

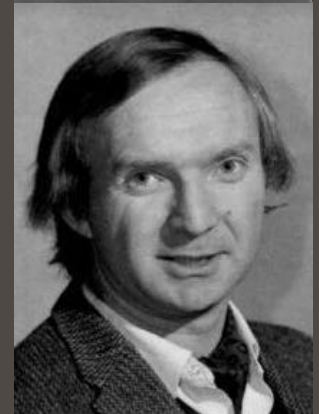
IN MEMORIAM: Michael K. Craddock

Accelerator Beam Physicist, Teacher & Historian

Ewart Blackmore, TRIUMF

Accelerating Science for Canada
Un accélérateur de la démarche scientifique canadienne

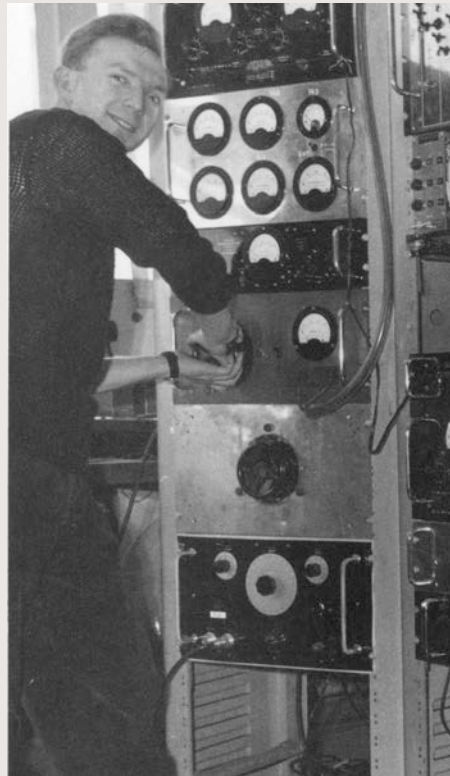
Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada



MKC - Education



Running the PLA



Student at Oxford

Bachelors & Masters in
Mathematics & Physics
from Oxford 1957 & 1961
Christ Church College

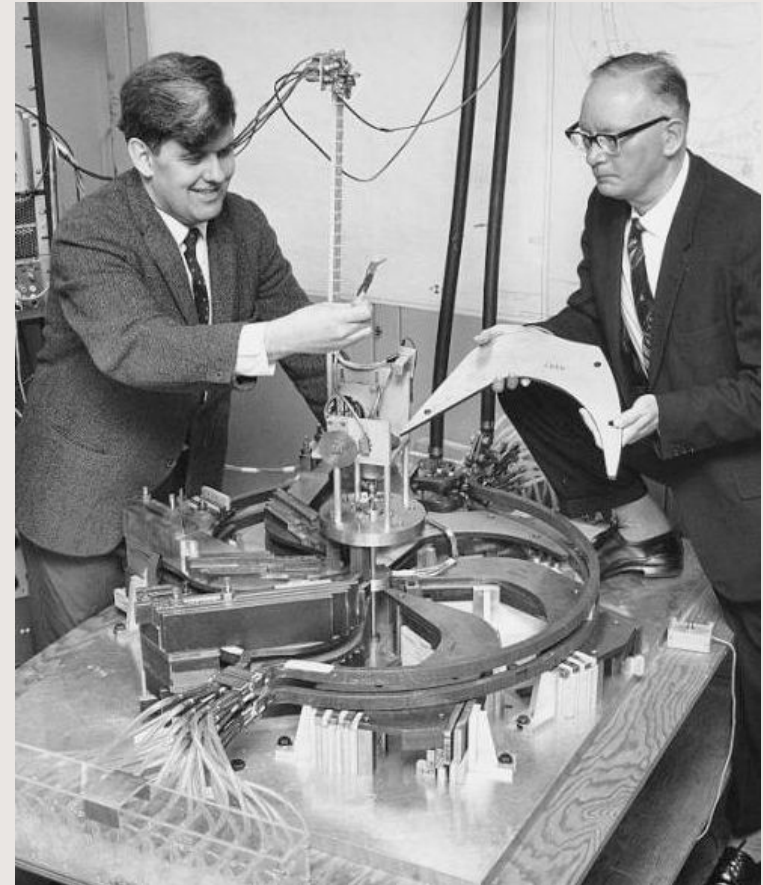
D. Phil. from Oxford 1964
Thesis “The Nuclear
Interactions of High Energy
Particles”
Supervisors D. Roaf, R. Hanna

Scientific Officer at Rutherford
Laboratory working on the
Proton Linear Accelerator PLA

UBC Nuclear Physics Group



**UBC 3 MeV Van de Graaff
built by J.B. Warren 1951**



**Erich Vogt & John Warren
“Founders of TRIUMF”**

Birth of TRIUMF <1966

Sept 1964: Mike Craddock joins UBC Physics

June 1965: CAP meeting in Vancouver, UBC Physics plus representatives from SFU and UVic for meeting on new accelerator plans.

MKC documents agreements reached on TRIUMF (Three Universities Meson Facility).

- Scaled down version of UCLA H- cyclotron.
- Preliminary proposal by March 1966 to be coordinated by Erich Vogt (John Warren going on sabbatical at RHEL).
- Craddock to look after cyclotron design.
- Consider Joop Burgerjon (UofM) as cyclotron engineer.
- Plan visit to Reg Richardson, Ken MacKenzie at UCLA
 - carried out in Dec 1965 to loan 1:20 scale model of magnet
- Proposal completed Nov 1966, approved for funding in 1968

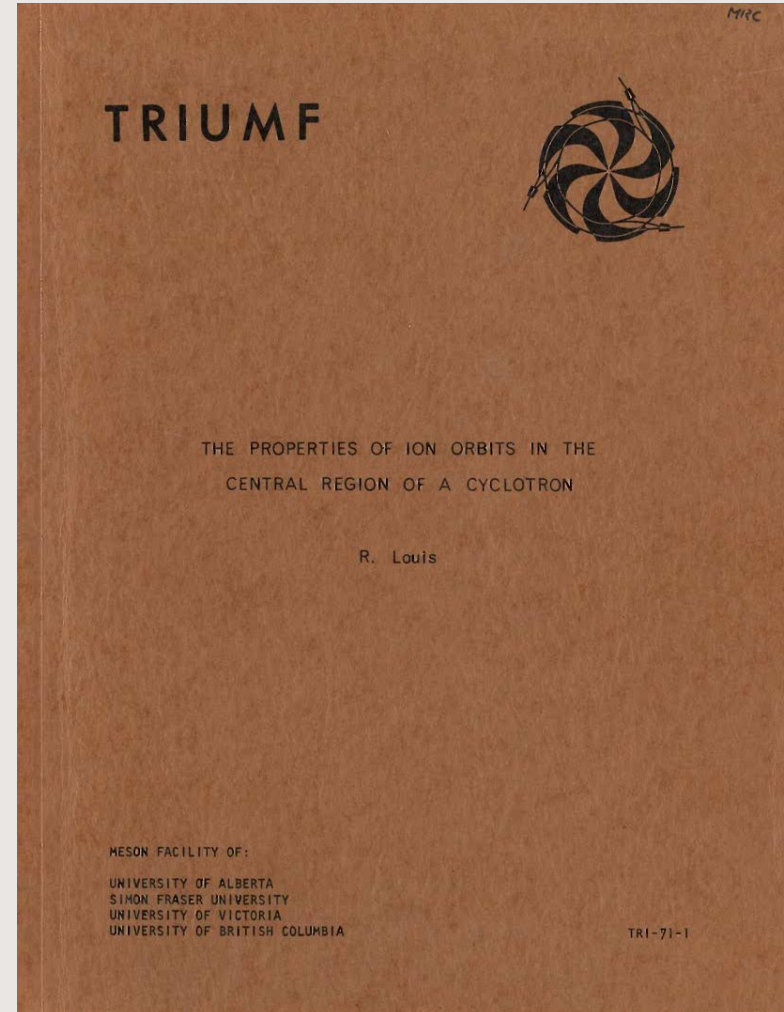
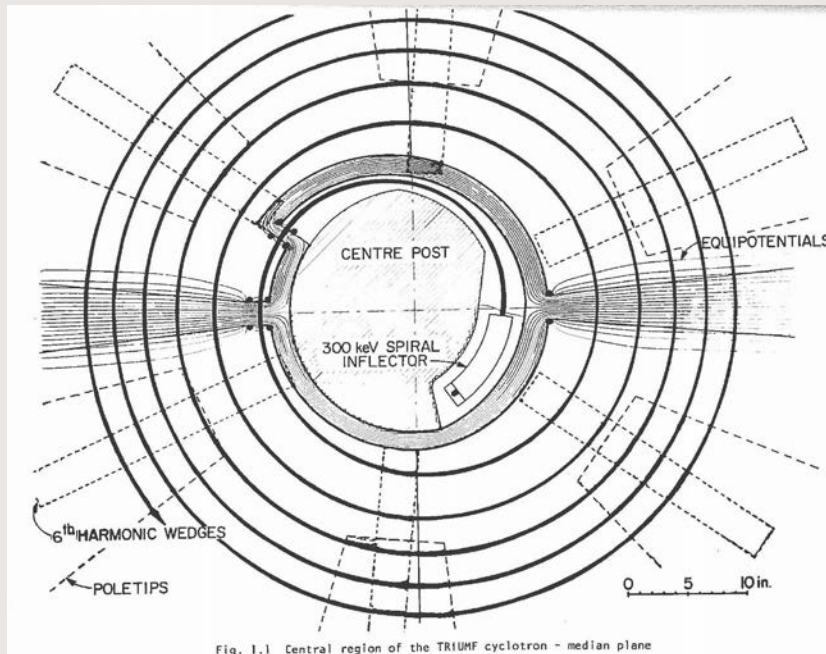
Competing Proposals 1966

TABLE 3.1 - Comparison of Meson Factories and Workshops

	H ⁻ Cyclotron		Ring Cyclotron	Linac	
	TRIUMF 1966	UCLA 1964	ETH Zurich	Los Alamos	ING ⁺
Energy (MeV)	500	600	510	800	975 MeV
Energy Variable (MeV)	200-500	200-600	No	200-800 (in steps)	(in 2.63 MeV steps)
Energy Resolution (Full Width)	0.3%	0.3%	0.4%	0.4%	-
Duty Factor Macrostructure	100%	100%	100%	6-12%	100%
Average Current (mA)	0.1**	0.2*	0.08	1.2	65
Beam Emittance (cm mr)	0.2	0.2	≲ 3	1	-
Average RF Power (MW)	0.83	1.3	0.24	6.1	90
Overall Size of Accelerator (ft)	56 diam.	70 diam.	43 diam.	2600 long	4940 long
Polarized Protons*** per second	1.2x10 ¹¹	1.2x10 ¹¹		2.4x10 ¹⁰	
Simultaneous Multiple Beams	Yes	Yes	No	No	No
Cost of Accelerator ⁺⁺ (Millions of dollars)	6.3	7.7	7.6	21.6	
Cost of project ⁺⁺	16.7	23.2	22.9	59.4	110

Beam Dynamics Calculations (1)

Robin Louis: First UBC/TRIUMF PhD
 Supervised by MKC 1968-1971
Properties of Orbits in the Centre Region of a Cyclotron
 Axial and radial focusing: electric and magnetic fields, space charge



Beam Dynamics Calculations (2)

Laurence Root 1969-1974

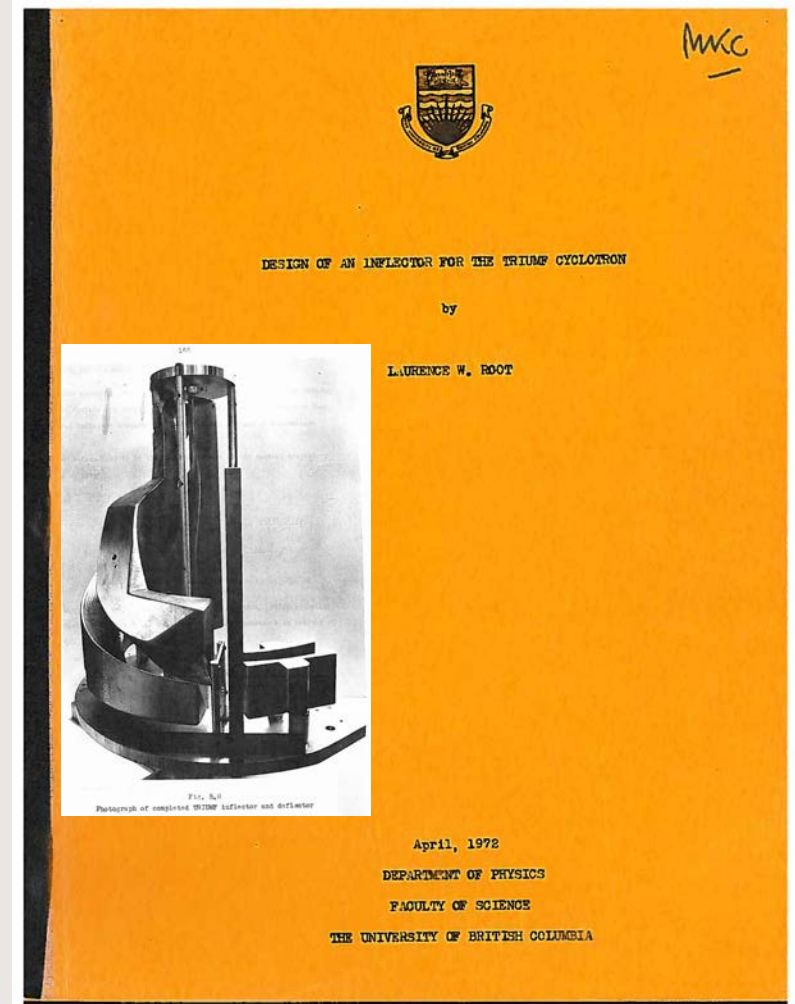
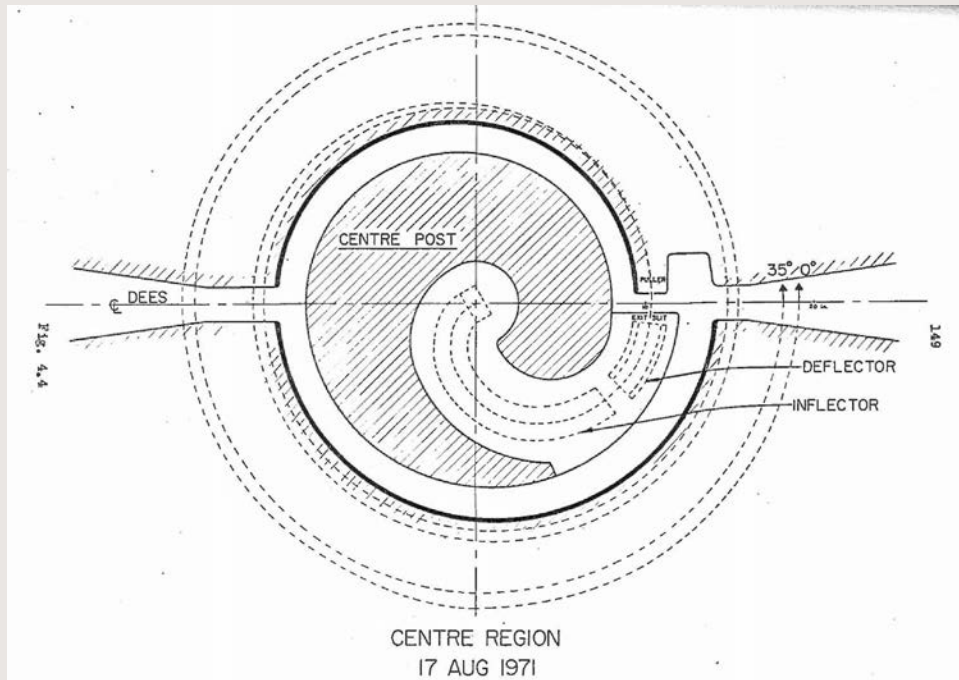
Supervised by MKC and EWB

Design of an Inflector for the TRIUMF

Cyclotron MSc 1972

Experimental & Theoretical Studies of H-

in Centre Region PhD 1974



TRIUMF Cyclotron

- 500 MeV, 100 μ A, H⁻ ions
- simultaneous extraction 2 beams
- cost \$8.4M in 1968

(1972) TRIUMF(110) UBC

Chief Eng'r Joop Burgerjon

Magnet: Al Otter Ed Auld

Beam George Mackenzie Mike Craddock

Dynamics: Gerardo Dutto
Corrie Kost

RF: Roger Poirier Karl Erdman
Milos Zach

Vacuum: Dennis Healey Dave Axen

ISIS: Peter Bosman Bruce White

Probes: Bruno Duelli (EWB)

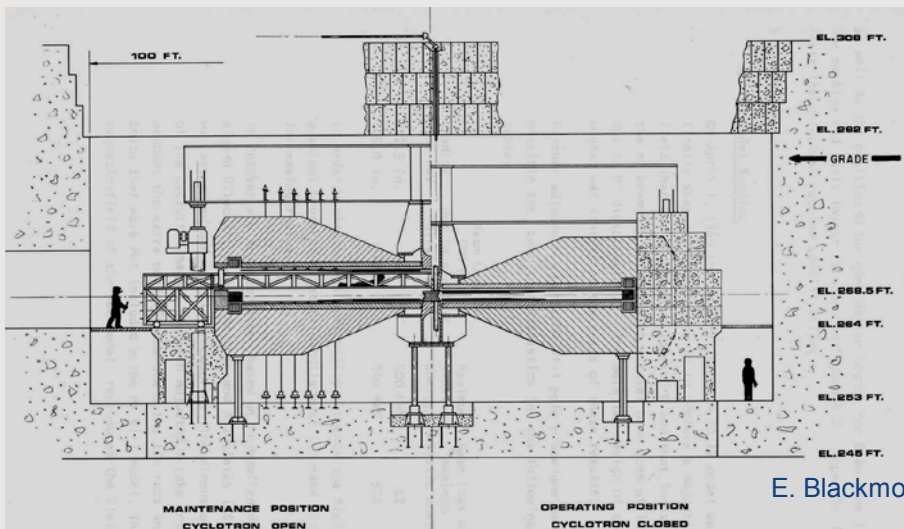
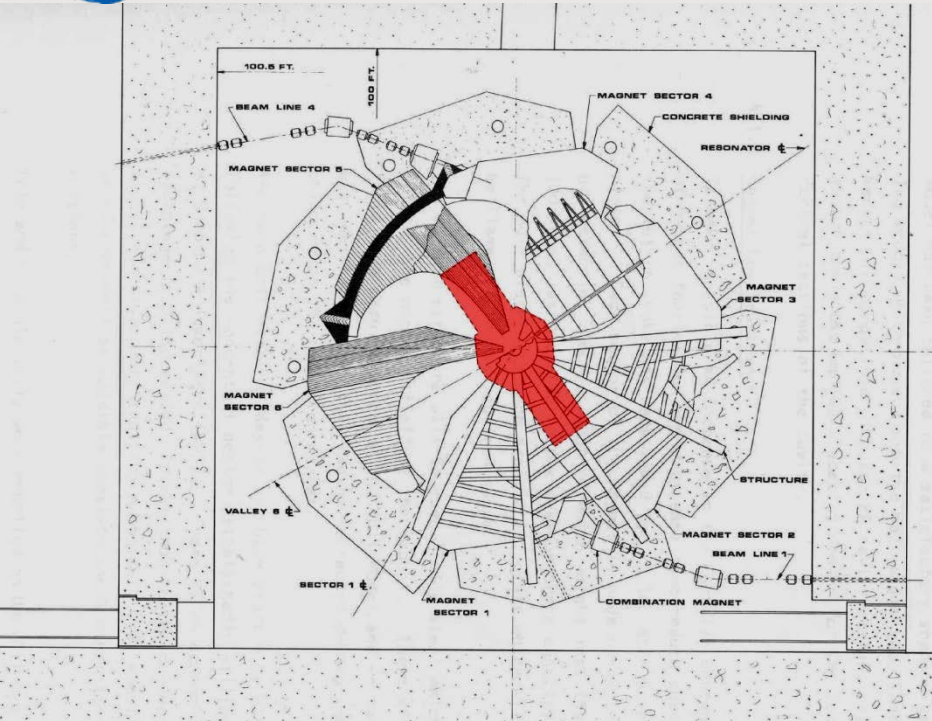
Controls: Don Heywood Dick Johnson

Dave Gurd Ken Dawson (UofA)

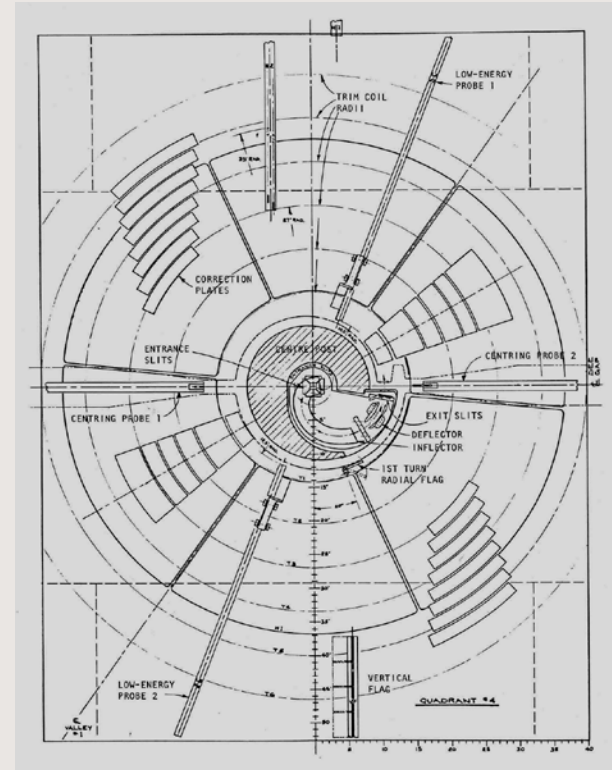
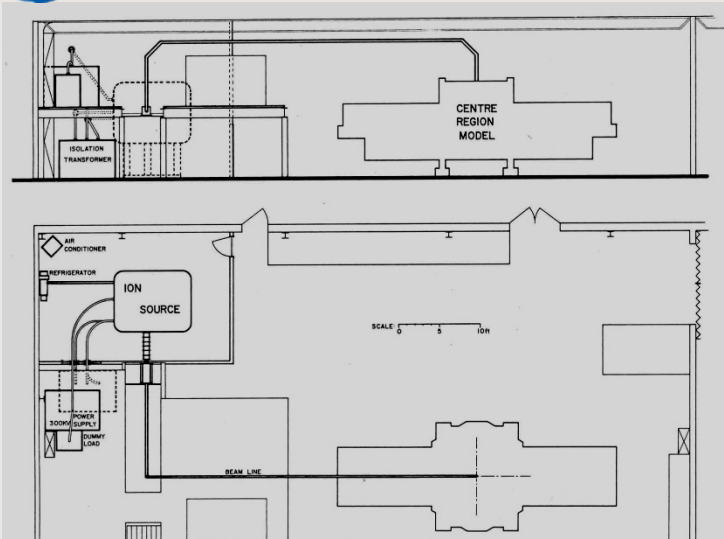
Safety: Ian Thorson Brian Pate (SFU)

Gary Wait

CRC: Ewart Blackmore



- 80 ton magnet
- 8 resonators with flux guides
- 300 keV ion source 0.5 mA
- 3 MeV in 6.5 turns, 100 μ A



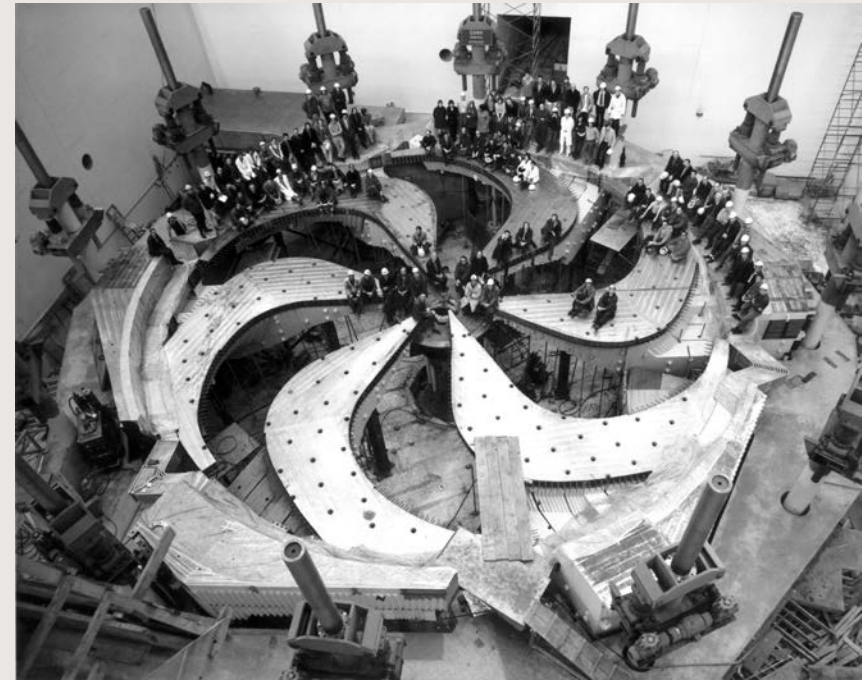
Centre Region Layout



1971-1973

Magnet

- fabrication and assembly went well (1972)
- 4000 tons of steel in 50 ton shipments
- first field maps-centre field too high by 100 g
- difference in steel permeability 0.5" vs 5"
- required gouging out 16 tons of steel
- field tolerance of 1 g required (1 in 4000)
- MKC & BD group responsible for daily shim prediction
- took ~ 9 months of shimming/measurements



Field mapping
using flip coils

The Commissioning Team



**First 500 MeV beam Dec 1974
35th Anniversary of First Beam**

MKC Scientific & Accelerator Contributions

- ❑ Head of Beam Dynamics-Accelerator Research Group at TRIUMF until retirement in 2001.
- ❑ Cyclotrons > Larger cyclotrons > Synchrotrons > FFAGs
- ❑ Prolific and exceptional writer, teacher, historian, world traveller and accelerator conference participant.
- ❑ Author or Co-author of > 112 papers, 14 graduate students with gave many invited talks.
- ❑ Chair of Cycl'1992, PAC 1985, 1997 and Intl.Org.Comm.
- ❑ Canadian contributor to CERN Courier for 29 years
- ❑ Final Contribution: *“Accelerator Science and Technology in Canada from the Microtron to TRIUMF, Superconducting Cyclotrons and the Canadian Light Source”*. Published in Rev. Accel. Sci. & Tech. 2015. with R. Laxdal.

Some Publications by M. K. Craddock

Particle Accelerator Conference (March 1975) Washington, DC

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*”.

8th International Cyclotron Conference (1978) Bloomington

E.W. Blackmore, M.K. Craddock, G. Dutto, C.J. Kost, G.H. Mackenzie, P.W. Schmor: *Measurements and Corrections to the Beam Properties in the TRIUMF Cyclotron*”

M.K. Craddock, C.J. Kost, J.R. Richardson: *A Ring Cyclotron KAON Factory.*

Particle Accelerator Conference (May 1991) San Francisco, CA

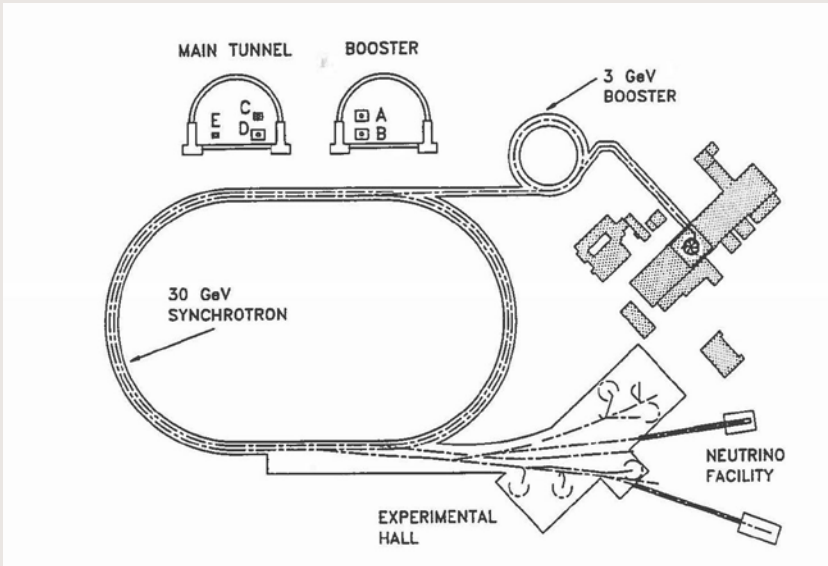
M.K. Craddock: *The TRIUMF KAON Factory.*

19th International Cyclotron Conference (2010) Lanzhou

M.K. Craddock *Eighty Years of Cyclotrons.*

M.K.Craddock, Y.N. Rao: *Cyclotron and FFAG Studies using Cyclotron Codes*

The KAON Factory (1978-1994)



KAON: kaons, antiprotons, other particles, neutrinos

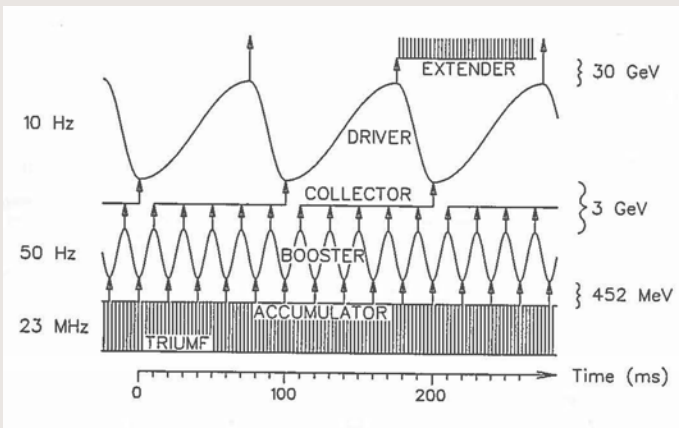
A Accumulator

B Booster

C Collector

D Driver

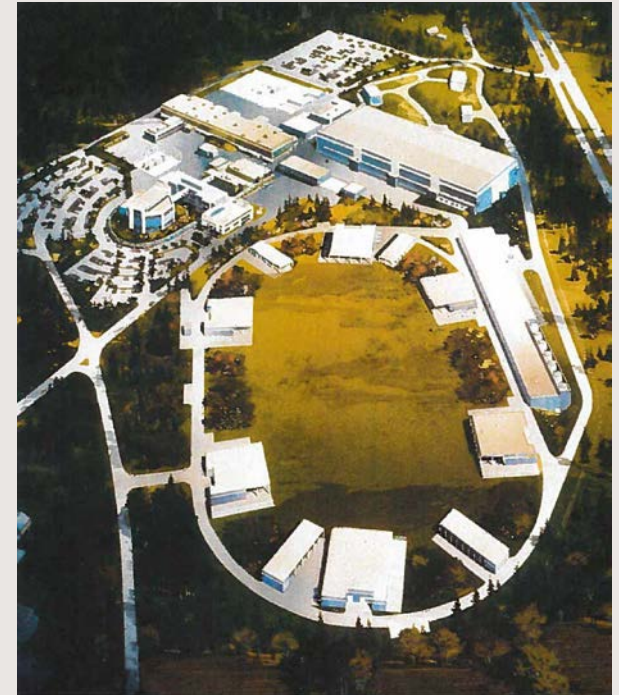
E Extender



Project Definition Study 1989-92
Design, Prototyping, Costing

Funding: 1/3 BC, 1/3 Canada,
1/3 international (HERA Model)

Kaon Factory International Participation



Cancelled 1994 by
Canadian gov't
J-PARC became the
KAON Factory



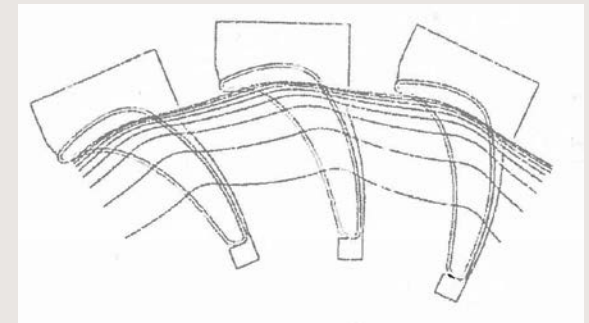
KAON Factory Design Benefits to TRIUMF

Beam Dynamics

- Cyclotron sector magnets with reverse bends (FFAG)
- Separate function lattices with high transition energy
- High intensity effects – instabilities, space charge and collective effects.

Technical

- Laminated synchrotron magnets
- Pulsed power supplies
- Radiofrequency systems
- Kicker systems
- Beam instrumentation
- Canadian industry capabilities



3.5 GeV cyclotron magnet sector with gullies

Canadian Contributions to the LHC (1995-2005)

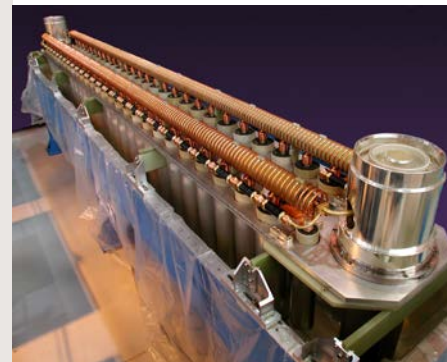
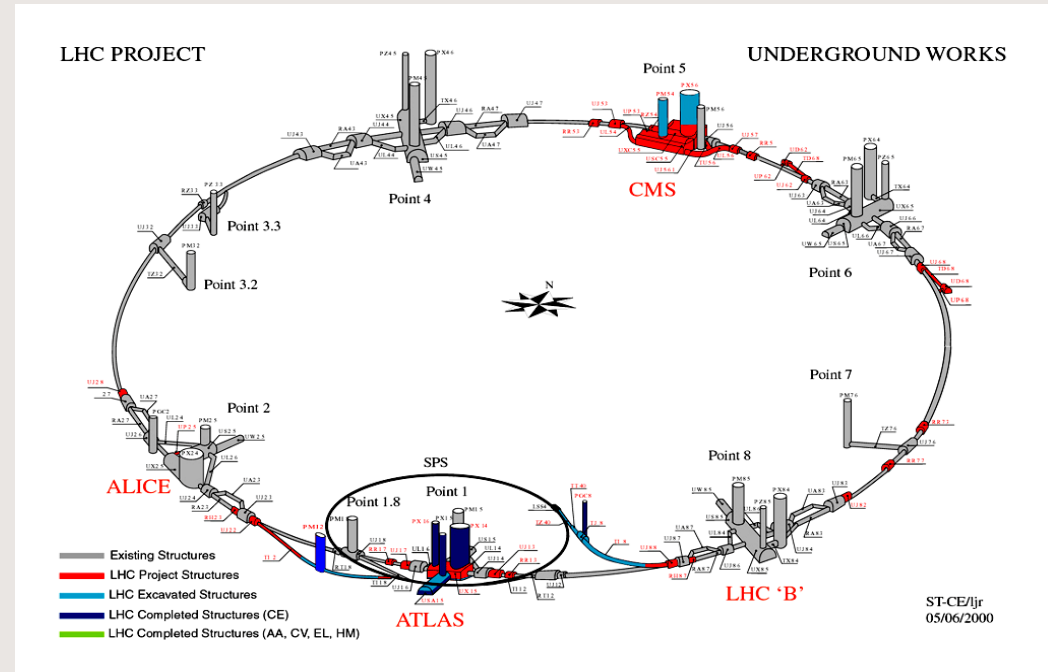
1995-2005 - \$41.5M

- PS conversion project – booster upgrade
- 52 warm magnets – beam collimation
- LHC kicker components
- beam instrumentation

Beam Dynamics

Craddock, Baartman, Koscielniak, Kaltchev, Jones

- Injection & high intensity operation of the PS injector complex
- Cleaning insertions for beam collimation in LHC



FFAG Accelerators & EMMA (2003-2015)

Craddock & Koscielniak

Non-Scaling FFAGs

Hard-edge approximations
and use of cyclotron codes
for tracking

Contributions to FFAG

Workshops and Schools

Contributions to the EMMA
electron FFAG model.

Michael Craddock

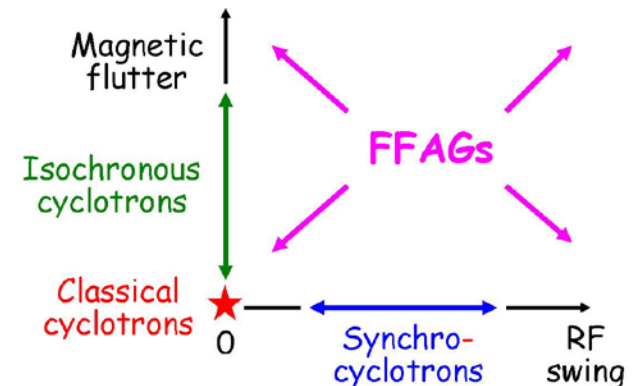
- Beam physicist
- Teacher/mentor
- Historian

FFAGs - Fixed Field Alternating Gradient accelerators

Fixed Magnetic Field - members of the **CYCLOTRON** family¹

Magnetic field variation $B(\theta)$	Fixed Frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Isochronous	FFAG

But FFAG enthusiasts sometimes express an alternative view:
- cyclotrons are just special cases of the FFAG!



1. E.M. McMillan, *Particle Accelerators*, in *Experimental Nuclear Physics*, III, 639-786 (1959)

Presented at FFAG School, Daresbury , 2011

Special Thanks to:

Michael Craddock for a well organized office and chronological history of his career – and for his many contributions to TRIUMF.

Rick Baartman, Shane Koscieleniak, Fred Jones, Bob Laxdal and Iouri Bylinsky for valuable input.