Research Campaign Whitepaper:

Fundamental Physics, Electrostatics, and Imaging Facility (FEIF)

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Summary

Fundamental physical processes of solid particles, imaged while moving at low velocities in rarefied gases, are the theme of a campaign of experiments using the proposed Fundamental Physics, Electrostatics, and Imaging Facility (FEIF), for the International Space Station (ISS). With its removable scientific modules, FEIF will allow the study of multiple physical systems, including *dusty plasmas* and *grain growth in the early stages of planet formation*.

A dusty plasma, also known as complex plasma, is a cloud of micron-size particles of solid matter immersed in a plasma containing electrons, positive ions, and neutral gas. The particles gain a large electric charge, leading to a rich variety of collective effects to be studied, including nonlinear dynamics, transport, and phase transitions. Microgravity conditions enable observations that are impossible on the ground, because gravity causes rapid sedimentation, and it also obscures weak forces acting on the dust grains.

For early planet formation, studies center on the growth of solid particles. Micron-size grains condense from the nebular gas and grow to centimeter-size by collisions. Further growth occurs through low-speed collisions and local gravitational instabilities. Microgravity conditions will be exploited by allowing these solid objects to be observed for minutes as they grow, collide, and form aggregates, all while moving at velocities of millimeters per second. Experiments are generally impossible under 1-g conditions, which cause a particle to fall like a rock in vacuum conditions, so that observations are too brief to observe collisional growth and fragmentation, before grains or aggregates fall to the chamber's bottom.

International collaboration and outreach will be encouraged.

A Flexible Platform

The FEIF is intended to allow a wide variety of physical experiments, especially those that require video imaging and vacuum conditions. The facility's infrastructure will provide data storage and telemetry, along with gas and vacuum handling. Also provided will be power, compressors, and other support systems needed by the removable scientific modules. The scientific modules are exchangeable; they will serve research for two envisioned topics: dusty plasma and planetary grain growth. Beyond these two topics, the modular design of FEIF could allow other scientific topics as well, for example soft condensed matter experiments.

Scientific Management and International Collaboration

Each scientific module will be developed for a Principal Investigator (PI), or a PI Team. The PIs will encourage collaborators, including those in other countries, to join their effort. The co-authors of this white paper are representative of the many possible collaborators.

International collaboration is envisioned on a no-exchange-of-funds basis, carried out at two levels: science and hardware. *At the scientific level,* scientists from other countries will be encouraged to propose experiments to the PI team, and then participate in performing the experiments. This international model has proven to be effective in the fruitful PK-4 (Plasma Kristal 4) mission for dusty plasmas, now aboard the International Space Station [Pustylnik 2016, 2020]. *At the hardware level*, the use of exchangeable scientific modules will make it feasible for another space agency to build and supply a scientific module. For example, we can foresee encouraging a space agency other than NASA to build a module for FEIF that will serve as the successor to the DLR's future COMPACT (Complex Plasma Facility).

Dusty Plasmas (also known as Complex Plasmas)

When atoms in a rarefied gas become ionized, the result is a plasma. It contains negative electrons and positive ions, which are not bound together as atoms. It also contains neutral gas atoms that did not become ionized. Plasmas exhibit a rich variety of collective behavior, like nonlinear waves, instabilities due to hydrodynamic flows, transport that can be anomalous, and nonequilibrium statistical physics.

The physics of a plasma becomes even richer, and more easily observable, by adding a fourth constituent: micron-size particles of solid matter. These particles are called “dust” in the plasma physicist’s shorthand, although in most experiments they are actually precision polymer microspheres, as in Fig. 1(a). They accumulate a large negative electric charge, about 10,000 electrons on a 5-micron sphere, by absorbing electrons from the surrounding plasma. Because of their large charges, dust particles repel one another strongly. However, they cannot simply run away from one another as they are confined to a finite volume. This confinement is provided by electric fields that naturally develop in a plasma. [Melzer 2019]

Fundamental physics experiments are performed in a vacuum chamber containing inert gas at low pressure. High voltages are applied to electrodes to ionize the gas. Then, a powder consisting of precision microparticles is injected into the plasma. Within milliseconds the dust particles become charged and exhibit collective behavior. The primary experimental diagnostic is direct imaging of microparticles by video cameras that view through vacuum-vessel windows.

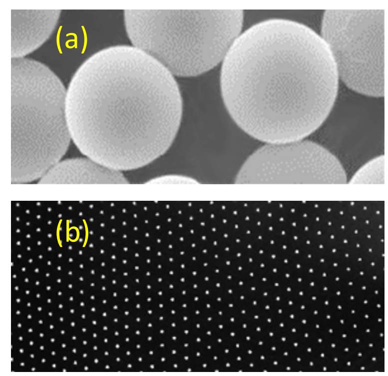


Fig. 1 Melamine formaldehyde polymer microspheres.

(a) electron micrograph (microparticles.de).

(b) Image of microspheres levitated as a single horizontal layer in a 1g laboratory dusty plasma. The particles self-organize, arranging themselves in a 2D crystalline lattice with a spacing of 0.5 mm (Ref. 2). To form a large 3D crystal requires microgravity.

If the dust particles have little kinetic energy, the dust particles organize themselves at fixed positions in space, like atoms in a crystalline lattice, as in Fig. 1(b). By giving the dust particles extra kinetic energy, this lattice can be melted, so that the particles collectively behave like a liquid.

Direct imaging is the main diagnostic approach in dusty plasma experiments. It is made possible by the convenient length and time scales of a dusty plasma. Dust particles are spaced far enough apart, about 0.5 mm, so that the medium is optically thin, and individual particles can be tracked precisely in video images. They move with time scales of about 0.1 s, which is also convenient for particle tracking.

Another attractive feature of dusty plasmas is their weak damping. For this, one can compare dusty plasmas and colloidal suspensions, which are both the subject of microgravity experiments with charged small solid particles. Both are often used as model systems to study soft-condensed-matter physics problems at an ‘atomic’ scale [Ivlev 2012]. Colloidal suspensions, however, use water or another liquid solvent, which is so dense that the particle motion is overdamped. In a dusty plasma, on the other hand, a rarefied gas is used instead of a liquid, so that particle motion is underdamped, enabling the study of time-dependent phenomena, for example shock waves [Samsonov 2003].

Interest in dusty plasmas, as a topic of research, has grown vigorously. Starting in the 1980s with a few dozen papers each year, now over a hundred papers are published yearly. Many papers have reported on microgravity experiments. The liveliness of this research area has been spurred in good part by its breadth. While many researchers explore fundamental physics topics, others are motivated by applications in planetary science, geophysics, space exploration, and industry.

Microgravity experiments with dusty plasmas developed initially with the Plasma Kristal (PK) collaborations of Germany and Russian, on the International Space Station. All of these experiments rely on direct video imaging. Beyond the PK series, an upgraded design, planned for the German Space Agency DLR, is named COMPACT [Konopka and Knapek 2021].

The first FEIF scientific module for dusty plasmas will allow a tailored interparticle interaction and advanced control of the background plasma's homogeneity and isotropy. This will be accomplished using electrodes, in a dodecahedral geometry. The interaction will be designed by reshaping the ion wakes that can dominate the interparticle interaction. Differently from earlier experiments and COMPACT, which promote strong singular ion wakes that force grains to align in strings [Pustylnik 2020], the dodecahedron setup should allow quasi-isotropic soft potentials [Kompaneets 2009]. This will open new classes of research, especially the study of critical-point phenomena, phase transitions, and atomistic dynamics of fluids [Kompaneets 2009, Thoma 2021], as well as stochastic processes and searches for a path to hyperuniform materials. The technological readiness of the dodecahedral prototype is well advanced already.

A second FEIF scientific module for dusty plasmas would center on magnetic effects, using a magnetic field of less than a kiloGauss. This would enable a new area of experiments by magnetizing electrons and manipulating superparamagnetic solid particles, as described in a topical white paper [Konopka Rosenberg 2021].

Early Planet Formation

Terrestrial planets, asteroids, and comets are all ultimately the result of solid matter condensing into micron-size grains in a circumstellar nebula and then growing through accretion into km-size and larger objects. Grains may form aggregates of up to a few cm in size through interparticle collisions at velocities of ~1 m/s or less. Further collisional growth requires even slower collisions to avoid disruption or bouncing of the aggregates [Güttler 2010]. Local instabilities in the nebula may provide environments where particles are shielded from turbulent gas flow, allowing gravitational collapse and agglomeration of particles at these low speeds [Johansen 2014]. The behavior of dust grains, fragile aggregates, and larger monomers in the wide-ranging collisional environment of protoplanetary disks is critical to understanding the formation of planetary building blocks such as asteroids and comets, and how that formation depends on local nebular conditions.

A microgravity environment is required for experimental studies of grain accretion and collisions between aggregates at the low speeds relevant for accretion. In an Earth-based laboratory, when grains are immersed in a rarefied gas, as in the protoplanetary nebula, the buoyant force is negligible and particles fall freely to the bottom of the chamber, reaching speeds of 1 m/s after only 5 cm. Instead, the experiment needs a long duration of free-fall conditions, without high-speed interactions with chamber walls. Long-duration microgravity allows collisions between grains and particle aggregates to be produced at a range of speeds down to < 1 mm/s [Brisset

2019]. The outcomes of these collisions, including velocity distributions of any fragments or rebounding particles, take longer to manifest than the free-fall time in a 1-g laboratory.

The first FEIF scientific module for early-planet-formation will turn to a scientific topic that relies on instrumentation already at a high technology-readiness level. This topic will be low-velocity collisions of cm-scale particles (which mimic surfaces of meter-scale particles) coated with dust, as in the COLLIDE experiments on the Space Shuttle [Colwell & Taylor 1999, Colwell 2003] and suborbital platforms, and PRIME experiments on parabolic flights [Brisset 2018]. Those experiments probed the boundary between the physical processes of erosion and accretion. Scientific advancements, to be made possible by this module, include determining the processes that control the accretion and fragmentation of aggregates; this will be made possible by longer duration observations, which will allow observing multiple collisions rather than single collisions, and with more complex multi-particle systems. Improved time resolution, by using high-speed imaging, will also aide the characterization of these collisional processes.

A second FEIF scientific module for early-planet-formation would provide ice-grain growth. These experiments will fill a gap in understanding the role water-ice plays in the formation of pebbles and larger objects in the protoplanetary disk, due to water ice's greater surface binding energy as compared to silicates. Millimeter-size coagulated grains of ice will be grown in a cryogenically cooled plasma chamber fed by inert gas and water vapor. The advantage of microgravity is that grains can grow without strong ion flows, to better mimic natural conditions. (Under 1-g conditions, a strong electric field generated by plasmas is needed to levitate ice grains as they grow. This electric field is highly perturbing, due to the way it drives ion wakes, which in turn force the grain growth to be anisotropic, developing as strings aligned with the electric field.) The apparatus will be based on ground-based experiments at Caltech [Marshall 2017].

Outreach

The proposed experiments are ideal for *outreach and education*. They are very visual, due to the emphasis on imaging. Opportunities for outreach have been demonstrated previously by parabolic flights for undergraduate students. It will be possible for undergraduates and high-school teachers to operate FEIF scientific payloads using telescience.

For NASA, a further point of interest is *dust mitigation*, which has been recognized as a technical challenge for Lunar and Martian habitats. Both topics suggested here, dusty plasmas and early-planet formation, involve electrostatic effects that are exploited in dust mitigation schemes.

Development approach and ISS accommodation

We anticipate accommodating the facility in a standard Express Rack (ER), as sketched in Fig. 2. Initial estimates of the power and volumetric constraints indicate that a single rack accommodation is suitable. The facility will consist of modules consisting of six middeck lockers (MDL): (1) gas control, (2) high vacuum, (3) power supplies, and (4) data acquisition and control. These four lockers are collectively called the 'infrastructure lockers,' and they will use ISS resources available in the ER interface (power, air/water cooling, N_2 gas, telemetry/command, NTSC video). Additionally (5-6) a PI-specific scientific module fits in a double-mid-deck locker. Two scientific modules will be built and launched as part of the first mission. Each science module will support 3 to 4 PI experiments. To improve the return on investment, the modular design of the facility will allow an exchange of scientific modules in missions beyond the proposed funding period. Minimal crew time is needed for facility integration and power-up.

The PI scientific investigations will be performed autonomously using telescience. Little crew time will be required, e.g. for transferring data storage disks between experiments. A telescience center at JPL will support routing telemetry/command to ISS and archiving of the data. PIs will observe NTSC video by telescience during the experiment. The archival data will be high-bandwidth digital video, along with low-bandwidth housekeeping data, and these will be delivered to the PI after the experiment.

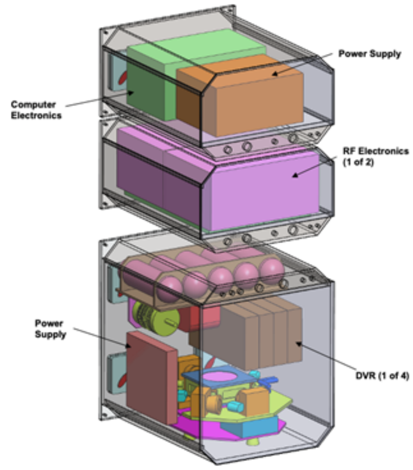


Fig. 2. Conceptual drawing of facility. Scientific module at bottom.

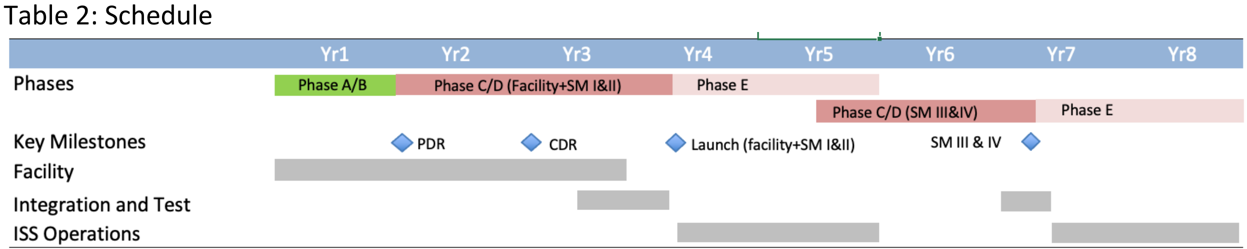
Schedule and Budget

A preliminary estimate of the budget and schedule for the facility is shown in Tables 1 and 2, respectively. Grassroots and engineering judgments in previous JPL-managed ISS projects/proposals are the basis for the estimate. Assumptions for the estimate are as follows. The budget includes: (1) Inflation rate applied to a previous a JPL cost estimation for dusty plasmas; (2) a second science module (SM) is built alongside the first one during FY23-26, assuming it will cost 90% of the first-unit cost; (3) project level of effort tasks is the same for the third and fourth SMs; (4) payload system management/SE stays the same for the third and fourth payload; (5) the third and fourth SM hardware is built in FY26-30 with recurring costs only, 45% of the first-unit cost; (6) reserves are only applied to WBS 01-03, and 05. It is assumed that the mission is Class-D. NRAs will support PIs; NRA costs are not included in the cost estimation of Table 1. We anticipate that the NRAs will be organized in two four-year cycles, with 3 to 4 flight candidate PI experiments selection per NRA cycle. Ground-based PIs (~10 grants) will be selected to perform basic research, develop concepts and breadboards for possible future scientific modules, provide theoretical support for the flight experiments, and analyze data. *The cost and schedule information contained in this document is of a budgetary and planning purpose nature and is intended for informational purpose only. It does not constitute a commitment of the part of JPL and/or Caltech.* Part of this work was carried out at JPL, California Institute of Technology, under a contract with NASA.

Table 1: ROM cost estimation

WBS Element	Total
01 Project Management	5
02 Project Systems Engineering	3
03 Safety/Mission Assurance	5
04 Science & Technology	10
04.01 Facility Science Team	10
05 Payload System	50
05.01 Payload System	3
05.02 Mechanical/Opt	20
05.03 Electrical	5
05.04 RF	4
05.05 Software	3
05.06 GSE	2
05.07 Power	4
05.08 Thermal	4
05.09 I&T	15
11 Education & Public Outreach	1
Subtotal (w/o reserves)	**80**
Reserves	20
Reserves %	*31%*
Mission Cost	**100**

Table 2: Schedule



*SM=Science Module

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