SERESSA 2022

5th to 9th of December at CERN, Geneva

COTS in (Deep) Space

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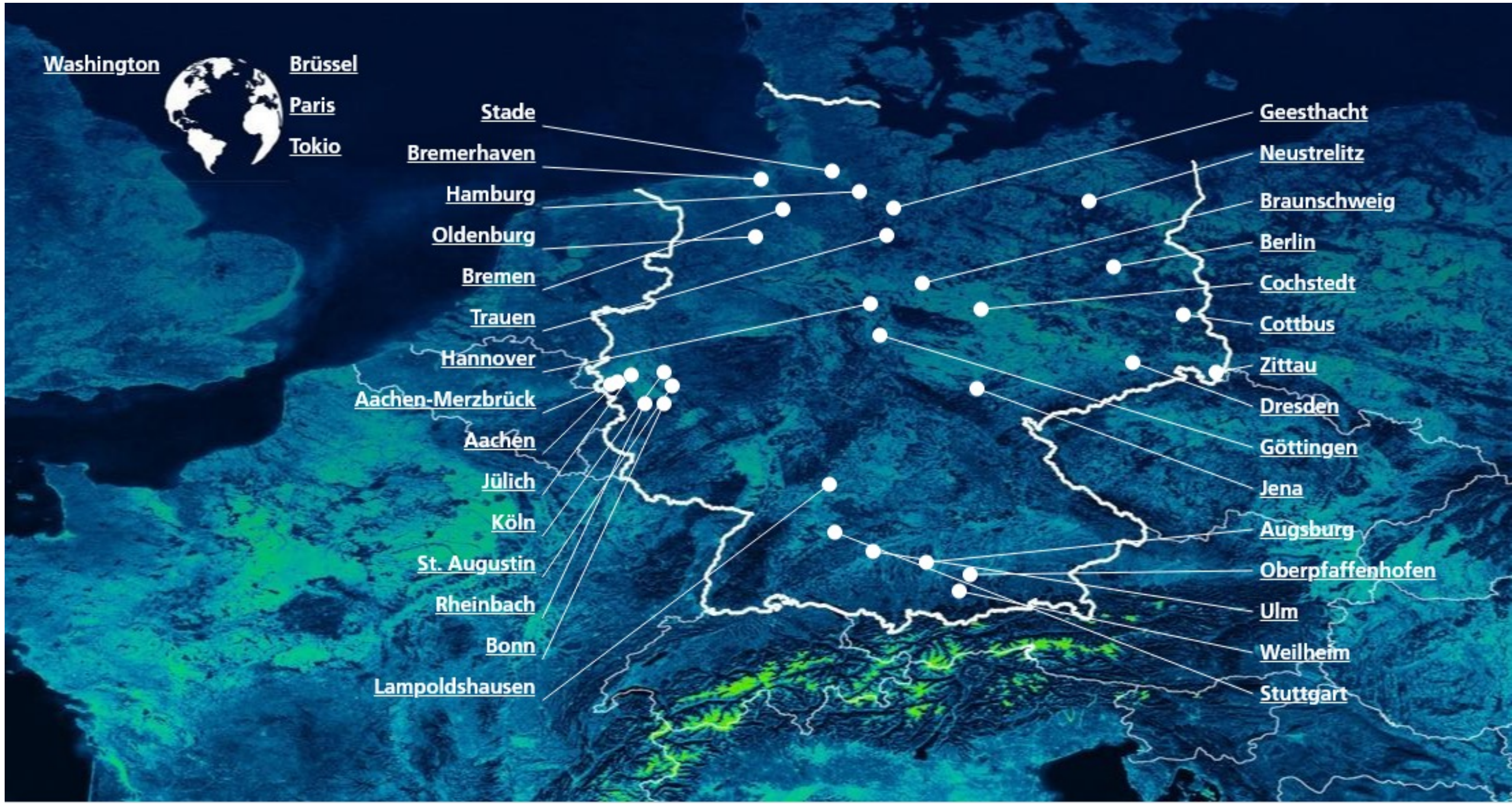
Agenda

- Introduction
- Challenge COTS
- Usage of COTS – a short overview
- Radiation Testing
- Some test results
- Conclusion

Introduction

German Aerospace Center - DLR

- The DLR is the national aeronautics and space research center of the Federal Republic of Germany.
- 55 research Institutes and facilities
- More than 10,000 employees
- 30 locations in Germany
- 4 offices world wide



Robotics and Mechatronics Center (RMC)

- The Robotics and Mechatronics Center (RMC) is a cluster and DLR's competence center for research and development in the areas of robotics, mechatronics and optical systems. It is formed by three institutes with key research areas for inter-institutional cooperation.

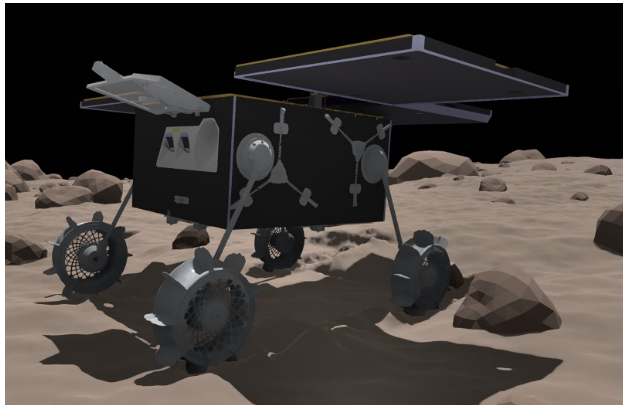
- Institute of Robotics and Mechatronics
- Institute of System Dynamics and Control
- Institute of Optical Sensor Systems

DLR-RM Activities in Space Robotics

❑ ROTEX (1993):	The first remotely controlled robot in Space (D2 mission)
❑ GETEX / ETS-VII (1999):	Video sensor controlled pick and place operations
❑ ROKVISS (2005 – 2010):	Robot at the outside of the ISS based on LWR technology
❑ MASCOT (-2018):	Contribution with the Mobility unit
❑ KONTUR-2 (-2018):	Telepresence experiments (ISS ←→Earth)
❑ CAESAR:	Robotic arm for On-Orbit-Servicing (in Preparation)
❑ LRU-2:	Field research on Mount Etna succeeded (ROBEX framework)
❑ MMX:	Contribution with the Locomotion Subsystem (together with SR)

Figure provided by Rokosmos

Figure provided by Rokosmos



Definition of COTS?

COTS - Definition

- ✓ Commercial off-the-shelf or commercially available off-the-shelf products are packaged or canned (ready-made) hardware or software, which are adapted aftermarket to the needs of the purchasing organization, rather than the commissioning of custom-made, or bespoke, solutions. A related term, Mil-COTS, refers to COTS products for use by the U.S. military.

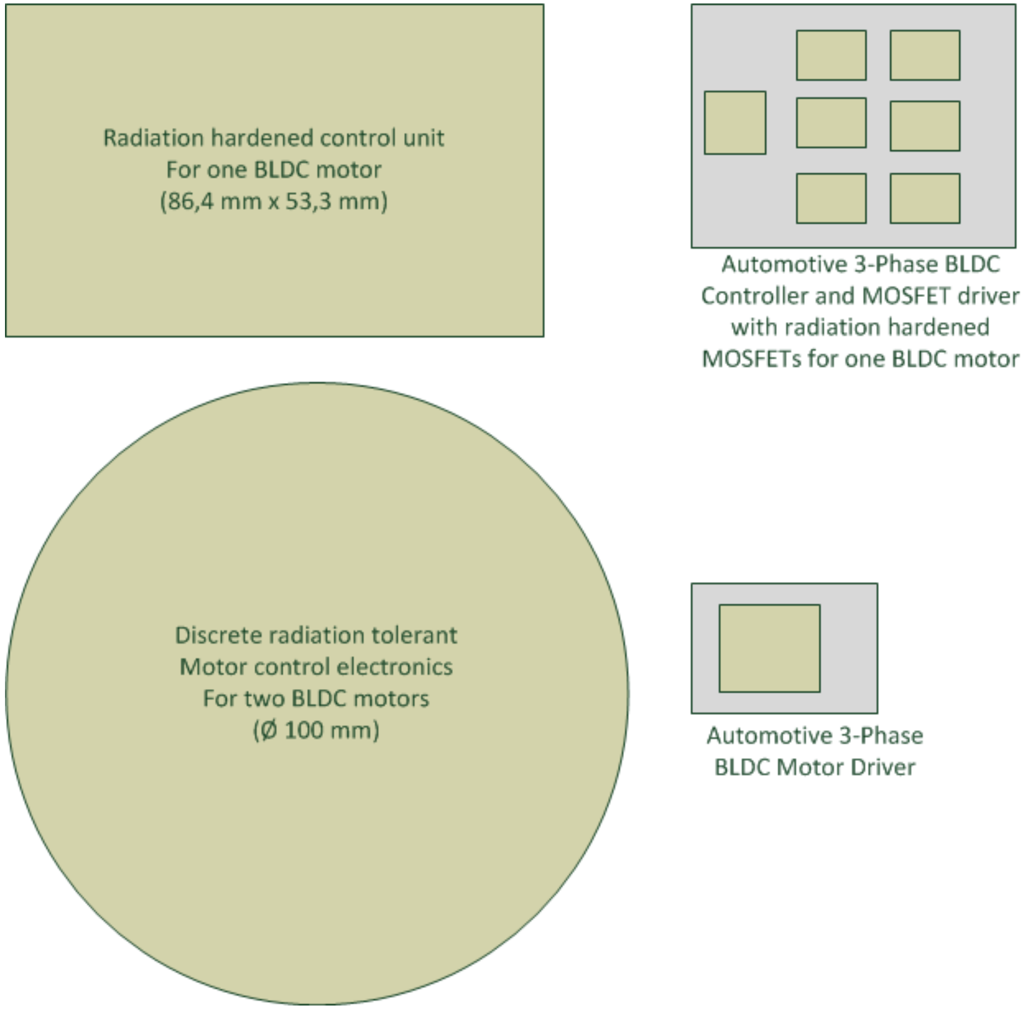
- ❑ In the space community the term COTS is usually used for commercially available electronic devices.
- ❑ There is no link to the classification of the parts (e.g. industrial, automotive)
- ❑ Usually Mil-Standard parts are not treated as COTS

Reasons for using COTS - overview

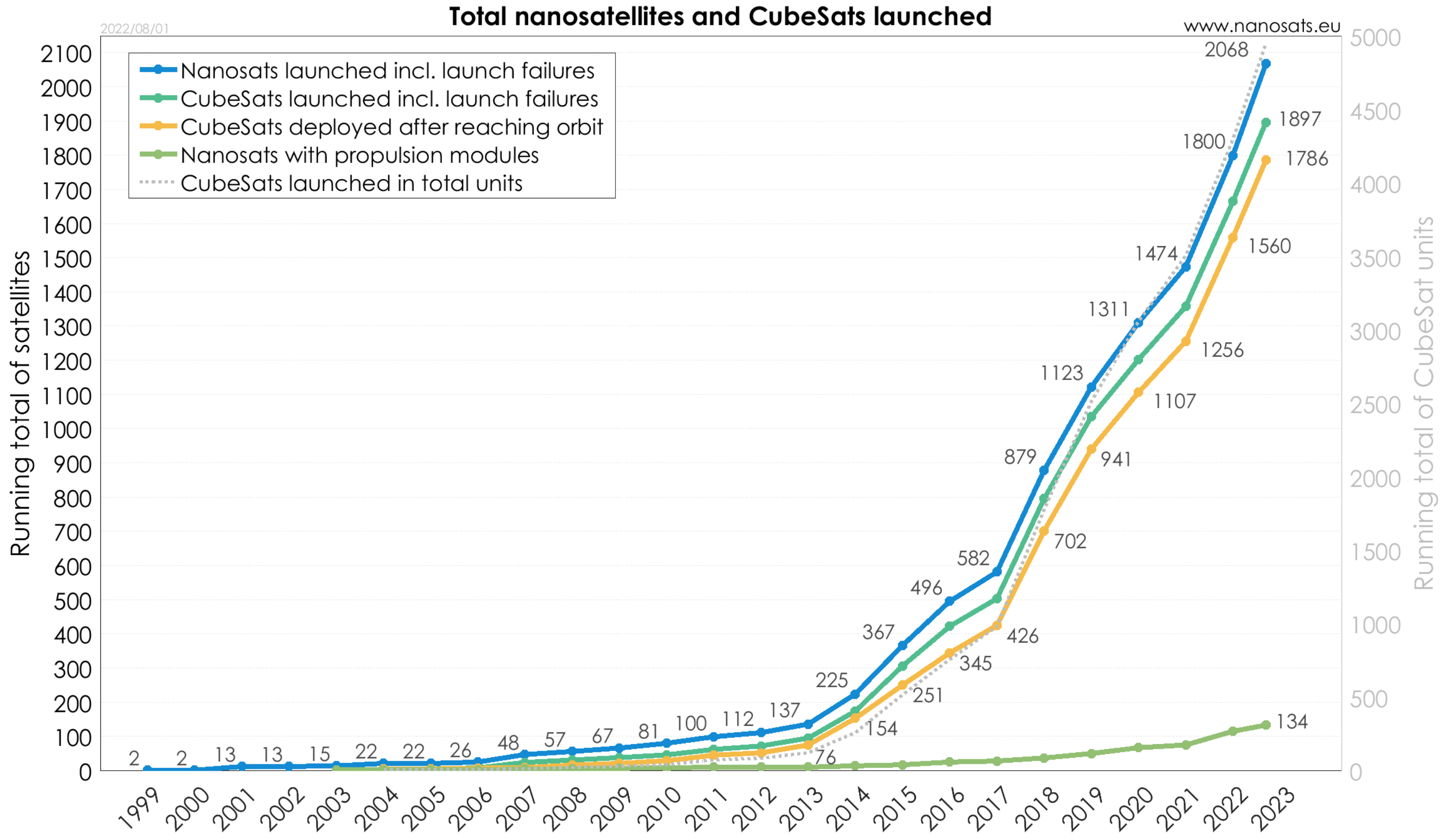
- Size of available radiation tolerant parts (*is getting better*)
- Performance of radiation tolerant parts (*is getting better*)
- Availability of radiation tolerant parts
- Total costs per part type (*e.g. for constellations*)
- At DLR-RM automotive rated parts preferred for spin-in:
  - Storage ~ -55°C up to +150°C
  - Operating ~ -40°C up to +150°C
  - Good overview on parts quality by the manufacturer
- Type of mission helps for using COTS

Reasons for using COTS – size of parts

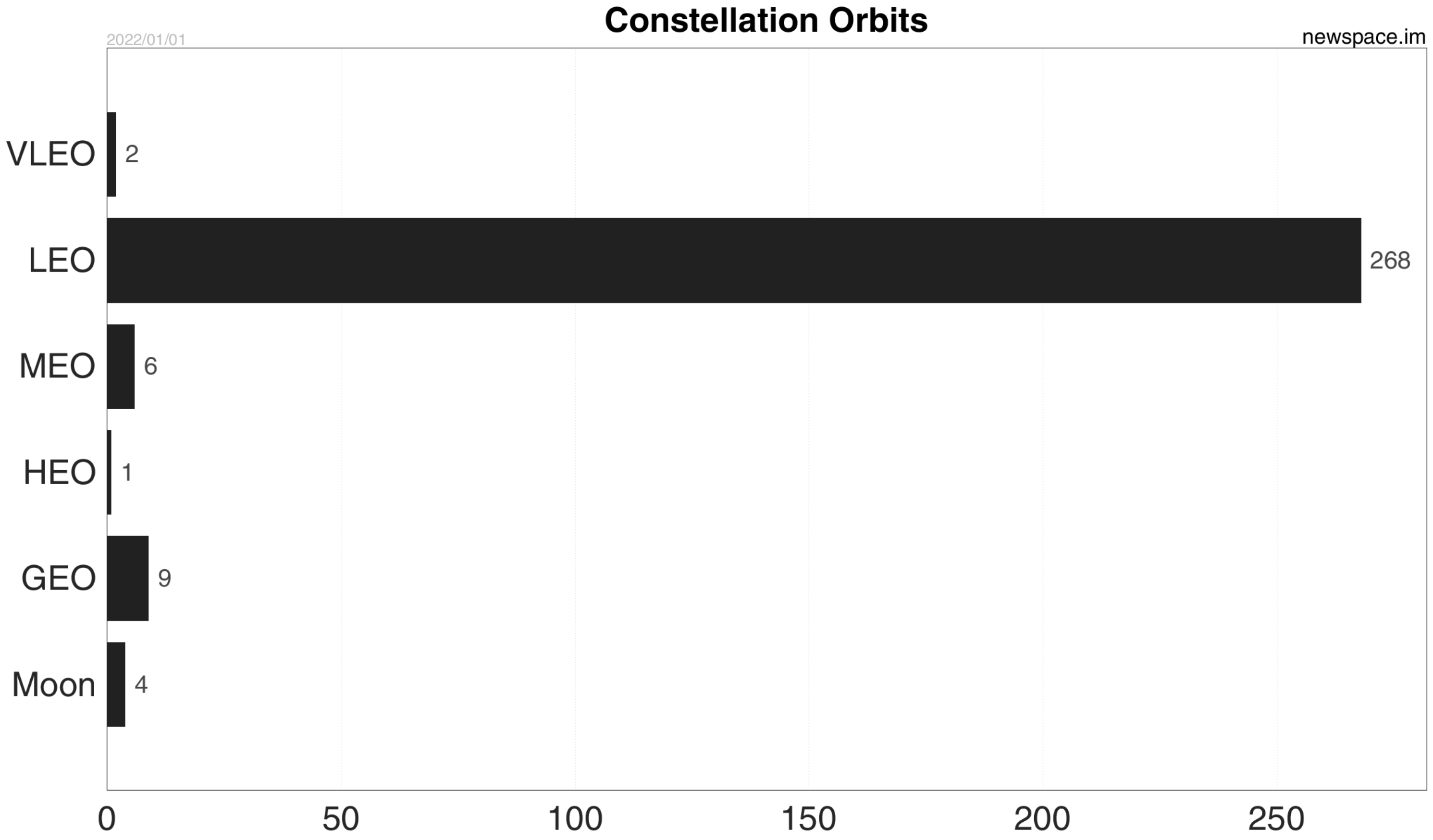
- New robotic systems for space applications are highly integrated mechatronic systems.
- Small form factor in order to reduce weight and therefore reduce costs for launch.
- Requires a responsible component and system engineering.



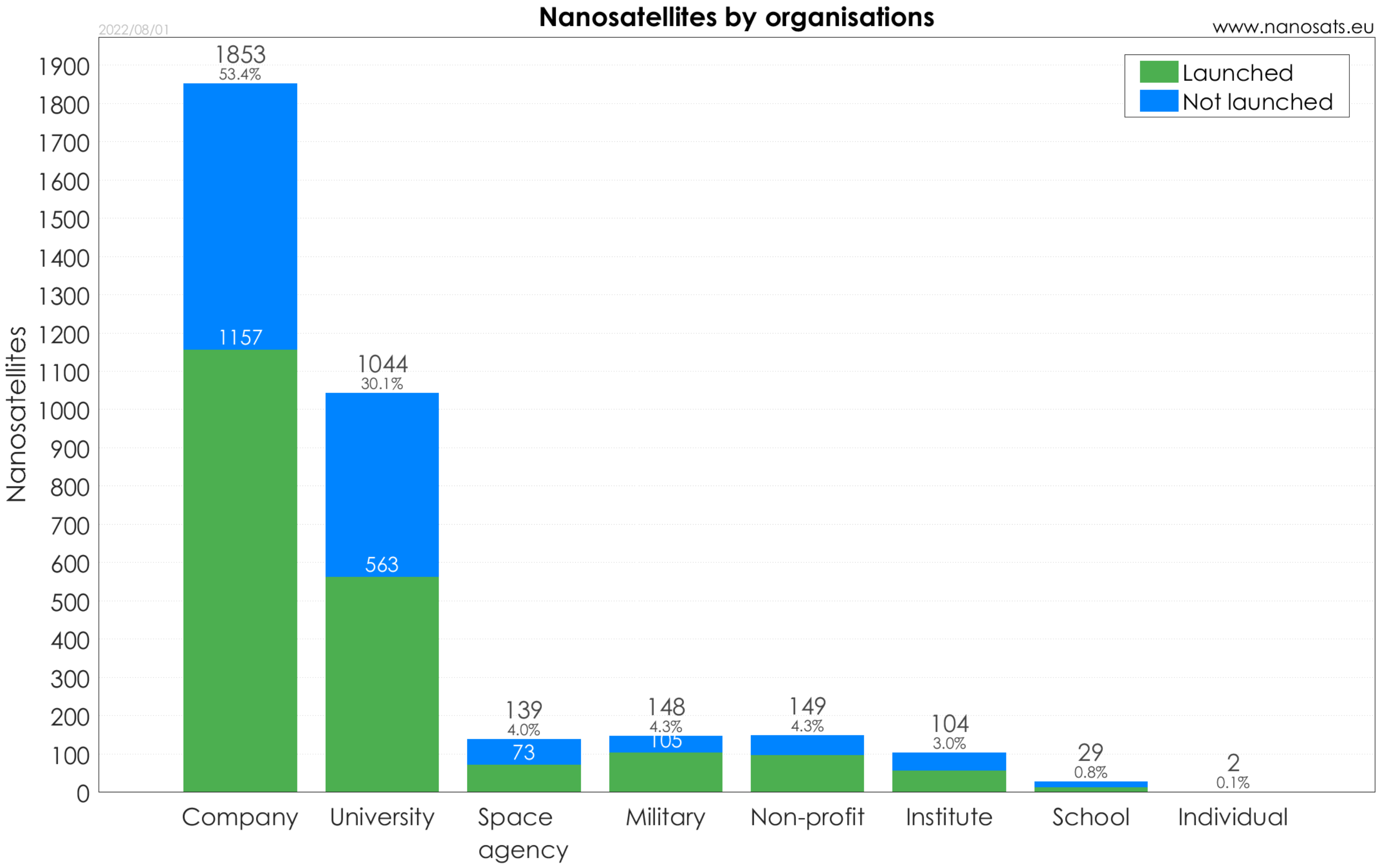
Reasons for using COTS – Number of satellites



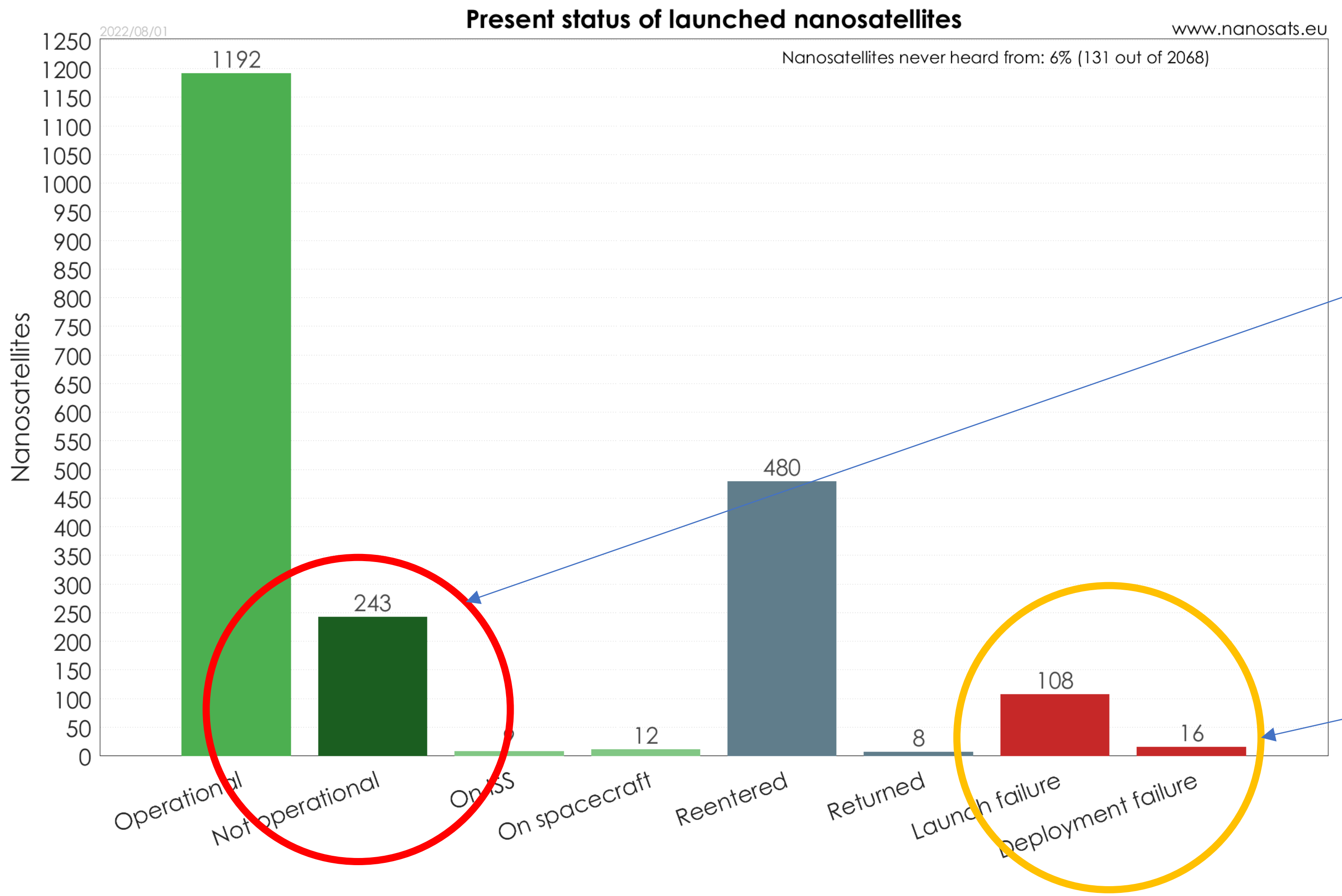
Reasons for using COTS – Type of Mission



Reasons for using COTS – Organizations



Reasons for using COTS – Challenges



What happened?

- ❑Systematic errors?
- ❑Part failure?
- ❑Failure due to vibration?
- ❑Failure due to vacuum or temperature?
- ❑…

No or not significant tests to save money or time?

Bad luck … It wasn't your day

Challenge COTS

Some basics when using COTS

- Guideline for usage of COTS: ECSS-Q-ST-60-13C

- Define mission risk class according to ECSS-Q-ST-60-13C. This helps to estimate the effort of the spin-in activities:
  - Management (DCL, Parts Control Board)
  - Parts Selection
  - Procurement (e.g. lot traceability)
  - Upscreening tasks & Inspection (e.g. radiation test, life test, DPA, …)
  - QA / PA Activities
  - System Design / Mission Planning

Some basics when using COTS

- It’s useful when the electronic interfaces (e.g. communication or power supply) from the subsystem using COTS to other subsystems or the main system are realized with radiation tolerant parts in order to avoid error propagation.

- FMEA / FMECA helps to find weak points

- Consider specificities

Specificities

Integrated circuits	Space	MIL	Commercial
Technology	Dedicated or not		Commercial
Manufacturing	Dedicated	Dedicated	Commercial
Qualification / Specification	Agency	Agency / Manufacturer	Manufacturer
Tests	Screening / Lot tests		Manufacturer
Temperature range	-55°C … 125°C		-55°C … 125°C / -40°C … 85°C / 0°C … 70°C
Package / Terminations	Harmetic, majority Sn/Pb		Hermetic, Plastic, Pb free
Life cycle	Many years		Up to Several years

Parts from one lot necessary (1/2)

- ❑COTS are usually traceable with their date code which represents the timing of the packaging
- ❑No direct link to the production date
- ❑Multiple production lines for one component → lot-to-lot variation
- ❑Outsourcing of different production steps (manufacturing, testing, packaging) → lot-to-lot variation

BUT

- ❑Increased number of fabless companies on the market → more centralized production
- ❑Manufacturer merging → less fabs

Parts from one lot necessary (2/2)

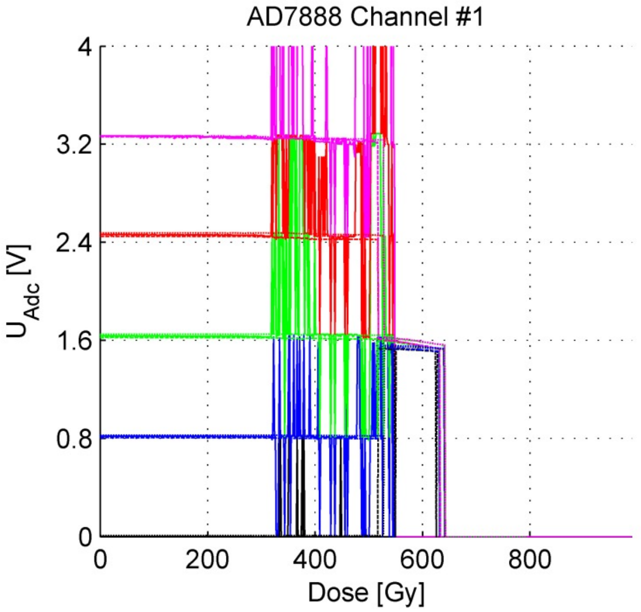
- ❑ Cooperation with manufacturer → best solution
  Parts from one lot, process information, maybe samples for testing are available

- ❑ Good and experienced QML part distributer → acceptable solution
  Parts from one lot probable, process information difficult

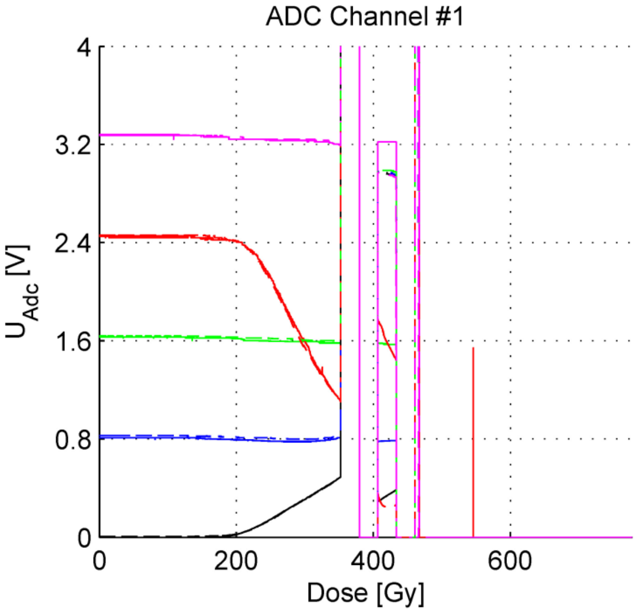
- ❑ Mass market distributor or product → real challenge
  Highly recommended to buy complete trays, bars or even wafers, no guarantee for one lot

Parts from one lot – a simple example

Example: Total Ionizing Dose Test of an eight channel SPI A/D converter from Analog Device



Samples from 2006



Samples from 2009

- Before irradiation with gamma rays (Co60), both A/D converter performed identically.
- I_{supply} = 10 mA
- 2006: I_{supply} was constant up to 350 Gy
- 2009: I_{supply} started to increase at 150 Gy and reached 175 mA at 350 Gy

Procurement (1/2)

- A high number of parts is for testing required (consider more than 40 parts)
- Controlled part storage highly recommended due to the long time from purchase to flight (Dry Nitrogen or dry air with RH of 15% to 20%)
- Counterfeit parts
  - Lucrative business → increasing number of parts detected. Select distributor carefully, even if the lead time is longer
  - Not only commercial parts → part buying agencies detect faked high-rel parts as well → incoming inspection

Procurement (2/2)

- Be aware that all these Upscreening tests may not guarantee the same level of reliability usually offered by space grade parts (AEC-Qxxx is not a fixed standard which is comparable from company to company).

- Missing part change notification leads to unexpected behavior, e.g. NASA alerted in 2016 about lot to lot variability on Flexible / Non-Flexible construction at chip capacitors.

- Incoming Inspection of parts highly recommended.

RoHS and Obsolescence

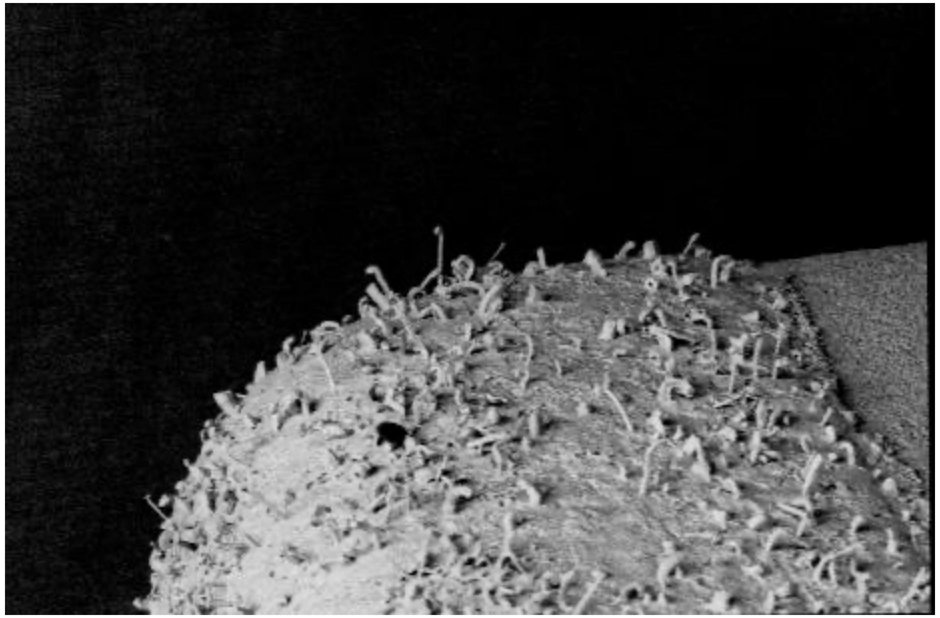
- Due to RoHS (Restriction of Hazardous Substances) campaign more and more parts containing lead are replaced by lead-free parts

- Solder process must be adapted;
  when RoHS and Non-RoHS parts are mixed on one board detailed information on the used materials is necessary.

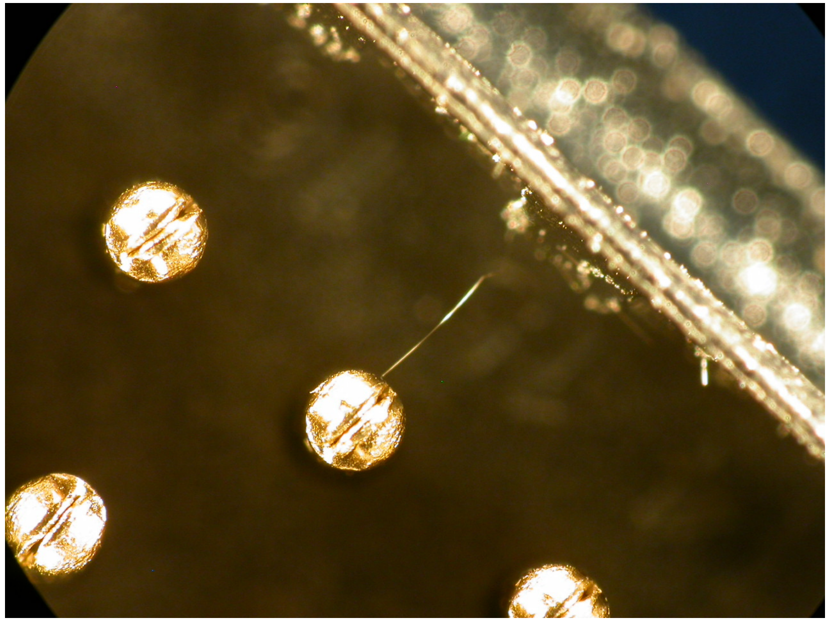
- High dynamics in the technology market → extremely short life cycle of COTS
  Sometimes the evaluation process lasts longer than the part is on the market.

Whisker

- Whisker growing in vacuum requires special attention and mitigation actions.
- Don’t relay on coatings only – whisker will be able to break through!

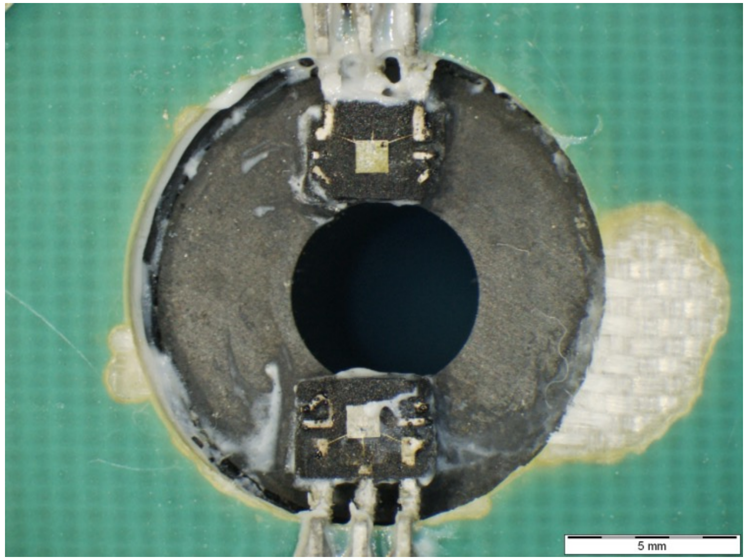


Credits: NASA Goddard Tin Whisker Homepage



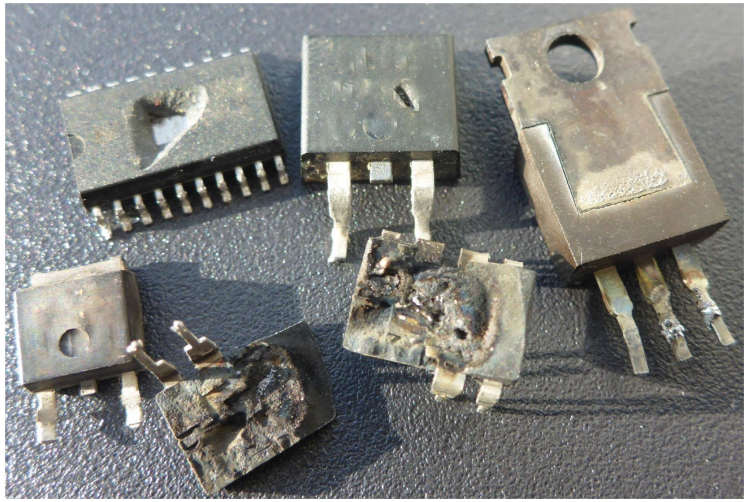
Credits: NASA Goddard Tin Whisker Homepage

Test preparation for Heavy Ion Testing



- ❑Package de-lidding e.g. by etching or backside thinning necessary due to limited energy of the accelerators.
- ❑Adaption of etching process necessary → additional samples required
- ❑When parts are small and fragile, supporting structures required
- ❑Part might behave different when the package was opened, but due to missing real alternatives (high energy accelerator) accepted practice.
- ❑Etching brings a lot of Hydrogen on the die.

Risk management



Credits: Ernst-Abbe-Hochschule Jena

- Adaptive latch-up protection might be necessary (variable threshold due to increasing supply current); triggered by current slew rate event.
- Radiation tolerant system supervisor might be necessary to restart COTS due to SEFI
- All additional hardware measures helps you, but jeopardize the space advantage of the COTS parts.
- Remember: Electronic components usually work with smoke. They are damaged when it leak from the package.

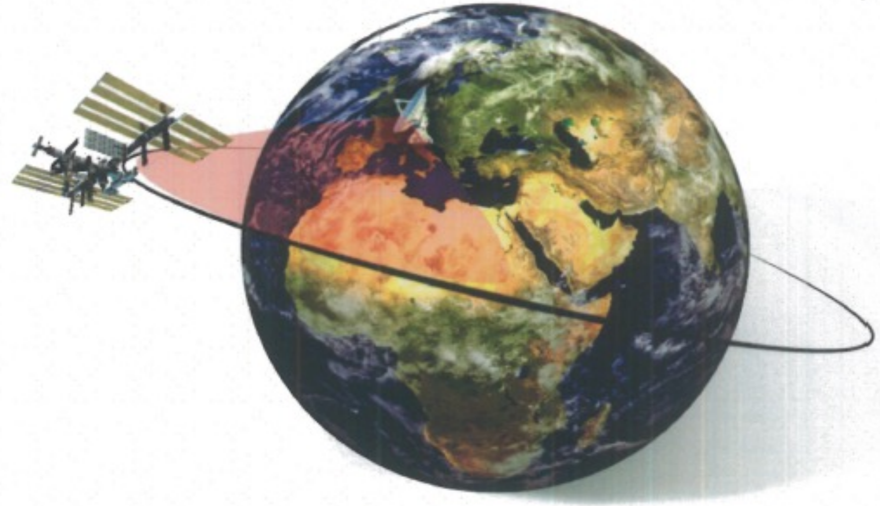
Usage of COTS

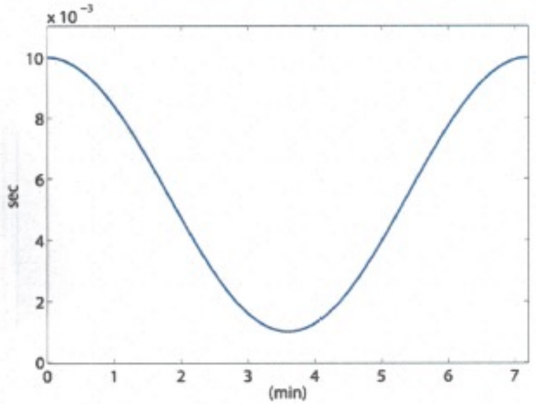
Usage of COTS

- Multiple sensors, motor control parts and brushless DC driver chips have been tested and partly used in missions, e.g.:
  - Accelerometer and Gyros
  - Distance sensors
  - SD-Cards
  - Multiple Hall-Effect sensors (analogue, digital, latching, non-latching)
  - Processors
  - Magneto resistive random access memory (MRAM)
  - Basic gates
  - Current sensors
  - Subsystems
- A few examples on the next few slides.

Usage of COTS – Kontur 2

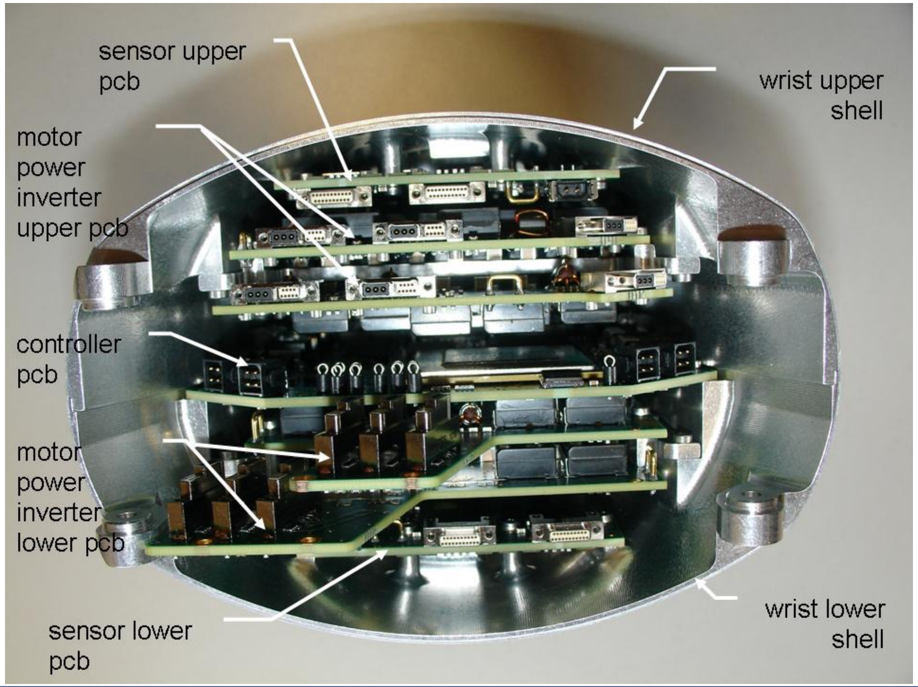
- ❑Remote control of Justin's arm on earth from the ISS
- ❑Tele-handshake with humans
- ❑Telepresence experiment with Ball (ISS – St. Petersburg – Oberpfaffenhofen
- ❑Development of a force feedback joystick for ISS





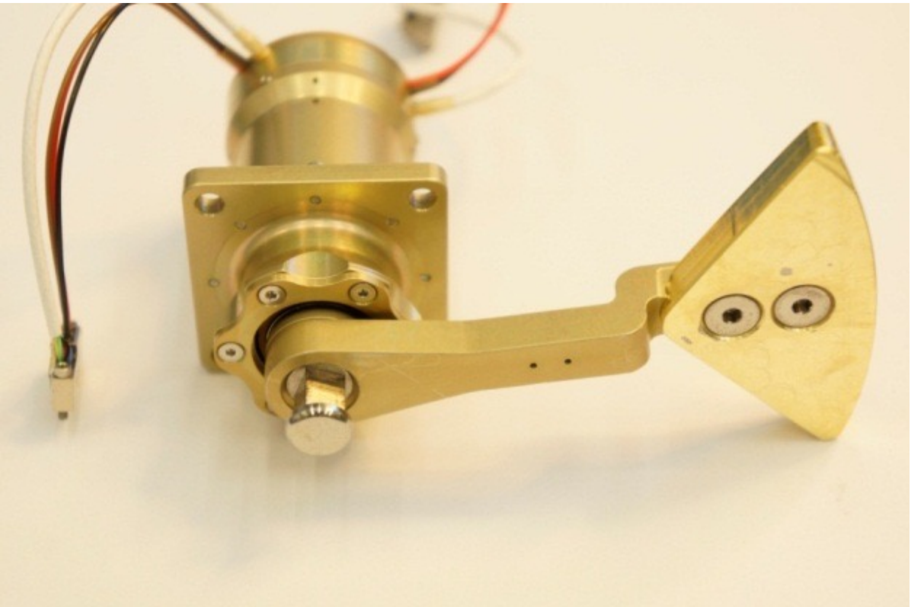
Usage of COTS – DEXHAND

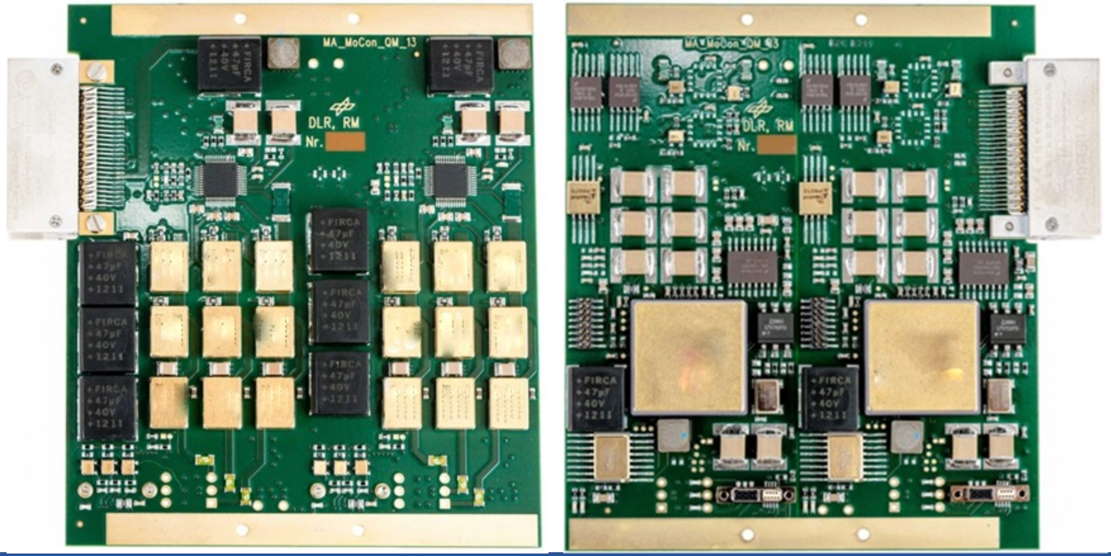
- ❑Technology demonstration of an anthropomorphic four fingered, torque controlled robot hand
- ❑Size of an EVA glove
- ❑Survive 6 months in external ISS environment
- ❑Autonomous and tele-manipulation operation

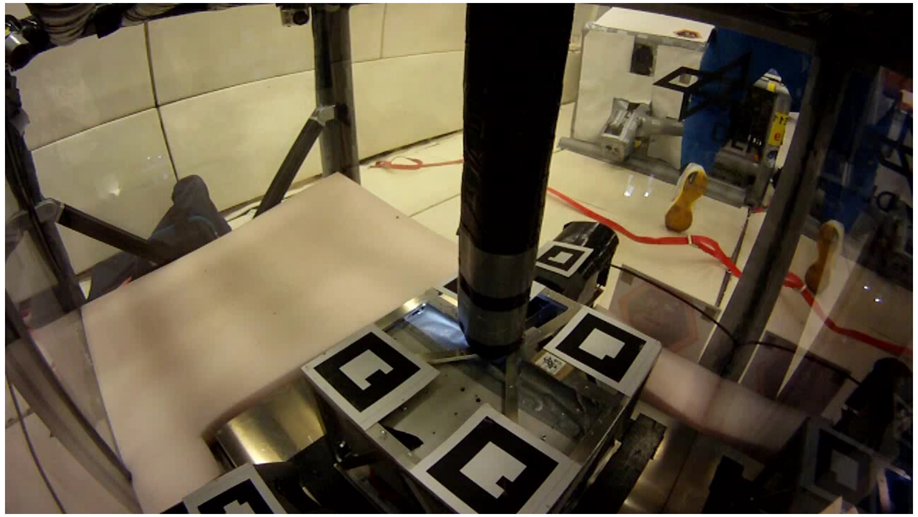


Usage of COTS – MASCOT

- 10 kg Lander (30 x 30 x 20 cm); Multiple Science Instruments on board
- Part of the Hayabusa (Sample Return Mission of JAXA) on Asteroid Ryugu (1999JU3)
- Launch was in December 2014; Arrival at Target: June 2018; Lander was active on 3rd of October 2018
- New innovative hopping / up righting mechanism for Lander (gravity ~ 17e-6 g)







Radiation testing

Radiation testing – Standards

Most important standards for radiation testing

- ✓ ESCC Basic Specification 22500 (displacement damage)
- ✓ ESCC Basic Specification 22900 (total ionizing dose)
- ✓ ESCC Basic Specification 23100 (evaluation and procurement)
- ✓ ESCC Basic Specification 25100 (single event)
- ✓ ECSS Standard ECSS-Q-ST-60-13C (Commercial EEE components)

And:

Test as you fly and fly as you have tested.

Particle Fluence definition

Particle Fluence

The **Particle Fluence Φ** is defined as the number of particles N emitted from or incident on a surface in a given period of time, divided by the area A of the surface.

- ✓ The Particle Fluence can also be calculated by integrating the flux density over the given period of time (e.g. during the irradiation period).
- ✓ The unit symbol does not identify the particle type. The particle name could be places before the term, e.g. proton fluence.
- ✓ The Particle Fluence is maximized when the surface is perpendicular to the direction of the incident particle flow.

$$\phi = \frac{N}{A}; \quad \left[\frac{1}{m^2}\right]$$

Dose definition

Dose

The **dose D** is a measure of the energy E deposited in matter by ionizing radiation per unit mass m.

- ✓ The SI unit of the dose is the gray (Gy), which is defined as one Joule of energy absorbed per kilogram of matter.
- ✓ The older, non-SI unit rad, is sometimes also used: 1 Rad = 0.01 Gy

$$D = \frac{E}{m}; \quad \left[\frac{J}{kg}\right]$$

LET definition

LET

The **linear energy transfer (LET)** is the amount of energy $\mathrm{d}E_x$ that an ionizing particle transfers to the material traversed per unit distance dx. It describes the action of radiation into matter and depends on the nature of the radiation as well as on the material traversed.

$$LET = \frac{dE_x}{d_x}; \; \left[\frac{MeV}{m}\right]$$

LET usage in the community

Electronic Stopping Power / LET

The electronic stopping power is the amount of energy lost by the incident ion along its path in the absorber medium when colliding with atomic electrons. It is expressed in units of energy per unit length: $\frac{MeV}{cm}$.

In the community, the LET is the electronic stopping power divided by the mass density of the absorber medium, i.e. the mass electronic stopping power.

The LET is usually expressed in units $\frac{MeV * cm^2}{mg}$.

LET is the unit of reference for SEE irradiation with heavy ions.

Cross-section definition

Cross-section

The **Cross-section σ** is a measure of the SEE sensitivity of a device under test. It is calculated as the ration of the number of observed events N for a given particle fluence ϕ.

- ✓ For proton irradiation, the SEE cross-section is expressed as a function of the proton energy.
- ✓ For heavy ion irradiation the SEE cross-section is expressed as a function of the ion LET.

$$\sigma = \frac{N}{\phi}$$

Other useful equations

Received dose	$D[Rad] = 1{,}6 * 10^{-5} * LET\left[\frac{MeV * cm^2}{mg}\right] * \phi[\frac{Ions}{cm^2}]$
Effective LET	$LET_{eff}(\Theta) = \frac{LET(0°)}{\cos(\Theta)}$
Effective Fluence	$\phi_{eff}(\Theta) = \phi(0°) * \cos(\Theta)$
Cross Section (tilted)	$\sigma_{eff} = \frac{number\ of\ events\ N}{\phi_{eff}} = \frac{number\ of\ events\ N}{\phi(0°) * \cos(\Theta)}$

Chosen parameter for irradiation

Parameter according to ESCC Basic Specifications ESCC 25100 / ESCC 22900	**Chosen parameter at DLR-RM (sometimes modified due to mission needs)**
$\Phi_{Ion} \leq 1.0 * 10^7 \frac{Ions}{cm^2}$	$\Phi_{Ion} = 1.0 * 10^7 \frac{Ions}{cm^2}$
$\Phi_{Proton} \leq 1.0 * 10^{11} \frac{Protons}{cm^2}$	$\Phi_{Proton} = 1.7 * 10^{10} \frac{Protons}{cm^2}$
$0.36 \frac{kRad(Si)}{hour} \leq Doserate_{Std} \leq 180 \frac{kRad(Si)}{hour}$	$0.36 \frac{kRad(Si)}{hour} \leq Doserate_{Std} \leq 180 \frac{kRad(Si)}{hour}$
$36 \frac{Rad(Si)}{hour} \leq Doserate_{low} \leq 360 \frac{Rad(Si)}{hour}$	$36 \frac{Rad(Si)}{hour} \leq Doserate_{low} \leq 360 \frac{Rad(Si)}{hour}$
"During the test a meaningful (i.e. statistically significant) number of events shall be recorded in one or multiple exposures of typical 1 to 20 minutes test time each." – according to ESCC25100	

Test facilities used by DLR-RM

RADiation Effects Facility of the University of Jyväskylä, RADEF (Finnland)

Heavy-Ions

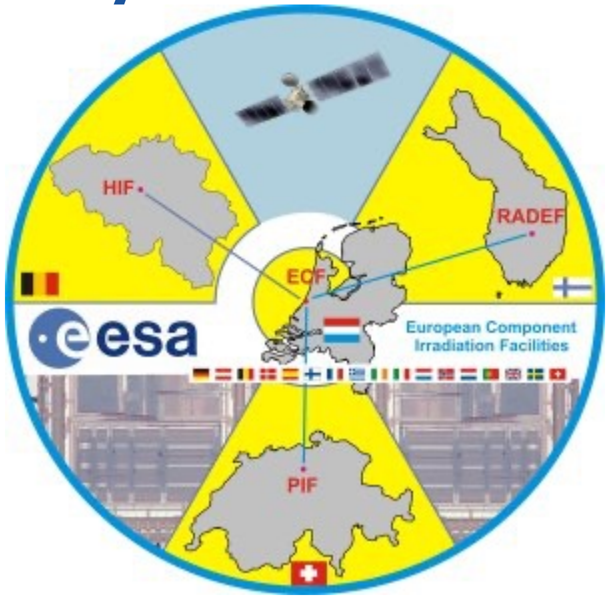
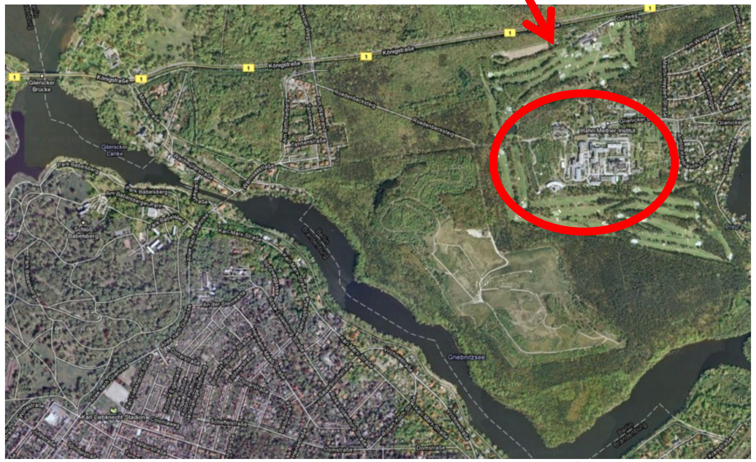


Figure provided by escies.org

Helmholtz-Zentrum Berlin Wannsee; Cobalt-60 source and proton therapy, HZB (Germany)

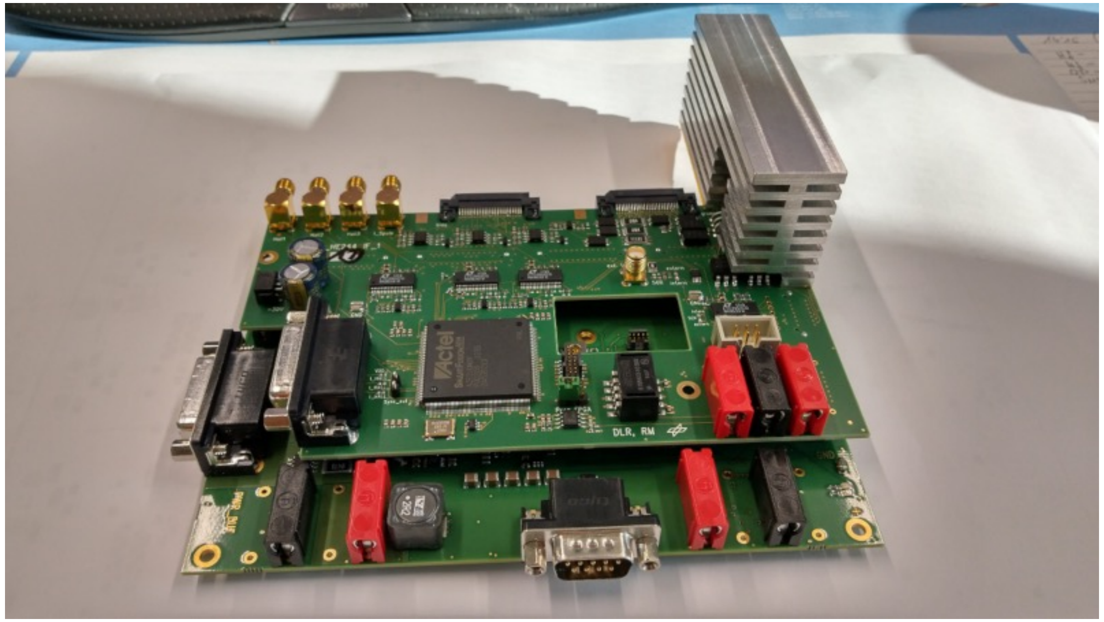
Total Dose (Co60) and Protons



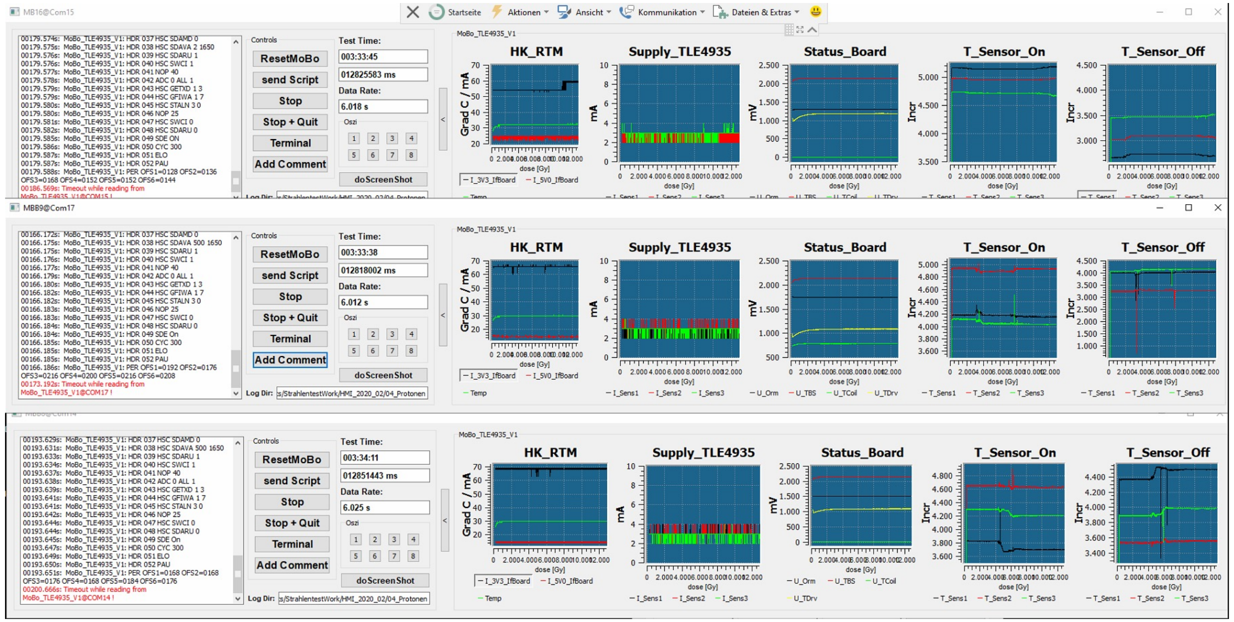
Courtesy by google

Universal test setup

- ❑Radiation Test Motherboard and test specific piggy back board
- ❑Software on the PC
- ❑Home made power supply (3 channels with 7 voltages each)



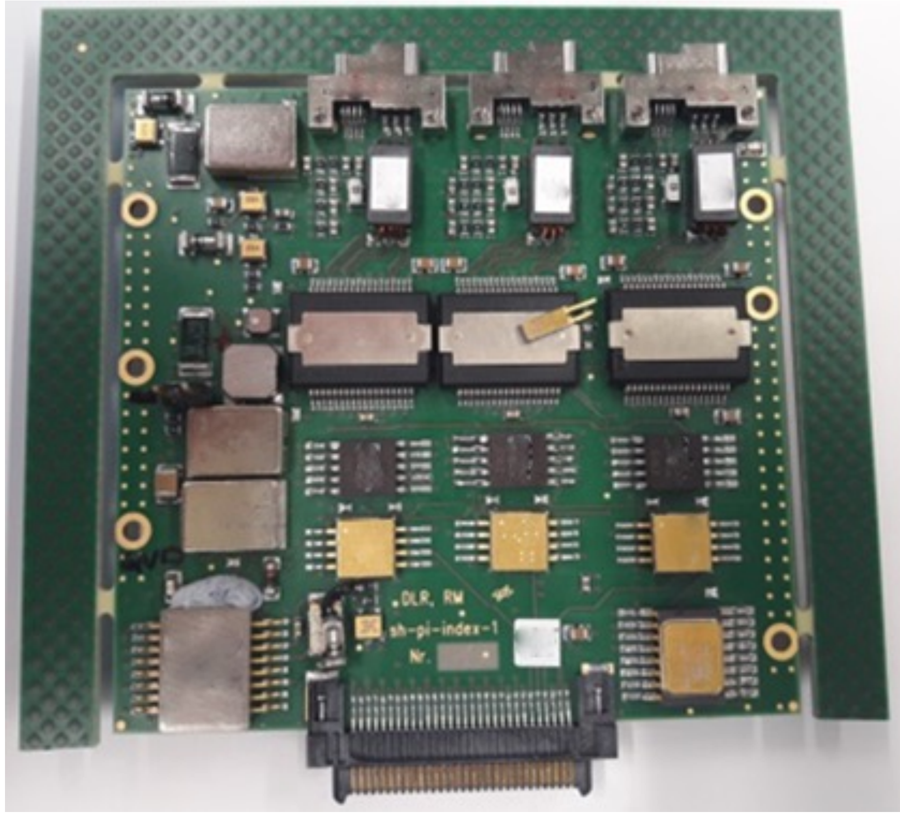
Radiation Test Motherboard with Interface-Addon-Board, Credits: H.-J. Sedlmayr et al, “Upscreening of Infineon Hall effect sensor for the MMX rover locomotion subsystem” in 2022 IEEE RADECS Data Workshop, 2012., Copyright ©2022, IEEE



Some Test results

3-Phase BLDC Motor Driver

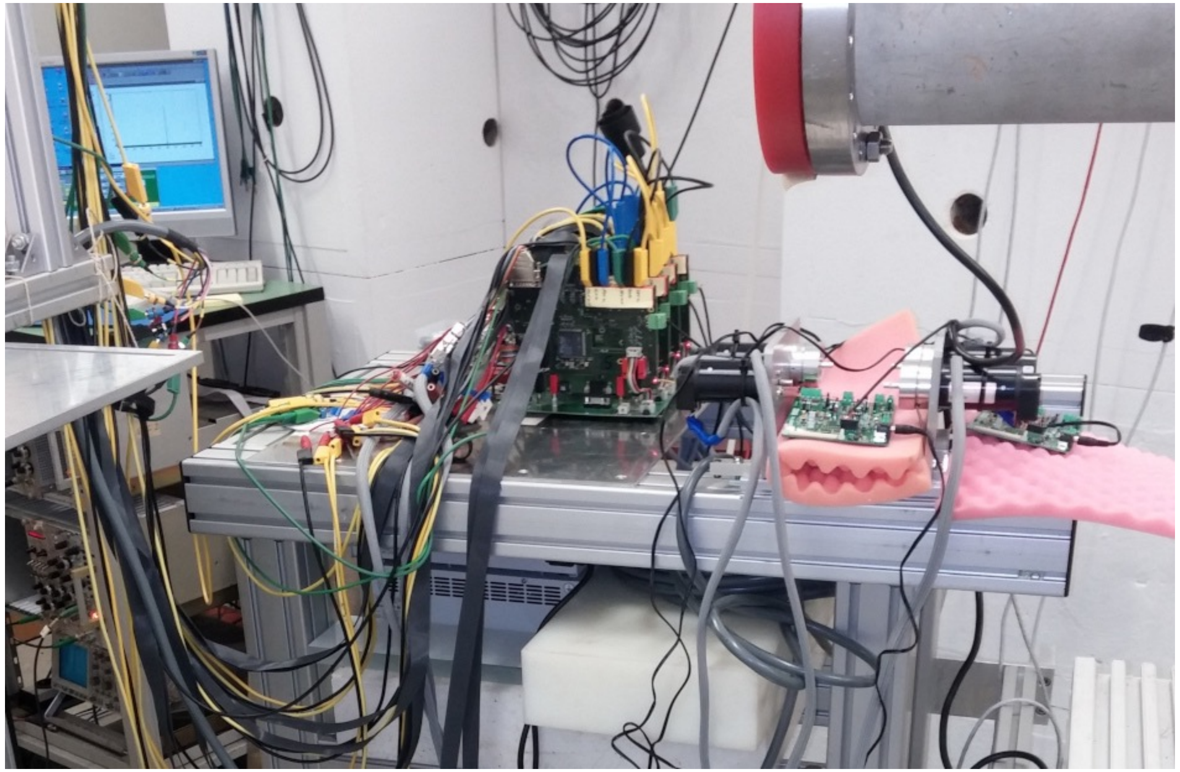
- ❑ Internal power MOSFETs
- ❑ Multiple security features integrated
- ❑ Needs external logic for motor commutation; e.g. FPGA
- ❑ COTS part used for multiple systems:
  - Spacehand: multiple year GEO mission
  - UMC (Universal Motion Controller) designed for medium radiation level
  - MMX



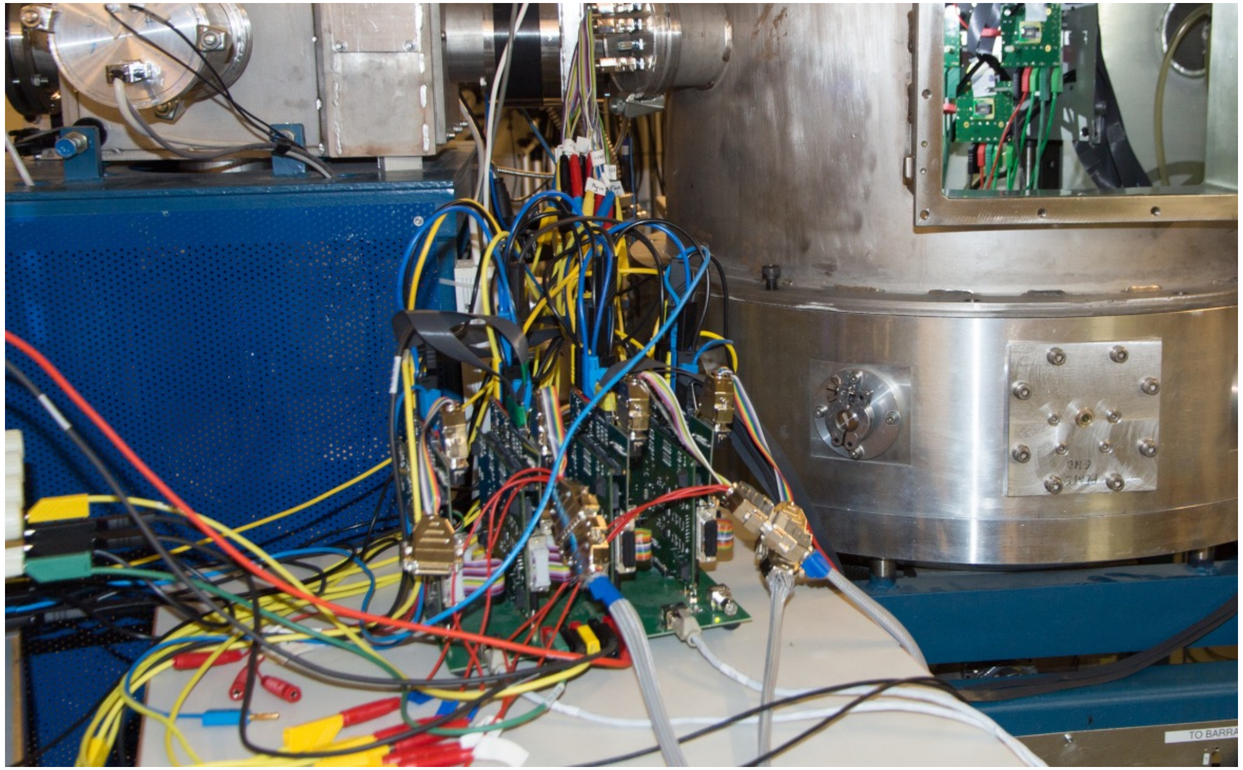
Spacehand Motor Driver Electronics Board, © DLR-RM

3-Phase BLDC Motor Driver

Examples for the test setup



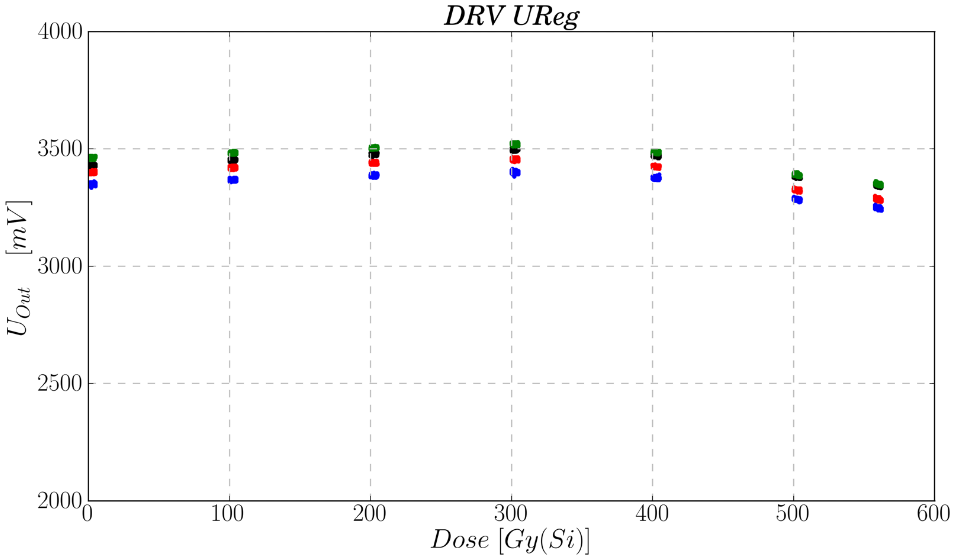
Test setup at the proton beam line, © DLR-RM



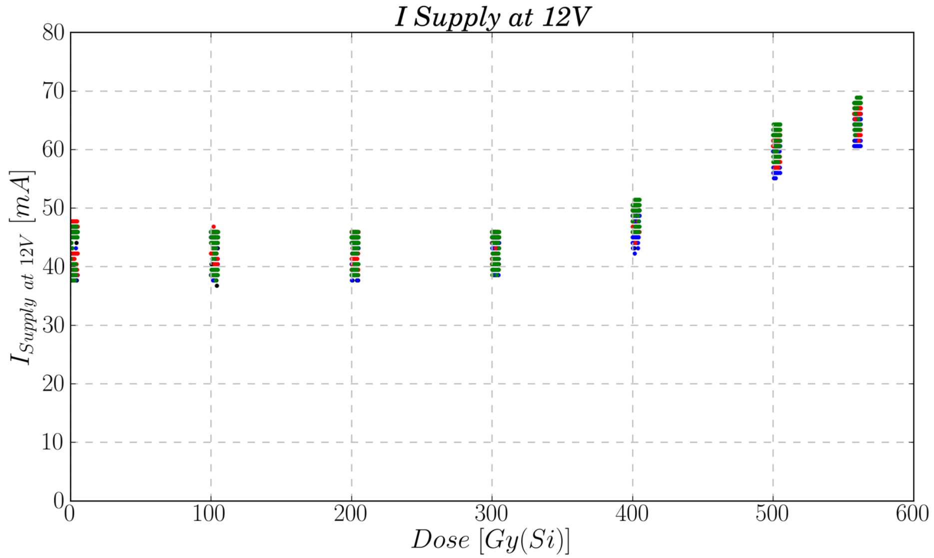
Test setup at the heavy ion beam chamber, © DLR-RM

3-Phase BLDC Motor Driver

- Total Ionizing Dose test performed at the HZB up to 550 Gy(Si)
- Dose rate = 3.82 Gy(Si)/hour (standard dose rate)



Voltage regulator over dose, Credits: H.-J. Sedlmayr et al, “Radiation test of a BLDC motor driver component,” in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE

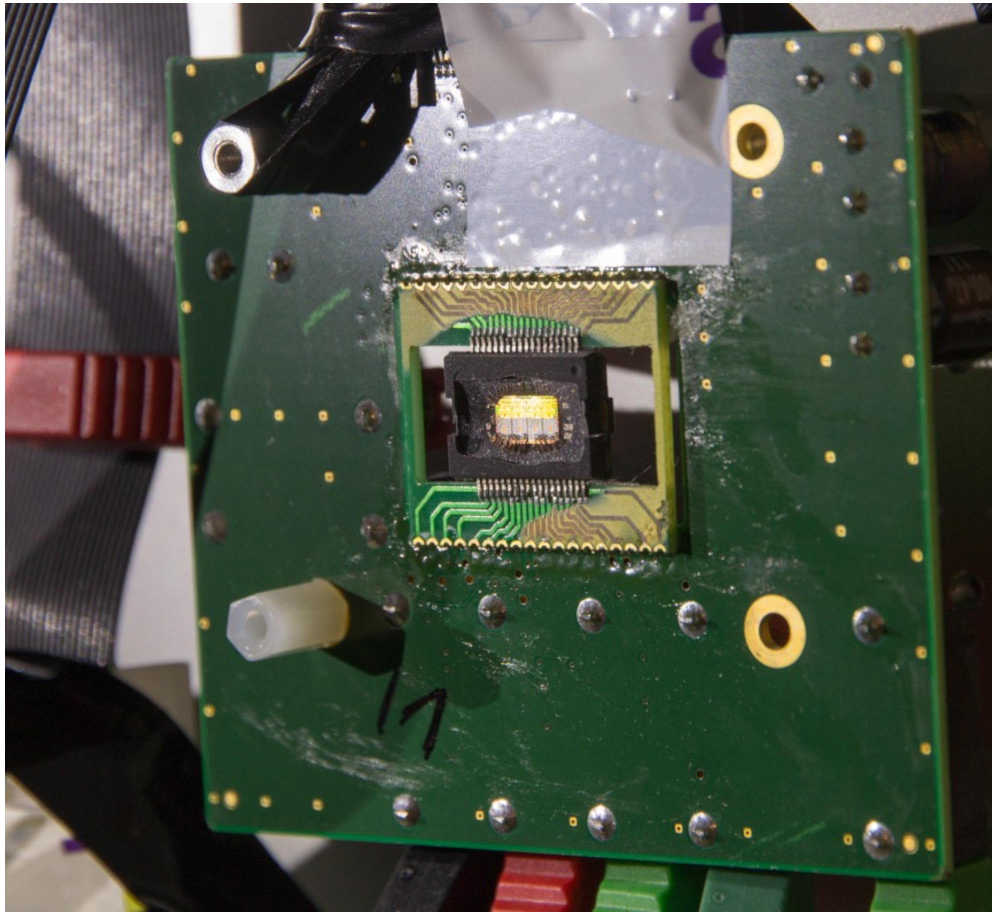


12V supply current over dose, Credits: H.-J. Sedlmayr et al, “Radiation test of a BLDC motor driver component,” in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE

3-Phase BLDC Motor Driver

- ❑Heavy ion test performed at RADEF
- ❑DUT delidded by chemical etching
- ❑$\Phi_{Ion} = 1.0 \ast 10^7 \frac{Ions}{cm^2}$ for each species

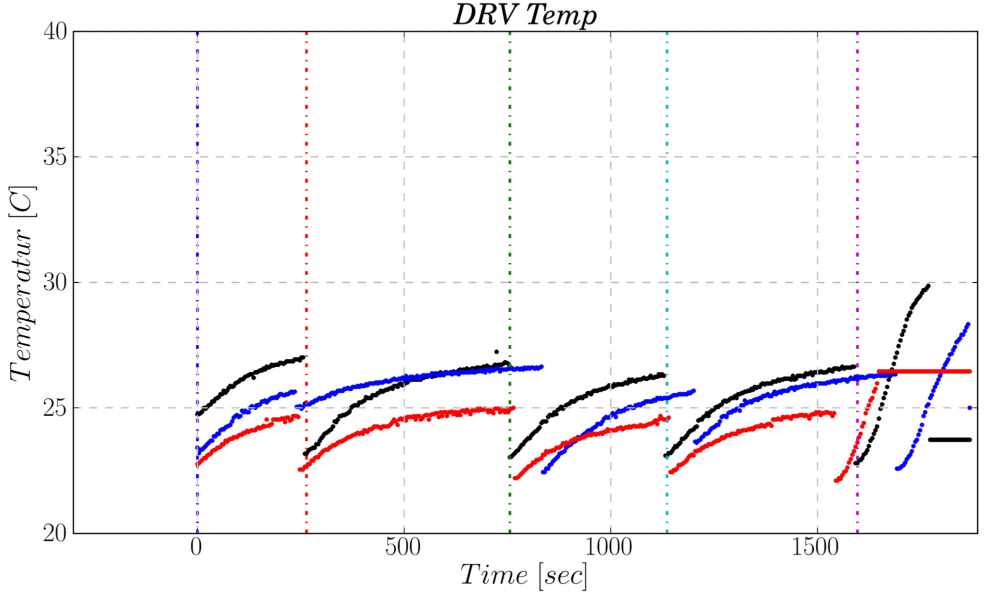
Ion species	LET value [$\frac{Mev \ast cm^2}{mg}$]
Nitrogen (normal incidence)	1.89
Nitrogen (tilted)	3.80
Krypton (normal incidence)	40.0
Krypton (tilted)	52.9
Xenon (normal incidence)	59.9



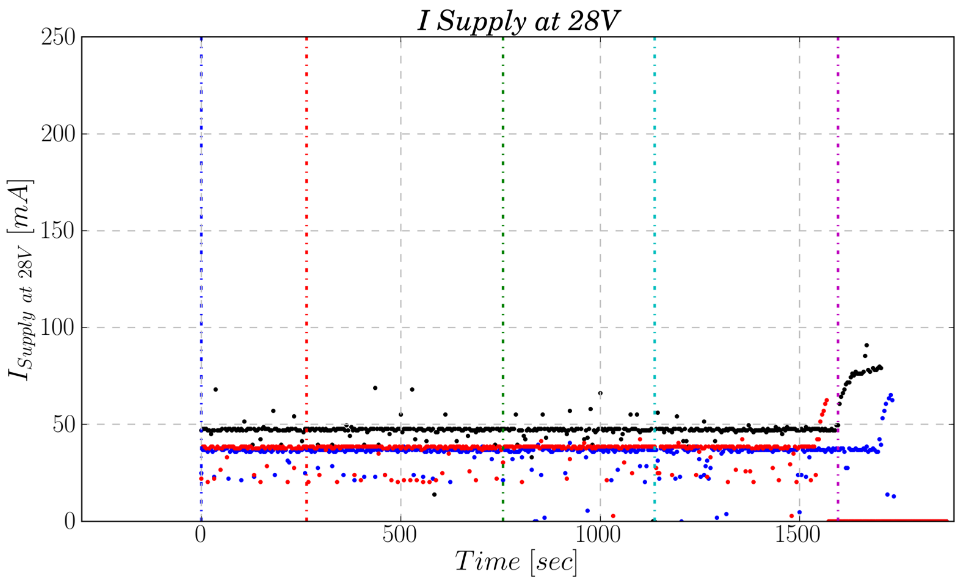
Delidded target in the RADEF test chamber, Credits: H.-J. Sedlmayr et al, "Radiation test of a BLDC motor driver component," in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE

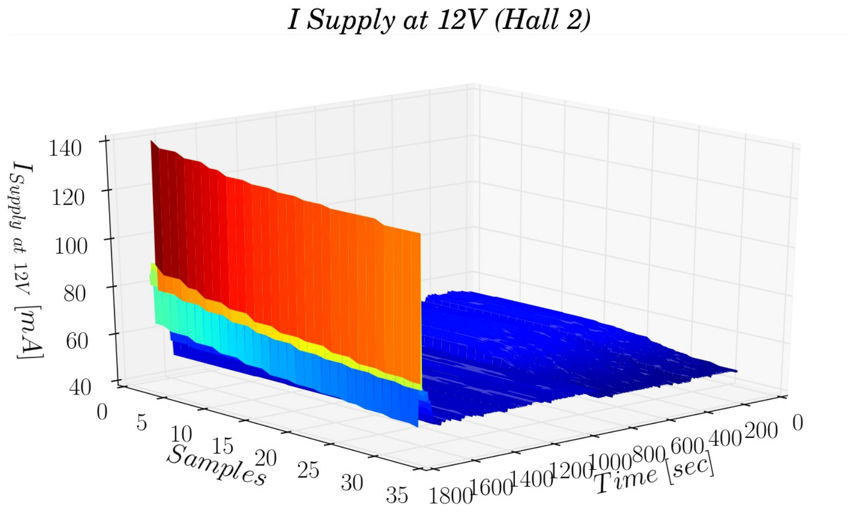
3-Phase BLDC Motor Driver

- ❑Works until 52.9 MeV · cm²/mg without error.
- ❑Micro latch-up at 59.9 MeV · cm²/mg measured.



Temperature reading over time, Credits: H.-J. Sedlmayr et al, “Radiation test of a BLDC motor driver component,” in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE

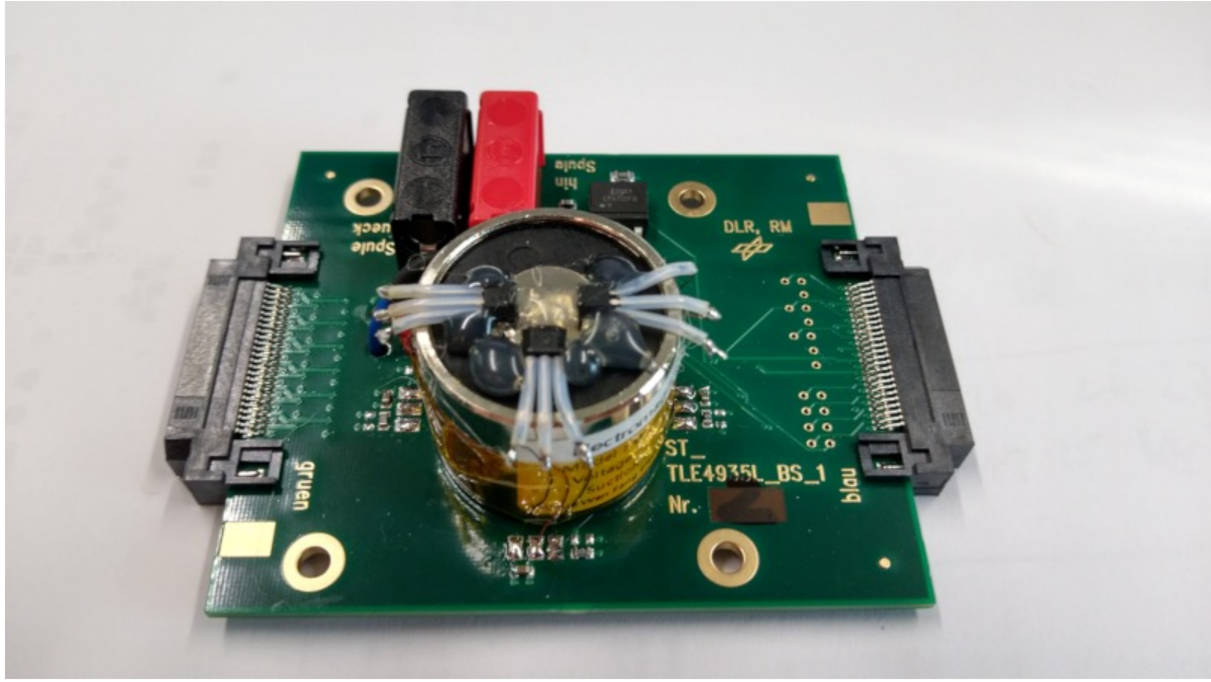




12V and 28V supply current during heavy ion irradiation over time, Credits: H.-J. Sedlmayr et al, “Radiation test of a BLDC motor driver component,” in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE

Hall Effect Sensor

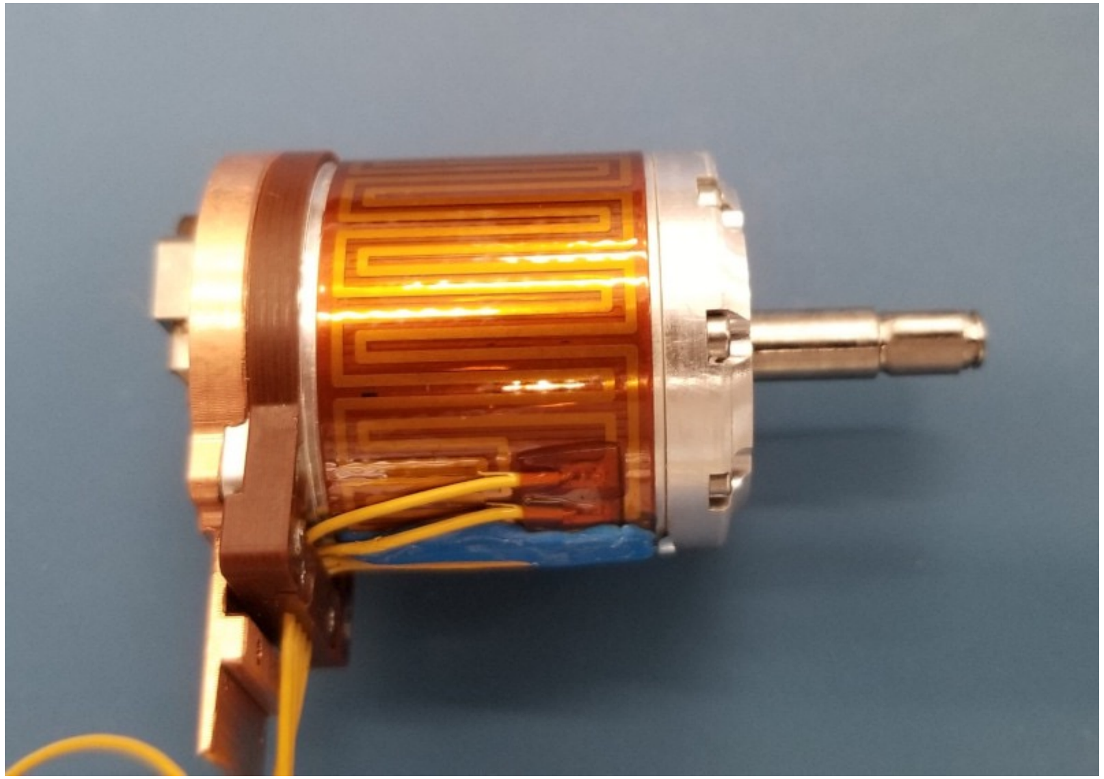
- ❑Latching Hall Effect Sensor
- ❑Open Collector output
- ❑Small Package, wide input voltage range
- ❑Automotive rated part



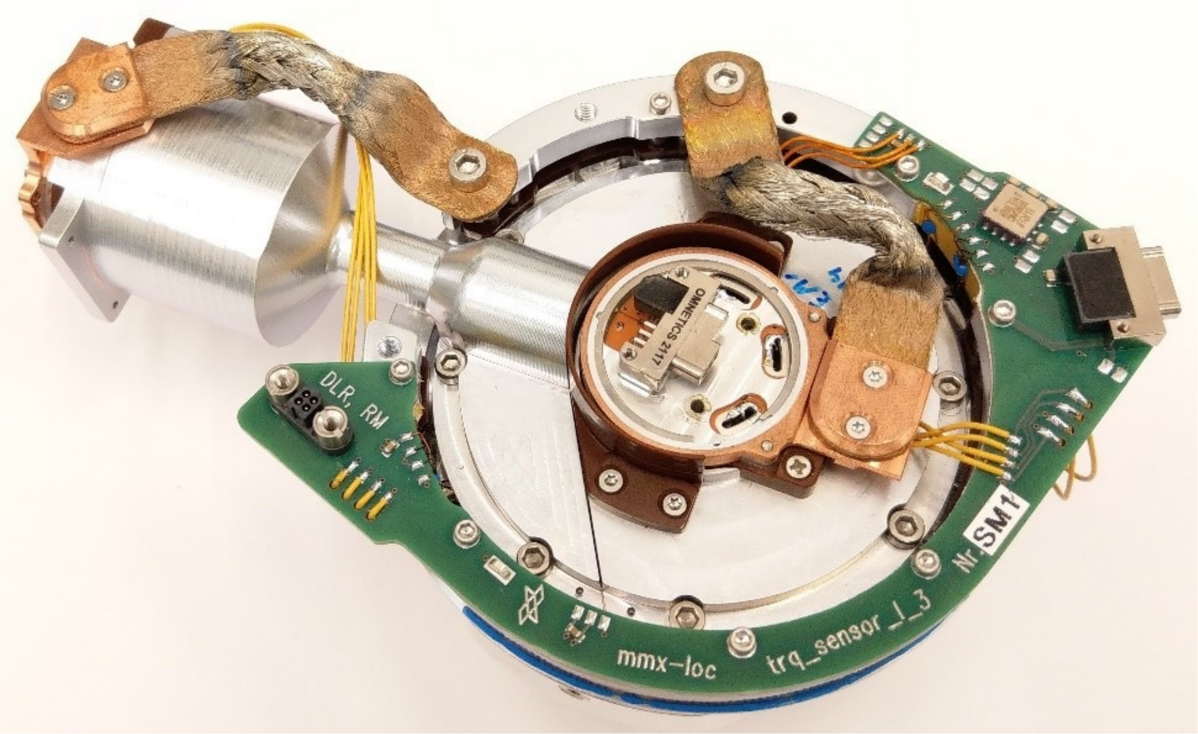
Test board with Hall effect sensors mounted on a stimulating coil,
Credits: H.-J. Sedlmayr et al, "Upscreening of Infineon Hall effect sensor for the MMX rover locomotion subsystem" in 2022 IEEE RADECS Data Workshop, 2012., Copyright ©2022, IEEE

Hall Effect Sensor

Usage in the MMX rover at the locomotion subsystem.



MMX actuator, Credits: S. Barthelmes et al., “MMX Rover Locomotion Subsystem – Development and Testing towards the Flight Model,” in 2022 IEEE Aerospace Conference, 2022, Copyright ©2022, IEEE



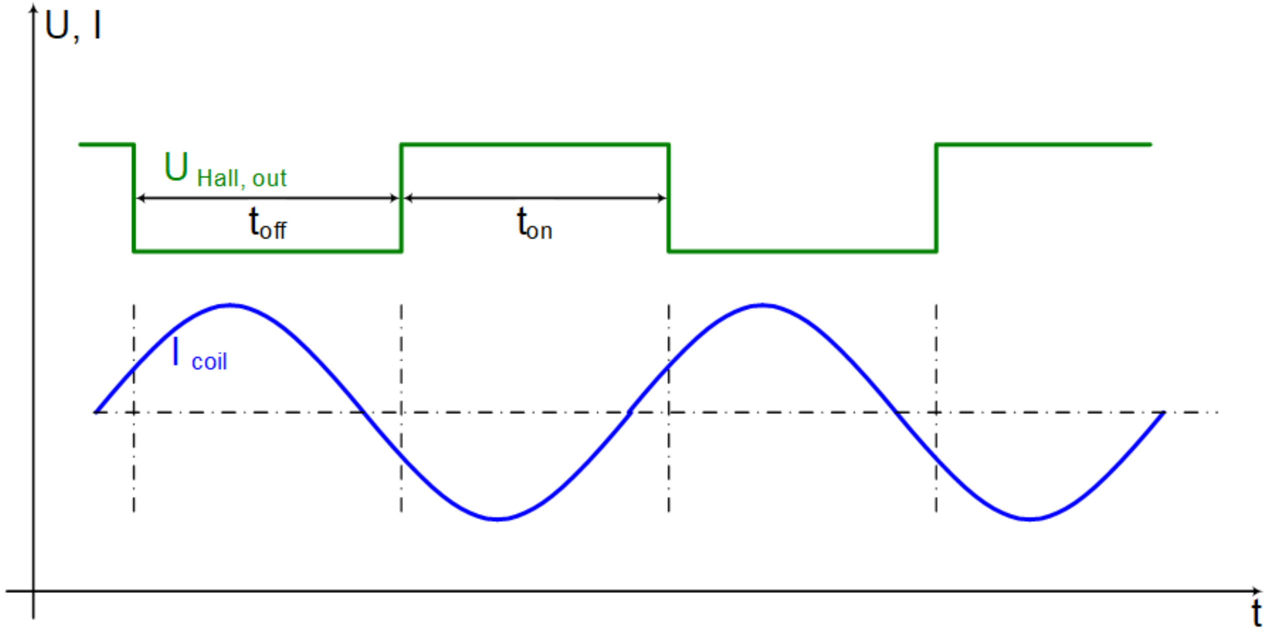
MMX shoulder module, Credits: S. Barthelmes et al., “MMX Rover Locomotion Subsystem – Development and Testing towards the Flight Model,” in 2022 IEEE Aerospace Conference, 2022, Copyright ©2022, IEEE

Hall Effect Sensor

- Same test setup for all tests.
- Coil driven by a sinusoidal voltage was used to stimulate the hall effect sensor:

$$b(t) = 4.5\ mT * \sin(2\pi \frac{t}{200\ ms});$$

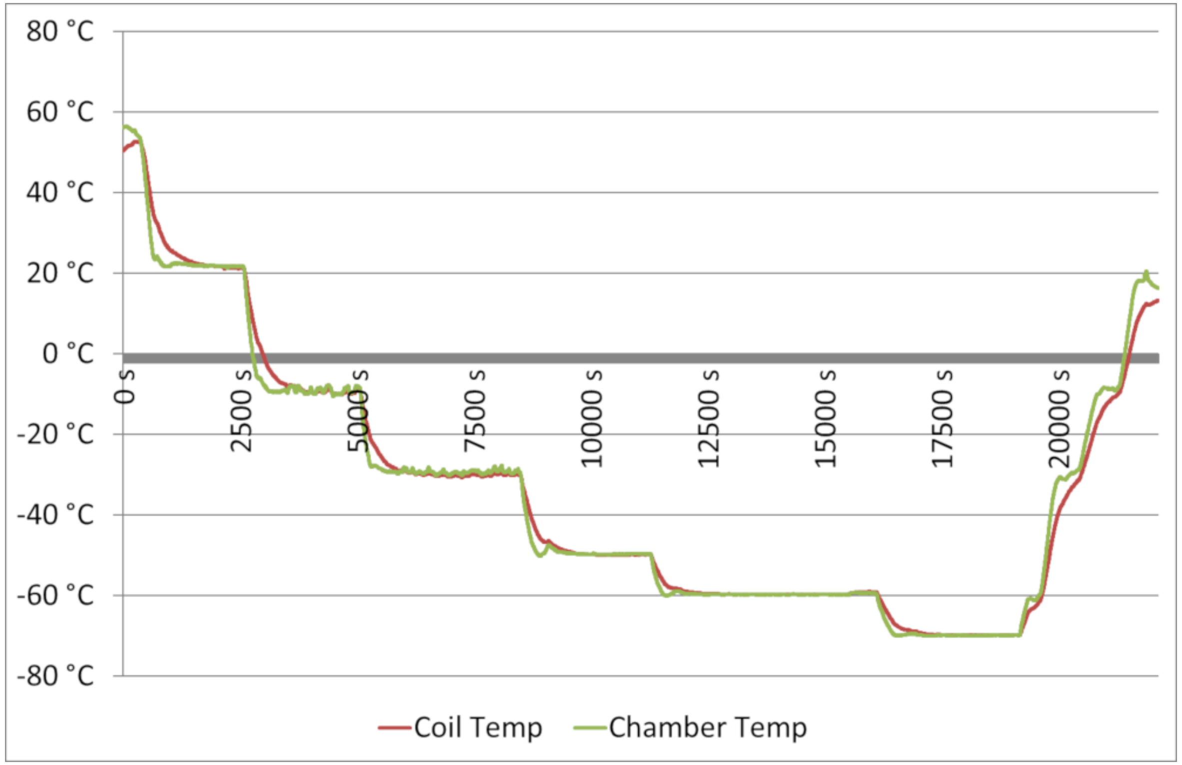
- Comparison of thermal cycled and non cycled devices during radiation test.



Thermal Cycling deep temperature functional test, Credits: H.-J. Sedlmayr et al, “Upscreening of Infineon Hall effect sensor for the MMX rover locomotion subsystem” in 2022 IEEE RADECS Data Workshop, 2012., Copyright ©2022, IEEE

Hall Effect Sensor

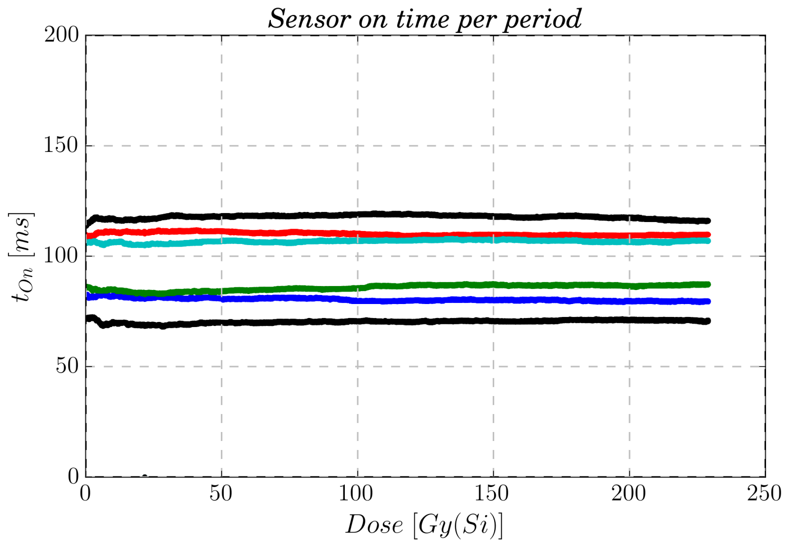
- Temperature range during the MMX mission:
  -75°C up to +85°C (non-operational),
  -30°C up to +85°C (operating)
- High temperature gradients
- Thermal cycling test: 100 cycles between -130°C and +60°C with a dwell time of 15 minutes
- Low temperature operating test



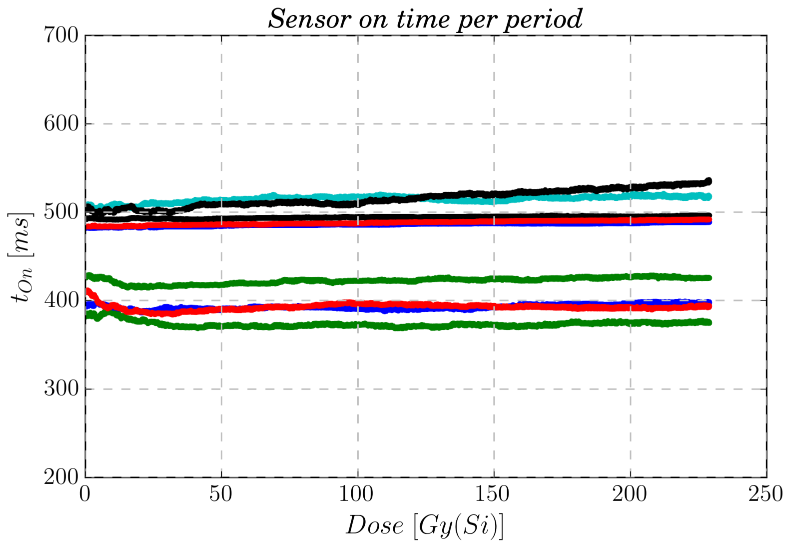
Thermal Cycling deep temperature functional test, Credits: H.-J. Sedlmayr et al, "Upscreening of Infineon Hall effect sensor for the MMX rover locomotion subsystem" in 2022 IEEE RADECS Data Workshop, 2012., Copyright ©2022, IEEE

Hall Effect Sensor

- Total Ionizing Dose test (ELDRS) performed at the HZB up to 230 Gy(Si)
- Dose rate = 2.04 Gy(Si)/hour (low dose rate)
- Test results in line with results of former test campaigns (different lot).



TID test results of the non cycled parts, Credits: H.-J. Sedlmayr et al, “Radiation test of a BLDC motor driver component,” in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE



TID test results of the cycled parts, Credits: H.-J. Sedlmayr et al, “Radiation test of a BLDC motor driver component,” in 2018 IEEE Radiation Effects Data Workshop, 2018., Copyright ©2018, IEEE

Conclusion

Conclusion

- COTS parts offers some fascinating features or high performance.

- Don’t expect to save money or time when using COTS parts especially when having a low number of used parts.

- Carefully trade is necessary whether all the benefits of the used COTS parts are worth to pay the prize in total. Reduction of the number of different part types helps a lot.

- Due to developments on the parts market, the introduction of COTS parts in space application is unavoidable, but rises some challenges for the component engineers.

- When using COTS, a different system setup or mission scenario might help.

- And finally: “All generalization are false – including this one” (Mark Twain)

Thank you for your attention.

Any Questions?

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