Plasma Physics and Controlled Fusion

PAPER • OPEN ACCESS

COMPACT—a new complex plasma facility for the ISS

To cite this article: C A Knapek *et al* 2022 *Plasma Phys. Control. Fusion* **64** 124006

OPEN ACCESS
IOP Publishing

Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion **64** (2022) 124006 (9pp)

https://doi.org/10.1088/1361-6587/ac9ff0

COMPACT—a new complex plasma facility for the ISS

C A Knapek[1,*], L Couedel[2], A Dove[3], J Goree[4], U Konopka[5], A Melzer[1], S Ratynskaia[6], M H Thoma[7] and H M Thomas[8]

[1] Institute of Physics, University of Greifswald, 17489 Greifswald, Germany
[2] Department of Physics & Engineering Physics, University of Saskatchewan, Saskatoon SK S7N 5E2, Canada
[3] Department of Physics, University of Central Florida, Orlando, FL 32816, United States of America
[4] Department of Physics & Astronomy, The University of Iowa, Iowa City, IA 52242, United States of America
[5] Physics Department, Auburn University, Auburn, AL 36849, United States of America
[6] Space & Plasma Physics, School of Electrical Engineering, Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden
[7] I. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany
[8] Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), 82234 Weßling, Germany

E-mail: christina.knapek@physik.uni-greifswald.de

Received 28 September 2022
Accepted for publication 3 November 2022
Published 15 November 2022

Abstract

Complex plasma is a state of soft matter where micrometer-sized particles are immersed in a weakly ionized gas. The particles acquire negative charges of the order of several thousand elementary charges in the plasma, and they can form gaseous, liquid and crystalline states. Direct optical observation of individual particles allows to study their dynamics on the kinetic level even in large many-particle systems. Gravity is the dominant force in ground-based experiments, restricting the research to vertically compressed, inhomogeneous clouds, or two-dimensional systems, and masking dynamical processes mediated by weaker forces. An environment with reduced gravity, such as provided on the International Space Station (ISS), is therefore essential to overcome this limitations. We will present the research goals for the next generation complex plasma facility COMPACT to be operated onboard the ISS. COMPACT is envisaged as an international multi-purpose and multi-user facility that gives access to the full three-dimensional kinetic properties of the particles.

Keywords: complex plasma, dusty plasma, low temperature plasma, microgravity research

1. Introduction

Complex or dusty plasma is a state of soft matter that consists of micrometer-sized particles immersed in a low-temperature plasma. The particles become charged by plasma constituents (electrons, ions) up to 10^3–10^4 elementary charges, and interact with each other and their surroundings via various forces. Depending on the particle charge, density and temperature, the electrostatic interaction can become very strong, and leads to collective effects and the occurrence of solid or liquid particle arrangements [1–4]. The cloud of particles is optically thin, so that imaging can be used to track ensembles of micron-sized particles, measuring their individual coordinates and velocities. This is a unique feature of complex plasma. With currently available optical diagnostics, all time scales relevant

* Author to whom any correspondence should be addressed.

for the system dynamics can be easily resolved. Therefore, complex plasmas can be regarded on the one hand as model systems for classical condensed matter physics where phenomena can be observed through dynamical tracking of individual particles ('proxy atoms') in a virtually undamped system. On the other hand, the particles serve as macroscopic, observable plasma constituents allowing us to reveal the kinetic dynamics of a plasma. Complex plasma therefore builds a bridge between single particle dynamics over mesoscopic systems to fully statistical systems.

Gravity strongly affects the behavior of complex plasmas due to the high mass of the microparticles. Within the main plasma volume, there are no forces such as buoyancy that can offset gravity, and the system of microparticles sediments into 2D, quasi-2D and stressed 3D systems close to the lower plasma boundary (the plasma sheath), where electric forces levitate the particles against gravity. These systems have been used for a number of fundamental investigations such as particle charging and interaction, waves, phase transitions and crystallization dynamics in 2D and stressed 3D systems, or hydrodynamic instabilities, shear flow, heat transport and anisotropic interactions in 2D systems, see e.g. reviews in [1–4]. However, to study near equilibrium particle interactions and dynamics unaffected by external forces, a homogeneous and isotropic 3D distribution of the microparticles in the bulk plasma is required, calling for experiments in a stable microgravity environment provided by e.g. the International Space Station (ISS). Several facilities for complex plasma research were (PKE-Nefedov [5], PK-3 Plus [6]) and are (PK-4 [7]) operated on the ISS with great success, involving more than 100 scientists worldwide and yielding over 120 refereed publications up to now.

To set the future research directions in the field, an international science definition team recently collected current open questions that will be addressed with the proposed future ISS facility COMPACT (Complex plasma facility), a multipurpose and multi-user facility with international accessibility and the involvement of a larger science community. The facility will be an important cornerstone of the roadmap for future complex plasma research under microgravity conditions [8]. The facility will be designed to offer a wide experimental parameter range to cover all requirements necessary to answer the science questions summarized in the next section. Former pre-development studies already provide valuable hardware components, that can be utilized for this purpose. Based on the expert knowledge available in the scientific community, complex plasma research can be extended into new regimes supported by a novel concept of a large and flexible plasma chamber [9] with capabilities for plasma and particle manipulation, advanced optical diagnostics (e.g. stereoscopy, [10, 11]) and new data analysis procedures based on artificial intelligence and machine learning [12–14].

The document is structured as follows: the overall science topics are presented in section 2. The hardware requirements, derived from these topics, and previously developed hardware that would fulfill the requirements and is available to use for COMPACT are presented in section 3. The paper is concluded in section 4 with a short outlook.

2. Scientific objectives

The major science objectives were identified to be from the fields of statistical physics, phase transitions, nonlinear dynamics, active matter, planetary physics and particles as diagnostics in plasmas. The specific research topics are summarized in the following sub-sections.

2.1. Statistical physics

Statistical physics and thermodynamics is one of the major field of physics. Many basic problems of many-particle systems in equilibrium and non-equilibrium are not solved and of great interest for fundamental as well as applied research. In particular, many important aspects of the state of matter and transport properties of many-body systems are not fully understood.

Complex plasmas are ideal model systems for studying those questions because of the following reasons. First, large systems containing sufficient microparticles can be produced and observed. Here sufficient means that the particle system is large enough to show a collective thermodynamic behavior. The amount of particles necessary for this depends on the details of the system, e.g. the interparticle interaction, but ranges from a few hundred to millions of particles which can easily be realized in complex plasmas. Second, the time scales of relaxation processes in complex plasmas are of the order of seconds allowing the observation of these processes in real time. Third, the position and velocity of the microparticles can be determined with high accuracy using sophisticated particle identification and tracking methods. The latter allows the complete reconstruction of the $6N$-dimensional phase space (N is the number of particles in the system) from which all microscopic and macroscopic information on the many-body system can be extracted. Fourth, microgravity experiments with complex plasmas enable the investigation of extended three-dimensional (3D) systems which are not possible in ground experiments.

The following list contains a number of interesting problems of statistical physics that will be tackled by using experiments with COMPACT under microgravity conditions.

(a) Equation of state: the equation of state is a relation between thermodynamic quantities, such as temperature T, volume V or pressure p, describing the state of matter. It has been measured in 2D systems on ground [15, 16]. Measurements in extended, homogeneous 3D systems would give new insights into the physics of complex plasmas, e.g. to what extent complex plasmas can be approximated by Yukawa systems.
(b) Nonreciprocal interactions: if an external electric field is applied to the plasma, the resulting ion flow produces a wake potential between microparticles and hence leads to an attractive, nonreciprocal force acting on the downstream particles, as shown in experiments performed with binary, quasi-2D systems on ground [17]. It is of interest to see whether this result also holds in the case of 3D systems,

located in the bulk plasma, in the presence of a (tunable) external electric field.

(c) Deviation from ideal gas: when the sizes of particles get larger, or the particle number density higher, the volume occupancy of the particles might not anymore be negligible and deviations towards van der Waals gas laws seem plausible. This behavior can be investigated in huge particle clouds under active manipulation that influences the number density as well as to some extent the particle interaction itself.

(d) Transport properties: recent microgravity experiments performed with the PK-4 facility on board the ISS yield a very small shear viscosity, or rather an upper limit for the viscosity [18]. This finding is in contrast to ground experiments measuring much larger viscosity coefficients. The reason for this discrepancy is still unclear. Experiments with COMPACT should allow a more precise and systematic measurement of the shear viscosity and other transport properties such as heat conductivity [19] or diffusion [20].

(e) Non-equilibrium thermodynamics: since the distribution function of the dust particles is fully available, it can be tested to what statistical class of systems a complex plasma belongs from the thermodynamical point-of-view, e.g. Gaussian or q-Gaussian [21], and what the underlying microscopic properties are for this classification. As a result of this study, conditions might be derived to tune a complex plasma to resemble a specific non-equilibrium system.

(f) The fluctuation theorem: the work fluctuation theorem [22] predicts a relation between the probability of a small system to loose energy relative to the probability to gain energy. Experiments involve a driving force that acts on the particles, e.g. gravity on a free-falling particle [23] or shear forces [24]. With COMPACT, the driving force could be mimicked using a tunable electric field acting on a charged particle and thus verify the fluctuation theorem for a wide parameter range, or derive the particle charge in a similar way as the determination of the particle mass of an arbitrarily shaped particle [25].

2.2. Phase transitions

The dynamics of phase transitions are difficult to measure on the atomic scales in conventional solid-state bodies, and little is known about the evolutionary paths of crystal structure development. Nevertheless a deeper understanding of those processes is important for applications such as material design, since the formation and evolution of nanoscale structures can have profound impact on optical, electrical and mechanical properties on the meso- or macroscale of a material. Complex plasmas offer a unique opportunity to observe phase transitions on the kinetic level. The particles are optically visible, and the time scales of e.g. crystallization or melting processes are accessible. In addition to the solid-liquid phase transition, complex plasmas can be used to study the supercooled state, and the system behavior close to or even beyond the glass transition point.

The quenching of liquids below their melting point by cooling or compression in a manner that prevents crystallization leads to substantial slowdown in dynamics and dramatic increase in their viscosity [26, 27] In the case of deep quenching, a dynamic arrest intervenes so that it is no longer possible to equilibrate the system within reasonable experimental times; the supercooled liquid thus transforms into a glass [26–28]. The microscopic foundation behind the rich phenomenology of supercooled liquids and glasses is far from being completely understood [29], despite the undeniable theoretical and computational progress during the last decades [30, 31]. Given their easily accessible spatiotemporal scales compared to molecular systems, soft matter systems play a crucial role in the study of slow dynamics [32, 33]. Thus, the addition of complex plasma glasses to this list of colloidal glasses would be invaluable. Experimental studies on the supercooled metastable liquid prior to the glass transition will focus on:

(a) Measurements of the self-part of the intermediate scattering function (the spatial Fourier transform of the van Hove correlation function) and the mean square displacement as functions of time [30] to reveal details of the structural relaxation from ballistic behavior over beta to alpha relaxation.

(b) Measurements of the length-scale of the increasingly large regions on which the particles relax in a cooperative way. A quantification of the increasing (towards the glass transition) spatial extent of the dynamic heterogeneity would provide additional evidence in favor of the interpretation of the glass transition as a critical phenomenon [34].

(c) Measurements of the characteristic features of non-linear response functions (e.g. third- or fifth-order dynamical susceptibilities) as the glass transition is approached [35].

Concerning the non-equilibrium glass beyond the glass transition, the studies will include the quantification of aging effects that are generated by the slow drift of the system to thermodynamic equilibrium [36], and the quantification of the violation of the fluctuation-dissipation theorem by simultaneous measurement of the response function and the autocorrelation function, which would also lead to the determination of the effective temperature of the glass [37].

2.3. Nonlinear dynamics

Nonlinear phenomena are ubiquitous in a variety of complex systems. Of large interest is the nonlinear behavior of fluids when the collective motion becomes turbulent or chaotic, or nonlinear wave phenomena. Complex plasma offer the possibility to study such nonlinear behavior on a microscopic level, yielding insights in the underlying physical processes and the reasons for the emergence of the nonlinear behavior beyond macroscopic descriptions. The main objectives are the investigation of turbulence and waves:

(a) Turbulence appears in natural fluid systems, and it is of extreme relevance to technical applications, e.g. flows in pipes, turbulence behind aircraft turbines, etc. Therefore, the understanding of the physical mechanisms behind turbulent motion and the onset and decay of large-scale nonlinear (turbulent) motion, is an active research area. Especially the connection of large-scale hydrodynamic motions to the underlying microscopic processes is of interest. This can yield new insights that might be helpful for problems such as proofing the existence of unique solutions of the Navier–Stokes equations for turbulent motion, one of the unsolved Millennium prize problems [38].

Complex plasmas are generally low-Reynolds number systems, which means turbulence occurs due to viscoelastic effects, and they are highly dissipative, making it necessary to force turbulent motion by respective energy input [39]. Combining complex plasma with active particles (see below), new classes of active turbulence, driven by internal instabilities, can be studied [40, 41]. Former complex plasma experiments showed, that the energy spectra of forced turbulent motion in a 3D particle system fitted well to the model of 2D turbulence, but it is not known why [39]. Another study showed that the transition from planar to turbulent traveling waves can be described similar to a percolating turbulent transition in hydrodynamic flows [42]. Including 3D optical diagnostics in COMPACT would allow to investigate the role of the third dimension. Further, a large chamber volume would allow to generate large particle systems (large-scale flows) and to work at low neutral gas pressures which would reduce the energy input necessary to drive turbulence.

(b) Nonlinear waves: dust acoustic or dust density waves (DAW, DDW) are ubiquitous in nature. They are longitudinal, nonlinear density waves that can be observed in laboratory complex plasmas [43], but also are believed to be present in space and astrophysical systems such as the Earth's mesosphere [44, 45], planetary rings (e.g. the Saturn rings, [46]), comet tails [47] and the Moon [48]. They can be excited through interaction with e.g. solar wind ions and related relative drifts between the ions and the dust component.

Further, large amplitude DAWs can contribute to particle agglomeration by accelerating micron-sized, charged particles to velocities that enable them to overcome the repulsive Coulomb barrier and finally form agglomerates. This was shown for laboratory dusty plasma as well as carbonaceous dust [49, 50]. Still, open questions remain, e.g. what are the effects of dust size distribution, how does strong coupling affect the DAWs, what is the critical particle density for self-excitation of DAWs? Though theoretical model exist, often the experimental evidence is still missing.

Additionally, dust acoustic waves exhibit a multitude of specific nonlinear phenomena such as solitary waves, shocks, or wave turbulence [42]. Recent studies show for example the emergence of rogue waves [51, 52], the reflection behavior of dissipative solitary waves [51], or the propagation of shock waves [53] that were studied experimentally on the ground as well as in microgravity, but leave a lot of open questions that can be tackled with COMPACT, e.g. how does further reducing the damping affect the wave propagation across interfaces, what is the formation mechanism behind multiscale wave turbulence, how is a shock wave affected by the direction of the ion flow with respect to the direction of wave propagation?

2.4. Active and non-spherical particles

Active particles have become a topic of highest interest over the recent years. Active particles are characterized by their ability to take energy from their environment and drive themselves far from equilibrium [54, 55]. This means the particles perform a non-thermal motion which often is directed, tumbling or rotating. From that kind of active motion, novel behavior emerges, like swarming, aligning, clustering, self-crowding ('jamming'), active microrheology, active turbulence, active baths and many more. Examples of active matter are natural objects like bacteria, flocks of birds, school of fish etc but also artificial, man-made objects like Janus spheres and rods, chiral particles or artificial self-propelled microswimmers [55]. Active particles have been studied in colloidal suspensions where hydrodynamic interactions play a key role or in granular systems where direct contact forces are relevant [56]. Both hydrodynamic interactions and contact forces are generally short-range. The hydrodynamic interaction in colloidal suspensions is essentially dipolar and in the limit of low Reynolds numbers. Dusty plasmas allow us to open up and explore a novel terrain: there is a long-range interactions among the particles that can be tuned from monopolar to (non-reciprocal) dipolar. Also, in contrast to studies of active matter in other media where often 2D environments prevail, in dusty plasmas 3D systems can be studied. With this a whole new parameter space can be scrutinized.

To be able to turn energy from the environment into non-random motion, active particles generally feature asymmetries or anisotropies to allow active behavior. Asymmetric or anisotropic particles have only been rarely studied in dusty plasmas since they are very susceptible to the non-equilibrium environment of Earth-bound dusty plasmas [57]. Janus particles generally have two different surfaces with distinct physical or chemical properties that, upon interaction with the surrounding medium, drives the particles along one of the surfaces, and first experiments have been performed on ground [58, 59].

The list of proposed investigations includes dust systems consisting of non-spherical particles like ellipsoidal particles, rods or dumbbells, as well as Janus particles:

(a) Structure and phase diagram in systems of non-spherical particles: simulations indicate that the corresponding phase diagram of non-spherical particles is very rich comprising a number of different equilibrium structures [60, 61]. The reason are the strong higher-order directed interaction terms (in particular dipole and quadrupole interaction) compared to the monopole interaction of spherical particles, that lead to different classes of structures such as rhombic, rectangular or triangular.

Measuring and identifying equilibrium structures (and transitions between them) of non-spherical particle systems will allow to compare the model predictions with the experimental results and from that the underlying particle-particle and particle-plasma interactions.

(b) Emergence of orientational order/liquid crystal phases: rod-like particles can exhibit liquid crystalline order (e.g. nematic or smectic phases) where there is no distinct translational order, but orientational order of the particle axes. Dust systems with their long-range interaction and comparatively low density span a whole new parameter space for the investigations of such oriented systems.

(c) Statistical physics of diatomic colloidal matter: the key science question is to understand how molecular rotation is coupled to thermodynamic and transport properties in dusty plasma matter. The rotational temperature, defined based on the elementary rotational kinetic energy of suspended dust particles, provides a connection to understanding diatomic gases (conventionally characterized using molecular rotation spectroscopy).

(d) Mode dynamics in systems of non-spherical particles: dusty plasmas are only weakly damped, which allows to study the (virtually undamped) modes of a system such as the phonon spectra [62, 63]. Hence, it is natural to extract the wave and phonon modes also for the systems of non-spherical particles and to compare them to those obtained for the spherical standard particles. The resulting mode spectra allow us to directly extract the additional contributions of the non-spherical properties of the particles to their interaction.

(e) Rheology of non-spherical particles: upon exertion of a strain (rate) force, the dust system with the non-spherical particles will respond with its visco-elastic properties. It can be assumed that a dust fluid consisting of non-spherical particles will, as already strongly-coupled systems of spherical particle, also exhibit non-Newtonian fluid behavior [64]. The viscoelastic properties can be analyzed from the application of a (periodic) shear stress.

(f) Statistical properties of active particles: a first step requires the investigation of the motion of the active particles in terms of relevant parameters. While some preliminary characterizations can already be made in the mainly two-dimensional, non-homogeneous situations of discharges on Earth [58, 59], these quantities have to be measured again under the more homogeneous plasma conditions of COMPACT where the active particles can freely move in three dimensions in the plasma bulk. Single particle properties such as the persistence length (or time), the mean velocity and time scale for re-orientation have to be determined from dedicated experiments, as well as statistical properties such as the velocity distribution function, the mean square displacement, effective diffusion constants, etc.

(g) Structure of dust systems with active particles: the local and global structure of the dust cloud in systems with various mixtures of active and standard particles will be studied with regard to e.g. the degree of order of the system in dependence on the mixing ratio. Of interest is also how the particle components arrange (e.g. randomly distributed or cluster formation), and how and on which length/time scales the energy of the active particles will be dissipated in the standard cloud.

(h) Rheology of active particle systems: it is interesting to check how a fluid picture of flow, turbulence and sound waves as measured in clouds of standard particles can be held up in a dust system with active particles. Similar as for the non-spherical particles the response of a dust system with active particles to an external shear stress will be studied.

(i) Collective behavior of active particle systems: emergence of cooperative or collective behavior is one of most fascinating questions in systems with active particles. Examples of such a behavior are swarming, clustering or self-crowding ('jamming'). It is very intriguing to study swarming, i.e. collective interaction of (neighboring) active particles [65] in active dusty plasmas where—in contrast to colloidal suspensions and granular matter—the interaction is quite long range and three-dimensional. Clustering and self-crowding occurs when the active particles are blocked in their motion by other oppositely moving particles. Then, small aggregates of mutually blocking particles can build clusters in a medium of otherwise unblocked active particles. Clustering and crowding require relatively high particle densities since in three dimensions there are many possible paths on which the particles can evade each other. In this sense, the transition from a non-blocking, fluid-like behavior to a clustering and crowding state can be viewed as a form of a fluid-to-glass transition [66].

2.5. Planetary physics

Complex plasmas are ubiquitous in nature: dust is widespread on the regolith surfaces of the Moon and asteroids, which are exposed to the plasma of the solar wind. Dust is also prevalent in the rings of outer planets, cometary tails, interplanetary and interstellar clouds, and Earth's mesosphere [67–71]. Plasma physics topics that deserve exploration in connection with dust in space are described below.

(a) Dust charging: the two main processes of dust charging in space are photoelectric charging due to solar UV, and collection of charged solar wind particles. These processes generally occur with ambient electron and ion densities that are much lower than is common in laboratory experiments with plasmas, but there are newly developed methods involving afterglow plasmas [72, 73] that can more nearly mimic solar-wind conditions. Temporal (plasma pulsing [74]), as well as spatial (gridded electrodes, [75]), afterglows can be realized with COMPACT to study dust charging processes.

(b) Dust mitigation: dust can pose a contamination problem for human exploration of the Moon, Mars and asteroids due to fouling equipment and inhalation hazards. Future habitats will require water-free cleaning methods for spacesuits, tools, solar panels, and other surfaces.

Electrostatic methods, using plasma or electron beams, show great promise. These methods can be developed mainly in laboratories, although some tests may require the microgravity of parabolic flights, or space exposure in low-Earth orbit [76].

(c) Natural movement: charged dust grains can be electrostatically lifted from one location on the lunar surface and deposited on another [77, 78]. The charge can originate from exposure to solar UV and the solar wind. This charging has been proposed to explain Mariner and Apollo observations of dust layers above the lunar horizon. Lofting processes can be studied to some extent on the ground, but observing motion in the absence of strong gravitational acceleration would benefit from parabolic flight conditions.

(d) Dust collisions and coagulation: in the early stages of planetary formation, small grains are consolidated into larger protoplanetary bodies. These collisions of dust grains with either other dust grains or larger solid bodies may often occur at low differential velocities, in a pre-solar nebula. Attaining such low velocities for an extended time in the laboratory is impractical under normal gravity conditions, so that microgravity conditions are essential for their study. Measuring the coagulation rate will allow model validation [79, 80]. The coagulation rate can be obtained directly from the number of particle-particle collisions and a known dust number concentration, requiring the injection of a defined number of dust particles. Contact charging during collisions can be studied in afterglow plasmas, with electric fields to control the grain velocities. The charge can then be inferred from the measured drift velocities, as well as the dependence of contact charging on the particle composition.

(e) Formation of ice particles: formation of ice particles is a step in forming planetary objects, which can occur in the partially ionized environment of pre-stellar nebula. Recent laboratory experiments have shown that charges in a plasma can play a large role in the shape of ice particles, as they grow from water vapor in a gas. One complication with those experiments is that due to gravity, they require an electric field to levitate the particles. This electric field also drives an ion flow, which may influence the morphology of ice grains as they grow [81].

2.6. Particles as diagnostics in plasmas

The charge of microparticles in plasma directly depends on local plasma conditions. At steady-state conditions, the microparticle surface potential is at floating potential with the microparticle charge determined by the equality of the electron and ion fluxes to and from their surfaces [4, 82]. Primarily, these charging currents are due to surrounding plasma primary ion and electron populations. Under specific conditions, such as astrophysical conditions or in tokamak plasmas, the emission of secondary electrons and photoelectrons can also contribute in a significant way to the microparticle charge [4, 82]. Microparticles can thus be seen as floating probes, with the floating potential dependent on the specific plasma parameters, which can be influenced by ion stream, ion collisions [83], secondary emission, photoemission, etc. Proposed experiments include:

(a) Mapping of electric potential, electric field in discharge: by injecting a few particles and tracing their trajectories in the inter-electrode space, it is possible to recover the force experienced by the particles. Combined with accurate modeling, these data allow mapping of the electric field and electric potential in the plasma [84, 85].

(b) Using the dispersion relation of waves in dense clouds to get plasma information: the wave dispersion relation in strongly coupled complex plasma depends strongly on the microparticle parameters (size, charge, density) as well as on the discharge parameters (power, pressure). Combined with theoretical studies, the dispersion relation of wave modes in strongly coupled plasma can lead to accurate measurement of these different parameters [86, 87].

(c) Afterglow conditions: (dis)charging of particles depends directly on the electron and ion dynamics in the afterglow phase (transition from ambipolar to free diffusion, influence of local electric fields when the discharge is switched off) [72]. Measurement of dust dynamics and dust charges in the late afterglow can help understanding these and previous plasma-on conditions.

(d) Dense clouds and time-resolved measurements of discharge electrical characteristics: dense clouds of microparticles have a strong influence on the plasma impedance. Measurements of phase resolved rf-current, rf-voltage, and self-bias allows direct measurement of plasma impedance from which different parameters can be recovered (plasma density, electron temperature, particle density, particle charge, etc) [88, 89].

3. Science requirements

From the science objectives collected in the previous section, a list of scientific requirements on the capabilities of the COMPACT facility can be deduced, as summarized below. This in turn will impose technical requirements on the hardware that will be described in the next section.

3.1. Statistical physics, phase transitions, nonlinear dynamics and active matter

These research areas all require large, homogeneous, and void-free particle systems. Edge effects due to the finite system size should be minimized as much as possible. A variation of general plasma parameters (neutral gas density, plasma density, electron temperature) is needed to perform experiments in different regimes regarding the damping, coupling strength and interaction force (particle charge). The possibility to change confinement or particle charge independent on the plasma source (e.g. change of electron temperature by some other means while the neutral gas pressure remains unchanged) will considerably increase the available parameter space compared to former facilities. Low gas pressures (<10 Pa) are necessary to reduce the damping of particle motion for studies of e.g. turbulence. Further needed are options to manipulate the particle systems to induce phase transitions (e.g. by compression) and excite waves (e.g. by electric excitation), options to induce and control particle flows to study rheology or turbulence, as well as options to control the ion flow in magnitude and direction. The latter two can be accomplished by e.g. spatially manipulating electric fields utilizing multi-electrode systems, at different time scales for particles or ions, respectively. Additionally, local particle manipulations such as laser heating to e.g. study heat transport are required.

A particle dispensation system has to provide a large variety of different particles: spherical melamine-formaldehyde or silica particles, non-spherical particles such as rods, dumbbells or ellipsoidals, and active Janus particles.

Optical particle diagnostics have to include a system overview with a large field of view at high spatial resolution for investigation of the large-scale structures. A 3D particle diagnostics with a smaller field of view at high spatial and temporal resolution, e.g. a stereoscopic setup, is necessary to obtain real-time 3D particle trajectories resolving the kinetic properties.

3.2. Planetary physics

For studies on dust in space, in general very low density plasmas are needed, and particle charges should be low. Also, charging through other sources (e.g. UV light) instead of plasma constituents is of interest. Further, water ice generation will require an additional water gas reservoir and cooling of the electrodes below 0 °C. Lunar or Martian dust simulants should be provided. Creating afterglow conditions to study dust charging or collisions requires spatial or temporal plasma-off conditions, e.g. by utilizing grid electrodes or a slowly pulsed plasma.

While there are hardware options to meet those requirements, it could become difficult to implement all of them in one facility, e.g. grid electrodes vs. multi-electrode system, water ice vs. clean plasma conditions for dust experiments. A feasible option is to build a second facility, based on the COMPACT hardware, and deploy it on parabolic flights for first experiments.

3.3. Particles as diagnostics of plasmas

Additionally to the requirements listed at the beginning of this section, here an option to inject small amounts of particles in a controlled way is needed if single particle trajectories are to be used to e.g. map electric fields in the plasma. Tracer particles (e.g. fluorescent particles) could be used in very dense systems. Time-resolved measurement of plasma impedance through electrode diagnostics (precise measurements of self-bias, phase-resolved rf current and voltage) have to be implemented, which is feasible considering the availability of current technological advancements in small-sized microcontroller and FPGA-based electronics.

3.4. Available hardware

A radio-frequency driven plasma chamber (the Zyflex chamber, [9]) has been developed during the precursor project Ekoplasma [90]. This chamber fulfills most of the listed requirements: it has a large inner volume for large particle systems, variable electrode separation to change the plasma volume and to compress or expand the particle system (e.g. to induce phase transitions or excite waves), segmented electrodes and a multi-channel rf-generator to manipulate plasma and particles, with an additional pulsed plasma mode. These capabilities are unique and have not been available on former ISS facilities for complex plasma research. Regarding the optical diagnostics, a 3D stereoscopic system consisting of four cameras has been developed at the university Greifswald [11]. As an example, an existing setup has a field of view of $16 \times 13 \times 2\,\text{mm}^3$ and can record up to 1000 fps, depending on the region of interest. Both hardware components have been in use in the laboratory and on parabolic flights and can be utilized for COMPACT.

4. Conclusion and outlook

The scientific objectives for a future facility for complex plasma research onboard the ISS—COMPACT—were presented. COMPACT is intended to be an international, multi-user facility, including new research directions such as active matter and planetary dust topics. With its advanced and unique technological capabilities compared to the predecessor facilities, COMPACT will enable studies of the above scientific objectives that are not accessible using existing instrumentation on the ISS. These studies will serve a broad scientific community. COMPACT will be built upon already developed hardware (plasma chamber, 3D optical diagnostics), minimizing the time and cost factors for hardware development.

The first industry phase was initiated by the German Space Agency in July 2022 as a combined feasibility and accommodation study. The intention is an accommodation in a NASA Express Rack, with a possible start to the ISS after 2026.

Data availability statement

No new data were created or analysed in this study.

Acknowledgment

The authors want to thank A M Lipaev and A Usachev from the Joint Institute for High Temperatures of the Russian Academy of Sciences in Moscow for their contributions to the scientific objectives in the early stages of the science definition phase. C A Knapek is funded by DLR/BMWi FKZ 50WM2161. A Dove is funded by NASA/JPL Grant No. 1655881. J Goree is funded by NASA/JPL RSA No. 1663801 and RSA No. 1672641, and United States National Science Foundation Grant No. PHY-1740379. U Konopka is funded by JPL-RSA-1571699, JPL-RSA-167198 and NSF-PHY-1740784. M Thoma is funded by DLR/BMWi FKZ 50WM1942 and 50WM2044.

ORCID iDs

C A Knapek https://orcid.org/0000-0001-7105-627X
L Couedel https://orcid.org/0000-0003-0749-9273
A Melzer https://orcid.org/0000-0001-9301-9357
S Ratynskaia https://orcid.org/0000-0002-6712-3625
H M Thomas https://orcid.org/0000-0001-8358-2023

References

[1] Morfill G E and Ivlev A V 2009 *Rev. Mod. Phys.* **81** 1353–404
[2] Fortov V, Ivlev A, Khrapak S, Khrapak A and Morfill G 2005 *Phys. Rep.* **421** 1–103
[3] Piel A 2016 *Plasma Phys. Control. Fusion* **59** 014001
[4] Melzer A 2019 *Physics of Dusty Plasmas: An Introduction* (Cham: Springer Nature)
[5] Nefedov A P *et al* 2003 *New J. Phys.* **5** 33
[6] Thomas H M *et al* 2008 *New J. Phys.* **10** 033036
[7] Pustylnik M Y *et al* 2016 *Rev. Sci. Instrum.* **87** 093505
[8] Thoma M H, Thomas H M, Knapek C A, Melzer A and Konopka U 2022 *npj Microgravity* accepted
[9] Knapek C A, Konopka U, Mohr D P, Huber P, Lipaev A M and Thomas H M 2021 *Rev. Sci. Instrum.* **92** 103505
[10] Melzer A, Himpel M, Killer C and Mulsow M 2016 *J. Plasma Phys.* **82** 615820102
[11] Himpel M and Melzer A 2019 *J. Imaging* **5** 28
[12] Himpel M and Melzer A 2021 *Mach. Learn.: Sci. Technol.* **2** 045019
[13] Ding Z, Matthews L S and Hyde T W 2021 *Mach. Learn.: Sci. Technol.* **2** 035017
[14] Dietz C, Budak J, Kamprich T, Kretschmer M and Thoma M H 2021 *Contrib. Plasma Phys.* **61** e202100079
[15] Oxtoby N P, Griffith E J, Durniak C, Ralph J F and Samsonov D 2013 *Phys. Rev. Lett.* **111** 015002
[16] Wieben F and Block D 2019 *Phys. Rev. Lett.* **123** 225001
[17] Ivlev A V *et al* 2008 *Phys. Rev. Lett.* **100** 095003
[18] Nosenko V *et al* 2020 *Phys. Rev. Res.* **2** 033404
[19] Nosenko V, Zhdanov S, Ivlev A V, Morfill G, Goree J and Piel A 2008 *Phys. Rev. Lett.* **100** 025003
[20] Nunomura S, Samsonov D, Zhdanov S and Morfill G 2006 *Phys. Rev. Lett.* **96** 015003
[21] Tsallis C 2009 *Braz. J. Phys.* **39** 337–56
[22] van Zon R and Cohen E G D 2003 *Phys. Rev.* E **67** 046102
[23] Wong C-S, Goree J and Gopalakrishnan R 2018 *Phys. Rev.* E **97** 050601
[24] Wong C-S, Goree J, Haralson Z and Liu B 2018 *Nat. Phys.* **14** 21–24
[25] Wong C-S, Gopalakrishnan R and Goree J 2019 *J. Aerosol Sci.* **129** 116–23
[26] Debenedetti P G and Stillinger F H 2001 *Nature* **410** 259–67
[27] Biroli G and Garrahan J P 2013 *J. Chem. Phys.* **138** 12A301
[28] Dyre J C 2006 *Rev. Mod. Phys.* **78** 953–72
[29] Cavagna A 2009 *Phys. Rep.* **476** 51–124
[30] Berthier L and Biroli G 2011 *Rev. Mod. Phys.* **83** 587–645
[31] Ninarello A, Berthier L and Coslovich D 2017 *Phys. Rev.* X **7** 021039
[32] Patrick Royall C, Williams S R, Ohtsuka T and Tanaka H 2008 *Nat. Mater.* **7** 556–61
[33] Ganapathi D, Chakrabarti D, Sood A K and Ganapathy R 2021 *Nat. Phys.* **17** 114–20
[34] Bennemann C, Donati C, Baschnagel J and Glotzer S C 1999 *Nature* **399** 246–9
[35] Bouchaud J-P and Biroli G 2005 *Phys. Rev.* B **72** 064204
[36] Hunter G L and Weeks E R 2012 *Rep. Prog. Phys.* **75** 066501
[37] Berthier L and Barrat J-L 2002 *J. Chem. Phys.* **116** 6228–42
[38] Millenium problems: Navier–stokes equation (available at: http://www.claymath.org/millennium-problems/navier-stokes-equation)
[39] Schwabe M, Zhdanov S and Räth C 2017 *Phys. Rev.* E **95** 041201
[40] Bratanov V, Jenko F and Frey E 2015 *Proc. Natl Acad. Sci.* **112** 15048–53
[41] Martínez-Prat B, Ignés-Mullol J, Casademunt J and Sagués F 2019 *Nat. Phys.* **15** 362–6
[42] Lin P-C, Chen W-J and Lin I 2020 *Phys. Plasmas* **27** 010703
[43] Merlino R L 2014 *J. Plasma Phys.* **80** 773–86
[44] Popel S, Kopnin S, Kosarev I and Yu M 2006 *Adv. Space Res.* **37** 414–9
[45] Banerjee G, Maitra S and Dasgupta C 2021 *Phys. Plasmas* **28** 012101
[46] Ghosh S, Chaudhuri T K, Sarkar S, Khan M and Gupta M 2001 *Astrophys. Space Sci.* **278** 465–77
[47] Mendis D and Horányi M 2013 *Rev. Geophys.* **51** 53–75
[48] Popel S I, Morfill G E, Shukla P K and Thomas H 2013 *J. Plasma Phys.* **79** 1071–4
[49] Du C-R, Thomas H M, Ivlev A V, Konopka U and Morfill G E 2010 *Phys. Plasmas* **17** 113710
[50] Dap S, Lacroix D, Hugon R, de Poucques L, Briancon J-L and Bougdira J 2012 *Phys. Rev. Lett.* **109** 245002
[51] Sun W *et al* 2018 *Europhys. Lett.* **122** 55001
[52] Tsai Y-Y, Tsai J-Y and Lin I 2016 *Nat. Phys.* **12** 573–7
[53] Kananovich A and Goree J 2020 *Phys. Plasmas* **27** 113704
[54] Ramaswamy S 2010 *Annu. Rev. Condens. Matter Phys.* **1** 323–45
[55] Bechinger C, Di Leonardo R, Löwen H, Reichhardt C, Volpe G and Volpe G 2016 *Rev. Mod. Phys.* **88** 045006
[56] Kumar N, Soni H, Ramaswamy S and Sood A K 2014 *Nat. Commun.* **5** 4688
[57] Annaratone B M *et al* 2001 *Phys. Rev.* E **63** 036406
[58] Nosenko V, Luoni F, Kaouk A, Rubin-Zuzic M and Thomas H 2020 *Phys. Rev. Res.* **2** 033226
[59] Vasilieva E V, Petrov O F and Vasiliev M M 2021 *Sci. Rep.* **11** 523
[60] Berardi R, Lintuvuori J S, Wilson M R and Zannoni C 2011 *J. Chem. Phys.* **135** 134119
[61] Lee H C, Chen D Y and Rosenstein B 1997 *Phys. Rev.* E **56** 4596–607
[62] Nunomura S, Goree J, Hu S, Wang X, Bhattacharjee A and Avinash K 2002 *Phys. Rev. Lett.* **89** 035001
[63] Liu B and Goree J 2005 *Phys. Rev.* E **71** 046410
[64] Solomon M J and Spicer P T 2010 *Soft Matter* **6** 1391–400
[65] Rubio Puzzo M L, De Virgiliis A and Grigera T S 2019 *Phys. Rev.* E **99** 052602
[66] Berthier L, Flenner E and Szamel G 2019 *J. Chem. Phys.* **150** 200901
[67] Goertz C K 1989 *Rev. Geophys.* **27** 271–92
[68] Goertz C K and Morfill G 1983 *Icarus* **53** 219–29
[69] Ivlev A V, Burkert A, Vasyunin A and Caselli P 2018 *Astrophys. J.* **861** 30
[70] Wu Z, Wang A, Farrell W M, Yan Y, Wang K, Houghton J and Jackson A W 2018 *Earth Planet. Sci. Lett.* **504** 94–105
[71] Wang X, Schwan J, Hsu H-W, Grün E and Horányi M 2016 *Geophys. Res. Lett.* **43** 6103–10
[72] Couëdel L, Mikikian M, Boufendi L and Samarian A A 2006 *Phys. Rev.* E **74** 026403
[73] Chaubey N, Goree J, Lanham S J and Kushner M J 2021 *Phys. Plasmas* **28** 103702

[74] Booth J P, Cunge G, Sadeghi N and Boswell R W 1997 *J. Appl. Phys.* **82** 552–60
[75] Knapek C A, Huber P, Mohr D P, Zaehringer E, Molotkov V I, Lipaev A M, Naumkin V, Konopka U, Thomas H M and Fortov V E 2018 *AIP Conf. Proc.* **1925** 020004
[76] Farr B, Wang X, Goree J, Hahn I, Israelsson U and Horányi M 2020 *Acta Astronaut.* **177** 405–9
[77] Hartzell C, Wang X, Scheeres D and Horányi M 2013 *Geophys. Res. Lett.* **40** 1038–42
[78] Dove A, Horányi M, Robertson S and Wang X 2018 *Planet. Space Sci.* **156** 92–95
[79] Gopalakrishnan R and Hogan C J Jr 2011 *Aerosol Sci. Technol.* **45** 1499–509
[80] Thajudeen T, Gopalakrishnan R and Hogan C J Jr 2012 *Aerosol Sci. Technol.* **46** 1174–86
[81] Chai K-B and Bellan P M 2015 *Astrophys. J.* **802** 112
[82] Piel A 2017 *Plasma Physics: An Introduction to Laboratory, Space and Fusion Plasmas* (Cham: Springer)
[83] Zobnin A V, Usachev A D, Petrov O F and Fortov V E 2008 *Phys. Plasmas* **15** 043705
[84] Samarian A and James B 2001 *Phys. Lett.* A **287** 125–30
[85] Ashrafi K S, Yousefi R, Chen M, Matthews L S and Hyde T W 2020 *Phys. Rev.* E **102** 043210
[86] Nunomura S, Samsonov D and Goree J 2000 *Phys. Rev. Lett.* **84** 5141–4
[87] Khrapak S *et al* 2003 *Phys. Plasmas* **10** 1–4
[88] Henault M, Wattieaux G, Lecas T, Renouard J P and Boufendi L 2016 *Phys. Plasmas* **23** 023504
[89] Wattieaux G and Boufendi L 2012 *Phys. Plasmas* **19** 033701
[90] Knapek C A *et al* 2018 Ekoplasma—the future of complex plasma research aboard the international space station *69th Int. Astronautical Congress (IAC)*