IN MEMORIAM: MICHAEL K. CRADDOCK*

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Abstract

Michael K. Craddock, TRIUMF accelerator physicist and UBC professor, died on 11 November, 2015 after a brief illness. Michael left the UK to join the UBC Nuclear Physics group in 1966, just at the time a new accelerator to replace the aging Van de Graaff was under consideration. He was a leading member of the founding team that decided on a 500 MeV H^- cyclotron and directed the beam dynamics design of the cyclotron to first beam in December 1974. With the cyclotron running at full intensity he moved his interest to higher energies and led the accelerator physics team in the design of the 30 GeV KAON Factory (1982-1994). After retirement from UBC in 2001 he moved his research interest to FFAGs.

INTRODUCTION

Michael Craddock was born on 15 April in Portsmouth, UK and received his early education there. He then attended Oxford University for his Bachelor's and Master's degrees in mathematics and physics in 1957 and 1961 and became a scientific officer at what was then the Rutherford High Energy Physics laboratory (RHEL) working on the 50 MeV proton linear accelerator (PLA) (see Fig. 1).

In parallel he pursued a D. Phil in nuclear physics at Oxford which he obtained in 1964. His thesis topic was "The Nuclear Interactions of High Energy Particles" under the supervision of D. Roaf and R. Hanna. The work involved developing a polarized source, beam polarimeter and cryogenic target for studying proton-He4 elastic scattering at 22 and 29 MeV. As an indication of his future thoroughness in research the thesis contains 14 pages of references. In 1966 Michael joined the Physics Department at the University of British Columbia, later with a joint appointment at TRIUMF, and was TRIUMF's leading beam physicist throughout his career.

Michael with a training in mathematics loved equations and his early note books are filled with formula relating to polarized proton sources, equations of charge at particle motion in magnetic and electric fields etc. He passed this approach on to his many graduate students and beam dynamics team, although eventually embraced computing simulations but usually they were carried out by others. He excelled in writing research papers – the references present only a small subset of his published papers, and was particularly interested in the history of accelerator developments. At the Cyclotron Conference in Lanzhou in 2010 he presented a paper on "Eighty Years of Cyclotrons" [1]. His last scientific article was a history of accelerator science and technology in Canada which was completed by Robert Laxdal and recently published [2].

Michael was a strong supporter of the international accelerator community beginning as the program chair for the 1972 Cyclotron conference in Vancouver, conference chairman for the 1985 and 1997 Particle Accelerator Conferences and also the 1992 Cyclotron conference. He was a valued member of the international organizing committees and scientific advisory boards for these conferences. He gave the after dinner address to the 1992 conference on "Proper and Improper Accelerators – In praise of Cyclotrons and their Builders".

At TRIUMF Michael was the head of the Beam Dynamics group or the Accelerator Research Division for much of his career and was instrumental in training a new generation of beam physicists. Some of these individuals are identified in the references and acknowledgements. (For 29 years he was TRIUMF's correspondent to the *CERN Courier*.)

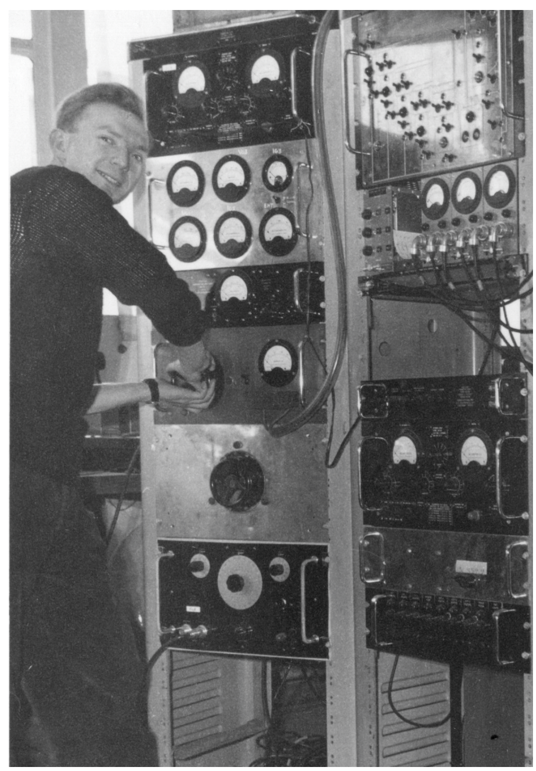

Figure 1: Michael Craddock at the controls of the Rutherford Laboratory PLA in 1964.

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THE TRIUMF CYCLOTRON

Michael Craddock wrote a summary of the 12 June 1965 meeting of representatives from the three British Columbia universities which included the first use of the acronym TRIUMF and the plan to develop a scaled-down version of Reg Richardson's UCLA proposal for an H^- cyclotron (520 MeV, 100 µA). The TRIUMF proposal was to be produced within a year, coordinated by Erich Vogt who was moving from Chalk River National Laboratory to UBC physics. John Warren the head of the nuclear physics group and builder of the 3 MeV Van de Graaff was going on sabbatical to RHEL during that time. Michael Craddock was responsible for the accelerator design and an early step was to bring the scale model of the UCLA magnet to UBC for field mapping. The proposal was completed by November 1966 at the same time Los Alamos was proposing an 800 MeV proton linac and ETH in Zurich was proposing a 590 MeV ring cyclotron for meson physics. All three meson factories were approved by 1968 with the USA choosing the LAMPF proposal over UCLA. John Warren was the first director of TRIUMF (1968-1971) and Reg Richardson was the second director (1972-1976).

The main technical challenges of the cyclotron were the design, engineering and field mapping of the 4000 ton 6-sector magnet which was limited to a maximum magnetic field if 0.576 T due to electromagnetic stripping of the H^- ions and the large radiofrequency structure which had to cover an orbit diameter of 16 m. Mike built up a beam dynamics group consisting of George Mackenzie (1968), Gerardo Dutto (1970) and Corrie Kost (1971) and supervised two early graduate students in the design of the centre region of the cyclotron and the axial injection with a spiral inflector [3]. The large magnet pole gap of 50 cm was a challenge for maintaining vertical focusing. The construction of a full-scale centre region model of the cyclotron led by Ewart Blackmore (1969) tested the ion source and axial injection with the inflector, the centre region design and the resonator structures and successfully accelerated an H^- beam of 100 µA beam to 3 MeV in 1972 [4].

Figure 2 shows the lower half of the TRIUMF cyclotron showing the staff in 1972 and the pole contours for shimming.

Meanwhile initial field measurements of the large magnet revealed that the centre field was too high by 100 g (0.01T) due to differences in permeability between the 0.5" plate used in the model magnets and the 5" plate used in the large magnet. Michael and his group were responsible for determining the position and number of magnet shims to be installed on the pole sides to overcome this problem and produce the required isochronous field to a level that could be corrected further with trim coils. Finally in November of 1974 after 9 months of shimming and with the radiofrequency cavities installed and the ion source ready, beam was injected into the cyclotron. With Reg Richardson at the controls and Michael and the other commissioning team members at his side the beam was worked out in energy (see Fig. 3). After a few technical stops the full energy beam was accelerated and extracted on 14 December 1974. The successful commissioning of the cyclotron was presented first at the June 1975 Particle Accelerator Conference [5] and then in August at the 7th Cyclotron Conference in Zurich [6].

Michael and his group continued to improve the beam performance to reach the design goal of 100 µA in 1977 and today the cyclotron operates routinely at 300 µA into 3 beamlines at different energies. Moreover for special applications it is possible to extract a stable 1 pA of beam on one beamline with more than 100 µA of beam circulating in the cyclotron, a benefit of H^- stripping extraction.

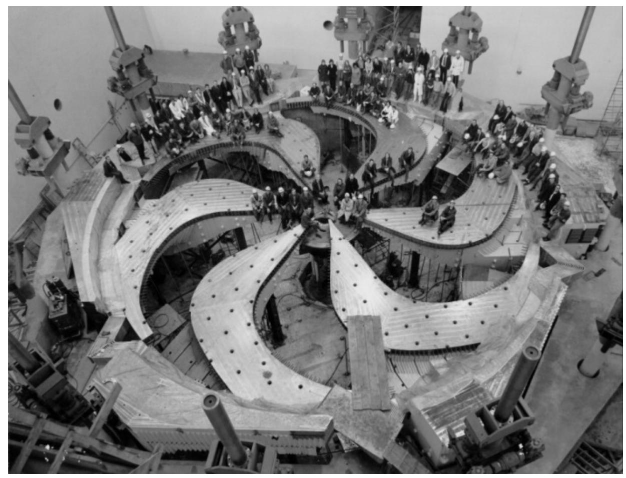

Figure 2: The lower half of the TRIUMF cyclotron showing the staff in 1972 and the pole contours for shimming.

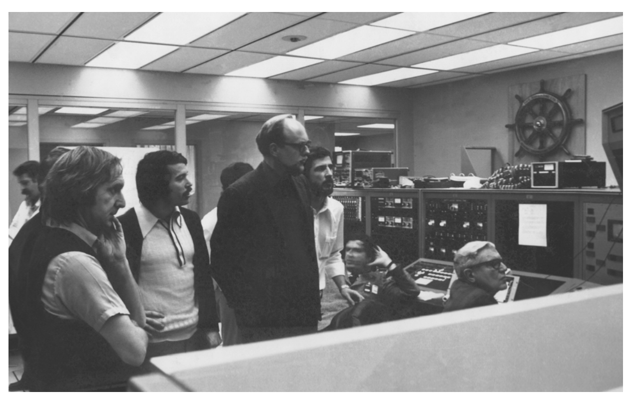

Figure 3: Reg Richardson tuning the TRIUMF cyclotron with Michael Craddock, Ewart Blackmore and George Mackenzie looking on (1974).

THE KAON FACTORY

With the TRIUMF cyclotron beam dynamics in good shape, Michael turned his attention to accelerators with higher energies at higher currents that would be sufficient to produce copious beams of kaons and other particles. The first phase focused on cyclotrons to determine how far this technology could be pushed. Working with Jan Botman and others a magnet design for a 15 GeV superconducting cyclotron was developed with injection

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at 430 MeV from TRIUMF into a 3.5 GeV ring followed by a 3.5 – 15 GeV ring. The magnet sector shapes for the 3.5 GeV are shown in Fig. 4. These sectors have reverse bends, so-called return field gullies which increase the flutter, much like the first FFAG proposals from MURA. Michael enjoyed producing acronyms and this became the CANUCK proposal (Canadian University Cyclotrons for Kaons) in 1983 [7].

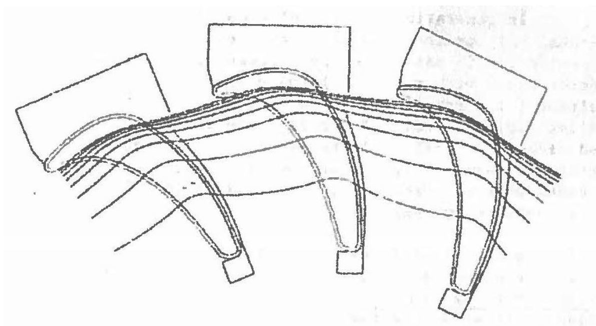

Figure 4: Sector design and orbits for the 3.5 GeV cyclotron using single gullies.

It soon became apparent that 15 GeV was not optimum for a Kaon Factory and that synchrotrons would be necessary. Michael, then head of the Accelerator Research Division and his group starting working on rings of synchrotrons that could be injected at 430 MeV from the TRIUMF cyclotron to produce 100 µA at 30 GeV. This culminated in a Project Definition Study led by Alan Astbury that produced a fully costed accelerator and experimental area design in 1992 [8]. With his love of acronyms Michael called the facility KAON for kaons, antiprotons, other hadrons and neutrinos and the 5 accelerator rings A(accumulator), B(booster), C(collector), D(driver) and E(extender) (see Fig. 5). The funding proposal with costs shared equally between Canada, British Columbia and International contributors was promoted relentlessly by Erich Vogt (Dr. Kaon) and Michael and came close to success. However the project did not get supported by a newly elected federal government in 1994, although TRIUMF did get a new future with 5 year funding for the ISAC radiative beam facility at TRIUMF and accelerator and ATLAS detector contributions to the Large Hadron Collider at CERN.

The design work on the KAON rings was not wasted. In travelling the accelerator world to promote KAON and to collaborate with other beam physicists on the issues of high intensity accelerators (see Fig. 6), Michael was able to attract new students and postdocs to study and work at UBC and TRIUMF. Accelerating high intensities to 30 GeV meant that beam losses had to be kept low, necessitating separated-function magnet lattices with the dispersion kept low to increase the transition energy above the top energy of all rings. Michael and his group published several papers on high γ_T lattices and on instabilities and collective effects [9, 10, 11]. Some of these ideas were later incorporated into the design of the J-PARC accelerators as this facility became the de-facto Kaon factory. In addition to beam dynamics studies, the technical and prototype work during the KAON were instrumental in TRIUMF personnel gaining significant expertise in synchrotron systems and this was applied to the LHC work described in the next section.

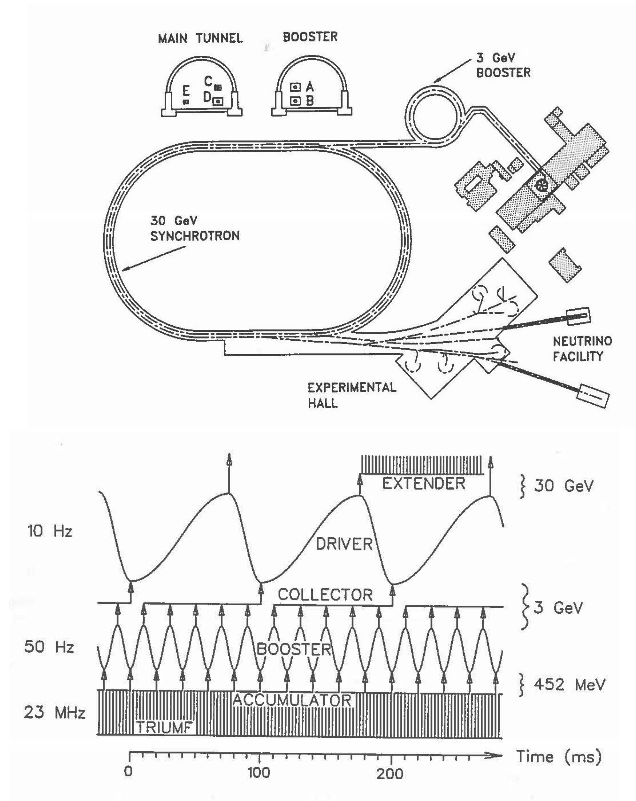

Figure 5: Layout of the KAON rings and the energy-time structure of the beam.

Figure 6: Michael Craddock at Troitsk in 1989 to discuss KAON Factories.

CANADIAN CONTRIBUTIONS TO THE LHC

Over the period 1995-2005, TRIUMF coordinated the $41.5M Canadian contribution to the LHC accelerators. This work involved procurement of magnets, rf systems, kickers, beam diagnostic, power converters and transformers coordinated by Ewart Blackmore [12] but

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also some important beam dynamics contributions coordinated by Michael Craddock. The most significant of these projects was the design of the beam cleaning insertions in the LHC ring to collimate beam halos with large transverse or off-momentum amplitudes [13]. This work was coupled to the fabrication of 52 large twin-aperture quadrupoles with conventional coils to operate in the high radiation environment of the beam cleaning region which was the largest part of the contribution. Other work carried out by Michael and his team involved simulation studies of higher beam currents in the PS complex, space charge and its effect on betatron resonances [14] and beam-beam interactions in the collision regions [15].

FFAGS AND EMMA

About 1999 there was a renewed interest in Fixed (magnetic) Field Alternating Gradient (FFAG) accelerators, initially considered for muon colliders. Groups in Japan and the U.S. came up with independent designs for fixed field (ring style) muon accelerators with very large momentum acceptance, so large an acceptance that other applications became of interest such as compact proton and heavy ion accelerators for hadron therapy. The Japanese designs are descendants of the so-called "scaling FFAGs" pioneered by the MURA group in the 1950s. The early US designs look like separated function synchrotrons, but with the "non-scaling" optics (employing reverse bending) contrived so that the central orbit moves (radially) very little during acceleration [16]. They have, in common with the KAON Factory Booster ring, a very careful manipulation of the dispersion function. Michael became interested in FFAGs about 2003 and having straddled the worlds of cyclotrons and synchrotrons was well placed to make a contribution to this renaissance and emphasized the commonality between the two approaches at the international FFAG workshops from 2004 to 2014.

In a series of calculations and papers from 2003 onward, Michael adapted the Schatz approach (a hard edge matrix method for determining orbits and focusing properties of separated sector cyclotrons) to the non-scaling FFAG lattice designs, and within 3 years was obtaining results that were found to be accurate to within a few percent of tracking codes. By 2007, the centre piece of the FFAG community was the EMMA (Electron Model with Medical Applications) demonstration machine under construction at Daresbury [17] and it was natural that Michael should apply the Schatz method to that machine. In 2009 he returned to the theme of unifying the FFAG efforts, opening a paper [18] with "Nevertheless, cyclotrons and FFAGs have been developed by two different communities, which have sometimes taken different approaches in their work. The studies described here bridge this gap to some extent by applying orbit codes developed for isochronous cyclotrons to FFAGs, and some FFAG ideas to cyclotrons."

That work occupied him for the remainder of this life, concluding in workable designs for a 1 GeV radial sector isochronous cyclotron with reverse bending. For FFAG'11 and onwards, Michael gave historical, overview and educational talks on Cyclotrons and FFAGs both old and modern, continuing to leave his legacy to the accelerator community (Figs. 7 and 8).

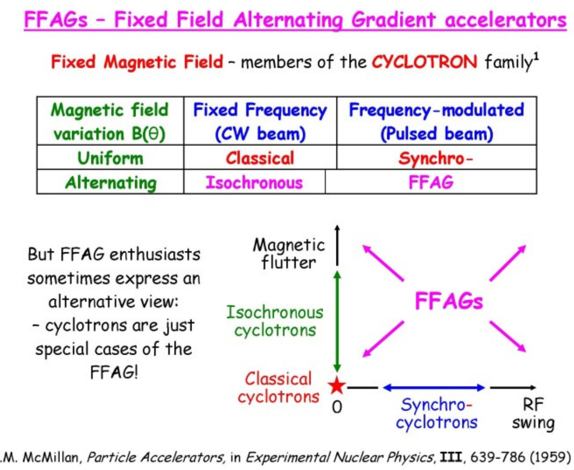

Figure 7: Slide from course at FFAG School in 2011 showing typical Michael Craddock style.

Figure 8: Michael Craddock in 2015.

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REFERENCES

[1] M.K. Craddock, "Eighty Years of Cyclotron", in *Proc. 19th Int. Cycl. Conf. (PAC'10)*, Lanzhou, 2010, p. 1.

[2] M.K. Craddock and R.E. Laxdal, "Accelerator Science and Technology in Canada from the Microtron to TRIUMF, Superconducting Cyclotrons and the Canadian Light Source", Reviews of Accel. Sci. & Tech.Vol. 8, 2005.

[3] R.J. Louis, G. Dutto, and M.K. Craddock, "Central Region Orbit Dynamics in the TRIUMF Cyclotron", IEEE NS-18, 1971, p. 282.

[4] E.W. Blackmore *et al.*, "Experimental Results from the TRIUMF Central Region Cyclotron", in *Proc. PAC'73*, IEEE NS-20, 248, San Francisco, 1973.

[5] J.R. Richardson, E.W. Blackmore, G. Dutto, C.J. Kost, G.H. Mackenzie, and M.K. Craddock. "Production of Simultaneous, Variable Energy Beams from the TRIUMF Cyclotron", in *Proc. PAC'75*, IEEE Trans. NS-24, 1975, p. 1402.

[6] J.R. Richardson, "The Status of TRIUMF", in *Proc. 7th Int. Cycl. Conf.*, Zurich, 1975.

[7] J.I.M. Botman, M.K. Craddock, C.J. Kost, and J.R. Richardson, "Magnet Sector Design for a 15-GeV Superconducting Cyclotron", IEEE Trans. NS-30, 1983, p. 2007.

[8] M.K. Craddock, "The TRIUMF KAON Factory", in *Proc. IEEE Particle Accelerator Conference*, San Francisco, 1991, p. 57.

[9] R.C. Gupta, J.I.M. Botman, and M.K. Craddock, "High Transition Energy Magnet Lattices", IEEE Trans. NS-32, 1985, p. 2308.

[10] R. Baartman and S. Koscielniak, "Stability of Hollow Beams in Longitudinal Phase Space", in *Proc. Particle Accelerator Conf.*, Vol. 28, 1990, p. 95.

[11] U. Wienands *et al.*, "A Racetrack Lattice for the TRIUMF KAON Factory Booster", in *Proc. HEACC'92*, Hamburg, 1992, p. 1073.

[12] M. Benedikt *et al.*, "The PS Complex as Proton Pre-Injector for the LHC – Design and Implementation Report", CERN 2000-03, Feb. 27, 2000.

[13] D.I. Kaltchev, M.K. Craddock, J.B. Jeanneret, and A. Verdier, "Optics Solutions for the Collimation Insertions of LHC", in *Proc. PAC'99*, New York, 1999; and CERN-LHC-Project-Report-305.

[14] W. Herr, M.P. Zorzano, and F. Jones, "Hybrid fast multipole method applied to beam-beam collisions in the strong-strong regime", *Phys. Rev.* ST Accel. Beams, p. 4, May 2001.

[15] R. Baartman, "Betatron Resonances with Space Charge", *AIP Conference Proceedings,* 448, 1998, p. 56.

[16] C. Johnstone and S. Koscielniak, "New Nonscaling FFAG for Medical Applications", in *Proc. PAC'07*, 2007, p. 2951.

[17] R. Barlow *et al.*, "EMMA – The World's First Non-scaling FFAG", *Nucl. Instr. Meth.*, vol. A624, 2010.

[18] M.K. Craddock and Y.N. Rao, "Cyclotron and FFAG Studies Using Cyclotron Codes", in *Proc. 19th Int. Cycl. Conf.*, Lanzhou, 2010, p. 395.

ISBN 978-3-95450-167-0