Facilities for Atomic Energy Research:

Particle Accelerators 1953-1957

Introduction

For historical reasons, the relationships between the atomic energy programme and the construction and use of particle accelerators was an ambivalent one.[1] The pre-history of the discovery of fission, the close technical connection between accelerators and electromagnetic separators, and the expectation that nuclear physics would provide the foundation for future atomic energy developments had all contributed to the inclusion of accelerators under the atomic energy umbrella in the immediate post-war period. With a single exception, the post-war British accelerators had been designed by the Harwell-Malvern team within the atomic energy programme. British physicist-engineers at or on loan from Harwell played a dominant role in the technical preparations for the new European accelerator centre, CERN. And all the contracting for British machines, even those for medical use, was handled through the Tube Alloys and later the Harwell contracts office.[2] By 1952, Harwell had not only a near-monopoly of accelerator expertise, but also by far the largest accelerator programme in the country. To a very large degree their accelerators were used for directly applicable atomic energy research. Even where research was treated by the administration as being unconnected with the atomic energy programme (I + D: "curiosity-oriented"),[3] as in aspects of solid-state physics and metallurgy, and of radiation chemistry, the scientists themselves often recognised that their work, while freely chosen, was of direct practical importance in laying the foundations for the materials research that would in due course dominate the atomic energy programme.[4] The need for publishable fundamental research, for freely selected research, and for the international prestige and university atmosphere that would result from these, was a constant refrain in the words of Cockcroft and his senior colleagues. But while they shared these aims, and indeed attached very high values to them, the vast majority of scientists did not see the fundamental research solely in this way. Their methods required a free research environment, but their perceived *aim* was to provide a foundation for directly practical work. Had this not been the case they would not have stayed at Harwell.

This said, however, the accelerators at Harwell did go beyond the immediate and officially perceived requirements of the atomic energy programme at Harwell. Given their expertise, and the limited resources of the universities, it was only natural that the Harwell staff should take a pioneering role in the development of new accelerators.[5] And once they had acquired these expensive and rare research tools it would have been quite unthinkable not to use them to their full potential, which inevitably meant doing some research not connected with atomic energy.

Most of the accelerators operating or under construction at Harwell by 1952 have been described by Gowing and Jay.[6] As a foundation for the discussion of the later period, however, a brief catalogue may still be useful.[7]

1. Chemistry Division 2 MeV Van de Graaff generator

This electrostatic accelerator was manufactured by ~~the High Voltage~~ private industry and used to produce beams of light particles for radiation chemistry.

2. Nuclear Physics Division 3.5 MeV Van de Graaff generator

This was designed and built at Harwell. It operated at up to 3.2 MeV with energy focussing within 1 keV, and produced a current of 30 microamps within a 2 mm diameter beam. Through the proton bombardment of light atoms it was used to produce neutrons of precisely known energies for neutron scattering studies of materials important in the atomic energy context.

3. 600 keV Cockcroft-Walton accelerator

This comprised a high-voltage set made by Phillips and an ion source and accelerating tube designed and built at Harwell. It produced a 70% monatomic beam current of 900 microamps focussable in the energy range 80 - 500 kV. Through the proton bombardment of light atoms it was used to produce neutrons of precisely known energies, the high current making possible a neutron current of 5×10^9 neutrons/sec; it was also used for the study of interactions between the nuclei of heavy hydrogen isotopes.

(4. 30 MeV electron synchrotron

This circular accelerator was developed from a modified betatron by the Harwell-Malvern group, partly as a development tool for a planned 300 MeV machine for Glasgow University. It was used to create γ-rays of up to 30 MeV by electron bombardment. The project as a whole was reasonably successful. In conjunction with English Electric, several machines were built for medical use, and machines in the 100 MeV – 150 MeV range were installed at Oxford and Glasgow universities. The Harwell machine was, however, of limited value as a research tool and had been sent to Australia before 1953)

5. 175 MeV 110" Synchro-cyclotron

This was a circular proton accelerator incorporating a synchronisation device to compensate for relativistic effects at the proton speeds reached. It had originally been planned as a 72" traditional cyclotron for isotope production, but was modified after the synchronising principle had been developed at Berkeley. Though intended to reach the energy for meson production it fell just short of this, but with a pulsed proton output of at 175 MeV it was a most successful tool for both applicable and non-applicable research at this energy. The machine was designed and built by a Harwell team contracting out to a number of industrial firms.

6. 4 MeV electron linear accelerator

This was the first travelling wave linac to operate in the world. It was 2m long and produced pulsed electron beams at between 3.5 and 4 MeV, with a mean beam current of 100 microamps. Through X-ray bombardment of Beryllium it was used to produce a pulsed neutron beam with a mean output of 10^9 neutrons/sec, flight distance of 10 m, and energy resolution within 100 eV. It was used to get precise neutron cross-section measurements of materials of importance in the atomic energy context.

7. 15 MeV electron linear accelerator

This was a development of the 4 MeV linac, designed jointly by Harwell and Mullards. It gave an electron current of 30 microamps at 15 MeV and, through bombardment of a Uranium target, a neutron beam output of 10^{11} neutrons/sec mean (10^{14} n/sec in the pulse), with a flight distance of 60 m.

The Neutron Project

The machines described above completed the programme of accelerator development laid down for Harwell in the post-war years, and the original intention was that, having established nuclear physics research in the UK, they should move away from this field of activity. By mid-1952, however, Cockcroft was already seeking permission to design and build a large and expensive proton linac at Harwell.[8] And in early 1953 a series of discussions took place at Harwell on the possibilities of improving the neutron source facilities offered by the small electron linacs. One possibility that was discussed was that of a neutron booster, in the form of a Plutonium blanket surrounding the Uranium target of the 15 MeV linac apparatus.[9] This would have the effect of multiplying the neutron output by a factor estimated at between 30 and 100, which would make a much wider range of neutron cross-section measurements to be made.[10] A second possibility discussed was that of a new electron linac of higher energy and significantly higher current than the existing machines.[11]

A design specification for a new 45 MeV high current electron linac had been prepared by Nuclear Physics Division, and in May 1953 this machine was approved by the Harwell TSC.[12] But for the moment it was not taken any further. The electron linac and proton linac proposals were to some extent rivals for the Harwell resources, and during the Summer attention was focussed on the possibilities for the larger machine.[13] One such possibility, that came to nothing but that deserves mention, was that of a 600 MeV deuteron linac with a fissile target, operating as an electricity and plutonium producer: a sort of sub-critical fast reactor. This was rejected, as Dunworth showed it was entirely uneconomical, but not before it had received serious consideration.[14] (And the fact that it was seriously considered points to the important fact that there was no atomic energy research need for the 600 MeV proton linac: we shall return to this below).

In the course of the Summer the proton linac project got off the ground, and once ~~the~~ it was ~~firmly~~ safely airborn discussion of the electron linac resumed. In late September a meeting was called to consider a proposal presented by Bretscher, that the 45 MeV high current electron linac and the neutron booster (now using U235 instead of Plutonium) be combined in the same set of apparatus.[15]

Although it was agreed that the case for this combined project was a strong one, Cockcroft was dubious about the staff and financial resources needed to carry it out alongside the proton linac project. He agreed, however, that a rough specification should be put out to industry, in the hope that they might be able to take on the accelerator element.[16] The enquiry was not entirely successful, in that there were only two quotations forthcoming, for an accelerator of only 25 MeV. But in March 1954 Cockcroft gave the project his support in principle.[17]

Although of lower energy, the accelerator now proposed still had an electron current of 20 times that of the existing 15 MeV machine, and due to the variation of the efficiency of the neutron-producing reaction in Uranium with energy, the neutron product of the new accelerator was estimated at 50 to 100 times that of the old, excluding the effect of the booster. Including the booster a neutron output of $10^{17}-10^{18}$ neutrons per second in the pulse ($10^{4}-10^{5}$ neutron/sec mean) was forecast, $10^{3}-10^{4}$ times that already available.[18] The project was formally approved in the Summer of 1954, justified partly by the need to keep in the forefront of international nuclear physics research, and partly by the need for improved neutron scattering information if the economics of different power reactor systems were to be ~~adequately~~ accurately compared.[19] The neutron output and time of flight performance (the time of flight was used to get an accurate measurement of the neutron energy) were shown to be better than could be obtained at similar cost from a circular accelerator ~~and~~ or reactor, and the needs of the atomic energy programme were accepted as requiring the new machine.[20]

From the early reactions to the neutron project proposal it seems unlikely that it would ever have been approved had a large part of it not been contracted to industry. The proton linac, though of less immediate practical value, was infinitely more glamorous and had first call on the Harwell resources. And the general philosophy that Harwell should not undertake themselves ~~such~~ major projects outside the atomic energy field was just becoming established. From the beginning, however, the use of industry caused trouble. Of the two quotations offered ~~one~~ the lower one, from Mullards, was considered unacceptable, and the contract therefore went to Metropolitan-Vickers (M-V).[21] Immediately, however, there was a question mark over whether M-V would provide the 6 MW klystrons essential to the accelerator.[22] Harwell considered going to Mullards for these, but M-V insisted that they could supply them and the situation was therefore left in their hands.[23] In December 1957, however, a full year after the accelerator should have been operating, it was still uncompleted, and there was still no sign of the klystrons.[24] The accelerator finally operated, substantially below expectations, just under two years late, and was not accepted by Harwell for yet another 6 months, until June 1959.[25] The booster, and a new neutron spectrometer capable of handling the increased neutron yield, were designed and built at Harwell without any difficulties.

Van de Graaff Generators

Although it was completed too late to be of use when it was really needed, the neutron project could be justified more or less on atomic energy grounds. But it also had a wider intended function, namely that of keeping Harwell at the frontiers of fundamental and not necessarily applicable research. By 1954, the need to diversify from strictly atomic energy work, which had always been recognised at Harwell, was also bothering Penney at Aldermaston.[26] As the weapons programme developed and increased in complexity, Penney badly needed to recruit top class nuclear physicists.[27] Looking around the universities, he was able to attract two of these, Sam Curran from Glasgow and Ken Allen from Liverpool, but only at a cost. Allen in particular had other offers, and he implied, in a letter to Cockcroft, that the price of his acceptance of that from AWRE would be a new 6 MeV Van de Graaff generator, suitable for non-weapons physics work and similar to that Devons was installing at Imperial College.[28] The AEA members were sympathetic to Penney's plight, and the Van de Graaff generator was duly ordered from the American High Voltage Engineering Corporation (HVEC) towards the end of 1954.[29] (?)

Nearly a year later, in September 1955, Penney asked for a further Van de Graaff machine (and also for a neutron beam reactor) to provide nuclear data for the thermonuclear weapons programme.[30] The new accelerator, a 3½ MeV model from HVEC, was duly approved and ordered, but only after Penney had examined, at the request of the AEX, the possibilities of British manufacture.[31] These possibilities were problematic. The inventor of the accelerator, Van de Graaff himself, was a consultant to HVEC, who had all the experience and expertise associated with the machines, together with a fistfull of patents. Of British firms only English Electric were prepared at this stage to manufacture a machine, and theirs would not be ~~so~~ as good as the HVEC one. Moreover, although they promised delivery in 18 months, AWRE were far from confident that this deadline could in fact be met. After discussions between Penney and Plowden, it was therefore agreed that an HVEC generator should be ordered, but that English Electric should be commissioned to do a design study of a new type of "tandem" van de Graaff generator in the 12MeV range. The hope was, of course, that they would then be able to supply the next generation of machines.[32]

That further facilities would be needed at Aldermaston was clear. The 3MeV van de Graaff was far from sufficient to meet their requirements, and Penney put in at one point a request for the new electron Linac being built at Harwell.[33] Progress on this was too slow for it to be of much use. But the results of the English Electric design study were encouraging, and although Don Fry of Harwell continued to entertain doubts as to English Electric's ability to deliver the goods, Penney decided in May 1956 to go ahead with an order for a tandem generator. On his suggestion Cockcroft asked for one too, and Cambridge University, who had applied to the DSIR for a similar machine from HVEC, were persuaded to join in the British project.[34] A joint team was set up between the three organisations, charged with supervising the design and production of three machines at English Electric.[35]

Unfortunately Simon chose this moment to entice Denys Wilkinson away from Cambridge to Oxford where, it was hoped, he would be able to use the tandem Van de Graaff planned for Harwell.[36] At the beginning of August, Wilkinson accepted, and since the Cambridge machine had been intended specifically for his use their requirement promptly ceased.[37] At the same time Harwell were asked by London office to justify their request, and quickly realised that they could not do so. In atomic energy terms they had no use for it at all.[38] In fact by this stage the plans for NIRNS had been approved, so that Harwell could place their order on behalf of the new establishment. Two orders therefore went forward.[39] But when asked to provide a firm quotation English Electric, foreseeing the difficulties the project might meet, refused to do so. The only alternative was M-V who had heard what was going on and put in a tender, and despite their unsatisfactory performance on other contracts it was therefore agreed to accept this.[40]

Like the other M-V accelerator projects of this period, the tandem generator ran into technical problems, largely due to a lack of coordination within the firm.[41] This time difficulties also arose with HVEC, who had in the past given design information freely to Harwell, but who now saw this information passing through the AWRE design team to a commercial ~~[illegible]~~ rival. A royalty payment was eventually reached, but a lot of goodwill had meanwhile been lost to no avail.[42] As Robinson of HVEC had predicted, both Harwell and Aldermaston had in the end to put a lot of effort into the new accelerators.[43] But although the project dropped behind schedule it was completed in well under three years, which for a firm working from scratch was not too bad.[44]

The Proton Linac

As we have already seen, the proton linac project was first proposed by Cockcroft in 1952. In his proposal to the AEB in July he noted indications that work done on ~~[illegible]~~ such a machine might turn out to be important in the atomic energy field, as a step to the use of accelerators for the production of ~~[illegible]~~ important materials such as tritium and polonium.[45] The following Winter, as we have also noted, consideration was also given to a proton linac as a plutonium producer.[46] Justifications such as these were far from convincing however, and it was clear to all concerned that Cockcroft's main concern ~~[illegible]~~ was to keep Harwell, and the country as a whole, in the forefront of nuclear physics research.[47] As well as the existing Harwell machines, British physicists could look forward to a 400 MeV synchro-cyclotron being built at ~~Birmingham~~ Liverpool and a 1 GeV proton synchrotron at Birmingham. There ~~was~~ were also the electron synchrotron at Glasgow and a variety of smaller machines. But in terms of the advancing front of international research ~~[illegible]~~ this array of accelerators looked grossly inadequate. Although Britain was not yet involved officially in CERN, the physicists were beginning to press that she should be, and this would take care of the problem at very high energies. But there was still a perceived lack of machines planned outside America for the study of π-mesons, and it was to fill this gap that Cockcroft proposed the 500-600 MeV proton linac to be designed and built at Harwell. The proposed machine, with a current of 1 microamp, would give a flux estimated at 4×10^5 mesons / cm^2 sec, as compared with the 100 mesons / cm^2 sec already available at Berkeley. And it would make possible a wide~~r~~ range of experiments ~~than~~ that would not be possible on any other accelerators then planned in the world.[48]

Note: GeV ≡ BeV, depending on country of origin!

Cockcroft was enthusiastic, but in the absence of any convincing atomic energy need for the accelerator, and given an estimated cost of £1 m or more, the AEB were naturally enough reluctant, and preferred to defer a decision for the time being, while design studies continued.[49] A year later, in July 1953, the proposal was revived in slightly altered form. The justifications for the machine were unaltered, but the national interest was emphasised rather more than it had been; and it was now proposed that the machine should be designed by a joint team from Imperial and University colleges London and built outside the fence at Harwell for university use, by a commercial manufacturer. Harwell's role would be that of design supervisors and contractors.[50]

The proposal to put the accelerator outside the fence hardly squared with the continued attempt to use the production of fissile material as a justification for it. But this time Cockcroft got his way.[51] The University design study was completed the following Spring. M-V, as the only firm equipped to handle such a large contract, were consulted on the manufacture, and at the beginning of October 1954 the position was carefully reviewed.[52] The proposal as it now stood was for a 250 yd long accelerator, to be built in three stages: 10-50 MeV, 50-150 MeV, and 150-600 MeV.[53] The estimated cost was £2m plus another £600,000 for buildings, which was twice the original estimate. Despite this, however, and despite the fact that it was expected to take 7 years to build, Fry, Pickavance and Mullett all concluded that the justification for the project remained strong, and Cockcroft decided to press ahead.[54]

The first problems, to be fair, could be blamed neither on Harwell nor on M-V. One of the main advantages of a linear accelerator over circular accelerators was that the proton beam ~~could~~ came straight out of the end of the machine, giving the maximum possible beam intensity. In circular machines, on the other hand, the beam had to be extracted through a process that was highly inefficient, causing a substantial drop in intensity. At Liverpool, however, work on the use of magnetic fields to extract the beam from the synchro-cyclotron was proving very successful. The difference in intensity ~~of~~ between the synchro-cyclotron beam and that of the proposed proton linac had originally been of the order of 1000, but looked like coming down to 100 or even less.[55] Then in mid-November, only 6 weeks after the decision to go ahead with the Linac, Le Couteur at Liverpool had some new ideas which promised to improve the synchro-cyclotron beam extraction dramatically, reducing the advantage of the linac to a factor of 10.[56] At the same time, partly as a result of constantly changing specifications from Harwell and partly due to a more careful analysis of their own costs, the M-V estimate for the linac shot up yet again from £2m to £3m.[57] And at the same time again a growing feeling among nuclear physicists that Britain should have a machine able to investigate the new 'strange particle' energy range materialised in the form of a request from Cambridge for a 5 GeV electron synchrotron, and a suggestion that this would have to be designed and built by Harwell.[58]

At a meeting of the TSC on the 6th of December, it was decided to continue with the linac on the grounds that it could be used at variable energies, which ~~the~~ a circular machine could not, and that it could be extended as required to higher energies (by adding on a further length), which again a circular machine could not.[59] Despite this decision, however, the Harwell people were troubled by the developments, and discussions were now taking place with an intensity that made firm decisions meaningless. Skinner of Liverpool, who had always opposed the proton linac, insisted that Harwell could not take on both this and the Cambridge machine.[60] The Harwell experts Pickavance, Mullett and Walkinshaw, suggested that an electron synchrotron, whether at Cambridge or at Harwell, should have priority over the Linac.[61] And following a meeting called by Massey at University College London, a meeting of those involved with the linac — Cockcroft, Pickavance and Fry from Harwell, Devons from Imperial College and Massey himself — was convened at the Royal Society ~~on~~ on the 16th of December. It was still agreed that Harwell should build a big accelerator of some sort, but by this stage the choice was once again open, with a proton synchrotron the favourite rather than the proton linac.[62]

Another possibility raised at these meetings was that the Harwell machine should form the basis of a new national centre for nuclear research, and from this point the two issues became inseparable. The continued history of the project is therefore described as part of the NIRNS story rather than here. Briefly, the second and third stages of the proton linac were formally abandoned within a few weeks, in January 1955.[63] The first stage, to 50 MeV was continued, with the intention of using it as an injector for a circular machine, as yet unspecified. After a design study of a 7GeV proton synchrotron had been completed this was chosen as the large machine, and it was approved in principle in mid-1956 and in fact a year later, for installation at NIRNS.[64] The 50 MeV linac also went to NIRNS, but not until its cost had ~~reached~~ increased still further, to over £1m.[65]

General Observations

The main interest of accelerators in this period seems to me to lie in the translation of high energy nuclear physics from the atomic energy context in which it had been placed in the immediate post-war period back to that of university research. I have tried to tell this story in my piece on NIRNS.

Within the atomic energy context, the accelerators, and especially those giving low and medium energies, were indispensable for fundamental but directly applicable work. But it would be difficult, and I think inappropriate, to describe this in detail. It was basically the determination of data (~~[illegible]~~ mainly neutron-cross-sections of relevant reactor materials but a lot of similar data too) essential to the atomic energy programme but of little intrinsic interest. The accelerators were also used for other fundamental research, and some of this rebounded into the atomic energy context, while some did not.

Besides this, however, the accelerator story does raise two points of general interest which seem to me to be worth mentioning. One concerns the use of industry for the manufacture of special equipment. The other concerns the mutual advantage to science and atomic energy of the relationship between accelerator work and the atomic energy programme.

(1) Use of industry.[68] By the time Harwell built the 7 GeV proton synchrotron for NIRNS, they had learnt the hard way the problems that resulted from putting this sort of work to industry. Instead of entrusting the project to an industrial concern they based it on a project team at AERE responsible both for the design of the accelerator and for contracting out individual requirements to industry on a fixed price basis. That they could do this, however, was due only to the grand scale of the previous disasters. The basic AEA policy was to put work out to industry whenever possible, the intentions being (a) to save AEA manpower and (b) to assist industry to compete in a high technology world. With the pressure for staff ceilings in the middle and late 1950s

this policy was strengthened, and it was then that it produced disastrous results in the Northern Groups, but it was already firmly established before.[67] And there is no doubt that it was based on sincere and well-meaning intentions. But in the case of accelerators and other highly specialised equipment it appears to have been wholly misconceived. Even for small accelerators that could be used for medical purposes the market was not really big enough to make a project worthwhile to industry. At first industrial hopes from such work were high, and they competed for Harwell's favours; but they too learnt by their mistakes. Many of the AEA requirements were of such a specialist nature that they were extremely unlikely to lead to production runs ~~[illegible]~~; ~~and~~ even if further orders did materialise early obsolescence was practically guaranteed in the fast-moving fields concerned. On top of this, the requirements were also extremely difficult to satisfy technically, and this meant that the firm concerned had to put their best men and resources on to the job, crippling themselves for other and potentially more valuable work. At the same time the senior Harwell staff, who knew a lot more about accelerators than any of the firms building them, had to spend far more time supervising the work of these firms than they would have had to supervising work at Harwell; and since it was ~~[illegible]~~ at this senior level that staff limitations were felt any saving of staff was therefore illusory.

On top of these general problems, of course, the individual firms had their own special problems. M-V were the only firm with sufficient resources to handle a big accelerator contract. But they (and the rest of the AEI empire) had a peculiar hierarchical organisation. For any complex project, such as the AEA projects tended to be, this entailed one of their departments sub-contracting to others. Coordination in this respect was poor, and the sub-contracts were often not even on the same costing basis as the main contract, which caused havoc. English Electric were run on feudal lines which made them excellent at straight-forward work but did not leave their engineers enough initiative for the pioneering work Harwell tended to need. And Mullards could not be used on highly classified work, not because of their own characteristics but because of their relationship with Philips.

Finally, yet another problem was that the Harwell scientists and engineers were, quite simply, the experts. They knew more than the firms did, and were at the forefront of developments. This meant that they tended to interfere with the firms' specifications and, more seriously, to keep updating the specifications as a project progressed, and as new information became available which bore on it. This appears to have been particularly important in the case of the proton linac, the specification of which was being revised by Harwell right up to its completion. This obviously played havoc with both the organisation and the costing of the work.

(2) Advantages of the nuclear physics / AEA alignment. 68

There is a tendency to look on the pursuit of fundamental and non applicable nuclear physics at Harwell as an aberration, something that should never really have been, and that could be justified only historically, and in terms of 'honey for the bees'. In fact, however, the arrangement seems to have had many advantages, the most significant of which related to the Harwell strength in electronics and instrumentation. The point here is that if a university had an accelerator it would use it in a certain way for certain experiments and that, generally, would be that. However, because of their need to obtain data of all sorts for the atomic energy project, the Harwell scientists were conditioned to look at an accelerator as only the beginning of a piece of apparatus. They were able to see the possibilities of fitting it up with a variety of experimental accessories, and they had the facilities to get these designed and built. The Nuclear Physics and Electronics divisions were in continual and healthy competition as to who could dream up new possibilities fastest.

This attitude at Harwell had at least two significant consequences. First, to the benefit of nuclear physics as a whole it ensured a utilisation of accelerators both in Harwell and elsewhere that the universities would have been highly unlikely to achieve on their own. It also prompted a recognition of ~~others~~ the value of other aspects of the particle beam produced than its mere energy, and it was on the basis of this that Britain was able to stay in the forefront of nuclear physics research despite not having the high energy machines of the Americans. Secondly, to the benefit of the atomic energy project, there was a considerable feed-back of the experimental tools and techniques developed for non-applicable research into specifically atomic energy research. This aspect is discussed in detail in my piece on the applications of pure research at Harwell, with Joan Freeman.

Notes and References

1. I+D, vol 2, pp 212-229. As will become apparent here and elsewhere, I am not happy with this treatment, but it is mainly a question of interpretations rather than facts.

2. Interview with Tozer

3. I think this is an unfortunate term, confusing the motives of the establishment as a whole with those of the individual scientists.

4. This was true before 1953 and increasingly thereafter.

5. For the development of the theme 'Harwell and the universities' see my separate piece on NIRNS.

6. I+D, vol 2, pp 257-9 ; Jay (1952) pp 43-55.

7. Sources for this are Jay (1952) pp 43-55, 66-89 ; Jay (1956) pp 82-111 ; interview with D. Fry by Jay, 16.3.54, filed in JH / Accelerators. The 15 MeV accelerator, not described in I+D, was operating by early 1953.

8. AEB (52) 23
Meeting of 3.6.52 ; Dunworth / Cockcroft 18.6.52 ; Lewis / Cockcroft 11.7.52, all in AERE 11/1/1/23(2)pt1 (AB6/1203).

9. Bretscher / Cockcroft 11.2.53, AERE ibid.

10. TSC (54) 11 ; AEX (54) 98. Copy on file JH / Accelerators.

11. D. Fry / Cockcroft 15.4.53 ; Meeting of 6.5.53, AERE ibid. The specification of the linac had developed during discussions, but by the time of the meeting it was seen as a pulsed neutron source with time of flight equipment, ie ~ the 15 MeV machine.

12. TSC (53) 17 ; TSC 25.5.53

13. See below

14. Meeting 10.6.53, AERE, ibid (embargoed).

15. Bretscher, memo. 24.9.53; Meeting of 28.9.53, AERE, ibid (embargoed). ~~[illegible]~~. See also Wiblin, memo, 25.9.53, AERE, ibid, and Egelstaff, memo, AERE, P71.

16. Meeting 28.9.53 (footnote 15)

17. Meeting 15.3.54, AERE P.71 ~~[illegible]~~. See also Wiblin's specification, ibid.

18. TSC(54)11. See also AERE report NIR 1418.

19. AEX(54)98, 140; AEX 9.9.54.

20. Ibid.

21. See General observations below. I have not been able to determine why the Mullard quotation was unsatisfactory.

22. Meeting 5.10.74, AERE P.71.

23. Meeting 22.11.54, ibid.

24. Wiblin, memo 31.1.57; Bretscher/Cockcroft 31.1.57; Bretscher, memo, 29.11.57; Meeting on klystron supply 12.12.57, AERE 11/1/1/23(2) pt 1 (AB6/1203)

25. RGMB(59)2, 73; RGMB 1.6.59; AEA(59)69. Meeting 18.11.58; Mullett/D. Fry 26.1.59, AERE ibid. The final cost of the accelerator was 30% over estimate, at about £½m.

26. See piece on civil research and pure science at AWRE.

27. AEX(54)141

28. Allen/Cockcroft 10.8.54, AERE 11/1/1/23 (AB6/1387).

29. AEX(54)141; AEA(54)12; AEX 9.9.54, 20.11.54; AEA 23.9.54.

30. AEX(55)115, 116, 125; AEX 8.9.58, 22.9.58.

31. *Ibid*; AWRE 0019, / VI a passim.

32. Penney, memo, 18.10.55, AWRE *ibid*.

33. HC 1.2.56.

34. Penney / Cockcroft 11.5.56, AWRE *ibid*. AERE DR/1/23(5) pt 1; Cockcroft / Plowden 29.5.56; ~~[illegible]~~/ Fry / Cockcroft 30.5.56; AERE *ibid*. AEX(56) 60;
~~35~~. AEX 31.5.56.

35. AEX 14.6.56. Penney / Mott 18.6.56; Mott / Penney 20.6.56, AWRE *ibid*.

36. Mott / Cockcroft 10.7.56, AERE *ibid*. Cockcroft / Penney 16.7.56; Cook / Cockcroft 18.7.56, AWRE *ibid*.

37. AEA 23.8.56. Mott / Cockcroft 1.8.56, AERE *ibid*.

38. HC 14.8.56

39. AEA (56) 95; AEA 20.9.56.

40. Meeting 1.8.56, AWRE *ibid*. AEA(56)87

41. Meeting 4.9.57, AWRE *ibid* and AERE *ibid*.

42. Robinson / Penney 6.11.56 and subsequent correspondence, AWRE *ibid* and AERE *ibid*.

43. Robinson / Mott 23.8.56, AWRE *ibid*.

44. AWRE *ibid*, passim.

45. Footnote 8 above

46. Footnote 14 above

47. AEB 8.7.52

48. AEB(52)23

49. AEB 8.7.52

50. AEB (53) 41, 43

51. Ibid.

52. AERE P. 34 pt 2 passim.

53. Tozer memo 10.9.54; Fry, Pickavance + Mullett, memo, 30.9.54, AERE ibid.

54. Fry / Wilson 5.10.54, AERE ibid.

55. Skinner / Cockcroft 12.10.54; Pickavance / ?, 20.10.54, AERE ibid.

56. Skinner / Cockcroft 18.11.54, AERE P.78a.
Le Couteur's report of his innovation was rejected for
57. publication by the Royal Society Proceedings — but it
worked: see AERE 11/Univ/8 pt 1.

57. TSC 6.12.54

58. Skinner / Cockcroft 18.11.54, AERE P.78a.
Pickavance, Mullett and Walkinshaw, memo.,
Dec 54, AERE P. 34 pt 2. This idea seems = just to have stemmed from Cockcroft. See my piece on NIRNS, and Mott / Wilkinson ~~[illegible]~~ 4.10.54, AERE 11/NI/1 pt 1.

59. TSC 6.12.54

60. Skinner / Cockcroft 18.11.54, AERE P.78a

61. Pickavance, Mullett and Walkinshaw, memo, Dec 54, AERE P.34 pt 2; Pickavance / ? 20.10.54, and Pickavance, lecture notes, Nov. 54, ibid.

62. Meeting at UCL, 7.12.54; Meeting at R.S., 14.12.54, ~~[illegible]~~ AERE ibid.

63. AEA (55) 10; TSC 3.1.55.

64. Ibid.; AEA 10.2.55; MC 9.5.56; AEA (57) 52; AEA 30.5.57.

65. ~~AEA (55) (57) 52 (58) 7, AEA~~
AEA (58) 7, 52; AEA 23.1.58, 29.5.58.

66. Interviews with Tozer, Cooke-Yarborough. AEA(57)52.

67. See my piece on inter-establishment relationships (structure of AEA).

68. Interviews with Lomer, Cooke-Yarborough. Discussions with Joan Freeman.