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INTERNATIONAL MICROGRAVITY PLASMA FACILITY / DUST PARTICLE FACILITY IMPF/DPF: A MULTI-USER MODULAR RESEARCH LABORATORY FOR "COMPLEX PLASMA" AND "INTERACTIONS IN COSMIC AND ATMOSPHERIC PARTICLE SYSTEMS"

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ABSTRACT

An overview is provided about different microgravity research facilities utilized from 1996 to present in the fields of "complex plasma" and "interactions in cosmic and atmospheric particle systems." Because of the synergetic commonalties in these research disciplines, the corresponding scientific advisory boards recommended to consolidate their efforts into the design and development of a joint research laboratory to be accommodation on-board of the International Space Station: the IMPF/DPF Laboratory. The key results of this Phase A study will be described.

1. SCIENTIFIC BACKGROUNDS - OVERVIEW

Complex plasmas, sometimes referred to as "dusty plasmas", are multi-component plasmas containing ions, electrons, and charged microparticles. These particles interact with each other through their strong Coulomb repulsion. As soon as the electrostatic energy of neighboring particles strongly exceeds the thermal energy, the particles arrange themselves in regular, solid like structures, called the *plasma crysta* l. A photo of a plasma crystal is shown in Figure 1. The crystal can serve as a model system to investigate structures and dynamics as well as the solid-liquid phase transition. Complex plasmas in general arise interest from several scientific disciplines including industrial applications such as contamination of materials during plasma processing and nanoparticle manufacturing. In the field of astrophysics, dusty plasmas are of interest due to the presence of dust particles in interstellar and interplanetary space, comet tails, moon and asteroid surfaces as well as protoplanetary disks.

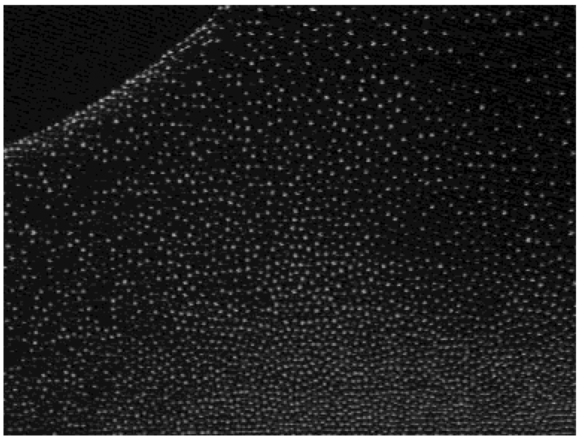

Figure 1: Section through a Plasma Crystal under microgravity conditions [1]

Another science community has set up a scientific program to study Interactions in Cosmic and Atmospheric Particle Systems (ICAPS). Dust or particles play a crucial role in these two research fields of atmospheric sciences and astrophysics.

For example if there were no particles or water vapor in our atmosphere, the weather as we know it would not exist. Studying “model” clouds on atmospheric timescales will give insight in the behavior of cloud droplets as well in mechanisms of scavenging pollutants from atmosphere. On a larger scale, dust is everywhere in our universe. The agglomeration of micron sized particles, through sticking collisions, is believed to be responsible for the early stages of planet formation. Images of particles agglomerates are shown in Figure 2. Moreover, small dust particles present in comets and on surfaces of asteroids and planets scatter stellar and solar light. By comparing astronomical observations with measurements done on collections of well-known particles the knowledge of the physical properties of interplanetary dust will increase considerably. Additional possible areas of application could be aerosol technology, pollution removal, material sciences as well as the paper industry and industrial particle characterization.

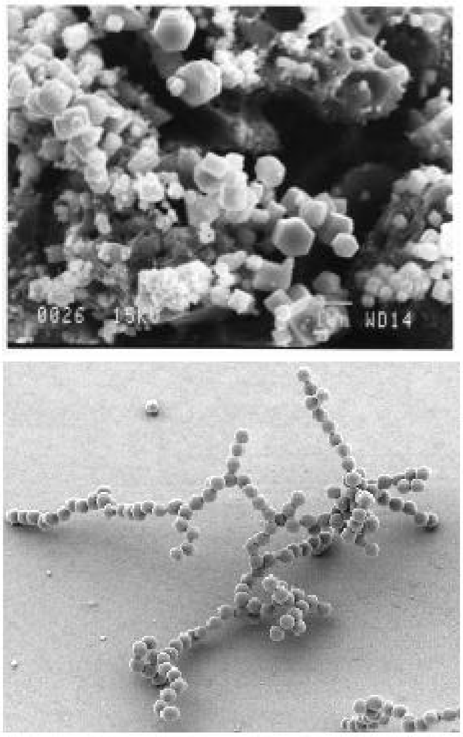

Figure 2: Examples of particle agglomerates [2]

2. PKE-NEFEDOV EXPERIMENT FACILITY

The phenomenon of *plasma crystal* was discovered in the early 1990’s, and since then many researchers have begun to investigate its properties. Under leadership of the Max-Planck-Institute for Extraterrestrial Physics in Munich, Germany, the investigation of larger plasma crystals under extended microgravity condition was initiated. Multiple parabolic flight campaigns and two sounding rocking flights TEXUS-35 (11/1996) and TEXUS-36 (04/1998) were performed. For a longer duration experiment, a Get Away Special GAS Experiment was envisioned initially, which eventually resulted in the design and flight of the PKE-Nefedov (formerly PKE-3) experiment facility aboard the Russian segment of International Space Station in 2001.

As shown in Figure 3 the facility is composed of two units, the experiment unit and the telescience unit. For safety reasons the actual experiment hardware is completely integrated in a hermetically sealed aluminum container. The man-machine interface for the experiment is via telescience unit only.

While experiments are performed, the experiment unit is temporary accommodated in the node of the Russian Service Module close to one of two vacuum ports while the telescience unit is temporary accommodated in the bay of the Russian Service Module. The total accumulated experiment time is limited by the available quantity of micro-particles and process gas; both are integrated in the sealed experiment unit.

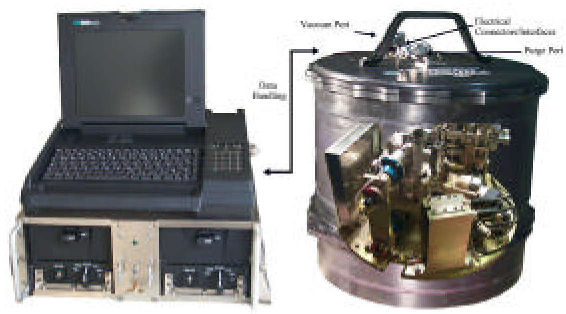

Figure 3: PKE-Nefedov Hardware: Telescience Unit and Experiment Unit [3]

The PKE-Nefedov Experiment facility was launched on flight 4P (PROGRESS-M1) in February 2001. Experiment runs took place during 5 different missions in March, May and October 2001, and in May and August 2002. The next mission is anticipated for February 2003. Figure 4 shows the hardware prior to temporary installation in the node of the Russian Service Module.

Figure 4: March 2001: Cosmonaut Sergej Krikalev with PKE-Nefedov Experiment Unit

For PKE-Nefedov, the roles and responsibilities in this bi-lateral German-Russian cooperation are [3]: the German side provides the basic science, developed and built the experiment and telescience units, and is responsible for servicing the PKE-Nefedov experiment facility throughout the mission while the Russian side supports science, manages and provides the flight opportunity as well as overall mission support including telescience capabilities. Partners and their responsibilities within this German-Russian cooperation are:

- German Space Agency DLR is the funding and controlling organization for the German part of the project
- Max-Planck-Institute for Extraterrestrial Physics MPE is responsible for science and has provided hardware of experiment apparatus
- Kayser-Threde GmbH designed and built instrumentation for experiment apparatus and telescience unit, co-ordinates the project with the Russian partners
- Russian Space Agency RKA acts as funding and controlling organization of the Russian part of the project.
- Institute for High Energy Density IHED is responsible for co-science and co-ordination of Russian partners
- RKK Energia is responsible for mission preparation and execution

In order to continue this successful bi-lateral German-Russian research coordination a replacement of PKE-Nefedov is planned. This new facility, named PK-3 Plus, will contain an improved radio-frequency RF plasma chamber and extended possibilities for changing physical control parameters. The PKE-3 Plus facility will be built and operated in the frame of the established German-Russian cooperation. Partners and their responsibilities within this German-Russian cooperation will remain the same as for PKE-Nefedov.

3. INTERNATIONAL MICROGRAVITY PLASMA FACILITY - IMPF

3.1 Introduction

The scientific interest in complex plasma research under extended microgravity condition is continuously growing. In response to ESA's Announcement of Opportunity "Physical Sciences and Microgravity Applications (AO 98/99)" the scientific proposal AO-99-033 for an *International Microgravity Plasma Facility IMPF* was submitted and judged by the peer review panel as "*outstanding*". From August 1999 to March 2000, the German Space Agency DLR funded a feasibility study for having a long-term dedicated multi-user complex plasma research facility on-board the International Space Station ISS, the International Microgravity Plasma Facility IMPF. The industrial contractor for IMPF feasibility study was Kayser-Threde in Munich, Germany. In order to assure that the future users of such a research facility are part of the feasibility study an international advisory board was initiated with members from England, France, Germany, Japan, Norway, The Netherlands, Russia, Taiwan, and USA. Based on the positive outcome of the feasibility study, DLR initiated an IMPF-VE (Vorentwicklung = Special Development) phase, in which selected critical hardware items were developed and tested on parabolic flight campaigns. In addition, a complete end-to-end system design for the IMPF facility was developed. Furthermore, extensive investigations in digital optical diagnostic data compression algorithms were performed in order to meet the very stringent requirements of the scientific community. The IMPF-VE design phase lasted from June 2000 to March 2002.

As for the initial IMPF study, Kayser-Threde (D) performed the IMPF-VE work. Kayser-Threde and the Max-Planck-Institute for Extraterrestrial Physics MPE had significant investments of their own in support of this project.

3.2 IMPF System Concept Overview

The International Microgravity Facility IMPF is a semi-autonomous mutli-user research facility to investigate "complex plasma" in regard to fundamental and applied sciences. IMPF will provide to researchers access to multiple process gases at selectable flow rates, selectable pressures within the plasma process chamber, different micro-particles sizes and shapes, multiple diagnostics tools, and data acquisition, handling and data storage.

The IMPF common infrastructure will remain on-orbit. In order to provide maximum flexibility of this research facility to its users it is envisioned to replace the plasma chamber and its corresponding diagnostics every 6 to 18 months. Consumables like process gases and data storage tapes will be replenished on a continuos basis.

3.3 IMPF System Accommodation

Based on the IMPF-VE study results IMPF could be accommodated in an International Standard Payload Rack ISPR like an EXPRESS Rack with 4 Middeck Lockers MDL and 2 x 4-PU ISIS Drawers (PU = Panel Unit, ISIS = International Subrack Interface Standard):

- **Experiment Locker:** Double Middeck Locker containing experiment plasma chamber, all corresponding diagnostics, and particle injectors. This locker shall be replaced every 6 to 18 months with a new experiment insert. Figure 5. shows the result of a packing investigation for the first experiment insert.
- **Power and Master Control Locker:** This MDL contains the IMPF facility master control processor and IMPF power distribution & generation sub-system.
- **Data Storage and Processing Locker:** This MDL contains all hardware for recording of the experiment and housekeeping data. Digital tape recorders provide the final data storage on tapes. Uncompressed real-time recording capability is 240 MBytes/sec for a total of 680 GBytes.
- **Gas and Vacuum Control Locker:** This MDL contains all hardware for controlling the vacuum for the IMPF experiment chamber, and for controlling and mixing process gases as supplied by the gas delivery system.
- **Gas Delivery System Drawer:** This unpowered 4-PU ISIS drawer supplies up to five different process gases to IMPF.
- **Data Tape Storage Drawer:** This unpowered 4-PU ISIS drawer stores all digital data tapes required for a 6 to 18 months experiment period.
- **Laptop:** A standard Payload and General Support Computer PGSC provides the on-orbit user interface to IMPF.

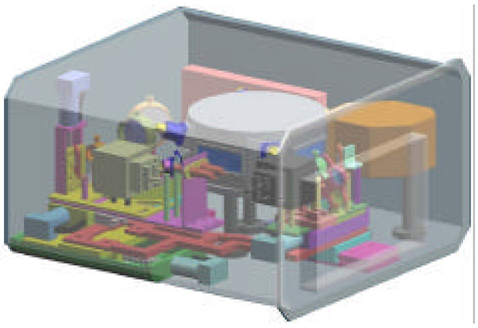

Figure 5: First IMPF Experiment Insert – Packaging Study for MDL enclosure

Figure 6 shows an accommodation concept based on an EXPRESS Rack in its 8/2 configuration.

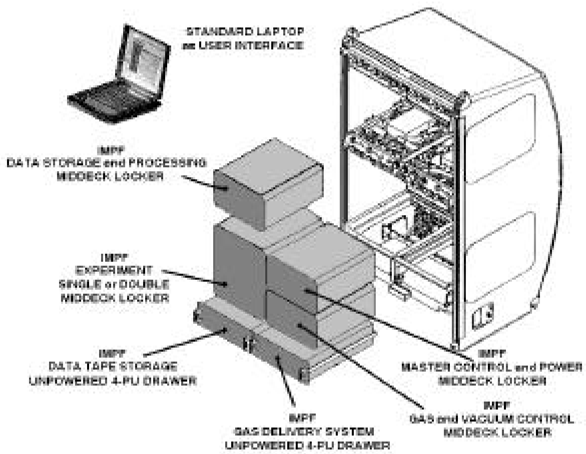

Figure 6: Standalone IMPF Accommodation Concept as of February 2002

4. DUST PARTICLE FACILITY - DPF

4.1 <u>Introduction</u>

Due to very similar and in many cases identical physical behavior between cosmic and atmospheric dust particles the ESA topical team *Interactions in Cosmic and Atmospheric Particle System ICAPS* was formed in 1998, combining the physical science topics in “Preplanetary Dust Aggregation and Related Subjects" and "Particle Aggregation and Dispersion". Members of this topical team were and are very active in developing and flying research facilities on parabolic flight campaigns, sounding rockets, and Get Away Special GAS. Examples of these experiments and their facilities are

- Cosmic Dust Aggregation Experiment CODAG: flown on STS-95, 10/1998, as GAS (see Figure 7.). This project was led by Univserty of Jena, Germany, and supported by the German Space Agency DLR and by the European Space Agency ESA.
- "PRopriétés Optiques des GRains Astronomiques et Atmosphériques" PROGRA^2 (Optical Properties of Astronomical and Atmospheric Grains): multiple parabolic flight campaigns in 2001 and 2002. PROGRA^2 is a multi-year program funded by the French Space Agency CNES, with co-investigators from Centre National de la Recherche Scientifique CNRS in Verrières-le-Buisson and in Orléans, France.
- Jet Growth Motion in Aerosols (JET): flown on sounding rocket MASER-8, 05/1999. This work is led by Université Libre de Bruxelles, Belgian, and supported by the European Space Agency ESA and Prodex/SSTC.

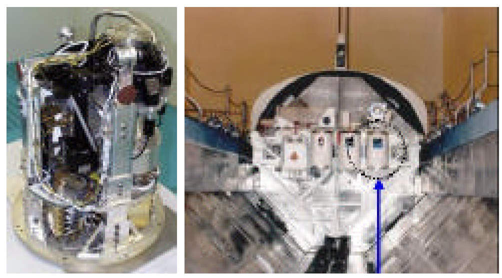

Figure 7: CODAG Experiment

In response to ESA’s Announcement of Opportunity “Physical Sciences and Microgravity Applications (AO 98/99)” the scientific proposal AO-99-018 for *Interactions in Cosmic and Atmospheric Particle Systems ICAPS* was submitted and judged by the peer review panel as “*outstanding*”.

4.2 DPF Feasibility Study

From October 2001 to May 2002, the European Space Agency ESA funded a feasibility study for having a long-term multi-user ICAPS research facility on-board the International Space Station ISS, the Dust Particle Facility DPF. This study was performed by Kayser-Threde (D) and its subcontractor Nubila (I). In order to assure that the future users of such a research facility are part of the feasibility study ESA's ICAPS topical team was utilised as advisory board with members from Finland, France, Germany, Italy, Japan, The Netherlands, Russia, and USA.

Since performance requirements for infrastructure item like data acquisition subsystem and gas/vacuum control subsystem for DPF were very similar to the IMPF subsystems, the system partitioning approach developed for IMPF could be used for this facility:

- DPF is a semi-autonomous mutli-user research facility to investigate interactions in cosmic and atmospheric particle systems.
- DPF will provide to researchers access to multiple gases at selectable flow rates, selectable pressures within the process chamber, different particle sizes and shapes, multiple diagnostics tools, and data acquisition, handling and data storage.
- DPF common infrastructure will remain on-orbit.
- In order to provide maximum flexibility of this research facility to its users it is envisioned to replace the process chamber and its corresponding diagnostics every 6 to 18 months.
- Consumables like process gases and data storage tapes will be replenished on a continuos basis.

The first two experiment inserts were identified and conceptually investigated. Figure 8. and Figure 9 provide the experiment set-ups based on a 12-PU drawer enclosures.

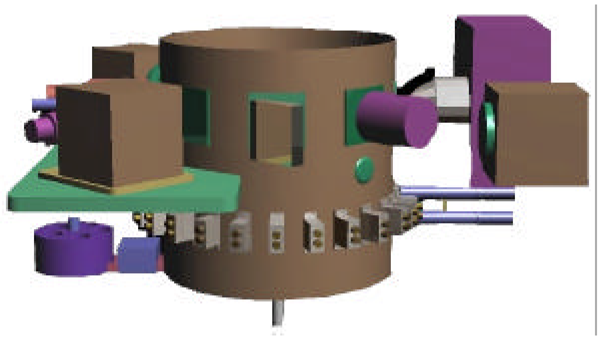

Figure 8: ICAPS experiment layout for investigation in atmospheric particle systems

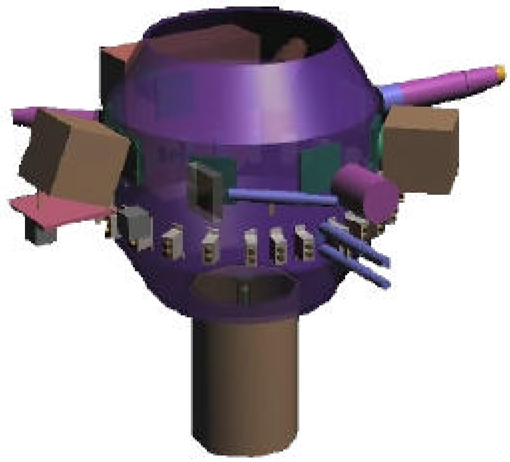

Figure 9: ICAPS experiment layout for investigation in cosmic particle systems

The initial approach for a DPF with shared accommodation in a non-dedicated rack was technically feasible but from a operational point of view not satisfactory. Therefore, some initial concept designs for a combined IMPF/DPF system with shared infrastructure were pursued. Based on those study results the ICAPS and IMPF advisory boards recommended in February 2002 and May 2002, respectively, to consolidate the hardware, accommodation and operation of the DPF and IMPF facilities.

5. IMPF / DPF LABORATORY

5.1 Introduction

Based on the recommendations from the IMPF and ICAPS advisory boards to consolidate the two research facilities, ESA funded a joint IMPF/ICAPS accommodation study. This study, which was from June 2002 to September 2002, concentrated on accommodation and definition of a dedicated rack. As for the initial Phase A study, this work was performed by Kayser-Threde (D) and its subcontractor Nubila (I).

The consolidated IMPF/DPF Laboratory us a semi-autonomous mutli-user research laboratory which supports two major science facilities: IMPF and DPF. The carrier in combination with the experiment support infrastructure will provide to researchers access to multiple process gases at selectable flow rates, selectable pressures within the process chambers, different particles sizes and shapes, multiple diagnostics tools, and high speed data acquisition, handling and data storage.

The IMPF/DPF carrier and experiment support infrastructure will remain on-orbit. In order to provide maximum flexibility of this research facility to its users it is envisioned to replace the process chamber and its corresponding diagnostics every 6 to 18 months. Consumables like process gases and data storage tapes will be replenished on a continuos basis.

5.2 Experiment Enclosures

For the accommodation concept to be developed for a consolidated IMPF/DPF Laboratory following design requirements were followed:

- the consolidated IMPF/DPF laboratory shall be accommodated into one International Standard Payload Rack ISPR
- the experiment enclosures available to the scientific communities shall be maximised
- reuse of hardware and software items already developed, or which are under development, shall be maximised where judged feasible

Multiple packaging studies were conducted. The resulting preferred option was to utilise a 12-PU drawer enclosure for each individual standard IMPF and DPF experiment enclosures. Mix-and-match possibilities are available, i.e. one separate 4-PU drawer and one separate 8-PU drawer can be utilised for the experiment set-up. Figure 10 provides an overview of the experiment inserts capabilities.

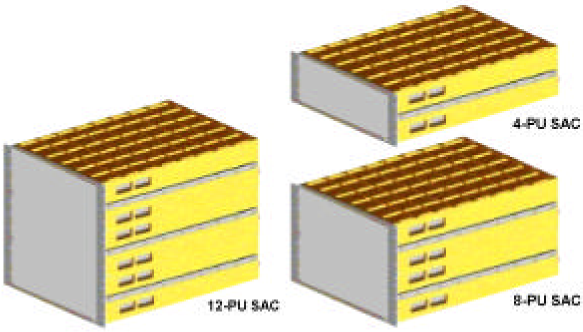

Figure 10: Experiment enclosures for IMPF and DPF experiment inserts

Each 12-PU Drawer Experiment Inserts can provide:

- apx. 110 litre payload volume
- up to 56 kg experimental payload mass
- access to 560 W power, inclusive avionics cooling

The laboratory infrastructure provides for the experiment insert access to:

- moderate temperature cooling water loop
- Waste Gas Interface inclusive turbo pump
- several process gases with selectable flow rate
- access to high speed digital data storage

The hardware and software interfaces for each experiment insert are identical resulting in maximisation of flexibility in accommodation with the rack. Figure 11. provides a front panel view of an experiment insert for IMPF and DPF.

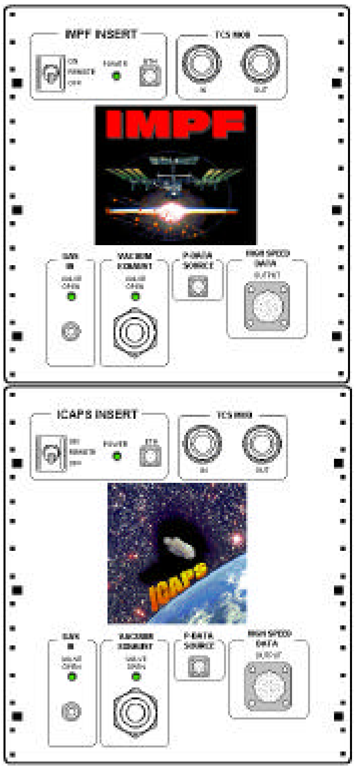

Figure 11: Standardized interfaces for IMPF and DPF Experiment inserts

As for the initial IMPF and DPF studies, the **Experiment Insert** contains the experiment vacuum chamber, all corresponding diagnostics, and particle injectors. This insert shall be replaced every 6 to 18 months with a new experiment insert.

5.3 IMPF / DPF System Accommodation

In order to maximise on existing hardware the carrier for the IMPF/DPF Laboratory will be most likely a Six-Post ISPR. utilising in 4-PU increments so-called Standard Active Containers SAC. Figure 12 provides the front view of the carrier with experiment inserts and experiment support infrastructure inserts installed.
The experiment support infrastructure consists of:

- **Facility Support Computer:** This custom-enclosure is an ORU located on a coldpalte within the carrier structure. It contains the experiment facilities master control processor. All communication and control interfaces between ISS and IMPF/DPF experiment inserts and other experiment support infrastructure are with this sub-system.
- **Data Storage and Processing:** This 8-PU SAC contains all hardware required for recording real-time the experiment and housekeeping data. Digital tape recorders provide the final data storage on tapes. Uncompressed real-time recording capability is 240 MBytes/sec for a total of 680 GBytes.
- **Gas and Vacuum Control:** This 8-PU SAC contains all hardware for controlling the vacuum for the IMPF and DPF experiment chambers, and for controlling and mixing process gases as supplied by the gas delivery system.
- **Gas Delivery System:** This unpowered 4-PU SAC supplies up to five different process gases to the process chambers via the gas/vacuum control subsystem.
- **Data Tape Storage:** This unpowered 4-PU SAC stores all digital data tapes required for a 6 to 18 months experiment period.
- **Laptop:** A standard Payload and General Support Computer PGSC provides the on-orbit user interface to the laboratory in general, and the IMPF and DPF experiment inserts.

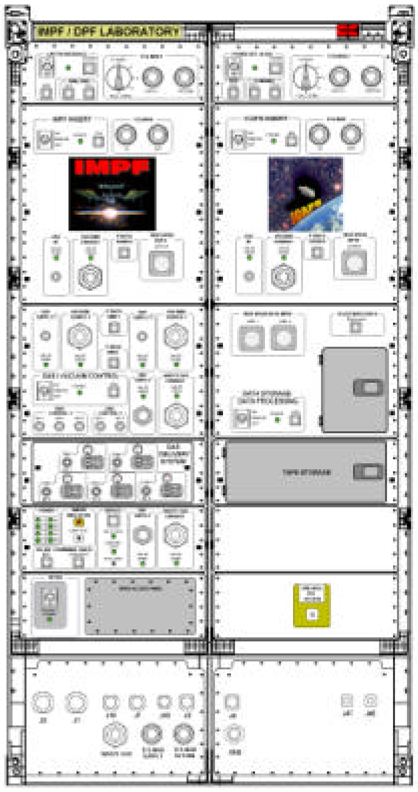

Figure 12: Accommodation layout and interfaces for IMPF/DPF Laboratory

The anticipated maximum power consumption of the IMPF/DPF Laboratory during normal experiment operation is 1.5 kW.

6. SUMMARY AND FUTURE PERSPECTIVES

An overview was provided regarding the status of different facilities related to the research fields of “complex plasma” and “interactions in cosmic and atmospheric particle systems”, namely PKE-Nefedov, PK-3+, IMPF, DPF, and the Consolidated IMPF/DPF Laboratory.
In September 2002, the *Human Spaceflight, Research and Application Programme Board* of the European Space Agency approved the initiation of Phase B for a Combined ICAPS/IMPF Laboratory.

7. REFERENCES

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2. ICAPS Publicity Team, Worms J.C., Fraser H.J., Blum J., Natali. S., *The Mutli-User Facility on the International Space Station for research on Interactions in Cosmic and Atmospheric Particle Systems*, Europe, 2002
3. Schmitt G. and Griethe W., *Plasma Crystal Experiment – the first microgravity facility aboard the Russian Service Module of the ISS*, IAF-00_J.2.10

8. ACKNOWLEDGEMENTS

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- The European Space Agency ESA which funded Phase A for DPF and the Consolidated IMPF/DPF Laboratory.
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