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What Happened

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Abstract
This is a condensed personal account of what happened in the pursuit of the scientific endeavors of Bernhard Blümich in the past 70 years. It revisits, amends, and extends a contribution written in 2010.

1 Childhood

It happened that I was born 7 years after the end of World War II in Berlin, the former capital of a Germany, which less than 10 years before was the seat of a government that drove the generations of my grandparents to commit inexpressible crime against humanity. When I grew up in West-Berlin, I witnessed the gradual demolition of the WWII ruins and the reconstruction of my city. When I was eight years old, West-Berlin was encircled by a deadly guarded wall, and Europe was split into East and West by the Iron Curtain (Fig. 1). A few years later, we could visit relatives in East-Berlin and East-Germany complying with the rules imposed by the allied states occupying the divided city and the divided country as well as by the two young German states struggling to come to terms with the heritage of their dark past.

I have three siblings, an elder and a younger brother and a younger sister. My father was a safety engineer specializing in industrial steam boilers, and my mother was trained to compute lenses for optical precision instruments as she could not finish high school in wartime Berlin. My grandfather was a chemist, the first scientist in the family, and our family of six first lived in two rooms of my grandparent's stately apartment in the British sector of the city, in one of the few houses in the street that survived the bombs of the war with only minor damage. When I was 6 years old, we moved from there into a small new house in the French Sector in Tegel, where I attended elementary school and high school. My high school was the Humboldt-Gymnasium, where we had good teachers, particularly in my favorite subjects, mathematics, physics, and languages. It carried the name Humboldt, because nearby was the Humboldt residence,

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Fig. 1 The Brandenburger Tor with the wall separating East- and West-Berlin. The sign reads "Attention, you are now leaving West-Berlin"

where the two brothers, Wilhelm and Alexander von Humboldt grew up in the eighteenth century. Only later, once I hosted Alexander-von-Humboldt scholars in my team at RWTH Aachen University, did I learn about their extraordinary impact on the concept of higher education in Germany and science in the period of enlightenment.

I grew up in a forward-looking time, where we had little, and opportunities were ample. My mother was very practically minded, and she kept telling us children: "Was Du heute kannst besorgen, das verschiebe nicht auf morgen" (Do without delay, what you can do today). Following my father's wish, all four siblings had to learn a musical instrument. Since I was the least gifted, it was decided that I should play the piano, because certain progress could be expected just by practicing. But whenever I practiced the piano in the living room, someone had to rearrange whatever had been placed before on top of the piano. This was so disturbing to me that I decided to build an electronic organ from scrap to practice without distraction in my own small attic room. I had help from one of my elder brother's ham-radio friends. But my Physics teacher decided I should compete in the 1972 state competition "Jugend Forscht", a science competition for high-school students, and I somewhat undeservedly ended up winning the first prize in Physics. The same year I began my university studies in Physics, a subject I chose as the most general one matching my interests, because I did not know what else to study. For lack of financial resources I studied at the Technical University in Berlin taking daily 1-hour bus and subway rides from and to home, trying to catch a seat in one of the smoke-free carriages, and reading textbooks on the ride.

2 Stochastic NMR

In my days, education at elementary and high school took a total of 12.5 years to qualify for university studies. After four semesters, one would finish the Vordiplom exams, which were intermediate to the Diplom exams after another 6 to 8 semesters before opting for the employment market or a dissertation to graduate with a

doctoral degree. I had to take an oral examination in Chemistry for Physicists after the third semester in 1973. Dieter Ziessow, a young assistant professor of Chemistry, was my examiner. After the examination he asked me if I were interested in a research project with him. I accepted. He gave me a page with FORTRAN commands, asked me to program solution (c) from the appendix to Torrey's 1949 paper on nutation [1] and advised me to read some chapters from Slichter's book [2]. Dieter Ziessow had converted his Bruker HFX 90 CW spectrometer with a PDP 11/20 computer and a Tektronics screen terminal to a Fourier spectrometer capable of advanced pulsed excitation, a unique setup in those days of CW NMR. Following up on Richard Ernst's and Reinhold Kaiser's papers on NMR with random noise excitation [3, 4], he was interested in implementing maximum length binary sequences for low-power excitation with pseudo-random noise excitation and processing the transverse magnetization response by Hadamard and Fourier transformations to liquid-state NMR spectra. But his spectra were contaminated by inexplicable noise, which with the help of my programming adventures could be identified to result from a clock-synchronization issue. I learned to program the mainframe IBM computer of the university with stacks of cards, and we spent many hours together in the NMR laboratory implementing the mainframe results on the PDP11/20 computer with 16 k core memory of 16-bit words, which operated the spectrometer with home-written software coded in assembler and machine language [5]. The work was published in German in 1974 [6], the same year that Reinhold Kaiser from Fredericton, New Brunswick, published the same methodology in the Journal of Magnetic Resonance [7].

West-Berlin was an island in East Germany enclosed by a wall and barbed wire fences guarded by militia on watch towers, wire-triggered guns, and dogs on long leashes trained to attack humans. Access to the free world was possible by car, train, and airplane through a few confined corridors. For a few summers I was lucky to experience the unconstrained life outside by working as a handyman in the rental bungalows of my friend's parents on the island of Ibiza. But I wanted to see more of the world and applied for a Fulbright scholarship in the USA. This was granted on short notice in the summer of 1974, and I ended up at Rensselaer Polytechnic Institute (RPI) in Troy, N.Y. With the help of professors familiar with the German educational system, because they had escaped the Nazi persecution, I was admitted as a graduate student and graduated with a Master of Science degree in Physics in 1976 with a thesis on CW NMR of ^{27}Al in glasses. My advisor was Philip Casabella, and in 1977 I married the daughter of his secretary Catherine McBride.

In late 1975 Paul Lauterbur gave a lecture at RPI on his method of back-projection MRI (Magnetic Resonance Imaging), and since then I wanted to build a small MRI machine capable of monitoring the breeding of a chicken egg. To enter the field of MRI I wrote to Anil Kumar, the first author of the 1974 paper by Kumar, Welti, Ernst on Fourier MRI [8] to become his PhD student. He carefully directed me to Richard Ernst, who wrote back with a preprint of the now famous 1976 paper on 2D NMR spectroscopy in the Journal of Chemical Physics [9]. Richard was willing to take me into his team but did not have money to pay me. So, I declined, and following extensive Greyhound bus trips across the United States I returned to the Technical University in Berlin, where I was told to spend another year to get a

decent Diploma in Physics to pursue doctoral studies, as no one knew what to do with an MS degree from the USA.

For my diploma thesis in Physics, I built the hardware for an infrared pump-and-probe system from TTL (Transistor-Transistor Logic) components driving optical shutters in a fashion reminiscent of the HETCOR (HETeronuclear CORrelation) experiment in 2D NMR spectroscopy [10]. The year I graduated, the employment market for physicists was bad. But since I had just gotten married, I wanted to work and earn a decent living. Yet I ended up applying for unemployment support from the government. During this time, it happened that I ran into Dieter Ziessow again, who suggested that I apply for a teaching assistantship in Chemistry. That was successful, and since teaching assistants usually pursue PhD work, I became Dieter Ziessow's PhD student. The first topic he suggested I did not like, but the second, riskier one, I took up: He asked me to find out how to obtain 2D spectra from continuous white noise excitation and handed me his notes of Jean Jeener's famous 1972 Basko Polje lecture in which he had proposed 2D NMR spectroscopy [11]. I spent 2 years studying nonlinear system analysis in terms of perturbation expansions with Volterra and Wiener series' analyzing the nuclear magnetization response to noise excitation on two PDP 11/20 computers simultaneously and reporting my failures to Dieter Ziessow about once a week. Eventually the simulations showed, and experiments proved, that the equivalent of 2D correlation spectra of the COSY (COrrelation SpectroscopY) and EXSY (EXchange SpectroscopY) type can be obtained from the third-order, nonlinear response to noise excitation in terms of 2D cross-sections through the Fourier transform of a 3D cross-correlation function of excitation and response (Fig. 2a) [12]. A major challenge in simulating and measuring stochastic 2D spectra was the lack of adequate software for processing and analysis. Following Ray Freeman's suggestion, I wrote a contour plot program to visualize the landscape of 2D spectra. Before that I checked the simulated spectra by means of maximum-intensity projections, which in those days I called skyline projections [13]. For many years these projections have been a standard constituent of commercial processing packages for multi-dimensional NMR spectra. These projections would never have been published if it were not for a random conversation at some NMR meeting with a fellow from Varian. I am most grateful to Dieter Ziessow not only for making it fun and exciting to do research but also for giving me the opportunity early on to attend conferences and meet the leading scientists and illustrious personalities in the magnetic resonance community.

Exploring the nonlinear NMR response to noise excitation was so interesting to me, that I stayed with Dieter Ziessow as a postdoc for another year before moving with my wife and our new-born daughter to Canada in 1982 to indulge into further aspects of stochastic NMR with Reinhold Kaiser at the University of New Brunswick in Fredericton. The results of this work became an integral part of my habilitation thesis, [14, 15]. One practical insight was that multi-quantum correlation spectra can be converted to single-quantum correlation spectra of the COSY type by a simple shear transformation which I find much easier to read than 2D spectra with a multi-quantum frequency axis [16]. Although we wanted to stay in North America, we ended up moving back to Germany, and I joined Hans-Wolfgang Spiess in 1983 at the University of Bayreuth, who there had just accepted the Chair

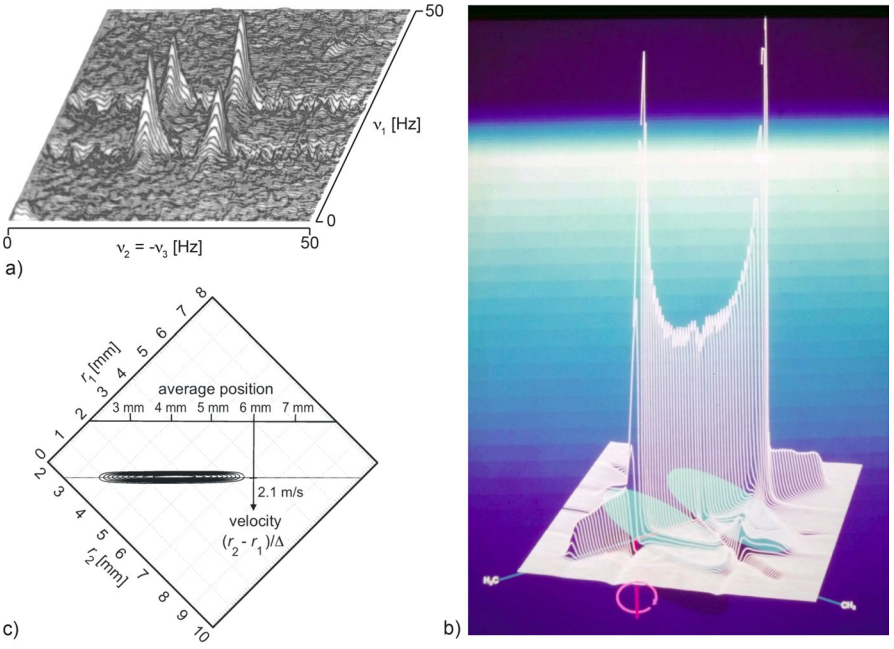

Fig. 2 Exchange NMR. **a** 90 MHz chemical exchange spectrum of dimethylformamide measured with stochastic excitation in 1980 [12]. **b** Artistic rendering of a deuteron exchange NMR spectrum of dimethylsulfone-d_6 [27]. **c** Position exchange correlation NMR map of a falling water drop [60]

of Macromolecular Chemistry II. It was my job to furnish the offices and chemical laboratories in a new building along with the NMR laboratory to be fitted with a Bruker CXP 200 solid-state NMR spectrometer. Without equipment, I spent time in the library reading Hamilton's original works on Quaternions following a suggestion of Spiess [16]. Quaternions are hypercomplex numbers useful for evaluating composite rotations [17, 18]. But after less than a year, Spiess became a director at the new Max-Planck Institute for Polymer Research in Mainz and our family of three moved to Mainz, where soon after our second daughter and two years later our son was born.

3 Solid-State NMR

Spiess was not particularly fond of stochastic NMR, because his mission was to shed light on the molecular dynamics of macromolecular chain molecules in the solid state, building on his wide-line deuteron NMR expertise [19]. Reluctantly I eventually shifted focus to solid-state NMR, but not before finishing off my mission with stochastic NMR. This included imaging with noise excitation [20] and the thesis of my first PhD student Jürgen Paff, a computer freak. He proved that an NMR echo can be generated from continuous white noise excitation in a particular 1D cross-section through the third-order cross-correlation function of the nonlinear NMR

response [21]. This conceptual insight led to the understanding of nonlinear interferometry as a multidimensional extension of linear interferometry including ways to generate 2D spectra with a modified Michelson interferometer [22].

Echoes have always fascinated me [23] and so has Erwin Hahn (Fig. 3). Moreover, together with Gina Hoatson from the College of William and Mary and Marcus Greferath, a potential PhD student, we tested in how far pseudo-random low-power excitation with maximum length binary sequences could be beneficial for accessing the impulse response (FID: Free Induction Decay) of the deuteron resonance in solids, which usually gets lost within the receiver deadtime [24]. But Marcus decided that he likes Mathematics better than Physical Chemistry. He is now a Professor of Mathematics at the University College Dublin and works on number sequences. Twenty-five years after collaborating at the Max-Planck Institute he sent me some sequences of numbers, Frank sequences, which can be used for coherent low-power excitation in NMR spectroscopy. To no surprise in retrospect, it turned out that coherent low-power excitation is more efficient than incoherent excitation [25], i.e., in terms of excitation power, Frank sequences are better than maximum length binary sequences for battery-operated magnetic resonance sensors.

When I joined the Spiess group, I got to know the world of wide-line solid-state NMR spectroscopy with its plethora of spin interactions that are averaged out by fast and isotropic molecular rotation in liquids and many of them by fast magic angle spinning (MAS) [19]. The expertise of the group was to analyze the specific shapes of deuteron powder spectra measured with the alignment echo, i. e. the spin-1 analogon of the stimulated echo at different mixing times to probe the geometry and the timescale of motion of chemical groups which were selectively deuterated by skilled chemists. Realizing that this three-pulse excitation is the basic pulse sequence for 2D Fourier exchange spectroscopy [26], I organized a group seminar on 2D spectroscopy intending to expand the methodological portfolio of the team. The initial resistance to the idea of 2D spectroscopy transformed to enthusiasm once the first experimental data acquired secretly by Claudia Schmidt revealed that the cross-peaks arrange in the shape of an ellipse in ^{2}H exchange spectra of polycrystalline powders governed by the ^{2}H quadrupole interaction (Fig. 2b) [27]. It was a small step from there to perform similar experiments with chemical shift resolution

Fig. 3 B. Blümich and E.L. Hahn 1995. Erwin sent the photo to BB on 8–22-1995 with a note saying: "Dear Bernhard, here is a photo of us nose to nose! Obviously, I am the winner. Regards, Erwin"

by observing the sideband patterns from the chemical shift anisotropy of ^{13}C at slow spinning speeds. This experiment was reduced to one dimension by suppressing the spinning sidebands with rf pulses in a preparation period preceding a mixing time, during which molecular reorientation destroys the initial nulling of sideband signals, so that spinning sidebands observed during the detection time indicate rotational motion of the chemical groups [28].

Among others, Peter Blümler and Klaus-Schmidt-Rohr joined the Spiess group during this time as students and Brad Chmelka as a postdoc, and I started my first independent research projects. With Peter we looked at the rotary echoes of the ^{2}H MAS FID and realized that the spinning sidebands after 1D FT (Fourier Transformation) of the single-pulse FID could be stacked to form a 2D spectrum which correlates chemical shift in one dimension with the associated sidebands tracing the wide-line powder spectrum in the second dimension [29]. This one-pulse experiment is reminiscent of Peter Mansfield's echo planar imaging method [30]. In fact, Peter's interest was in MRI, and mine was shifting there, because to move on I had to develop my own scientific footprint away from solid-state spectroscopy of polymers which was tied to the Max-Planck Institute and backed by resources unavailable at the university level. Nevertheless, solid-state NMR spectroscopy of polymers remained an important activity throughout the years after leaving the Max-Planck Institute and moving on to RWTH Aachen University especially after Dan Demco had joined the team in 1998 and Marko Bertmer in 1999.

Dan Demco was a professor at the Technical University in Cluj-Napoca, Rumania. But he had left his home university for the sake of better working conditions in western Europe. He eventually came to Aachen from the Max-Planck Institute for Polymer Research in Mainz, where we had already collaborated, studying elastomers by solid-state NMR methods [31]. He was a force of nature, who published a huge number of papers with us until his retirement from when on he joined the DWI Leibnitz Institute for Interactive Materials next door to us at the University in Aachen. He made particularly important contributions to understanding spin diffusion and utilizing it to characterize semi-crystalline polymers [32–34], to MRI of anisotropic spin interactions [35, 36] and granular flow [37, 38], and to NMR in inhomogeneous fields [39, 40]. Dan Demco attracted many talented PhD students from the Technical University in Cluj Napoca, which awarded me the degree doctor honoris causa in 2002. Radu Fechete was the most outstanding one, who worked on solid-state NMR, spin diffusion, mobile NMR, and NMR imaging of soft matter. He now is a lecturer of Physics at the Technical University Cluj-Napoca. Marco Bertmer came from Hellmut Eckert's group in Münster and empowered the work in solid-state NMR spectroscopy with his methodological expertise in magic-angle spinning NMR [32, 41–43].

When Jagadesh Bharatam from the Indian Institute of Chemical Technologies stayed with us in 2002 with a stipend of the Alexander-von-Humboldt foundation. We extended our high-field solid-state NMR studies to porous media. Jagadeesh found that the molecular dynamics of thin lipid films in nanopores are enhanced by the topological constraints of the pore [44, 45]. Further on, Jeff Reimer from UC Berkeley spent his sabbaticals in 2005/6 as a Mercator guest professor and in 2014/15 with a Humboldt Research Award at RWTH Aachen University, and we

became interested in molecular organic frameworks [46, 47]. I greatly enjoyed his company and our many discussions on NMR in the chemical engineering sciences and beyond.

4 NMR Imaging

Along with the habilitation at a university and then being a "Privatdozent" (an unpaid university lecturer) comes the duty to teach one course per semester with the privilege of advising one's own PhD students. The first course I lectured at the University of Mainz in this context was in the fall semester of 1988 on NMR tomography and spatially resolved spectroscopy. Soon after, I met Winfried Kuhn from the Fraunhofer Institute in St. Ingbert, who was engaged in publishing an article in Angewandte Chemie on non-medical MRI, which he referred to as NMR Microscopy [48]. At the same time, Paul Callaghan was about to publish his book on the Principles of Nuclear Magnetic Resonance Microscopy [49]. Winfried and I were both excited about the emerging possibilities of using field gradients in magnetic resonance, and over a glass of beer or two, we decided to organize an International Conference on Magnetic Resonance Microscopy (ICMRM) in Heidelberg in 1991. Among others, Paul Lauterbur, Peter Mansfield, Raymond Andrew, Paul Callaghan, Rainer Kimmich, Axel Haase, Jerry Ackerman, Joe Ackerman, Eiichi Fukushima, Al Garroway, Henk van As, Larry Hall, Jörg Kärger, Lynn Jelinski, David Cory, Yang Xia, Jim Pope, George Mateescu, and Larry Berliner attended and gave lectures. Ever since this conference takes place every two years, now alternating with the Conference on Magnetic Resonance in Porous Media (MRPM), which started a year earlier and serves a closely related community. A year later the ICMRM was integrated into the AMPERE Society forming the Division of Spatially Resolved Magnetic Resonance. This name I preferred over Magnetic Resonance Microscopy because the identifying feature was field gradients, which introduce spatial resolution not only for imaging, but also beyond. Several other new divisions have been established within the AMPERE Society since then. Also, summarizing the main contributions of the first ICMRM, a book was published entitled Magnetic Resonance Microscopy [50]. Four books have been published in this series so far, the last one in 2022 [51].

Based on the notes of my 1988 imaging lecture, I began writing a book on NMR Imaging of Materials [52]. But progress was slow, even though I spent my 6-month sabbatical beginning in the fall of1992 at the University of Amherst writing, instead of interacting with the colleagues at the Department of Polymer Science and Engineering. From 1988 to 1993 I applied at several universities to gain academic independence as a university professor. Eventually, while in Amherst, a position was offered to me as full professor of Macromolecular Chemistry at RWTH Aachen University. I cut my sabbatical short, and our whole family of 5 travelled across the United States in a van from university to university to Chuck Wade at the IBM Research Center in Palo Alto and back, largely covering the travel expenses by honoraria from lectures. We visited Eiichi Fukushima in Albuquerque, Brad Chmelka in Santa Barbara, Alex Pines in Berkeley, and the 34th ENC in St. Louis, where the

whole family luxuriously stayed in the vice-presidential suite of the Adams Mark Hotel as a benefit of being chair elect for the 1994 ENC in Asilomar.

At RWTH Aachen University, my intention was to set up a laboratory for NMR imaging of polymers, and I opted for a horizontal bore magnet align my work orthogonal to the work at the MPI in Mainz and which would be suited to study rubber products like shoe soles under dynamic mechanical load. Our prior MRI work in Mainz had shown that imaging of rigid polymers was challenging and of little practical use although interesting from the academic point of view [53]. More promising for MRI were studies of soft matter like elastomers [54]. Elastomers are soft matter of crosslinked macromolecules and have NMR properties like human tissue for which MRI is a highly successful diagnostic tool. In fact, investigations of aging, fatigue and strain of elastomers have been a rewarding endeavor for many years [54–56] and enabled several research projects in cooperation with industry.

While polymeric objects can in most cases be cut without serious penalty to image their morphology, their function depends on their integrity. For example, a car tire warms up when rolling, and the interplay of heat generated by cyclic deformation of the bulk and dissipated through the surface gives rise to a temperature distribution. This temperature distribution we could image by T_2 parameter maps of rubber cylinders during dynamic shear deformation [57]. But once having accepted the position at RWTH University, it was quite a struggle to set up the NMR laboratory. To win the consent of my colleagues we agreed to set up the laboratory in a spacious basement room which had been used for storage of outdated furniture and equipment. This lab we named MARC, short for Magnetic Resonance Center. It happened to be the first analytical center available to a group of research teams at the university. Maurice Goldman was the guest of honor at the opening ceremony in 1995.

At the beginning there was no adequate NMR equipment at RWTH Aachen University for me to use so that experimental work continued at the Max-Plank Institute in Mainz, while a new home was being built for the family to move in to from our house overlooking the vineyards near Mainz, and the new courses on the Physical Chemistry of Macromolecular Materials and related subjects were being prepared. Teaching Macromolecular Chemistry was a challenge, because as a trained physicist I had little knowledge of Chemistry. In addition, Robert Kosfeld, who lived in Aachen, had suffered a stroke, and asked me to continue his work as editor in the Springer series NMR – Basic Principles and Progress with four volumes on Solid-State NMR [58]. These events, setting up a research group in Aachen, and chairing the 35th ENC 1994 in Asilomar were a great distraction from working on the book NMR Imaging of Materials [52]. But I was lucky to get good students and Peter Blümler as a postdoc into the group, so that despite the heavy workload this was an exciting and fun time (Fig. 4).

Once the new solid-state imaging spectrometers had arrived, we continued with methodical imaging work on elastomers [55, 57]. Peter convinced a young chemistry student by the name of Song-I Han to do a research internship with him. Song-I continued with her Diploma thesis in Chemistry and her dissertation in my group. Thanks to her exceptional talents and with the help of Peter and Siegfried Stapf (see below) we managed to image the flow vortices in water drops falling through

a vertical-bore magnet [59, 60] and later in drops levitated inside the NMR probe [60–62]. Song-I was also a good sparring partner in advancing the understanding of exchange experiments, in particular the position-exchange experiment (Fig. 2c) [63]. This experiment relies on a gradient-field pulse pair, whereby the amplitude of one pulse is varied independently of the other under the known imaging constraints of spatial resolution and field of view. Along the diagonal both gradient-field pulses are the same, encoding average position, and on the secondary diagonal they are opposite, encoding position difference corresponding to velocity. This means that the exchange spectrum obtained by 2D Fourier transformation of the measured data shows a projection of the moving object parallel to the diagonal which is offset from the diagonal by its velocity. Rotating this 2D exchange spectrum by 45° converts it into a position-velocity correlation map. By similar arguments, a velocity exchange map can be interpreted in terms of a velocity–acceleration correlation map [64]. After some further thought one arrives at the conclusion, that short gradient field-pulses give access to the time derivatives of the position of moving objects in a finite difference approximation [65]. These considerations were first spelled out in the introduction of the Book NMR Imaging of Materials [52] which eventually got published after 12 years in 2000, thanks to the grace of Paul Callaghan who had invited me in 1998 for a few months to his university in Palmerston North, New Zealand, to continue writing the book. Exchange NMR resurfaced as a topic of interest especially when mobile and compact instruments can be employed [66, 67]. This eventually led us to analyzing multi-site exchange [68, 69] and spatially resolved 2D relaxometry [70].

Just in time, Siegfried Stapf had joined the group as a post-doc from Ken Packer's team at the University of Nottingham, succeeding Peter Blümler in 1999. His prolific work focused primarily on MRI and subsequently on field-cycling relaxometry. He had significant impact on advancing the methodology and applications of flow imaging and NMR of fluids confined to and flowing through porous media [59–61, 64, 71–73] in part through collaboration with chemical engineering [74, 75]. In

Fig. 4 Smoking Pines' cigars with pines. Peter Blümer, Manfred Wilhelm, Brad Chmelka and Bernhard Blümich at the Blümich's in 1994 in their small village near Aachen enjoying the Cuban cigars that were supposed to go to Alex Pines in front of a row of pine seedling from the ENC in Asilomar

2004 he did his habilitation in Aachen and has since moved on to be a professor of Polymer Physics at the University in Ilmenau.

While materials MRI is interesting, the use of MRI in the applies sciences is unique in studying transport phenomena of interest to chemical and medical engineers [75]. Examples are fluid flow through fixed-bed reactors [73, 74], multi-phase flow [62], hollow fiber filtration [76, 77], online-monitoring of rubber extrusion [78, 79], the rheology of blood [80, 81], the flow patterns in an aneurism invoked by the changing flow geometry [82], the chaotic flow vortices inside an electrochemical cell invoked by the magnetohydrodynamic effect [83], and reactive bubble flow [84]. In many applications, high-time resolution is needed, and along with others we optimized flow MRI to shorten the imaging time [62, 85].

With time I got the impression, that although my book on NMR Imaging of Materials found some attention, only few would read it. It has a lot of detail and is not suited for teaching and course work. So, I began condensing the content to slides and statements to make a tutorial book on NMR, which students can resort to refresh their knowledge. The first publisher I contacted rejected the idea of such a book, but Springer liked it right away, and the book "Essential NMR" was published in 2005 [86]. A revised edition appeared in 2019. Soon after, the book was translated to Russian [87]. When I received my copies of the Russian edition, I discovered the logo of a major NMR instrument manufacturer on each page and pages of an NMR almanac in an appendix. The book had been pirated for use as an advertising brochure for Russia and first distributed to attendees of the Zavoisky Symposium in Kazan in 2007. I realized that the publisher had little interest in defending the authors' rights and that it took personal connections to friends at the company to resolve the issue. About 2000 of the 3000 printed copies were eventually destroyed and a new edition published [88].

5 Mobile NMR

Solid-state NMR experiments and NMR imaging experiments tend to use expensive high-field magnets and sophisticated pulse sequences. In the past months at the MPI I remember sitting together with Peter Blümler in the electronics workshop discussing how NMR is getting more and more complicated and expensive. So, we contemplated what the simplest and least expensive device would be that delivers an NMR signal. Peter remarked that it would be nice to have an NMR scanner like an ultrasound scanner that can be moved across the surface of an object to characterize its physical properties. The next day he came back with a drawing of a permanent stray-field magnet fitted with a surface coil [89]. We were convinced that this approach would work because we knew from our recent MRI measurements that NMR signals can be measured with surface coils, and that detectable signals are generated in inhomogeneous fields with echoes. As acronyms are popular in NMR we named the device NMR-MOUSE for MObile Universal Surface Explorer the same day. This name became quite popular and eventually a registered trademark of RWTH Aachen University.

My first funded project in Aachen was to construct the NMR-MOUSE. Peter Blümler had joined the team as a staff scientist following a stint at the IBM Research Laboratory in Palo Alto. With his many talents he quickly became the first person whom students asked when needing help with theory, experiments, and advice, or when the spectrometer was broken, and he was the anchor of social life in the group. In terms of research direction, I was convinced of the ample opportunities of NMR in inhomogeneous fields that must be waiting to be explored, because there is only one homogeneous field while there are several grades of inhomogeneous fields, NMR imaging being the most prominent example of NMR in a linearly inhomogeneous field. We got our first signals from the NMR-MOUSE in 1995 [90], a few weeks after Bob Kleinberg had visited us from Schlumberger, who had just successfully launched the first commercial well-logging tool that year [91].

It was Eiichi Fukushima, who reminded us, what we should have known from my favorite sessions at the ENC entitled "Exotica", that stray-field NMR was by no means new. Stray-field relaxometry had been studied first by Jasper Jackson with permanent magnets for oil-well logging and other nondestructive testing applications [92], and by Samoilenko et al. with superconducting magnets for solid-state imaging [93]. Moreover, the unilateral NMR technique with mobile permanent and electromagnets had been explored for a wide range of applications at the Southwest Research Institute in San Antonio, Texas [94, 95]. So, we reinvented the wheel but not quite the same one. To optimize sensitivity the approach of others at the time was to aim for high field homogeneity at low field to collect signal from a large sensitive volume, while stray field NMR at high field benefitted from stronger spin polarization and could afford large gradients and thus smaller sensitive volume. Our priority was to get a small sensor that provides a useful signal, and we maximized field strength at low field at the expense of large stray-field gradient, which, in a way, is a combination of both concepts. Right away we started to explore hitherto largely uncharted territory in materials testing. Our NMR-MOUSE turned out to be quite useful to differentiate the state of wear and tear of polymer materials, and even produced signal from a polymer coat covering a steel plate despite the strong distortions of the stray field by the steel [96].

The same year we published the NMR-MOUSE [90], Gisela Guthausen (née Zimmer) joined our team from Michael Mehring in Stuttgart as a postdoc. With her excellent Physics background and remarkable endurance, she was a driving force in exploring measurement methods and applications of the NMR-MOUSE in the early days [97–99]. Recognizing that the NMR-MOUSE essentially acquires the information of one pixel from an NMR image, our applications of the NMR-MOUSE focused primarily on soft matter, where medical MRI has its impact. A consequential study turned out to be a comparison of depth profiles obtained with the NMR-MOUSE and NMR images of rubber-tire sections with textile belts [100]. Because tires with steel belts could also be analyzed with the NMR-MOUSE but not by conventional MRI, it opened the door to many projects with industry, in particular the tire industry [101], where expensive racetrack tire testing could in many cases be replaced by far less expensive laboratory testing with the NMR-MOUSE (Fig. 5a) [102, 103]. Along with exploring interesting applications of the NMR-MOUSE, we

analyzed the magnetization response to different echo sequences in inhomogeneous fields to optimize the measurement methodology [39, 40].

The original NMR-MOUSE has a horse-shoe magnet constructed from two permanent-magnet cuboids placed on an iron yoke and magnetized in opposite directions perpendicular to the yoke [94, 97]. It exhibits a static magnetic field parallel to its surface. In 2002, we constructed an even simpler stray-field sensor, the bar-magnet NMR-MOUSE, making use of the stray-field emanating from the face of an axially polarized cylinder magnet [104]. While the original NMR-MOUSE functions well with a simple wire-loop radio-frequency coil producing a $\boldsymbol{B}_1$ field perpendicular to its surface, the bar-magnet NMR-MOUSE necessitates the $\boldsymbol{B}_1$ field to be parallel to the cylinder face so that figure-8 type surface coils and combinations thereof need to be employed. On one hand, the spatial localization of the sensitive volume is less favorable, but on the other hand, such coils self-cancel far-field electromagnetic noise. Given that $\boldsymbol{B}_0$ of the original NMR-MOUSE is parallel to its surface, the degree of macroscopic order of oriented matter like tendon and strained elastomers could be investigated via their relaxation anisotropy, which is difficult to study inside an MRI magnet [105–107]. But the small size of the NMR-MOUSE also enabled new experimental approaches to study material properties by placing it inside a desiccator [108] or an oven [109]. Also, the device can serve as a quality-control sensor in a production line [110] or for finished products like electrical cable insulation or air-spring bellows [111]. Moreover, the small size of the sensitive volume

Fig. 5 Mobile and compact NMR instruments. **a** The NMR-MOUSE at a science show of RWTH Aachen University in 1997. **b** Juan Perlo holding a small stray-field tomograph next to our 300 MHz solid-state MRI magnet [135]. **c** The Profile NMR-MOUSE mounted on a manual lift, measuring a depth profile of a car-tire tread, and operated by a Bruker Minispec console packed inside a pilot's travel case in 2005 [143]. **d** Juan Perlo (sitting) and Federico Casanova measuring a chemical shift resolved ^{1}H NMR spectrum of crude oil in a beaker on top of the magnet in 2005 [171]. **e** Miniature spectroscopy magnet in 2010 [125]. **f** The first benchtop NMR spectrometer with a magnet by ACT GmbH and a KEA console from Magritek ltd. in 2012

yielded localized NMR parameters that exhibited a variance reporting the statistical nature of synthetic polymer materials like the crosslink density in elastomers [112, 113] and the crystallinity in polyethylene pipes which changes with age and upon annealing well below the melting temperature [86, 114, 115].

Exploring the different uses of the NMR-MOUSE went along with improving the sensor. Probe ringing could eventually be pinned down to electro-strictive coupling of the radio-frequency surface coil with the permanent magnets. It could sufficiently be reduced with copper shields thanks to the efforts of Michael Adams, our NMR electronics engineer, and Vladimir Anferov, a professor of Physics visiting from Kaliningrad [116]. His wife, Sophia Anferova, came to Aachen first as a visiting scientist and moved forward the applications of the NMR-MOUSE in porous media like building materials and rock in collaboration with Geophysics from RWTH Aachen University [117]. Peter Blümler had moved on to the University of Kent in 1999 but had left us his knowhow to build Halbach magnets from permanent magnet cubes [118]. Klaus Kupferschläger, our gifted mechanic, built one for our partners in Geophysics that was subsequently employed for porosity and permeability analyses of geophysical drill cores [119, 120], and we built a prototype of an NMR core scanner where the magnet slides along the drill core to locally record the position dependent relaxation-time distributions [121]. Later, we also built a slim-line logging tool that slides along permanently installed plastic pipes to map the 3D moisture distribution in the vadose zone of a field in different seasons over a year [122, 123]. Moreover, we explored the use of compact Halbach magnets for relaxometry studies of polymer aging [124], and eventually evaluated other types of magnets to improve their homogeneity towards resolving the ^{1}H chemical shift [125–129] with the vision to miniaturize magnetic resonance hardware for use at the site of demand [130].

Not long after we got the first signal from the NMR-MOUSE, we became interested in resolving pixels within a plane of the sensitive volume parallel to the scanner surface. It was Pablo Prado, who joined the team in 1998 with a stipend from the Alexander von Humboldt Foundation from Bruce Balcom's group in Fredericton, N.B., who fitted the NMR-MOUSE with gradient coils and produced the first 1D images with it [131]. We kept pursuing the development of unilateral MRI from 1999 to 2005 in a collaborative effort supported by DFG (Deutsche Forschungsgmeinschaft), the German Research foundation, with electrical engineers, mechanical engineers, and radiologists [132]. Single-sided MRI suffers from even poorer signal-to-noise ratio than unilateral relaxometry, but we could obtain useful images of material defects, however, only at long measuring times [133]. Although Pablo Prado stayed for less than a full year, his impact was significant not only scientifically but also for the evolution of the team. He attracted Federico Casanova from Cordoba in Argentina as a postdoc to our team. Federico arrived in 2002 also with a Humboldt stipend. Right away he convinced me to hire his student, Juan Perlo. Both have become invaluable members of the team, who subsequently attracted Ernesto Danieli in 2007 with his Humboldt postdoc stipend and Josefina Perlo, Juan's sister, for her postdoc to Aachen. Federico and Juan are now the CEO's of Magritek GmbH in Aachen, and Ernesto and Josefina are leading staff along with Jürgen Kolz, who worked on his PhD degree in my group with the NMR-MOUSE.

Federico Casanova started working on the hardware and measurement methodology of the NMR-MOUSE right away and a bit later together with Juan Perlo. Their first innovation was to reduce the size of the stray-field MRI sensor to fit into the palm of a hand (Fig. 5b) [134, 135]. Then they improved the sensitivity of the phase-encoding imaging method by adding the echoes from the CPMG detection train [136] and moved on to measure 3D images composed of multiple slices perpendicular to scanner surface [137], velocity distributions [138], and velocity profiles [139]. The measurement depth was varied by simply changing the NMR frequency making use of the $\boldsymbol{B}_0$-field variation with distance from the NMR-MOUSE at the expense of varying the shape of the sensitive slice with frequency. Later Ernesto Danieli succeeded with a clever arrangement of shim magnets in the gaps of the NMR-MOUSE to produce a planar 2 mm thick sensitive slice with a homogeneous gradient [140] with which distributions of diffusion coefficients could be measured quickly as a function of depth through live biological tissue like skin [140, 141] and intestine [142]. Such profiles across the human skin promise to be of use for bedside guiding of dialysis procedures [141].

The magnet designed in the collaborative research project on single-sided MRI had complicated shape to assure that the stray-field was flat at a particular distance from the magnet surface [132]. Juan and Federico noticed that the design could be reduced to two horseshoe magnets placed side by side a particular distance apart [143]. With this sensor, they obtained depth profiles in soft matter with a record spatial resolution of 2.3 µm. When positioned on a precision displacement stage, high-resolution depth profiles can be measured by shifting the sensitive slice though the object step by step (Fig. 5c) in a manner of producing images by addressing voxels one by one like in Damadian's early FONAR MRI method [144].

This Profile NMR-MOUSE became the IP [145] of a nonprofit organization, AixNMR, which I had started in 2001 together with a consultant to leverage income from projects with industry to finance research projects in a way less bureaucratic than through the university administration. One of our partners was Bruker for whom we produced the NMR-MOUSE, and we used the Bruker Minispec console packed into a pilot's aluminum travel case to operate the MOUSE (Fig. 5c). The same year we also had the first Colloquium on Mobile NMR with support by AixNMR, where people from academia and industry interested in development, applications, and measurement methodology of compact NMR instruments met in Aachen to discuss recent progress. The number of participants grew steadily from around 20 to about 80 in 2006. By then, organizing the colloquium each year became too much of a burden for the group, so that it was integrated into the interleaved biannual international conferences on Magnetic Resonance Microscopy and Magnetic Resonance in Porous Media.

Sometime in 1999, Annalaura Segre from the CNR in Rome mentioned, how nice it would be to study objects of cultural heritage with the NMR-MOUSE. Soon after in 2000 we could participate the EUREKA project "E!224–EUROCARE MOUSE: Nuclear Magnetic Resonance Mobile Scanner For On-Field Non-Invasive Diagnosis Of Porosity/H20 Infiltration In Materials" and performed our first outdoor measurements of a fresco 2002 inside a cryptoporticus near the Coliseum in Rome. But what I did not realize at the time was that this project was the back door for Bruker to

produce their own stray-field sensor. Bruker also named it MOUSE, but then the name had to be changed, because RWTH Aachen University owned the trademark NMR-MOUSE. Subsequently we then replaced the Bruker Minispec console by a Kea console from Magritek for our NMR-MOUSE studies as it was also easier to operate and program. In retrospect, the Bruker competition did not matter much, because a few years later we had the patented Profile NMR-MOUSE capable of measuring high-resolution depth profiles [143, 145], which is far more useful for most cultural heritage studies and a multitude of other materials applications. Also, we could participate in several follow-up projects of the European Community on heritage science and art diagnostics until my retirement in 2019, and the funding allowed us to spend resources on magnet development and many interesting adventures with the NMR-MOUSE.

My first PhD student involved in cultural heritage work with the NMR-MOUSE was Shatrughan Sharma who came to RWTH Aachen University from the IIT in Delhi. His Advisor there was Prof. A.S. Brar whom I met in 2001 while on an extended trip to India which began with a Symposium on Spatially Resolved Magnetic Resonance in Chennai. Professor Brar was a polymer chemist with interest in NMR. He visited us in Aachen a few times and then moved on to become Vice Chancellor of the University in Lucknow and later of Guru Nanak Dev University (GNDU) in Amritsar. We hit it off well, and I visited GNDU several times. In 2015 I received the degree Dr. honoris causa from there in an illustrious ceremony.

Following up on our 2002 excursion to Rome, where we first measured a Roman wall painting, Shatrughan analyzed the pore-size distributions of Roman bricks and the impact of stone strengthener on sandstone samples with the NMR-MOUSE [146]. Stone conservation is still a relevant topic to study by unilateral NMR [147]. Several subsequent dissertations included investigations of cultural heritage with the NMR-MOUSE. Among others we studied paper degradation [148], the stratigraphy of paintings including the aging of paint binder [149], Ötzi the iceman [150], Charlemagne's tibia [151], frescoes at excavation sites [152], and master violins [153]. Summaries of our cultural heritage studies are given in books and reviews [151, 154–159]. Much of this work is exploratory, but two applications found attention in the cultural heritage community. One concerns the restoration of easel paintings by removing the degraded varnish with a solvent [160]. The solvent also enters the binder and leaches from it the low molecular weight fraction of molecules, making the binder brittle [161]. So, being sensitive to moisture the solvent uptake and drying can be monitored with the NMR-MOUSE, and solvent-cleaning procedures can be optimized [162]. This work was initialized by Tyler Meldrum during his Humboldt-postdoc time in 2011/2012. The other application concerns the analysis of the mortar stratigraphy of frescoes. Frescoed walls and fresco fragments which exhibit the same stratigraphy are likely to have been made with the same workmanship at the same time. The comparison of depth profiles from frescoes thus contributes valuable information to reconstruct the history and use of ancient buildings [152]. I am still involved in analyzing the stratigraphy of wall paintings thanks to Eleonora Del Federico. She attended the 5th Colloquium on Mobile NMR in Perugia in 2005 and acquired an NMR-MOUSE to start her career as a professor at the Pratt Institute in Brooklyn,

N.Y. [155, 163]. We are working together ever since. Other interesting applications of the NMR-MOUSE concern the space and time-dependent photo-curing of dental resins [164], the quantification of the crumb-rubber fraction in asphalt [165], and the fluid transport through stacks of thin, porous material layers in health-care products [166, 167].

In 2001, Rainer Kimmich had shown that the effect of an inhomogeneous detection field $\boldsymbol{B}_0(\boldsymbol{r})$ can by removed by formation of echoes generated with radio-frequency fields $\boldsymbol{B}_1(\boldsymbol{r})$ if the spatial dependencies of both fields match [168]. We were eager to try if one could obtain chemical shift resolution in the strong gradients of the NMR-MOUSE in this way, and Vicky Demas from Alex Pines' group in Berkely came to Aachen to work on this together with Juan Perlo. The Berkeley-Aachen team could indeed show, that the ^{19}F chemical shift can be resolved in the inhomogeneous stray-fields of the NMR-MOUSE [169]. Subsequently Juan and Federico figured out that it is easier to produce a stray-field with a sweet spot sufficiently homogeneous to resolve the ^{1}H chemical shift than to match the spatial dependencies of two magnetic stray-fields, and in 2005 they succeeded in measuring chemical-shift resolved spectra from fluids in a beaker on top of a stray-field magnet (Fig. 5d) [170]. Although conceptually interesting, the approach is of little practical use because of the extremely critical conditions that need to be met to successfully measure chemical shift resolved spectra in magnetic stray fields.

Stray-field NMR is the dominant incarnation of mobile NMR, because the sensor is readily moved to the site of the object for analysis. Compact NMR is somewhat different, as it includes stationary NMR instruments which need to be compact but not necessarily mobile. The principles and applications of stray-field NMR depth profiling are summarized in an extensive review which I wrote during my sabbatical as a Miller professor at UC Berkely hosted by Alex Pines and Jeff Reimer [154] and in a book edited under the leadership of Federico Casanova and Juan Perlo [171]. Compact NMR includes stray-field NMR relaxometry and benchtop NMR spectroscopy [126]. It is explained in the book "Compact NMR" [151], which my coauthors Sabina Haber-Pohlmeier and Wasif Zia, a PhD student from Pakistan, encouraged me to complete. This book is meant for NMR novices to serve as a guide to different types of experiments with compact instruments.

In 2006, the endeavor with the nonprofit organization AixNMR ended in disaster when I realized too late that the trusted consultant of the organization had pocketed considerable sums of money for himself, and that the organization was close to bankruptcy. Following a court procedure which ended in my favor and near endless tax issues, AixNMR was dissolved after the dept had been paid back. One of the missions of AixNMR was to start a commercial enterprise for consulting and building NMR hardware like the NMR-MOUSE. This happened at the last brink during these turbulent times, and the company was registered in 2006 by the name ACT for Aachen Center of Technology. Eventually, Federico and Juan took over the company when it was no longer possible to pay them through university projects. This step was eyed with suspicion by many, who did not want to believe, that foreigners from a different continent can successfully run a company in Germany. But history has proven they can.

6 Compact NMR

Working with the NMR-MOUSE and on stray-field NMR spectroscopy, Ernesto Danieli, Federico Casanova, and Juan Perlo learned how to shim the magnetic field generated by a combination of permanent magnet blocks. Moving just one of the blocks by a minute distance has a strong impact on the field profile. Thus, they came up with the idea to shim the magnetic field of a Halbach magnet with movable magnet slabs placed in between the trapezoidal magnet elements of a Halbach ring. In 2010, they built a small Halbach magnet the size of a flashlight battery which could accommodate a standard liquid-state NMR sample tube with 5 mm diameter (Fig. 5e) and had a magnetic field good enough to measure liquid state ^{1}H NMR spectra at 27 MHz [125, 172]. Then, they packed the magnet into a small stand-alone case, and we followed our first chemical reaction with the magnet under the fume hood in 2011 [173]. But Gisela Guthausen at the Karlsruhe Institute of Technology was a step ahead of us working with a prototype Bruker Minispec spectrometer modified for high field homogeneity. She had measured ^{1}H 2D NMR spectra already in 2010 [174]. Meanwhile Federico, Juan and Ernesto spent tremendous effort to improve the technology of the small, 27 MHz Halbach magnet to a level, where it can be manufactured reproducibly and operated at 40 MHz without disturbing temperature drift. The first such magnets were produced by ACT GmbH and operated with a separate KEA console from Magritek (Fig. 5f).

For several years by then, ACT GmbH and Magritek Ltd. have already been cooperating closely, manufacturing NMR-MOUSE magnets in Germany and spectrometer consoles in New Zealand. The Magritek KEA spectrometer resulted from Paul Callaghan's expeditions to Antarctica where he studied sea ice in the Earth's magnetic field along with Andrew Coy being one member of the team and now the CEO of Magritek Ltd. [175]. By 2011 Paul was already seriously ill with colon cancer. Nevertheless, he was full of energy pushing forward and spent a sabbatical at Cambridge University, UK, to finish his book on Translational Dynamics and Magnetic Resonance [176], while already contemplating his next book on economics, because the economic future of New Zealand was dear to his heart. I visited him in Cambridge, and walking along the Cam River we discussed our companies and that they should merge (Fig. 6). The merger became effective on August 1st, 2012, which unfortunately Paul could not witness anymore. The new company kept the name Magritek. The same year the ACT magnet and the KEA console were integrated into one elegant case, and the resulting 40 MHz benchtop spectrometer was named "Spinsolve".

At the university we explored the new research opportunities enabled by the Spinsolve spectrometer for chemical analysis on the workbench in cooperation with Magritek. We set the Spinsolve up on the benchtop for chemical analysis [177–180] as well as inside the fume hood for reaction monitoring [181–183], and we attached it to a fermenter [184]. One of the most prolific students was Kawarpal Singh, who came to Aachen for his PhD degree from Guru Nanak Dev University on the recommendation the Vice Chancellor Prof. A.S. Brar. Kawarpal

Fig. 6 Bernhard Blümich and Paul Callaghan in Cambridge, August 8th, 2011 This was the day when both agreed to merge Magritek ltd. and ACT GmbH

studied several chemical compounds and reactions with our 1 T Spinsolve spectrometer. Among others, he showed, that even at such low field strength one could perform a complete analysis of a complex molecule like strychnine, when resourcefully making use of 1D and 2D NMR methods of ^{1}H and ^{13}C [178]. This magnetic field is even sufficient to discriminate raw styrene butadiene rubber from different manufacturers and by different copolymerization techniques based on the chain statistics of the copolymer in solution with the help of chemometrics [179]. The interest in benchtop NMR spectroscopy grew rapidly within academia and industry [180, 185, 186]. Already in 2016, a special issue of an analytical chemistry journal was devoted to Compact NMR with several contributions on benchtop NMR spectroscopy [187]. Today, different companies produce tabletop spectrometers which differ in sensitivity, resolution, and field strength. Like in early days of high-field NMR, it is advisable to compare spectra from one's own samples to judge the performance of different spectrometers for one's needs. Live demonstrations of benchtop spectrometers and scientific results obtained with benchtop spectrometers are now an integral part of the post COVID NMR conference culture. The technology for even smaller and inexpensive spectrometers is being developed, but the market opportunities for personal NMR spectrometers still wait to be discovered [130, 188].

7 Hyperpolarization

In 1998, we started collaborating with Stephan Appelt from the Research Center in Jülich, who intended to get his Habilitation at RWTH Aachen University. He had returned to Germany from William Happer's group in Princeton and knew how to build Xenon hyper-polarizers. Hyperpolarized xenon was interesting for our imaging

endeavors [189, 190]. On the other hand, the concept of mobile and compact NMR appealed to Stephan. So, his activities shifted to high-resolution spectroscopy at the Earth's magnetic field, and he impressively demonstrated the wealth of chemical information that can be obtained with simple instrumentation at such low field [191, 192] compared to the field strengths of tabletop NMR instruments [193, 194].

In 2004 Stephan Appelt completed his habilitation in Chemistry at RWTH Aachen University, and in 2007 he was nominated Extraordinary Professor of Low-Field NMR. While ordinary professors are endowed with budget and personnel by the university, extraordinary professors are not. But I was happy to host him with my resources, as I liked his creativity and intellectual depth, which was a great enrichment to the Chemistry Department and our NMR team. Stephan's classes on the theory of NMR and quantum mechanics attracted the most gifted students, and some of them ended up doing their graduate work under his supervision with us. Once Ralph Adams et al. had published their seminal work on reversible ParaHydrogen Induced Polarization (PHIP) or Signal Amplification by Reversable Exchange (SABRE) [195], we began exploring this new concept for sensitivity enhancement at low field and to challenge the sensitivity limit of NMR in the range of 0.2 to 5 mT with Stephan's home-built equipment [196, 197].

To employ the SABRE methodology in applications of practical relevance, we addressed two fundamental issues by contributing to the development of a SABRE catalyst that works in the presence of water [198, 199] and to studies how to hyperpolarize rare spins [200–202]. Stephan had written his own software to calculate the PHIP spectra at arbitrary field strength down to zero field, and discovered, that the roof effect observed in the strong *J*-coupling regime at high field is inverted when the field-dependent Zeeman coupling can be treated as a perturbation to the field-independent *J*-coupling at ultra-low field [203–205]. An accidental discovery was the SABRE sustained self-oscillation which is known as RASER for Radio-Amplification by Stimulated Emission of Radiation [206–208]. Recording this oscillation gives access to unprecedented high-resolution spectra, and Stephan worked out the underlying theory in the general language of cybernetics which allowed him to simulate the observed time domain traces and spectra in detail [208]. I was lucky to partake in those exciting discoveries.

8 Wrap-Up

What happened? I was raised and educated in West-Berlin. Despite the wall I had the chance to leave the divided city (Fig. 1) to explore the world and engage in the adventures of scientific discovery in the global magnetic resonance universe thanks a kick-start I got from Dieter Ziessow in 1973. Throughout my life I had the good fortune of meeting and working with gifted people who made my work fun, challenging, and exciting. I am grateful to each one of them. Events with determining impact were my Fulbright scholarship in the USA, where I finally mastered the English language and met my wife, and the support by the Alexander von Humboldt foundation who enabled highly talented postdocs and visitors to join my group in Aachen. By working in Chemistry at the interface between Physics and Engineering,

it was always challenging to recruit students with an interest in NMR methodology. But in 2015, when already approaching retirement, we found an effective mechanism with support of the German Academic Exchange Service DAAD by establishing the Aachen California Network ACalNet of student and staff exchange involving among others my colleagues Jeff Reimer and Alex Pines at UC Berkeley, Song-I Han at UC Santa Barbara, and Louis Bouchard at UC Los Angeles. The network assisted in identifying the best students at the respective locations and enabled them to work in a partner institution across the Atlantic for a few months while also supporting staff exchange to stimulate further cooperation.

The mandatory retirement in Germany forced an end to my work as a professor, and the transition to retirement peaked in a Transition Colloquium at the end of July 2019 when I transited from "dutiful professor to duty free spirit" with many friends and former students attending. The emeritus status does not exist in Germany so that I now enjoy the role of a postprof, hosted by Thomas Wiegand, who came from ETH Zürich to continue the NMR focus in Chemistry at RWTH Aachen University. Without management duties arising from operating a large research team, I can concentrate again for extended time on mobile NMR in collaboration with Jens Anders at the University of Stuttgart [209] and on exchange NMR [210]. But the little administration left to me now lets me appreciate even more the long-term comfort I have been spoiled with by my office assistants Ingrid Schmitz and Gerlind Breuer, and by Markus Küppers, who, after graduating with a thesis on MRI in 2005, has since diligently and reliably administered the many projects and technical issues encountered in my teaching and research. Last but not the least, I am grateful to my wife Mary-Joan and my children Gwendolyn, Franziska, and Max for their support of a frequently absent-minded husband and father.

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