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ACOUSTICS IN GÖTTINGEN: RESEARCH AT THE DRITTES PHYSIKALISCHES INSTITUT DURING THE 20TH CENTURY (AND BEYOND)

Robert Mettin* **Werner Lauterborn**
Drittes Physikalisches Institut
Georg August University Göttingen
Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

ABSTRACT

After its foundation in 1947, the Third Institute of Physics (Drittes Physikalisches Institut) at the University of Göttingen soon became one of the main centers of acoustics research in Germany, and also in Europe and possibly the world. This advancement was strongly connected with the personalities of Erwin Meyer, the founding director, and his successors, Manfred R. Schroeder and Werner Lauterborn. But also the variety, broad interest and interaction of all research groups at the Institute contributed to a special, cooperative and very fruitful atmosphere at the “Drittes”. Here, we very briefly review some scientific topics and important achievements at the Institute until the turn of the millennium, referring to general and physical acoustics, room and concert hall acoustics, underwater sound, and ultrasound and cavitation. The latter subjects are described in more detail to highlight the very early, but partly not well-known, fundamental and seminal works that had been conducted in Göttingen, already paving the way to important applications and actual research until today.

Keywords: *acoustics research history, room acoustics, ultrasound, cavitation bubble dynamics, sonoluminescence*

1. INTRODUCTION

The ”Drittes Physikalisches Institut” (DPI) was founded in 1947 at the University of Göttingen by uniting the ”Institut für Angewandte Elektrizität” (Applied Electricity) and the ”Institut für Angewandte Mathematik und Mechanik” (Applied Mathematics and Mechanics). Both had been established in 1889, following an initiative of the famous mathematician Felix Klein, to install applied research in Göttingen on a sound base. While the very roots of the ”Drittes” lie in the applied sciences, the future should as well bring essential fundamental insights — primarily in acoustics, but also in optics, microwaves, and nonlinear dynamics. The variety of the Institute’s research spectrum was well described in German by the former adjunct ”Schwingungsphysik”, which might be best translated to English by ”oscillation and wave physics”.

Figure 1. The Institute building at Bürgerstraße 42 in Göttingen around the year 2000.

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*__*Corresponding author*__: robert.mettin@phys.uni-goettingen.de.

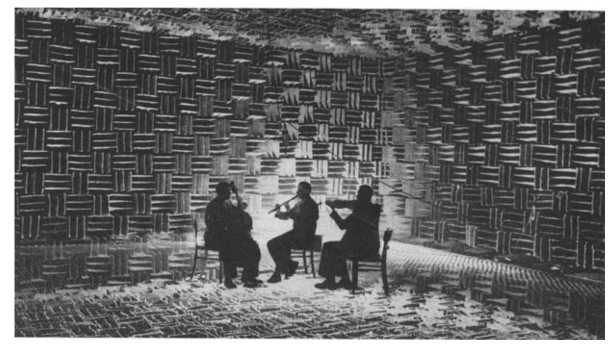

Figure 2. Anechoic room at DPI: inner dimensions of $5.5 \times 10 \times 14\,\mathrm{m}^3$, and anechoic for acoustic waves above 70 Hz and for electromagnetic waves.

Most of the topics under study at the Institute were already pursued under Erwin Meyer, the founding director. He had a strong standing in applied and technical acoustics, electroacoustics, underwater sound, building acoustics, room and concert hall acoustics, but also started early research in ultrasound and cavitation. His successor as director in 1969, Manfred R. Schroeder, pursued room acoustics and added a focus on hearing and speech acoustics, coding and digital signal processing. This came along with applications of mathematics like number theory and fractals, and with the employment of computers. Werner Lauterborn became the third director in 1994. He further reinforced the use of scientific computing and established coherent optics and nonlinear dynamics in the Institute's profile. He was and still is very active in acoustic and optic cavitation, and this line of research led to pioneering works in laser science, high-speed photography and high-speed holography, as well as in chaotic systems. All directors were open to quite a variation of topics, and the Institute's research till and around the millennium is not sufficiently described without the contributions of many other groups and names being active in acoustics and further fields. Notably, room acoustics, acoustic cavitation and sonoluminescence (Kuttruff), ultrasound and microwave spectroscopy (Pottel, Kaatze), acoustics in rarefied gases (Sessler), aeroacoustics (Mechel, Ronneberger), underwater sound, absorbers and active noise control (Wille, Guicking), hearing research and psychoacoustics (Strube, Kollmeier, Kohlrausch) and nonlinear systems (Kurz, Parlitz, Holzfuss, Mettin) have been pursued deeply. Further areas of study comprised low temperature physics, hypersound and phonon research, as well as organic semiconductors (Helberg, Eisenmenger).

In the following we will sketch some important works and results of the broad spectrum of acoustics research at the Drittes. Due to the format of this article, this can be done only very briefly and by no means in completeness. For more details, we refer the reader to other sources, where the scientific history and activities at DPI have been portrayed quite elaborately. Namely, we recommend Dieter Guicking's book on Erwin Meyer [1], the Festschrift to the Institute's 60th anniversary [2], the Memorial Volume in Honor of Manfred R. Schroeder [3] and the book chapter "Erwin Meyer – Akustik in Göttingen" by Peter Költzsch [4].

2. GENERAL, PHYSICAL AND TECHNICAL ACOUSTICS

Erwin Meyer's interest and research was very broad, and thus nearly all aspects of acoustics were touched by his work. A consequent expression of this was his suggestion and co-foundation of the "European" acoustics journal *Acustica* in 1951. He served as the German editor the rest of his life, and this journal became a main channel of dissemination of the scientific results from the Institute until the 1990s, and partly till today.[1] Many earlier articles had been written in German, which was quite customary at that times, but this possibly hindered a wider spread and international recognition of several seminal works.
Later, Meyer condensed his deep general and practical knowledge together with Ernst-Georg Neumann into the textbook *Physikalische und technische Akustik* (or just the "Meyer-Neumann") [5] that should become a long-term standard in Germany (and via translation to English as well abroad). Another standard was set by the textbook *Schwingungslehre*, written by Meyer and Dieter Guicking [6]. It was also by these (and other) books how the DPI coined the German acoustics community.

To have access to modern research facilities, the institute building near the city center of Göttingen (Fig. 1) was soon extended. The first installation was an emblematic anechoic chamber of quite large dimensions, suitable for sound as well as electromagnetic radiation, see Fig. 2 [7]. Its walls and also the floor (below a metallic net to walk upon) were equipped with large wedges of porous material (glass-wool) as absorbers, a common technique nowadays. The wedges had been made ab-

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[1] Later, the journal was merged to become *Acta Acustica united with Acustica* and now continues as *Acta Acustica*.

sorbant to electromagnetic waves by graphite powder. The room served for a variety of measurements, ranging from sound source characterization to hearing research and psychological acoustics.

Another unique facility was added a few years later: a reverberation room, again suitable for acoustic and electromagnetic waves due to a copper foil on the walls, floor and ceiling [8]. Figure 3 shows the interior of the room that had inclined corners, equipped with additional reflectors to generate a diffuse sound field, suitable for instance for absorbance measurements of materials.

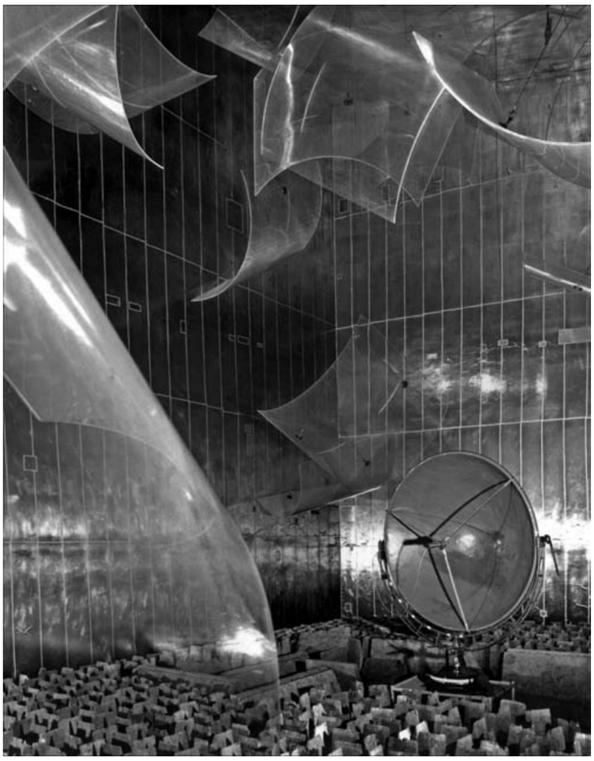

Figure 3. Reverberant room at DPI: volume of 342 m^3, acoustical reverberation times of 33 s at 100 Hz and 13 s at 1000 Hz. The floor is covered here by some tested absorbing material.

Further installations were a deep water tank (see below), a nitrogen liquefier and a high vacuum coating plant. The latter two served to support research of hypersound and phonons in solids by Wolfgang Eisenmenger and coworkers [9]. Eisenmenger also constructed a new underwater shock wave generator based on an electromagnetic principle [10], nowadays used in lithotripter machines. He designed new pressure sensors and determined front thicknesses of shock waves in water and other liquids [11]. For more information on the many works on measurement techniques and metrology at DPI, as well as on electroacoustics, musical acoustics and building acoustics, we refer to [1–4].

3. ROOM AND CONCERT HALL ACOUSTICS

After ample studies on reflectors an diffusers for the improvement of acoustic quality in rooms by Meyer [12], directional diffusivity of the sound field came into focus as a quality measure [13], apart from the reverberation time alone. Figure 3 shows such a directional measurement, performed with a parabolic reflector microphone. It turned out that the clearness of the auditory impression was further determined by the early reflections, and in particular from the side, as later also measured by M. R. Schroeder [14]. Schroeder had already developed in 1954 the statistical theory of reverberant sound fields in rooms, identifying a limit frequency beyond which the acoustic modes overlap and thus can be described in a statistical way [15, 16] – nowadays known as the *Schroeder frequency*. Major studies on concert hall acoustics were conducted by Meyer, Kuttruff, Schroeder and coworkers, and they coined many findings and techniques in room acoustics (e.g., the *Schroeder curve* or *Schroeder reflectors*). For the long-term impact of these studies, see [1,3]).

4. UNDERWATER SOUND

The Institute housed a larger deep water tank where underwater sound experiments were conducted [17]. The basin was equipped with absorbing walls which allowed for measurements of backscatter from objects. Again, absorbing materials were investigated, here for underwater sound — a branch of Meyer‘s research actually dating back to the time before and during WW II. Among many other projects, it was investigated how flat plates radiate sound into water, i.e., how ships radiate sound. Further, it was successfully attempted to discriminate between sonar backscatter signals from metallic objects and those of stone. For this purpose, also simple artificial neural networks had been employed, a pioneering step at the beginning of the 1990s. For a quite detailed list of the underwater sound studies, we refer to [1] and the according chapter by D. Guicking in [3].

Figure 4. Deep water tank of $7 \times 4 \times 4\, m^3$ for measurements with waterborne sound. The walls of this basin were coated with absorbers effective in the frequency range from 5 to 70 kHz.

5. ULTRASOUND AND CAVITATION

It is impressive to see the early groundbreaking works on ultrasound in liquids and acoustic cavitation, even on sonoluminescence, at Meyer's institute in the 1950s and 1960s. Further seminal studies followed in the later decades until the millenium and beyond, establishing cross-links to fluid dynamics, optics, scientific computing, nonlinear dynamics, and chemistry. The line of cavitation research at DPI is still very active, representing today the inheritance of the Institute's great past in acoustics.

5.1 Cavitation spectra and cleaning

In 1953, Meyer and Skudrzyk [18] studied the sound propagation in bubbly liquids theoretically and experimentally in the ultrasonic regime, and they found quite good agreement for the damping. Already before, Esche had investigated the nowadays well-known acoustic emission spectra of ultrasonic cavitation in a seminal paper [19]. He covered an impressive range of frequencies from 3 kHz to 3.3 MHz and noted in particular the subharmonic of the driving frequency, along with broadband noise, as a characteristic of cavitation emissions. Further, he measured the steep rise of the cavitation inception threshold with frequency, and his data is still actual as a reference. Further theoretical and experimental analysis of acoustic cavitation emission spectra was done by Bohn in 1957 [20]. He discusses in detail the possible origin of broadband noise and concludes that high pressure peaks from bubble implosions are the main source under intense cavitation conditions. As well in 1957, Olaf published an elaborate experimental study of ultrasonic cleaning [21], again for a wide range of frequencies (15 kHz to 2.5 MHz). His results clearly showed for the first time that cavitation is the main agent of the cleaning process, which had only been suspected before: static overpressure could suppress cavitation and at the same time all cleaning effects.

5.2 Bubble collapse: high-speed imaging and simulations

Already in the 1950s, high speed photography was applied to follow the collapse of vapour and cavitation bubbles [22, 23]. The optic and photographic techniques had been developed in the Institute and were at highest standard, reaching 105 000 frames per second with exposure times below 100 ns. The illumination by a sophisticated electric spark method allowed for the imaging of shock waves from collapsing bubbles and bubble clouds. These were as well analysed by fast hydrophones, also constructed and manufactured in-house [24, 25]. Over the years, the frame rates to study cavitation bubbles have been increased up to finally 100 million frames per second [26], elucidating fine details of the amazingly fast and complex process of bubble collapse, see Fig. 5.

As acoustic cavitation bubbles are distributed over three-dimensional volumes, also holography has been applied for recording [27] and extended to high-speed holocinematography with up to 300 000 holograms per second [28–30]. Holograms have been fed into computers to get the 3D size and space distribution. Also stereoscopic recordings of cavitation bubble clouds have been done for getting 3D images of the cloud [31]. A survey has been given in [32].

Today, high-speed imaging is much more common

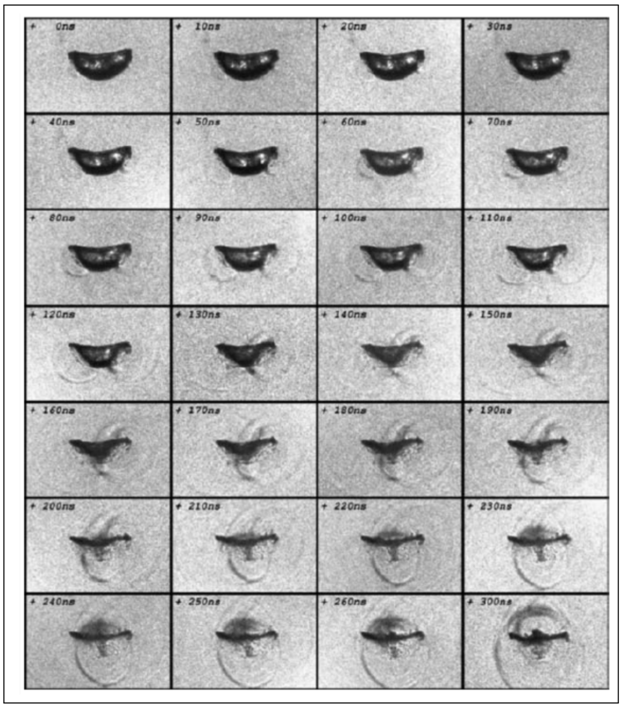

Figure 5. High-speed recording of the final stage of a jetting bubble collapse with its complex sequence of shock waves. The bubble is close to a solid boundary (to the bottom, not visible). Exposure time and framing interval 10 ns. From [26], Copyright Cambridge University Press, 2003.

and a standard technique in cavitation science, forming an important backbone of the research. However, the ever advancing computational resources have established numerical simulations as a second important tool which is quite rapidly growing, both in extension and in potential. At DPI, numerical calculations have been done since the 1960s, still under Erwin Meyer. With respect to sonoluminescence, Kuttruff was calculating collapse pressures and temperatures of collapsing bubbles [33] in 1962, and Strube calculated in an impressive work the shape stability of spherical bubbles and excitation of surface modes in 1971 [34]. Lauterborn added the nonlinear resonance curves of driven bubbles ([35], see below). Since then, bubble and collapse simulations became more and more extended and refined, further surpassing the reproduction of high-speed observations and making predictions of the unresolved and yet unseen. For instance, elaborate Molecular Dynamics simulations have explored the structure of the extremely heated interior and sonoluminescence of an imploding bubble [36], or expensive CFD studies for bubbles collapsing at solids have predicted new jetting modalities with jet speeds in the range of 1000 m/s [37], later also seen in experiments at DPI and at other groups.

5.3 Optic cavitation

In the course of adding coherent optics to the research topics at DPI, Lauterborn, his scholar Vogel, and coworkers investigated the focusing of intense laser pulses in liquids [38]. Once the electrical breakdown threshold is crossed, a hot plasma spot is created, and a bubble expands which subsequently collapses. This phenomenon, termed optic cavitation, served subsequently as an ideal tool for cavitation studies and allowed for detailed investigation of bubble jetting [39] and further collapse dynamics [40], shock wave emissions [41], or material damage [42]. Optic cavitation is nowadays a standard technique, and the early and seminal contributions at DPI opened up the path to many important applications of lasers far beyond acoustics, for instance in eye surgery and material processing.

5.4 Nonlinear Dynamics

For several reasons, the investigation of acoustic cavitation provoked the preoccupation with nonlinear systems. One side was the sound propagation of finite amplitude waves in liquids and in particular under presence of bubbles [18]. But at the heart of cavitation lies the dynamics of bubbles which is intrinsically nonlinear. In 1956, Güth published an analytic approach to the nonlinear oscillations of harmonically driven spherical bubbles [43]. He demonstrated that subharmonic solutions exist if the bubbles are driven above (linear) resonance, as known for other nonlinear driven oscillators, and he suggested such solutions as a source of the subharmonic components in acoustic cavitation spectra. The numerical approach by Lauterborn from 1973, finally published in 1976, highlighted the richness of possible dynamics of strongly driven bubbles [35]. Among nonlinear resonances and hysteresis, the study showed that also bubbles driven below the linear resonance can oscillate at higher periods. This can happen near ultraharmonic resonances, a case much more commonly met in acoustic cavitation. Furthermore, indications for chaotic (non-periodic) solutions had been given. These have been later confirmed and much more elaborated in the framework of bifurcation analysis, for instance by Parlitz [44]. This stimulated many more fundamental investigations of nonlinear systems at DPI, extending on different and coupled nonlinear oscillators, but also on methods for nonlinear system analysis, time series prediction, synchronization, and more.

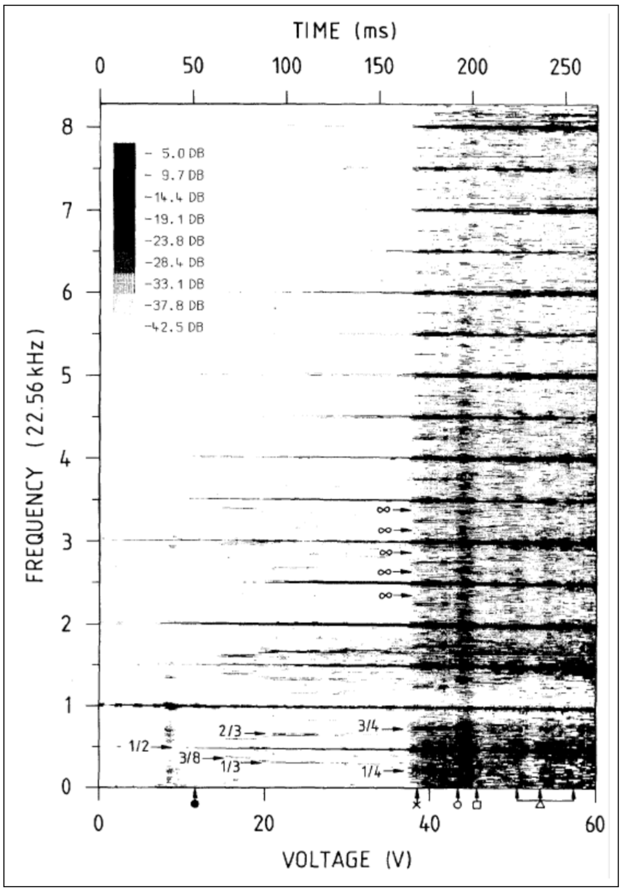

Figure 6. Spectral bifurcation diagram: The driving voltage of the transducer is linearly increased from 0 to 60 V in 256 ms. From [45]. Copyright: American Physical Society, 1981.

Experimentally, the subharmonic cavitation spectra and the according bubble oscillations had been investigated by Lauterborn and coworkers more closely. Employing an upward ramping of the driving pressure, a period doubling cascade could be identified [45] as shown in Fig. 6. This lead to the conjecture of chaotic dynamics in developed acoustic cavitation, one form of ”acoustic chaos” or ”acoustic turbulence”. Imaging of the bubbles revealed that full bubble structures can oscillate in a period doubled fashion [46], and it has been confirmed in later studies that indeed a low-dimensional dynamics can be dominant [47]. Today, the topic of acoustic cavitation spectra is still under investigation, one application being the diagnosis of ultrasonic cleaning systems.

5.5 Sonoluminescence

Meyer, Kuttruff and coworkers clarified already end of the 1950s that bubble collapse and sonoluminescence light emission happened synchronously, a fact that was disputed at that times. The correlation was shown first by phase related imaging of bubbles and registration of light [48, 49], later with an ingenious method and much higher precision by coincident measurement of shock waves and light [33]. As origin of the light, the ”hot spot” in the collapsed bubble was correctly advocated and corroborated by these works, but nevertheless, many other theories circulated until the millennium. Quite remarkable are also the experiments by Schmid, who in 1959 observed single bubble collapse luminescence in an arrest tube setup [50]. Later, he investigated the influence of the filling gas on the light emission of imploding hollow glas spheres in different liquids, favouring krypton in glycerine [51]. Research on sonoluminescence continued at DPI and is still active today, investigating many more details and possibly having realised one of Meyer and Kuttruff’s dreams, namely to directly see bubbles collapsing and flashing in an acoustic cavitation bubble field, as shown in Fig. 7 [52].

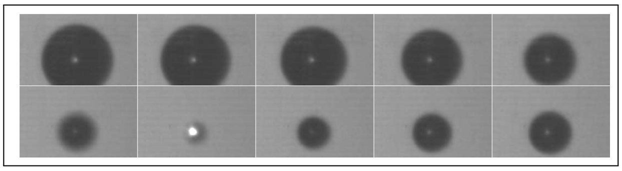

Figure 7. Collapse of a xenon bubble in phosphoric acid, driven at 23 kHz and recorded at 525 kfps. The sonoluminescence flash is seen on the 2$^{\text{nd}}$ frame, bottom row. (Courtesy: C. Cairós; see also [52])

6. CONCLUSIONS

Only a few topics from the vast amount of acoustic work in Göttingen could be addressed. Most of them root in the pioneering works done under the auspices of Erwin Meyer since 1947. It can be rightly stated that his school had a great influence on the acoustics research in Germany, Europe, and possibly worldwide, and it was — and still is — perpetuated by many former DPI scholars in own research groups at other institutions.

7. ACKNOWLEDGEMENTS

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