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The recent death of Reg Richardson has robbed the cyclotron community of its most senior figure. His many achievements over a long career include the first demonstration of phase stability, the first synchrocyclotron, the first sector-focused cyclotron, and one of the two cyclotron meson factories.

1 Introduction

John Reginald Richardson, who was one of the dominant figures in the development of cyclotrons over his long career, and a founder of these conferences, died in California on November 25, 1997, after a lengthy illness.

Figure 1: Reg Richardson - 1940 and 1975

Reg was born in Edmonton in western Canada in 1912. His parents were professional musicians who had emigrated from Scarborough in England in 1905. The family soon moved to Vancouver and he spent his early boyhood just a few blocks from Stanley Park. Then at the age of 10 his parents moved on again to California. After high school in Los Angeles he attended UCLA, where Glenn Seaborg was a contemporary and remembers him as the top physics student in their class of '33.

Already showing a talent for recognizing the best scientific opportunities available, Reg then enrolled at Berkeley and acquired Ernest Lawrence as his supervisor, receiving his Ph.D. in 1937 for a study of the photodisintegration of the deuteron. Following a year as National Research Fellow at the University of Michigan, he was appointed Assistant Professor of Physics at the University of Illinois - in both places continuing his studies of nuclear structure and bringing Berkeley expertise to bear on newly-constructed cyclotrons. In 1942, however, following U.S. entry into the war, he returned to Berkeley to work on developing calutrons for electromagnetic separation of uranium for the Manhattan Project.

2 Phase Stability and Synchrocyclotrons

When the principle of phase stability was discovered by Veksler and McMillan, it was at first thought that moderately high-energy injection was required, so that it could not be readily applied to cyclotrons. Reg, however, from his calutron experience, was able to show that 1-5% of the ions emerging from an ion source could be captured in the stable bucket. In 1946 he led an *ad hoc* group of Ed Lofgren, Ken MacKenzie, Bernard Peters, Fred Schmidt and Byron Wright in converting the fixed-frequency 37-inch cyclotron at Berkeley to fm operation as the first synchrocyclotron [1]. This not only provided the first demonstration of the phase-stability principle (Goward and Barnes' first operation of a synchrotron followed a few months later), but also confirmed the feasibility of converting the 184-inch cyclotron from classical to synchro-cyclotron. Lawrence's decisive reaction to this result is described by Reg in his recollections [2].

That year he also took up a faculty appointment at UCLA, and was soon joined by MacKenzie and Wright, and also by David Saxon, forming a strong nuclear physics group. Moreover, the 37-inch cyclotron was obtained from Berkeley and converted to a 20 MeV synchrocyclotron, providing a leading research facility and an essential tool for the many graduate students attracted there. In this small group lively political and social dis-

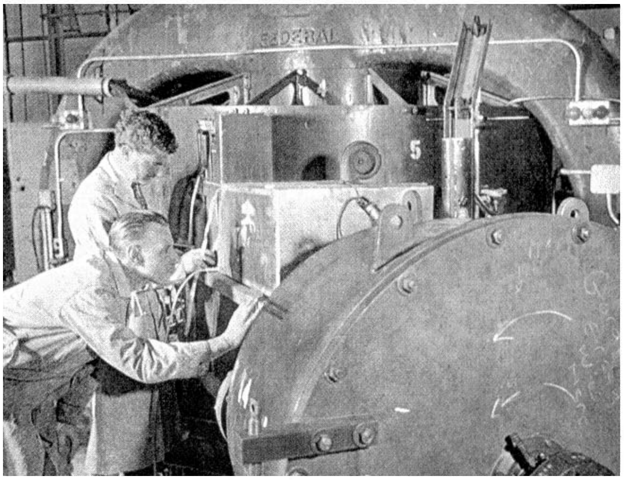

Figure 2: Reg and Ernest Lawrence with the modified 37-inch cyclotron (rotating capacitor in foreground).

cussions took place, with Reg being conservative and the others liberal. David Saxon particularly remembers the time of the loyalty oaths at the university, when Reg readily agreed to testify on his behalf at a hearing, although their political beliefs were very different.

3 Sector-Focusing Cyclotrons

In the next few years many higher-energy synchrocyclotrons were built, providing usable secondary beams of pions and muons, and inaugurating the era of accelerator-based particle physics. But the pulsed operation of these machines limited beam intensities to < 1 μA, so when a need for intense 200-300 MeV deuteron beams led to the construction of the 60-foot diameter Mark I linac at Livermore, Reg championed a more modest alternative, a cw cyclotron based on L.H. Thomas's pre-war suggestion of using a magnetic field increasing radially to maintain fixed orbit frequency into the relativistic regime, while varying azimuthally to provide axial focusing. He had retained his connexions with Berkeley, and there in 1950 he led David Judd, John Jungerman, Elmer Kelly, Robert Pyle, Robert Thornton and Byron Wright in building the first sector-focused cyclotrons– two electron models (Figure 3) which reached $\beta = 0.5$ [3]. Such cyclotrons are not as forgiving to tune as synchrocyclotrons, and require a very accurately tailored magnetic field (to about 0.1% in this case). This could not be achieved by shaping the iron alone but required the adjustment of over 50 trimming coils, using the beam as a probe. Reg's skill and perseverance in bringing the beam to full energy led one of the engineers, who normally classified physicists as "2-knob men" or "4-knob men", according to their tuning ability, to concede that here was a "10-knob man".

This work remained classified until 1955, but once the secret was out sector-focused cyclotrons rapidly proliferated. With the incorporation of further ideas, such as strong focusing via spiral sectors, superconducting magnets, separated sectors and external injection , there are now more than 250 operating around the world, providing beams ranging from 1.5 mA of 590 MeV protons to a few pA of 25 MeV/u $^{238}U^{39+}$.

Back at UCLA Reg led the design and construction of a 50 MeV cyclotron (Figure 4), taking full advantage of Kerst's spiral sector focusing and Wright and Rickey's H^- ion acceleration concept to provide clean beam extraction at variable energy. This was completed in 1962 [4], greatly increasing the range of experiments available. Reg was determined to show that a small lab could be the first to produce relativistic protons at high intensity, and indeed UCLA won the race with the much better funded national labs at Berkeley and Oak Ridge by a year.

One example of Reg's skill at cyclotron design is illustrated by the time that the UCLA magnetic field data was sent to Berkeley to run on an IBM computer to verify his hand calculations. When there was a big disagreement between the two, Reg declared that the computer was wrong! It turned out that a sector number of 3 instead of 4 had been used at Berkeley by mistake, and when the correction was made the agreement was fine. This reinforced Reg's lifelong suspicion of computers.

Tom Cahill remembers the tuning method used by Reg to make sure the beam was at full energy. Before the cyclotron was moved to its shielded vault, he put a radiation meter on the control console and set it to 100 mR/h. He then tuned up the beam until the meter reached full scale, when he sent everyone else out of the building and continued tuning.

Graduate education at the UCLA cyclotron was very much in the Lawrence tradition, with students being given full responsibility for building their equipment, and

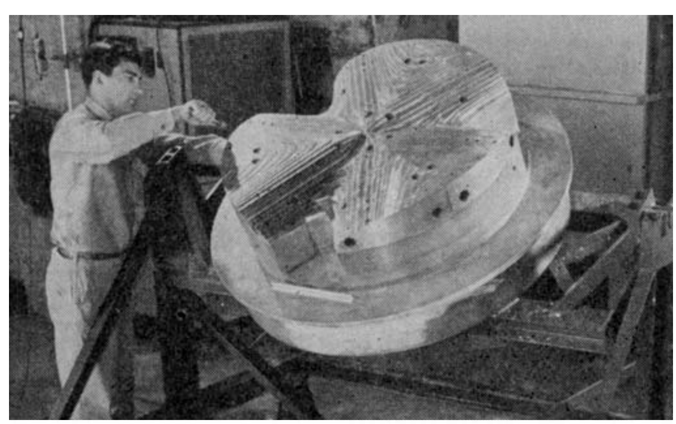

Figure 3: One of the magnet poles for the second electron model sector-focused cyclotron.

Figure 4: Reg and Byron Wright with the UCLA H$^-$ cyclotron.

receiving hands-on training from the technicians in skills such using a lathe and hard soldering. Each student had to complete an experimental project before going on toward his Ph.D. There were no engineers so students had to make their own drawings of new equipment. Reg and the other faculty were excellent teachers and recruited many students from their courses. Graduate student Tom Cahill relished "the freedom Reg gave us as students, with real responsibilities for important components of the program. How often today do graduate students have the freedom to fail, without which success is a bit hollow? Reg trusted us, and we responded."

Each year Reg's birthday was celebrated by taking left-over alcohol from the deflector cleaning supply and adding it to orange juice. When everyone reached a good mood, Reg could be persuaded to sing his composition "The Cyclotron Song" to the tune of "Sweet Betsy from Pike" (or "The Ould Orange Flute"):

Oh the cyclotron protons swing round all the day;
They bump into copper and tungsten we say,
Into zinc, into fluorine, into tantalum too,
But my boy (or girl) just take care they don't bump into you!!

A range of six meters in air do they have.
If they hit you, my boy, no more hair will you have;
So it pays to take care when the beam's in the air,
Or you'll lose all your interest in the charms of the fair!

Those protons excite some compound nuclei,
Which emit some fast neutrons of energy high;
If those neutrons collide inside of your hide,
To you sex will be theory that's never applied.

By this time Reg had become a major figure in national and international physics. Within the U.S. he was a member of the Committee of Senior Reviewers for the USAEC, and served on review committees for various national laboratories. He also spent two sabbatical years in London as liaison scientist for the U.S. Office of Naval Research.

Internationally, he had become well-known as the author of two major review articles – one on cyclotrons in the 1948 *Encyclopaedia Britannica*, and one on sector-focused cyclotrons in *Progress in Nuclear Techniques* [5], which became a bible for many of us in the sixties. He was also one of the founders of this conference series, hosting the second conference at UCLA in 1962, and initiating its sponsorship by IUPAP.

4 Meson Factories

His 1963 proposal for a 750 MeV H$^-$ cyclotron "meson factory" [6] – a term he coined – was unsuccessful in attracting funds to UCLA, but was adopted in Canada in a downsized version, making possible the successful construction of the 520 MeV, 200 μA TRIUMF cyclotron (Figure 5) – a project over whose construction and commissioning [7] Reg presided with great effectiveness as the second director (1971-6). He personally tuned the beam from injection to extraction – a much-enjoyed reward for all the years of planning and administration. His personal involvement with the project and its staff in those formative years inspired great devotion and provided an important lesson in management style.

Figure 5: Reg (centre) and the TRIUMF staff during assembly of the 520 MeV cyclotron.

It was not inappropriate that Reg's meson factory should be built near Vancouver: since 1946, he had maintained a summer home nearby on Galiano Island, and it was there that the design was conceived. After retiring as director, another relaxing summer on Galiano produced schemes of kaon factories – and the ink on the 30 GeV KAON proposal was hardly dry before he had schemes afoot for the addition of a superconducting ring to reach 100 GeV [8].

5 Nuclear and Particle Physics

Throughout his career Reg continued to participate in nuclear and particle physics experiments, the most notable perhaps being those which introduced the Kurie plot for determining β-decay energies [9], the first measurement of the lifetime of the charged pion, some "tweaking of the dragon's tail", and comprehensive surveys of nucleon-nucleon scattering.

In 1948 Reg visited Berkeley to measure the lifetime of the π^- meson. He used the cyclotron principle that ions in a magnetic field take a constant time to make a revolution, independent of their speed, measuring the π^- intensity with photographic plates after 0.5 and 1.5 revolutions in the 184-inch cyclotron fringing field. This was surely one of the last papers [10] to report measurement of a fundamental particle property by a single author!

During this time Reg also worked with David Judd and others on a system in which the "dragon's tail was tweaked". This involved rotating disks of fissile material through a slot in a subcritical sphere to produce a burst of neutrons for testing shielding in a proposed airplane to be powered by a nuclear reactor [11].

The nucleon-nucleon scattering experiments started at UCLA at energies up to 14 MeV, continued up to 50 MeV with the new cyclotron, and concluded at TRIUMF over the range 180-520 MeV. He was one of the founders of the International Conference on Few-Body Problems in Physics.

6 Concluding Remarks

Reg's greatest legacy, however, must be the more than 250 sector-focused cyclotrons now in operation around the world, whose intense beams have opened up new opportunities in many fields. This was acknowledged when he was awarded the Wilson Prize of the American Physical Society in 1991, the citation reading:

> *"For his original contributions to the development of cyclotrons. These include the first experimental demonstration of phase stability, the first synchrocyclotron, and the first sector-focused cyclotron. This work is the basis of numerous cyclotrons that have had and continue to have major impact on nuclear physics, solid state physics, chemistry and medicine."*

Reg will be greatly missed by his colleagues, past students and family, to whom he was devoted. He greatly enjoyed water sports, including boating and snorkeling, and in well-organized retirement was able to split the year between his three homes in Malibu (California), Maui (Hawaii) and Galiano Island (British Columbia). He will be remembered not only for his monumental achievements and his impact on generations of nuclear and accelerator physics students, but also for his elegant style and for the warm hospitality which he and his family always offered.

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