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THE DEVELOPMENT OF MAGNETIC RESONANCE IMAGING AND SPECTROSCOPY

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Some of Eddy Boskamp's memories about RF coil history

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In the summer of 1983, right after finishing my Physics and Mathematics PhD, I was offered 2 jobs at Philips, the Dutch equivalent to GE. One of the jobs was at the R&D lab in Eindhoven, the other was at Philips Medical systems in Best, the Netherlands, where they had just started researching a brand-new diagnostic imaging technique, called Nuclear Magnetic Resonance at the time. I was intrigued, could I really work on a tool that would clearly benefit mankind directly, rather than some obscure set of interatomic or internuclear potential curves, the topics of my master's and PhD work? I did not have to think about it that long. Shortly thereafter, in July of 1983 I was hired at Philips Medical Systems, and my initial task was to figure out how to do spectroscopy on the future Philips system, I guess I was chosen because of my nuclear and atomic physics background. I sold my house in Utrecht, where I had moved from my hometown of Rotterdam to finish my PhD and moved into a rental in Eindhoven about a 10 min commute from work. In those early days, Philips only had a 0.3T resistive system. It was water-cooled and just outside the building was a heat exchanger to keep its temperature under control. Some of the folks from the R&D lab were always there working on it to stabilize the field. Upon my arrival all MRI engineers were in a trailer. I had to share an office with Peter van der Meulen and Gert van Yperen, right next door were many Hardware, pulse sequence engineers and physicists that have earned my respect: Jan van Eggermond, Jan Groen, Ewoud Vreugdenhil, Ruud Kemner, Michael Duijvestein, Hans Tuithof to name a few. We quickly grew out of that "building", so Philips invested in a brand-new 5 story building for the MR business, where we moved in 1986. In the meantime, more engineers and physicists had joined the team: Rob van Heelsbergen, Peter Wardenier, Giel Mens, Jan Konijn to name a few.

It was only a few months after my arrival that we got our first superconductive magnet from Oxford Industries. It was a 0.5T magnet, a major improvement over the 0.3T resistive system. In the meantime, I had made a simple circular coil to gather a crude phosphorus spectrum. I had no RF experience other than what I had learned in college from Bleaney and Bleaney: Electricity and Magnetism. The book dealt with EM waves, resonant circuits and even had a chapter about Magnetic Resonance. At the end of 1983 I had already tried proton imaging with a local coil, but there was a problem with the uniformity of the local coil's transmit field. Clearly the images would have a larger FOV if we did the excitation with the uniform field from the large body excitation coil, but this meant that we had to detune the receive coil during the transmit pulse or a large current would be induced therein. I achieved this with an array of varactor diodes at first and with PIN diodes later. I presented this work at the RSNA of 1984 and also showed the first spine images made with a receive only rectangular coil at 0.5T. During 1984 I also wrote a bunch of fortran programs to calculate B1+ uniformity for Ruud Kemner's "saddle" body coil and RF shield which was quite uniform outside the cylindrical RF shield but very non uniform

when inserted, confirmed by the calculation. Philips stayed with this linear Saddle coil in the first year, but then introduced a quadrature version which was basically 2 perpendicular saddle coils. In 1986 we were at 1.5T and introduced the birdcage resonator into the system after learning about the concept from GE presentations and Cecil Hayes' patent. In that same year I introduced a large number of flexible receive coils that were varactor tuned with the help of some software and digital to analog converters. The coils had integrated preamplifiers to maximize SNR. At that time we did not have array coils yet, so the preamps were not yet used to decouple array elements from each other. That would come later after the technique was introduced by Pete Roemer in 1991. I tried out the early concepts of the varactor tuned flex coils at Emory university in Atlanta (Dr Bernardino, Hoffman, Pettigrew) where we had installed one of our early 1.5T systems. Around 1985 I was responsible for all RF coil work in Best, and with the first birdcage body coil I proceeded to CNC machine the coil frame from polycarbonate sheets. Up until then the body coil frames were made from epoxy fiberglass by a local company that also made boats. The accuracy and roundness of the coils was underwhelming and impacted tuning, isolation and field uniformity inside a cylindrical RF shield that was only 2 cm bigger in the radial direction.

In the 80's I would regularly travel to our R&D lab in Hamburg, Germany where I worked with Peter Röschmann on topics like quadrature receive coils and new concepts for body coils. Peter was an exceptional RF scientist who authored a lot of papers on the topic of RF coils at high field. In the latter half of the 80's our lab in Hamburg had one of the first 2T systems, considered a super high field at that time. There were opinions that at such a high proton larmor frequency the RF field would not penetrate the body due to the skin effect, and hence whole-body imaging would be impossible. Peter did groundbreaking work on this system showing whole body images. He had spent some of his career at Columbia (Dr Hilal) and in Birmingham Alabama (Dr. Pohost) where I first met Thomas Vaughan in the late 80's.

By 1988 I was travelling back and forth to the USA several times a year for customer visits, conferences and RF installations. Philips decided to move me there to set up an RF engineering department in Shelton, CT, so I picked up my family and went. In Shelton I worked on quadrature Knee and Cspine coils across all frequencies. Because of the proximity there were many visits to NYU (Dr Weinreb) and Columbia (Dr Hilal) with colleagues Howard Simon and Steven Einstein. We had Medrad (Indianola PA) manufacture the coils, so I flew there a couple of times a year to meet with their RF engineer George Misic. I was an experienced pilot at that time. Renting a Piper Seneca was convenient, especially for site visits where I had to take some people along as well as equipment. In 1991 Philips wanted me back in the Netherlands, but we liked it here in the USA, so I decided to move to Medical Advances in Milwaukee. It was a small startup with about 10 employees making RF coils for MRI. The quality of their coils was very poor initially because they did not do any durability testing. I introduced rigorous engineering practices, a phase review process with many detailed steps per phase, built several test cages and tested every design at extreme B1+ magnitudes and duty cycles while recording the heat generated in blocking networks of various designs. After the improvement in quality sales went up. There was direct sales to the end user but also to major OEMs like GE, Picker, Siemens, Elscint and Philips. I was running all of Engineering. The company grew to 65 employees by the end of 1994. During this productive period, I wrote many patents and introduced many designs. There were regular trips to Cleveland to visit Neil Holland and Dave Molyneaux, Siemens in Erlangen (Herman Requardt), as well as many sites throughout the USA for on-site testing. Meetings at GE and the Medical College of

Wisconsin (Jim Hyde, Eric Wong and Andrzej Jesmanowicz) were also frequent. Prof Dr Paul Lauterbur invited me to Urbana IL and asked me to build some coils for his new 7T system. During my visit we went over the specifications. Unfortunately, his high field magnet never became operational but Dr Lauterbur went on to earn the Nobel prize in Medicine which he shared with Sir Peter Mansfield in 2003

In the early days of 1995, I worked with Randy Duensing at inVivo in Gainsville Florida, but I soon got a call from GE who wanted me to join their open MRI team. This meant I would not have to sell my house in Milwaukee, so I went for it.

Arriving at GE I joined a small team of people working on GE's interventional system also known as the double doughnut system. The system had 2 magnet coils with space in between for a surgeon to operate on the patient. I worked with Dr Ferenc Jolesz at the Brigham and Women's hospital in Boston to come up with the input requirements and soon thereafter introduced a number of flexible transmit receive coils. The system did not have a whole body transmit coil at the time. Within about a year I became part of GE's Applied Science lab, where I worked on advanced RF coil concepts. Scott Hinks, Jean Brittain, Graeme McKinnon, Kevin King, Jim Tropp were colleagues in ASL, but I also worked with the R&D lab in Schenectady NY (John Schenk, Bill Edelstein, Chuck Dumoulin, Chris Hardy, Ron Watkins and Randy Giaquinto). I worked on many exciting projects like shifting the RF shield to the outside of the Z gradient because the Z gradient was wound in such a way that it would not couple with the Birdcage body coil, Cooling in the RF space, Fast drop off body coils to avoid the star artifact, high channel count transmit arrays at 3T and 7T to improve uniformity of B1+, a body coil and RF shield for a vertical open 0.7T system which was a thermal challenge, 9.3T multinuclear coils for Dr. Thulborn. During my ASL days I had good relationships with Prof Steve Wright at Texas A&M and prof Rich Magin at UIC. They both sent me their graduate and PhD students who spent many months in my lab doing their thesis work. GE paid their stipend and there was a good chance of them being hired after they were done. I was an adjunct at Texas A&M, UIC, and Marquette. Krishna Kurpad was one of Steve's PhD students who worked with me on integrating the last stage of the RF power amps into the transmit arrays as current sources, which would provide decoupling between the channels of a transmit array much like the preamp decoupling scheme introduced by Roemer in 1991 for receiver arrays.

GE in the late 90's decided to outsource the RF coils to which I was strongly opposed because of the quality of the coils I saw from those 3rd party suppliers. In the end the financially oriented managers purchased US-Asia instruments in Aurora, OH and transformed it into GE coils , where GE is now manufacturing its receiver arrays. As I predicted it took time to bring their quality to a higher level than US Asia instruments quality, but they are now making great coils (Fraser Robb, Victor Taracila, Tom Stickle).

In 2010 ISMRM awarded me a fellowship for my early work in RF coils. I had been very active in ISMRM all along, going to all their meetings since 1985, being president of several study groups for a few years, teaching RF during the weekend educational sessions, moderate RF and safety sessions, review abstracts and so on. Unfortunately, I could not make it to that 2010 ISMRM for some unfortunate personal reasons.

Since 2011 I was Principal engineer for RF coils at GE. Pete Roemer returned to GE after GE bought his business and he became a close colleague and friend. I worked on Body coils with the local team, as well as the engineering teams in Tokyo and Beijing, but I also did work on advanced topics via simulation and prototyping. During those days I did a lot of full wave analysis to better understand cable waves and interactions, decoupling of arrays, and RF current density in transmit coils and arrays. I helped Bob Stormont and

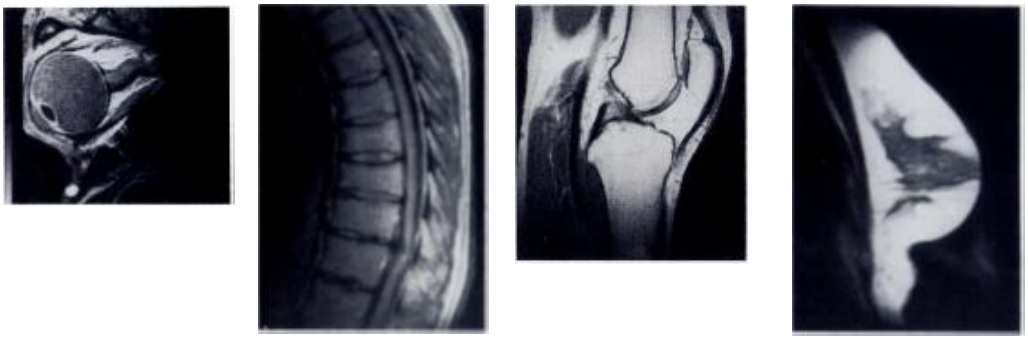
Scott Lindsay with some simulations for their distributed capacitance coil concepts which are now known as the GE air coils. Their array coils were a big success because they allowed more freedom in overlapping array elements. More than half of the coils now built in Aurora are air coils.
For personal reasons I had to leave Wisconsin in 2016 and moved to San Diego to work with Christine Chung at UCSD as a remote GE scientist. My work was concentrated on a Brachial Plexus array that was worn like a vest. The air coil elements were sewn into the vest.
In 2018 there was a significant lay off at GE, and unfortunately, I was affected. I immediately had 4 job offers: One from Stanford / Berkeley/ InkSpace (John Pauly, Greig Scott, Shreyas Vasanawala, Mikki Lustig, Ana Arias), one from QED (Hiro Fujita), one from GE coils, who wanted me back, and one from Hyperfine. I decided to move back to Connecticut to work for the Hyperfine start up. The circle was complete: I had started off with low field at Philips and now I was doing low field again. I had also started my US residency in Connecticut back in 1989. The Hyperfine system is a portable magnet…..well I would not want to lift it, but it has wheels, and you can therefor move it to the bedside in the ER or ICU. The magnet is a permanent 64 mT magnet with a proton larmor frequency of about 2.7 MHz. At Hyperfine I worked with many great physicists and Electrical Engineers like Mike Poole, Mike Twieg, Hadrien Dyvorne, Cedric Hugon, Gang Chen. Their head coil is a transmit receive array with a solenoidal transmit coil and an 8 channel receiver array. At this low frequency the coils are copper loss dominated and thus extra attention is given to the unloaded Q of the coils. The coils are made using multiple turns of Litz wire for the highest Q. I worked on improving the SNR and a motion correction system using 175 MHz dipole antennas integrated into the coil. Unlike the 2.7 MHz coil, the 175 MHz dipoles detune when the distance to the patient's head changes. Detecting the change in reflected power and skipping a line in k space every time motion occurs, which later in the scan gets reacquired, resulted in motion free images that made DWI feasible at such a low field strength. Since the system is a head only system and is primarily used for detecting stroke, good DWI images are a must.
During the most recent 2 years at Hyperfine, I worked on several integrated whole body Transmit coil concepts for the portable MRI, as well as new shielding and RF shimming concepts to satisfy the FCC emissions requirements. I was a regular visitor at Intertek's lab in Massachusetts, where they have a 10 meter anechoic chamber for calibrated emission measurements across a broad spectrum. Many of those sessions were on the 3rd shift, but with a constant supply of coffee it was manageable.
I am presently still working at Hyperfine, despite my age (68). The concept of not contributing to science anymore does not appeal to me, so if that is the meaning of retirement, then retirement has to wait or be of a form where I can still do this work part time, while also having the time to visit my kids and grandkids.

Ed Boskamp PhD

Head shot

1984 0.5T Spine coil (Philips)

1984 0.5T Breast coil (Philips)



1984 0.5T images on the early Philips scanner, all acquired with receive only surface coils (decoupled from the transmit coil s)

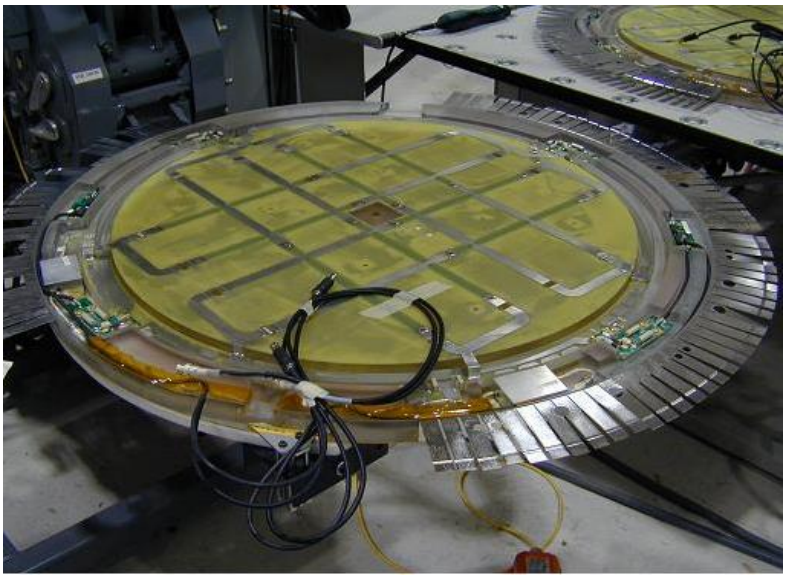
1986 Philips 1.5T spine coil: no surface mount components yet (Philips)

1987: checking the whole body Transmit coil for Philips T5

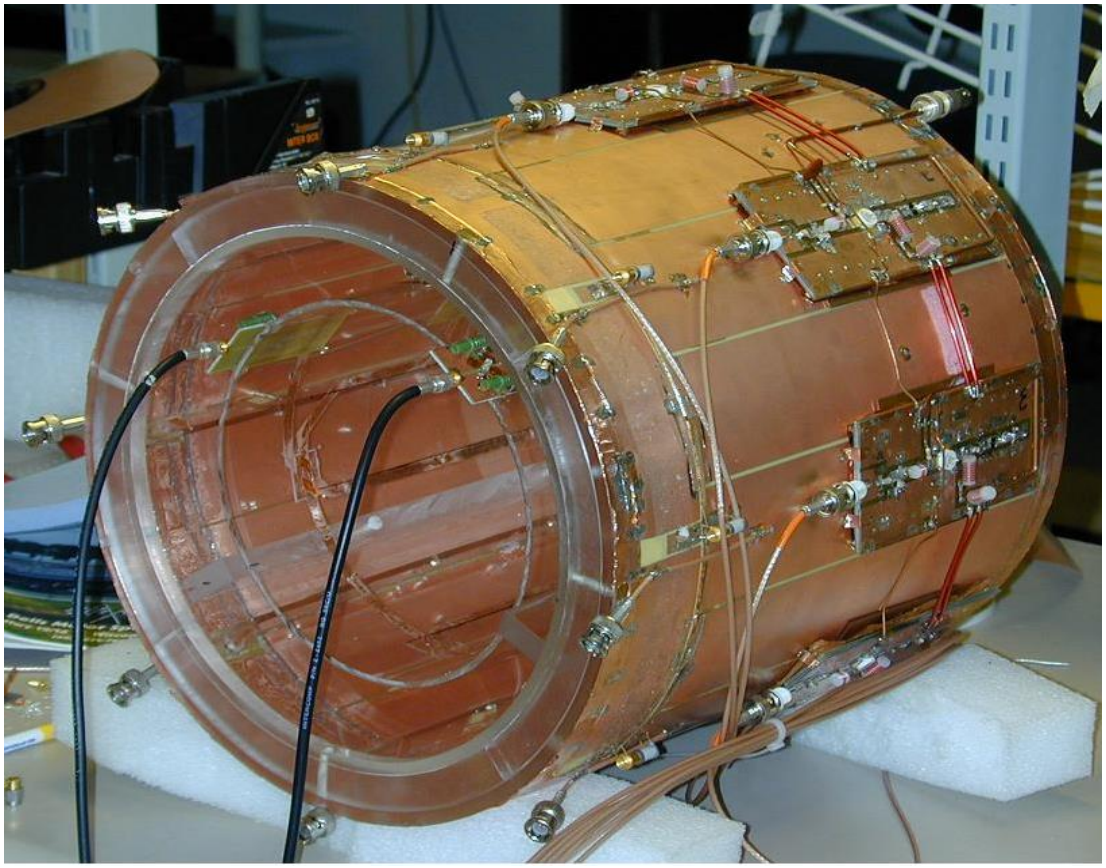
1990 Medical Advances Head Neck coil

1990 Medical Advances Foot / Knee coil

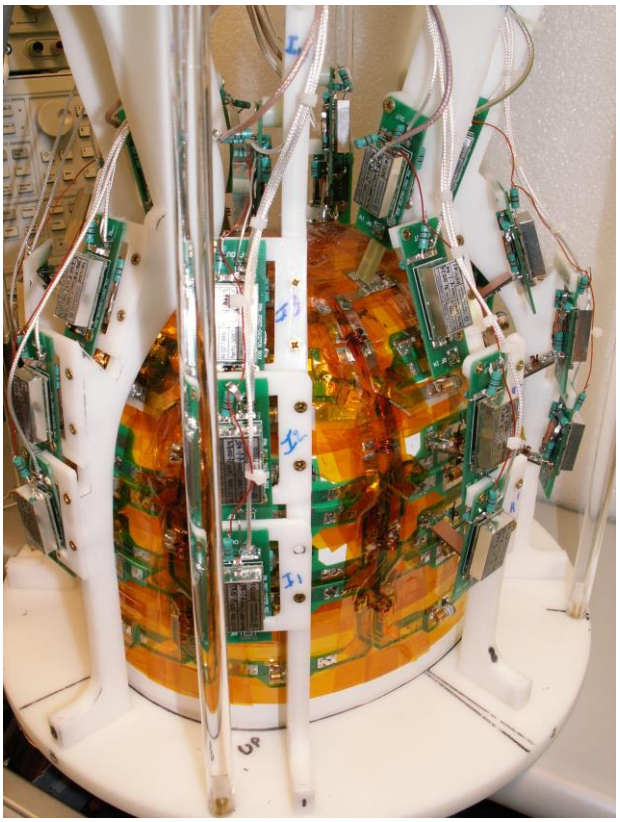
1991 Medical Advances abdominal array



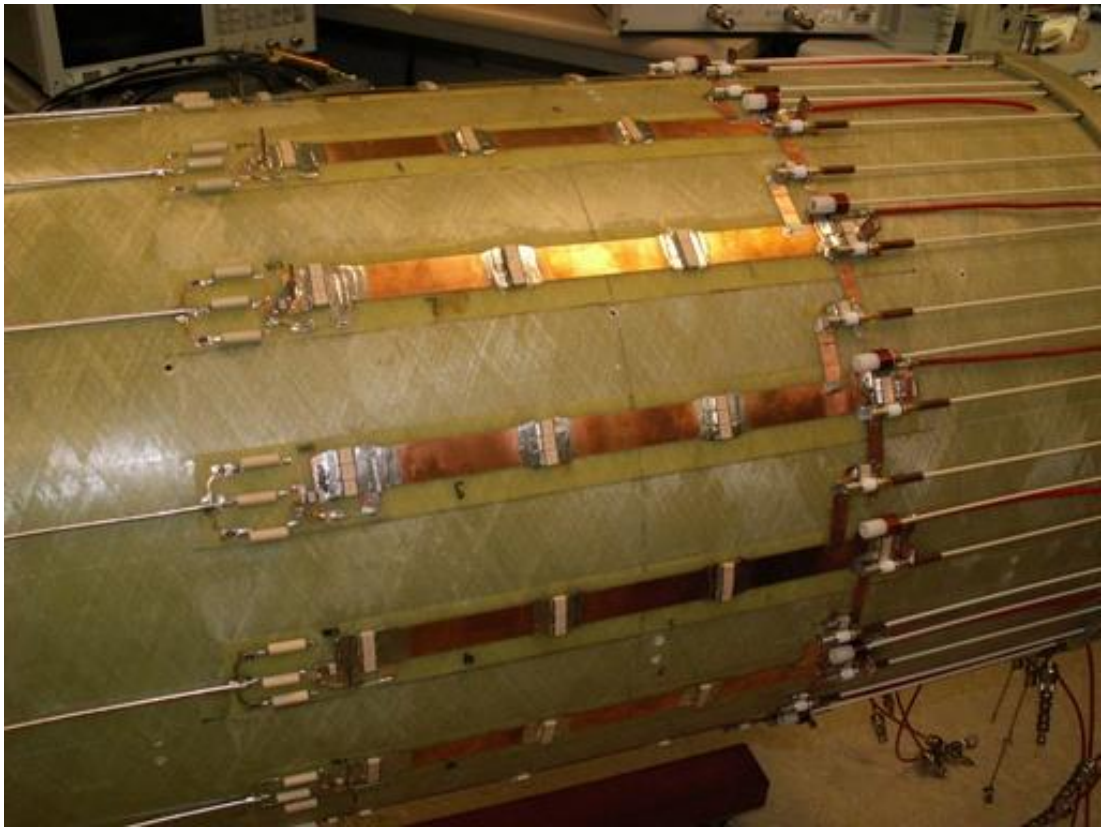
1999:29 MHz RF Body coil for vertical MRI system (one half of coil shown)



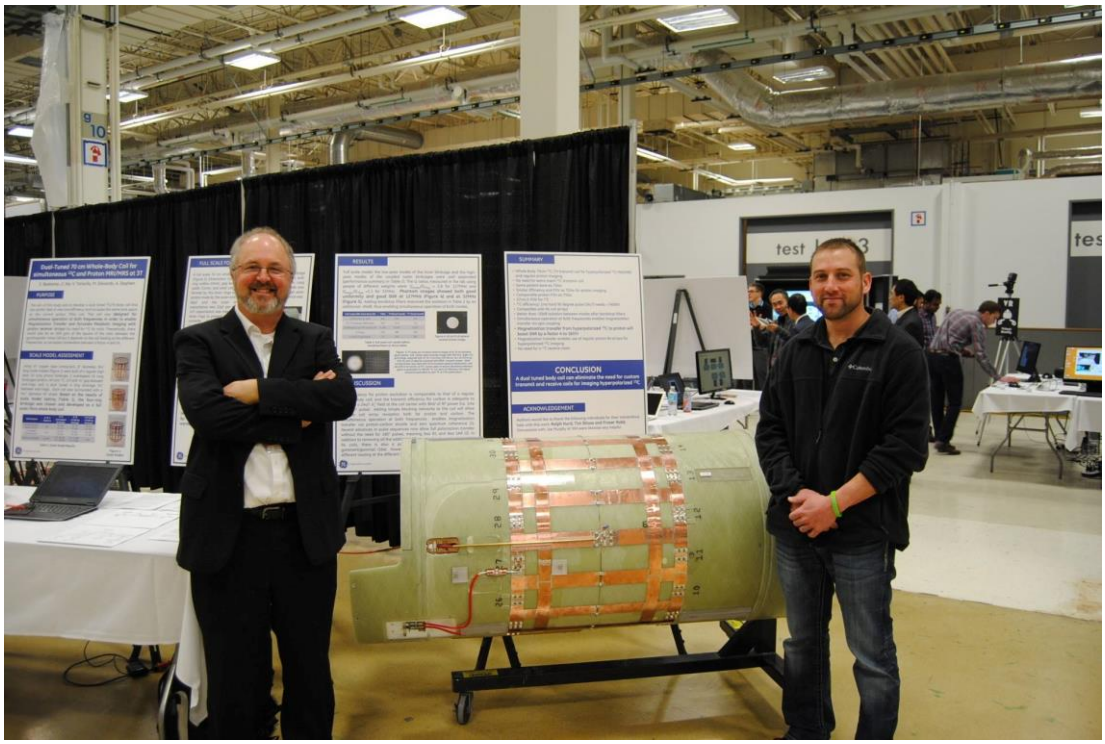
2002 With K. Kurpad, 8 channel 3T Transmit array with integrated MOSFET RF current sources



2006: with Scott Lindsay, 34 channel 3T Brain coil



2008: 16 channel 3T whole body Transmit array



2018: With Mike Edwards, Dual tuned Carbon / Proton transmit body coil

2022: 2.7 MHz transmit receive array for the 64 mT Hyperfine system