This paper will review the technological and commercial challenges that have defined the development of Ultra High Field (UHF) MRI magnet systems over the last 15 years when magnets with field strengths of 7T and above have been available for human applications such as spectroscopy, fMRI, CSI and MRI.

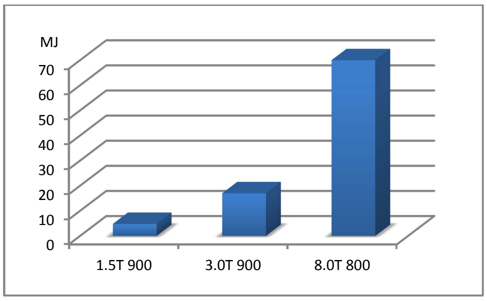

Figure 1 Stored Energy of Human Compatible Magnet

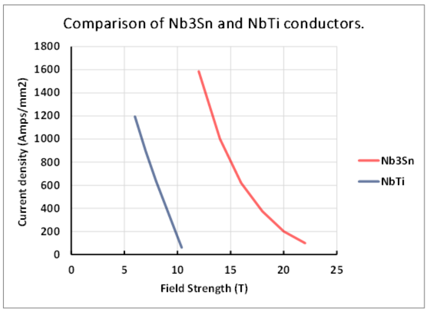

Figure 2 Performance of superconducting wire

1998 2006 – Passively Shielded Systems

The first true UHF magnet, an 8T 80cm bore system, was designed and built by Magnex Scientific Ltd (Abingdon, UK) for Ohio State University and successfully installed in 1998. The technology was developed by extending expertise from preclinical magnets to human-sized magnets with the principal design challenge being the handling of the huge amount of stored energy (Figure 1). The magnet was wound from a "wire-in-channel" conductor onto a set of aluminum formers, the cryostat incorporated two cryocoolers located in a low field region on extended turrets and a training quench in the factory verified the quench protection system.

In 1999, shortly after the 8T magnet was delivered, the second UHF magnet was installed. This was a 7T 90cm bore Magnex magnet and was installed at the Center for Magnetic Resonance Research (CMRR) University of Minnesota. This passively shielded 7T 90cm bore magnet was a highly successful design and has remained in production to the present day, with over 30 systems installed worldwide, having been adopted by all the major system vendors.

2003 saw the development of the first 9.4T whole-body magnet system by GE Magnetics Oxford Ltd (Abingdon, UK). The magnet was delivered to the University of Illinois at Chicago and integrated by their team with a Bruker Biospin spectrometer. The main theoretical limit on field is set by conductor performance and 9.4T is the highest practical field strength that can be achieved with niobium titanium (NbTi) conductor operating at 4.2K. Figure 2 shows that Niobium Titanium is unable to carry much current above 10T. Whilst moving to Niobium Tin (Nb_3Sn) is an option for higher field magnets it is an order of magnitude more expensive and difficult to handle, therefore it is generally used only in small bore magnet systems (<40cm bore).

2006 2010 – Introduction of Actively Shielded Systems

The large passive shield UHF magnets built up to 2006 needed between 200 and 650 tonnes of passive room-shields to constrain the stray field. In 2006 the first actively shielded UHF human magnet was produced by Magnex. The magnet had a bore of 680mm and was developed for head studies in Lausanne, with a homogeneous 30cm diameter spherical volume. Additionally the cryostat incorporated a new cryogenic system enabling it to operate with zero boil off.

In 2010 the first whole body 7T actively shielded magnet was developed for the National Institutes of Health (NIH), with a bore of 83cm and zero boil off cryogenics and was followed the next year by installation of a 90cm version of this magnet at the CMRR University of Minnesota.

2010 - today

Reducing the magnet temperature by pumping on the helium bath enables a central field strength of 11.7T to be achieved using NbTi conductor. An 11.7T 68cm bore magnet has been built for NIH (Agilent). It has two standard two stage coolers but also incorporates a third radiation shield cooled by a 4.2K cold head. The cold head cools the inner radiation shield to 5K and this significantly reduces the radiation heat load on the helium vessel so minimizing helium consumption. It is thus possible to achieve a refill interval of up to 12 months. The magnet was successfully installed at the NIH at the end of 2012 however suffered mechanical damage during a quench that required it to return to the factory for repair.

Currently, the largest UHF magnet (10.5T 88cm bore) has a mass of 100 tonnes and has just been developed for University of Minnesota (Agilent Technologies Ltd). Following successful factory tests installation will begin at the end of 2013. However, this magnet is dwarfed by the 11.74T active shield magnet currently under construction by the CEA Neurospin facility in France.

In March 2013 Agilent Technologies announced it was exiting the specialty magnet business, it is anticipated that the last UHF magnet will leave their Oxford facility in 2015. The closure of this facility has led to a major disruption to the worldwide supply of UHF magnets. Today a number of magnet companies are looking at entering this challenging business sector although for the very highest field magnets (above 10T) the market size is very limited and a partnership between government and industry as demonstrated by the CEA is probably the way forward.