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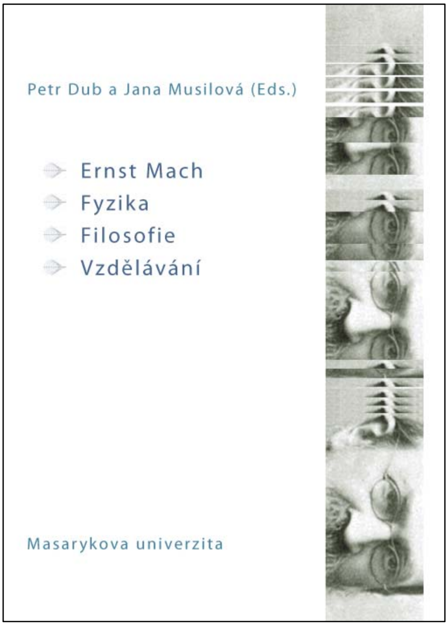
THE ERNST-MACH-INSTITUT: PRESENT FIELDS OF RESEARCH CONTINUATION OF MACH'S SHOCK WAVE INVESTIGATIONS

The present research program of the Ernst-Mach-Institut is presented. The Institute is one of 58 institutes of the Fraunhofer-Gesellschaft, all of which are working in fields of applied research. It was founded in 1959 by Hubert Schardin, a famous physicist working in fluid dynamics and ballistics. The institute's name was chosen in honour of the great achievements and merits in physics of Ernst Mach, especially in the fields of shock waves in air and high speed photography. It is presented how these topics have been further investigated for many years. Shock wave studies have also been extended for solid materials by means of special acceleration techniques. The main tools for this purpose are a variety of light gas guns - their operation principle is explained - forming a unique research facility in Europe. Respective masses of milligrams up to many kilograms can be accelerated from m/s up to 10 km/s. The main applications for this technology are the following: Experimental space debris simulation for spacecraft protection; Simulation of natural high-speed impact phenomena; Ballistic missile defence tests; Terminal ballistic research. Other fields of work at the institute are the following: Dynamic material testing at very high deformation rates; Detonics; Development of high-speed visualization and testing equipment; Development of numerical simulation methods and material models; Security research. A fundamental working principle of the institute is doing both numerical and experimental studies in combination, whenever possible.



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The Institute – Founding, Funding, and Organisation

The Ernst-Mach-Institut (Fraunhofer-Institut für Kurzzeitdynamik, EMI) was founded in the year 1959 by Hubert Schardin as one of the early few institutes of the Fraunhofer-Gesellschaft. Schardin was well known for his aerodynamic and ballistics investigations. The institute was given its name in honor of Ernst Mach.

The Fraunhofer-Gesellschaft had started to work in various fields of applied research, funded by the German federal and state governments, as well as by industrial companies. At present, the Fraunhofer-Gesellschaft runs 56 applied research institutes distributed all over Germany (see Fig. 1), with an annual budget of 1.3 billion €. Individual institutes cooperate in so-called Fraunhofer Alliances (see Fig. 2).

Figure 1: Local distribution of Fraunhofer Institutes.

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The Ernst-Mach-Institut (EMI) has presently a staff of about 240 employees, with 60 scientists and 180 technical and administrative personnel. The annual budget in 2007 was about 18 million €.

Ernst Mach – Continuation of his Shock Wave Investigations

As presented in Fig. 3, the mathematical, scientific, and philosophical (positivism) interests of Ernst Mach were numerous and interdisciplinary.

One of his great merits was the investigation and first visualization of shock waves in air. As a prominent example, Fig. 4 shows a Schlieren photo of a hypervelocity projectile with a head wave. Mach applied fast optical methods like discharge flashes of simple capacitors (e.g. Leidener Flasche) to photograph such events [1]. His major contributions to gas dynamics are summarized in this figure. Since then, terms like Mach Wave, Mach Number, Mach Reflection etc. have been well known.

Numerous original materials of Ernst Mach like photo plates, notebooks, and letters have been in the possession of the Ernst-Mach-Institut. As an example, Fig. 5 shows a letter of Albert Einstein to Mach. For conservation reasons, all these documents were handed over to the Deutsche Museum, München, in the year 1997.

At the institute, shock wave investigations initiated by Mach have been continued for many years studying shock wave propagation and reflection under numerous geometric conditions. Fig. 6 shows a shock wave at a slope with well developed reflected wave and Mach stem. Many studies have been performed in order to simulate shock wave behavior

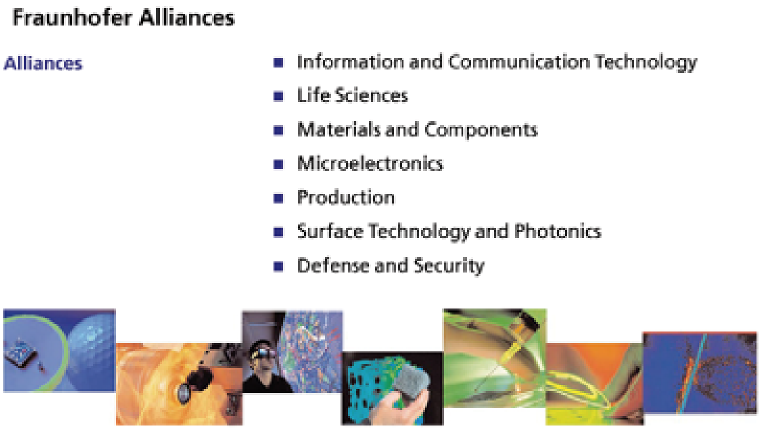


Figure 2: Work areas of Fraunhofer Alliances.

during all kinds of explosions including nuclear events. Schlieren-, Color-Schlieren- and Interferometer-Techniques have been applied for recording [2]. Figs. 7 and 8 show wave patterns recorded by means of a Mach-Zehnder-Interferometer. Fig. 9 shows a Schlieren record of a wave passing a vertical wall in front of a building. The result of a numerical simulation of this process has been superposed in colors [3].

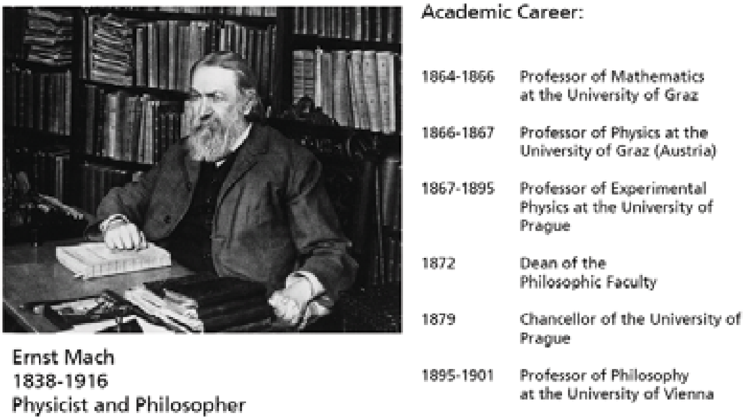


Figure 3: The variety of Mach's interests and academic activities.

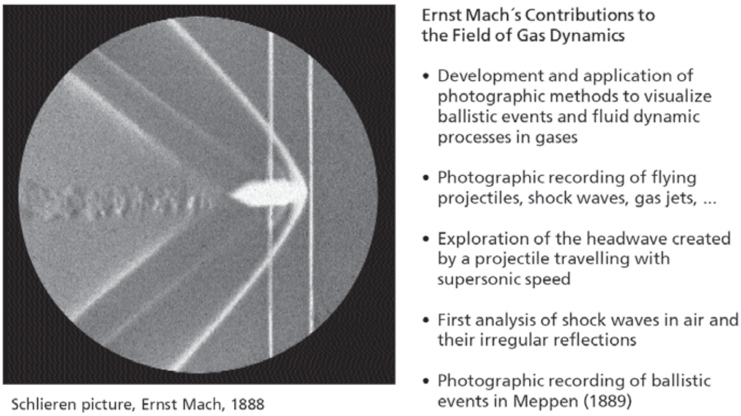
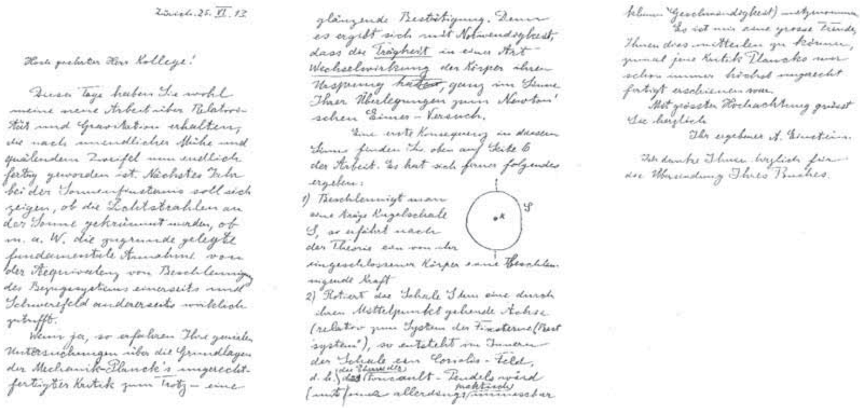


Figure 4: One of the first Schlieren photographic records of a shock wave in air.



Zürich. 25. VI. 13.

Hoch geehrter Herr Kollege!

Dieser Tage haben Sie wohl meine neue Arbeit über Relativität und Gravitation erhalten, die nach unendlicher Mühe und quälendem Zweifel nun endlich fertig geworden ist. Nächstes Jahr bei der Sonnenfinsternis soll sich zeigen, ob die Lichtstrahlen an der Sonne gekrümmt werden, ob m. a. W. die zugrunde gelegte fundamentale Annahme von der Aequivalenz von Beschleunigung des Bezugssystems einerseits und Schwerefeld andererseits wirklich zutrifft.

Wenn ja, so erfahren Ihre genialen Untersuchungen über die Grundlagen der Mechanik – Planck's ungerechtfertigter Kritik zum Trotz – eine glänzende Bestätigung. Denn es ergibt sich mit Notwendigkeit, dass die Trägheit in einer Art Wechselwirkung der Körper ihren Ursprung habe, ganz im Sinne Ihrer Überlegungen zum Newton'schen Eimer-Versuch.

Eine erste Konsequenz in diesem Sinne finden Sie oben auf Seite 6 der Arbeit. Es hat sich ferner folgendes ergeben:

1) Beschleunigt man eine träge Kugelschale S, so erfährt nach der Theorie ein von ihr eingeschlossener Körper eine beschleunigende Kraft.

2) Rotiert die Schale S um eine durch ihren Mittelpunkt gehende Achse (relativ zum System der Fixsterne („Restsystem")), so entsteht im Innern der Schale ein Coriolis-Feld, d. h. die Schwingungsebene des Foucault-Pendels wird (mit freilich allerdings praktisch unmessbar kleiner Geschwindigkeit) mitgenommen.

Es ist mir eine grosse Freude, Ihnen dies mitteilen zu können, zumal jene Kritik Plancks mir schon immer höchst ungerechtfertigt erschienen war.

Mit grösster Hochachtung grüsst Sie herzlich

Ihr ergebener A. Einstein.

Ich danke Ihnen herzlich für die Übersendung Ihres Buches.

Figure 5: Copy of an original letter of A. Einstein to E. Mach.

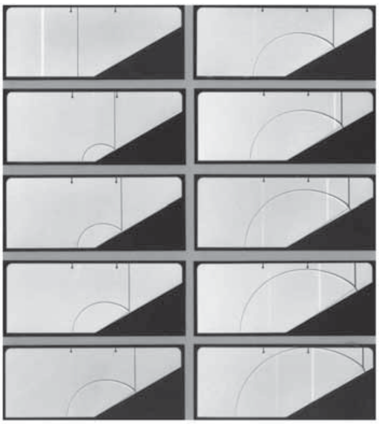


Figure 6: Shock wave reflection with Mach stem.

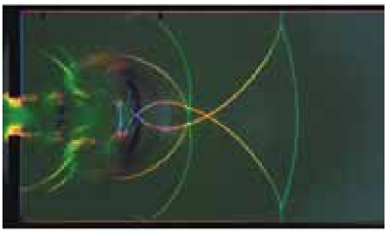


Figure 7: Color Schlieren interferogram of a shock wave behind an aperture.

Figure 8: Color Schlieren interferogram of shock wave diffraction at a sharp edge.

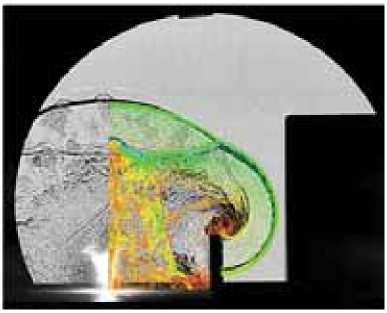


Figure 9: Air shock passing a vertical wall (experimental and numerical simulation).

Shock Waves in Solid Matter

Shock wave investigations have also been extended to the study of shock effects in solid matter.

There are essentially two possibilities to produce shock waves in solids:

- Detonation of explosives
- Impact of hypervelocity particles or projectiles

Both methods have been applied at the EMI.

Concerning the impact method, it may be necessary to explain the operation principle [4] of light gas guns (see Fig. 10): A given mass of gun propellant is initiated in a powder chamber. The propellant drives a polyethylene piston which compresses the given mass of a light gas (He or H_2) within a so-called pump tube up to several thousand bar. At a pre-determined terminal pressure, a steel diaphragm at the end of the pump tube opens and the highly compressed and heated gas can expand into a launch tube where a projectile, housed in a sabot of polycarbonate is accelerated. Velocities up to $10\ \mathrm{km.s^{-1}}$ and even higher can be achieved depending on the projectile mass [5]. The effectiveness of this method is based on the high expansion velocity a gas with low molecular weight will achieve at a given total energy.

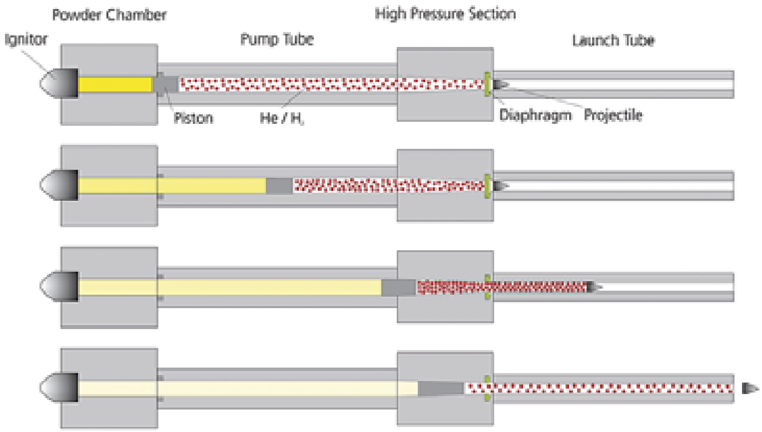


Figure 10: Operation principle of a light gas gun.

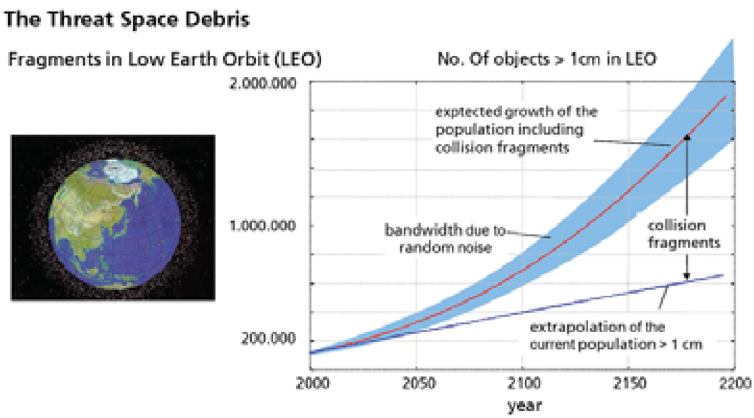


Figure 11: Development of the near earth space debris population.

Experimental Space Debris Simulation for Spacecraft Protection

Space debris impact has become a serious hazard for space flight, which is orders of magnitude higher than the natural micrometeoroid hazard. As shown in Fig. 11, the debris

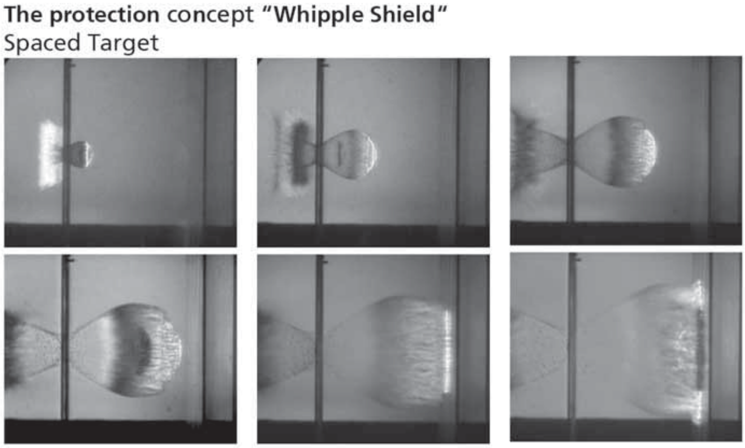


Figure 12: Demonstration of the „Whipple“ shielding principle.

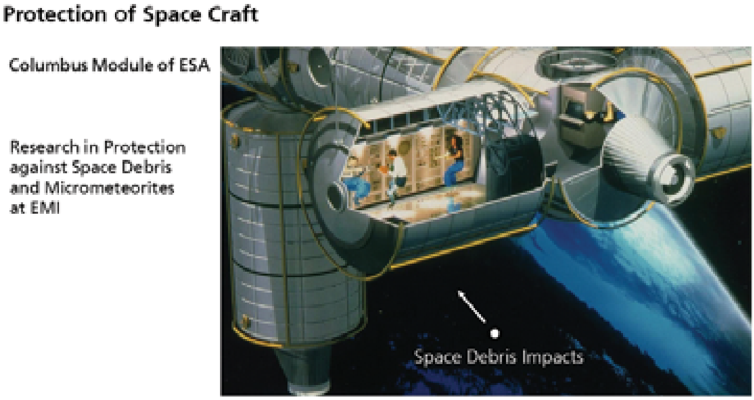


Figure 13: Columbus Module attached to the International Space Station ISS (artist's view).

population is exponentially growing due to increasing numbers of spacecraft launches and in-space collision and fragmentation processes. There exist already special orbits which are contaminated to such an extent that spacecraft (shuttles, ISS) have to fly escape maneuvres. Possible spacecrafts, especially manned spacecrafts, are protected nowadays by shield systems. Essentially, these protection systems take advantage of the so-called Whipple principle which is demonstrated by means of a laboratory impact experiment (Fig. 12). A hypervelocity particle hits a thin front plate and perforates it. Due to a strong shock wave produced during this process, the incoming particle will be finely fragmented, respectively vaporized. The fragment/vapor cloud behind the front plate can propagate and expand due to a certain spacing between front plate (shield) and spacecraft wall. Thus, the energy capturing is spread over a large area of the spacecraft wall and the fragment/vapor cloud cannot perforate it any more. This principle has also been applied for the Columbus module of the ESA (Fig. 13) [6].

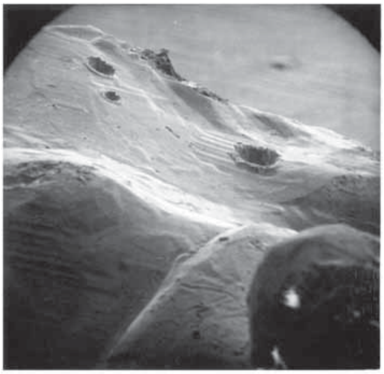


Figure 14: Microcraters on a lunar Fe-Ni sample from the Apollo 16 mission.

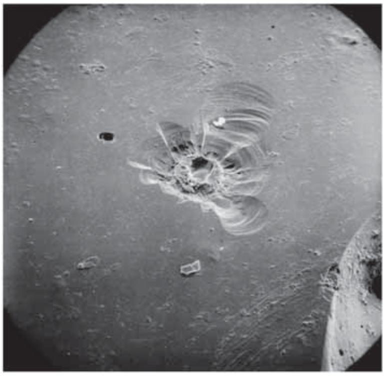


Figure 15: Microcrater on a lunar glass sample from the Apollo 16 mission.

Simulation of Natural Impact Phenomena

Fig. 14 shows a Fe-Ni particle found in lunar dust of an Apollo 16 sample, which was exposed at the lunar surface for geologic times and therefore displays small meteorite impact craters. Fig. 15 shows a similar impact in a lunar glass sample, also found in Apollo 16 dust. The crater cross section of Fig. 16 demonstrates how well such phenomena can be simulated in the laboratory. Notice the typical hypervelocity crater rim and the molten material inside the crater interior. It also displays a shock wave reflection effect at the bottom of the Al target (spallation).

Another prominent shock wave structure is shown in Fig. 17. It is a so-called shatter cone coming from the Steinheimer Becken. Such structures are predominantly found in limestone and sandstone layers of terrestrial impact craters. Also these structures could be nicely simulated in the hypervelocity laboratory. Fig. 18 shows such a laboratory shatter cone made by impacting a 1.5 mm diameter Fe sphere at about $4\ \mathrm{km.s^{-1}}$ into a limestone target. Impact craters on a terrestrial scale (see Fig. 19) are simulated applying numerical methods (Fig. 20) [7].

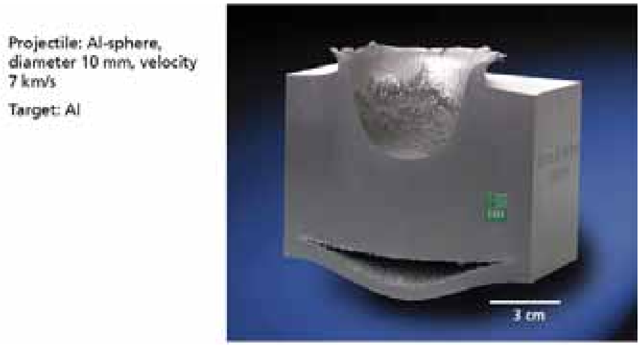


Figure 16: Demonstration of an experimental hypervelocity impact in metal.

Figure 17: Natural „shatter cone" coming from the Steinheimer Becken, Germany.

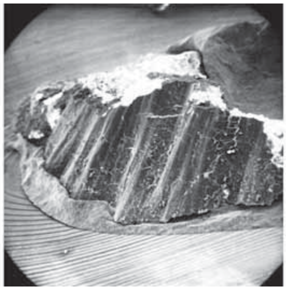


Figure 18: Experimental impact induced shatter cone in a limestone target.

Figure 19: Barringer Crater near Flagstaff, Arizona.

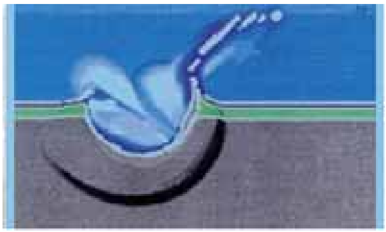


Figure 20: Numerical simulation of a large scale impact.

Ballistic Missile Defense Tests and Terminal Ballistic Research

An important method of defending against ballistic missiles (TBM) is to fire interceptor vehicles which hit and destroy missile warheads (direct hit). Fig. 21 demonstrates a model scale impact of an interceptor projectile into a model warhead experimentally and numerically. By means of such experiments and numerical simulations, destroy mechanisms, e.g. in this case the amount of disabled sub-munitions can be studied quantitatively [e.g. 8].

Fig. 22 summarizes extensive experimental work which has been performed at the institute in the field of armor protection against ballistic threats [9].

Dynamic Material Testing, Modeling, and Numerical Simulation [10]

Dynamic material testing up to highest strain rates is performed by means of methods and devices indicated in Fig. 23. Especially Taylor and planar impact test methods are applied to gain dynamic material parameters during extremely fast deformations. Fig. 24 shows that multi-scale material behavior within atomic/molecular dimensions up to macroscopic mechanical properties results in respectively different material models.

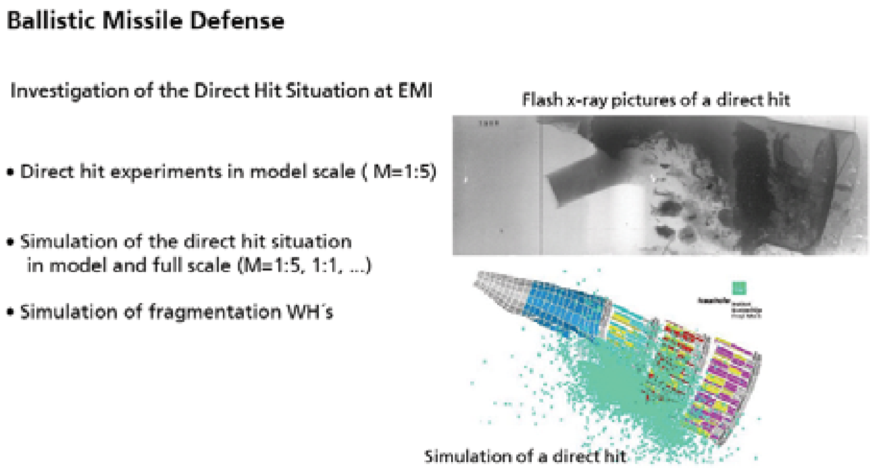


Figure 21: TBM defense: Impact of a model interceptor into a model warhead.

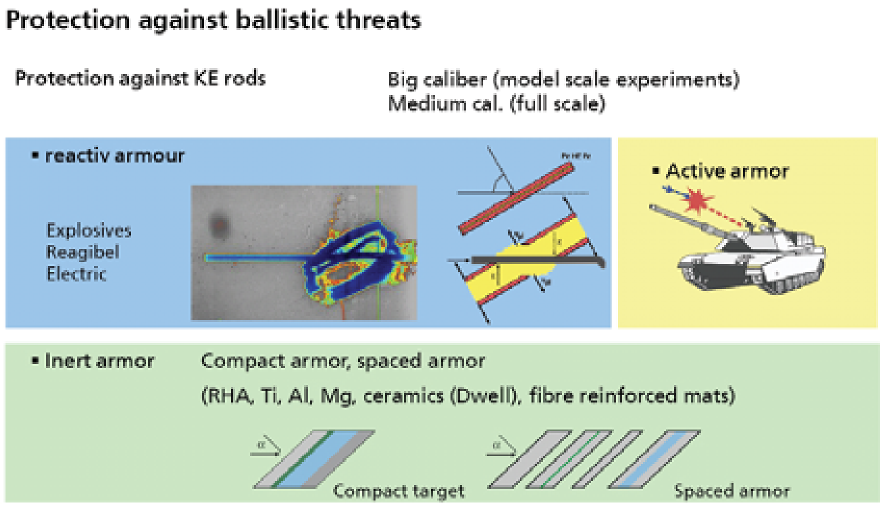


Figure 22: Protection of armor against rod projectiles.

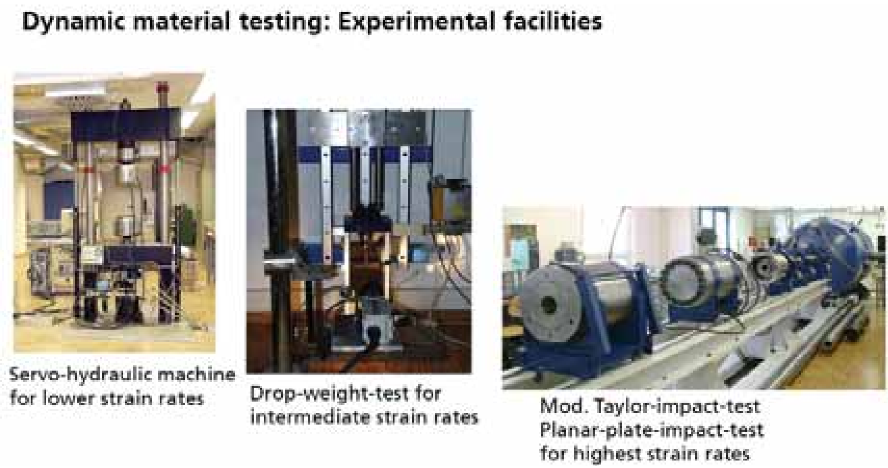


Figure 23: Dynamic material testing: Testing machines and methods.

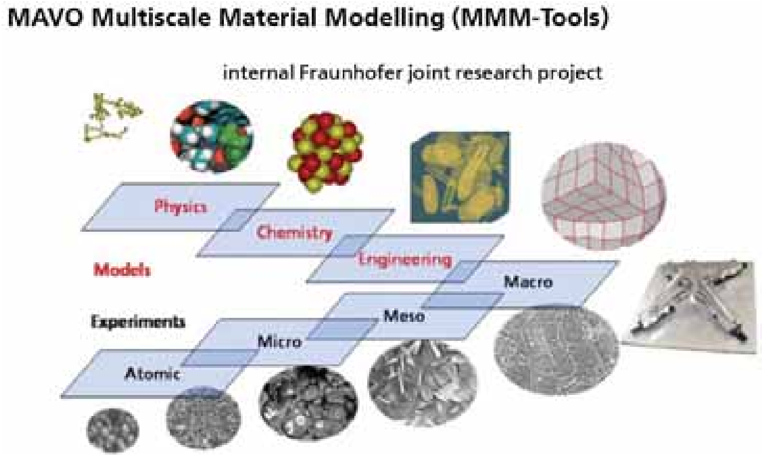


Figure 24: Multi-scale material modeling.

Numerical simulation codes applied at EMI are presented in Fig. 25. Depending on respective physical events commercial and in-house developed codes (e.g. „Sophia“) are applied. Fig. 26 shows a prominent example of excellent correspondence between experiment and numerical simulation. It is a hypervelocity impact of fragments into an arrangement of canisters, as they could be considered as sub-munitions of a rocket warhead. The upper picture series shows a numerical simulation result of the lower flash X-ray photo sequence of the impact process.

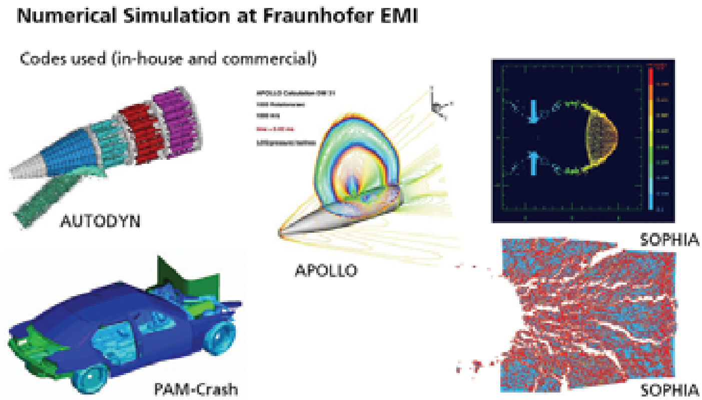


Figure 25: Numerical simulation tools available at EMI.

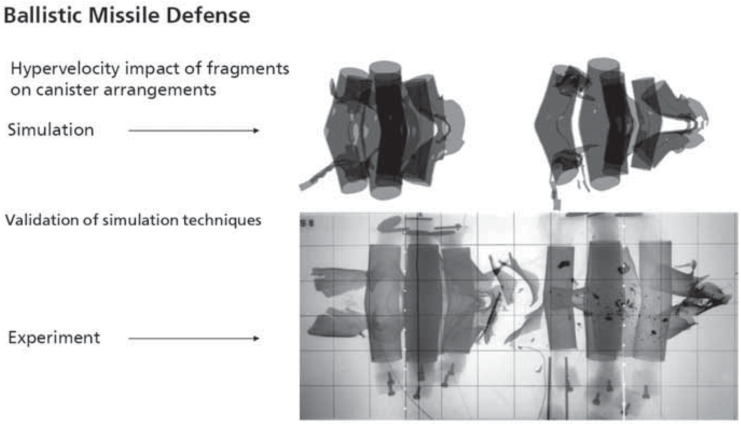


Figure 26: TBM defense: fragment impact into submunition vessels.

Development of Special Test Equipment and Security Research

In-house development of testing and measurement devices, generally not commercially available, constitutes another important field of work of the Institute.

Some recent examples:

- A recording system consisting of a multi-flash-X-ray channel system allows a $3-\mathrm{D}$ observation of physical processes outside and inside structures under extreme loading and deformation/fragmentation conditions by means of flash-X-ray cine-tomography (Fig. 27) [11].
- A so-called „g-Rec" high-acceleration recording system has been developed to measure extreme deceleration levels, e.g. within projectiles during penetration processes, at high time resolution up to 80 000 g.
- A special water tank system has been developed and equipped with recording devices to study supercavitation phenomena at high time resolution. For example, Fig. 28 shows the record sequence of a supercavitation projectile.

The field of security research at EMI has been recently promoted and extended due to considerable activities of the „Fraunhofer Defense and Security Alliance", responding to strong emphasis and impulses from German and European government institutions. Among various other topics, building security, traffic, terrorism threats, catastrophes etc. belong to the broad spectrum of up-to-date security science and technology.

Long-term research projects at EMI in the fields of ammunition storage (e.g. ESQRA = Explosives Safety Quantitative Risk Assessment) [12], studies of detonation processes, shock wave and pressure propagation, provide an ideal data base to join new research programs in this important field of work.

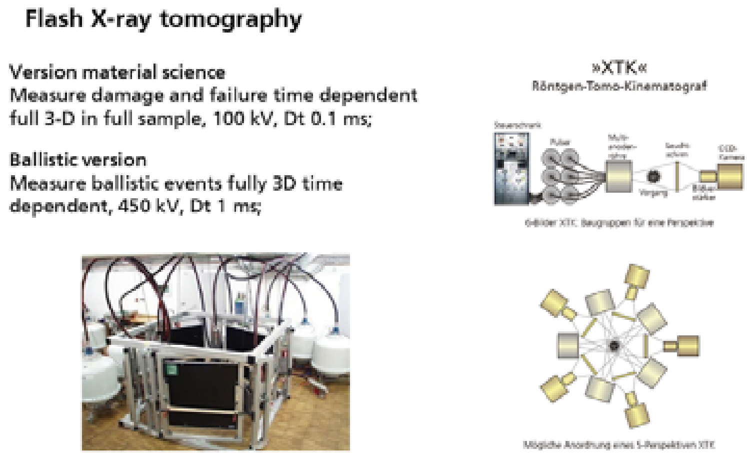


Figure 27: Arrangement for flash X-ray cine-tomographic methods.

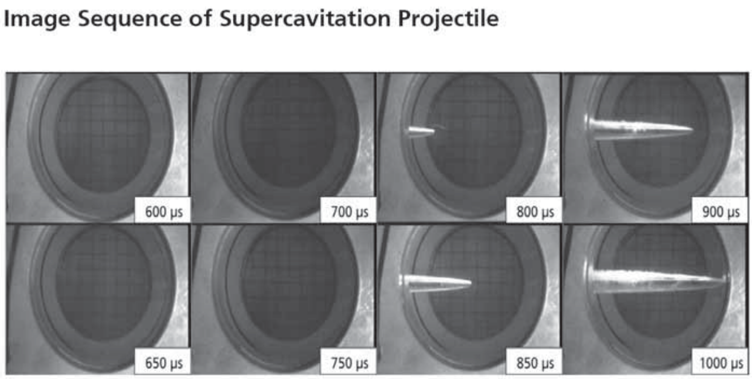


Figure 28: Supercavitation record of a fast projectile in water.

Conclusion

Present activities of the Ernst-Mach-Institut, Freiburg, Germany, have been presented. The Institute's research activities go back to and are based on early investigations of shock wave processes by Ernst Mach. They have been continued and extended. Various other fields of work, e.g. in impact physics, material testing and modeling, security research and others, have developed in the course of the institute's history.

The heritage of Ernst Mach consisting of many original photos, correspondence, notes, drawings etc. had been collected and taken care of by the institute for many years, and for reasons of preservation and maintenance has been transferred to the Deutsche Museum, München, in the year 1997.

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