World Record Magnets for Condensed Matter Physics Research

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I thought that I knew Bell Labs well when I joined as a Member of Technical Staff in November 1987. I had visited often while I was a graduate student doing my Ph.D. research at MIT's Francis Bitter Magnet Lab. Peter Wolff, then the Director of the Bitter Lab, was my thesis advisor of record, however, two frequent Bitter Lab visitors were my *de facto* thesis advisors, Horst Stormer at Bell Labs and Dan Tsui who had recently moved to Princeton from Bell Labs. Horst and Dan had brought me into their research group late in 1983 to help commission and operate a dilution refrigerator that had been specially designed and constructed by Peter Berglund to be compatible with the Bitter Lab's 28T hybrid magnet. The magnet offered the world's most intense DC magnetic field to visiting researchers, combining an outer superconducting electromagnet with an inner resistive electromagnet that required megawatts of DC electrical power and cooling water capacity to be able to be energized for hours at a time while experiments were being run.

This combination of dilution refrigerator temperatures and the world's most powerful magnets was necessary for the next generation experiments on the fractional quantum Hall effect that were to become the subject of my thesis. This drive to access a previously inaccessible region of experimental phase space was an example of Horst Stormer's research strategy: "Be the first one to carry a flashlight into a dark room. Look around for something new and exciting. If you don't find anything, move into the next room." That strategy had led Horst and Dan to their 1982 discovery and subsequent exploration of the fractional quantum Hall effect [1-4], research that led to the 1998 Nobel Prize in Physics together with Bob Laughlin, the theorist who explained the many-body phenomenon by providing many-body wavefunctions for the ground state and fractionally-charged quasiparticle excitations. [5]

I came to Bell Labs because I was keenly aware of the talent and the unique record of achievement of quite a few Bell Labs researchers. My goal was to design and construct a pulsed magnet system to provide magnetic fields roughly twice those that could be achieved with DC hybrid magnets. By foregoing the need for cooling the magnet, pulsed magnets could be made much smaller however the magnetic field pulses would be restricted to being 10 to 100msec in duration. The 500kJ capacitor bank that energized the pulsed magnet was much less expensive (half a million of my boss's boss's 1987 dollars) and simpler to operate than the 10MW DC power supplies necessary for DC magnets. As such, capacitor-bank-driven pulsed magnets offered an under-exploited sweet spot that offered higher magnetic fields yet lower costs and simpler operations. I came to Bell Labs with the plan to establish a research program using a capacitor bank and pulsed magnets of my own design, with a goal to publish research on the fractional quantum Hall effect and other condensed matter systems that required ultra-high magnetic fields to explore new dark rooms with a unique new flashlight.

The time was ripe for pulsed magnets to become much more productive for research. Several laboratories around the world had been operating pulsed magnets non-destructively to 50T for experiments - including laboratories at MIT, Leuven, Toulouse, and several laboratories in Japan. But copper-niobium nano-composites had been developed by Joze Bevk [6-8] that offered an unprecedented combination of high-strength (comparable to steel), high-conductivity (comparable to copper), and high ductility (such that 2mm x 3mm conductors could be wrapped into a coil with a 1cm diameter inner bore). The efficacy of these nano-composites in pulsed magnets had recently been demonstrated to achieve 68T by Si Foner at the MIT Bitter Lab [9-10].

Pulsed magnet systems were incredibly noisy at the time, both electrically and acoustically, which provided severe challenges to achieving good signal to noise due to direct electrical coupling and vibrational coupling from the power supply to the experiment. Power electronics had evolved to a point that one could imagine triggering the capacitor bank with quiet thyristors (each 80 to 100mm in diameter, stacked in series to handle the large voltages and in parallel to handle the large currents). They would replace the mechanical switches and ignitrons that were then state of the art. The former used the closing of a mechanical switch – and the accompanying arc flash – to trigger the magnet pulse, while the former would use a small spark from an electrode to vaporize a pool of mercury whose plasma would support the large electrical current during the magnet pulse...and would occasionally pre-trigger before the experiment was ready to go. Or leak mercury.

Data acquisition electronics had also evolved to become suitable for application to pulsed magnetic field experiments. At this time, most data were taken using dual-trace oscilloscopes featuring cathode ray tubes that were triggered by the onset of the pulsed magnetic field. The voltage traces on the oscilloscope screen recorded both the magnetic field versus time and an experimental measurement versus time. The traces were photographed and then painstakingly digitized to construct - by hand - the trace of the experimental measurement versus magnetic field. A number of laboratories were achieving better results using the new digital oscilloscopes that used 8-bit analog-to-digital converters, but these digitizers were developed primarily for repetitive experiments, such as pulsed laser experiments, that gathered a thousands of traces in fractions of a second, adding up multiple traces to get a clean experimental signal with the noise canceled out and offering more than 8 bits of effective dynamic range by dithering offset voltages from trace to trace. Pulsed magnets at the time could only be energized typically once an hour, so these standard techniques to suppress noise and enhance resolution were unsuitable for pulsed magnet experiments. But one vendor had recently released a 12-bit digital oscilloscope with enough memory to record hundreds of milliseconds of data at a 4Mb/sec data rate. Each could record two channels and two could be synchronized to provide a total of four channels of data, one for magnetic field versus time and three for experimental measurements. They were state of the art and within reach of a single investigator laboratory at Bell Labs.

What I came to appreciate within days of arriving at Bell Labs was the remarkably collaborative spirit of a vastly broader scope of world-class expertise than I could have previously imagined. While there was an organizational chart, it was amazingly flat, with virtually everyone holding the same title: Member of Technical Staff (MTS). Those in management were accomplished scientists...as far as I could see as a new MTS, it was scientists all the way up. And while the organizational chart was well-ordered on paper, the day-to-day Bell Labs was creatively chaotic, with offices, laboratories, and conference rooms seemingly randomly assigned, the better to encourage serendipitous conversations and collaborations. Anyone could talk to anyone. Indeed, data were presented and debated not only at seminars, but over lunch, during walks around campus, and over afternoon tea. Even salary increases were collectively debated and decided upon by multiple department heads, so researchers were not working to impress a single supervisor. It was clear that new science and technology was the path to success.

The first page in my informal lab notebook is dated "18 Nov 87". It includes notes from a conversation with Phil Platzman, the Department Head who had hired me and who convinced his boss to fund my pulsed magnet initiative via a four paragraph white paper that got the budgetary arithmetic mostly correct. Phil Platzman – *on my first day at Bell Labs* - mentioned two experiments that might be of interest while I was designing and building my pulsed magnet system. One involved the low-dimensional Bechgaard salts. Phil suggested that I talk to Gilles Montambaux, who was a theory postdoc at Bell Labs at the time. Gilles and I coauthored a Physical Review Letters [11] in 1990 with Robert Haddon, a long-time Bell

Labs researcher who I found after sending emails around the world asking who could grow the highest quality single crystals of these particular organic salts. "The best in the world come from your building," I was told by someone I emailed in Europe. Although Robert Haddon had not grown such samples in years, he was gracious enough to re-establish his past capability while implementing "a few new ideas I have to improve the quality." We performed the experiments using a superconducting magnet in Horst Stormer's lab, provided to us whenever he was not using it for his own experiments on the fractional quantum Hall effect.

Also on that first page, from my Phil Platzman conversation, is the (misspelled!) name of Loren Pfeiffer. Loren Pfeiffer and Ken West had recently revolutionized the molecular beam epitaxial growth of high-quality two-dimensional electron systems in GaAs/AlGaAs heterostructures and quantum wells. A major component of my career and the careers of many of my Bell Labs colleagues were enabled by collaborations with Pfeiffer and West.

These early experiments, using research infrastructure of others at Bell Labs and the MIT Francis Bitter Magnet Lab, enabled me to establish a research program while I was working to realize a pulsed magnet laboratory at Bell Labs.

I am struck by how many of the early notes in my first Bell Labs notebook are names of Bell Labs scientists followed by a short description of their expertise. The goal, clearly conveyed by Phil Platzman, was for me to become part of the distributed neural network at Bell Labs, the labwide professional connections that underpinned the Bell Labs culture. Quite a few of my new colleagues would make profound contributions to the success of our pulsed magnet initiative. On page 6 appears the name of John Plewes [12], an MTS who was a self-described "heat 'em and beat 'em" metallurgist who was happy to provide infrastructure for processing and testing the nano-composite materials to be used in pulsed magnets, from wire-drawing to tensile testing. On the same page, appears the (badly misspelled!) name of Joze Bevk. I was staggered to learn that the world expert on the Cu-Nb nano-composite that I wanted to use in pulsed magnets was an MTS whose lab was right around several corners from my own. And, while his present research interests and responsibilities on silicon kept him busy, he found the time to collaborate on designing and fabricating our nano-composites, interpreting our test results, and suggesting changes to further improve tensile strength, ductility, and conductivity.

But the biggest boost to my career came from Al Passner [13], one of the gifted technicians at Bell Labs who combined a profound knowledge of high-power electronics and data acquisition with a thoroughly entertaining approach to problem solving. Together, we puzzled out how to build our pulsed magnet lab and to construct pulsed magnets. A first-of-its-kind capacitor bank (Figure 1) was built commercially [14] following specifications developed by modeling the performance of hypothetical pulsed magnets made of plausible materials. Our computer modelling program was greatly enhanced by the contributions of Phil Snyder, an American Physical Society Summer Intern.

By February 1989, fifteen months after my first day at Bell Labs, the capacitor bank had been installed at Bell Labs and met its specifications. That year, the data acquisition systems were built, coil winding and wire insulation equipment installed, and initial experiments were completed to 49T using a conservatively-designed coil with heavily-insulated conductor.

In 1990, we published our first Physical Review Letters using our pulsed magnets, a paper describing resonant tunneling through a GaAs quantum well structure grown by Pfeiffer and West. [15] The 50T pulsed magnetic fields that we were then able to achieve were necessary to realize electron cyclotron energies that were resonant with and/or exceeded the energy to emit LO phonons in GaAs and/or AlAs. This enabled us to perform spectroscopy on two-dimensional magnetopolarons. I was not convinced that the result was sufficiently exciting to declare our pulsed magnetic field laboratory a success. But Al Passner explained that I had missed the point: this achievement was clearly enough for my boss's boss to explain to *his* boss that authorizing the money to build the lab had proven to be a good idea. And that the future was bright.

In the next few years, we had extended the use of our 50T magnets to study resonant tunneling from a two-dimensional electron system to spectroscopically measure the energy gap of the one-third fractional quantum Hall state [16] and to begin to close the energy gap in a Kondo insulator, both described in a conference proceedings published in 1994. [17]

During these years, Al Passner and I were networking with Bell Labs materials scientists to make a run at the world record for nondestructive generation of magnetic fields. With the advice and metallurgical equipment of John Plewes, we were able to perform months of testing on short samples of copper-niobium composites manufactured under our direction by a commercial vendor. In January 1989, we received our first quote for delivery of 100 pounds of copper-niobium nanocomposite wire with specifications suitable for realizing our pulsed magnet designs: rectangular cross-sections with ultimate tensile strength exceeding 200ksi, resistivity less than 3.0 micro-ohm cm (which corresponds to a conductivity exceeding 58% IACS, the International Annealed Copper Standard), and a ductility such that the conductor can be wound into a five-turn pigtail of 0.750 inch inner diameter. Less important to us was the precise rectangular cross-section, provided that it was around 0.1 inches on a side, give or take 20%. The reason is that the wire needed to be drawn down from a 4-inch diameter billet, restacked, then drawn down to final dimensions. We needed to meet the tensile strength and ductility specifications in order for the magnet to succeed. The precise cross-section did not matter as much, because it only affected the total inductance of the magnet coil. We could tune the voltage and capacitance of our capacitor bank to get the pulse shape we wanted to avoid burning up the magnet during a pulse.

We needed to center the magnet coil inside a steel cylinder to react against the huge forces that could rip our coil apart...and to catch any fragments that might otherwise launch if our coils ripped apart. A.J. Jayaraman (previously at Bell Labs, who had recently moved to the University of Hawaii) suggested a particular high-strength, high-durability steel, a titanium-strengthened 18% nickel maraging steel. And finally, we needed insulating beads to fill the annular volume between the magnet coil and the steel cylinder. The idea is that we needed a supporting material - namely ultra-strong, ultra-tough beads - that would support magnet coils of any size...that never were perfect cylinders (due to imperfections in our coil winding). We wanted beads because beads would allow liquid nitrogen to directly contact the outer diameter surface of the magnet coil to enable rapid cooling after every pulse. Spoiler Alert: That large cooling interface eventually enabled the Bell Labs magnets to repeat sixty tesla pulses every nineteen minutes, a pulse repetition rate that has yet to equaled by any national magnet laboratory at the time of this writing...and a rapid pulse repetition rate results in an immediate increase in scientific productivity.

To determine which beads might be the best for our application, Al and I requested samples from any and every company that advertised ultra-tough beads. Al Passner then would perform his dynamic bead toughness testing protocol, a simple and rapid protocol that was dramatically conclusive. Step 1: Al placed the candidate bead on a steel plate. Step 2: Al hit the bead with a hammer. The first dozen beads of various materials, tested over several months, all shattered into useless dust. So we canvassed the Bell Labs neural network and found Dave Johnson, a world-class ceramicist. Once he heard about our application, he suggested partially-stabilized zirconium oxide beads, explaining that, above 1100C, zirconium oxide transitions into a tetragonal crystalline phase that is 10% lower in volume than the lower-temperature cubic phase. Adding 10-15% of an element like calcium, magnesium, or yttrium will stabilize the cubic crystalline phase over all temperatures. If smaller concentrations of stabilizer elements are added, the material cools into a two-phase state, with small tetragonal regions incorporated into a cubic matrix. Under huge stresses, if a crack front hits a tetragonal region, it transforms into the less dense cubic phase, disrupting the crack propagation by, in effect, consuming the crack itself. Dave further helped us find a commercial source for 1mm diameter beads of partially-stabilized zirconium oxide. In January 1989, a vial of 50 beads arrived at Bell Labs. When Al Passner hit these beads with his hammer they...disappeared! He tried a second bead with the same results. What was going on? The third bead ended up flying toward Al's belly, where the minor pain of its impact made us realize that THESE beads were not shattering. They were being propelled – undamaged - out from between the hammer and the steel plate in random directions. So Al developed a static bead toughness testing protocol: he placed the bead between two plates of steel and put the "bead sandwich" into a vice. The result was one undamaged bead and two steel plates, each with a perfect bead-sized hemispherical dent. We had found our bead and, thanks to the vast network of Bell Labs researchers, we had identified the complete list of materials necessary to realize our third-generation magnets!

By early 1993, Al Passner, Joze Bevk, and I set a new world record for non-destructive pulsed magnetic fields, building two magnets (Figures 2 and 3**)** that achieved 72T. These third-generation magnets featured an inner-most layer of Cu-Ni-Be (a strong but particularly ductile conductor), six layers of Cu-Nb (the highest-strength nanocomposite), and seven outer-most layers of Cu-Alumina (a strong, but particularly high-conductivity conductor). This tailored conductor properties to address the most important constraints that varied throughout the entire coil winding pack. It also helped to conserve the rare and expensive CuNb nanocomposite. The magnet pulse took 5msec to reach peak field and the higher conductivity Cu-Alumina enabled a longer exponential decay of the magnet pulse, featuring a ~25msec time constant.

The world record achievement was noted in the May/June 1993 issue of the AT&T Technical Journal and more thoroughly described in the refereed literature shortly thereafter. [18] These magnets routinely delivered many hundreds of 60T pulses before the inevitable metal fatigue or insulation breakdown lead to a "magnet disassembly event", and event that was relatively mild because our magnet coil and support (beads plus steel cylinder) were designed to arrest the propagation of damage from its point of origin. In 1995, Bevk, Passner, and I applied for a patent on our wire processing protocols that had improved the strength and ductility of CuNb nanocomposite.

The routine 60T magnetic field pulses enabled us to fully close the Kondo insulator gap in $Ce_3Pt_4Bi_3$, thereby completing our work on that heavy fermion compound. [19,20] However, at this point, my plans to use pulsed magnetic fields to study the two-dimensional electron system in the extreme quantum limit were confronted with a cold reality: while we had increased peak magnetic fields by twenty percent, Loren Pfeiffer and Ken West had reduced the electron density in their high-quality samples by an order of magnitude, pushing phenomena that were at 50T down to 5T. I needed to pivot to a research frontier where the magnetic field energy scale was fixed by a Higher Power than Loren and Ken.

So I turned to studying high-temperature superconductivity, climbing the steep learning curve with the assistance of the finest search engine I have ever experienced: conversations in the corridors at Bell Labs. While I had certainly been intrigued by high-temperature superconductivity, it soon became clear how intense magnetic fields could open up a new research frontier on these still-enigmatic superconductors. Sam Martin and his Bell Labs collaborators had reported on the transport properties of both single-layer and double-layer BiSrCaCuO single crystals, finding a linear-in-temperature resistivity from 700K down to the superconducting transition temperature T_c for transport in the copper oxygen plane and a surprising insulating behavior in the resistivity for transport between the copper oxygen planes. [21,22] An obvious question was whether these behaviors extended to extremely low temperatures when the superconducting phase was suppressed.

I, thus, launched a research program on high temperature superconductors with the strategy of using intense magnetic fields as the gentlest way to suppress the superconducting phase and reveal the underlying (resistive) state that gives rise to high-temperature superconductivity. It is a research strategy that is now followed by dozens of research groups around the world, including many who visit the United States' National High Magnetic Field Laboratory where I have spent the balance of my career after leaving Bell Laboratories in 1998.

But before we could really get going on our high-temperature superconductivity research program, during an era when AT&T had privatized and, thus, needed to compete with other for-profit corporations, Bell Labs researchers were asked to contribute to commercialized (or commercializable) technologies whenever possible. Research on high-temperature superconductivity was not perceived (fairly enough, at that time) as qualifying and, by any reasonable metric, too many Bell Labs researchers were working on high-temperature superconductivity already. My colleagues and I had just demonstrated a world-leading magnet technology and were learning to make the first low-noise and precise measurements of the absolute resistivity of a sample in the challenging environment of an intense magnet pulse.

We were lucky that, during the summer of 1994, Al Passner and I had worked with Joel Javitt from Bell Labs' Advanced Wireless Communications Technology Department, assessing the feasibility of an unusual wireless application involving radiating power to an inexpensive remote tag and detection of the tag's response. We needed to respond within a week. We judged the proposal from the engineers to be feasible but complex, and they opted for a much simpler remote "tag" that was simply a passive LC oscillator, a strategy that gave them the functionality that they needed. In 1995, Joel contacted us with a much bigger follow up request. He needed to know the inductance of X turns of wire of a given size. He also needed to know the mutual inductance between a remote LC oscillator buried under a train track and a pickup coil on board a locomotive as it passed over the remote LC oscillator. Neither calculation had a formula that could be applied, but both could be solved by the computer code that Al Passner, Phil Snyder, and I had developed to model our pulsed magnets. In 1995, we completed what we called the "TRAINS R US" project which enabled a locomotive to identify which track it was on. This earned bonus points for AT&T and contributed to winning a 10-year telecommunications service agreement from CSX Transportation Inc worth more than $250M to AT&T. I asked that a memo be sent from Joel's management chain to my management chain detailing our contribution...and we found ourselves free to pursue our interests in high-temperature superconductivity!

By now, our garden variety pulse was 62 tesla every twenty minutes, producing data about 10T above our competitors with a pulse repetition rate that was three times faster. In some experiments on Kondo insulators and high-temperature cuprate superconductors, we were measuring the resistivity of exactly the same samples on which competing pulsed magnet labs could not get good results. It was the perfect time for Yoichi Ando, then a researcher at the Central Research Institute of the Electric Power Industry (CRIEPI) in Tokyo, to join our collaboration for two years, bringing samples that colleagues of his in Japan had grown. We quickly learned that magnetic fields of 60T range were required to completely suppress the superconducting phase and reveal the properties of the resistive state at low temperatures (~1K). Previous attempts to suppress the superconducting phase used chemical dopants to introduce disorder. The disorder suppressed the superconducting state, but it also dramatically increased the resistivity of the non-superconducting state. Magnetic fields proved a much more gentle technique for suppressing superconductivity, leaving transport properties unchanged except for a relatively small (typically negligible) magnetoresistance. With all the energy required to generate the magnetic field, 60T imposes only ~6meV energies on electronic systems, whether coupling to electron orbits (cyclotron energy) or spins (Zeeman energy). This was much gentler than the 100's of meV's of the disorder potential that results from chemical doping. That said, our studies in the low temperature limit were restricted to $(La,Sr)_2CuO_4$ (LSCO) and La-doped Bi-2201 (La:Bi2201), the two cuprates with the lowest upper critical magnetic fields. Indeed, later experiments in Los Alamos have shown that $YBa_2Cu_3O_{7-\delta}$ remains superconducting below 15K even in magnetic fields of 100T.

By gently "peeling back" the superconducting phase, we were able to extend Sam Martin's measurements to ~ 1K, finding that the in-plane resistivity of optimally-doped La:Bi-2201 remains metallic while the c-axis resistivity continues to increase and seems to want to diverge in the zero temperature limit [23]. An even more surprising result was found when we studied superconducting samples in the underdoped regime, i.e. samples with fewer carriers than samples that maximize the value of T_c. Here, when magnetic fields have suppressed the superconductivity in LSCO, we found insulating behavior in both in-plane and c-axis resistivity that exhibits a still-unexplained logarithmic divergence with decreasing temperature. [24,25] Similarly robust logarithmic divergences were later found in La:Bi-2201 [25,26] and YBCO [27], although the doping range over which the logarithmic divergence is observed is smaller in these compounds: indeed, it is only observed in extremely underdoped YBCO samples in which T_c is very nearly zero.

By extending our measurements to multiple doping levels, we mapped out a metal-to-insulator crossover in LSCO that exists in the "normal" (ie resistive) state at the same doping at which high-temperature superconductivity is optimal. [28] This coincidence between the normal state and superconducting state was a first suggestion that a low-temperature phase transition might underlie the superconducting dome in the temperature versus doping phase diagram of the high-temperature superconducting cuprates. Later Hall voltage measurements in our pulsed magnets showed a peak in the Hall number in both LSCO [29] and La:Bi2201 [30] at the same doping at which Tc is highest, further evidence of a quantum phase transition around which high-temperature superconductivity is stabilized.

In March 1998, several months before I left Bell Labs, I gave an internal solid state seminar titled "Phase Diagrams of High-Tc Superconductors" that summarized our work on LSCO, Bi-2201, and YBCO, including systematic variations of the temperature dependence of the upper critical magnetic field for these materials that feature very different anisotropies. [31]

Also in 1998, a collaborative Bell Labs team demonstrated the efficacy of micromachined silicon structures to realize novel measurement techniques suitable for use in pulsed magnets. By making samples and sample probes smaller, eddy current heating is greatly reduced in metallic samples and mechanical resonances increase in frequency such that the millisecond pulse of the magnet becomes slow in comparison. Our trampoline magnetometer was, in effect, a parallel plate capacitor, ~400 microns on a side, with the bottom plate deposited on the (immobile) substrate. The top plate - on which the platelet sample was mounted - was held above the bottom plate by small silicon springs. A magnetic force resulting from a changing magnetic moment of the sample induces a change in the gap size between the plates, a displacement that can be measured with great speed and sensitivity using a capacitive bridge circuit. We demonstrated the device by detecting the deHaas-vanAlphen quantum oscillations from a very small sample of an organic superconductor whose superconductivity had been suppressed by the magnetic field. [32]

The pulsed magnet lab at Bell Labs then ceased operations in preparation for my July 1998 move to Los Alamos National Laboratory to direct the Pulsed Field Facility of the United States' National High Magnetic Field Laboratory, where much larger pulsed magnetic field infrastructure (worth hundreds of millions of dollars) was coming online, where together this new team of colleagues developed non-destructive pulsed magnets that achieved 100T in 2012. That non-destructive pulsed magnet technology, powered in part by a 1.4GW motor-generator (the largest in the United States) offers routine pulses of 90T. The pulses are provided in service to a much larger user community than we could have possibly served with our Bell Labs pulsed magnet laboratory. In 2015, Brad Ramshaw, who spent several years at the Los Alamos pulsed magnet laboratory before becoming a professor at Cornell, used these 90T pulses to observe quantum oscillations in YBCO near optimum doping, finding that the effective mass of the quasiparticles is enhanced – and apparently diverging – in the vicinity of optimum doping in YBCO. [33] This is clear evidence of enhanced quasiparticle interactions near a quantum phase transition in the cuprate superconductors, the phase transition that was first evidenced in LSCO and La:Bi-2201 in the Bell Labs pulsed magnet laboratory.

Bevk, Passner, and I were finally awarded Patent #5,787,747 for "Process and Apparatus for Making *in-situ*-Formed Multifilamentary Composites" in August of 1998, a patent that described a wire-drawing process for developing high-strength multifilamentary composites by maintaining a high density of dislocations. These dislocations are thermodynamically unstable and form as the wire's cross section is reduced, a process that also heats the wire. High temperatures enhance dislocation mobility, which increases the likelihood that two dislocations will collide and annihilate each other. The 24-page patent, at the level of this physicist's understanding, can be summarized in four words: "draw the wire slowly". Clearly, the success of the Bell Labs pulsed magnet laboratory depended upon the deep insights and contributions of many of my Bell Labs colleagues, for which I am extremely grateful. These colleagues contributed to the Bell Labs environment that was both extremely competitive and collaborative, altogether, all at once.

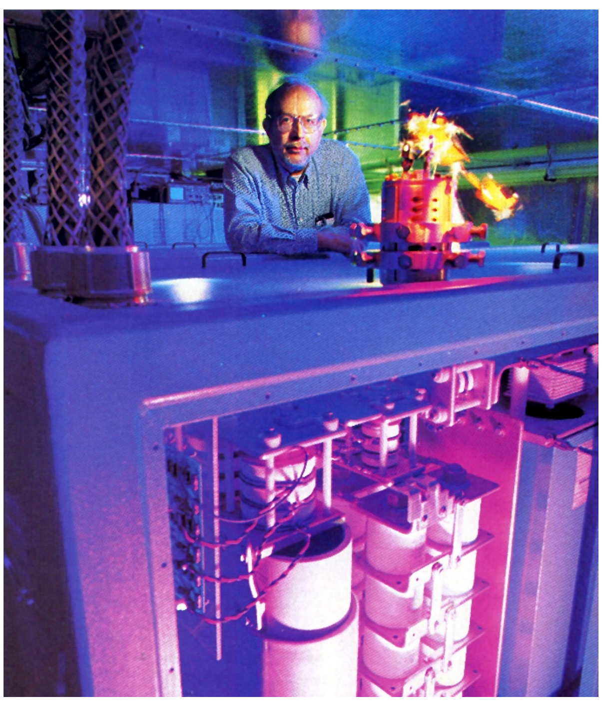

Figure 1: Al Passner with the 12kV, 512kJ capacitor bank used to energize the pulsed magnets. Our second-generation 50T magnet is shown sitting on top of the capacitor bank, with sparks added for visual impact. The energy stored in the electric field of the capacitors is transferred to create the intense magnetic field in the (much smaller) magnet. (Image appeared in Ref. 34. Used with permission of the photographer, Chip Simons)

Figure 2: The two world-record 72T pulsed magnets [18]. At left is the completely assembled magnet, housed in the VascoMax steel casing used to precompress the magnet coil... and to contain any “magnet disassembly events”. At right is the magnet coil removed from its casing, wound with three different conductors chosen for high ductility (layer 1), high strength (layers 2-7), and high conductivity (layers 8-14).

Figure 3: One of world-record 72T pulsed magnets [18], shown with the author holding two halves of a second magnet coil (cut in half to facilitate post-pulse analysis). The experimental sample and plastic cryostat tails fit inside the 9.2mm diameter clear bore of the magnet coil at the center of the coil windings. At extreme left is one of the twelve thyristors used to switch the capacitor bank that energized the magnets. The thyristors were stacked three in series and four in parallel to handle the 12kV voltage and 325kA current specifications, respectively.

[1] D.C. Tsui, H.L. Stormer, A.C. Gossard, "Two-dimensional magneto-transport in the extreme quantum limit", Phys. Rev. Lett. **48**, 1559 (1982)

[2] D.C. Tsui, H.L. Stormer, A.C. Gossard, "Zero-resistance state of two-dimensional electrons in a quantizing magnetic field", Phys. Rev. **B25**, 1405 (1982)

[3] H.L. Stormer, A. Chang, D.C. Tsui, J.C.M. Hwang, A.C. Gossard, W. Wiegmann, "Fractional quantization of the Hall effect", Phys. Rev. Lett. **50**, 1953 (1983)

[4] D.C. Tsui, H.L. Stormer, J.C.M. Hwang, J.S. Brooks, M.J. Naughton, "Observation of a fractional quantum number", Phys. Rev. **B28**, 2274 (1983)

[5] R.B. Laughlin, "Anomalous quantum Hall effect: an incompressible quantum fluid with fractionally charged excitations", Phys. Rev. Lett. **50**, 1395 (1983)

[6] J. Bevk, James P. Harbison, Joseph L. Bell, "Anomalous increase in strength of *in situ* formed Cu-Nb multifilamentary composites", J. Appl. Phys. **49**, 6031 (1978)

[7] Keith R. Karasek, J. Bevk, "Normal-state resistivity of *in situ*-formed ultrafine filamentary Cu-Nb composites", J. Appl. Phys. **52**, 1370 (1981)

[8] J. Bevk, "Ultrafine filamentary composites", Annu. Rev. Mater. Sci. **13**, 319-338 (1983).

[9] S. Foner, "68.4T-long pulse magnet: Test of high strength microcomposite Cu/Nb conductor", Appl. Phys. Lett. **49**, 982 (1986)

[10] S. Foner, E. Bobrov, C. Renaud, E. Gregory, J. Wong, "68.4T pulsed magnet fabricated with a wire-wound metal-matrix Cu/Nb microcomposite", IEEE Trans. on Magnetics **24**, 1059 (1988)

[11] G.S. Boebinger, G. Montambaux, M.L. Kaplan, R.C. Haddon, S.V. Chichester, L.Y. Chiang, "Anomalous magnetoresistance anisotropy in metallic and spin density wave phases of the quasi-one-dimensional organic conductor $(TMTSF)_2$ ClO_4", Phys. Rev. Lett. **64**, 591 (1990).

[12] "A History of Engineering and Science in the Bell System, Physical Sciences (1925-1980)" S. Millman, editor. (1983), Chapter 18 "Improving the Mechanical Properties of Materials", pp.566-567. ISBN: 0-932764-03-7

[13] Al Passner is featured elsewhere in this volume, in "Positron and Plasma Research at Bell Labs after 1980". (see photo in that article)

[14] H.G. Hammon III, D. Strachan-Brown, R. Hitchcock, D. Spelts, G.S. Boebinger, "The design and test of a 500-kJ, 325-kA energy discharge bank employing solid state switching", Proc of 7th IEEE Pulsed Power Conference, Monterey, CA, 305 (1989).

[15] G.S. Boebinger, A.F.J. Levi, S. Schmitt-Rink, A. Passner, L.N. Pfeiffer, K.W. West, "Direct observation of two-dimensional magnetopolarons in a resonant tunnel junction", Phys. Rev. Lett. **65,** 235 (1990).

[16] G.S. Boebinger, A.F.J. Levi, A. Passner, L.N. Pfeiffer, K.W. West, "Direct observation of the electron spectral function in the integer and fractional quantum Hall regimes by resonant tunneling", Phys. Rev. **B47,** 16608 (1993).

[17] G.S. Boebinger, "Experiments in pulsed magnetic fields at AT&T Bell Laboratories", Physica **B201**, 20 (1994).

[18] G.S. Boebinger, A. Passner, J. Bevk, "Seventy-two tesla non-destructive pulsed magnetic fields at AT&T Bell Laboratories", Physica **B201**, 560 (1994). DOI: 10.1016/0921-4526(94)91161-4

[19] G.S. Boebinger, A. Passner, P.C. Canfield, Z. Fisk, "Studies of the Kondo insulator, $Ce_3 Bi_4 Pt_3$, in 61 tesla pulsed magnetic fields", Physica **B211**, 227 (1995)

[20] Z. Fisk, J.L. Sarrao, S.L. Cooper, P. Nyhus, G.S. Boebinger, A. Passner, P.C. Canfield, "Kondo Insulators", Physica B-Condensed Matter **223-224,** 409 (1996).

[21] S. Martin, A.T. Fiory, R.M. Fleming, L.F. Schneemeyer, J.V. Waszczak, "Normal-state transport properties of $Bi_{2+x}Sr_{2-y}CuO_6$ crystals", Phys. Rev. **B41 (RC)**, 846 (1990)

[22] S. Martin, A.T. Fiory, R.M. Fleming, L.F. Schneemeyer, J.V. Waszczak, "Temperature dependence of the resistivity tensor in superconducting $Bi_2Sr_{2.2}Ca_{0.8}Cu_2O_8$ crystals", Phys. Rev. Lett. **60**, 2194 (1988)

[23] Yoichi Ando, G.S. Boebinger, A. Passner, N.L. Wang, C. Geibel, F. Steglich, "Metallic in-plane and divergent out-of-plane resistivity of a high-Tc cuprate in the zero-temperature limit", Phys. Rev. Lett. **77**, 2065 (1996). (See also errata: Phys. Rev. Lett. **79**, 2595 (1997).

[24] Yoichi Ando, G.S. Boebinger, A. Passner, Tsuyoshi Kimura, Kohji Kishio, "Logarithmic divergence of both in-plane and out-of-plane normal-state resistivities of superconducting $La_{(2-x)} Sr_x CuO_4$ in the zero-temperature limit", Phys. Rev. Lett. **75**, 4662 (1995)

[25] Yoichi Ando*, G.S. Boebinger, A. Passner, N.L. Wang, C. Geibel, F. Steglich, I.E. Trofimov, F.F. Balakirev, "Normal-State Hall Effect and the Insulating Resistivity of High-Tc Cuprates at Low Temperatures", Phys. Rev. **B56,** R8530 (1997).

[26] S. Ono, Yoichi Ando, T. Murayama, F. F. Balakirev, J. B. Betts, G. S. Boebinger, "Metal-to-Insulator Crossover in the Low-Temperature Normal State of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$", Phys. Rev. Lett. **85**, 638 (2000).

[27] Nicholas Doiron-Leyraud, Mike Sutherland, S.Y. Li, Louis Taillefer, Ruixing Liang, D.A. Bonn, W.N. Hardy, "Onset of a Boson mode at the superconducting critical point of underdoped $YBa_2Cu_3O_y$", Phys. Rev. Lett. **97**, 207001 (2006)

[28] G.S. Boebinger, Yoichi Ando, A. Passner, T. Kimura, M. Okuya, J. Shimoyama, K. Kishio, K. Tamasaku, N. Ichikawa, S. Uchida, "Insulator-to-metal crossover in the normal state of $La_{2-x}Sr_xCuO_4$ near optimum doping", Phys. Rev. Lett. **77**, 5417 (1996)

[29] F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, "Quantum Phase Transition in the Magnetic-Field-Induced Normal State of Optimum-Doped High-Tc Cuprate Superconductors at Low Temperatures", Phys.Rev.Lett. **102**, 017004 (2009)

[30] Fedor F. Balakirev, Jonathan B. Betts, Albert Migliori, S. Ono, Yoichi Ando & Gregory S. Boebinger, Nature **424**, 912 (2003). "Signature of optimal doping in Hall-effect measurements on a high-temperature superconductor"

[31] Y. Ando, G.S. Boebinger, A. Passner, L.F. Schneemeyer, T. Kimura, M. Okuya, S. Watauchi, J. Shimoyama, K. Kishio, K, Tamasaku, "Resistive upper critical fields and irreversibility lines of optimally doped high-Tc cuprates", Phys. Rev. **B60**, 12475 (1999).

[32] V. Aksyuk, F.F. Balakirev, G.S. Boebinger, P.L. Gammel, R.C. Haddon, D.J. Bishop, "Micromechanical Trampoline Magnetometers for use in Large Pulsed Magnetic Fields", Science **280**, 720 (1998).

[33] B. J. Ramshaw, S. E. Sebastian, R. D. McDonald, James Day, B. S. Tan, Z. Zhu, J. B. Betts, Ruixing Liang, D. A. Bonn, W. N. Hardy, N. Harrison, "Quasiparticle mass enhancement approaching optimal doping in a high-Tc superconductor", Science **348**, 317 (2015)

[34] This image appeared in Greg Boebinger, Al Passner, Joze Bevk, *"Building World-Record Magnets",* Scientific American, June 1995, p.58.