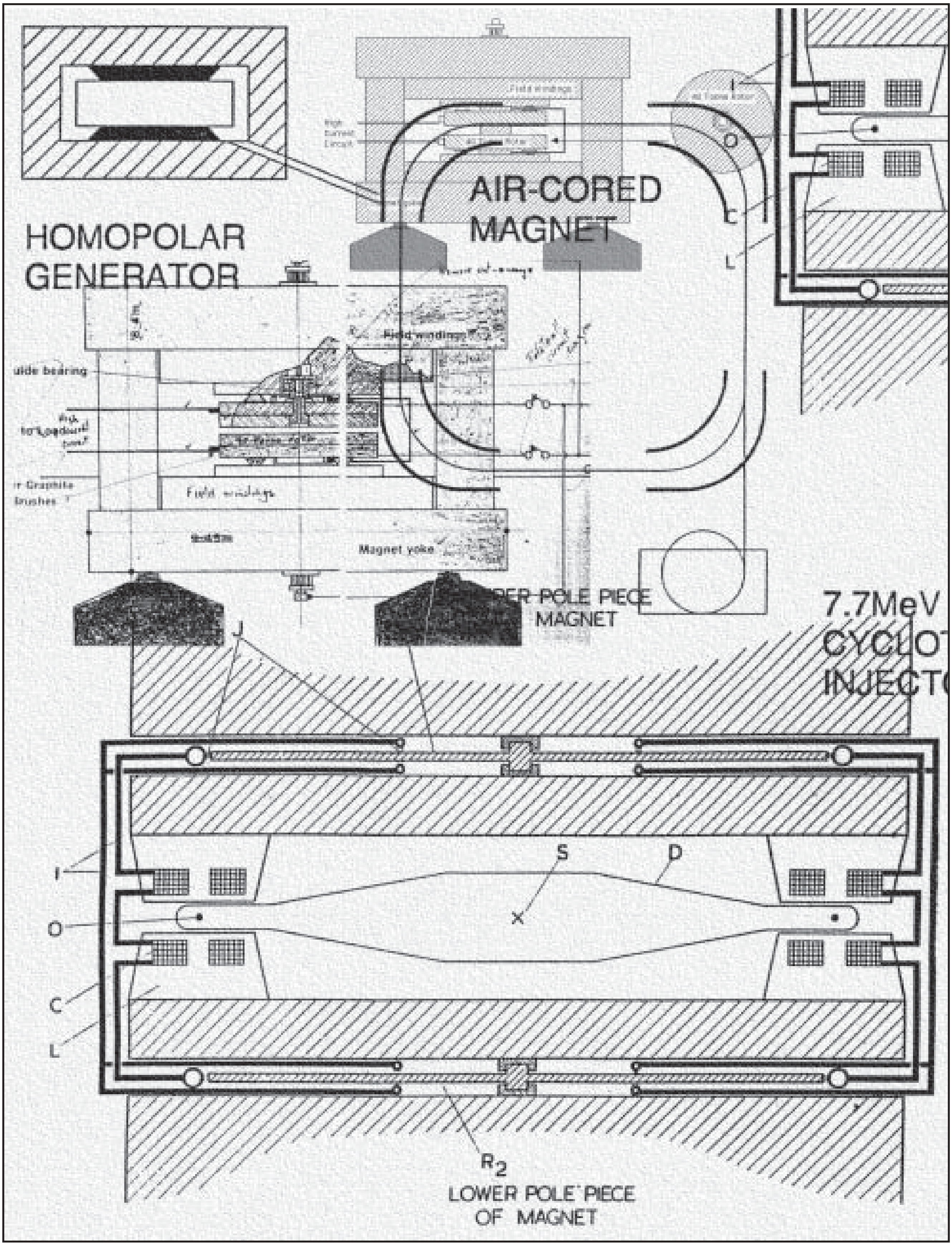
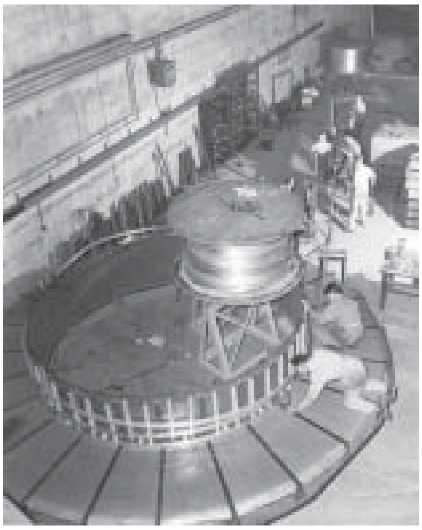
Chapter 2

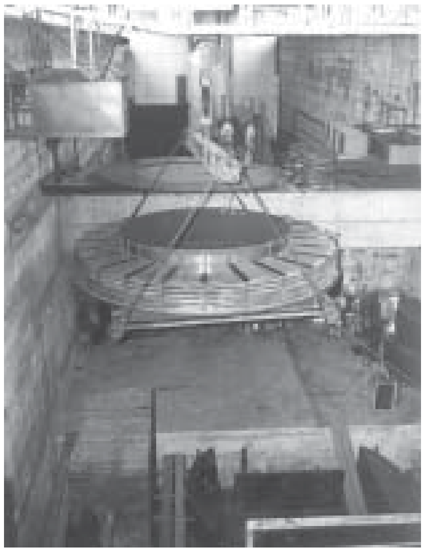
The Big Machine





August 8 1953

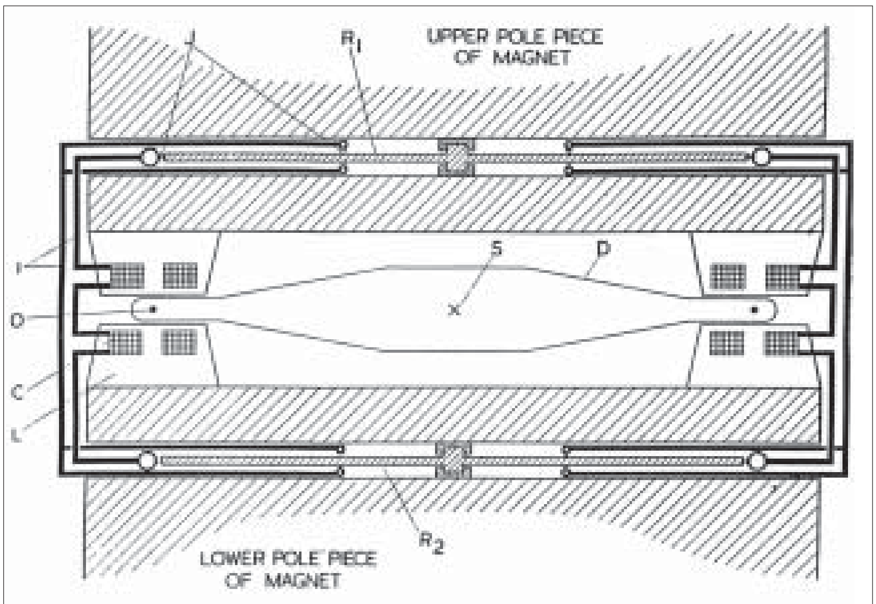
The design of the so-called cyclo-synchrotron that was published in 1950 was innovative, and one that Oliphant believed would provide Australia with world-class facilities at minimal cost. Protons were to be accelerated to 200 MeV by a synchro-cyclotron[1] before injection into a synchrotron orbit, defined by an air-cored magnet, for final acceleration to 2 GeV. With a field of ~6.5T, the synchrotron orbit could be accommodated within the 136" diameter poles of the synchro-cyclotron magnet. The current of about one million amperes needed to energize the air-cored magnet was to be provided by a homopolar generator[2], comprised of two discs rotating within the magnetic circuit of the synchro-cyclotron. Jets of liquid sodium, at the periphery and an inner radius of each of the rotors, would serve as contacts to switch and provide the current for the air-cored magnet.



October 2 1953

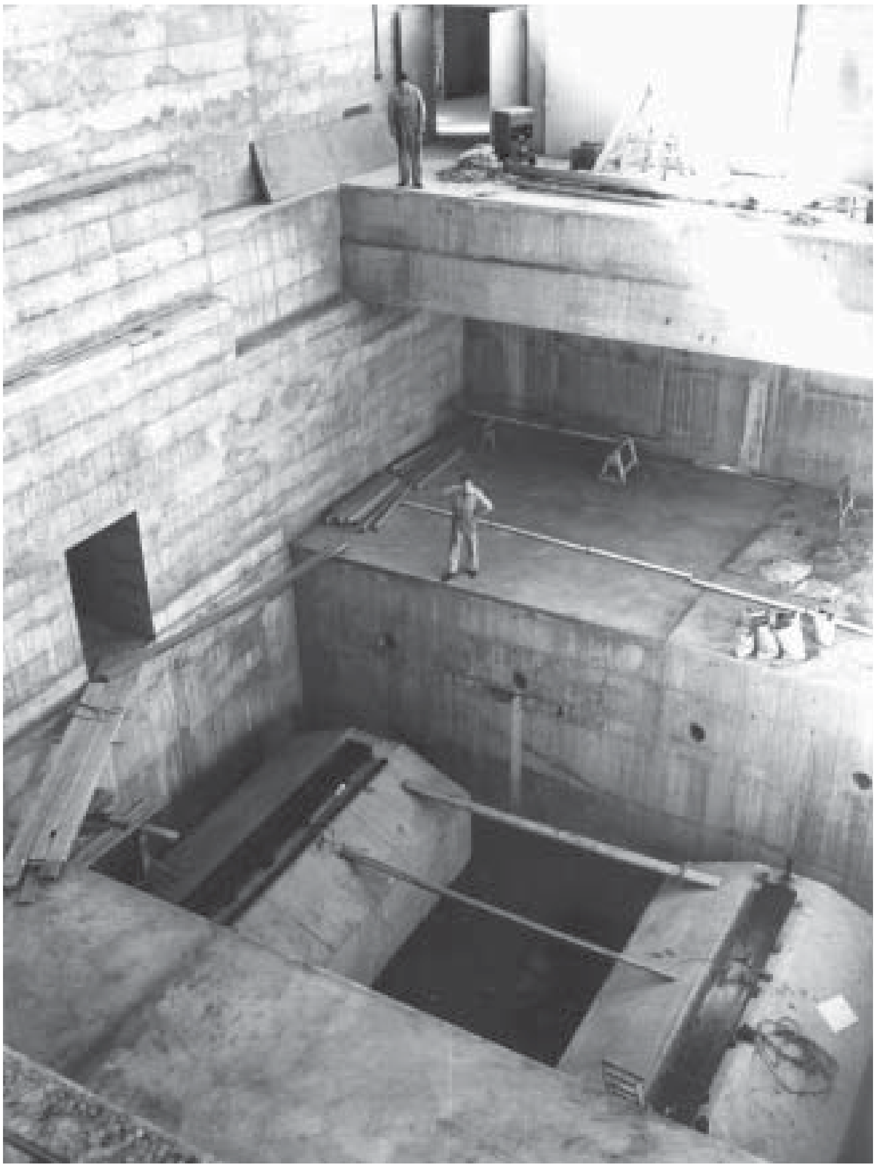
It is by no means straightforward to identify the savings that contributed to the minimal cost claimed. Certainly the accelerator was compact, minimizing some building costs and removing the need for extensive distributed vacuum systems, but at the expense of pulse repetition rate — 10 seconds or more between pulses, and much more importantly, the need to develop a homopolar generator of such a scale and complexity.

There was a general perception, perhaps not deliberately fostered but certainly not contradicted, that a significant economy stemmed from having only the one iron-cored magnet of the synchro-cyclotron weighing about 1400 tons. An early design study in 1948 for the Bevatron at Berkeley, though for a somewhat higher energy, had included magnets with a total weight some ten times larger[3]. In 1956, Oliphant visited Dubna in the USSR where magnets containing some 36,000 tons of steel were part of a 10 GeV accelerator under construction. By then, with the Canberra “big machine” aiming at a new goal of 10.6 GeV as a result of design changes, extremely favourable



Schematic diagram of the 2 GeV cyclo-synchrotron (taken from M.L. Oliphant, Nature 165 (1950 466). R1 and R2 are the homopolar rotors, O is the synchrotron orbit and C indicates the coils of the air-cored magnet.

The "pit" area prior to installation of the magnet yoke, showing the two concrete support plinths (September 8 1952).



Sequential progress of the magnet, from the winding of the coils to final installation of them.

Circa July 1954.

magnet cost comparisons were valid. In fact though, the magnets for the Cosmotron at Brookhaven National Laboratory, that became the first GeV proton accelerator to operate, weighed only 2000 tons.

September 15 1954.

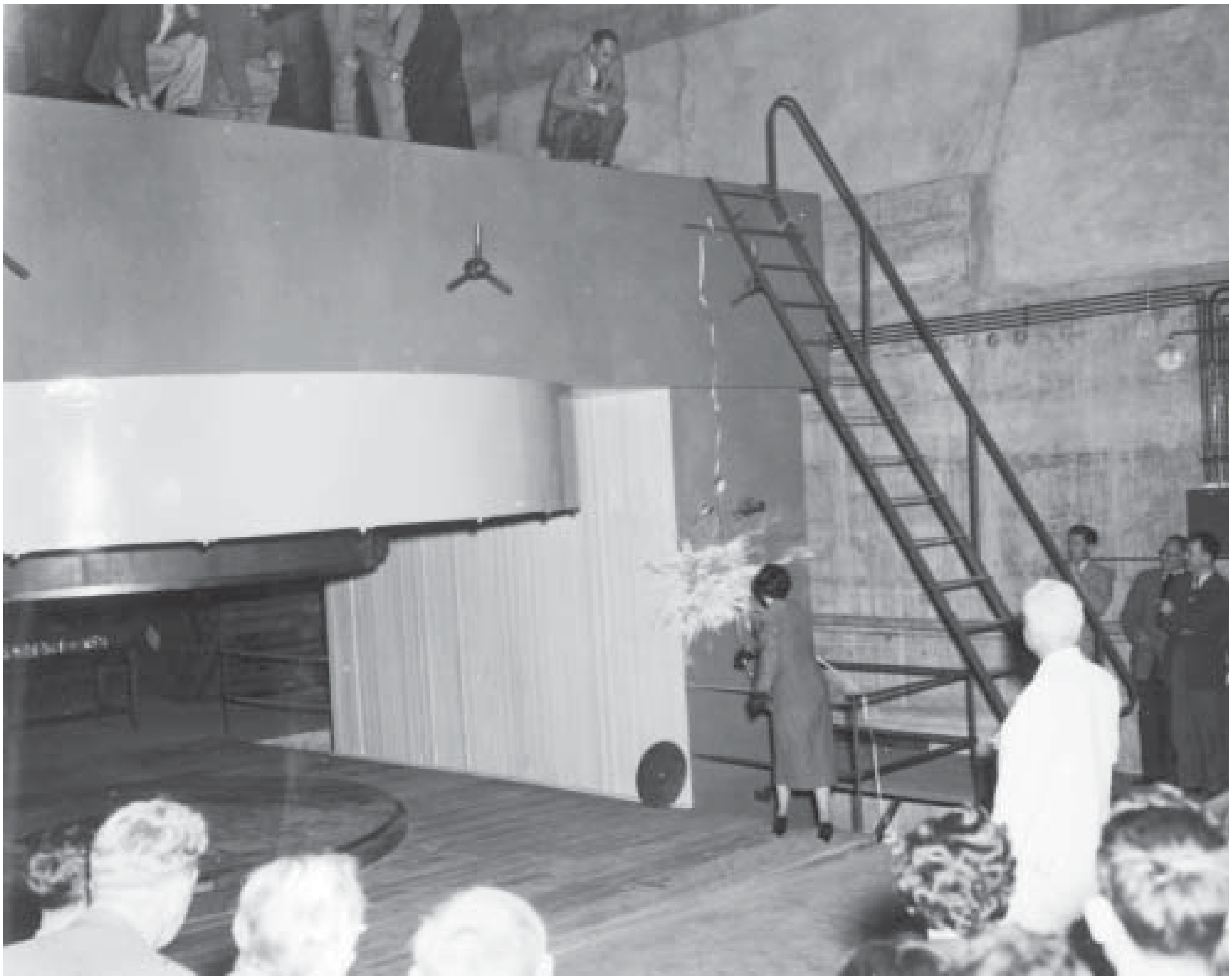
Otherwise, the intention to inject 200 MeV protons into the synchrotron orbit was potentially superior to much lower energy injection, with the companion benefit of reducing greatly the frequency range needed for the accelerating field within the synchrotron. The latter probably represented the only obvious simplification of the design. Overall, it must be concluded that Oliphant had placed a great deal of emphasis on innovation, and rather less than circumstances warranted, on less challenging, but essentially proven, technology. Unwisely optimistic, he predicted it would take two to three years to complete. With an already established laboratory and workshop facility, completion within such a short time would have been remarkable enough. At ANU though, Oliphant was faced with a truly "green-field" project in chaotic circumstances. Just getting buildings completed for laboratories and a workshop consumed most of those first three years. Moreover, he was attempting a project not greatly different in either scale or capital cost from that of the Cosmotron with a small work-force. It was the smallness of that group that provided the economies of minimal cost. The delays, and ultimately the non-completion of the accelerator at ANU, can be attributed to the judgement to go ahead under such circumstances. Such criticism springs readily from the wisdom of hindsight. The reality was that Oliphant had no alternative unless he were to confine the School to the single activity of accelerator construction. Such a course of action might well have been possible regardless of the recommendations of the advisers, but seemingly was never contemplated by Oliphant.

In many ways, the period between 1948 and 1952 proved to be the least propitious during which to make decisions about accelerators. The end of the period was marked by the "re-discovery" of strong or alternating gradient focussing[4]. (The original work by Christofilos in Athens during 1949 was not published). Later accelerator designers had available a powerful new technique that changed accelerators significantly, but earlier projects were constrained to be completed as planned. The beginning of the period was marked by a change of *modus operandi*. Pre-war accelerator development had been carried out by small, dedicated bands of physicists and perhaps a few engineers working on shoestring budgets at universities. There was a

∆ In the foreground (L-R), Jimmy Edwards, Phoebe Edwards, Rosa Oliphant and Ron Purchase at the naming ceremony. The gloves in this and the related photograph are a reminder of past convention.

▻ A white-coated Mark Oliphant demonstrates the magnet to Sir William Slim, the Governor-General on October 28 1954.

∇ The launch of Heracles by Phoebe Edwards (November 19 1954).

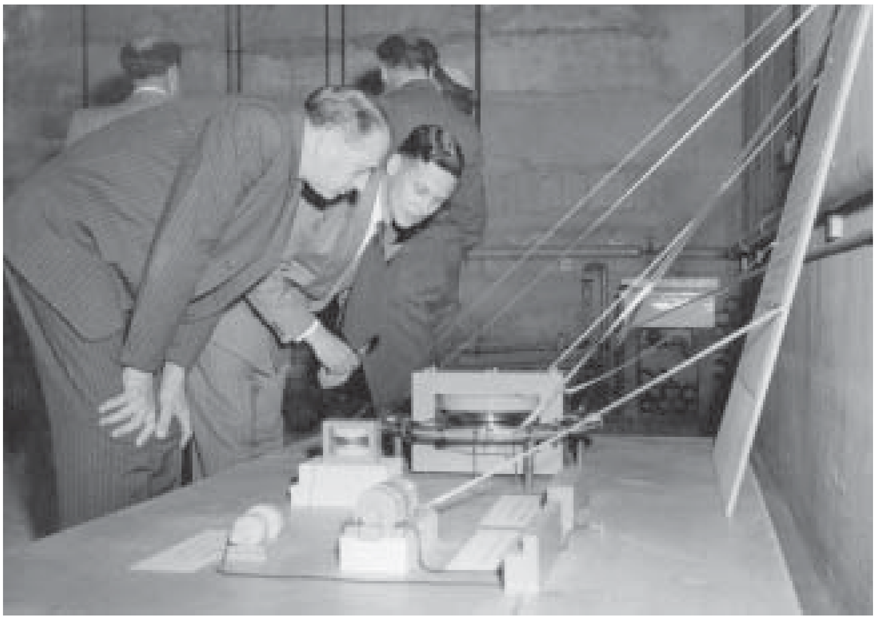


tendency to concentrate on proof of principle operation before turning to the task of research implementation. Though the serial process was partly one of inclination, it was difficult to arrange otherwise without a schedule for completion that could be accepted confidently. The Birmingham 1 GeV accelerator continued the tradition into the late forties. It seemed that Oliphant remained conditioned to, or was prepared to accept, the former mentality, as a legacy from the golden days at Cambridge with Rutherford, despite his war-time experience. The lessons of the Manhattan project were not lost on others though. Large scale facilities could be completed rapidly with efficient planning of adequate financial and manpower resources. Moreover, a new evolving process in the US was to have research groups preparing for the initial experimental research in parallel with the construction team. In every sense, the two parties drove one another to meet deadlines.

The stately pace of low budget, university-style assembly of large accelerators had probably passed its use-by date already in 1950. Though started first, the Birmingham synchrotron was overtaken by the Cosmotron that produced a 2.2 GeV beam in May 1952 and had achieved the design energy of 3 GeV just before first operation at Birmingham in June 1953. Less than one year later, in March 1954, the Bevatron at Berkeley was producing a proton beam with an energy of 5 GeV[5].

The ANU planning group during 1948-1950 could scarcely have foreseen that the quest for ever-higher energies was to become a matter of national and multi-national pride. By 1956, the Russian 10 GeV machine was well advanced and a 25 GeV accelerator was under way at CERN in Switzerland. CERN was established as a combine of twelve European countries in 1953/4. Thus the definition of world-class facilities was changing rapidly.

Preparations for fabrication of the cyclotron magnet, reported by the *University News* of April 1950 as one of the largest in the world, quickly began. The design by Blamey and Shenton was then practically complete, allowing the steel to be ordered. By March 1952, the steel had been rolled and the larger part of it machined at Garden Island Dockyard of the Royal Australian Navy. It was anticipated that delivery of the steel could be taken toward the middle of the year, with erection to begin soon thereafter. Building delays meant that assembly had to be postponed until the end of the year. Nonetheless, it was to be November 19 1954 before the completed magnet was inaugurated and named Heracles by Phoebe Edwards. In the meantime, Blamey had built a 30" diameter magnet and



◅ *Lesley Melville, the Vice-Chancellor, and Ernest Titterton viewing a model of the proposed 10.6 GeV accelerator. The model shows an interim design in which the air-cored magnet surrounded the homopolar generator (November 13 1953).*

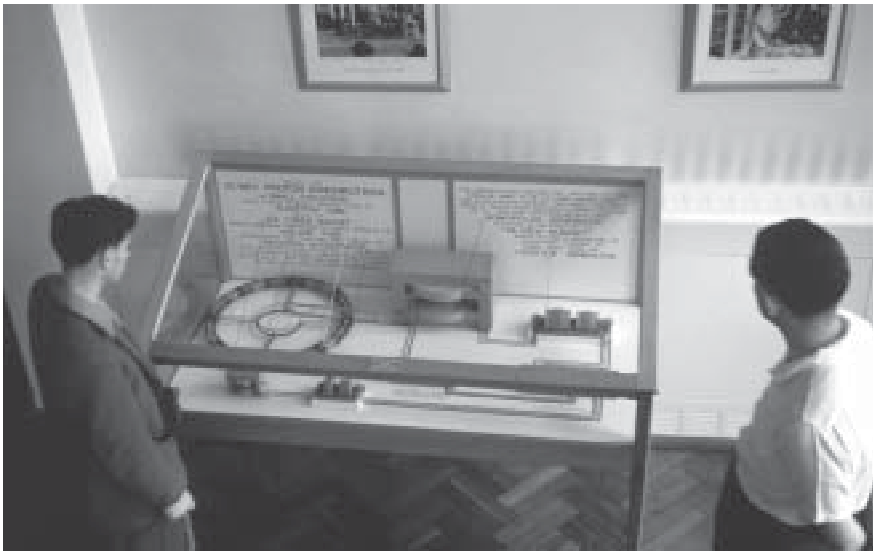
▻ *Sectioned elevation of the homopolar generator, showing the foundations, magnet, coils, rotors, bearings and pulse and motor connections. The final air thrust bearings that overcame the limitations of earlier bearings were designed by Oliphant and Inall.*

▻ *The jet system of the prototype generator (November 19 1953).*

▻ *The 30" magnet built for the prototype homopolar generator (June 9 1953).*

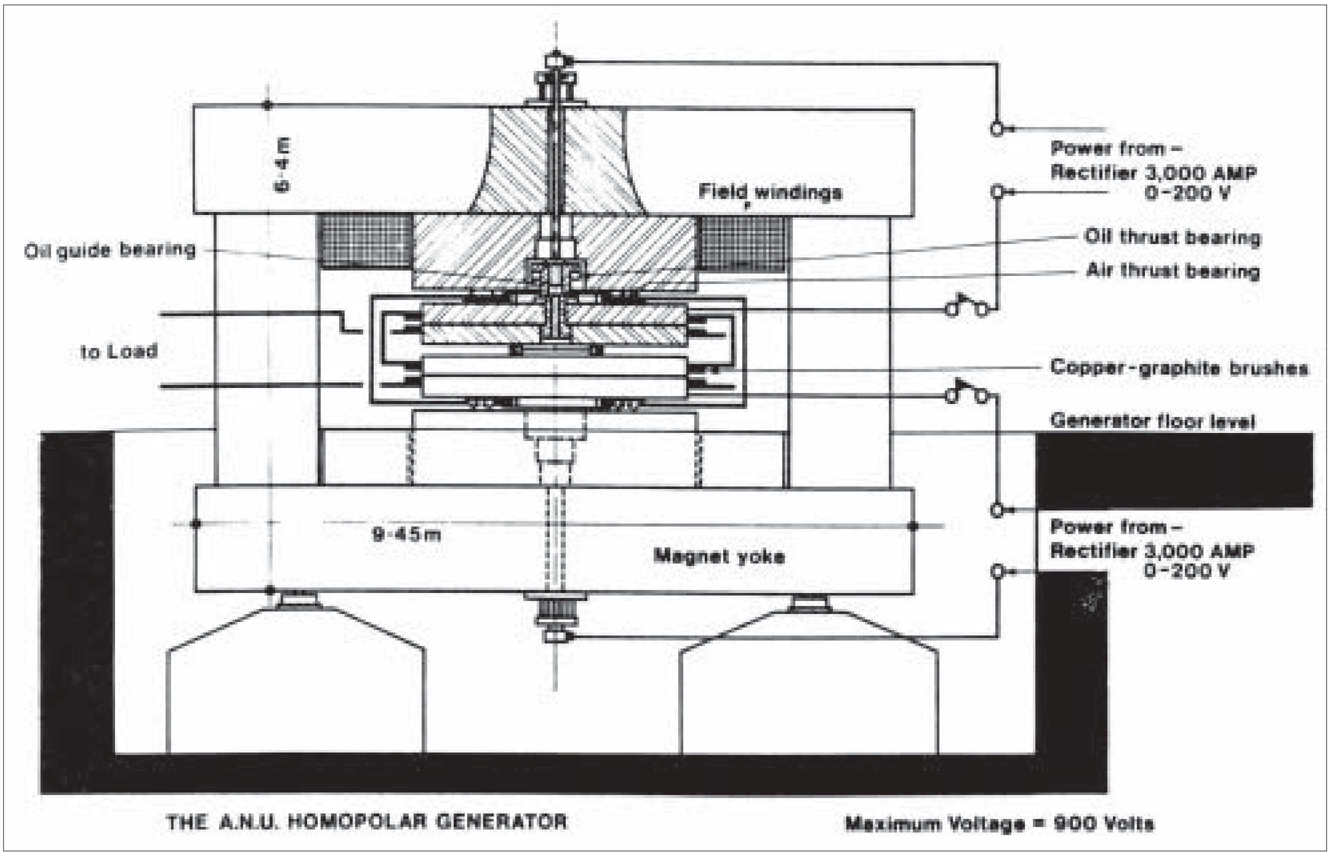
used it to construct and test successfully a model homopolar generator. Mercury, instead of liquid sodium, was used for the contacts.

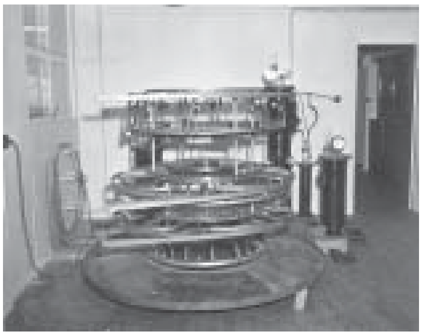
The large magnet was the first demonstrable achievement of the project. Oliphant delighted in showing it off to visiting dignitaries. Though physicists never wear lab coats while plying their trade, Oliphant invariably donned a white one on such occasions. Happy as those occasions might have been, they had been preceded by much frustration and soul-searching, then by a dramatic change of direction. In 1953, the slow rate of progress, coupled with initial operation of the Cosmotron the year before and imminent start-up of the Bevatron, led to a new, even more audacious design[6]. The energy to be achieved was increased to 10.6 GeV, higher than any other machine proposed at the time. The synchro-cyclotron was abandoned. The magnet would be used instead solely for a much larger homopolar generator, capable of producing close to two million amperes, that would power an air-cored magnet defining a synchrotron orbit about 30 feet in diameter. Protons would be injected into the synchrotron from a 7.7 MeV cyclotron to be assembled using the small magnet from the model homopolar generator. Again, completion in two to three years was predicted.

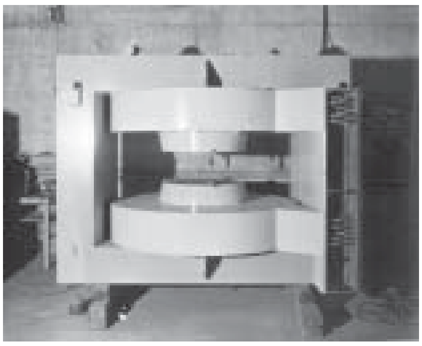


◅ *A model of the final design of the 10.6 GeV accelerator. It was on display in the foyer of the Chifley Building for many years (1960).*

▻ *The beginning of the construction of the 7.7 MeV cyclotron at the northern end of the accelerator wing (circa 1955).*

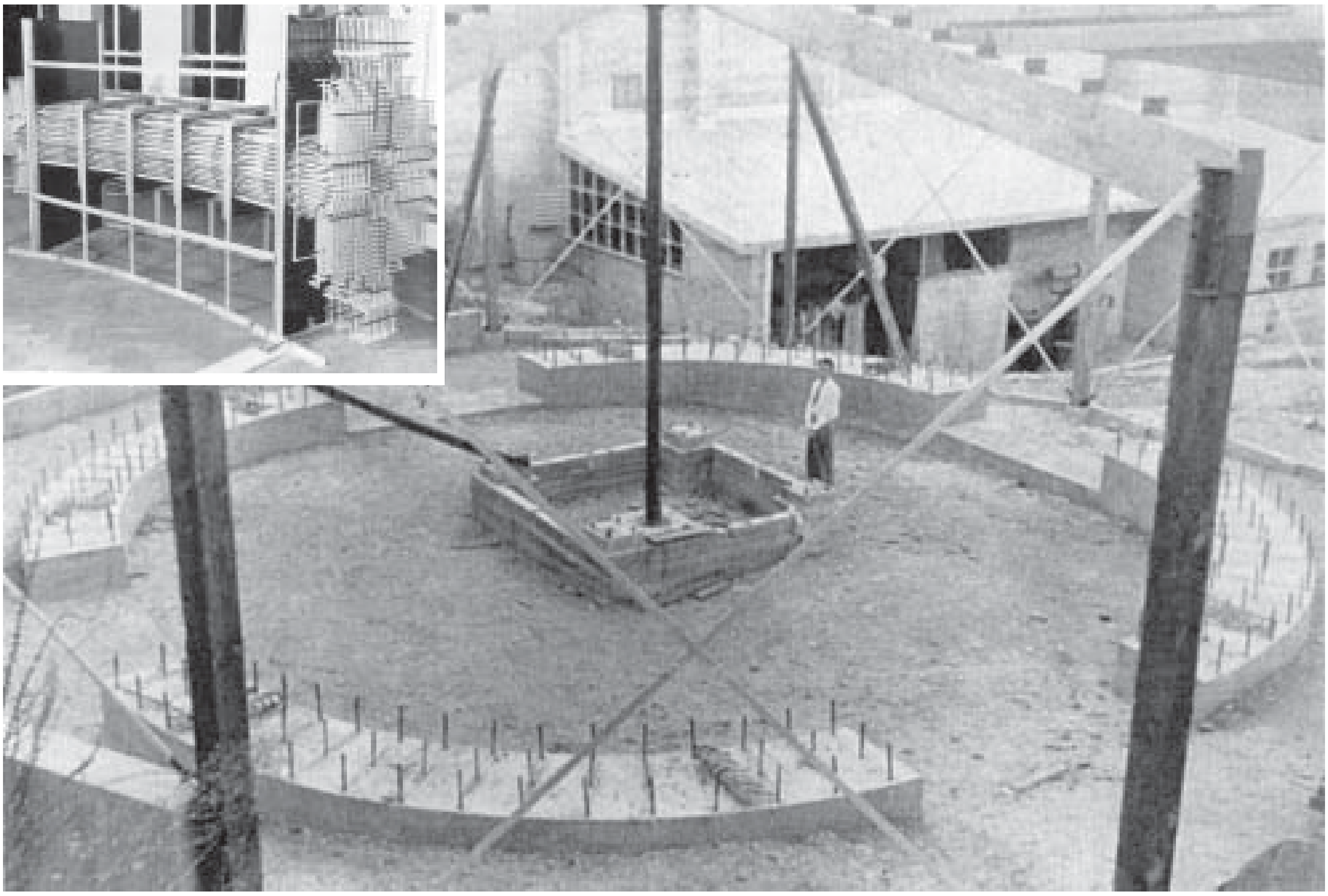






Specifications for the upgraded homopolar generator were impressive. Two rotors, each weighing 40 tons, would be motor-driven to 900 rpm in an atmosphere of nitrogen before extraction of the current oscillation over a 1.8 second time span. Each of the counter-rotating rotors was comprised of two separate disks, insulated from one another electrically, but joined with a rubber bond. Thus the four disks were in effect four individual homopolar generators that could be inter-connected in various configurations. Mild steel forgings intended to be the poles of the synchro-cyclotron magnet, were available to be machined as the disks. Instead of liquid sodium, the sodium-potassium alloy, NaK would be used for the contacts. The alloy is a liquid at room temperature, though no less active chemically. However, there was one serious drawback. Current pulses would only be available at intervals of 10 minutes. Some critics suggested that the slow pulse rate was inconsistent with even testing and establishing accelerator operation, let alone able to support realistic research.

Duty cycle aside, it was an ingenious scheme and truly one that could be costed extremely favourably against existing installations — capital-wise. The accelerator team though was still small and continued to be, although some additional funds were obtained in 1957. In 1953, it comprised Blamey, Berry “Wibs” Smith who came in 1952, Wilson and Shenton. Hibbard finally rejoined the group in 1954. Following the death of Wilson, David Robertson came in 1955 to work on the radio-frequency elements of the accelerator. Bernie Wadsworth came to assist him in 1958. Shenton left in October 1957. Much of the design thereafter was done by Peter Carden, an engineer taken on in 1955. Inall, formerly in Nuclear Physics, and Dick Marshall, another engineer, became members of the group in 1955 and 1958 respectively. Altogether, the group had the expertise and



dedication required — as indeed was borne out in due course, but needed vastly more technical support and workshop capacity.

It would seem that the decision to implement the new configuration was by no means a unanimous one. Anecdotal evidence, though plainly not always reliable but equally, sometimes all that is available, has it that many stormy meetings of Particle Physics occurred before Oliphant decided the issue unilaterally. An obvious alternative would have been the completion of the 200 MeV synchro-cyclotron as a stand-alone research facility. Few accelerators were built in that energy range. Those at Harvard and Harwell began operation in 1949 and the Uppsala machine was near to completion in 1953. All sustained a significant research use well into the sixties. The Harvard machine later pioneered the precise treatment of discrete cancer growths with high energy proton beams, while the Uppsala machine was recently refurbished to serve as injector for a high-energy, heavy ion accelerator at the The Svedberg Laboratory. Here though, Oliphant's determination to achieve an accelerator triumph over-rode the opportunity to establish an effective research facility that was, in relative terms, readily within reach.

Judged from hindsight, another alternative to the dilemma faced in 1953 would appear to have been completion of the cyclotron, but with the incorporation of strong-focussing to enable fixed frequency, or isochronous, operation. The poles had not been machined at that stage, allowing complete flexibility of implementation. On the face of it, an opportunity existed to make an important, pioneering development, more modest than the big machine. However, the thrust of the original paper in 1952 was the application of strong focussing to

△ *A field of dreams- the foundation for the air cored magnet. Inset: the half quadrant model of the magnet (1956).*

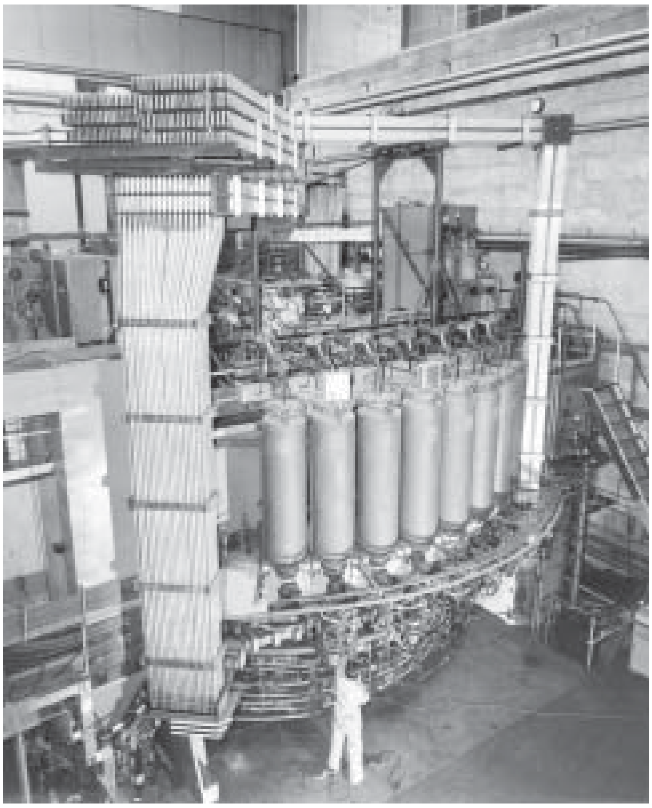
◁ *Top right. The homopolar generator during the period of operation using NaK. The cylinders around the periphery contained compressed nitrogen to drive the NaK into the jet system at rates of up to 1 ton/second. Part of the busbar array needed to carry the enormous current pulse from the generator is evident in the foreground. The configuration of busbars (with respect to current flow direction and position) was carefully designed to minimise the otherwise potentially destructive forces between them (March 2 1962).*

The NaK jet system. ▻

large synchrotrons and quadrupole lens devices. It was not until 1955 that extension of the technique to sector-focussing cyclotrons was pointed out. The first such proton machine, producing a modest energy of 12 MeV, operated in Delft in the Netherlands in 1958.

Until early 1958 when Titterton was given School and University approval to seek funding for the EN tandem, the notion that the experimental nuclear physicists would move onto "the big machine" was given lip-service, even if commitment was hardly apparent. Aside from the emulsion and scanning facilities, which were used for gamma ray and neutron reaction studies, there was no other effort, actual or planned, that could be interpreted as preparation for the 2, and later 10.6 GeV accelerator. Whether this reflected a judgement by Titterton of the likelihood of the machine being completed, or his belief that there would be adequate lead time if and when it neared completion, must remain a matter for speculation. The nexus was broken in 1958 when the Federal Government allocated £A600,000 (present day equivalent ~$US10M) to Titterton for the installation of the tandem and associated facilities.

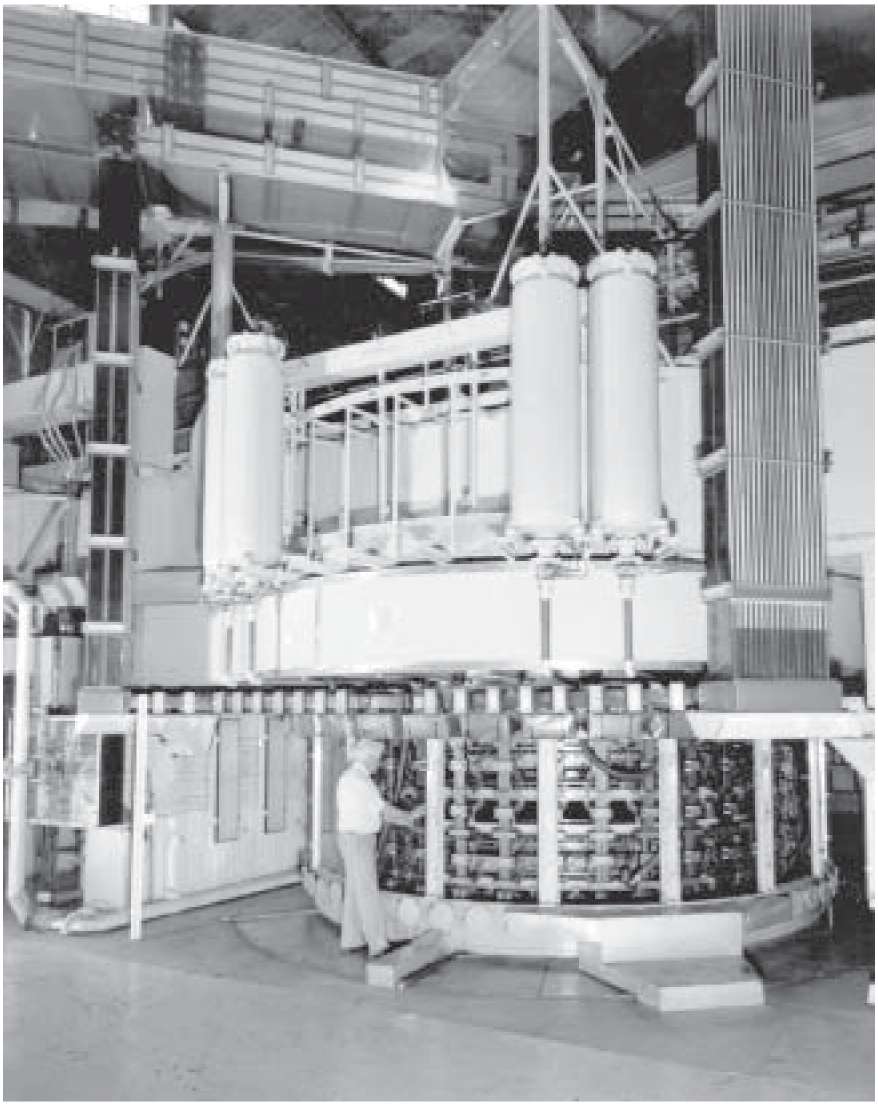
Inevitably, the proposal to buy the tandem provoked controversy. On the one hand, Oliphant must have seen the decision as reflecting a lack of confidence that "the big machine" would be completed. On



the other hand, as a machine-builder of the old school, he disdained commercially-built devices, preferring those assembled by physicists with "fire in their bellies"[7]. There was also conflict wider afield, since the capabilities of the EN were considered by some to merely duplicate those of a variable energy cyclotron nearing completion in Melbourne. Relations between the two groups became somewhat strained with the advent of the EN, exacerbated no doubt by memories that the creation of the ANU had stifled any plans by Laby to expand nuclear facilities in Melbourne. In reality, most of the research program at Canberra used beams other than protons so that there was little basis for any sense of rivalry.

The biography of Oliphant states that "this (the £600,000) was as much as had been spent up to that time on Oliphant's new accelerator. Yet it was obtained with little difficulty and less dissent"[8]. The Department of Nuclear Physics retains a different impression of the events. Titterton maintained to staff of the department that "getting it out of the School", that is gaining Oliphant's approval, if not benediction, was the hardest part of the battle.

The homopolar generator finally operated on June 5 1962, being delayed mainly by bearing problems. First tests used only one rotor, the other was clamped. Even so, currents of 1.8 million amperes were obtained[9]. In the interim, the injector cyclotron had been completed by Smith and a student



The final version of the homopolar generator after the NaK system had been replaced with copper graphite brushes. Four of the eight cylinders of compressed air that operated the brushes can be seen. Ken Inall is in the foreground.

Hilary Morton, and a full sized model of one half of a quadrant of the air-cored magnet assembled by Hibbard in order to confirm design calculations at low currents. The calculations had been done laboriously using Facit calculators, the workhorses of the fifties. The design of the R.F. acceleration modules had been finalized.

The cyclotron was completed in 1955 and produced sources of several radioactive nuclides for projects around the campus. In 1957/8 it was used by Don Gemmell, a student in Nuclear Physics, along with Smith and Morton to measure a number of inverse photonuclear excitation functions[10]. These measurements had been suggested by Titterton and were, at the time, ground-breaking since it has been anticipated they could only be done with a foreshadowed new generation of electrostatic accelerators. With Gemmell's thesis project complete, Titterton wanted to extend the measurements, but Oliphant insisted that the cyclotron be moved to the roundhouse, in readiness to serve as injector for the big machine. Again, rather than exploiting the opportunity of gaining research results from some aspect of the project, the single-minded drive to complete the major project prevailed.

By the time the homopolar generator operated for the first time though, project momentum had been lost and the big machine had already faded away. It was last mentioned in the 1960 annual report of the group; thereafter only progress with the homopolar generator was reported.

There had been critics of the big machine venture of course. In particular, the group at Sydney headed by Harry Messel finally launched a scathing attack on it in Canberra in 1957. Outwardly, relations between the groups were cordial with occasional exchange visits to Sydney or Canberra involving research presentations and discussions. Initially, there was good-natured bantering between the groups on the relative merits of accelerator-based research as compared to what could be done by exposing emulsions to cosmic rays. Publicly, as he sought funds for his Nuclear Foundation, Messel made much of the high energy particles that nature provided for free, raising inevitable concerns that he was undermining the credibility of accelerators, in Canberra and elsewhere as well. At the last of those exchange visits, John Blatt, who was then at the University of Sydney, opened proceedings with an especially trenchant tirade. With still no end in sight, immediate abandonment was proposed to stop the waste of even more funds. The Canberra group responded with icy dignity. A stridently critical article appeared in the national weekly magazine, *The Bulletin*, early in 1961, under the by-then hackneyed title of "White Oliphant"[11]. Although much of the Sydney criticism was recycled, Messel vigorously denied any involvement with the article, and indeed subsequent events confirmed that he had not been[12]. The flurry of unfavourable publicity generated by the article had little, if any, influence on the inevitability of non-completion.

Tragically, the triumph of successful operation of the homopolar generator was short-lived. An explosion involving NaK occurred in July 1962. Though the damage to the generator was slight, a technician, George Lagos, was blinded. The procedures used for the handling of NaK were vindicated by a subsequent enquiry, but its use was abandoned nevertheless. After lengthy, heated debate, Marshall was given approval to try graphite/copper brushes[13] and these proved an immediate success. Finally in 1963, the homopolar generator was a reliable source of pulsed, mega-ampere currents but of course, there was no air-cored magnet into which the current could be directed. It remains the largest homopolar generator ever built. Beautifully engineered, reflecting the skills, ingenuity and perseverence of Blamey, Hibbard, Inall, Carden and Marshall, along with the supporting technical team, it was a remarkable achievement.

Belatedly, but inevitably so in the circumstances, various research applications of the generator were sought. Plasma research had been initiated some time before within the Department with future use of the homopolar generator in mind. Applications better matched to the maximum output were initiated or evaluated.[14] Carden designed a pulsed 30T magnet, comprised of two solenoids. Marshall developed a large rail-gun and Inall became involved with a project using xenon flash lamps to pump a neodymium laser. For one reason or another, none of the projects was provided with sustained support. Ultimately, the homopolar generator was used to energise the plasma research device LT4, albeit with currents well below the maximum available. The generator fired its last "shot" on December 13 1985 and then was dismantled.

In absolute terms, the overall accelerator project was a failure. However, "the big machine" led to the establishment of the Research School of Physical Sciences and the development of a substantial technical and workshop infrastructure that has underpinned highly successful research in many areas. In a wider sense, the accelerator was a key element in the founding of a now-significant research university.

The capital invested in it by the Federal Government, modest by international standards, if not for Australia at the time, has yielded worthwhile dividends even though no beam was produced.

By Oliphant's account[15], Florey had advised him not to go to Canberra because he would be committing "scientific hari-kari". At times Oliphant, immersed in the frustrations, misfortunes and tragedies that occurred, would have been inclined to agree. However, he was doing more than just trying to get an accelerator completed. Other departments were established and well-supported with staff and funds under his selfless guidance. It is testimony to the strength and diversity of the research vigour, within the School he founded, that non-completion of the accelerator had remarkably little effect on the perceptions of either the School or large scale research to those outside it. While Oliphant's judgement may have been questioned, his scientific credentials, determination and loyalty to the ANU never were.

Perhaps Florey instead committed scientific hari-kari by not achieving the stature of a founding Director of a School at the ANU.

1 As the energy sought increased, cyclotron design was bedevilled by the conflicting requirements of beam focussing, needed to constrain the particles being accelerated to the median plane, and of compensation for the relativistic mass change of particles as their energy increased. The former requires a magnetic field decreasing at larger radius whereas an increase with radius is needed for the latter.

Hence the development of the synchro-cyclotron in which a decreasing field obtained, but the frequency of the accelerating electric field was varied as the orbit radius of the particles increased, in order to maintain synchronous acceleration as the mass increased.

On the other hand, a synchrotron has a fixed *orbit and both the confining magnetic field and the frequency are increased together during acceleration as the energy and mass of the particles increase. Discrete pulses of particles acquire high energies by making many thousands of revolutions around the orbit in the time span of a second or so.*

The discovery of strong focussing (see note 4) provided machine designers with a powerful new technique. For example, by having a magnetic field with "hills and valleys" in the field of each orbit, but with the mean field increasing with radius, simultaneous focussing and relativistic compensation are possible.

2 *The homopolar generator was first devised by Faraday. Though the simplest of dynamos, explanation of how it works is non-trivial. As Oliphant said in introductory remarks to the SESCAS'77 Workshop on Energy Storage, Compression and Switching in November 1977:*

"It is possible to understand how it works .... by considering what happens to individual electrons in the rotating conductor, but not by application of macroscopic circuit theory."

For present purposes, a simple model, based on the idea that instantaneous induced voltages in a conductor moving in a magnetic field are a function of velocity, suffices. For a rotor, the velocity and therefore the voltage is a function of radius. With a narrow wedge rotor, drawing a current between the periphery and an inner radius then seems straightforward. Extension of the wedge to a complete disk is not, and one must take refuge behind the statement above.

3 *Brobeck, W.M. Rev. Sci. Inst. 19 (1948) 545.*

4 *Courant, E.D., Livingston, M.S. and Snyder H.S. Phys. Rev. 88 (1952) 1190.*

In brief, the successive application of focussing and defocussing forces on particles can be readily contrived to provide strong, nett focussing regardless of the order of application of those forces.

5 *Blewett, J.P., Ann. Rev. Nuc. Sci. 4 (1954) 1.*

6 *Oliphant, M.L., Proc. Roy. Soc. (London) A234 (1956) 441.*

7 *A favourite expression of Oliphant. The cited context was that of the opening address he gave at a conference organized by Titterton in 1968 to mark successful operation and research use of the EN tandem accelerator.*

8 *Cockburn, S. and Ellyard, D. Oliphant — The life and times of Sir Mark Oliphant , Axiom Books (Adelaide) 1981 (page 177).*

9 *Blamey, J.W., Carolen, P.O.,Hibbard, L.V., Inall, E.K., Marshall, R.A. and Oliphant, M.L. Nature 195 (1962) 113*

10 *Gemmell, D.S., Morton, A.H. and Smith, W.I.B., Nuclear Physics 10 (1959) 45. Gemmell, D.S., Morton, A.H. and Titterton, E.W., ibid, 33.*

11 *The Bulletin January 25 1961.*

12 *Reference 8), p. 238.*

13 *Marshall won the battles of the debate and seemingly the war. Some old generals never tire of revisiting the battlefield. Oliphant concluded the address mentioned in reference 2), with the remark:*

"In retrospect, we were probably wrong here in Canberra to abandon liquid metal brushes. We should have returned to our original plan to use ring-jets of liquid sodium, operating the whole machine at about 100˚C. But it is not profitable to cry over spilt milk, or even over spilt NaK. Mr Marshall has produced a remarkably successful solid-state collecting system, and for that we are very grateful."

14 *The Proceedings of the SESCAS'77 Workshop (edited by E.K. Inall) contain excellent reviews and bibliographies of these applications.*

15 *An oft-quoted remark by Oliphant, repeated at the opening of an ANU historical display at the National Library in March 1996.*