

The Heavy Ion Accelerator Facility: Research Achievements and Aspirations

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Abstract. An overview of Australia's Heavy Ion Accelerator Facility (HIAF) is presented, including a survey of the accelerator infrastructure and its capabilities, as well as the beam-line instrumentation. Some recent research achievements are highlighted. Accelerator upgrades and instrumentation developments in progress are described, along with some aspirations for the longer-term development of the Facility and its associated research programs.

1 Introduction

An overview of the Heavy Ion Accelerator Facility (HIAF) is presented along with a survey of the beam-line instrumentation and research programs. The Facility is described in Section 2. An overview of the beam-line instrumentation and the research programs follows in Section 3. Some aspirations for Facility and research program development are presented in Section 4. Figure 1 shows an overview of the Facility and beam-line instrumentation.

2 The Heavy Ion Accelerator Facility

2.1 The accelerators and beam lines

The Heavy Ion Accelerator Facility comprises the 14UD Pelletron accelerator and a superconducting 'booster' linear accelerator (LINAC) housed in and operated by the Department of Nuclear Physics in the Research School of Physics at the Australian National University (ANU). The HIAF supports Australia's only experimental nuclear physics program (both fundamental and applied), a major accelerator mass spectrometry program, and facilities for ion-beam modification and analysis of materials. Newer initiatives include aspects of radiobiology [1–3], and detector characterisation for Australia's growing contributions to dark matter particle physics research, particularly for the SABRE experiment [4–6].

The 14UD Pelletron electrostatic accelerator manufactured by the National Electrostatics Corporation (NEC) has been in operation since 1973. The Department has maintained a good working relationship with NEC, a Wisconsin, USA based company that continues to specialise in custom-made ion-beam accelerators and associated components. Voltage performance upgrades in the late 1980s included the installation of NEC compressed geometry accelerator tube sections, which increased the effective acceleration length by 12%, and the local development of a robust resistor system for the column and tube. Despite its

age, the 14UD Pelletron continues to run very reliably on the whole; experiments are routinely run at terminal voltages near 15 MV. However, the ageing ceramic is a known vulnerability and funding has been received in 2019 from the National Collaborative Research Infrastructure Strategy (NCRIS) and the ANU to replace the acceleration tube and column posts over the coming two years.

There are at present two negative-ion Cs sputter sources. A NEC Multi-Sample SNICS (Source of Negative Ions by Caesium Sputtering) is used exclusively for Accelerator Mass Spectrometry (AMS), while a single-sample high-intensity source equipped with a gas cathode serves the remainder of the research program. An order has been placed with NEC to upgrade the injection system for AMS by adding an electrostatic analyser between the Multi-Sample SNICS source and the inflection magnet. As part of the same upgrade, a new ECR plus rubidium exchange source will provide helium beams. Installation is expected in 2021.

Beams are injected into the 14UD through a double-focusing dipole magnet (the inflection magnet) for mass selection. The injection stage also includes a versatile pulsing system that enables compression of the beam into pulses about 1-ns wide and a chopper system that allows repetition rates from ~ 107 ns up to many milliseconds. The fundamental frequency (9.375 MHz) of the double-gridded buncher in the injection system determines the minimum pulse separation. Even narrower beam pulses can be achieved in the LINAC area by post-acceleration bunching.

The high-voltage terminal of the 14UD includes both a foil stripper and a differentially pumped gas stripper. A second foil stripper is installed one third of the way down the high-energy tube.

The 14UD in stand-alone operation services most of the experimental program, however it can also inject into a superconducting linear accelerator, which has been in operation since the mid 1990s. The LINAC comprises twelve Pb-plated split loop resonators housed in four cryostats.

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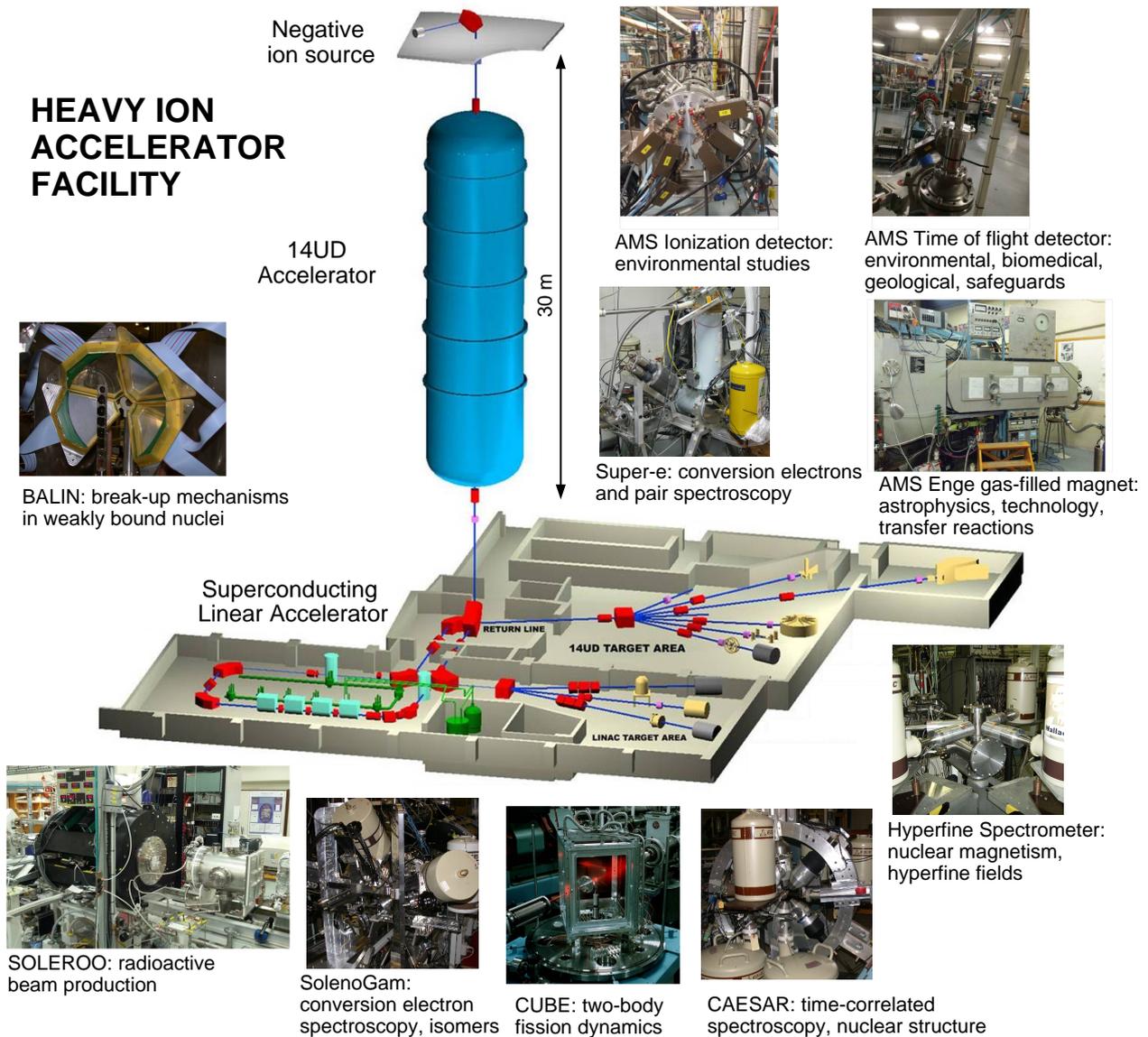


Figure 1. The Heavy Ion Accelerator Facility (HIAF) and its research instrumentation.

These can add 6 MV/q of energy to a beta-matched pulsed beam from the 14UD. At present the LINAC is required for a period of a month every 1 to 2 years.

There are seven beam lines in the original 14UD target area plus three newer ones in the LINAC Hall. Beams either directly from the 14UD or from the LINAC can be delivered into both target areas, although at present LINAC beams tend to be delivered only to the beam lines in the LINAC Hall because most of the research demand for boosted beams is associated with the specialised equipment for reaction dynamics studies located there. A more detailed description of the beam-line instrumentation is given below in Section 3.2.

Accelerator systems and beam optics are largely controlled by a locally developed EPICS-based computer system, with only a few of the 14UD control systems (for

example the chain motors and rotating shafts) yet to be migrated to computer control.

HIAF typically runs about 5000 hours per year, depending on the downtime needed for accelerator development.

Some “HIAF records” illustrate the capabilities of the Facility: The heaviest beam accelerated to date is ^{244}Pu , among several $A \sim 240$ actinides for AMS [7]. The highest energy beam from the 14UD plus LINAC is 382-MeV ^{64}Ni for recent Reaction Dynamics studies currently under analysis. The heaviest beam for a published nuclear physics experiment is ^{116}Cd , Coulomb excited in inverse kinematics for a transient-field g -factor measurement [8].

2.2 Data acquisition

Two almost identical VME crate-based data acquisition (DAQ) systems are available in the Control Room for use

by all experimenters. A third portable VME-based DAQ is used mainly in target area 1, plus a fourth dedicated to reaction dynamics resides in the LINAC Hall. These 4 VME systems have the same software, although the hardware differs. A portable Pixie-16 digital DAQ from XIA [9] is finding increasing use for the spectroscopy and dark matter research programs, and a second Pixie-16 system has been delivered recently. A Pixie DAQ is also an integral part of the fast isotope-cycling system used by the AMS group.

2.3 Operational aspects

The Heavy Ion Accelerator Facility enjoys excellent technical support for maintenance and development of the accelerators as well as for innovative beam-line instrumentation. The HIAF also includes a target preparation laboratory and clean rooms for AMS sample preparation.

Experimenters run the accelerator - there are no accelerator operators. While this puts an extra burden on the academic staff running experiments and supporting outside users, it has advantages in that beam energy and beam species changes can be made rapidly and frequently by the experimenters when required.

There is no program advisory committee (PAC) to allocate beam time, although pressure on beam-time availability forces experimenters to make strategic decisions on their accelerator use. Outside users are welcome and gain access by collaboration with HIAF researchers. Beam time is scheduled in 8-10 week periods, although pre-booking on a longer time-scale is the norm for international users.

3 Research program and beam-line instrumentation

3.1 Research themes

The research conducted at HIAF can be grouped into three broad themes: (i) *Quantum Physics of Nuclei*, (ii) *Nuclei in the Cosmos*, and (iii) *Nuclei for Society*. The three main research groups focus on Reaction Dynamics, Nuclear Structure, and AMS. At present, these three main themes each use about 30% of the available beam time, with other activities using the remaining 10%.

3.1.1 Quantum Physics of Nuclei

This theme represents much of the work of the Reaction Dynamics and Nuclear Structure groups. It encompasses studies on the foundations of the nuclear force, the nuclear many-body problem in nuclear reactions and nuclear structure, and the quantum mechanics of nuclear dynamics, excitations, correlations, and decay. It also includes nuclear methods in fundamental physics. There are strong links between the experimental and theoretical research activities.

3.1.2 Nuclei in the Cosmos

Aspects of nuclear astrophysics are included in the research activities of the three major groups (AMS, Nuclear Structure, Reaction Dynamics). Examples are use of AMS to search for supernova remnants (e.g. ^{60}Fe) on Earth [10], reaction dynamics relevant to the Li-abundance problem [11], and extensive studies to improve the measurement of the radiative width of the Hoyle state in ^{12}C [12, 13]. Dark Matter related research is a newer activity that will grow as the Stawell Underground Physics Laboratory (SUPL) comes online in 2020 and with the recent announcement of funding for an Australian Research Council (ARC) Centre of Excellence in Dark Matter Particle Physics (funded for 7 years from mid 2020) [6].

3.1.3 Nuclei for Society

Nuclear physics for medicine includes established research to both compute and measure the emission of Auger electrons from medical radioisotopes, and developing research to support hadron therapy and radiobiology. The AMS program has supported extensive research into environmental science for several decades now. The initial emphasis was on ^{36}Cl measurements, e.g. to date groundwater, but recent work has focused more on landscape evolution studies and the development and application of AMS to measure the migration of bomb-spike actinides through the environment.

The Department of Nuclear Physics engages with the International Atomic Energy Agency Nuclear Data Project. It hosts the internal conversion coefficient website (bricc.anu.edu.au), which has around 8000 unique visitors per year. The Department also contributes to nuclear education to support Australia's obligations and roles in Nuclear Safety, Security and Safeguards. It promotes discussion on applications of nuclear technology in society including aspects of nuclear energy generation and nuclear waste management. One example is the contribution in these proceedings by Professor L.L. Riedinger (University of Tennessee, Knoxville) on the changing picture of energy generation in Australia and the United States [14].

3.2 Beam-line instrumentation and research

There are ten separate beam lines that can receive beam from the HIAF accelerators. Each beam line hosts specialist detection equipment, largely designed and built in-house, that supports a wide range of research projects driven by the local research groups with a strong network of national and international collaborators. In a typical 5-year period more than 30 groups representing a dozen countries run collaborative experiments at HIAF.

The following description of the key experimental equipment is presented in the order of the beam line numbering, beginning with beam lines 1-7 in the original 14UD target area (target area 1) and followed by beam lines A-C in the LINAC hall (target area 2).

3.2.1 Line 1: Caesar array

The CAESAR array of 11 Compton suppressed γ -ray detectors has been a key instrument for nuclear spectroscopy. Research themes include studies of nuclear shape-coexistence, the identification and characterization of metastable states in heavy nuclei, and the coupling of single-particle motion to octupole collectivity in certain groups of nuclei (see, e.g. Refs. [15, 16] and references therein). Highlights of recent work include the addition of LaBr₃ detectors for lifetime measurements on the sub-nanosecond time scale, and experiments to eliminate possible alternative explanations of recent evidence of isomer depletion due to nuclear excitation by electron capture [17].

3.2.2 Line 2: Hyperfine spectrometer

The Hyperfine Spectrometer [18] allows the application of a magnetic field to a target that can be cooled to 4 K. Perturbed particle-angular correlations are measured to determine nuclear moments or study atomic physics, ion-solid interactions, or materials science via hyperfine interactions methods. Research over the last decade has included a strong focus on methodology and technique development for g -factor measurements on neutron-rich nuclei produced at international radioactive beam facilities, by the transient-field and recoil in vacuum methods [19–25]. Current work, also tied to experiments at international radioactive beam facilities, has explored the nature of weakly collective nuclei [26], and the emergence of nuclear collectivity near doubly magic ¹³²Sn, through g -factor and $B(E2)$ measurements, and comparisons with detailed shell model calculations [27–30].

The first in-beam time-dependent perturbed angular correlations measured with LaBr₃ detectors were reported recently [31]. Further experiments of this type, which can precisely measure the g factors of states with lifetimes of a few nanoseconds, are planned.

3.2.3 Line 3: 2-metre Scattering Chamber

After not being used for more than a decade, the 2-metre diameter scattering chamber is being refurbished to study the quantum mechanics of dissipation and thermalisation processes in nuclear collisions.

3.2.4 Line 4: General purpose

Line 4 is the only general purpose beam line at present. It has been in heavy demand for measurements that complement other HIAF research programs and for detector characterisation and development. For example, γ -ray angular distributions were measured following (p,p') excitation of nuclei such as ¹²C, and ^{50,52}Cr, complementing electron spectroscopy measurements with the Super-e that aim to determine electric monopole ($E0$) transition strengths between shape-coexisting nuclear states. Quenching factors for dark matter detector characterisation have been measured using neutrons produced by ⁷Li(p,n)⁷Be as a proxy

for a neutral dark matter particle inducing a nuclear recoil in a scintillator detector [6]. In these studies, the light yield from nuclear recoils of known energy can be determined and compared to the detector response to photons of similar energy. The heavy-ion response of the new scintillator material Gadolinium Aluminium Gallium Garnet (GAGG) coupled to silicon photomultipliers has also been investigated in collaboration with Dr J. M. Allmond (Oak Ridge National Laboratory).

3.2.5 Lines 5 and 7: AMS

HIAF provides one of the world's highest particle energies used in AMS. Two beam lines are dedicated to AMS. Both include a Wien (or velocity) filter and multi-anode particle detection systems. Line 5 extends beyond the first AMS detector, which can be removed. This beam line can be configured to include a 6-m time-of-flight set up for enhanced isotope separation. The beam can also continue into the Enge magnetic spectrometer, operated as a gas-filled magnet system with a position-sensitive multi-anode gas ionisation detector at the focal plane, to achieve unique levels of isobar suppression. Applications include environmental studies, as well as geological-, climate- and astrophysics-related research [10, 32–36].

The HIAF group pioneered actinide AMS and successfully applied it to projects in environmental, biomedical, safeguards and geological research [37]. Utilising the isotopes released into the environment by atmospheric nuclear tests, reprocessing plants or nuclear accidents, these environmental tracers and time markers have been applied to study soil erosion and sediment transport - major problems for Australia. Future work aims to exploit ²³⁶U and Pu isotopic fingerprints carried by ocean currents as tracers of ocean water movement.

3.2.6 Line 5: ENGE Spectrograph and transfer reactions

Funding has been received in 2019 from the ANU Major Equipment Committee to refurbish the Enge magnetic spectrometer for transfer reactions. The upgrades include re-establishing the ability to move the Enge to different angles (it is used at a fixed angle for the AMS measurements described above) and to build a new focal plane detector consisting of a position-sensitive ionisation chamber followed by a plastic scintillator detector. Experiments to measure the spectroscopic factors of nuclear states of relevance to studies of fundamental physics (e.g. neutrinoless double beta decay, the CKM quark-mixing matrix, and EDM searches) and studies to probe the multiparticle-multihole structure of proposed deformed-intruder excitations (shape coexistence) are planned.

3.2.7 Line 6: Super-e: conversion electrons and pair spectroscopy

The Super-e is a superconducting electron spectrometer, a sensitive and powerful instrument to study nuclear structure and assign quantum numbers to nuclear excitations

through the measurement of conversion electrons [38]. It has been upgraded for electron-positron pair spectroscopy by installing a six-fold segmented Si detector. A current major project is to determine the radiative width of the Hoyle state in ^{12}C [12, 13], which is the pathway for the creation of carbon in the universe. More recently, pair spectroscopy has been used to study $E0$ transitions in relatively low- Z nuclei. Examples are $0^+ \rightarrow 0^+$ transitions in the $N = Z$ nuclei ^{24}Mg and ^{40}Ca , and a systematic study of $E0$ transition strengths near $N = 28$ and $Z = 28$ that is finding that strong $E0$ transitions occur only in the semi-magic isotopes [39–41].

3.2.8 Lines A and B: 6.5- and 8-Tesla Solenoids, SOLEROO and SolenoGam

An 8-Tesla superconducting solenoid is installed on Line A in target area 2, and a 6.5-Tesla solenoid is installed on Line B. These instruments function as efficient solenoidal separators for fusion-evaporation reaction products, allowing determination of fusion cross sections to better than 1% precision [42]. This sensitivity opens a window into the quantum states of the colliding system at the moment of fusion. For recent developments see Bezzina *et al.* in these proceedings [43].

The solenoidal separators have proven to be extremely versatile instruments, with applications ranging from basic nuclear physics, through materials science, to light radioactive ion beam production (SOLEROO) [44]. SolenoGam is an array of electron and γ -ray detectors that can be placed in close geometry around the focal plane of the solenoid, hence enabling the spectroscopy of long-lived weakly-populated states to be performed in a low-background environment [45].

SOLEROO is a low-mass radioactive ion beam capability that has been developed using the 6.5-Tesla superconducting solenoid as the separator element. SOLEROO separates the large background of primary-beam particles from the radioactive species of interest. A further rejection of unwanted nuclear species leaving the solenoid is achieved by tracking each emerging particle and identifying them event-by-event using a pair of position sensitive parallel plate avalanche counters. The tagged secondary beam is combined with a high efficiency 512-pixel silicon detector array for nuclear experiments.

3.2.9 Line C: CUBE and BALIN

The CUBE is a wide-acceptance spectrometer consisting of large-area position-sensitive multi-wire proportional counters (MWPC) [46]. It can be configured to suit a wide range of experiments studying nuclear fusion and fission. It can also be combined with γ -ray and charged-particle detectors [47]. Colliding nuclei can merge together (fusion) or separate after the exchange of some mass (quasi-fission). The CUBE has shown that quasi-fission is more prevalent than expected and has helped to provide insight into the completion between the processes that determine whether fusion or quasi-fission occurs. As such, it provides key information on reaction outcomes to understand

the fusion process leading to the production of new super-heavy elements. Recent measurements of the mass angular distributions of fission fragments and cross sections have given insights into the timescales of fast non-equilibrium deep inelastic [48] and quasifission processes, which both reduce the chance of compound nucleus formation and hence superheavy element production [49]. Systematic studies of quasifission in ^{48}Ca -induced reactions are reported in these proceedings [50].

Consisting of position-sensitive double-sided silicon strip detectors ($\Delta E - E$ telescopes) with large angular coverage and high granularity, the BALIN array has recently been used to measure the full distribution in energy and angle of the light reaction products from $^7\text{Li}+^{209}\text{Bi}$, and in conjunction with SOLEROO, from $^8\text{Li}+^{209}\text{Bi}$ [51]. For polonium isotopes, the dominant incomplete fusion product, only a small fraction can be explained by projectile breakup followed by capture: the dominant mechanism is triton cluster transfer. Suppression of complete fusion is therefore primarily a consequence of clustering in weakly bound nuclei rather than their breakup prior to reaching the fusion barrier [52].

3.3 Other research activity

Along with the research that is strongly based on the accelerator facilities, the Department undertakes several projects that make less intensive use of the accelerator. The growing activity in dark matter research is summarized by Bignell *et al.* in these proceedings [6].

Auger electrons emitted by radioisotopes undergoing electron capture, or with strong internal conversion, have great potential for targeted cancer therapy. However the Auger emission (spectrum, intensity, multiplicity) from medical radioisotopes is relatively poorly known. As part of an IAEA Coordinated Research Project, the ANU was charged to develop a new computer code for atomic radiations (X-rays and Auger electrons) from medical radioisotopes. The BrIccEmis code has been developed [53, 54], and together with Dr Maarten Vos (ANU, Department of Electronic Materials Engineering), measurements of Auger emission from ^{125}I have been completed and compared with BrIccEmis [55]. In these proceedings, progress toward the development of a new on-line data base for Auger and X-ray spectra is reported by Tee *et al.* [56].

4 Facility development and aspirations

Several research and facility development projects, which have already been funded, have been mentioned above (e.g., new ion source for ^3He and ^4He beams; upgrades of injection, accelerator tube and column; Enge refurbishment for transfer reactions). Concerning future aspirations, the Research School of Physics Building Plan allocates space for a future stand-alone linear accelerator. This space would be used for new beam lines in the period leading up to the funding of the accelerator. In the mean time, an extension of beam-line 7 beyond the AMS

detector is planned for new research and applications of heavy-ion irradiation. Projects include material modification and component testing for deployment in space as well as medical physics applications, including research to support hadron therapy and an external beam capability for radiobiology [3].

If funding for accelerator upgrades were to be allocated in increments, a practical path would be to begin by replacing the current superconducting LINAC modules based on lead-plated copper technology with pure niobium resonators, which could achieve an energy boost four times that of the present LINAC with the same physical footprint.

5 Conclusions

The Heavy Ion Accelerator Facility is a university-based national facility with strong international links that supports research and training across a wide range of pure and applied nuclear physics methodologies.

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