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Containerless Processing on ISS: Experiment operations in ESA's EML, the Electromagnetic Levitator

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Abstract

EML is an electromagnetic levitation facility built for the ISS aiming at processing liquid metals or semiconductors under microgravity and thus reduced electromagnetic field and convection conditions. Its diagnostics and processing methods allow to measure thermophysical properties in the liquid state and to investigate solidification phenomena. EML resides in the European Drawer Rack inside the Columbus Module and inboard the ISS since June 2014. The payload was developed by an industrial consortium under the leadership of Airbus DS on behalf of the European Space Agency.

The Microgravity User Support Centre MUSC at Cologne, Germany, has been assigned the responsibility for EML operations under ESA contract and operates the experiments on behalf of the international science community.

Since April 2015 EML is in use for science runs. In this timeframe over one thousand individual experiments on 36 metallic alloys were performed, including the first successful processing of different semiconductors in EML. To enhance the scientific output the 'Sample Coupling Electronics' has been integrated into EML, whereby electrical resistivity and thermal expansion can be derived.

During the ESA mission "Horizons" with the German astronaut Alexander Gerst, in late summer 2018 it is planned to upgrade the operating system of one of the main diagnostic tool of EML – the High Speed Camera. The advantages of the lossless compression and more disk space for performing and post processing of science runs will be discussed.

Keywords: Electromagnetic Levitator, EML, MUSC, DLR

1. Electromagnetic Levitation

Containerless processing of metallic alloys and semiconductors with the Electromagnetic Levitator (EML) is performed since April 2015 on the ISS. EML is a class 2 payload inside the European Drawer Rack (EDR), a multifacility rack located in the European contribution to the ISS, the Columbus Module.

By means of an electromagnetic quadrupole field and a superposed electromagnetic dipole field EML is able to containerlessly position a liquid metallic droplet and to heat it up independently, which would not be possible under 1g conditions. Processing under UHV or noble gas, the sample can be heated, molten and brought in the meta-stable state of an undercooled melt. It is possible to introduce different contactless kinds of stimuli, like heater pulses and modulations with different shapes. With the help of an integrated trigger needle the nucleation can be triggered in a defined timely manner. Of course all diagnostics applied in EML are contactless as well, e.g. a pyrometer for temperature measurements, an axial camera and perpendicular a high speed camera with radial view and up to 30000 frames per second. Since February 2017, the Sample Coupling Electronics (SCE) is available to measure electrical resistivity and density (see chapter 7).

EML is used by a large international investigator group from Europe, USA and Russia. Samples and melt cycles are shared between the investigator teams to optimize the scientific output by minimizing the effort.

The investigator teams are interested in different topics like solidification phenomena and measurement of thermophysical properties. Statistics of nucleation, undercooling and solidification speeds as well as morphology and phase transitions can be determined with the high speed video images in conjunction with the temperature profile. In the course of the modulation calorimetry, modulations of the heater voltages are used to determine heat capacity, effective thermal conductivity and enthalpies by measuring the temperature response of the sample. Whereas pulses of the heater voltages are used to measure surface tension and viscosity. Using subpixel resolution techniques on both video views enable precise size measurements for determining of the thermal expansion of the sample in different temperature regimes [1, 2].

2. Structure of Experiments

The scientific experiments in EML are grouped into Batches. One Batch is related to a specific sample chamber with 18 dedicated samples. Each sample can be molten many times, hence one Batch consists in the range of about thousand individual melt cycles. For practical reasons, each Batch is divided into several sub-batches.

Driven by the first results gained from the performed Batch 1 experiments in the timeframe between April 2015 and December 2016 the scientific community demanded additional data points on the Batch 1 samples. This sub-batch is currently being performed on-orbit in late summer and autumn 2018.

In order to account for the ground based development time of the individual sub-batches, an interlaced approach was taken to optimize the on-orbit utilization (see Fig. 1). After the original Batch 1 experiment runs were performed, the swap to Batch 2 and a new sample chamber with new samples inside was performed (SCH swap). While the first experiments were conducted on the new batch 2 samples, the ground support program for additional Batch 1 add-on experiments took place on ground. Thus during May 2017 and May 2018 two sub-batches of together 470 cycles of Batch 2 where performed in orbit in parallel to the preparation of 160 Batch 1.3 experiment runs. In summer 2018 the Batch 1 sample chamber was reinstalled onto EML and the additional cycles are planned to be finished in autumn 2018. Afterwards Batch 2 is to be finished. The request for additional cycles for Batch 2 is already formulated by the PIs even with Batch 2 operations still ongoing.

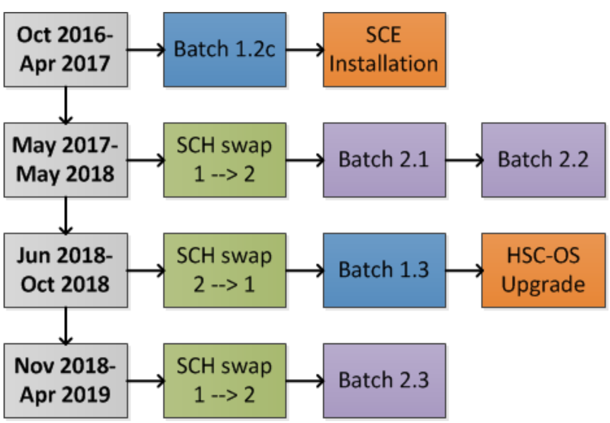

Fig. 1. Planned interlaced approach Batch 1 and 2

3. Planning

In order to perform an experiment on orbit with a reasonable outcome, many steps, which depends on each other, have to be performed. As usual the major steps can be divided into preparation, performance and postprocessing. Two different action lines of the preparation merge together in the on orbit performance: These are the experiment preparation on one hand and the operational preparation on the other hand.

3.1 Experiment Preparation

The experiment preparation consists of the following main parts [1]

- Sample characterization:
  It comprises the examination of sample specific characteristics which need to be known for the processing inside EML, as the temperature dependent evaporation rate, the sample coupling to the RF fields and the spectral emissivity [3].
- Detailed experiment planning:
  It comprises the development of so called Science Protocols which assemble a detailed verbal and graphical description of the planned experiment. These are the basis for the later generation of the Experiment Parameter Sets and the camera configuration files and scientific resource requirements.
- Experiment validation:
  All developed Parameter Sets and facility settings are tested in the operational model (flight spare for the early phase of EML on-orbit operations) on ground.

3.2 Operational Preparation

The operational preparation consists of

- Resource allocation and coordination
- Procedures development for ground and on-orbit operations
- Ground Segment set-up

and will be described here after.

3.2.1 Resource Allocation and Coordination

The resource allocation and coordination is defined by the interfaces between MUSC towards ESA and COL-CC.

The most restricted resource is crew time. For EML, the experiment itself is performed via ground commanding without crew interaction, nevertheless an astronaut is needed to change facility settings according to the requirements of the respective experiment, e.g. on the EML High Speed Camera and hand gas valve settings regarding Argon or Helium as the gas atmosphere in the process chamber during the runs. These crew activities are relatively short and recurring with typical durations of five to ten minutes and can be accommodated straight forward.

More challenging is the planning of long crew activities like a swap between two EML Sample Chambers with a duration of 60 minutes or a hardware update of EML (such as the installation of a new diagnostic device, the Sample Coupling Electronics SCE (ref. Chapter 7) with a crew time of 4 hours or HSC-OS upgrade 5 hours).

Further resources needed by the EML experiments are power, access to Columbus vent line, high rate data bandwidth for the download of science videos, medium rate telemetry and commanding capability. During the science runs, the TM/TC turnaround time is required to be no longer that than 5 seconds. To ensure this, EML is granted a so called “command window”, which is a timeframe of exclusive telecommanding.

A good microgravity level without disturbances during experiment phases is also mandatory. To achieve optimum microgravity conditions, experiments are deconflicted with all activities that are known to induce microgravity disturbances such as planned Thruster Firings of the ISS or Docking/Undocking events. In addition, the experiments are always performed during crew sleep to minimize disturbances induced by crew presence in Columbus. EML operations use the service of the NASA PIMS Team. It has been agreed that one (SAMS) sensor is always active in the Columbus module, while EML experiments are ongoing.

The experiment execution on the levitated sample is always observed with high compressed real time video of both EML internal cameras. This insures the proper experiment performance through monitoring and controlling the sample in addition to facility settings. Immediate reaction from the ground operator in case the hot (or molten) sample gets unstable, and thus endangered the integrity of the facility, ensures a timely switch-off of the science run. During this phase a minimum of 18Mbps better 32Mbps download bandwidth has to be available.

Periods when the on-board crew is not sleeping are used to download the stored science videos obtained during the night. For each melting cycle usually two videos of together about 10GB are stored on the EML camera hard disks. Taking eight cycles per night into account, in average about 80GB of science data has to be downloaded during daytime. Thus it is coordinated with the FCT that the maximum available bandwidth is made available for EML data download. Depending on the requirements of the other payloads in Columbus this is up to 32Mbps.

3.2.2 Procedures development

For each activity both in orbit and on ground a dedicated operating procedure has to be in place. For activities performed from ground only the procedures are collected in the so called Ground Command Procedure Book (GCP-Book). Each payload has its individual GCP-Book and has some kind of freedom in syntax and semantic, only warnings and hazard controls has to be ensured.

For activities performed by the crew the procedures are collected on board the ISS and are written with a defined syntax, according to the established international Payload Operating Development File (PODF) standard.

Both kinds of procedures are developed and authored by MUSC with inputs from the payload developer Airbus. Each procedure has to be tested and validated either on the full functional operational ground model (OM) which is under MUSC custodian-ship or on the trainings model at the European Astronaut Center EAC. Afterwards each procedure undergoes at least one review cycle including all stakeholders (EML operations team, payload developer Airbus, Columbus Control Center COL-CC, Crew Office), before it is published.

3.2.3 Ground Segment

For operating EML from the MUSC control room located at DLR Cologne, MUSC is connected to the ESA IGS (Interconnecting Ground Segment). The EML TM&TC Ground Segment is based on the CD-MCS architecture of the Payload Data Center PDC. Console positions at MUSC are connected to PDC via a VPN connection giving them remote desktop administration of the EML/EDR CD-MCS machines and providing monitoring and control functionality. These enable MUSC to receive telemetry (low and medium rate facility status data and video) and telecommand capabilities to control the payload behavior and experiment performance in real-time [1, 2].

In addition, for the video data visualisation, dedicated ground support equipment has been developed which demultiplexes the incoming HR data streams, and processes them into readable video files.

4. Experiment Execution

The experiment preparation and the operation preparation together lead to a flowchart with a defined experiment flow and booked dates for experiment execution which is used by the scientific community on one hand and the operations planning team on the other hand (see Fig. 2).

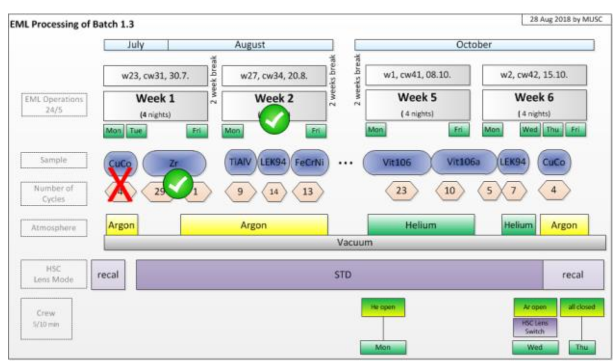

Fig. 2. Flowchart Batch 1.3 (exemplary)

Envelope of the EML experiments is facility preparation and conditioning and data handling, especially the high amount of science video data. Hence an operational scenario of 24/5 is established: a typical science operations week for EML starts with the run-up of the EML facility on Monday morning, doing preparation and postprocessing at crew daytime alternating with experiments during crew sleep. Run-down of EML is usually on Friday evening, after the data download is completed (see Fig. 3).

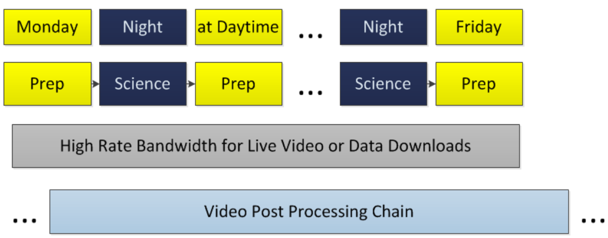

Fig. 3. Operational Scenario

Most of the samples in EML are very sensitive to contamination by e.g. oxygen in the surrounding process atmosphere. Hence processing will be performed either under UHV conditions or under ultra clean noble gas atmosphere. Experience from early batch 1 operations has shown that the process chamber and also the connected gas hoses have to be conditioned beforehand by running the EML Turbo Molecular Pump (TMP) for a long time and by evacuating and purging of all tubings prior to the start of the first experiment of the night. After a non-operational period of EML for some weeks the TMP is kept running continuously for up to one week, whereas after a short break of one or two weeks several hours are sufficient. In a timeframe of about one crew day a vacuum level in the range of lower 10^{-7} mbar regime can be established. In case of experiments under UHV the TMP keeps running, in case of experiments under gas a dedicated purging and filling procedure is in place to guarantee best possible and clean process atmosphere [1].

Prior to a science run another task is to run-up all diagnostic inside EML, like SCE, pyrometer and both camera systems. The live video for experiment control has to be established in conjunction with the Video Management Unit (VMU) inside EDR.

Currently in one night about 8 EML science runs can be performed. This number is limited by some operational constraints like the available AOS time, a short assessment of the last melt cycle to optimize the parameters of the upcoming run by commanding and the long-time of 35 minutes to transfer the radial science video of the last cycle from the ring buffer of the High Speed Camera to the internal hard disk.

5. Postprocessing

Right after the last experiment cycle of the night the conditioning process as described above is started again to optimize processing conditions for the upcoming experiments. In parallel the download of the stored science video data is initiated. During the download the operator on console needs to check the completeness of the incoming data and if there are any packet losses encountered, the download has to be restarted. Afterwards the raw video data has to be processed into cine-file format, this complex task consists of many steps which has to be performed in the ground segment and with a dedicated software-tool. Checking the completeness and quality of the generated science video is required. In case of detected issues the cine production and/or the download of the raw video files has to be repeated. Only in case of a good end result, the original raw data files are deleted on-orbit to free up disk space.

The science community can access their data via our dedicated archiving system gateway which in the end contains a data set for each science runs. The major contributions are the science videos, which are supported by the telemetry data (heater and positioner settings), the temperature-time-profile and a copy of the processed live video are made available. Quick look graphs and the process video are also archived and distributed.

Preparation, execution and postprocessing of experiment runs is in principle performed in parallel, although the postprocessing chain do not stop with the on-console work, but is continued beyond, due to the complexity and duration of the tasks.

6. Science operations challenges: semiconductors and magnetic samples

One of the operational challenges during Batch 2 processing was the processing of semiconductors. In July 2017 the first semiconductor, Germanium, was successfully processed and melted in EML on the ISS.

In the meanwhile MUSC processed in the course of the Semitherm project led by Prof. Konrad Samwer, 14 cycles of Si25Ge75 and 15 cycles of Si50Ge50 successfully [4].

Before a sample can be heated and subsequently melted it has to be stably positioned. Otherwise, the sample may suffer from strong translatory and oscillatory movements during melting, which may lead to a loss of the sample and potential facility damage. The coupling of a sample to the magnetic field of the coil depends on the electric conductivity. The electric conductivity of a semiconductor highly depends on his temperature and is behaving as an insulator at room temperature, resulting in the effect, that it can be heated sufficient, but the positioning force is low. The circular reasoning here is, that a “cold” semiconductor cannot be stable positioned but to heat it up it has to be positioned. To get rid of this circle the EML operator used a successive approach which is highly depending of the observed sample behavior in the live video. In this timeframe many commands need to be send by the operator to react on the observed sample behaviour. Only if the sample is stably positioned on one point the automated melting and processing by means of the experiment parameter set is started. The big picture is shortly described here after.

The following risk mitigation was established for the semiconductor experiments: First of all the sample is contained in a cup not a cage, which minimized the risk of escaping of the hot sample. Secondly the positioner voltages and the heater voltages are toggled manually and step by step to higher values. After each step the system in disbalance of positioner field, heater field and rising temperature (therefore rising electrical conductivity) is observed. In case of any seen unexpected movement of the sample or any other risk to the facility the heater and positioner were switched off by ground command to cool down the sample. This is repeated until a stable positioning of the sample in the center of the coils is observed. On one point, the sample will be positioned enough to allow a manual mechanical damping out of the translations and rotations. When the sample is quiet it is safe to leave the manual sample control and to use the predefined parameter set to finally jump into the melting phase, which is the first step of the scientific relevant part of the experiment run.

Ferro-magnetic samples constitute a similar challenge. In these cases the sample has to be heated up above the Curie-Temperature. Below the material dependent Curie-Temperature the sample is not moving towards the field minimum, but maximum, which is against the container wall. In the EML facility on the ISS we already processed five different magnetic sample on Batch 1 and 2.

The processing of samples in EML and especially the challenge of processing semiconductors or magnetic samples places highest demands to the operators on console at MUSC to gain the best scientific output without any danger to the facility.

It must be noted that apart from the challenging sample classes, for most of the materials selected for investigation in the EML payload, the science operations are more straight forward. Usually, the sample processing is initiated via the predefined parameter sets from the start and less manual interaction during the experiment is required. The bulk metallic glasses for example show an excellent positioning behaviour so that a broad range of heater pulses and stimulations can be applied. In one case it was even possible to solidify the sample in the amorphous state. During the upcoming Batch 2.3 operations, it will be attempted to repeat this and to save the bulk metallic glass for later ground analysis.

7. EML Enhancement by Sample Coupling Electronics

In February 2017 prior Batch 2, a new diagnostic device, the Sample Coupling Electronic (SCE), was integrated into EML by the European Astronaut Thomas Pesquet (see Fig. 4). The SCE was developed by the DLR Institute of Materials Physics in Space and built by Airbus DS on behalf of the German Space Agency.

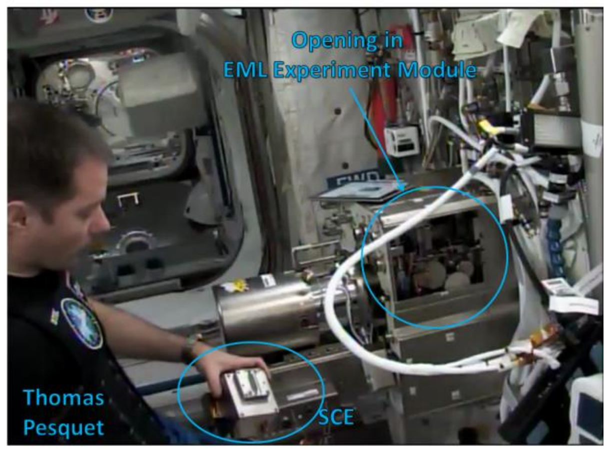

Fig. 4. Thomas Pesquet during SCE installation on-orbit

For stable positioning and heating of the sample two independent magnetic fields are generated and superpositioned within the same coil. The quadrupole field stabilizes a spherical sample against external residual forces in the centre where the magnetic field strength is weakest. The dipole field which is nearly homogeneous in the vicinity of the sample is highly efficient in heating the sample.

Hence the electrically conducting sample is positioned and heated by the two magnetic fields but evidently both fields are influenced by the resistivity and geometry of the sample. Therefore the feedback of the sample to the coil is used for an inductive contactless measurement of the electrical sample resistivity and measurement of the thermal expansion of the sample.

In the manner described above MUSC prepared the hardware installation crew procedure and the ground procedure for the commissioning afterwards. Figure 4 shows the SCE and the opening in the Experiment

Module (EXM) where the SCE has to be integrated. Inside the EXM the Process Chamber and most of the diagnostic tools are hosted as well. On the front side of the EXM the cylindrical Sample Chamber and the High Speed Camera are attached.

For removal of the EXM all cables and hoses had to be demated. As the later installation of the SCE into EXM was already foreseen during EML development, a cover and a plug for easy plugin were already integrated. After successful installation of the SCE, the EXM has to be re-installed in EML and all loose cables have to be mated. Whereas demating of the cables and hoses is a straight forward task, the mating has to be done in a dedicated sequence. The location of each cable is color coded to help the astronaut find the correct one in the amount of cables and connections.

This 4 hours crew activity was supported from ground from MUSC by means of two “over the shoulder” video streams. Thus helpful advices to the astronaut could be provided if necessary and an optical check of proper installation was conducted. Afterwards EML was first checked out by ground commanding to be sure the complete EML facility behaves nominally and as expected, and the commissioning of the SCE was performed.

Since then EML Batch 2.1 and 2.2 with 13 different samples were performed, 11 of them uses the SCE for scientific measurement. To reach best possible outcome the SCE has to be calibrated each time the generator of the heater field is switched on. Operational wise this is done by empty coil measurements prior the performance of the to be measured melt cycle. In case of more SCE measurements the operator on console makes to be sure the heater will not be switched off, neither by the EP Set nor by command.

8. EML enhancement by HSC-OS Upgrade

In autumn 2018 it is planned to have a major upgrade of the operating system of the High Speed Camera (HSC-OS). Two main improvements are implemented: a hardware compressor board and a new hard disk.

The advantage of the new hard disk is more storage capacity of now 1 TB. As described above in the postprocessing this relaxes the bottleneck in the data production chain, because the science raw videos of more melt cycles could be stored.

First of all the new hardware based compression capabilities provides lossless compression which is essential for the accuracy of the science videos. Secondly a compressed video can be downloaded in shorter times or with less bandwidth which relax the need of this scarce resource. Thirdly the time for transfer a science video from the HSC internal ring-buffer to the hard disk will be faster by a factor of 7. Thus a typical video of 8Gb will be transferred in about 5 minutes instead of currently about 35 minutes.

The hardware of the HSC-OS is a stack with 5 boards. This has to be integrated into the EML Experiment Control Module (ECM) (see Fig. 5). Therefor the crew has to demate all cables and hoses from the ECM, open the covers to access the location of the old stack. Next is the exchange of the old HSC-OS with the new one and afterwards reinstalling of the ECM into EDR and mating of all cables and hoses.

A duration of 5 hours is planned for this activity including preparation and stowage time. MUSC developed the crew procedure for this complex task und will support the astronaut from ground during the execution. After the successful installation, a ground-only activity will be performed to thoroughly test the functionality of the new devices.

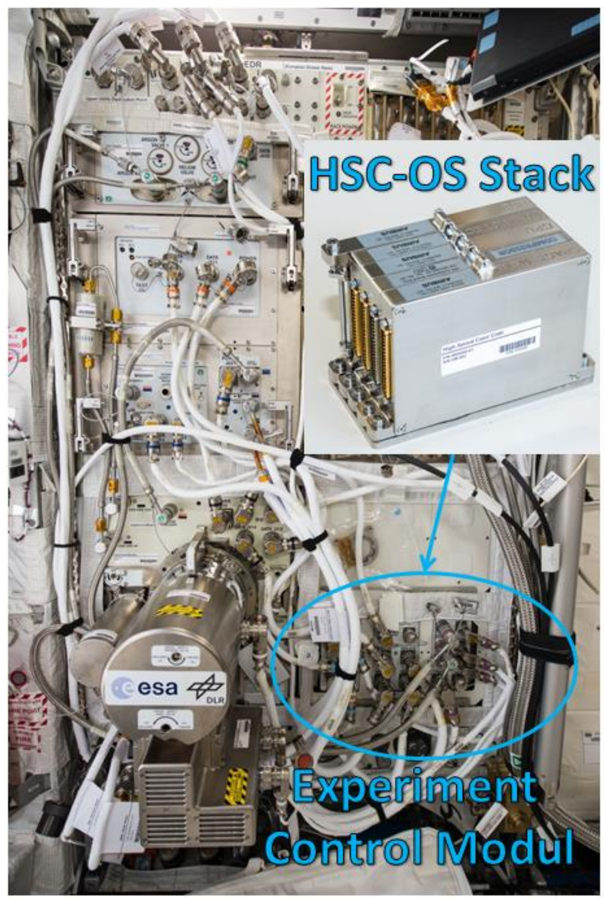

Fig. 5. HSC-OS Stack for integration into EML Experiment Control Modul

9. Outlook

It is currently planned to completely finalize Batch 1 experiments in October 2018. After the crew activity to exchange the Batch 1 sample chamber by the Batch2 sample chamber, the Batch 1 sample chamber will be downloaded to ground, possibly with SpaceX-16. The scientists are then able to continue their work by e.g. assessing the microstructure of the returned samples itself.

In the first part of 2019 the finalization of all basically planned cycles is foreseen. First indications from the involved scientific community bring an additional subbatch 2.4 into account to add significant values to the already achieved data points. This subbatch will be defined as soon as all initial Batch 2 cycles are performed. It will have to undergo the same preparation approach described in this paper before it can be performed on orbit.

In parallel, the ground support program of EML Batch 3 was started in August 2018. As usual 18 samples (plus two reserves) are selected, which are shared between 12 individual scientific project teams. The estimated timeframe for the on orbit performance is 2020 until 2021. Batch 3 consists of about one thousand melting cycles.

Under review is the EML Oxygen Control System (OCS) as a further enhancement of the EML measurement and control capabilities. Most of the samples in EML are very sensitive to oxygen in the surrounding process atmosphere. The OCS will allow precisely determining and controlling the oxygen partial pressure in the process atmosphere and would therefore allow improving and characterizing the process atmosphere and sample condition [5].

With this evolution, the electromagnetic levitation on-board the ISS can be further operated with up-to-date diagnostic hardware and thus continues to provide the opportunity for successful scientific research.

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