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Early Synchrotron Design in the UK, 1945 – 50

J D Lawson

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EARLY SYNCHROTRON DESIGN IN THE UK, 1945 - 50

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Abstract

In 1945 it was decided to initiate a programme of synchrotron development under the aegis of the newly formed Atomic Energy Research Establishment at Harwell. The work was carried out at Malvern, in premises used during the war for radar research, mainly by scientists transferred shortly after the end of the war. Two 30 MeV machines were designed and constructed there, partly for use in physics research, and partly as prototypes for larger machines to be built in Glasgow and Oxford. The most notable achievement was the conversion of a small American betatron by Goward and Barnes to become the world's first synchrotron in 1946.

The activities of the Malvern team during the five year period from 1945 are described; extensive references to the published literature and laboratory reports are made, but other material not recorded elsewhere is described.

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PREFACE

This paper was originally presented at the Birmingham Synchrotron 40th Anniversary Reunion held at the University on 16 September 1993; it appears in the Proceedings and is reproduced by kind permission of the School of Physics and Space Research. It relies very much on the author's recollections, and it is hoped that a more thoroughly researched report will be available later.

1 Introduction

During the second world war Britain's nuclear physicists were deployed in research directed towards winning the war. Many were engaged in developments associated with radar, (or 'radiolocation' as it was then called), both at Universities and at Government Laboratories, such as TRE and RRDE at Malvern. Others contributed to the atomic bomb programme, both in the UK, and in the USA, mainly at Los Alamos and Berkeley, and at Chalk River in Canada. Besides contributing directly to the design of the bomb itself, British physicists were actively involved in other aspects, such as the techniques required for uranium isotope separation, and instrumentation to detect blast and radiation effects.

Towards the end of the war, when victory seemed assured, the nuclear physicists began looking towards the peacetime future. The construction of new particle accelerators to achieve even higher energies was seen as one of the more important possibilities. Those working at Berkeley on the electromagnetic separator were familiar with the accelerators there, and following the independent invention (or discovery?) there of the principle of phase-stability by Edwin McMillan in 1945[(1)], exciting possibilities were immediately apparent. Indeed, even before this, Marcus Oliphant, while working on the electromagnetic separators at Oak Ridge, had put forward the idea of a ring magnet with frequency increasing with magnetic field to preserve synchronism[(2)], though he missed the essential feature of phase stability needed to make a very high energy machine a practical proposition. His idea was to accelerate protons to an energy of order 1 GeV, where he guessed that quite new phenomena would be observed[(3)].

In November 1945, shortly after the setting up of the 'Department of Atomic Energy' under the Ministry of Supply, the first meeting of a 'Panel on Apparatus for Accelerating Particles' was held at the British Thompson-Houston laboratories under the chairmanship of Oliphant[(4)]. This was organised by the former Department of Scientific and Industrial Research, and there were representatives from the Universities of Birmingham, Cambridge, Glasgow, Liverpool, London and Oxford, from Industrial firms British Thomson-Houston, English Electric, the General Electric

Company and Metropolitan-Vickers, and from the Government Laboratories TRE, NPL and the Royal Arsenal and from the Medical Research Council. There was wide ranging discussion, and though the synchrotron concept and plans for a machine at Birmingham were described by Oliphant, no other suggestions for building one were mentioned. There were, however, suggestions for betatrons; Professor Philip Dee was interested in one with an energy of 200 MeV for Glasgow University. There was much discussion of different linear accelerator concepts, and Dr L H Gray 'estimated that up to six machines with voltages of the order of 30 MeV might be required for medical purposes'. Another new idea mentioned was the microtron, ascribed to Julian Schwinger. Remarkably, it is stated in these minutes that 'there was at present no great interest in further cyclotrons'; clearly the possibility of frequency modulated machines was not yet widely appreciated.

After this time events moved rapidly, especially at the newly established Atomic Energy Research Establishment (AERE) being set up on a disused wartime airfield at Harwell. By the end of the year design and construction of a synchrotron of energy 30 MeV was being considered. In this talk the discussion is restricted to the electron synchrotron programme; the Birmingham proton synchrotron is described in the next contribution by John Walker. Linear accelerator and cyclotron developments are not included.

Not all the physicists returned to their Universities after the war, some remained in government service and joined the Atomic Energy programme under the direction of John Cockcroft. The AERE physicists also wanted to build and use accelerators, and they had the advantage that many of the skilled technical staff at Malvern were keen to transfer, as well as those returning from Deep River in Canada. The staff working on the synchrotron remained temporarily at Malvern, together with those on the linear accelerator project and those in the electronics division, under the overall direction of Dennis Taylor. The 110 inch frequency modulated cyclotron, a much larger installation that could not readily be moved, was started on the new site at Harwell. The question of the extent to which AERE staff could involve themselves in 'curiosity oriented' research as well as 'mission oriented' research directly relevant to the power and weapons programmes was a vexed one, and occasioned some argument, especially between Cockcroft and James Chadwick, who had returned to Liverpool University after his wartime role as Director of the British contribution to the bomb, under the code name of the 'Tube Alloys' project[5]. Accelerators were, of course, relevant to the Atomic Energy programme also for more applied tasks, such as generating neutrons by photo-disintegration from high energy X-rays produced in turn by electrons accelerated to energies between 10 and 20 MeV. The determination of cross-sections of neutron reactions was clearly important in the design of reactors and their shielding[6,7].

2 Early Plans at Malvern: The World's First Synchrotron

By the end of 1945 a programme for synchrotron research had been outlined, and a group was being assembled at Malvern under Donald Fry, who had been in charge of the microwave aerials group at TRE. These early discussions had naturally involved the electrical engineering industry, in particular the larger companies, Metropolitan-Vickers, English Electric and British Thomson-Houston.

Following the American groups the advantages of a synchrotron for the photo-production of mesons was now recognised, and the idea of building a 200 MeV betatron at Glasgow was abandoned in favour of a 300 MeV synchrotron. (It should be recalled that at that time only one type of meson was known, the μ and π had not been distinguished). Dee requested help from Harwell, and it was agreed to start by building a machine at 30 MeV. This was partly to explore the design and operation of synchrotrons before embarking on the larger project, but it was recognized that interesting physics could be done with 30 MeV electrons and X-rays, such as studies of γ-n reactions and nuclear photo-disintegration. Further, interest was expressed by the medical community in the potential application to cancer therapy, and it was considered appropriate that Harwell should contribute to this work. Because of the long range of X-rays and their secondary electrons at these high energies the ionization density in an irradiated solid initially increases to a depth of about 8 gm/cm^2, thereafter decaying in a distance of a few times this amount. The possibility of treating deep-seated tumours without the excessive surface damage associated with conventional X-ray energies of a few hundred kilovolts was recognised.

By the end of 1946 a further request had been made to AERE; Lord Cherwell had written to Cockcroft in November asking for help with a machine of about 150 MeV to be built at the Clarendon Laboratory in Oxford.

In 1945 the work on radar had moved from Malvern College down the hill to 'The Duke', previously a Naval Station. One outpost remained, however, 'The Lees', a small self-contained area outside the main College grounds where huts had been erected to house the top secret countermeasures group. It was here that the synchrotron and linear accelerator were to be built and housed, together with the electronics group under Taylor, designing equipment specifically for Harwell. Recruiting staff for these new enterprises was vigorously pursued, and three key members of the synchrotron group soon moved into the Lees to start work there. In overall charge of the synchrotron under Fry was John Gallop, an electrical engineer with industrial experience needed for large scale items such as the magnet and its power supply. John Dain, from TRE, was to take responsibility for all the electronic controls and circuitry; Frank Goward, an expert in aerials from TRE was in overall charge of the physics, and the original team contained three others from TRE: John Wilkins and Herbert Payne were responsible for the resonator and RF system, and Herbert Watson was in charge of all vacuum aspects and the injector gun. Supporting this team at Malvern was the mathematician William (Bill) Walkinshaw, a member of the Harwell Theory group under Klaus Fuchs. Although Walkinshaw's main contribution was to the linear accelerator programme, he did contribute to the synchrotron work and his role in reviewing and explaining the various theoretical papers being published in the USA was invaluable.

By the time this team had become organized an American team at the General Electric Co at Schenectady in the USA was already well on the way to building what was to be the first synchrotron. Having already built several betatrons they were well acquainted with much of the technology required. At this time there was one betatron in the UK, this was one of Donald Kerst's original models built by the Allis Chalmers Co. It had been brought over by air by William Koch and installed at Woolwich Arsenal by him in A R Greatbach's section which was concerned with examining for flaws in armour plate using penetrating X-rays. [See Appendix on p20].

At this point it is convenient to summarize the principle of the betatron with reference to Fig. 1[8]. An alternating current at the supply frequency is passed through the coils; a pulse of electrons is injected from the gun at the instant that the magnetic field at the equilibrium orbit is such that the Lorentz force just balances the centrifugal force. The

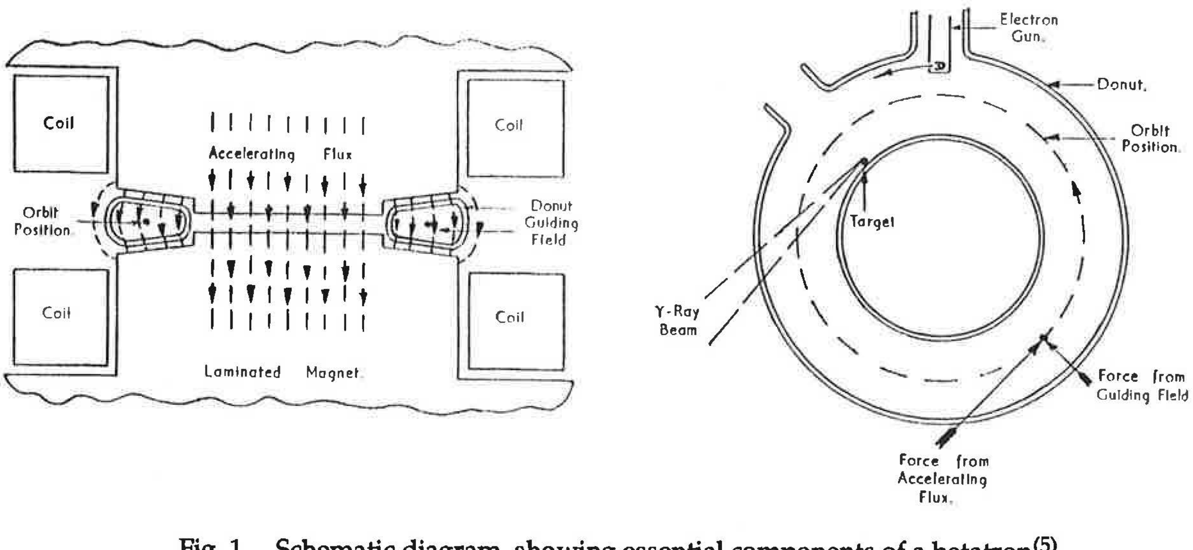

Fig. 1 Schematic diagram, showing essential components of a betatron[5].

Correction and Addition to RAL-94-10

Since this report was issued I have been in communication with Dr H W Koch concerning the small betatron that was converted by Goward to make the world's first synchrotron. This was not, as stated on page 4 (and in ref. 10), built by Allis Chalmers Co., but was specially commissioned by A R Greatbach of the Woolwich Arsenal Research Laboratory during a visit to the USA in 1942. He saw the possibility of using a small machine with sealed-off vacuum chamber for inspecting unexploded bombs that needed to be defused in situ. The betatron was designed by Kerst, and constructed in the University of Illinois workshops by Ernest Englund. Koch, then a graduate student, assisted in the construction and tested the machine in its oil filled container box in the University Electrical Engineering Laboratory towards the end of 1943. Early in the next year he took it to Woolwich and installed it there. By that time, however, conventional bombing had given way to attacks by the V1 'flying bombs' and V2 rockets, and the machine was not used for its original purpose.

This information is taken from a draft obituary of D W Kerst by K Symon and H W Koch, and a letter Koch to Lawson dated 29 March 1994.

orbit radius then remains constant as the field rises and the particle accelerates, provided that the total magnetic flux through the orbit is twice what it would be if the field were uniform at all radii, (the Wideröe 2:1 condition). Betatron oscillations about the equilibrium orbit are stable provided that the field at the orbit falls off with radius, but less rapidly than 1/r. Near the peak of the magnet field the iron within the orbit is designed to saturate, so that the orbit radius contracts and the electrons strike a target to produce X-rays.

Returning to the betatron at Woolwich, Goward realized that this could be converted to a synchrotron by increasing the magnet current, so that saturation occurred earlier in the cycle, and building a resonator around the vacuum chamber (or 'donut') in the form of a shorted quarter-wave line with a gap in the inner conductor, tuned to a frequency equal to the speed of light divided by the circumference of the orbit. At the betatron energy of 4 MeV the electron velocity was already within 1% of that of light. Then, just as the iron begins to saturate, the RF would be switched on, accelerating the particles by means of the electric field across the gap to a higher energy. This is illustrated in Fig. 2. Goward accordingly assembled an RF power supply from units available at TRE, and constructed a simple resonator. The form of the resonator is indicated in Fig. 3. If the resonator were made of metal tubes, as indicated in the figure, eddy currents induced by the changing magnetic field would distort the guide field and the beam would be lost. It was therefore constructed of wires, joined only at one point by a planar ring parallel to the magnetic field. It was held together by dielectric spacers, and made in two halves which clipped together around the toroidal vacuum chamber. With this very simple equipment Goward, together with D E Barnes of Woolwich Arsenal

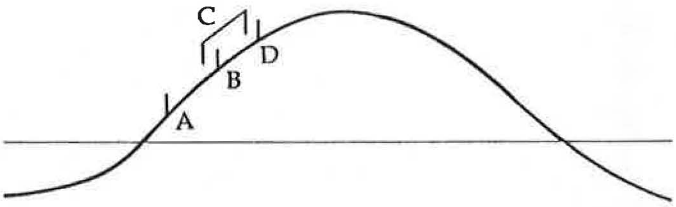

Fig. 2 Magnetic field variation during positive half-cycle, showing (A) injection pulse, (B) output pulse for betatron operation, (C) radio frequency envelope and (D) output pulse for operation as synchrotron.

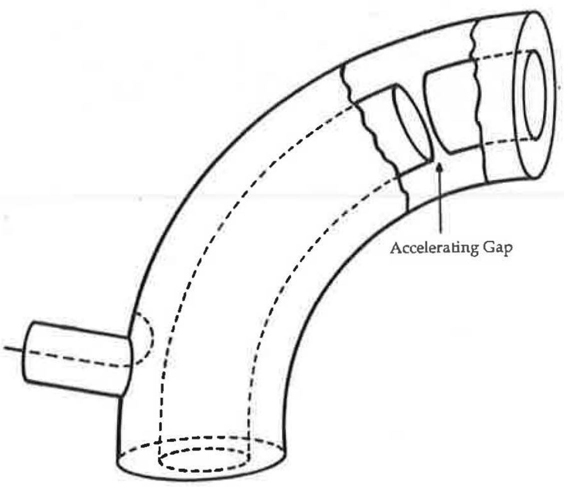

Fig. 3 Schematic drawing of quarter-wave resonator. The actual resonator used was designed to fit round the vacuum chamber, and was constructed of wires to avoid eddy current loops. (Details in text).

demonstrated synchrotron acceleration for the first time in August 1946, two months before the General Electric machine operated in the USA. Electrons were accelerated from the betatron energy of 4 MeV to 8 MeV(9).

The machine was moved to Malvern, and by replacing the coils, adding air cooling and providing a DC bias field it was possible further to increase the energy to 14 MeV(10). The X-ray intensity was greatly improved also by increasing the injection energy from 2 to 20 KeV. A photograph of the modified machine is shown in Fig. 4. With these modifications it was used both for general experiments on synchrotron operation, and for experiments on medical applications. Extensive studies were made of the distribution of ionization in materials simulating human tissue, with various filters and collimators.

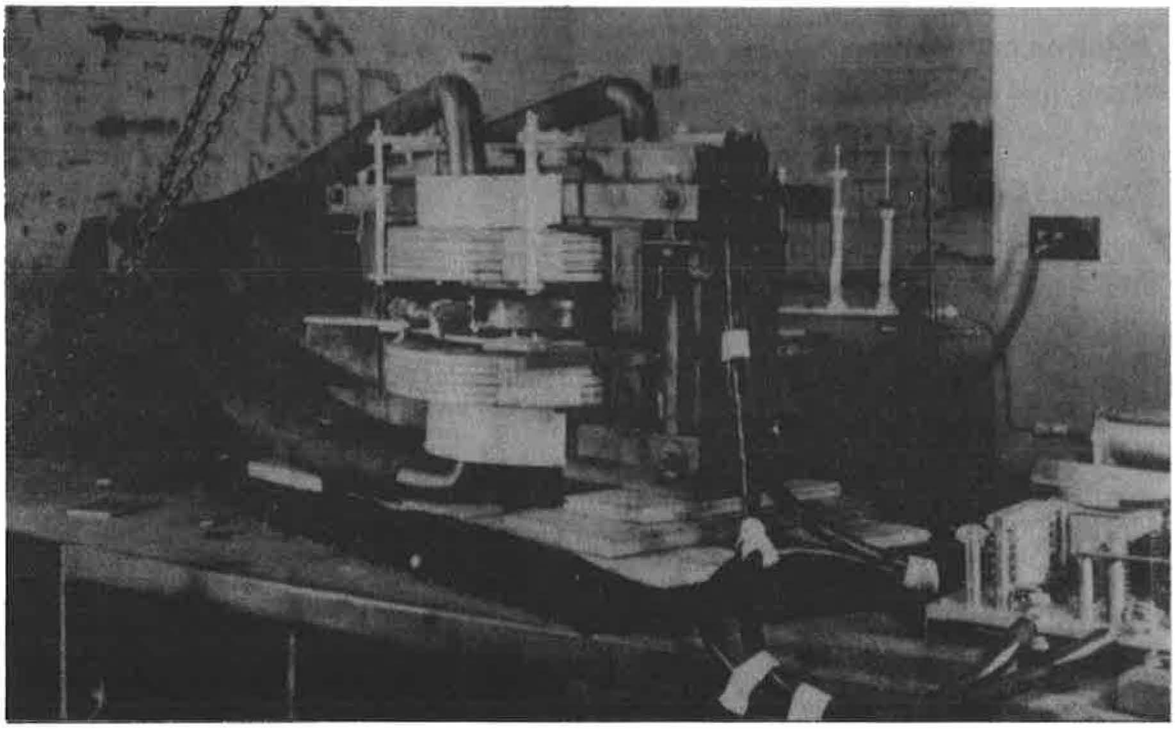

Fig. 4 The world's first synchrotron, installed at Malvern. The extra cooling system and rf feed to the resonator may be clearly seen.

3 Design and construction of the 30 MeV machines

The practicability of synchrotron acceleration having been established by the end of 1946 by Goward and Barnes' experiment and the American General Electric machine, which first operated in October(11), what was now required could clearly be seen. Construction of the first machine was well under way, and delivery of the magnet was expected during 1947. In January 1947 a fairly detailed specification of the parameters and work required had been prepared by Goward, Gallop and Dain(12). Some of the more important parameters of the first 30 MeV machine are tabulated below.

Energy at full excitation	30 MeV
X-ray output at 1 metre	10 Roentgens/minute
Injection energy	10 keV
Orbit radius	10 cm
Field at maximum energy	1T
Field index, $n = -(r/B)(dB/dr)$	0.7
Aperture of good field	6 cm square
Magnet coils	2 x 185 turns
Volts per coil	5 KV in series
Current per coil	100A rms
Resonant capacity	30 μF
Quality factor (Q)	50
Magnet weight	3 tons
Resonator frequency	477 MHz
Mean RF power	10 watts

It was envisaged that several machines would ultimately be needed, and that these would be built by English Electric, who were building the magnet for the first one, to be assembled at Malvern. Two magnet designs were considered, an 'H' magnet and a more symmetrical 'C' magnet; eventually both types were constructed. The H magnet had the advantage of accessibility to the vacuum chamber but was less economical and less likely to produce a field with good azimuthal uniformity. Since access was considered very important in initial experiments, the H magnet design was chosen for the first machine. Both designs as ultimately built are shown in Fig. 5.

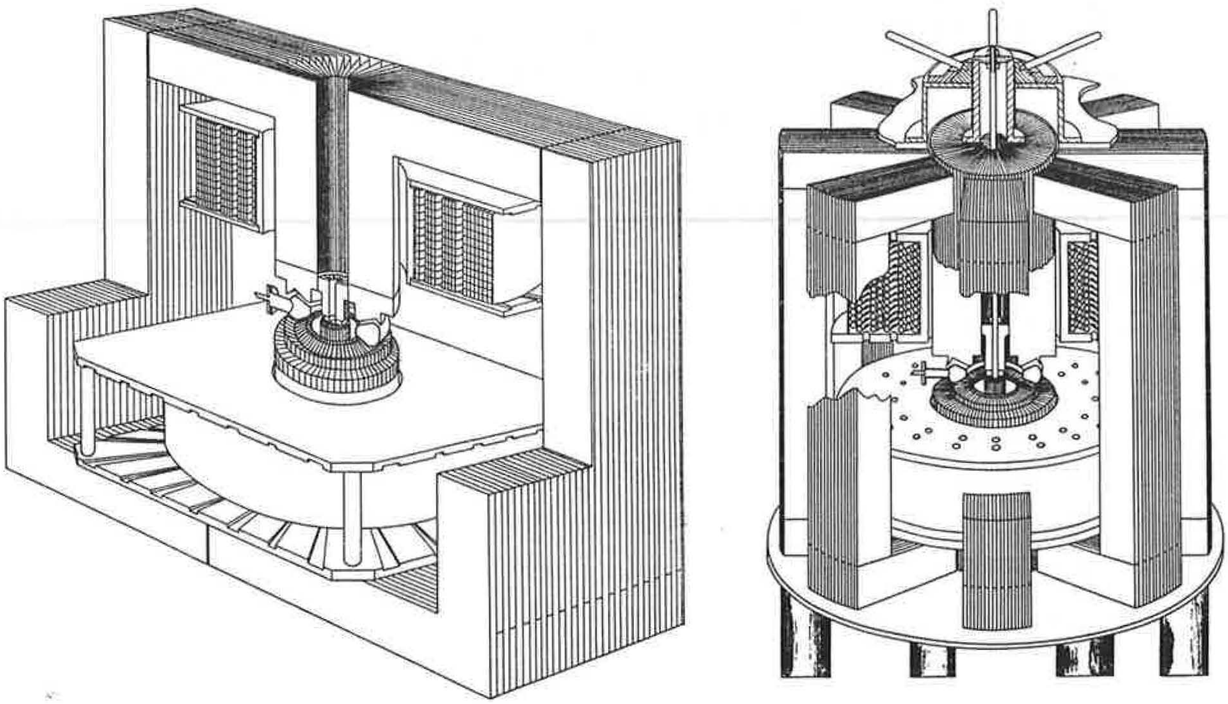

Fig. 5 'H' and 'C' magnet designs for the 30 MeV synchrotrons built at Malvern[13].

The year 1947 was occupied not only with building and commissioning the machine, but in analysing the expected performance and considering the problems of the 300 MeV machine for Glasgow. In this machine the ratio of available aperture width to radius was much less, implying tighter tolerances on field accuracy, and possible problems at the betatron-synchrotron transition, where synchrotron oscillations might cause loss by electrons striking the walls. Robert (Bob) Carruthers joined the group in this year, and started work on the RF system and magnet power supply. The magnet was to be a larger version of the 30 MeV C design, to be built by Metropolitan-Vickers, who together with the Malvern Group and Glasgow University were to be responsible for overall design and construction. It was also agreed that the machine for Oxford would be built by English Electric, and technical help would be given by the Malvern group. This was intermediate in size between the 30 and 300 MeV machines, and presented no special problems.

During the construction of the first 30 MeV machine there was activity analysing its expected performance, and that of the more critical larger machines. This was led by Goward, and a number of papers were published, particularly on pole face design, particle trapping at the betatron - synchrotron transition, the effects of magnetic field errors and ideas for beam extraction. This problem appeared particularly difficult, and a number of suggestions had been published in the USA, some applicable to betatrons, where beams had already been rather crudely extracted. Work was also done at Oxford in preparation for the machine there by Thomas Kaiser and Jim Tuck, who performed experiments on the 14 MeV converted betatron. Information from the American work, where papers on betatron operation had been published, and from the 70 MeV GE machine, which was working well, was also available. Eventually, after some constructional problems which delayed the delivery of the magnet until mid 1947, the first beam was obtained in October(13).

4 Design features of the 30 MeV machines

The design and operation of the 30 MeV machines, with both types of magnet, are described in two papers read before the Institution of Electrical Engineers in April 1950, and the numerous references to specialized detailed papers therein(14,15). Design information quoted below is from these papers unless referenced otherwise. Features of the larger machines, then at an early stage, are also described, since for several items, such as the power supply and vacuum chambers, different techniques are required. Photographs of machines with H and C magnets are shown in Figs. 6 and 7, and a schematic diagram of components in Fig. 8. The greater compactness of the second design is clearly seen, but it is evident also that the vacuum chamber is less accessible for experiments, and furthermore, one of the C units needed to be removed

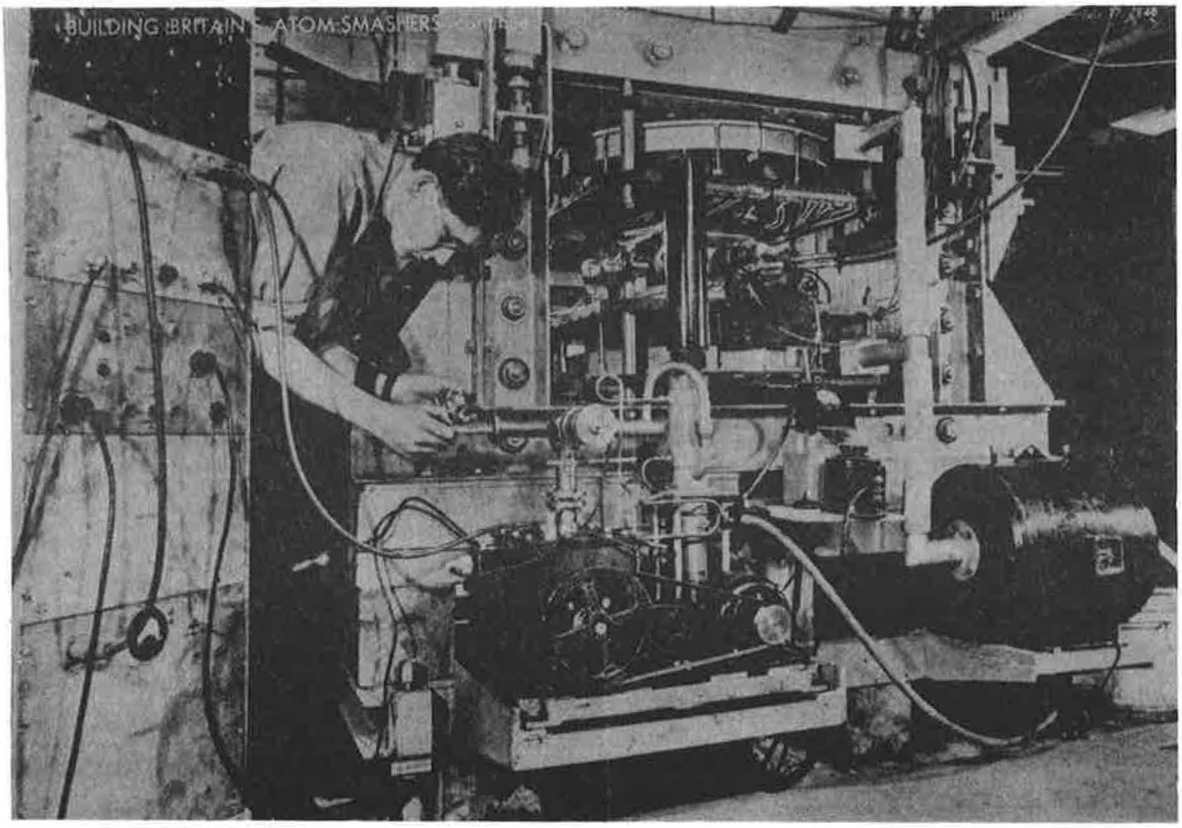

Fig. 6 First 30 MeV machine at Malvern, with H magnet[16].

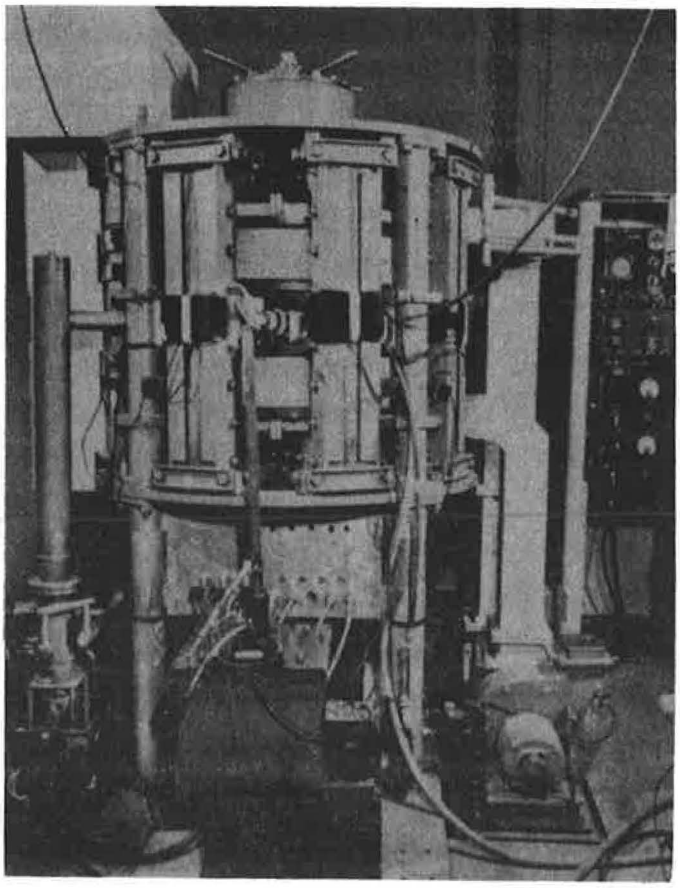

Fig. 7 Second machine at Malvern, with C magnet. The greater compactness of this design, but reduced accessibility to the vacuum chamber is evident.

in order to replace it. Another feature of this design, seen in Fig. 7, is that azimuthal magnet inhomogeneities can be more readily be corrected by 'trim' coils wound on the C's. Details of the magnets can be seen from Fig. 5. The magnet poles were designed to have a value of $n = -(r/B)(dB/dr)$ near to 0.7, to give a ratio of betatron oscillation frequency to rotation frequency $(1-n)^{1/2}$ of order 0.5. The necessary shape was found empirically from electrolytic tank measurements, and numerically by relaxation technique. Coils above and below the orbit carrying current proportional to the field were provided to enable the field gradient, and hence n, to be varied.

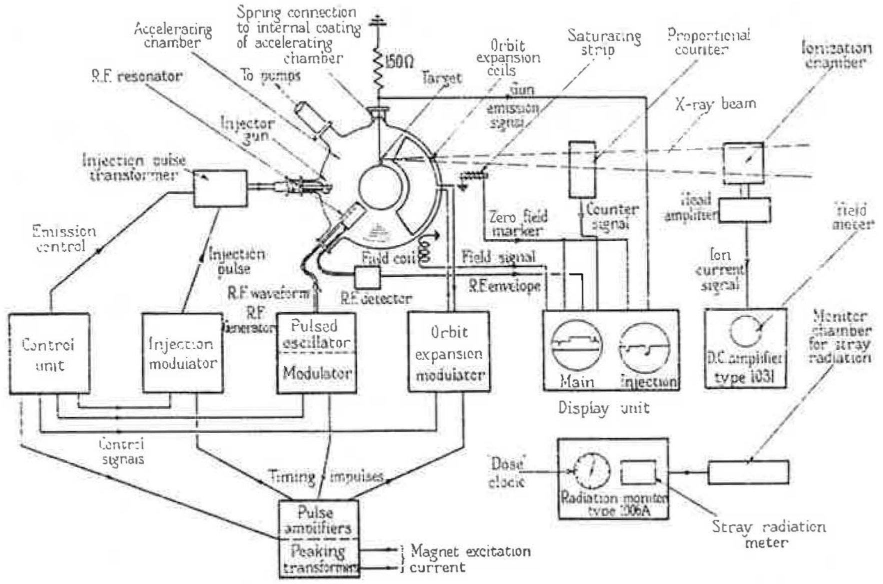

Fig. 8 Schematic diagram of components of Malvern machines(13).

The energizing circuit in both cases was a series driven resonant circuit at the supply frequency controlled by a large manually adjusted variable ratio auto-transformer ('variac'), (Fig. 9). 'Metrosil' was included for emergency voltage limitation, and trimming condensers plus variable inductance were included for fine tuning. This was very necessary at the time, since the mains frequency was by no means stable; after 5 pm, when the industrial load was shed, the frequency increased; it was allowed to rise so that the total number of cycles in a 24 hour period was the same as if there had been no variation from 50 Hz.

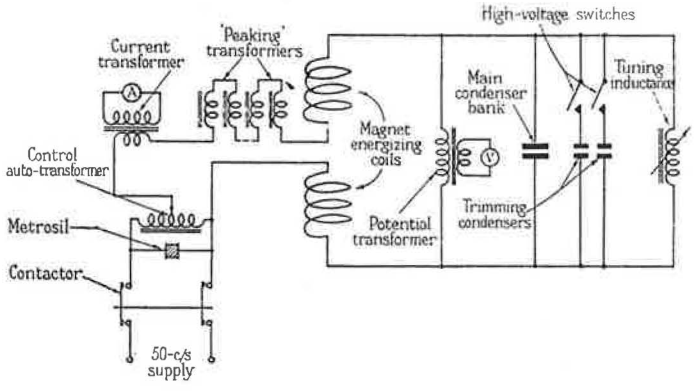

Fig. 9 Magnet energizing circuit(13).

For the larger machines a different type of power supply was needed. At Glasgow operation was at 5 pulses per second, with only a single oscillatory cycle occurring per pulse. The switching was performed by BK56 ignitrons developed by BTH, four in parallel carrying each half-cycle of current. The ignitrons which conduct the first half-cycle were triggered by a pulse synchronized to a sub-multiple of the 50 Hz supply frequency, while those conducting the second half-cycle were triggered from a biased peaking transformer in such a way as to ensure a smooth transition between the two half-cycles. The average reactive power was 33MVA, with mean power consumption of about 60 kW. The charging current for the condensers was provided by a conventional three phase hard valve rectifier and passed through a series pentode value and a voltage stabilizer. Operation at 16.4 kV provided a peak field of 0.9T needed for operation at 340 MeV[17]. A drawing of the magnet is shown in ref. 17, although broadly similar to Fig. 5b the magnet was ring-shaped, and the central betatron cores were replaced by 'flux bars'.

Returning to the 30 MeV machines, the accelerating field was provided by a quarter-wave line resonator, made of silver plated on 'Faradex'. This is a ceramic with high dielectric constant, so that the resonator length was only 2cm enabling it to be easily inserted through the side arm. The silver coating was 20 microns thick, with a circumferential strip etched away to provide the accelerating gap. The coating was sufficiently thin that eddy currents produced negligible field perturbation of the guide field. The Q-factor was 500 at the operating frequency of 477 MHz. The resonator, shown in Fig. 10, was water cooled, and fed with a peak power of 60 watts, which provided 100 volts across the gap. The voltage gain per turn required for acceleration was about 20.

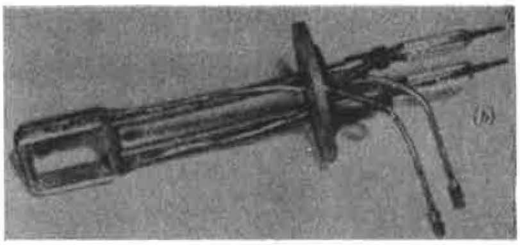

Fig. 10 Resonator for Malvern machines [13].

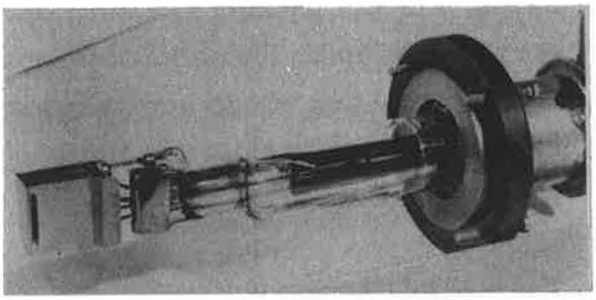

Fig. 11 Injector gun for Malvern machines[13].

The injector gun, based on Kerst's original design[18], is shown in Fig. 11. The cathode was a helix of 0.25 mm tungsten wire mounted within a semi-cylindrical 'Wehnelt' electrode, all of which was pulsed negatively, allowing electrons to pass through the vertical 1.8 mm gap in the surrounding earthed molybdenum shield. The gun, could withstand up to 40 kV.

The original vacuum chamber was made of two flat circular pyrex plates with circular holes, joined by black vacuum wax to two cylinders, the outer of which had sidearms to accommodate gun, ionization vacuum gauge, resonator and vacuum outlet. The interior was roughened by sandblasting, and an earthed film of nichrome evaporated on to it. Lack of, or damage to, this film allows charge to accumulate which inhibits injection and capture into stable orbits. This type of chamber was soon replaced by a more satisfactory 'blown' design, ingeniously constructed by GEC from large borosilicate glass cathode ray tubes. The centre of the face, and the neck of the tube were heated to softening point and pushed together to form a 'donut' shaped tube, as shown in Fig. 12. The side-arms, which were larger than in the original design, were sealed on mid-way through this operation. Three of them were fitted with ground glass flanges for water-cooled greased vacuum joints. Platinum was fired on the inside to provide the conducting coating.

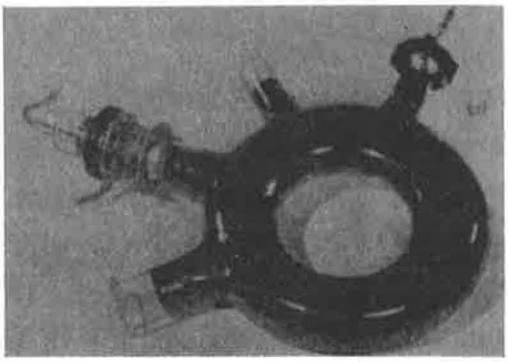

Fig. 12 Vacuum chamber for Malvern machines[13].

Pumping was from 2 inch Metropolitan Vickers diffusion pumps using Apiezon B oil, with cone joints sealed by J-oil. The pumping line was attached by a waxed joint and sylphon bellows to the unflanged side arm. The pumping speed of 10 litres/sec at the vacuum chamber produced an operating pressure in the range of 2 to 10×10^{-6} torr. The pressure was measured by an ionization gauge improvized from a first world war R1 army triode, and the backing pressure by a Pirani gauge initially improvised from an electric light bulb. Phosphorus pentoxide traps were used to remove water vapour, and a feature that would horrify modern safety officers was the use of liquid oxygen in the cold traps, in close proximity to the hot oil. Liquid nitrogen was not available commercially at the time.

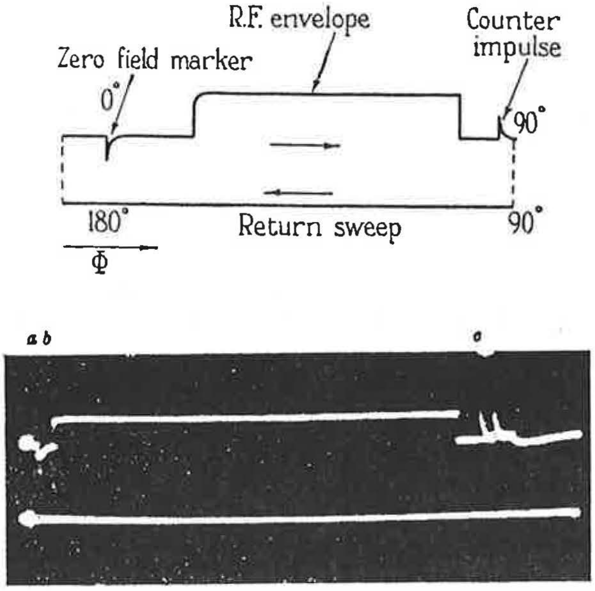

Fig. 13 Display of injection pulse, rf envelope and Geiger counter output[12,13].

The control circuitry used many of the features that had been developed for radar applications during the war. An additional feature, however, was the use of high permeability saturable peaking strips which could be set to respond at a pre-determined magnet current by varying the bias current. Finally, an integrator was used to provide a timebase proportional to the magnetic field, on which were displayed zero field, injection pulse, RF pulse and X-ray output. The forward sweep was during the rising field (0-90° phase) and the backward one, from 90° - 180°, was displayed below it. The negative half-cycle was not shown. This display is exhibited in Fig. 13 (from ref. 14) together with a photograph from ref. 13. The X-ray output was indicated by a

Geiger counter, a quantitative measurement of the average output being provided by an ionization chamber. Two pulses may be seen; the later one is at the time expected, the origin of the earlier one will be explained later.

Experiments on this machine are described in section 6, after a diversion on other activities during 1947-8.

5 A failed experiment, links with fusion, and an impractical suggestion

At this point some 'dead ends', which commonly occur, but are rarely recorded, will be described.

First, it should be mentioned that close links were kept with the Birmingham synchrotron in the early days. Discussions on theory and common problems were often held. An essential difference between the proton machine there and the electron machines was that the former required that the frequency be varied over a large range during acceleration. This problem seemed especially difficult because the change was required to be most rapid at lower energies where the frequency was low, whereas any mechanical tuning device required relatively large movement at the low frequency end.

The idea of making an electron model with frequency modulation rather than betatron acceleration, was put forward by Goward, and early in 1947 John Lawson was recruited from TRE and given the problem of making the model. This was to have the same pole shape and dimensions as the 30 MeV machines, but with a slow rise time of one second and maximum energy of 3 MeV. This would require a small magnet yoke, and radial slots in solid iron would suffice to prevent eddy currents. The gun and vacuum system would be the same as for the 30 MeV machines, and because of the low peak field and slow rate of rise the power supply would be small[19,20].

Unfortunately this project was embarked upon in the wrong way. Instead of overview of the whole scheme being taken to see where the greatest problems would be, it was tackled piecemeal. The magnet, which would take the longest time for manufacture was designed and ordered, and experiments were undertaken to make an oscillator covering the required frequency range. A butterfly oscillator with grounded grid triodes was completed which covered the range of 100 - 500 MHz, and a matched accelerating electrode designed on the (unjustified) assumption that a very small accelerating voltage would be adequate to provide the 12 mV per turn needed for the very slow rate of acceleration. After this stage unconsidered problems began to appear, such as the design of a mechanism to drive the butterfly shaft with the right frequency - time characteristic, and the need for exceptionally good vacuum to avoid gas scattering. These were found to be so severe that the project was cancelled. This was just at the time that the C-magnet and second 30 MeV machine was commissioned, and Lawson was given charge of the original H-magnet machine and asked, among other things, to extract the beam.

During work on this machine an interesting proposal was made by Sir George Thomson of Imperial College, who was working on early ideas for controlled thermonuclear reactions in a toroidal tube containing hot plasma isolated from the walls by magnetic fields(21). Following suggestions of Rudolph Peierls at Birmingham he decided to investigate the possibility of confinement in the field of a very large current circulating in a torus. This would be continuously injected from a gun, and space-charge forces which normally limit the current would be neutralized by ionizing residual gas in the torus. Although the details were not yet clearly thought out, the problem of gas scattering was studied experimentally by Watson in the 30 MeV machine, and shown to disperse the beam before appreciable ionization could occur. The result of these experiments, but not the reason for doing them, was published(22). It was found that the output decreased exponentially with pressure over a wide range of parameters. Injection voltage and rate of rise of magnetic field were varied, and a general formula incorporating these parameters was found empirically. Most experiments were conducted with air as the background gas, but hydrogen was also tried and found to be roughly equivalent to air at one tenth the pressure. The scattering problem would, of course, be reduced if the acceleration were more rapid, and Thomson instigated a programme to build an ironless betatron with very rapid rate of field rise at Imperial College. Some details of the work were published, but not its object(23,24). He also suggested that the betatron might capture a greater current if a toroidal winding carrying constant current were would round the vacuum chamber. This appears to be the first suggestion of this scheme, now known as the 'modified betatron', which has been much studied recently though no useful device has been built. The experiment was done on the 14 MeV converted betatron, but the current decreased in the presence of the azimuthal field. The theory was worked out for the first time by Walkinshaw; who showed that the field produces coupling between vertical and horizontal betatron oscillations, producing normal modes whose projections on a plane through the vertical axis is elliptical rather than horizontal and vertical straight lines(25). For the parameters of the experiment this would reduce the injected current.

Another early idea for a proton synchrotron avoiding the use of a continuously time varying radiofrequency system was the 'harmonic synchrotron', proposed by Kaiser and Tuck at Oxford, and independently by R B R Shersby-Harvie at Malvern[26-28]. In this scheme acceleration is by a resonator operating at a high harmonic of the orbital rotation frequency, $\omega_g = m\omega$. As the particle velocity increases the orbit radius increases also; after a suitable time the accelerating field is switched off so that the orbit radius then contracts to its original value. This is arranged to occur when $\omega_g = (m-1)\,\omega$ after which the process is repeated, so that $\omega_g = (m-2)\,\omega$ and so on. If m is always large the radial excursion can be kept small. More than one gap can be used provided that the relative phases at which the gaps are fed are adjusted to give a rotating wave with the required phase velocity. If this is done, however, some particles are inevitably lost at each transition. The scheme is obviously complicated, and no machine of this type appears to have been designed.

6 Experiments in 'Machine Physics'

As soon as machines became operational there was intense activity in measuring their characteristics, varying the parameters to see how critical they were, and comparing with expectations from the fairly detailed theory of betatrons and synchrotrons that had already been published[29].

By the time the 30 MeV machine first operated much had already been done on the American 70 MeV machine, and furthermore, several problems such as the effect of field errors and the important and difficult question of injection efficiency had already been studied by Kerst and others in the USA on betatrons. A brief history of American work and list of references is given in the book by Livingston and Blewett[30]. Experiments on the 14 MeV machine are described in ref. 10 by the authors and by Kaiser and Tuck from Oxford[31]. Work on the later 30 MeV machine is described in refs. 14 and 15.

The precise mechanism of injection is unclear. The gun is placed outside the equilibrium orbit, and electrons are injected when the magnetic field has risen to a value such that the radius at which the centrifugal and Lorentz forces balance is that of the 'equilibrium orbit' at the centre of the vacuum chamber. The orbits for electrons entering at various times during the injection interval can readily be calculated if the interaction between the electrons is neglected. If this is done however, it is found that the electrons invariably strike the gun structure again since this inevitably projects a few mm beyond the emitting surface. This is because of the very slow rate of damping, and the fact that part of the gun structure extends further into the vacuum chamber than the points from which the electrons are emitted. This suggests a collective mechanism of some sort, and indeed it was found that if the gun current was progressively reduced by lowering the cathode temperature, a cut-off existed below which nothing was injected. Kerst suggested a possible mechanism; since the magnetic energy associated with a current loop varies as the square of the current, injection of later electrons must reduce the energy of those already circulating[32]. Others invoked effects associated with the electrostatic space-charge. This problem was much studied, particularly (rather later) by Soviet workers. Interested readers should consult the 100 page article by Gonella, which contains over 300 references (and also a list of 43 electron betatrons and synchrotrons)[33].

Following experiments on a betatron in the USA by Adams[34] a further experiment on the 30 MeV machine, in which a rapidly pulsed 'orbit contraction coil' produced a rapidly increasing field in the magnet at the time of injection, showed no cut-off, but produced no increase of current at full gun emission. A similar type of device on the later Oxford machine produced a substantial increase in output[35]. It was also found (on the 30 MeV machine) that the effective vertical aperture, found by inserting a moveable horizontal wire, was greater when the orbit contraction coil was used. Numerous other experiments, described in refs. 14 and 15 unless otherwise indicated, were performed. The timing and length of the injected pulse, and the position of the gun were systematically varied; it was found, for example, that injection from inside the equilibrium orbit was equally efficient. The n value at injection was also varied by a pulsed coil attached to the poles above and below the orbit radius. Azimuthal harmonic errors in the field were deliberately introduced at injection again by suitable windings attached to the pole faces, and the aperture constricted in various ways to find out how important these factors were. Comparison with theory was made where possible. The dependence on resonator frequency and power was also measured. A series of experiments on the effect of pulsing the rf power off for short periods were performed on the 14 MeV machine and compared with theory[31].

A suggestion as to how the puzzling double pulse illustrated in Fig. 14 might arise was made by Lawson. This arose by analogy from the observation that in the evening the magnet excitation would suddenly drop to a very low value. As the industrial load was shed from the supply network, the frequency, which was just below 50 Hz during the day, began to rise. Since the magnet represented a non-linear inductance which decreased with current amplitude the resonance curve for the magnet circuit was of the form shown in Fig. 14; two states of excitation were possible over the frequency range between the dotted lines. As the frequency gradually increased the excitation followed the path ABCD. (For a decreasing frequency the path DEFA would be followed, showing a hysteresis effect). During operation resonance was

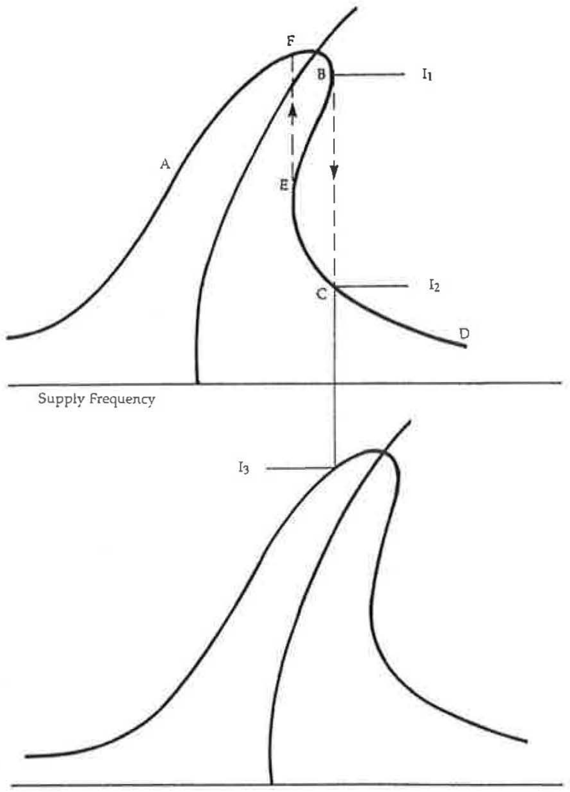

Fig. 14 Non-linear resonance curve for magnet, in which inductance varies with the amplitude of the exciting current. As the excitation frequency drifts to a value f_1, the current amplitude drops suddenly from I, to I_2. Removing condensers from the resonant circuit shifts the resonance curve to higher frequencies, with current of I_3.

restored by removing the excitation, switching out a small fraction of the condenser bank and restoring the excitation, so that the resonance curve was shifted as shown.

Returning to the double pulse, the n value of the magnet is roughly 0.75, giving $Q = \sqrt{1 - n} \approx 0.5$, so that about half a cycle of betatron oscillation occurs per revolution. If now there is a perturbation at some azimuth arising from an error in the n-value, resonant build-up occurs. If, in addition the oscillation is non-linear, as in Fig. 14, and exact resonance occurs for a finite amplitude of oscillation, there will be two stable orbits, the normal one and another which closes after two turns, as shown in Fig. 15. (A 'phase-plot' is shown in Fig. 16. Such diagrams

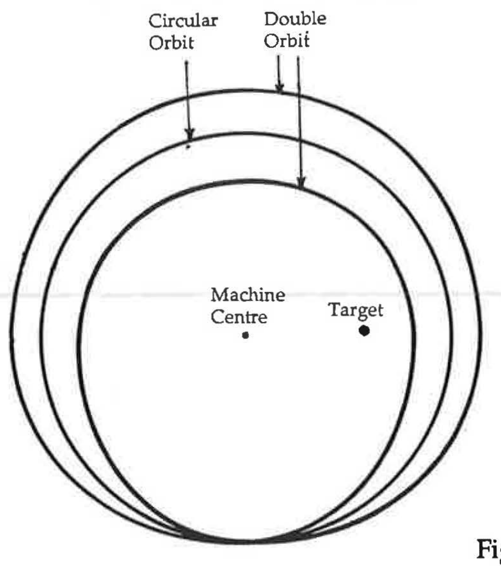

Fig. 15 Two stable orbits in synchrotron with $n \sim 0.75$, non-linear restoring force, and harmonic perturbation. Particles oscillating about the 'double orbit' hit the target first as the orbit contracts after the rf has been switched off.

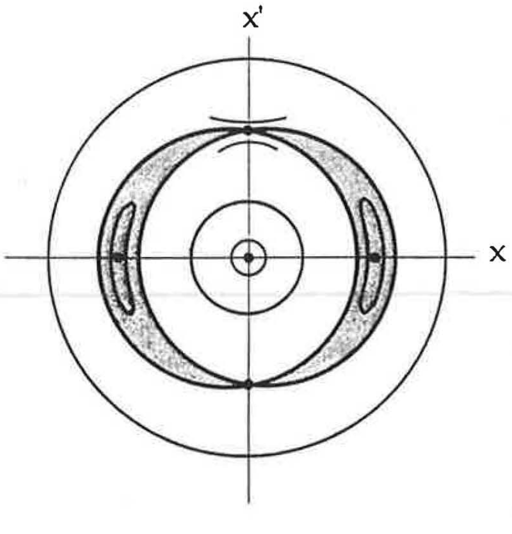

Fig. 16 Schematic sketch of phase-space diagram for machine with double orbit. Coordinates x and x' are plotted at the same azimuth on successive revolutions. The shaded area represents the double orbit regime, with successive points lying on curves in the two parts, which enclose a pair of stable fixed points. There are unstable fixed points where the separatrix curves cross, and a stable fixed point at the centre.

were of course unknown to us at the time of this experiment). If at injection some particles are captured into each orbit, and further, the orientation of the target is as shown, then the particles in the orbit that closes after two turns will hit the target before those in the normal orbit, giving the double pulse shown in Fig. 13. This hypothesis was tested by a simple experiment. By walking round the machine carrying a piece of iron (a small transformer) it was possible to vary the azimuthal pertribatron and the relative amplitudes of the two pulses. Indeed, by standing in suitable positions it was possible to make either disappear completely.

7 Beam extraction

Although several schemes for beam extraction were proposed and analysed, this was found to be rather difficult and met with only limited success. Two components are necessary, an electrostatic or magnetic extractor channel outside the range of the normal orbits, able dramatically to reduce the curvature over a range of azimuth, and a device to displace the orbits so that particles enter the channel. A magnetic channel can either be a region magnetically shielded by a shunt of laminated iron, or pulsed coils to produce a field in opposition to the main field. A pulsed system has the advantage of not perturbing nearby orbits at injection, but large currents are needed to annul the guide field. Electrostatic schemes require the use of a septum, unless the effect of vertical fringing fields can be tolerated. The orbit displacement can be achieved in two ways, either by a rapid sideways movement induced by a pulsed coil over a limited azimuthal range to give a first harmonic field component, (suggested for the Glasgow synchrotron but not used(37)), or by a pulsed axially symmetrical coil designed to increase the n-value above unity, so that the particles spiral out with rapidly increasing pitch towards the shunt.

Extraction from a small betatron using the second method of displacement and a magnetic shunt had already been achieved in the USA in 1946(38). Papers on this and other schemes as well as various proposals are quoted in refs. 14 and 15. Extraction from a synchrotron, using the same displacement method and an electrostatic septum, was also accomplished in the USA at 50 MeV on the GE machine in 1950 though the beam was rather broad(39). The beam was extracted at 20 MeV from the Malvern machine in the same year, (whether earlier or later is not clear)(40). Again the beam was caused to spiral outwards by a pulsed coil increasing the n value to exceed unity. It then entered a pulsed magnetic shunt consisting of four parallel conductors arranged in a square 2 mm apart. These carried a current of 3000 amps, in opposite directions in the inner and outer pairs; this produced a field which combined with the magnet field to produce an approximately tangential line of zero field, with stable radial (but unstable vertical) focusing. Details of the design are given in ref. 40, and operation at 20 MeV is described in ref. 41. The beam quality was rather poor, the extraction efficiency being estimated as being between 15% and 50%. Further development (including a modulator with longer life valves) was needed to make the beam usable for experiments, but owing to the closure of the programme (see below) this was not carried out.

8 Experimental programme

A description of the various experiments carried out at Malvern and on the two medical 30 MeV machines is outside the scope of this talk, nevertheless a few comments (without references) will be made. The 14 MeV machine was used exclusively for the medical studies on the distribution of ionization from the radiation in targets of various materials and geometrical configuration, yielding empirical information needed for cancer treatment. Similar work was done on the two 30 MeV machines operated by the Medical Research Council in Cambridge and London.

The principal series of physics experiments on the 30 MeV machine at Malvern was on photo-disintegration of the light elements, particularly the $\gamma + C \rightarrow 3\alpha$ reaction and photo-fission of uranium, both using the nuclear emulsion technique that had been developed at Bristol for cosmic ray studies. Thresholds for γ-n reactions were measured for a number of elements, but attempts to determine the shape of the 'giant resonance' curve were not successful. It is possible to measure neutron yield as a function of peak X-ray energy, but finding the shape of the resonance curve involves the solution of an integral equation, and this requires very accurate data, especially of the shape of the distribution at the top end of the bremsstrahlung spectrum. Despite several proposals, no accurate measurements of the spectral distribution could be made, so theoretical values were used. Measurements were made of the angular distribution of the X-radiation of the target, and fair agreement was found with theory, which involves a convolution of the angular distribution from multiple scattering at various levels in the target with the angular distribution of radiation associated with a single radiative collision.

An ionization chamber with thick walls and disc shaped air volume was constructed, and the response to a theoretical bremsstrahlung spectrum as a function of energy up to 30 MeV calculated. Using also the knowledge of the angular distribution of radiation it was possible in principle to measure the current striking the target in the synchrotron.

9 Concluding remarks

The synchrotron programme at Malvern was terminated at the end of 1950. By this time it was realised that linear accelerators provided a more intense, reliable, and accessible beam for physics experiments and medical work for energies up to 30 MeV. Furthermore, the basic work and expertise required for the Glasgow and Oxford machines had been completed. A third reason was that the Korean war had started, and priorities returned to defence. A number of staff, including the author, were abruptly moved to defence related work.

The original H magnet 30 MeV machine, with extracted beam, was transferred to University College, London, but proved unreliable and was abandoned. The C magnet machine was moved to Harwell where photo-disintegration experiments continued for a short while, after which the machine was sent to Melbourne University.

The Oxford and Glasgow machines duly came into operation in 1952 and 1954, and ran for a number of years. Extracted beams were not obtained; experiments at Oxford concentrated on electrodynamic phenomena, such as Delbrück scattering, and at Glasgow on photo-meson production. Work on the proton machine at Birmingham is described elsewhere; at Harwell interest shifted to the possibilities of a large national proton machine, and to early ideas for CERN. Strong-focusing was discovered towards the end of 1952, and interest revived. This is one discovery that we could easily have made at Malvern, but failed to do. Some further research into what happened in the years 1950-53 is intended.

APPENDIX

Information concerning the Woolwich betatron has been received since this report was completed. This is taken verbatim from draft obituary notice for D W Kerst by K Symon and H W Koch.

By now the US had entered the war in Europe and support for Kerst's work became increasingly difficult to obtain. Fortunately again, the British in the Armament Research Department at the Woolwich Arsenal, London, saw the potential of the betatron for inspecting bomb duds in situ that needed to be defused. They contracted with Kerst for the development of a portable 4 MeV betatron including a sealed-off accelerator tube. This machine was tested and delivered by one of the graduate students (Koch) to the London Arsenal in March 1944.

REFERENCES

Some referenced material (denoted by asterisk) is not generally available. it Iis hoped that this will later be archived. The prefix PRO refers to the British Public Record Office, Kew, where material is available for inspection. In the meanwhile the author will be happy to provide information or photocopies.

1 McMillan E M, Phys. Rev. **68** 143 (1945).

2 Oliphant M, 'The Genesis of the Nuffield Cyclotron and the Proton Synchrotron', University of Birmingham Department of Physics, (1967).

3 Oliphant M, 'The Acceleration of Particles to Very High Energies', Memo submitted to DSIR, September 1943. Birmingham University Archive.

4 Minutes of 1st Meeting of Panel on Apparatus for Accelerating Particles, 16th November 1945, PRO AB6/83.

5 Gowing M, 'Independence and Deterrence: Britain and Atomic Energy 1945-1952', Vol. 2 Ch. 18, Macmillan, London (1957).

6 Jay K E B, 'Harwell, The British Atomic Energy Research Establishment', pp 52-53. HMSO 1952.

7 Meeting of the Accelerating Systems Panel, Harwell, 9 October 1946. PRO AB12/4.

8 Goward F K, 'Betatrons and Synchrotrons' in 'The Acceleration of Particles to High Energies', based on a session at the IOP Physics Convention, May 1949. Institute of Physics (1950).

9 Goward F K and Barnes D E, Nature, **158** 413 (1946).

10 Abson W and Holmes L S, 'A 14 MeV Synchrotron', AERE report G/R 192, (1948).

11 Elder F R, Gurewitsch A M, Langmuir R V, and Pollock H C, J Appl. Phys. **18** 810 (1947).

12 Goward F K, Gallop J W and Dain J, '30 MeV Synchrotron Specification', AERE report AE1002, (January 1947).

13 Fry D W, Gallop J W, Goward F K and Dain J, Nature **161** 504 (1948).

14 Fry D W , Dain J, Watson H H H and Payne H E, Proc. IEEE **97** Part 1 305 (1950).

15 Goward F K, Lawson J D, Wilkins J J and Carruthers R, Proc. IEE **97** Part 1 320 (1950). The lengthy discussion following these two papers is also of interest (p 234).

16 'Building Britain's Atom Smashers'. 'Illustrated' Magazine, Odhams (Watford) Ltd., July 17 1948.

17 McFarlane W, Barden S E and Oldroyd D L, Nature **176** 666 1955.

18 Kerst D W, Rev. Sci. Inst. **13** 387 (1942).

19 J D Lawson, 'A Frequency Modulated Synchrotron', July 1947.*
20 Walkinshaw W. Notes based on Synchrotron Colloquium, 5 Dec 1947.*
21 Hendry J and Lawson J D, 'Fusion Research in the UK, 1945 - 1960', AEA (Technology) report AHO 1, Her Majestey's Stationery Office, London, (1993).
22 Watson H H H, Proc. Phys. Soc. **B62** 206 (1949).
23 Latham R and Pentz M J, Nature **164** 485 (1949).
24 Latham R, Pentz M J and Blackman M, Proc. Phys. Soc. **B65** 79 (1951).
25 Walkinshaw W and Wyllie K, 'The Effect of an Orbital Magnetic Field on Betatron Output'. AERE Math Memo/58/WW (June 1948).*
26 Kaiser T R and Tuck J L, Nature **162** 616 (1948).
27 Harvie R B R-S-, 'On a Modified Form of Synchrotron' AERE memo 8/5b/P1/M4. (Date?).*
28 Lawson J D, 'Harmonic Synchrotron for Accelerating Protons' AERE memo G/M119 (February 1949).
29 Bohm D and Foldy L, Phys. Rev. **70** 249 (1946).
30 Livingston M S and Blewett J P, 'Particle Accelerators', McGraw Hill (1962).
31 Kaiser T R and Tuck J L, Proc. Phys. Soc. **A63** 52 and 67 (1950).
32 Kerst D W, Phys. Rev. **74** 503 (1948).
33 Gonella L, Supplement No 3 to Nuovo Cimento, **3** 303 (1966).
34 Adams G D, Rev. Sci. Inst. **19** 607 (1948).
35 Moffatt J, J. Sci. Inst. **35** 447 (1958).
36 Lawson J D, Nature **165** 109 (1950).
37 Goward F K and Dain J, Nature **159** 636 (1947).
38 Skaggs L S, Almy G M, Kerst D W, and Lanzl L H, Phys. Rev. **70** 95 (1946).
39 Letter, Pollock H C to Lawson J D, Nov. 3 1950.*
40 Lawson J D, AERE memo G/M 117, Jan 1949.
41 Lawson J D, Walford H E and Aram J H, Nature **166** 234 (1950).