HTS Bulk Experiments performed for and under Space Conditions

F. N. Werfel, U. Floegel - Delor, T. Riedel, P. Schirrmeister, R. Koenig, V. Kantarbar, and M. Liebmann

***Abstract* - In the shadow of dominant long-length high-temperature superconductors bulk HTS show a considerable effort of magnetic engineering application. Bulk HTS are capable of providing easily magnetic fields of several tesla, levitates self-stabilized mirrors or measuring instruments, and can be used as a passive magnetic shield. By simulating space conditions we have been investigated the possible degradation of YBCO material under 160 MeV proton irradiation at a radiative dose of 10-20 krad. We report the successful preparation of an HTS bearing cosmic background radiation, the fabrication and testing of a bulk superconducting device operating in the Columbus laboratory of the International Space Station (ISS). The Magvector/ MFX experiment operates the last 4 years at the ISS. It measures the interaction of an YBCO HTS with the Earth magnetic field using sensitive flux gate sensors in µT level. Laboratory shielding results are given. Dependent on the bulk conductivity at T>T$_c$ and T<T$_c$ the Earth magnetic field interaction causes distortions of the surrounding electromagnetic (EM) field. Possible benefits of HTS bulk devices on applications in space will be discussed.**

***Index Terms*—HTS bulk, space application, flux shielding, compression, proton irradiation, MFX experiment.**

I. Introduction

Proposal and use of superconductors in space have a long tradition. One primarily reason is the radiation exposure from solar energetic particles (SEP) and Galactic Cosmic Radiation being a substantial risk for exploration beyond the confines of the Earth's magnetic field. Superconductors seem the only solution when scientific instruments should be levitated during far-distance space missions under favorable terms. However, the preferred observational Sun-Earth-Lagrange point two (L2), where successful satellite missions like NASA CMB, WMAP and ESA CMB [1] are located, has a cosmic ray environment more violent than that at the near Earth orbit. The Mars rover Curiosity mission has allowed to calculate the averaged radiation to 1.84 mS/day that is for a 180-day journey an exposure of more than 8 times higher than the radiation limit for a worker in a nuclear power plant in the same time [2]. The concept of shielding and protecting astronauts using superconductors has been studied since the time of Wernher von Braun [3] with a great number of proposals and studies within the last two decades [4]-[12]. Most of the previous concepts propose active shielding with superconducting toroid or double helix magnet technology. The use of new high temperature superconductor generation based

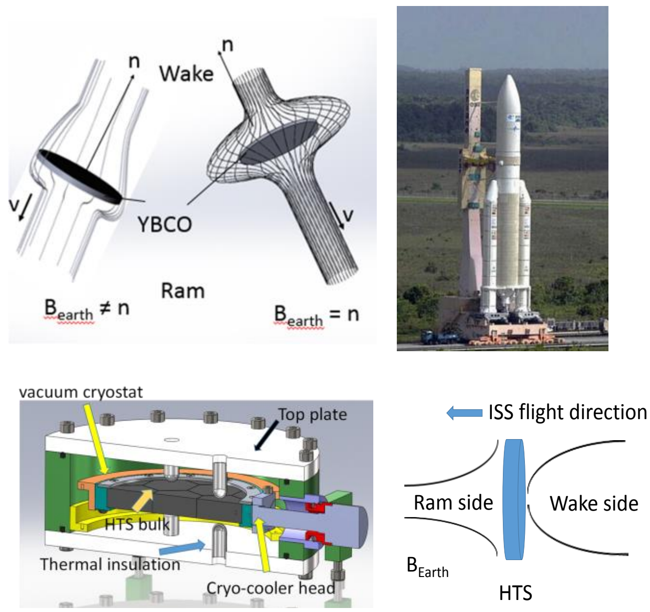

Fig. 1. Concept of YBCO bulk investigation under space conditions. Particle impact control by trapped flux measurement and conductor interaction with Earth magnetic field B_{Earth} running in Magvector/ MFX experiment since 2014 at the ISS.

on thin film architecture for space application however possess a great risk and drawback. For space flights beyond the Earth's magnetosphere galactic cosmic rays (GCRs) and solar energetic particles (SEPs) are a significant hazard, primarily for crews and spacecraft equipment. Coils based on thin film HTS coated conductors may suffer a degradation especially under SEPs. The situation is similar as it has been experienced in the time of replacing electronic tubes by semiconductors. It needs a look for alternatives.

According to previous studies effective shielding is a primary challenge and not solved today. Additionally, because of the immense power needed to energize coils, passive devices as robust HTS bulks may be handled easier. Preliminary results of preparing and using bulk superconductors in space application has been reported already [13]. Here, we continue and assort the experiments into two groups: Investigation with bulk samples being or were in space, and bulk HTS pre-studies for future space application.

We present scientific-technical investigation and results of electromagnetic stability of YBCO bulks under proton

Manuscript received 2018
F. N. Werfel, U. Floegel - Delor, T. Riedel, P. Schirrmeister, R. Koenig, and V. Kantarbar are with Adelwitz Technologiezentrum GmbH (ATZ), Torgau, Germany, Phone +49 3421 778900, e-mail: werfel@t-online.de; floegel-delor@t-online.de.
Support and cooperation with the Deutsche Luft- und Raumfahrt (DLR), Cologne and Airbus Defense, Bremen, both Germany, and ISAS of Japan Aerospace Exploration Agency (JAXA), Japan is greatly acknowledged.

irradiation, homogeneous magnetic levitation, and the interaction of a conductor in the ISS with the surrounding Earth magnetic field. In parallel, we have been measured size-dependent shielding performance of bulk plates in micro-Tesla level.

At first, the trapped magnetic flux stability of bulk HTS under conditions of the International Space Station (ISS) is studied. Additionally, at a further step multi-seed bulk material is investigated by proton irradiation experiments [13]-[14].

A large superconducting magnetic bearing (SMB) to suspend and rotate a cosmic microwave background (CMB) polarizer at 4.2 K extremely sensitive is studied. The bulk stability results favor a space application without thought.

Finally, the MFX/MAGVECTOR experiment operating for four years successfully onboard the ISS [15]-[16] analyze how the Earth magnetic field interacts with a large bulk YBCO superconductor at variable electric conductivity. Using sensitive flux gate sensors placed around the superconductor cryostat, researchers can get knowledge how the geomagnetic field is modified by a body of different electrical properties. Fig. 1 shows the qualitative model together with a figure of the ram and wake side of the superconductor. The results of MFX are of special interest for future technical application as shielding and magnetic pressure generation.

Parallel, laboratory measurements of screening and flux exclusion of the Earth magnetic field B_{Earth} and its modification by YBCO plates complete the comprehensive bulk study.

II. YBCO BULKS UNDER SPACE-LIKE CONDITIONS

A. *YBCO bulks at the Columbus laboratory on ISS*

HTS bulk material in the near Earth space shouldn't show any changes in the electromagnetic structure when deposit at the ISS. For this investigation two cylindrical YBCO bulks with the size D x h 30 x 4 mm² were characterized by scanning trapped field measurements before launching into the space and after returning to Earth. As a small-mission experiment the samples were attached to the German Blue-Dot mission and stored in the ISS for the duration of about 5 months. After the mission time, together with the German Astronaut the samples returned back to Earth. Then the trapped flux measurements were repeated under the same experimental conditions. The results are displayed in Fig. 2.

A careful inspection of the averaged and maximum flux density values of the 41 x 41 matrix including the characteristic fine structure before and after mission showed nearly identical parameters, as expected. No significant changes in the trapped flux scanning pictures before and after space deposition could be detected. The deviation of the two measuring cycles prior and past mission was less than two percent.

The aim of that experimental part was twofold: (i) the observation of any variation or long-time effect on the electromagnetic properties of bulk YBCO under ISS conditions. Simultaneously, a test for the parallel long-duration MFX/MAGVECTOR program, where a larger superconductor is located in a corresponding cryostat at the Columbus laboratory of the ISS. Second: (ii) a confirmation and

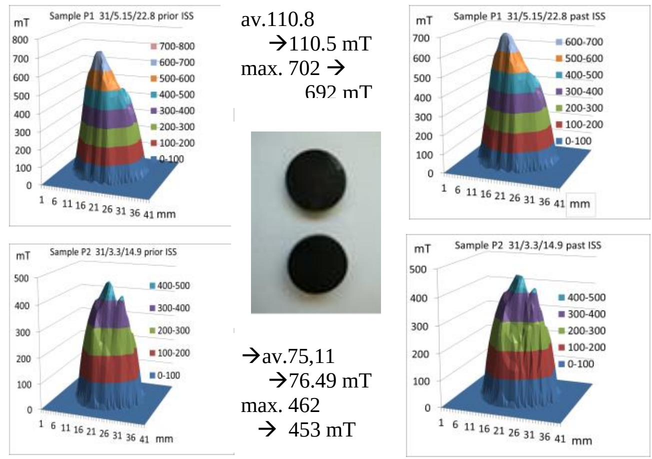

Fig. 2. Comparison of trapped field measurements of two 30 mm YBCO single crystal samples of thickness 3 mm (lower bulk) and 4 mm (top position). The samples were transported to the International Space Station (ISS) with the German mission "blue dot", stored in the ESA Columbus laboratory and returned 5 months later with the astronaut A. Gerst. The values describe parameter prior mission →parameter after returning.

experimental prove of the general parameter stability of bulk HTS under long- time space mission for prospective levitation (bearing) and shielding effects.

B) *YBCO magnetic bearing to modulate CMB polarization*

One of the favorable application of bulk superconductors in space is the self-stabilizing levitation in form of a superconducting magnetic bearing (SMB). Without lubrication, mechanical ripple, and extremely low friction the SMB operates contactless by magnetic flux pinning either in radial or axial geometry. The employment of SMB for a polarization modulator in CMB radiation detection experiment has been utilized world-wide (EBEX, POLARBEAR, and SWIPE). It is

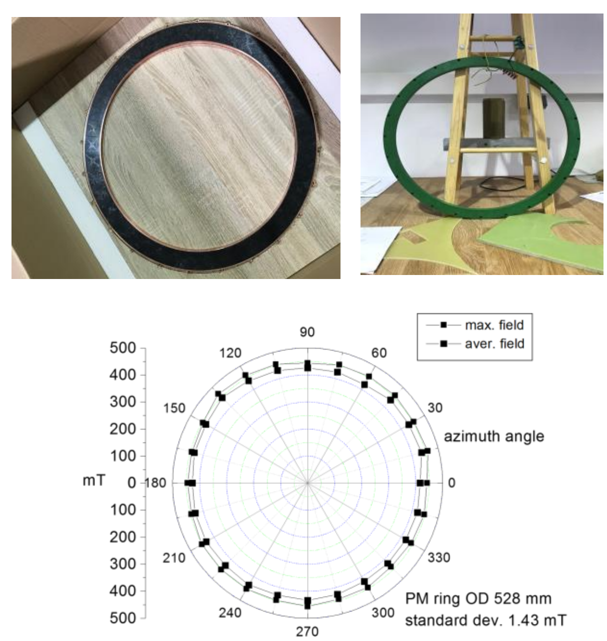

Fig. 3. Large HTS magnetic bearing (D=560 mm) for cosmic microwave background (CMB) polarization modulator consisting of YBCO stator (top left) and PM rotor (top right) together with the measured magnetic homogeneity of the PM ring (bottom).

a unique probe to test the existence of cosmic inflation at the beginning of the universe.

For most of the HTS applications space conditions are to be an asset. As lower the temperature as higher the critical current Jc. The basic physics behind the HTS magnetic bearing is for T<Tc throughout the temperature scale the same. Magnetic flux pinning, forces and stiffnesses are increased with lower operating temperature while all kind of loss mechanism (hysteresis, eddy currents) are beneficially decreased.

A photograph of the basic superconducting stator and PM rotor together with the rim distribution of the PM ring 5 mm above the PM surface is depicted in Fig. 3. The superconducting ring consists of 46 segmented single grain YBCO tiles, glued in and supported by a corresponding copper ring. The outer stator diameter OD is about 560 mm, and the rotor inner free space of 470 mm is the open window for the detector and support for the rotating half-wave-plate (HWP) to modulate CMB polarization. Under cooling the YBCO/copper ring shrinks and comprises thermo-mechanical compression. For the 560 mm YBCO/Cu ring we measured at 77 K a diameter difference of 1.7 mm relative to RT, in agreement with the calculated $\Delta l/l$=0.302 % for Cu at 300 K → 77 K temperature transition.

A key for low-friction of the CMB magnetic bearing is the homogeneity quality of the PM ring. The PM ring in Fig. 3 consists of 16 pieces of 22.5° NdFeB segmented tiles in a G-10 fixture. At the interface between two tiles the magnetization is intermitted giving a periodic signal of the measured magnetic field under rotation. That magnetic flux inhomogeneity ΔB between the tiles together with the inhomogeneity within a tile causes friction and energy loss when the bearing rotates. A consideration of the typical slow- down of the bearing is shown in Fig. 4. The spin-down behavior can be modeled by three factors: (i) hysteresis loss which is proportional to $(\Delta B)^3$, (ii) losses due to eddy currents going with $(\Delta B)^2$, (iii) at normal pressure the aerodynamic drag which depends on the rotational frequency. The slow-down curve of the naked rotor/stator accelerated by hand at LN_2 cooling allows to calculate the friction coefficient η. By solving the differential equation $d\omega/dt + c\omega = 0$ with $c = \eta/J_z$ (J_z rotor inertia torque) we obtain friction coefficients of $\eta = 1.19 \times 10^{-4}$ Nms (higher speed region) and $\eta = 0.96 \times 10^{-4}$ Nms (lower speed part). The moment of inertia of the PM ring is estimated to $J_z = m R^2 = 0.243$ kgm². The nonlinearity of the spin-down curve in Fig. 4 arises of the air drag. Without air the slow-down curve should be linear and the spin-down behavior depend on magnetic interaction between rotor and YBCO stator (hysteresis, eddy currents).Without air we deduce from earlier measurements a friction coefficient of $\eta < 10^{-6}$ Nms.

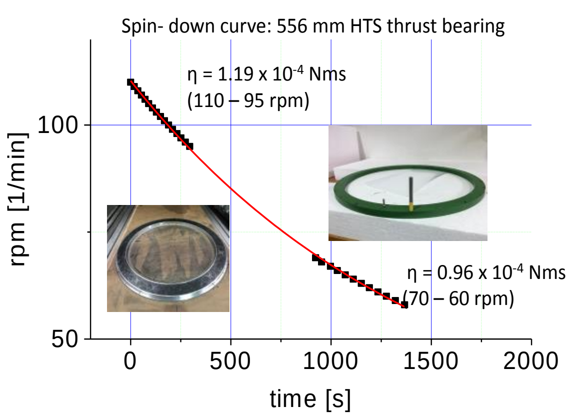

Fig. 4. Spin-down curve of the CMB superconducting bearing at LN_2 cooling. The degree of rpm decay depend on the magnetic inhomogeneity of the PM ring ΔB which causes magnetic hysteresis and eddy current effects. The non-linearity of the curve arises from ambient pressure air drag.

C) *Proton irradiation*

In the next experiment bulk superconductors has been investigated for particle interaction and stability for their possible application in long-duration space missions. Significant improvements of the critical current density has been observed under heavy Neutron impact on YBCO single crystals and thin films [17]. The effect is explained by the generation of additional pinning centers.

One of the major cosmic ray population is a proton. At the Heavy Ion Medical Accelerator in Chiba (HIMAC) Japan, for possible damage we carried out proton irradiation tests. At room temperature and ambient pressure the YBCO samples were placed along the proton beam line. The proton energy was 160 MeV. Per irradiation test the amount was chosen to be the water equivalent of 10 krad. That level corresponds to an equivalent dose obtained during a 5 years stay at L2. Before trapped field measurements the samples were protected and the radiative level has to be reduced within a few weeks. Altogether we performed three measurement sets, before irradiation, after first irradiation, and after a second irradiation, all under identical conditions. Simultaneously, similar YBCO samples without proton irradiation were monitored to observe possible changes with time.

The experiment shown in Fig. 5 followed a first radiation exposure of 4 YBCO single grain samples of cylindrical geometry OD30 mm x H15 mm. In a second step 3-seed YBCO in rectangular shape L66 mm x W33mm x H14 mm were selected to control the grain boundaries under irradiation. Again, in a field cooling (fc) process the tiles were magnetically excited (1.5 T; B||c) and the trapped field scanned by a Hall probe. Then the samples were irradiated singular and a second time with protons after 3 months. A few weeks waiting for

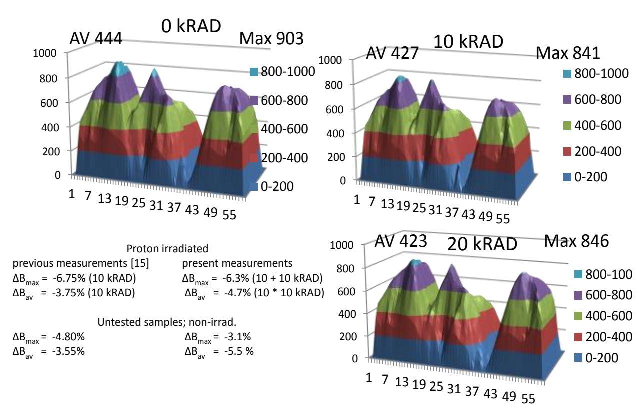

Fig. 5. Scanning trapped field profiles before and after proton irradiation. The water equivalent dose of 10 krad corresponds to an expected 5 years stay at the Sun-Earth Lagrange point two (L2) under cosmic ray environment.

decreasing the generated radiation level was necessary. Excitation and Hall probe scanning measurements of the samples has been then repeated. A careful inspection of trapped field structure in the scanning pictures in Fig. 5 between the untested bulk, displayed on top left, and the same sample irradiated (top right) showed no significant changes. The same procedure was repeated a few months later, with an additional doze of 10 krad to totally 20 krad irradiation. Except the trapped field structure numerical results of the maximum value B_{max} and its change ΔB_{max} are compared. The averaged value of the scanned trapped magnetic flux B_{av} and its change with irradiation ΔB_{av} are taken for comparison. The irradiation results referenced to the untested samples values revealed no significant differences. Hence, we assume a great electromagnetic stability of bulk HTS against heavy proton irradiation. A planned SMB with HTS bulk seems to have no functional risks even for a longer L2 mission operation.

D) Low magnetic field interaction (MFX)

As for the magnetic bearing behavior low magnetic field interaction under lower temperatures in space (flux guiding, screening, compensation, and pumping) follow the experimental laboratory results obtained at 77 K on Earth.

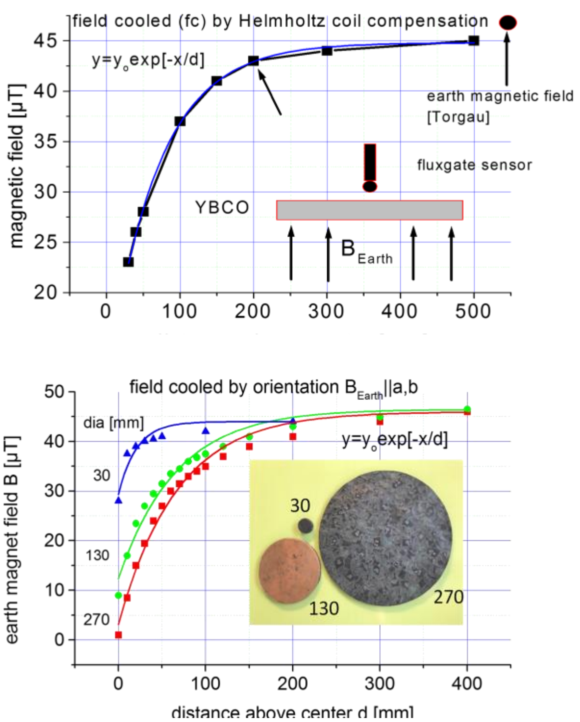

Fig. 6. Earth magnetic field shielding experiment with a 110 mm x 12 mm YBCO plate (top) and size variable shielding performance (bottom). The flux gate Hall sensor FC 100 was each time in central position and detected the Earth magnetic flux shielded by the HTS plates at 77 K.

Onboard the Columbus laboratory of the International Space Station (ISS) the experiment Magvector/MFX measures the field conditions of the Ram and Wake side (Fig. 1) around a HTS bulk while moving through the Earth magnetic field with 28 000 km/h [15]-[16]. With different conductivity properties an YBCO sample the ISS is the ideal location for electromagnetic and field measurements. When warm, the melt textured bulk is more a semi-conductor, and for $T<T_c$ a nearly perfect electrical conductor, having quite different physical consequences for the electromagnetic field around.

The experimental cryostat has been built up by ATZ in cooperation with the German DLR and Astrium/Airbus. The MFX fabrication and qualification was performed within 15 months. It was not a process that every laboratory would undertake slightly. Safety and test requirements for all technical parts were stringent but straightforward by all partners. Like other space projects a large number of technical and technological processes had to be solved within a short time.

The MFX experiment consists of a compact non-magnetic vacuum cryostat with an attached Stirling cryo-cooler schematically shown in Fig. 1. A 3-D Helmholtz coil serves for field compensation in x, y, z directions. The cryo-cooler head is connected with the inner bulk HTS by means of an Al alloy ring enabling radial thermal management of the superconductor.

More than a dozen Hall and temperature sensors monitor the conditions of the conductor state while interacting with the Earth magnetic field permanently. Reference sensors are used for the detection of the actual local temperature and local Earth field conditions. Fig. 1 displays a functional modeling of the field interaction. Below that the central part of the MFX device with the cryostat, the YBCO bulk and the Stirling cryo-cooler head is shown. The accumulated data are expected to describe the interaction of the superconducting body similar as it is measured in [13]. The interaction on ram and on wake side is deduced qualitatively from the parallel measurements in Fig. 6.

The interesting question arises from magnitude of the effect of superelevation of the Earth field on the ram side and the opposite behavior on the wake side in the space. The qualitative magnetic field behavior assumed on ram and wake side of a superconducting plate is sketched in Fig. 1. , for the symmetric and asymmetric case. According to Fig. 1 a field compression is expected on ram, while on the wake a field depletion takes place. In the central-symmetrical case (normal vector parallel to B_{Earth}) the field distribution should display a circular distribution. Clearly, in most situations the position of the ISS will cause an asymmetric distorted field around the HTS.

For comparison with the space measurements Fig. 6 gives laboratory shielding experiments with bulk superconductors at LN_2 temperature. The measurements were performed with flux gate Hall sensors located central behind the HTS bulks at different distances. In order to prevent the inevitable B_{Earth} to be trapped into YBCO plates a Helmholtz coil is used to compensate (Fig. 6, top). To obtain the plates field-free in the lower Fig. 6 the YBCO samples were field cooled (fc)with the plate surfaces parallel to the direction of the vector of the Earth magnet field. Behind the YBCO plates B_{Earth} is shielded and follows perfectly an exponential decay (top) as it is expected from the ram/wake model in Fig. 1. Small deviations in shielding behavior between experiment and calculated curves for the three sized samples (Fig. 6, bottom) point to some imperfections caused by the not perfect B_{Earth} exclusion due to the B_{Earth}||a, b crystal orientation geometry during the field cooling process (in contrast to Helmholtz).

III. Conclusion

The scientific and technical skills of HTS bulks under space and space-near conditions are investigated. A bulk high-T_c superconductor is capable to operate advantageously in space application. Levitation and shielding using HTS bulk seem stable. Even under hard proton radiation exposure (20 krad), measurements give evidence for no significant electromagnetic changes or degradation. Hence, bulk HTS material maintain the technological potential even for far-space missions. HTS bulk can shield magnetic fields or provide a self-stabilized levitation. The successful space experiment Magvector/MFX in the ISS allows insides and details into ways how magnetic fields influence solar bodies of different electrical conductivity in space.

References

[1] D.M. Hassler et al., SCIENCE Vl. 343, 24. Jan. 2014

[2] J. H. Adams et al." Revolutionary Concepts of Radiation Shielding for Human Exploration of Space", NASA TM-2005-213688

[3] W. v. Braun, "Will mighty magnets protect voyagers to planets". Popular Science (January), 98–100 (1969)

[4] L.W. Townsend, "Overview of active methods for shielding spacecraft from energetic space radiation", 1st International Workshop on Space Radiation Research and 11th Annual NASA Space Radiation Health Investigators' Workshop, Arona (Italy), May 27-31, 2000, Physica Medica - Vol. XVII, Supplement 1, 84, 2001.

[5] J.A.Hoffman, P. Fisher, and O.Batischev, "Use of Superconducting Magnet Technology for Astronaut Radiation Protection", NIAC Phase I Final Report, Contract CP 04-01, 2005.

[6] P.Spillantini, F.Taccetti, P.Papini, L.Rossi, "Radiation shielding of spacecraft in manned interplanetary flights", Nuclear Instruments and Methods in Physics Research, A 443, 254-263, 2000.

[7] S. G. Shepherd, B. T. Kress, "Comment on: "Applications for Deployed High Temperature Superconducting Coils in Spacecraft Engineering: A Review and Analysis" by J. C. Cocks et al." J. British Interplanetary Soc., 60, 129-132, 2007.

[8] R. Musenich, V. Calvelli, S. Farinon, R. Battiston, W. J. Burger, P. Spillantini, "A Magnesium Diboride Superconducting Toroid for Astroparticle Shielding", IEEE Trans. Appl. Supercond., 24 (3), 4601504, 2014.

[9] R. Battiston, W. J. Burger, V. Calvelli, V. I. Datskov, S. Farinon, and R. Musenich, "Superconducting magnets for astroparticle shielding in interplanetary manned missions," IEEE Trans. Appl. Supercond., 23 (3), 4101604, 2013.

[10] S, Westover, R. Meinke, W. Burger, A.Ilin, S. Nerolich, S. Washburn, Magnet Architectures and Active Radiation Shielding Study with High Temperature Superconductors, NIAC Phase 2 Symposium, February 4, 2014.

[11] F. Ambroglini, R. Battiston, W. J. Burger, Evaluation of Superconducting Magnet Shield Configurations for Long Duration Manned Space Missions", Front. Oncol., June 8, 6, 2016.

[12] V. Calvelli, R. Musenich, F. Tunesi, R. Battiston, "A Novel Configuration for Superconducting Space Radiation Shields",,IEEE Trans. Appl. Supercond. 27, (4) 2017.

[13] F. N. Werfel, U. Floegel - Delor, R. Rothfeld, T. Riedel, P. Schirrmeister, R. Koenig, and V. Kantarbar, Impact of Cryogenics and Superconducting Components for HTS Magnetic Levitation Devices, IEEE Trans. Appl. Supercond. Vol. 27, 4 (2017).

[14] T. Matsumura et al. "Effect of Proton Irradiation to a Trapped Field Bulk YBCO for Use in Space, J. Latex class files, Vol. 14, 8 (August 2015)

[15] http://www.nasa.gov/mission_pages/station/research/experiments/1176. html, date 14.07. 2014.

[16] http://eea.spaceflight.esa.int/portal/exp/?id=9446; experiment record No. 9446, May 2014, updated 2015, 2016.

[17] F.M. Sauerzopf, "Anisotropic flux pinning in YBa2Cu3O7-x single crystals: The influence of defect size and density as determined from neutron irradiation" Physical Review B 57, 10959 (1998).