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A History of Accelerators in Australia

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Abstract:

Over a period of almost sixty years, a surprisingly diverse range of accelerator activity has occurred.

The earliest involved the electrostatic machines constructed at the University of Melbourne between 1938 and 1950. The most ambitious project undertaken, a 10.6 GeV proton synchrotron at Canberra, was never completed.

These and other developments in laboratories throughout the country will be reviewed.

Reference A1.2

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1. Introduction - An Overview

Australia has a surprisingly long and rich history of accelerator development. In broad outline, a rapid expansion of accelerator facilities within the country in the first twenty years of the nuclear age, and the subsequent contraction to fewer installations for nuclear research mirror events elsewhere. There has been a steady increase in the number of accelerators acquired for research or applications in areas other than nuclear physics. Even so, support for major accelerator projects has sharply diminished, regardless of the project purpose. Present expansion of basic nuclear physics research capability and the recent establishment of a dedicated accelerator mass spectrometry facility have each been reliant on the acquisition and refurbishment of equipment from overseas laboratories that have closed.

The history includes significant pioneering contributions. For example, construction of the highest energy accelerator (10.6 GeV) at the time was attempted, though not completed, in Australia in the early fifties. One of the first variable energy cyclotrons was designed and built at the University of Melbourne (1953-59) and the first major NEC accelerator with a rated terminal voltage above 10 MV was installed in Canberra (1972/4).

The earliest accelerator in Australia began to operate at the University of Melbourne in 1938, just six years after a laboratory-accelerated beam had been first used by Cockcroft and Walton to initiate nuclear reactions [1]. Martin and Hill constructed a 200 kV Cockcroft-Walton to serve as a neutron generator using the d-d reaction [2]. Martin had been at the Cavendish Laboratory at Cambridge with Rutherford between 1923 and 1927. Under his leadership, further accelerators were built in the first decade of the post-war period or purchased in later years

to support a vigorous research program in nuclear physics at Melbourne. Presently, only one of them, an NEC 5U machine is operated there, mainly for high-resolution micro-probe beam studies. Nuclear research at Melbourne has become largely a "suitcase" activity, using facilities at CERN and in the US, Canada and Japan, as well as those in Australia.

However, during the immediate post-war period of expansion, two other institutions emerged, to become significant also as centres of sustained accelerator activity.

The Australian National University was established by an Act of Parliament in 1946, though site development and research staffing on location did not begin until 1950. An essential factor in the decision to establish the ANU at that time was the implied agreement by Oliphant, then building a 1 GeV proton synchrotron at Birmingham, to return to Australia as founding director of the Research School of Physical Sciences. He came to Canberra in 1950 to build a 2 GeV proton cyclo-synchrotron ("the big machine"). Design changes several years later were aimed at achieving 10.6 GeV. Nuclear physicists, appointed originally to be the users of the Canberra synchrotron, became involved in nuclear spectroscopy instead. Eight accelerators, beginning with a 1.2 MV Cockcroft Walton in 1951/2, were installed over a span of twenty five years to provide front-line facilities. The 14UD NEC Pelletron and a 2 MV HVEC AK Van de Graaff remain operational at the Department of Nuclear Physics. A booster is presently being added to the 14UD.

The Atomic Energy Act of 1953 led to the formation of the Australian Atomic Energy Commission (now ANSTO, the Australian Nuclear Science and Technology Organisation). In brief, the AAEC was to address and advise on issues relating to nuclear energy in Australia. Facilities at Lucas Heights in New South Wales were formally opened in 1955. Two research reactors were assembled on the site. Support

research facilities included a 1.3 MV pulsed electron Van de Graaff (1961/2) and a 3 MV Van de Graaff (1962/4). Both continue to be operated there for applied work. More recently (1990/2), the former Rutgers FN was refurbished and upgraded to become a major AMS facility.

The remaining accelerators currently operating in Australia are more purpose-specific. Excluding hospital electron accelerators for radiation treatment, there are two cyclotrons, one in Sydney and the other in Melbourne, that produce radio-isotopes for nuclear medicine diagnostic applications, and three small tandem accelerators. A 2.8 MV tandetron at Commonwealth Scientific and Industrial Research Organisation, North Ryde, NSW provides detailed analyses of minerals by means of a variety of nuclear analysis techniques. The other two, a 1 MV tandetron at Royal Melbourne Institute of Technology in Melbourne and a 1.7 MV NEC high-intensity implanter at ANU are used for Rutherford Back Scattering analysis and the production of electronic materials, respectively.

2. A Chronology of Accelerators in Australia

The tables that follow list chronologically, by type, the accelerators that have been built or installed in Australia. Information regarding the accelerators in Melbourne was obtained from [2] and a published history of the Melbourne Department of Physics [3].

2.1. Cockcroft-Walton Accelerators

The four accelerators in this category are summarised in Table 1. The neutron generators at Melbourne were used for studies of neutron-

proton and neutron-deuteron scattering, using a cloud chamber as detector.

The smaller machine at Canberra mainly provided 14 MeV neutrons from the $t(d,n)^4He$ reaction for measurements of neutron-induced reactions. Purser, who later founded the General Ionex Corporation, carried out his graduate work with it.

The research program supported by the 1.2 MV accelerator (Figure 1) included both spectroscopy of light nuclei and photodisintegration studies. For the latter, the high current capability of the machine was exploited to produce intense fluxes of 14.8 and 17.6 MeV gamma rays from the 441 KeV resonance of the $^7Li(p,\gamma)^8Be$ reaction.

2.2 Single-Ended Van de Graaffs

The inventory of single-ended Van de Graaff's (Table 2) spans the entire sequence of development of such machines, from the free-standing, air-insulated devices constructed in Melbourne (Figure 2 and Figure 3) to the pressurised, SF_6-insulated 5U now at Melbourne also. Tube development has been even more dramatic. Where the 5U has titanium and alumina tube sections sealed with metal gaskets, the tube of the original 1 MV machine was comprised of glass sections coupled with improvised seals of tape and transformer varnish.

Both Van de Graaffs at Canberra were used as helium injectors for the EN tandem. The original 2 MV machine was intended to serve as both injector and a stand-alone facility. However, because alignment for neutral helium injection proved critical, the AK was used solely as an injector during the period 1962-67, until it was replaced by the smaller JN machine.

Remarkably, all three Van de Graaffs installed in the early sixties continue to operate, supporting productive research in diverse areas.

2.3 Tandem Accelerators

All of the tandem accelerators listed in Table 3 remain in operation, although two of them had brief respites, including ocean voyages, before being re-commissioned.

The 5MV EN tandem had particular significance for the Department of Nuclear Physics at the ANU in Canberra. Until 1958, the future role of the Department was explicitly linked to use of the 10.6 GeV synchrotron. Acquisitions of the two Cockcroft-Waltons and the ex-Harwell electron synchrotron were interim measures to enable the establishment of support facilities and to attract staff. The nexus was broken in 1958 when Titterton persuaded the Federal Government to allocate £A600,000 (present day equivalent ~ $US10M) for the installation of the tandem and associated facilities.

Inevitably, the proposal to buy the EN provoked controversy. On the one hand, Oliphant saw the decision as reflecting a lack of confidence that 'the big machine" would be completed. On the other, as a machine-builder of the old school, he disdained commercially-built devices, preferring those assembled by physicists with "fire in their bellies". 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. Although, at the time, both groups had electron synchrotrons operating (Table 5) and competed co-operatively in photodisintegration studies, relations between them became somewhat strained with the advent of the EN. In reality, most of the research program at Canberra used beams other than protons, in particular d, ^{3}He, ^{4}He and ^{16}O, so that there was little basis for any sense of rivalry.

Throughout the sixties, Titterton pressed for funding to upgrade the EN. Direct access to the Federal Government was no longer an option.

An Australian Universities Commission had been established to control funding allocations for both teaching and research. With hindsight, it can be judged fortunate that funding for the upgrade ($A2.2M) did not eventuate until 1969.

Early upgrade proposals had been addressed in terms of the then popular three-stage acceleration, involving either neutral hydrogen injection or a negative ion source at the terminal of the first accelerator. Various configurations of the existing EN and an added FN were considered. By 1969 though, limitations of three-stage acceleration were apparent, especially with the growing research emphasis on heavy ion beams. Accordingly, the funding was used to obtain a negative ion cyclotron injector for the EN and the NEC 14UD Pelletron accelerator. Smith and Titterton at the ANU had probably been the first to suggest the cyclo-graaff scheme, soon after HVEC proposed to build the first EN tandem. However, the first cyclo-graaff was demonstrated at Duke University in 1970. The Canberra cyclo-graaff operated successfully between 1972 and 1979 when the EN was closed down. Proton beams were used for reaction studies and deuteron beams both as a source of mono-energetic neutrons (with the associated particle technique) and for gamma ray measurements.

The 14UD was born out of discussions between Herb and Titterton at NEC where the fledgling company was building the first substantial NEC machine, an 8UD with a 4 MV single-ended injector, for Sao Paulo. By Titterton's account, Herb was very reluctant to attempt an accelerator with a rated voltage above 10MV, but was finally persuaded to quote for a 14MV machine. The ANU considered offers by three manufacturers, choosing that of NEC, largely on the basis of the as yet largely unproven titanium and alumina tube modules developed by Herb's group.

It was a courageous decision by both parties. Construction of the pressure vessel (Figure 4) and the gas handling system were undertaken on site by ANU, so that NEC could only test the tube and column in air at Madison. ANU also was responsible for beam handling elements and the target area. Thus the project was a major departure from the custom of acceptance tests at the site of the manufacturer, prior to shipment. Nonetheless, the 14UD was completed successfully [4] and continues to provide sustained, reliable operation. It is pertinent to note that slow cycle, AMS radio-chlorine measurements, for which stable accelerator operation is crucial, are made at 14MV.

ANSTO obtained the FN from Rutgers in 1989 when it had become evident that funding, sought for new facilities as part of a joint proposal with ANU to establish a National Accelerator Facility, was unlikely to eventuate. Completely refurbished, the FN now provides the basis of an internationally-competitive AMS facility. The major emphasis on radio-carbon dating at ANSTO complements the AMS activity at ANU, where a radio-chlorine program was begun in 1985, in collaboration with ANSTO & CSIRO.

Unfortunately though, AMS could have been established in Australia as early as 1980. Polach, of the ANU Radiocarbon Laboratory, proposed in 1979 that the EN be used for radio-carbon measurements at ANU. At that juncture, purchase of the EN was being considered by several Australian groups, including AAEC, CSIRO and Macquarie University, and by the Division of Scientific and Industrial Reserach, New Zealand. The ANU Department of Nuclear Physics offered technical support to Polach, but wanted the EN re-located to make space for a proposed booster and target areas associated with it. Polach was unable to obtain the necessary funds to move the EN and it was sold to DSIR in the latter half of 1979. To compound the misfortune of Polach, a more

suitable booster configuration was devised in 1984 that did not use the area that had been occupied by the EN.

2.4 Cyclotrons

The operational cyclotrons in Table 4 are used exclusively for isotope production. As elsewhere, nuclear medicine expanded rapidly during the early seventies. Reactor-produced radio-isotopes were available from AAEC, but those from cyclotron facilities had to be imported. Obviously there were severe restraints on the use of the short-lived isotopes. The AAEC, with the backing of several hospital groups, sought funding for a production cyclotron.

When it became clear in 1976/7 that the ANU could not continue to operate both the 14UD accelerator and the EN tandem, a concerted effort was made to keep the cyclotron injector in Australia for isotope production [5]. Objections that the energy of 26 MeV was too low to produce ^{201}Tl, a key isotope for heart scans, were shown to be unfounded. Adequate yields, remarkably free of contaminant activity, were demonstrated at Canberra and used for test scans of laboratory animals [6]. Nonetheless, the AAEC preferred the option of a more modern and higher energy machine. In the event, the ANU cyclotron was sold in 1980 to Nihon Mediphysics in Japan. Australia imported ^{201}Tl from Nihon until a 30 MeV cyclotron at Sydney was finally operating almost thirteen years later. As with the EN and AMS, the opportunity for Australia to be at the forefront, rather than belatedly catching up, was lost.

The small 7.7 MeV cyclotron at Canberra had a varied history. The magnet used for it was built as part of a prototype homopolar generator assembled by Blamey. Mercury, rather than the liquid sodium proposed for the full-scale generator of the synchrotron (Section 3.1) was used for

contacts. When the synchrotron was re-designed, the cyclotron was built to be the injector for it.

The machine was used to produce some radio-isotopes for research groups between 1956 and 1958. It was also used by the Department of Nuclear Physics at ANU to measure excitation functions of a number of (p,γ) reactions [7,8]. Research programs associated with proposals for the early EN tandems invariably highlighted the measurement of such excitation functions since they are the inverse of (γ,p) photodisintegration. However, the cyclotron was successfully exploited for the first measurements, prior to completion of the Chalk River EN, using foil absorbers to vary the incident energy.

Further research use of the machine was thwarted by the insistence of Oliphant that the cyclotron be re-located in "the round house" built to accommodate the synchrotron.

2.5 Electron Accelerators

Bremsstrahlung radiation from electron accelerators was used to study photonuclear reactions at both Melbourne and Canberra. As indicated in Table 5, an early betatron, built to the specifications of the first betatron of Kerst [9], was upgraded in stages to 18 MeV.

The Canberra 33 MeV synchrotron was obtained from Harwell in 1954. It operated from 1955 until November 1961, when a short-circuit occurred in a magnet winding. Since the research program envisaged was close to completion, repairs were not undertaken. Thies from the University of Western Australia finally persuaded the ANU to give him the machine, despite Canberra misgivings that the transfer would prove to be a troublesome liability, rather than a research opportunity. In fact, Thies installed the synchrotron successfully and it was operated in Perth

for many years thereafter to support further work on photonuclear reactions.

2.6 Super-Conducting Booster

Installation of a booster linac, comprised initially of three cryostat modules, each containing three split-loop, lead plated resonators is presently nearing completion at the ANU in Canberra. Further modules are planned.

Addition of a booster to the 14UD accelerator had been foreshadowed even before completion of the 14UD. The campaign started in earnest in 1981. In anticipation, room temperature and super-bunching were developed in 1982/3 and resonator manufacture started. A series of proposals between 1981 and 1989 for funding of a booster, that would provide roughly the equivalent to a doubling of the 14UD terminal voltage, were unsuccessful. The period was a turbulent one in Australia, with the many changes in science bureaucracy and the funding of university research seeming inevitably to exclude any avenue of access for the proposals to be considered, let alone funded.

Late in 1991, when the closure of the NSF facility at Daresbury was announced for the end of 1992 (later extended to March 31, 1993), the Department of Nuclear Physics was invited to consider the transfer of the Daresbury booster to Canberra, in exchange for subsequent access to ANU facilities by U.K. groups. Fortunately, pragmatism prevailed over superstition. The booster on offer had been established in similar circumstances at Daresbury, with cryostat modules obtained from Oxford after the accelerator facilities there were closed. An ANU/SERC agreement was signed in September 1992. Ownership of the booster was transferred to ANU, which was to be responsible for shipping and a portion of the dismantling costs. In return, U.K. user groups were

guaranteed up to 20% of total available operating time at ANU for an initial five year period, mutually anticipated to be extended thereafter. Already about 30 U.K. researchers, many of them making several visits, have carried out research using the 14UD.

Two shipments of the components of the booster, and additional magnets on loan from Daresbury, arrived in April and November 1993. Even though much of the first shipment suffered severe condensation damage due to inadequate packing, first beam tests of the loop ("the October revolution") took place only one year later. Injected beam from the 14UD was transported through much of the system, with the resonators passive, to check computer control of beam line elements and to confirm beam optics calculations. Initial beam trials with active resonators are scheduled for September/October 1995.

3. Some Accelerators of Special Significance

The present section describes three of the accelerator installations in more detail. Each was significant in its own right, but of at least equal interest, was obviously a product of the time, reflecting the technology - sometimes primitive, though also surprisingly sophisticated, and problems that then prevailed.

3.1 The Melbourne 1MV Van de Graaff

Construction of the Van de Graaff began in April 1946, with first operation in 1948. Detailed descriptions have been given by Hirst [10] and Martin et al [11]. The associated references are essentially an honour roll of many of the pioneers of accelerator development. The overall design was that given by von Ardenne [12], one of the ion sources

used was first described by Oliphant and Rutherford [13], while the analysing magnet followed "the well-known design" of Cockcroft [14].

A 62 cm diameter column and two 10 cm diameter struts, all of bakelized paper, supported the terminal. Porcelain struts were substituted in an effort to reduce leakage, but were in turn replaced by ones of better quality bakelized paper. The charging belts (initially one, but later two using common roller pulleys) were of rubberised cotton. Each provided a short-circuit current of ~250μa. Separate v-belt driven alternators soon replaced the batteries that were first used to provide power for the ion source.

A persistent problem of electrical discharges at the junction of the column insulator and the terminal was finally solved with corona rings. The initial solution of spraying the room with carbon tetrachloride caused health problems for personnel.

The cascade-type accelerating tube consisted of twelve identical sections. Vacuum coupling of the sections was somewhat unusual. Steel flanges were bonded to each end of cylindrical glass sections with picein wax. A small triangular groove at the junction of the flanges was filled with the plasticine Apiezon-Q* , smeared over with vacuum grease. In time, it appeared that the grease diffused into the tube, "impairing high voltage operation". A design modification allowed the junction to be wrapped with cellulose tape. The tape, coated with the transformer varnish, glyptal, produced a "cleaner" and more durable vacuum coupling.

Though O-rings were used in "a vacuum gate", it is evident that wider use was by no means common then. Even in 1952 Livingston, in a review article on cyclotrons [15], stated that "vacuum seals have become

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* Manufactured by Apiezon Products Ltd, London, UK

more or less standardised with experience. The basic pattern is a narrow rubber gasket confined in a groove and compressed to give metal-to-metal contact between flanges. The commercially available O-rings, which have a round cross-section and are made in a wide range of sizes, have been adapted to this use in many laboratories".

A rotating voltmeter, calibrated at reaction resonances, was used to measure the terminal voltage. (Interestingly, the circuitry of the voltmeter included a 6H6GT tube, the same rectifier used a decade later by HVEC for the EN). Early calibrations were uncertain though. Whereas later determinations of the resonance energy (~441 keV) for the ^{7}Li (p,γ)^{8}Be reaction confirmed the original measurement in 1936 [16], the energy for the intense resonance of the ^{19}F (p,$\alpha\gamma$)^{16}O reaction near 870 keV proved more difficult to establish. Measurements varied over a range of ~15 keV. In particular, the value of 862 keV reported by Bernet, Herb and Parkinson [17] was at one extreme of the range. In 1949, the Wisconsin group made amends. A precision electrostatic analyser was employed to determine beam energies, yielding a result of 0.8735±0.0009 MeV [18].

Analysed beam currents of up to 30μa were obtained for studies of the ^{7}Li (p,α) and ^{6}Li (d,α) reactions. Although the alpha-particles were detected with zinc sulphide, photomultipliers replaced the human observers of earlier years at Cambridge.

Measurements made between 100 keV and 1 MeV with the Van de Graaff were extended to 60 keV using a smaller device, contrived from the ion source and three sections of the 1 MV tube. The rectified output of a 60 kV transformer provided acceleration.

3.2 The Canberra 10.6 GeV Synchrotron - "The White Oliphant"

The original design of the Canberra machine is shown schematically in Figure 5 [19]. Protons, accelerated to 200 MeV by a synchro-cyclotron, were to be injected 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 148" diameter of the poles of the cyclotron magnet. The current of $\sim 10^6$ amperes needed to energise the air-cored magnet was to be provided by a homopolar generator, comprised of two discs rotating within the magnetic circuit of the cyclotron. Jets of liquid sodium, at the periphery and an inner radius of each of the rotors, would serve as contacts to switch and extract the short-circuit current.

Oliphant believed that the innovative design would provide Australia with world-class facilities at minimal cost. The magnet required would weigh about 1400 tons. By comparison, the preliminary proposal for the Bevatron required magnets with a total weight of ~13,000 tons and an orbit about 160 feet in diameter to produce 10 GeV protons [20].

The large cost reduction of the design was at the expense of pulse repetition rate - about 10 seconds between pulses, and more importantly, the need to develop a homopolar generator of such a scale and complexity. Unwisely optimistic, Oliphant 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 less than favourable circumstances.

The building to house the accelerator and the associated laboratories and workshops was begun early in 1950 and commissioned

finally on September 5th 1952, much later than planned. Post-war shortages of materials (bricks were rationed, the ANU being allocated 14% of the quota available to Canberra) and tradesmen, especially carpenters, had led to frustrating delays. Extensive workshop facilities were established, including a large boring mill obtained as part of war reparations from Germany.

The project moved slowly, hampered by staffing problems (two key members of the former Birmingham group suffered health problems and died unexpectedly; Gooden before departure and Wilson, soon after arriving in Canberra) and the complexity of the design. The cyclotron magnet was completed in 1954 (Figure 6) and a small prototype homopolar generator had been built and tested earlier.

In 1953, a major design change eventuated [21] because of the slow progress and of planned accelerators elsewhere. The energy sought was raised to 10.6 GeV. The synchro-cyclotron was abandoned. The magnet would be used instead solely for a much larger homopolar generator, capable of producing ~2 x 10^6 amperes, that would power the air-cored magnet of a synchrotron orbit about 30 feet in diameter (Figure 7). Protons would be injected into the synchrotron from a 7.7 MeV cyclotron. Again, completion in two or three years was predicted.

Specifications for the upgraded homopolar generator were impressive. Two rotors, each weighing 40 tons, would be motor-driven to 900 rpm before extraction of the short-circuit current over a 2 second time span. Instead of liquid sodium, the sodium-potassium alloy, NaK, would be used for the contacts. However, there was one serious draw-back. Current pulses would only be available at intervals of 10 minutes. Some critics suggested that the slow pulse rate was inconsistent with even demonstrating accelerator operation, realistic research use being out of the question.

The homopolar generator finally operated in June 1962, being delayed mainly by bearing problems. In the interim, the injector cyclotron had been completed (Section 2.4) and installed in the octagonal synchrotron building (completed in 1956 and dubbed the round-house), one of four sections of the air-cored magnet was complete after a model had confirmed design calculations and design of the r.f. acceleration modules had been finalised.

By then though, project momentum had been lost and the synchrotron 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. A stridently critical article appeared in a national weekly magazine, the Bulletin, early in 1961, under the by then hackneyed title of White Oliphant. Previous criticism of the project by other groups, notably one at the University of Sydney, was recycled [22]. Nonetheless, the flurry of unfavourable publicity had little, if any, influence on the inevitability of non-completion.

A tragic explosion, involving NaK, occurred in July 1962. Though damage was slight, a technician was blinded. The use of NaK was abandoned in favour of solid graphite/copper brushes. Various research applications of the generator were evaluated. Ultimately, the generator was used to energise several plasma research devices, albeit with currents well below the maximum available.

In absolute terms, the 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 under-pinned subsequent research in diverse 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.

3.3 The Canberra EN Tandem - a typical installation of an era.

The EN is presented here (Figure 8) as representative of similar facilities that operated between 1960 and 1975 or thereabouts. Many were larger of course. It was a time of intense competition, as HVEC met customer demands for higher terminal voltages with a rapid progression from the first EN delivery in 1958 to that of an FN (7.5MV) in 1963 and of the MP (10 MV) in 1965. In parallel, numerous three-stage configurations were installed, based on cyclotrons or Van de Graaff (single-ended or tandem) injectors. HVEC alone produced 53 tandems (26 EN's, 17 FN's and 10 MP's) between 1958 and 1971 as well as 27 single-ended CN (6 MV) Van de Graaffs in the period 1950-1966) [23]. However, though each facility had particular strengths and often unique characteristics, all were involved in the rapid developments of the period and shared common problems.

Many of the problems merely reflected the times. In the early sixties, power supplies and control circuits were based on vacuum tubes, magnets were powered by motor generator sets and accelerator vacuum methods remained somewhat primitive. These three aspects were responsible for much down-time, scheduled or otherwise. For example, mercury diffusion pumps were used for the original main vacuum systems to prevent hydrocarbon contamination of the tubes. Dry ice, and later two-stage refrigeration, was used to cool the associated alcohol-filled traps. Though reasonably effective, the traps had to be warmed up on a regular basis to prevent mercury starvation. By the end of the decade, solid state electronics and turbo-molecular pumps had provided solutions.

The original acceleration tubes had to be conditioned for high voltage operation; stable operation was not possible without conditioning to or above the required voltage. Once conditioned though, the level was not preserved and dropped to lower voltages quickly. Moreover, difficulties with electron loading were often severe, especially when heavy ion beams were accelerated. HVEC introduced inclined-field tubes in 1963 to reduce electron loading and the related problem of conditioning. The tubes had alternate sets of electrodes, parallel to each other, but inclined to the direction of beam motion. The angle of inclination reversed at intervals along the tube. Thus ions oscillated about the tube axis, whereas electrons were swept off-axis near their point of origin. Early installations were successful, though the benefits of the reduced need for conditioning were found to be at the cost of tube lifetimes (as short as 3000 hours). Further, the oscillatory trajectory of beam ions meant that the voltage gradient along the tube became a critical factor affecting the exit direction of the beam. For neutral helium injection and highly-charged ions ($\gtrsim 5^+$), variant tubes were developed (Mark II) with a number of conventional normal electrodes, immediately after the terminal, to stiffen the beam before acceleration by inclined fields. By 1967, difficulties with the tubes were manifest everywhere. Commonly, beams emerged off-axis from either type of tube and troublesome beam instabilities were evident with Mark II tubes. HVEC was compelled to recommend that Mark II tubes be no longer used, suggesting terminal steering as a substitute to both control entry of low rigidity beams into the high energy section and achieve on-axis beam emergence. Thereafter tube experiences featured less prominently in laboratory annual reports. Even so, tube lifetimes remained typically in the vicinity of 12000-15000 hours if used consistently near maximum voltage, adding significantly to operating costs.

The EN at Canberra was one of the first to use foil stripping almost exclusively. An original wheel with 30 foils, installed in 1969, was replaced in 1970 by an assembly of eight, sequentially latching disks, each having provision for 15 foils and 15 spaces (ie 120 foils). It was progressively upgraded to accommodate 240 foils. The last inclined field tubes were installed in 1969, operating for over 30,000 hours subsequently, often at 6 MV or higher. The extended life presumably was due to the use of foil, rather than gas, stripping. Perhaps if foils had been used a year or two earlier, the decision to purchase the 14UD, based as it was largely on tube considerations, might well have been different.

Many of the beam handling problems with the inclined field tubes undoubtedly stemmed from incorrect voltage gradients along the tubes. The carbon-composite resistors used by HVEC were unusual. Not only was their resistance a strong function of the applied voltage, but the resistance (as determined at some voltage) increased significantly with use.

Resistors were carefully measured with a high voltage tester and graded appropriately along the tube. Even so, it was always a leap of faith to believe that the correct oscillatory trajectory would obtain at any one terminal voltage, let alone at all, for an extended period. Most EN's had problems with the resistors near the low energy side of the terminal. Failure of either or both of the two nearest was frequent (every 3-6 months). At Canberra, two replacements made up of Welwyn 40 MΩ resistors* were installed in April 1964, lasting nearly five years before one failed. If memory is correct, the repaired resistor and its original companion were still in the accelerator when it was sold in 1980. Independently, Argonne had tried different Welwyn resistors (with external spark gaps) at the prompting of HVEC. They failed very

* Manufactured by Welwyn Ltd., Bedlington, Northumberland, UK

quickly, making it difficult to convince other laboratories or HVEC to try Welwyn resistors. Even Welwyn thought that yet another type of resistor with an internal spark gap would be preferable.

In the quest to extend available beams, a variety of smaller injectors and ion sources was installed. The most common objectives were helium beams and polarised beams of protons and deuterons.

Initially, intense (1-2μa) helium beams were obtained by neutral injection. A small (~1 MV) Van de Graaff was used to provide a beam of ~200μa of He^+ that was charge-exchanged at the tandem entrance. Early installations during 1961/2 included Caltech, Chalk River, Argonne and ANU, where a 2 MV injector was used until replaced by a 1 MV JN in 1967. Elsewhere, groups developed negative helium sources, progressing from 10-30 na beams with the standard duo-plasmatron at FSU to 200-300 na from a modified source at Pennsylvania. The breakthrough came in 1966/7 with the advent of lithium-exchange sources. At least comparable intensities to those from helium injection were achieved, but with greater stability and of course higher energies were possible. At Canberra, the two methods used were in parallel as a Pennsylvania-type source (1966) and then a lithium exchange source (1968) were built. Finally, by 1973, use of neutral helium was abandoned.

So far as polarised beams were concerned, the experience at Canberra unfortunately was typical of events at a number of other laboratories. A source was purchased in 1970. Despite intensive effort, proton beams, about 70% polarised, never exceeded the level of a few nanoamperes. The source project stopped in 1975.

Finally , the EN facility shared a fate common to many similar installations in being closed down. Even so, and again typically, many components of it continue to operate - the EN in New Zealand as an AMS laboratory, the cyclotron as an isotope producer

in Japan while the 24" double focussing spectrometer remains at ANU for the precision measurement of isotopic anomalies in meteoritic material.

4. Epilogue

The history presented has concentrated mainly on technical aspects. From this viewpoint, a sound record of achievement and noteworthy contributions to accelerator use and development can be claimed. Clearly though, an overall performance assessment must also evaluate the quantity and quality of research output that the accelerators have sustained.

In part, the operating records provide an indication of the research output, explicitly of quantity and implicitly of quality, for at least those still operating. The latter implication stems from the assumption that continued research funding is linked with some perceived achievement of excellence. The ANU EN tandem operated for more than 90,000 hours in Canberra, while the 3MV KN at Lucas Heights, the 14UD Pelletron and the 2MV AK at Canberra are each nearing or have exceeded 100,000 hours of use.

Another essential component of research output is graduate training. ANU has produced ~100 PhD graduates in experimental nuclear physics and the University of Melbourne probably a comparable number. Users of ANSTO facilities are spread over a variety of disciplines, contributing to significant graduate training other than accelerator or nuclear science.

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Table 1. Cockcroft-Walton Accelerators

Rated Voltage	Location	Maker	Period of Use	Comments
200 KV	University of Melbourne	University of Melbourne (Martin & Hill)	1938-51	d-d neutron generator
200 KV	University of Melbourne	University of Melbourne (Darby & Swan)	1946-51	d-d neutron generator. Higher current intensity than original.
1.2 MV	ANU, Canberra	Philips, Eindhoven	1951-67	Current of 1 ma protons achieved. Sold to University of NSW 1967.
0.6 MV	ANU, Canberra	Philips and ANU (Inall)	1954-60	Destroyed by fire, July 1960.

Table 2. Single-Ended Van de Graaffs

Rated Voltage	Location	Maker	Period of Use	Comments
1 MV	University of Melbourne	University of Melbourne (Martin, Hirst & Dunbar)	1948-60	Air-insulated. Construction started April 1946.
0.8 MV	University of Melbourne	University of Melbourne (?)	1952-73	Air-insulated. Designated the Statitron.
1.3 MV	AAEC, Lucas Heights	HVEC Burlington, MA	1962-present	Installation 1961/2. D.C. electron beams of ~35μA or 3μs pulsed.
2 MV	ANU, Canberra (Nuclear Physics)	HVEC Model AK	1962-present	Original helium injector. Now used for RBS by Department of Electronic Materials Engineering.
3 MV	AAEC, Lucas Heights	HVEC Model KN	1964-present	Installation 1962/4.
1 MV	ANU, Canberra (Nuclear Physics)	HVEC Model JN	1967-73	Used as helium injector. Superseded by lithex source. Sold to Queensland Institute of Technology 1973.

Table 2 - Single-Ended Van de Graaffs Cont.

Rated Voltage	Location	Maker	Period of Use	Comments
2 MV	Western Australia Institute of Technology	HVEC	1971-present	Now at University of NSW. Acquired by Chemical Physics, CSIRO in 1986 but remained in storage. Set up in Sydney in 19??
0.4 MV	ANU, Canberra (Department of Physics, Faculties)	HVEC Model LC400	1971-present	The so-called teaching laboratory. Used for undergraduate training.
5 MV	University of Melbourne	NEC Madison, WI Model 5U	1975-present	Used to develop state of the art micro-probe beams.

Table 3. Tandem Accelerators

Nominal Rated Voltage	Location	Maker	Period of Use	Comments
5 MV	ANU, Canberra (Nuclear Physics)	HVEC model EN (EN5)	1961-78 (Canberra) 1985-present (New Zealand)	Highest voltage achieved 7 MV. Sold to DSIR, New Zealand. Shipped from Canberra in 1981. Now operating as AMS facility at Wellington, NZ.
14 MV	ANU, Canberra (Nuclear Physics)	NEC Model 14UD	1974-present	Has compressed geometry tube. Resistors have replaced corona point voltage distribution system. Now rated at 16 MV. A booster (ex Oxford/ Daresbury) is being added.
1 MV	RMIT, Melbourne	General Ionex tandetron	1981-present	
2.8 MV	CSIRO, North Ryde	General Ionex tandetron	1983-present	
1.7 MV	ANU, Canberra (Electronic Materials Engineering)	NEC	1990-present	SNICS source. Beam intensities of several hundred microamps available.
7.5 MV	ANSTO, Lucas Heights	HVEC Model FN (FN1)	1964-89 (Rutgers) 1991-present (ANSTO)	Obtained from Rutgers University, New Jersey. Mainly used for AMS measurements.

Table 4. Cyclotrons

Energy	Location	Maker	Period of Use	Comments
10.6 GeV (Protons)	ANU, Canberra (Particle Physics)	ANU (Oliphant, Blamey, Hibbard & Smith)	-	Not completed 1950-60. The homopolar generator that was to power the air-cored magnet was used for plasma research.
7.7 MeV (Protons)	ANU, Canberra (Particle Physics)	ANU (Smith & Morton)	1957-58	30" magnet originally used for proto-type homopolar generator. Built as injector for proton synchrotron. (Used for ρ,γ)
12 MeV (Protons)	University of Melbourne	University of Melbourne (Caro & Rouse)	1959-74	A pioneering variable energy cyclotron.
26 MeV (Protons)	ANU, Canberra (Nuclear Physics)	The Cyclotron Corporation Berkeley, CA	1972-79	Used as injector for EN tandem to provide 26-38 MeV protons or 14-26 MeV deuterons. Sold to Nihon Mediphysics, Japan. Shipped May 1980.
10 MeV (Protons)	Austin Hospital, Melbourne	Ion Beam Corp Cyclone 10/5	1992-present	Used for radio-isotope production. (^{11}C, ^{13}N, ^{15}O and ^{18}F)
30 MeV (Protons)	Royal Prince Alfred Hospital, Sydney		1991-present	Used for radio-isotope production.

Table 5. Electron Accelerators*

Energy	Location	Maker	Period of Use	Comments
2.8 MeV	University of Melbourne	University of Melbourne (Lasich)	1946-49	Betatron.
18 MeV	University of Melbourne	University of Melbourne (Muirhead)	1949-62	The original betatron was upgraded to a synchrotron. In two stages, the energy was increased to 14 MeV and then 18 MeV.
33 MeV	ANU, Canberra (Nuclear Physics)	Metropolitan-Vickers (ex Harwell)	1955-61	A gift of the UK Government. Given to the University of Western Australia in 1962. It operated there for a number of years.
30 MeV	University of Melbourne	Siemens	1962-86	

* Excluding hospital radiation treatment facilities.

Figure 1. The 1.2 MV Cockcroft-Walton accelerator installed at the ANU, Canberra in 1951.

Figure 2. The first Van de Graaff (1 MV) built at the University of Melbourne between 1946 and 1948 (from reference [10]).

Figure 3. The "Statitron" Van de Graaff at the University of Melbourne (1952-1973) (from reference [10]).

Figure 4. The final stage of assembly of the 14UD pressure vessel at ANU, Canberra in December 1971.

Figure 5. Schematic section view of the proposed 2 GeV cyclo-synchrotron. (Taken from reference [19]).

O is the synchrotron orbit; R_1 and R_2 the homopolar rotors; J the sodium jets and C the air-cored magnet.

Figure 6. The near-complete magnet for the cyclo-synchrotron (1954).

Figure 7. Simplified schematic diagram of the modified configuration to raise the energy to 10.6 GeV.

Figure 8. A schematic "snap-shot" of the Canberra EN tandem in 1972.

Figure 1

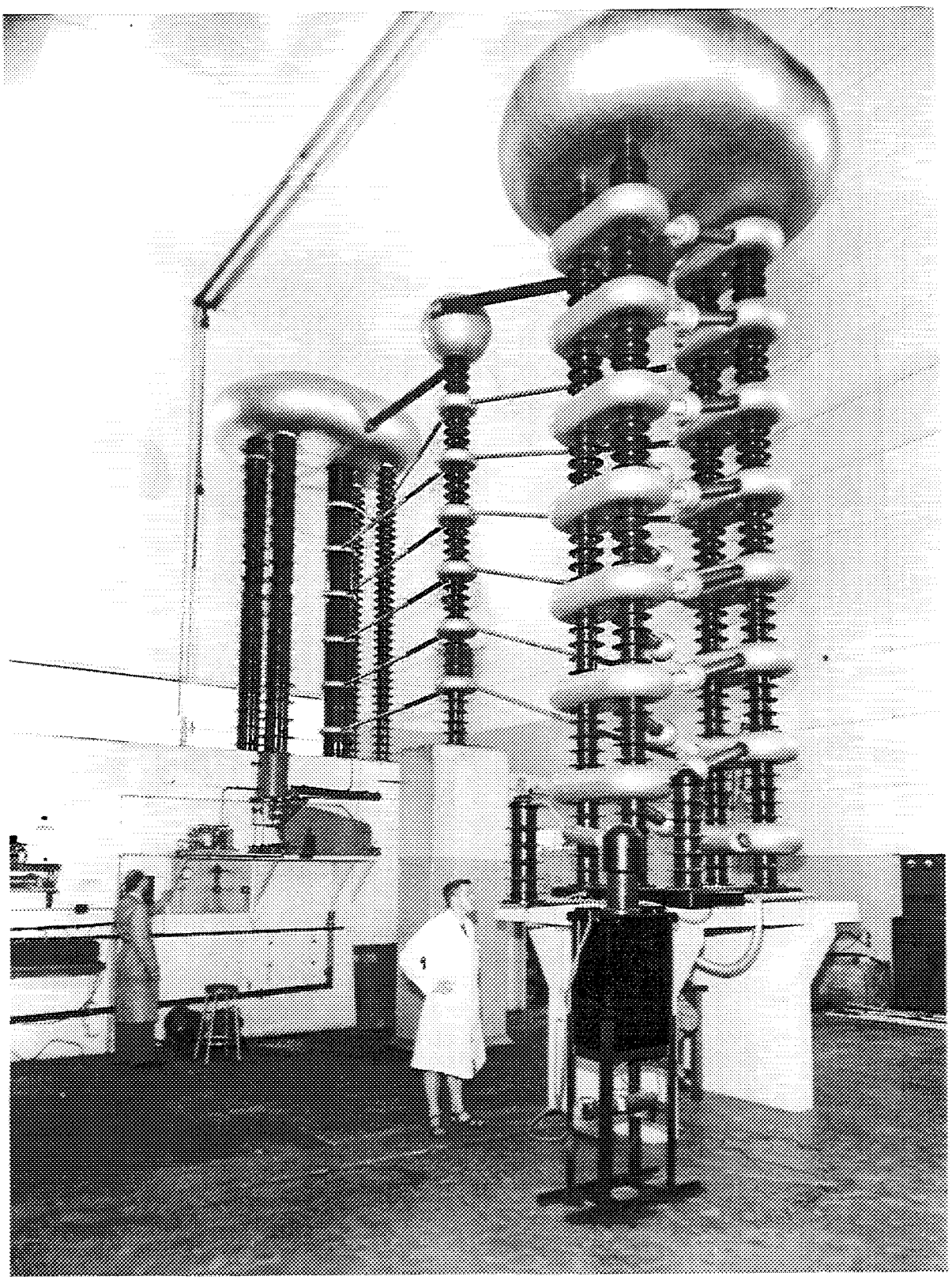


Figure 2

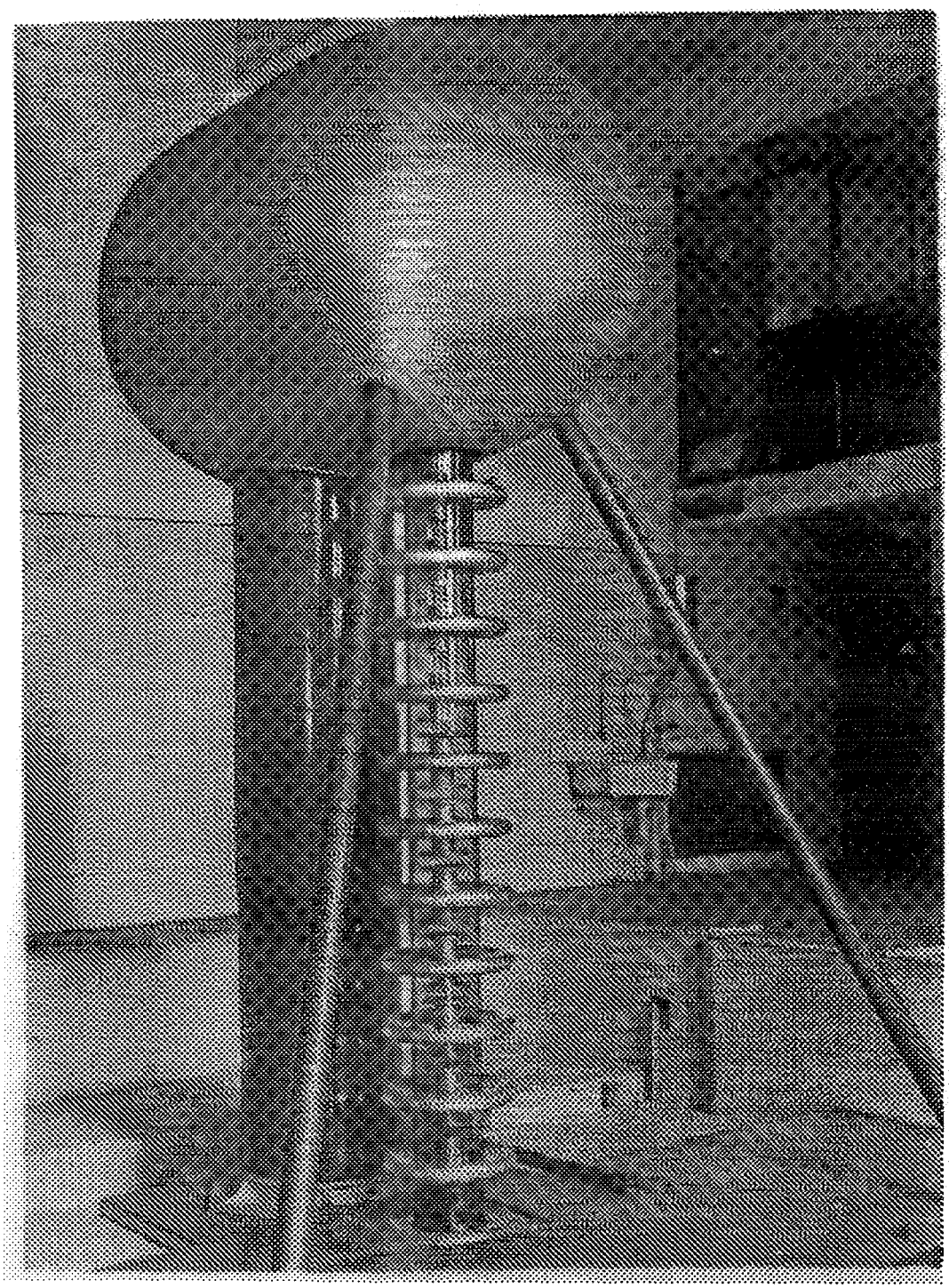


Figure 3

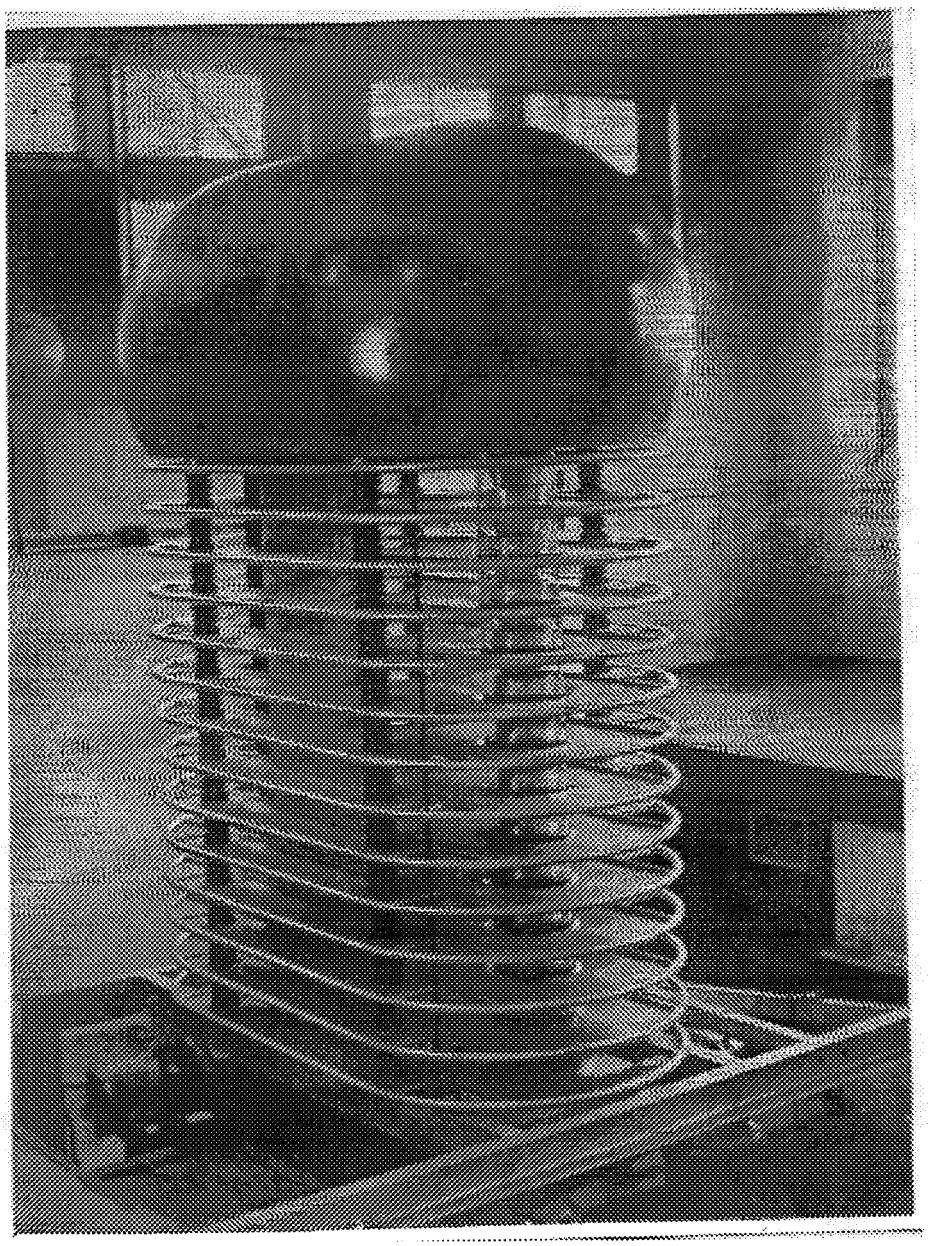


Figure 4

Figure 5

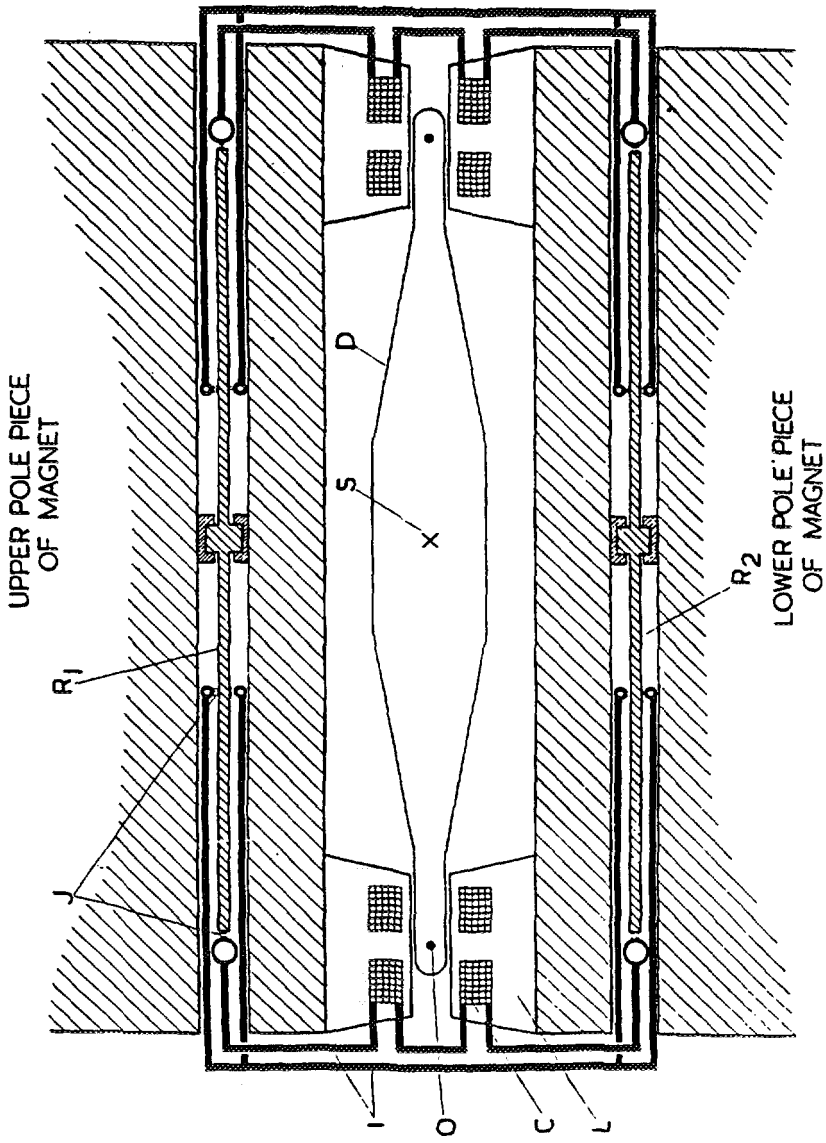

UPPER POLE PIECE OF MAGNET
LOWER POLE PIECE OF MAGNET
D
S
X
R_1
R_2
J
I
O
C
L

Figure 6

Figure 7

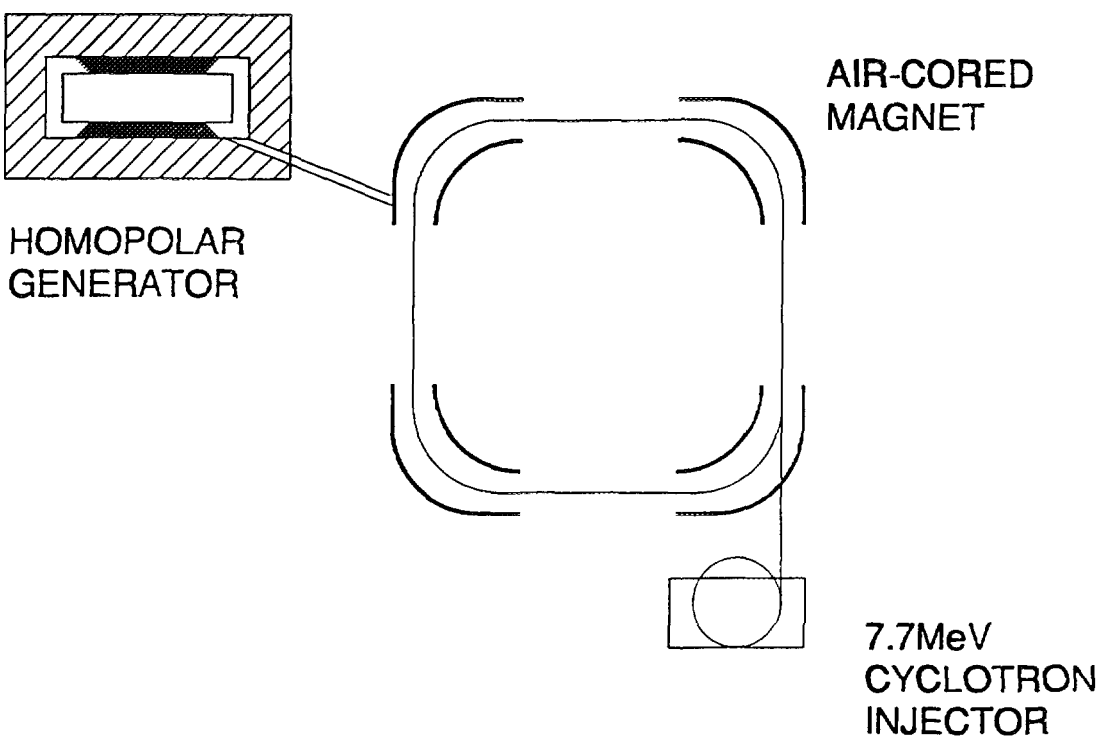
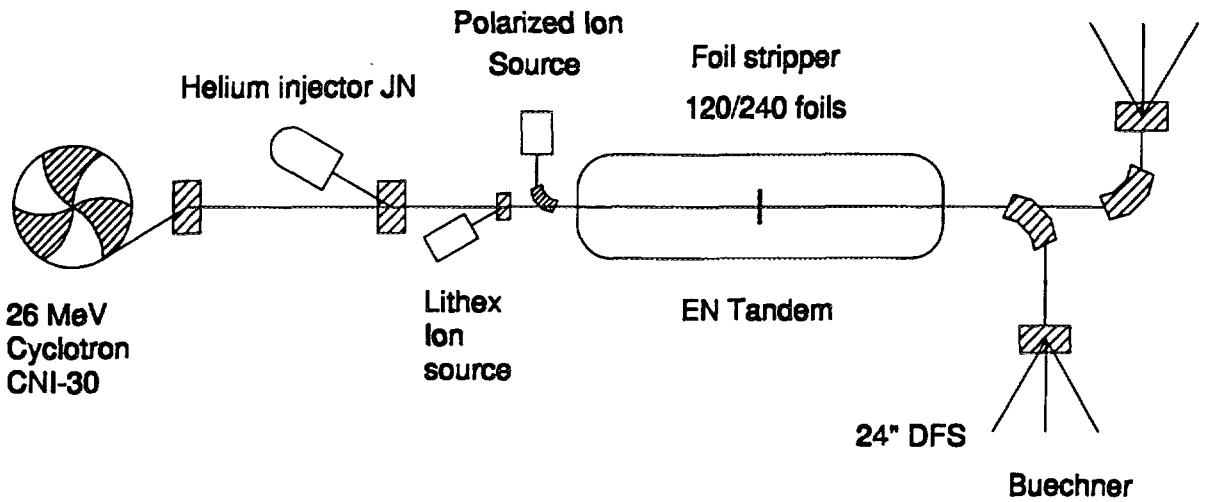

AIR-CORED
MAGNET
HOMOPOLAR
GENERATOR
7.7MeV
CYCLOTRON
INJECTOR

Figure 8


Polarized Ion
Source
Foil stripper
120/240 foils
Helium injector JN
26 MeV
Cyclotron
CNI-30
Lithex
Ion
source
EN Tandem
24" DFS
Buechner