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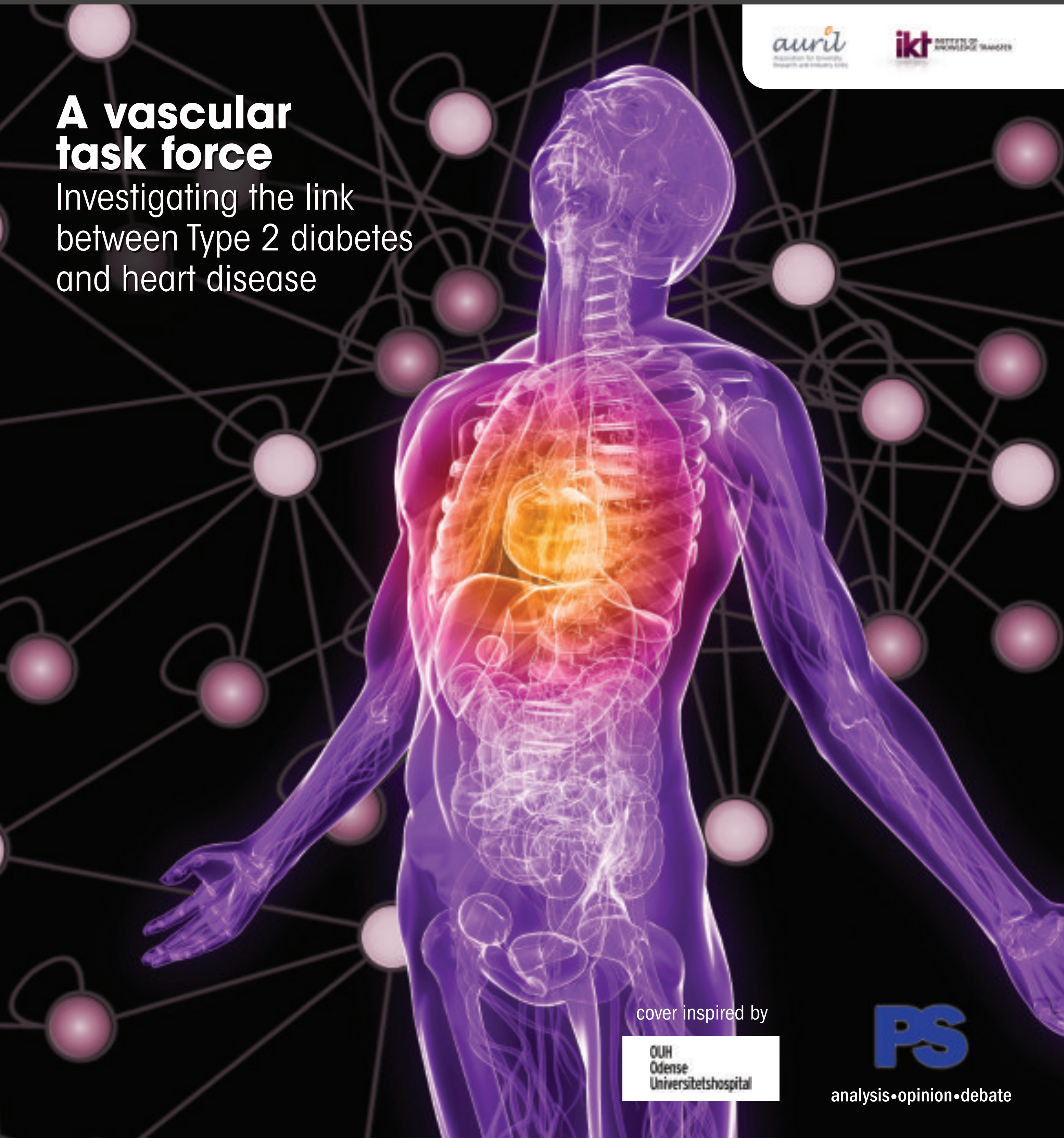

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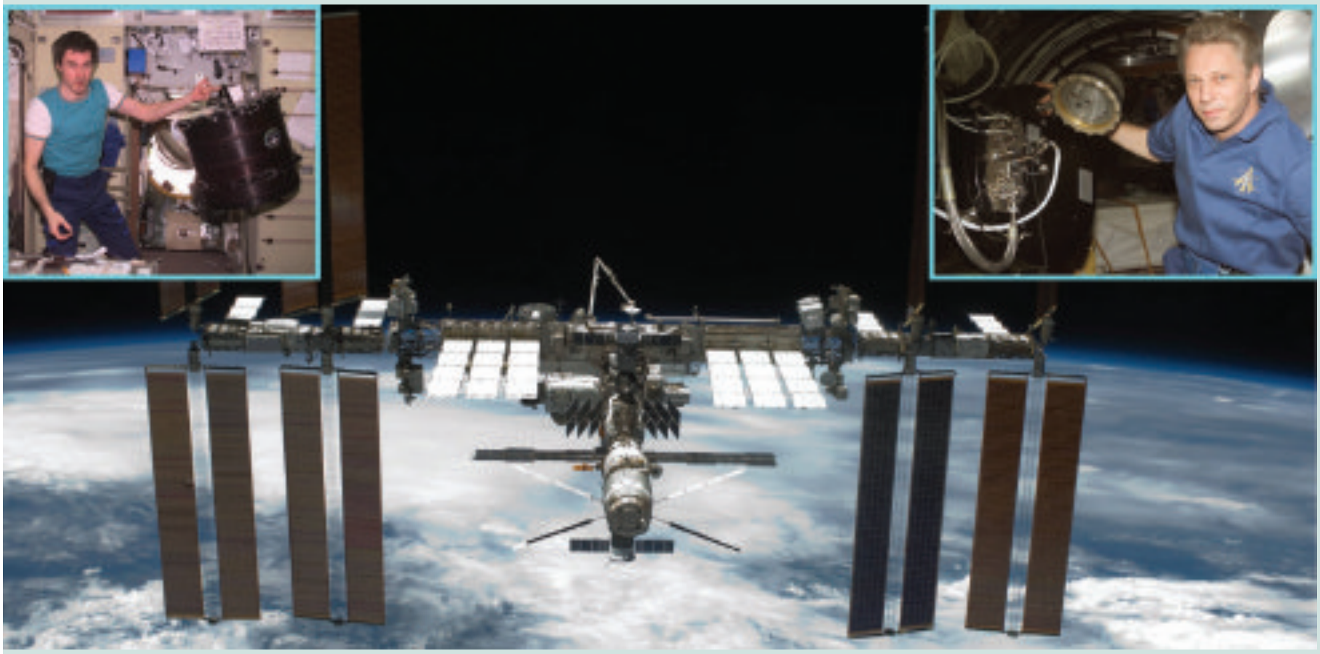
Basic research in space – Applications on Earth

Transfer of basic research to applications is a long, sometimes never-ending story. This is especially true for fundamental research performed under microgravity conditions on the International Space Station (ISS). Although this is the nature of basic science it is not always understood in the public. The question 'What is your research for?' always arises – and the scientist is animated to predict a future so far away from his current research that he may not believe it himself. How strange such a 'transfer story' can be, far from the imagination of the scientist 10 years ago and of course not predicted, is shown by the plasma crystal research on the ISS and its spin-off in plasma medicine.

This plasma crystal research is of purely basic character with intellectual objectives to gain knowledge about a new form of matter that doesn't exist naturally. From a physics point of view this opens up new insights into many fields, like solid state, fluid or plasma physics. 'Plasma' (neutral and charged particles) is the most disordered state of matter – 'crystals' are the most ordered. A 'plasma crystal' is an ordered plasma – made possible through the addition of charged microparticles (micrometer = one thousandth of a mm) – a very heavy component of the plasma. These interact with each other via their charges and form structures similar to those of natural liquids, even solids. The microparticles can be visualised individually and this allows an investigation of physical processes at a hitherto unprecedented resolution, as if one could see atoms individually, interacting in slow motion.

Microparticles are heavy and gravity forces them to sediment. In the laboratory counteracting volume forces are necessary to levitate the particles. This produces a very unstable balance and introduces stress to the overall system. Large, homogeneous systems can be formed only under microgravity conditions. The first such long-term investigations in this relatively new field of research started nearly 11 years ago with the Russian-German bilateral 'Plasma-Kristall-Experiment' project PKE-Nefedov on the International Space Station (ISS). The deal between the nations was very simple: Germany provides the space qualified hard and software and Russia provides everything else (the ISS, launch, accommodation, communication, crew training, crew time, etc.). This laboratory was operational from 2001-2005 and was the most successful basic research programme on the ISS at that time. It was replaced



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The International Space Station (ISS) home of the plasma crystal laboratories PKE-Nefedov and PK-3 Plus over the last 11 years. Insert left: Russian cosmonaut Sergei Krikalev (currently Head of the Yuri Gagarin Cosmonaut Training Centre) performed experiments in 2001 and 2005. Insert right: ESA Astronaut Thomas Reiter (currently Director of ESA's Directorate of Human Spaceflight and Operations) performed experiments during his stay in 2006

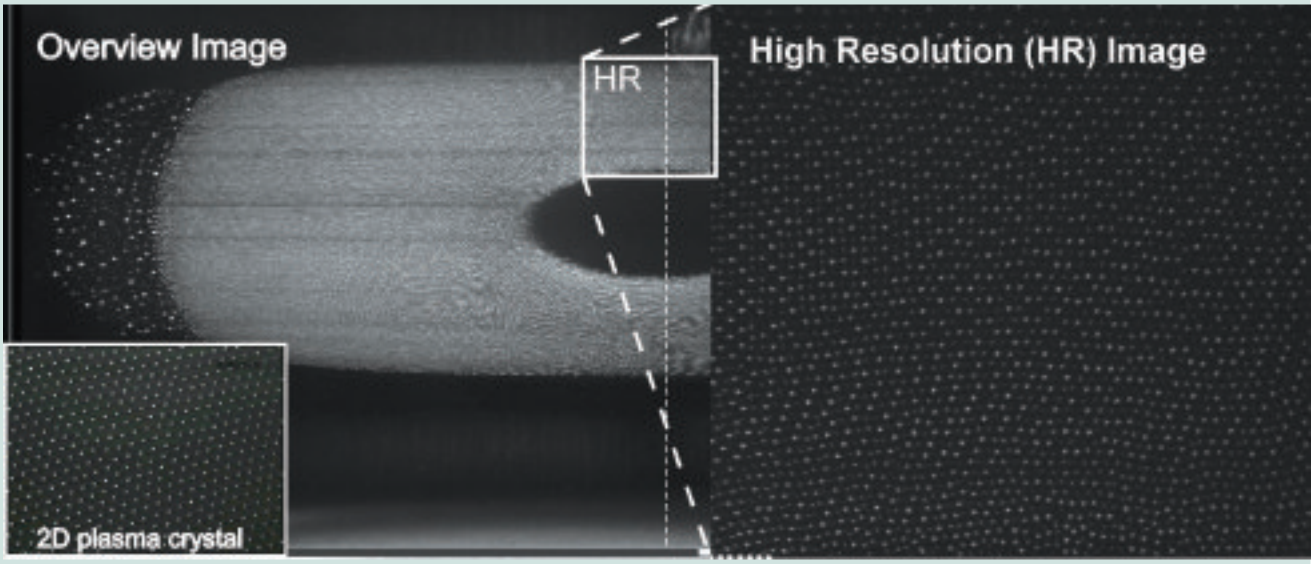

Fig. 1: Original images of large 3D plasma crystals observed with the PK-3 Plus laboratory on the ISS. The observation shows a 2D cut through a large complex plasma volume (left: overview, right: high resolution image). The insert on the left shows a typical 2D plasma crystal observed under gravity conditions

by the second generation lab PK-3 Plus in 2006, which is still operational and produces interesting scientific results on a regular basis. One of the most important features of this bilateral project is its continuity: we can perform experiments, receive data and analyse the results – then we can go back to our laboratory on the ISS and repeat and verify or refine our experiments. This is very similar to the work in the lab on ground and very important for real progress in basic research.

Results from the ISS – plasma crystal

The view into 'atomic' structure and 'atomic' dynamics of **solids or liquids** is of fundamental interest. This is possible with our plasma crystal (German: Plasma-Kristall and Russian: Plazmennyi-Kristall) PK-laboratories under microgravity conditions on the ISS. For instance, large 3D crystalline systems (see Fig. 1) could be studied for the first time – especially details of a moving crystallisation front.

Results from the ISS – lane formation

One of the remarkable examples of a 'non-equilibrium phase transition' is the **formation of lanes** – a truly universal phenomenon occurring in nature when two species of 'particles' are driven against each other. This can be observed in highly populated pedestrian zones – where the 'particles' are humans – but it also occurs in physical systems (colloidal dispersions, lattice gases and molecular ions). In other words, laning is one of these ubiquitous generic processes of considerable interest in different branches of physics. It is an instability that occurs on the particle scale, i.e. the size of the structures formed is comparable to interparticle distances. Particle-resolved experiments made possible with PK-3 Plus on the ISS (shown in Fig. 2 and 2a) contribute greatly to understand this process.

Results from the ISS – demixing of fluids

The **demixing of fluids**, e.g. oil in water, is another ubiquitous phenomenon observed in various systems ranging from molecular fluids to colloidal suspensions. This phenomenon, the tendency for particles of different types to mix or demix, remains of fundamental importance for many industrial applications. Clearly, it is better to understand this fundamentally rather than revert to 'trial and error'. The phase separation in binary complex plasmas has been observed in several dedicated experiments performed under microgravity conditions in the PK-3 Plus laboratory on the ISS (see Fig. 2 and 2b). When the small particles (see the lanes in Fig. 2a) approached the centre of the chamber and thus the driving field practically vanished, an apparent phase separation was observed accompanied by the formation of a small-particle droplet with a well-defined ellipsoidal shape (see Fig. 2b).

The future in space – PlasmaLab

Most qualitative properties of many generic processes have no critical dependence on the particular form of the interparticle interaction (this is why our experiments on the ISS are so useful). But there are very interesting new effects that occur when the interaction becomes anisotropic or/and multiscale (e.g. short-range repulsion and long-range attraction). Hence, to 'design' particle systems with prescribed interactions is considered the 'ultimate advance' – and with plasma crystals it can be done. Preliminary experiments to test the feasibility have already been conducted on the ISS. Without going into details, it was possible to produce liquid ordered particle states – so-called **'string fluids'** (also sometimes called 'smart fluids') with PK-3 Plus by applying an external alternating electric field. The transition between isotropic and string fluid states was reversible – decreasing the externally applied field brought the particles back into their initial isotropic fluid state.

This first successful attempt to tune the interaction potential (along one direction so far) will lead to the next big step of research on the ISS. In a current pre-development phase we are developing a plasma laboratory **(PlasmaLab)** that can tune the interaction potential in all three dimensions. This makes it possible to create a wealth of new 'anisotropic' solid states, a new era of fundamental research – with microgravity as the essential element for its success.

From space to Earth

From the cold plasma technology developed for our space experiments it was not a major but an unpredictable step to develop cold plasma devices for application on Earth – **'cold atmospheric plasmas'**. The main difference is the pressure and the type of gas used – in space experiments we use typically pressures below one thousandth of a bar and Argon gas, on Earth the pressure is 1 bar and the preferred gas is air.

Cold Atmospheric Plasmas (CAP) – some facts

The simplest CAP designs require only air and electrical power. In air there are some 600 chemical reactions that take place (involving only oxygen, nitrogen and water vapour). It is possible to 'engineer' the plasma so that some of the major chemical species produced are identical with those that our own immune system generates in its fight against infection – the plasma acts as a natural aid to our immune response – a new weapon in the fight against infection. After a short while these plasma chemical products recombine and revert back to the original atmospheric constituents. There is no waste, no containers – CAP are a 100% clean and sustainable resource.

CAP application areas

Hygiene

In the US about two million hospital acquired infections occur annually, leading to 90,000 deaths. Bacteria increasingly develop resistance against antibiotics and there are practically no new antibiotic drug developments in sight. In the US an estimated 100,000 new infections with *MRSA (Methicillin Resistant Staphylococcus Aureus)* occur each year with a death rate of about 20%.

Infectious diseases

Infectious diseases represent the second most important cause of death, 14.9 million per year, worldwide. Especially for epidemics and natural disasters easily accessible remedies are needed.

Skin diseases

The skin is our largest organ (about 2m² in area) and provides our first line of defence against external microbial or other threats. Tinea pedis with incidences up to 80% in different countries is the most common skin disease. Acne (17 million in the US) affects almost 85% of youths.

Cancer

Cancer accounts for over six million deaths annually worldwide. Surgery and chemotherapy (with the associated decreased immune response) are the most important treatments.

Cold Atmospheric Plasmas (CAP) – some results

To study the possible role of CAP in hygiene and medicine, we formed a large consortium of over 50 experts in plasma physics, plasma chemistry,

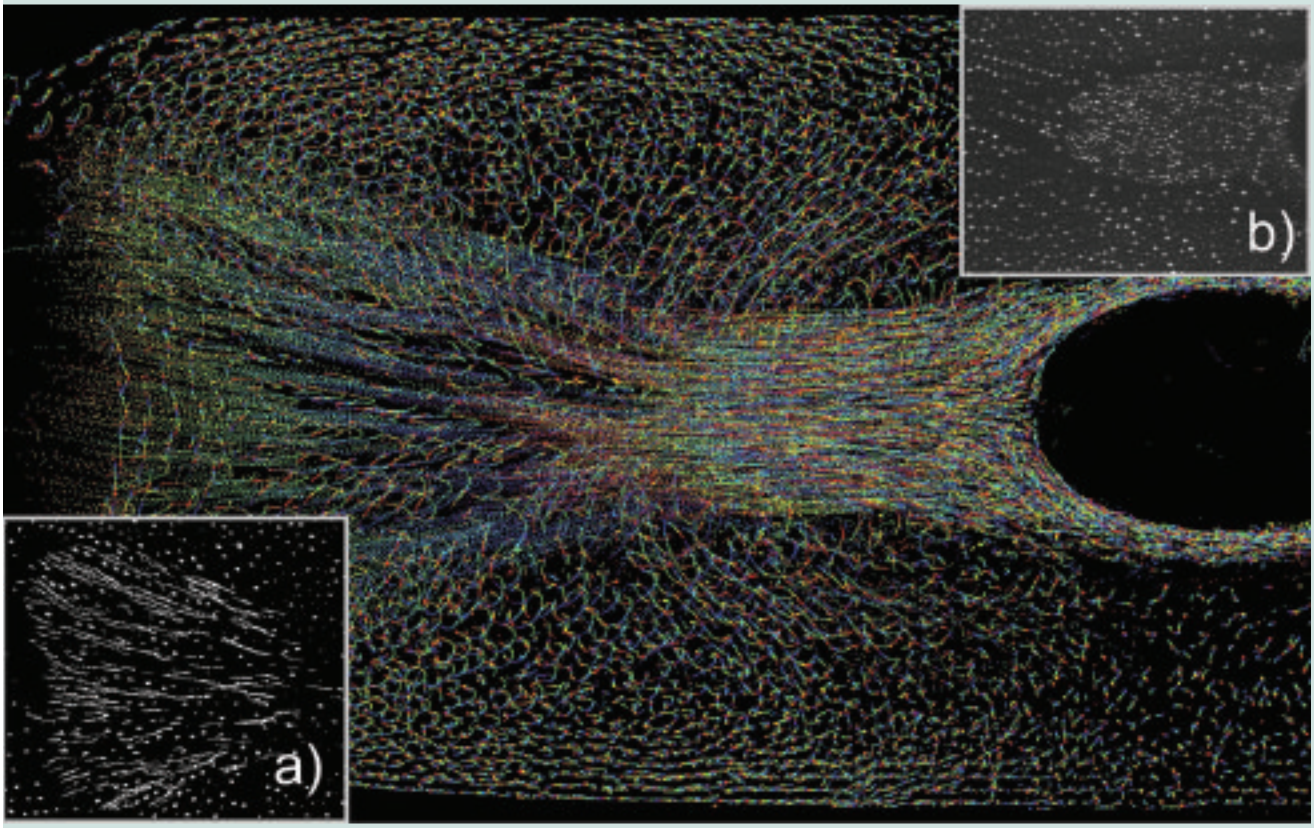

Fig. 2: Trajectories (colour coded) of particles penetrating from the left side into a stable cloud of bigger particles, first leading to lane formation (see insert a), where the small particles follow one another and later to phase separation (see insert b), where the lanes 'merge' and form a droplet

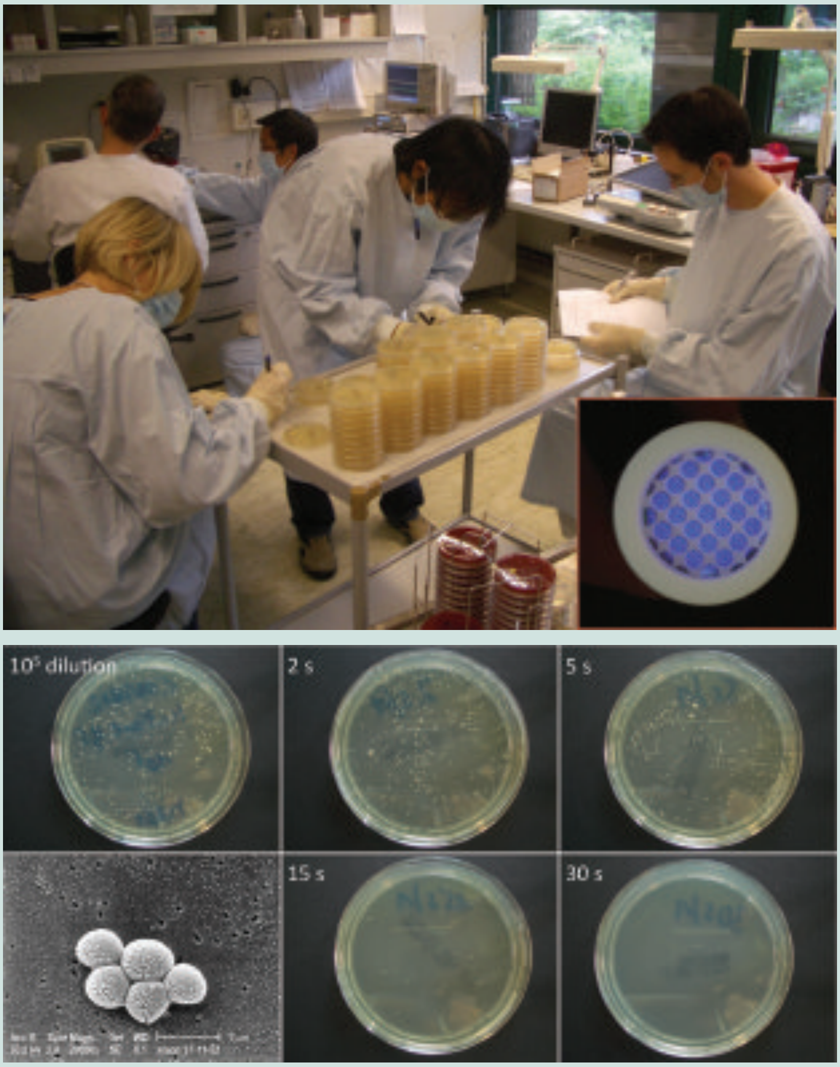

Fig. 3: (Top) physicists in a bacterial cleanroom, testing plasma effects on *EHEC 104*. The inset shows the plasma discharge used in these tests. (Bottom) plasma destroys highly antibiotically resistant *MRSA* bacteria in seconds. The picture shows bacteria colonies grown from single surviving bacteria after plasma treatment. Each bright dot represents one such survivor. The top left shows a comparison – the original bacterial load of 20 million diluted to 200 bacteria. The bottom left shows *MRSA* bacteria (roughly spherical with a diameter of 1/2 micrometer)

engineering, microbiology, cell biology and medicine – with the aim to conduct basic research and appropriate medical trials.

CAP and hygiene

Comprehensive tests have shown that CAP can be safely used on human tissue and skin. All bacterial strains that were tested in the laboratory (including *MRSA, EHEC 104*) could be inactivated within typically 10 seconds. This shows that CAP open a new path for the fight against infectious diseases.

CAP clinical trials

In the world's first clinical trials we could show in over 2,000 plasma treatments of chronic wounds that the bacterial loads (and hence infectious complications) were significantly reduced compared to wounds that only had the topical (state-of-the-art) treatment, that there were no negative side effects and that the patients accepted the contact and pain-free treatment very well. Apart from prevention and containment of infectious diseases, CAP can also play an important role in therapy and rehabilitation. In 2009 the first clinical trials on skin graft wounds showed that plasma treatment resulted in a significantly improved and faster healing than wound areas that received only topical treatment.

CAP – skin diseases

In another clinical study, a skin disease (Hailey-Hailey, a genetic disorder with no known cure) was CAP treated, originally with the aim to reduce secondary infections. It turned out that the skin irritation was reduced considerably – CAP apparently has an added effect of a long-term relief.

Final remarks

We will not go into details of how the plasma works. For now it suffices to state that the use of a gaseous agent for disinfection, sterilisation and medical therapy heralds a new era in the constant fight against diseases – and that it was made possible (in our case) by the transfer of know-how and technology from space experiments performed on the ISS. It also demonstrates that very real benefits and progress may derive from basic research from some very unexpected directions. And that sometimes it may arrive faster than we think.

Acknowledgements

This work was funded by DLR/BMWi (FKZs 50WM9852, 50WM0203 and 50WP0708), ESA and the Max-Planck Society.

We wish to thank our Russian colleagues from RAS-JIHT in Moscow, in particular Prof. Vladimir Fortov, and the astro/cosmonauts for the excellent partnership in this research.

For references to publications and details see also www.mpe.mpg.de/theory/plasma-crystal and www.mpe.mpg.de/theory/plasma-med.

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