Journal of Magnetic Resonance 213 (2011) 355–356

Contents lists available at SciVerse ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Historical Perspective

The first cryoprobe – Some recollections

Peter Styles *, Nick F. Soffe, Christopher A. Scott

Interview with the author(s).

A video interview with the author(s) associated with this Historical Perspective and the original article can be found in the online version, at doi:10.1016/j.jmr.2011.08.013.

1. Introduction

The work that was reported in this paper [1] was made possible by two complementary factors. First, those of us working in the Dept. of Biochemistry benefited from a long tradition of NMR instrumentation development, and secondly, a loosely funded collaboration between this department and the Rutherford Appleton Laboratory enabled us to assemble a team whose expertise covered the range of theoretical and practical skills required to design, manufacture and evaluate the apparatus.

2. The conceptual background

One of us (PS) was privileged to have spent a year working with David Hoult at the time when he was formulating and testing his ideas about probe sensitivity. These culminated in his seminal paper demystifying the factors which determined the sensitivity of an NMR probe and receiver [2]. In contrast to previous convoluted expressions for S:N, Hoult appreciated that one could deal quite separately with the signal and noise components, the former being determined by coil/sample geometry, the second defined by the thermal noise generated by the ohmic resistance of the coil with an additional contribution from the subsequent amplifier chain. More specifically, the fundamental noise source in the probe was simply:

$$\text{Vnoise} \; \alpha \sqrt{(\text{RT})}$$

where R and T are the r.f. resistance and temperature of the coil.

Clearly, by cooling the coil, both terms decrease and unless the material is superconducting, the major improvement comes from the T term with the improvement increasing dramatically as one approaches liquid helium temperatures. This had been noted by Hoult in his paper, together with the caveat that realisable gains would be limited by the loss of filling factor and an increase in the proportion of noise originating in the pre-amplifier. Our challenge was to see how these various factors would play out in a practical apparatus.

* Corresponding author.
E-mail address: peter.styles@physiol.ox.ac.uk (P. Styles).

3. Target specification of the prototype

From the outset, we determined that this project would only be worthwhile if it had relevance to important practical applications of NMR. We needed to demonstrate that one could perform a useful NMR experiment and achieve a performance that was a significant improvement over the very best that could be achieved in a conventional probe. However, we realised that, as a first attempt, we needed to be realistic about the challenge and not try to make the problem too demanding. Specifically, we decided to work at a modest frequency, in a magnet with a decent clear bore size and with a sample diameter that kept the unavoidable signal loss due to filling factor within reasonable bounds. Using our 180 MHz extra-wide bore magnet, a C^{13} experiment in a 10 mm sample tube was chosen which satisfied the above criteria and additionally gave us the chance to evaluate the implementation of high power decoupling. An incomplete list of the unanswered questions and potential pitfalls that we envisaged is:

1. What temperature could we achieve in the absence of a radiation shield around the coil?
2. What was the minimum loss of filling factor that we could achieve given the need for adequate clearances to allow for thermal contraction on cooling the apparatus?
3. What preamplifier noise figure could we achieve? The pre-amp would need to be cooled and connected to the probe without suffering additional losses. Could we make it reliable under conditions of repeated temperature cycling?
4. Would the transmitter pulse and/or proton decoupling destroy the pre-amp or ruin its noise performance?
5. Would there be inductive coupling between the cold receiver and surrounding conducting structures that would introduce ‘hot’ noise which could mask the coil’s inherent performance?
6. Would the increased Q of the coil cause problems of limited bandwidth and/or unacceptable ringing?
7. Could we shim the probe?

The project was a part time undertaking involving two NMR electronic designers (PS and NFS), a physicist and leader of the Rutherford team (CAS), a cryogenic designer (DAC), an electronics engineer (DJW), a design draftsman (FR) and a technician (PCJW).

1090-7807/$ - see front matter © 2011 Published by Elsevier Inc.
doi:10.1016/j.jmr.2011.08.013

Regrettably, the authors of this article have lost touch with the other team members whose contributions we here acknowledge. The prototype apparatus was a very substantial bath cryostat with the pre-amp positioned below the coil and both components tuned together.

4. Results and what we learnt

It worked! The paper shows that we were able to record decent quality spectra with substantially improved S:N as compared with the best that could be achieved using a conventional probe at the same frequency and sample size. Furthermore, there were no nasty surprises. The noise did not increase when we offered up the room temperature components, the transmitter pulse (applied with a separate room temperature coil) did not cause any problems and proton decoupling was trouble free. There were, however, certain difficulties. First, although the cryostat had delivered the required temperature at the coil (hard to measure exactly, but approaching that of liquid helium), it was hopelessly unmanageable for routine use being so heavy that we needed a fork lift trolley to get it into the magnet. Furthermore, it took an age to fill with cryogens and get to temperature. Other problems were that its design made it very difficult to achieve small clearances between the coil and the sample, and that the integrated coupling of coil and pre-amp made it impossible to separately evaluate the noise from these two components. Finally, dis- and re-assembly for the purpose of making modifications or repairs was a major undertaking.

In summary, we had clearly demonstrated that cryogenic cooling of an NMR receiver was feasible and that very significant gains in sensitivity were possible, gains that couldn't be realised by any other approach. However, we were still a long way short of having a system which might reasonably be considered suitable for use in our lab or for eventual commercialisation.

5. Moving forwards

In order to move the project forward, we raised a small grant from the British Technology Group (BTG) to build and test a new probe, one which would better satisfy the criteria for routine use. The bath cryostat had served its purpose, but we decided that a flow cryostat was what was needed. We approached AS Scientific Ltd. (Abingdon, Oxford) and arranged a meeting with the founder and managing director, Mr. Colin Hillier. Having described in outline what we needed, Colin put a large sheet of paper on his drawing board, and together we fleshed out the specification, layout and dimensions of a new probe. About an hour later, he had produced an almost complete working drawing of what we were after. It was a master class in cryogenic design, the likes of which none of us have seen before or since. The delivered prototype was almost exactly the same as the original drawing, was capable of reaching the design coil temperature of 10 K, and, we recollect, cost us just £3000!

This new probe was a massive improvement on the original prototype. Simple to insert into the magnet, it reached its operating temperature after about an hour, used only modest amounts of liquid helium, was adequately robust and facilitated closer coupling between the coil and the sample. Although there was provision for incorporating the pre-amp within the cryostat, we always operated it with an external pre-amp cooled in liquid nitrogen. This enabled us to measure each element separately and without the need to disassemble the probe in order to adjust and service the electronics. We continued with our choice of ^{13}C samples in 10 mm tubes, but increased the frequency to a more useful 90 MHz (360 MHz for ^{1}H) with the assembly fitting into a standard wide bore magnet.

As with our first prototype, the flow cryostat did what was expected of it. The S:N improvement was again substantial despite the more demanding specification in terms of frequency. Again, there were no unexpected problems and at last we had put together a system which one could reasonably use on a routine basis. We considered that we were within sight of a commercial product, but that the necessary resources to take the final step would require the attention of one or more of the major NMR manufacturers. The probe's performance was reported in a short paper [3], and despite the novelty of the original work, we consider that the realisation of a practical apparatus was at least as important as the earlier 'proof of principle'.

6. Looking back

Looking back to the start of this journey, this work was made possible by a casual approach to funding that would be a complete anathema to most modern agencies. The Dept of Biochemistry and the Rutherford Laboratory had previously been involved in a collaboration with Oxford Instruments and the Harwell Atomic Energy Authority in the development of niobium tin magnets and associated instrumentation. With this history, the Science and Engineering Research Council, UK (SERC) funded our project on the basis of 'why don't you see if there are other ways in which the Rutherford can help with the NMR effort in Oxford'. Both probe projects, and particularly the second, were conducted on a part time basis, fitted in when time allowed. It is perhaps a pity that this relaxed approach to the funding and implementation of blue skies experimentation has all but disappeared in the modern era.

Now that cryoprobes have become established as 'must have' accessories for many NMR research groups, it's amusing to recall how we and others viewed our efforts and achievements at the time. The original work was, we suspect, widely considered to be more of a curiosity than an exciting precursor of future NMR instrumentation. The reaction to our second probe is more telling. Although this was a practical working apparatus, we were advised that the work was not patentable as Hoult had already identified the underlying principle [2]. We were, however, optimistic that one of the NMR manufacturers would show an interest and offered to demonstrate the probe in operation. One of the major companies did see the probe working in the way that we had described, but felt that commercial development wasn't justified. A second company declined to see a demo unless we were prepared to show the internal workings of the apparatus! With this resounding indifference, the probe was put in the cupboard and we all reverted to our proper jobs. It is enormously rewarding to find that, some three decades after we first started to play with cooled NMR probes, that effort has eventually born fruit.

References

[1] P. Styles, N.F. Soffe, C.A. Scott, D.A. Cragg, F. Row, D.J. White, P.C.J. White, A high resolution NMR probe in which the coil and preamplifier are cooled with liquid helium, J. Magn. Reson. 60 (1984) 397–404.
[2] D.I. Hoult, R.E. Richards, The signal-to-noise ratio of the nuclear magnetic resonance experiment, J. Magn. Reson. 24 (1976) 71–85.
[3] P. Styles, N.F. Soffe, C.A. Scott, An improved cryogenically cooled probe for high-resolution NMR, J. Magn. Reson. 84 (1989) 376–378.