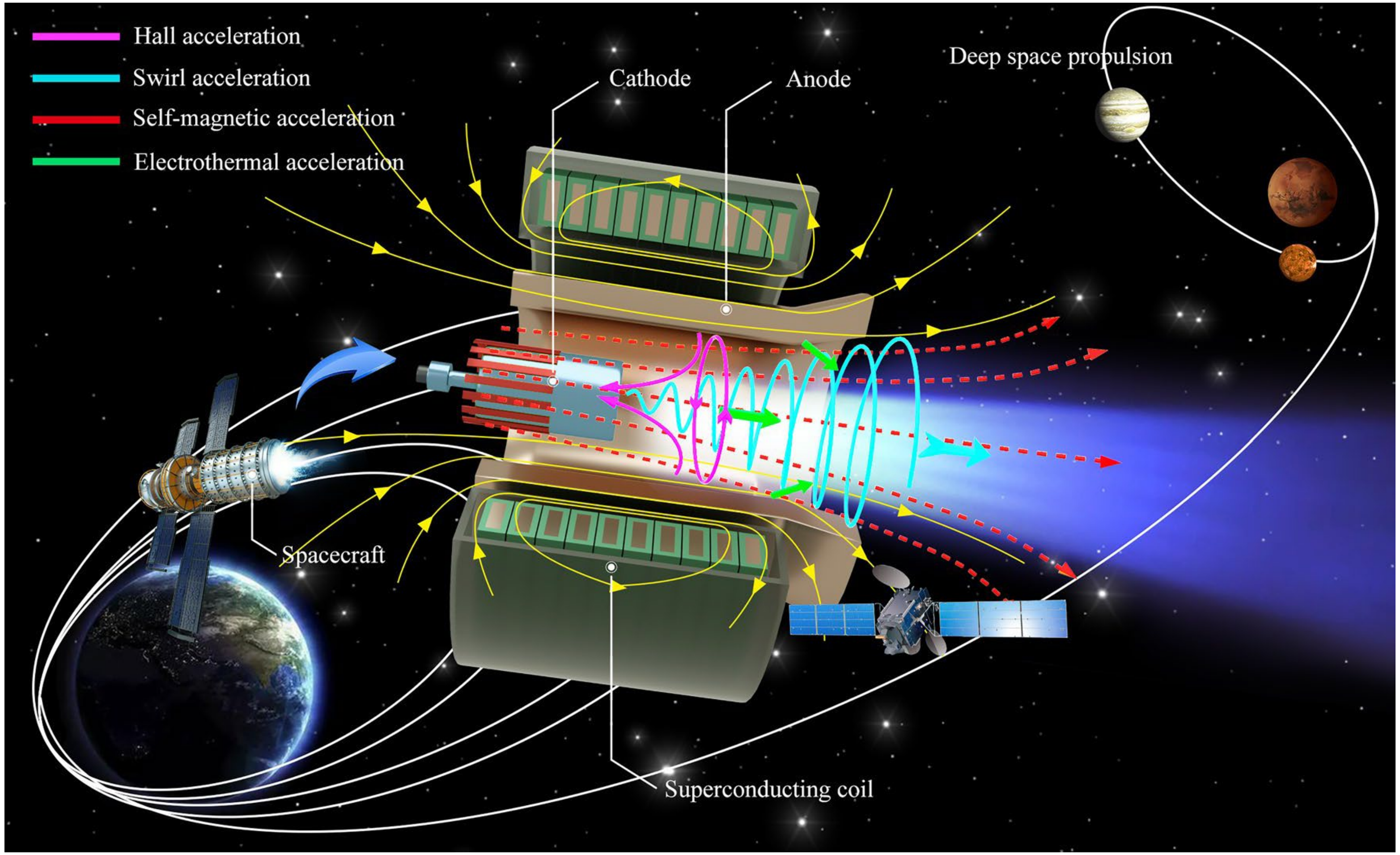
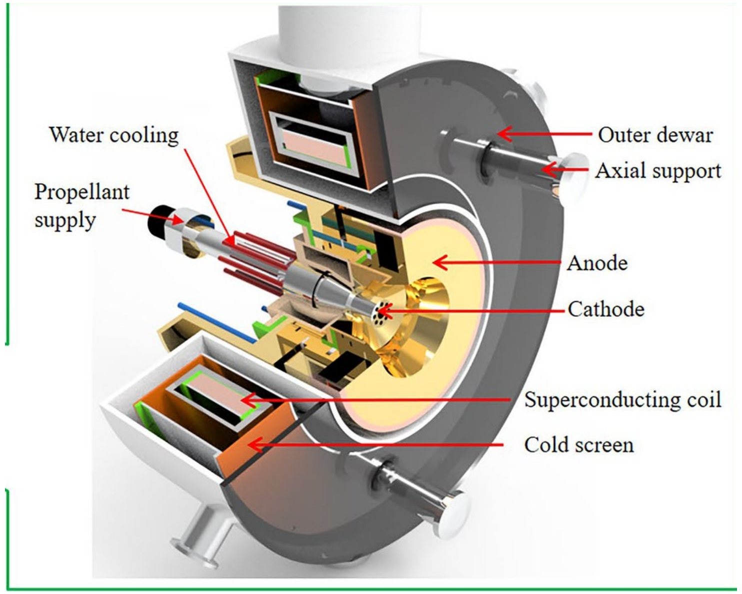


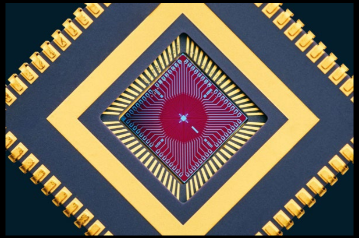
Ionized gas accelerated with electric and magnetic fields

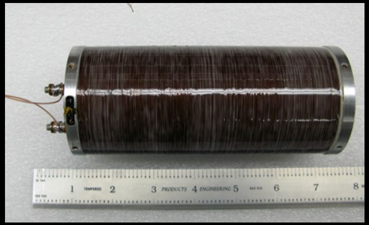


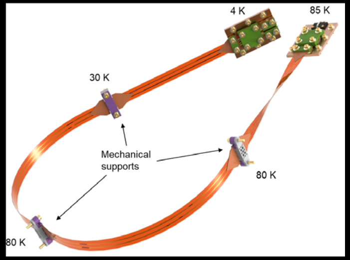
Zheng, J. *et al.*, Integrated study on the comprehensive magnetic-field configuration performance in the 150 kW superconducting magnetoplasmadynamic thruster". *Sci Rep* **11**, 20706 (2021).

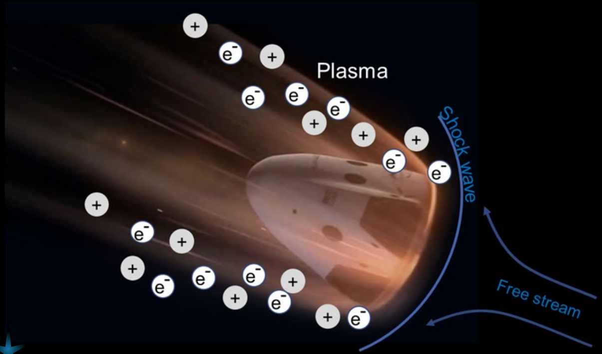
Summary

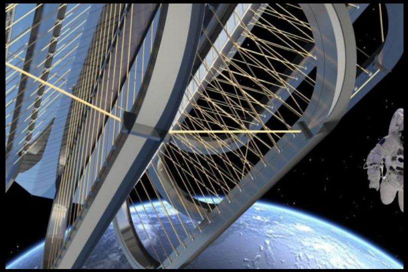
Superconductors in Space











Cryogenics in Space