John Stuart Foster and Canada's First Cyclotron

CAP Congress – Halifax 2018

David Hanna

McGill University

Sources and Acknowledgements

John Stuart Foster, 1890 - 1964
R.E. Bell - Biogr. Mems. Fell. R. Soc. 12, pp 147-161, 1966

John Stuart Foster, McGill University, and the
Renascence of Nuclear Physics in Montreal, 1935-1950
J. Thomas – Historical Studies in the Physical Sciences 14, pp 357-377, 1984

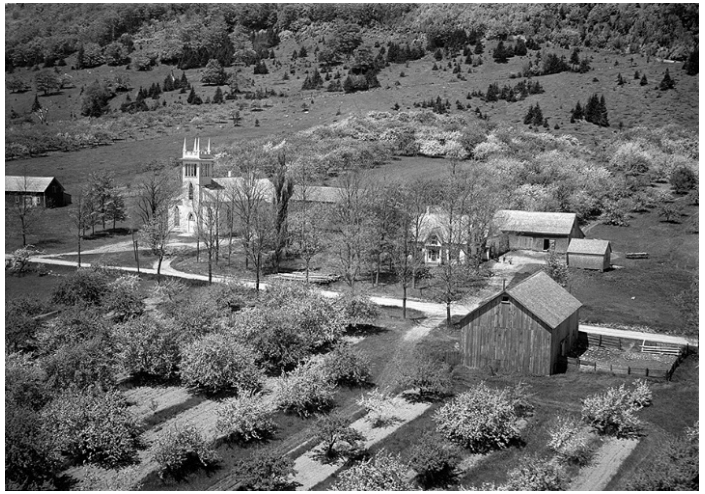
The Physics Department of McGill University: A Brief History 1889 - 1939
M. Cohen - unpublished

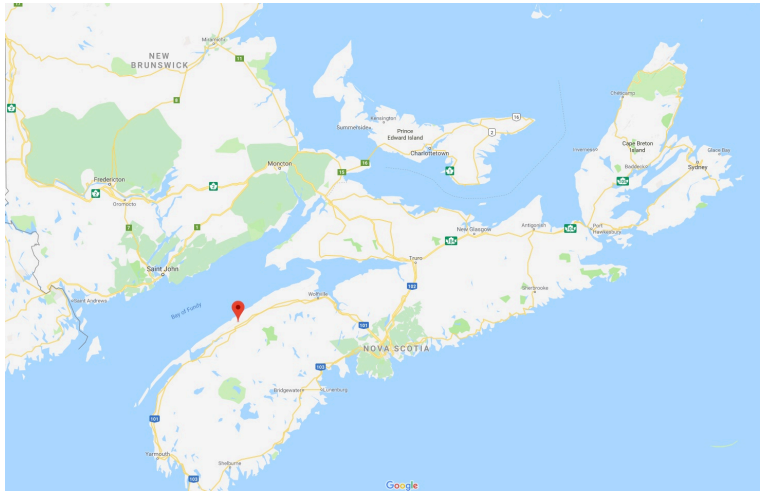
John Crawford, emeritus professor, McGill University Physics Department

Jean Barrette, emeritus professor, McGill University Physics Department

John Stuart Foster (1890 -1964)

born 1890/05/30 in Clarence, NS





attended Pictou Academy, Acadia,
and Mount Allison Universities
(graduated 1914)

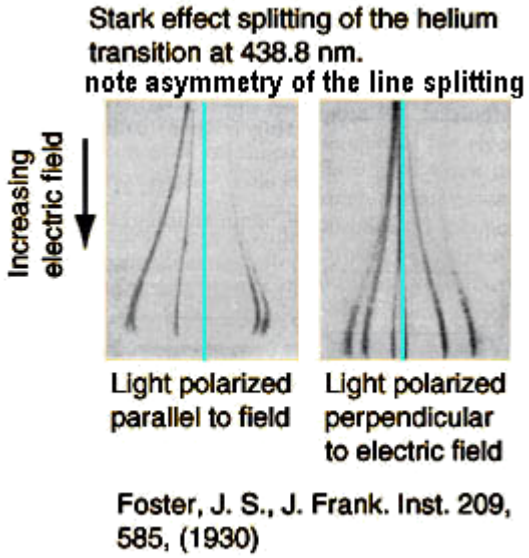
spent (latter part of ?) WW I in USA
(Fort Monmouth, NJ – US Army signals corps)

awarded one of the newly-established (US) National Research Fellowships

PhD studies at Yale 1920 – 1924

thesis:
Stark-effect spectroscopy in hydrogen and helium

fellow student:
Ernest Lawrence – later inventor of the cyclotron



Foster, J. S., J. Frank. Inst. 209, 585, (1930)

E.O. Lawrence at Yale

Assistant Professor at McGill (1924)

he joined

Arthur Eve	- chair
Louis King	- radio engineering
Norman Shaw	- thermodynamics
Alice Vibert Douglas	- astronomy
David Keys	- electrical properties of matter

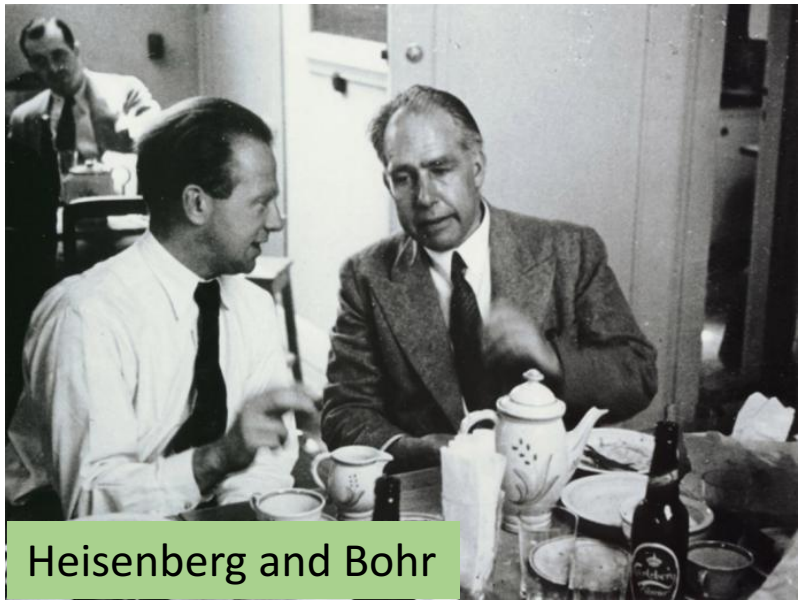
Foster was the first professor who had not come via some kind of Cambridge connection

He was also the most modern – the Stark effect is very much a quantum phenomenon

The effect of Rutherford at McGill had pretty much decayed away – no serious nuclear physics was being done

Institute for Theoretical Physics in Copenhagen (1926-27)

- published his most important work (Stark – related)
- obtained the admiration and respect of Bohr and Heisenberg
- came to appreciate the direct, simple, intuitive approach to theory and experiment



Heisenberg and Bohr

Application of Quantum Mechanics to the Stark Effect in Helium.

By J. Stuart Foster, Ph.D., Assistant Professor of Physics, McGill University; Fellow of the International Education Board (in Copenhagen).

(Communicated by N. Bohr, For. Mem. R.S.—Received August 8, 1927.)

[Plates 6–13.]

Introduction.—Many interesting features of the Stark-effect may be seen with unusual clearness in the arc spectra of helium, and these we shall mention very briefly before referring to the theory.

35 pages of text and diagrams.....

In conclusion, the writer wishes to express his best thanks to Prof. Bohr for his interest in this work, the major part of which was done in Copenhagen. His thanks are also extended to Dr. Heisenberg for many helpful and friendly discussions.

Accomplishments and Honours

1929 - Fellow of the Royal Society of Canada

1930 - Sterling Fellow of Yale

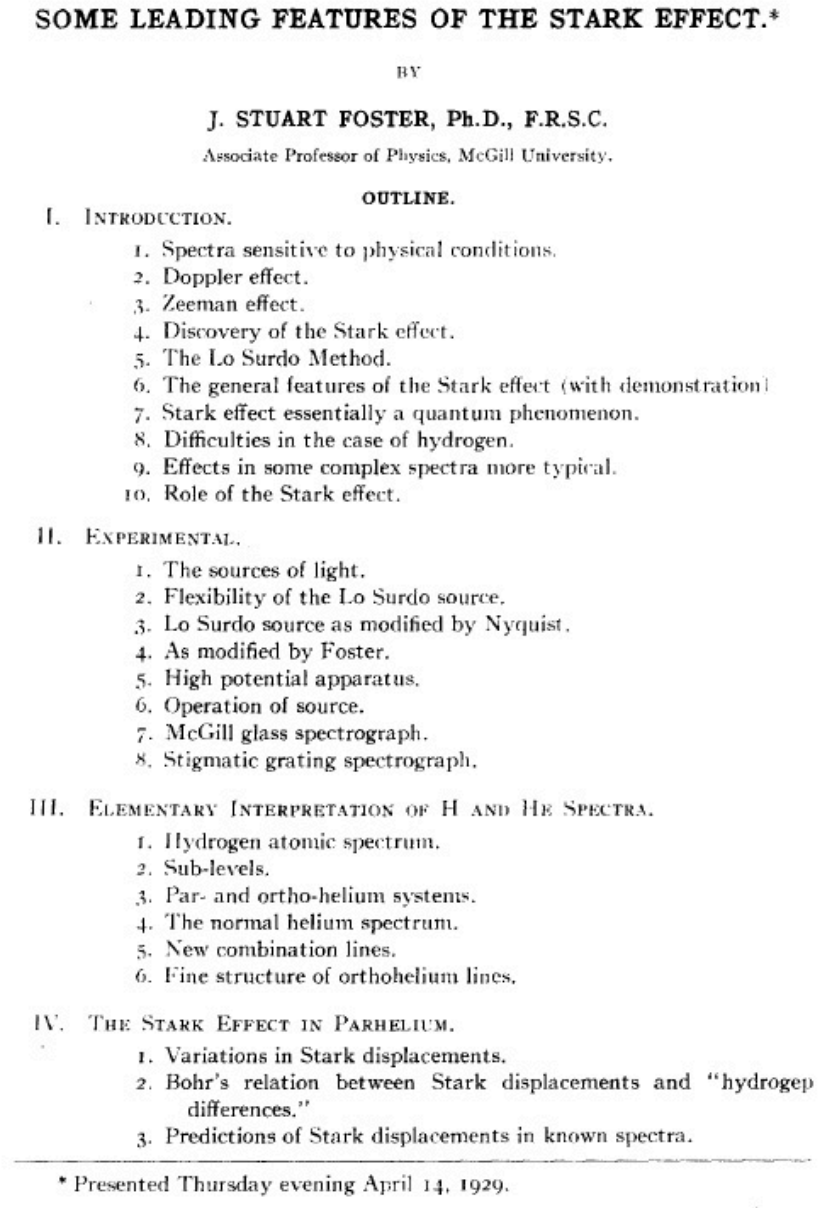
1935 - Fellow of the Royal Society of London

1935 – Macdonald Professor of Physics at McGill

25 graduate students wrote theses on the Stark effect but by the end of the 1920s it was getting to be a ‘mature’ science

Foster had reached the point where university administrators knew him and wanted to keep him

"As far as I could learn abroad Dr. Foster's work has created much favourable comment and he is rapidly winning for himself a splendid place in the world of Physics. Undoubtedly, he will go far and I am most anxious to keep him at McGill.” – Principal Arthur Currie



SOME LEADING FEATURES OF THE STARK EFFECT.*

BY

J. STUART FOSTER, Ph.D., F.R.S.C.

Associate Professor of Physics, McGill University.

OUTLINE.

I. INTRODUCTION.
1. Spectra sensitive to physical conditions.
2. Doppler effect.
3. Zeeman effect.
4. Discovery of the Stark effect.
5. The Lo Surdo Method.
6. The general features of the Stark effect (with demonstration)
7. Stark effect essentially a quantum phenomenon.
8. Difficulties in the case of hydrogen.
9. Effects in some complex spectra more typical.
10. Role of the Stark effect.

II. EXPERIMENTAL.
1. The sources of light.
2. Flexibility of the Lo Surdo source.
3. Lo Surdo source as modified by Nyquist.
4. As modified by Foster.
5. High potential apparatus.
6. Operation of source.
7. McGill glass spectrograph.
8. Stigmatic grating spectrograph.

III. ELEMENTARY INTERPRETATION OF H AND He SPECTRA.
1. Hydrogen atomic spectrum.
2. Sub-levels.
3. Par- and ortho-helium systems.
4. The normal helium spectrum.
5. New combination lines.
6. Fine structure of orthohelium lines.

IV. THE STARK EFFECT IN PARHELIUM.
1. Variations in Stark displacements.
2. Bohr's relation between Stark displacements and "hydrogen differences."
3. Predictions of Stark displacements in known spectra.

* Presented Thursday evening April 14, 1929.

Journal of the Franklin Institute (1930) - 45 pages

Particle Accelerators

nuclear physics was limited by the energies of naturally-occuring high-energy particles (e.g. alpha particles from radium)

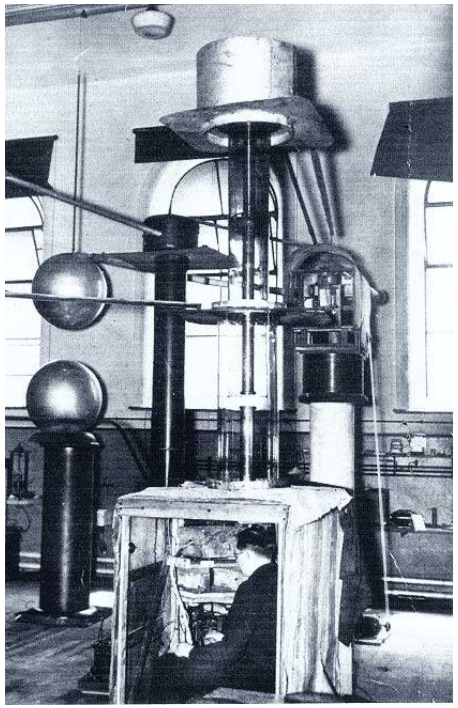
people were trying to devise ways to accelerate particles like protons *artificially*

three classes

- electrostatic
  - Van de Graaff - 1929
  - Cockcroft-Walton - 1932

- induction
  - Betatron – 1935

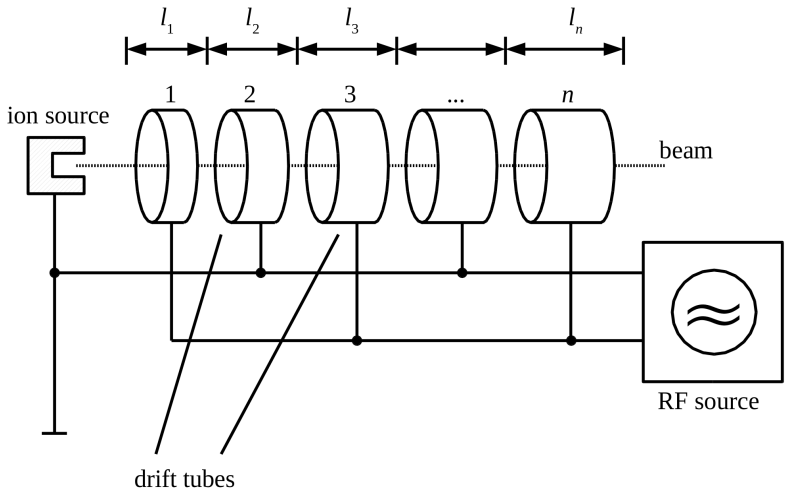
- radiofrequency
  - Drift-tube (Wideroe) Linac - 1928
  - Cyclotron – 1931



Cyclotrons

the idea is to exploit a natural resonance to give the accelerated proton a series of small kicks – two for each circular orbit in the magnetic field

$$v = \frac{qBR}{m} \qquad E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$



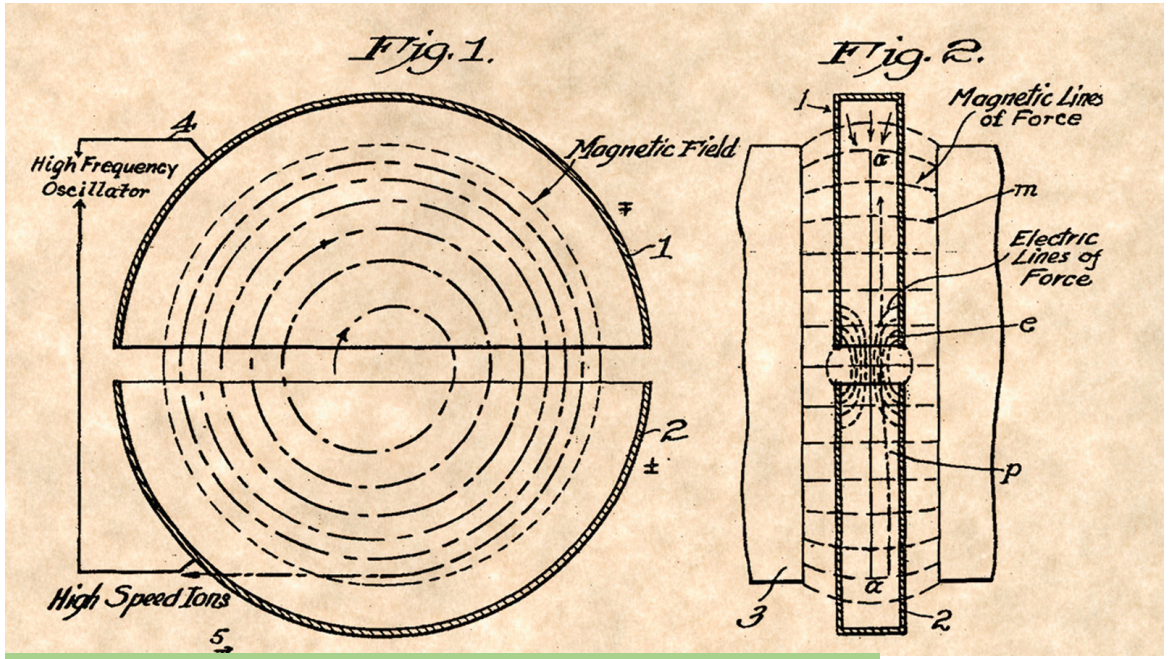
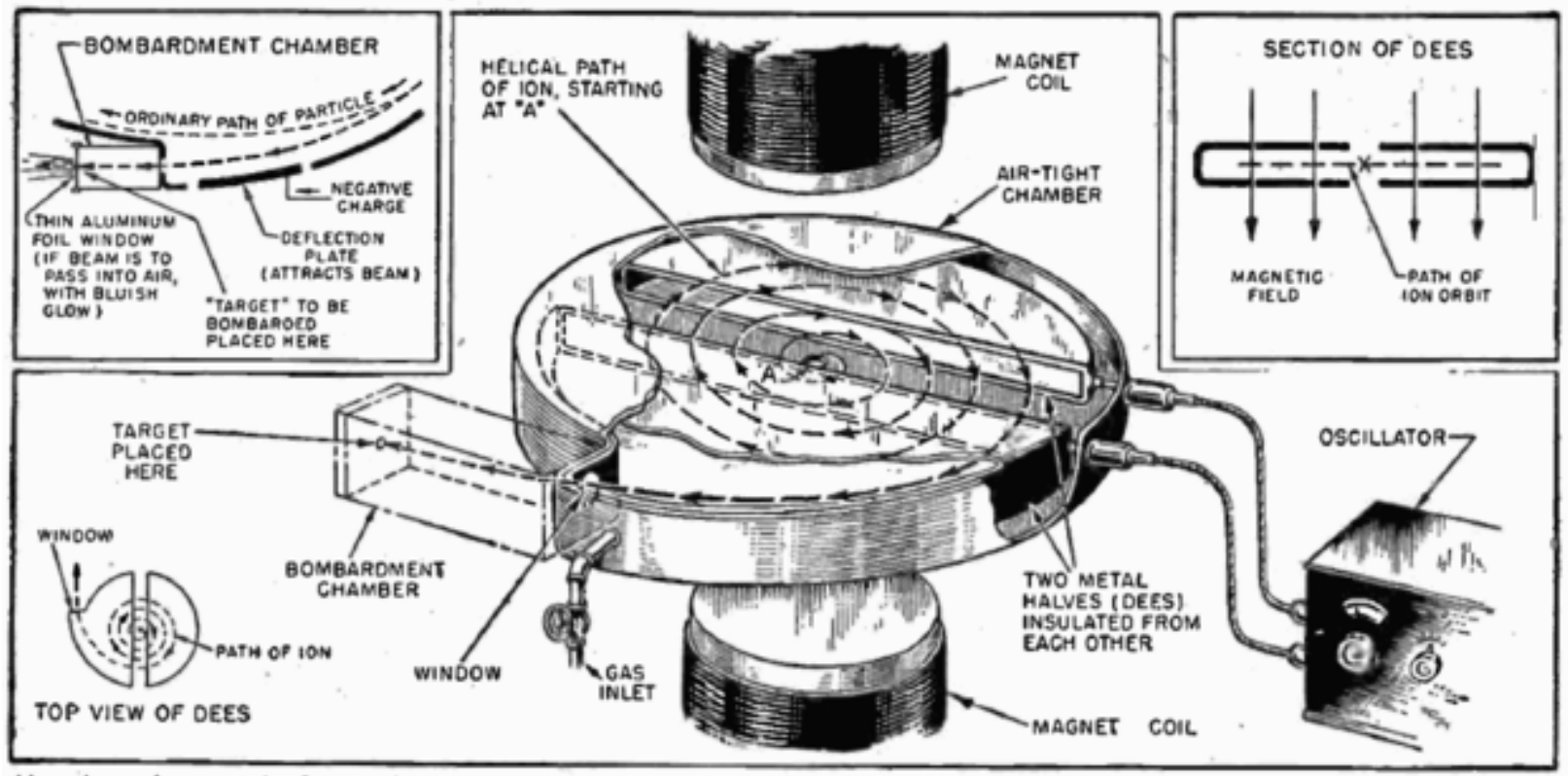


Diagram from the original patent application (1932)

inspiration came from Wideroe's drift-tube linac

Lawrence's genius was to see that bending in a B field would allow one to coil up a very long accelerator

Cyclotron principle

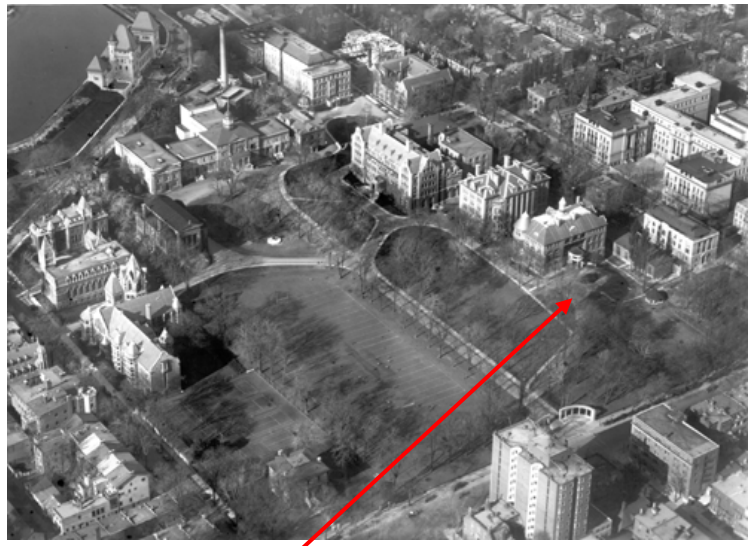


Cyclotron evolution

1931 – 4.5 inch – 80 keV protons

1934 – 27 inch – 1.6 MeV protons

Cyclotron proposal

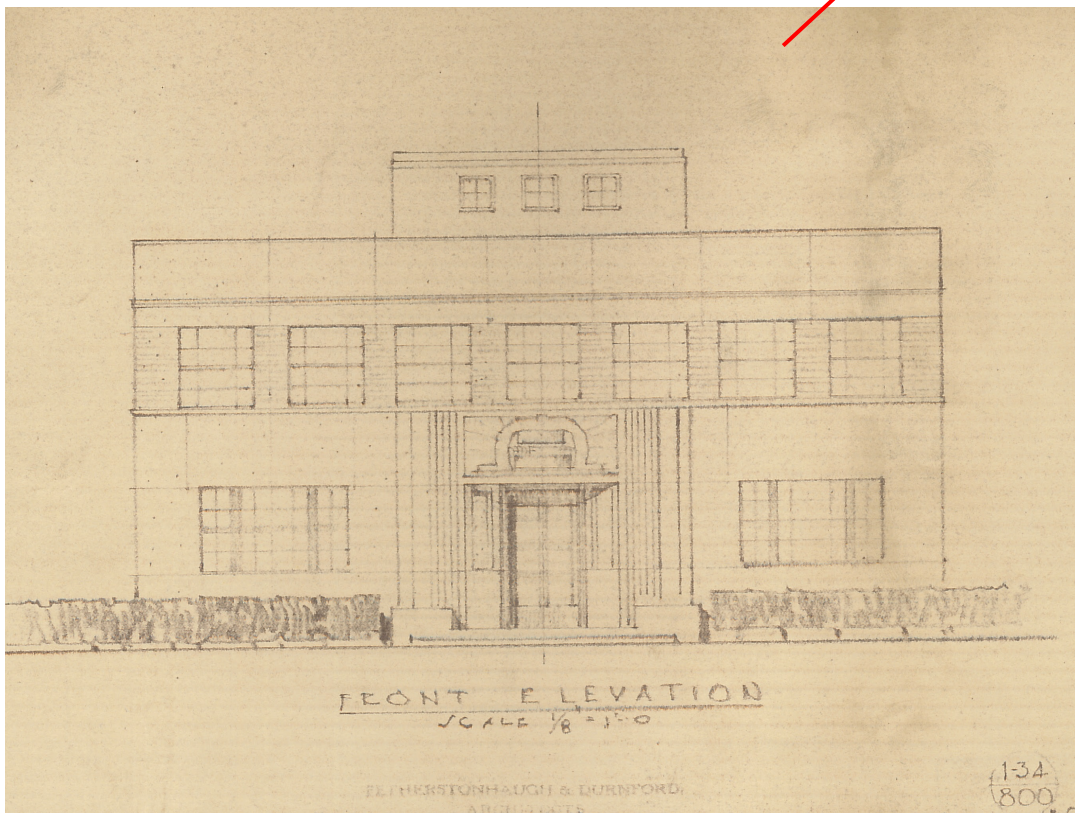


- idea first broached by Foster in the fall of 1933

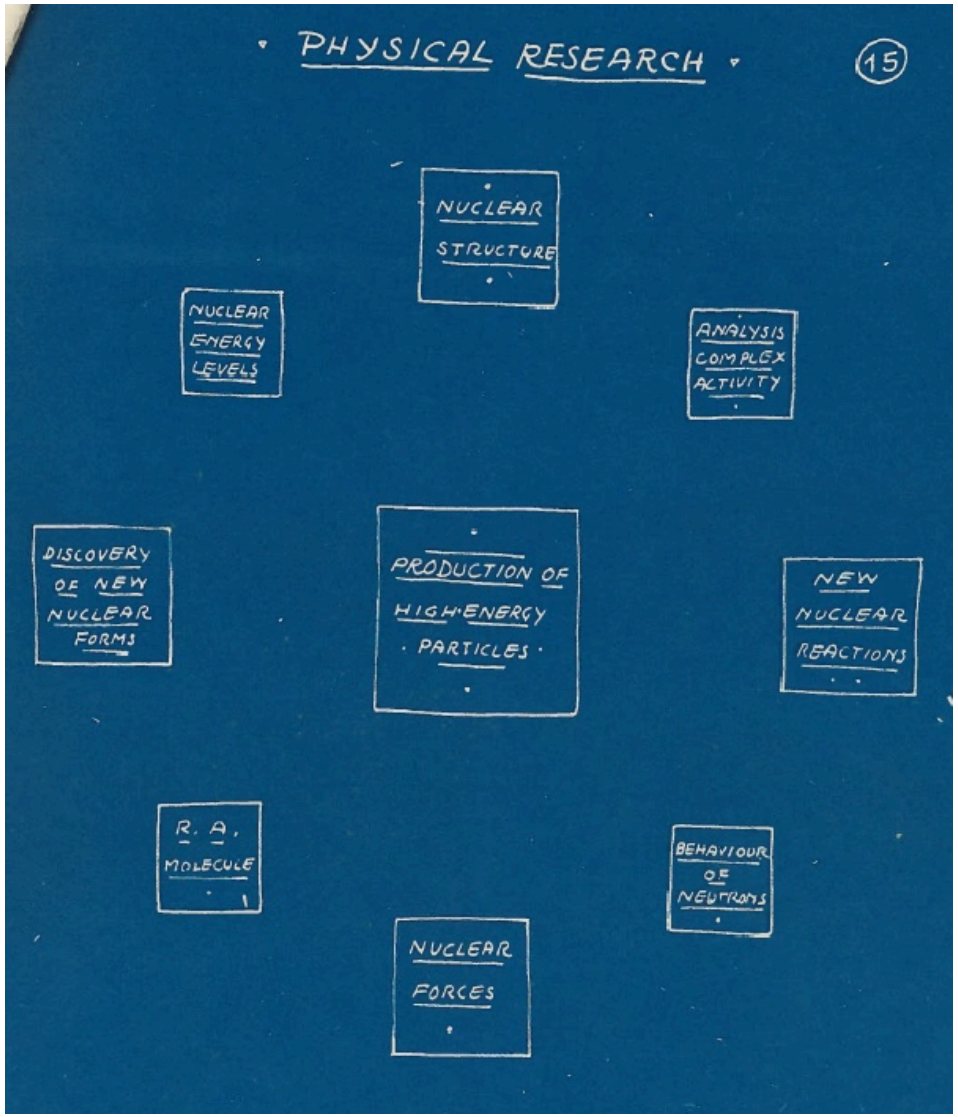
- Robert Thornton (PhD 1933) dispatched to Berkeley on a Moyse Travelling Fellowship
  - McGill was biggest single contributor of guest manpower to the Rad Lab for some time afterwards
  - Arthur V Snell was in the same cohort

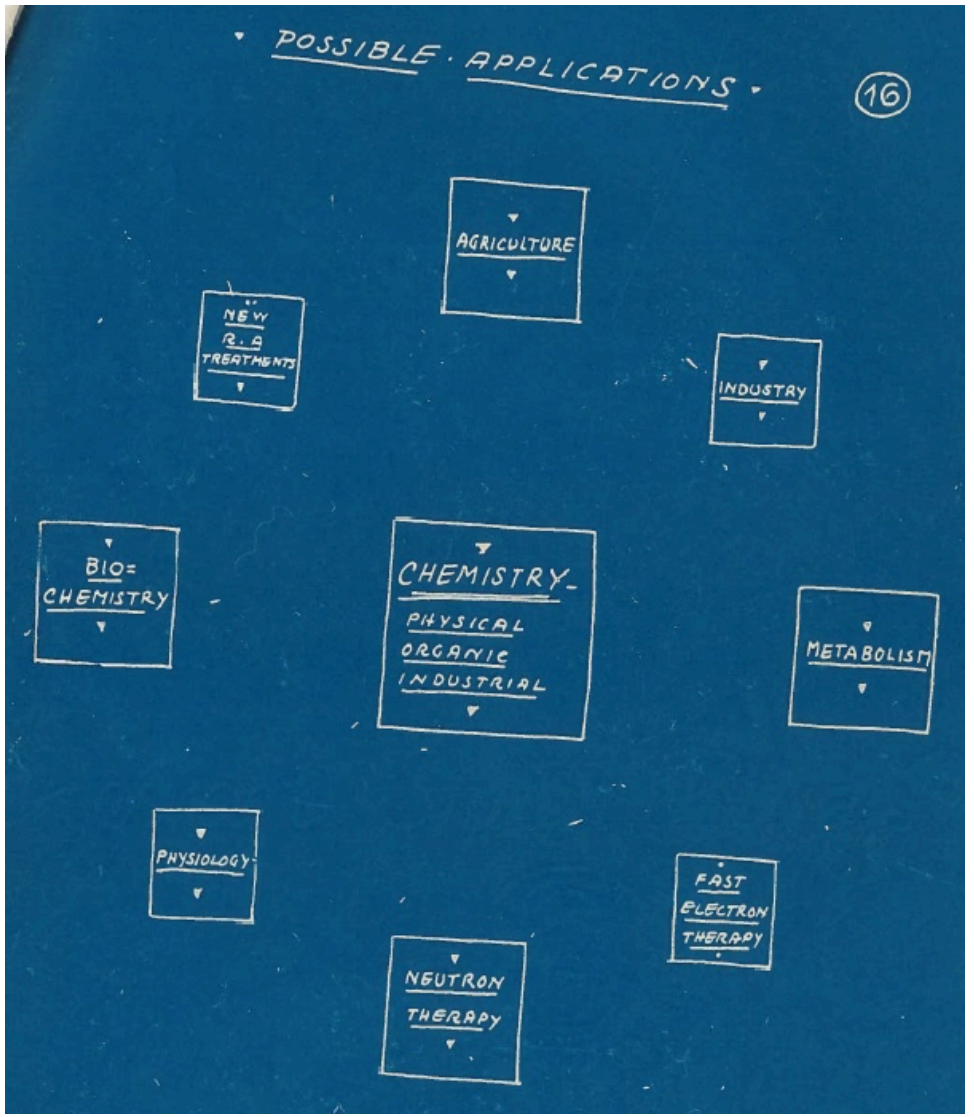
- presentation to McGill board of governors in December 1936
  - enthusiastic response

- proposal submitted to board November 1937
  - 15 MeV
  - $30.3 k equipment ← wrong emphasis?
  - $63.0 k building
  - emphasis placed on preventing a “brain-drain”
  - multidisciplinary use also – see next slide



Cyclotron proposal





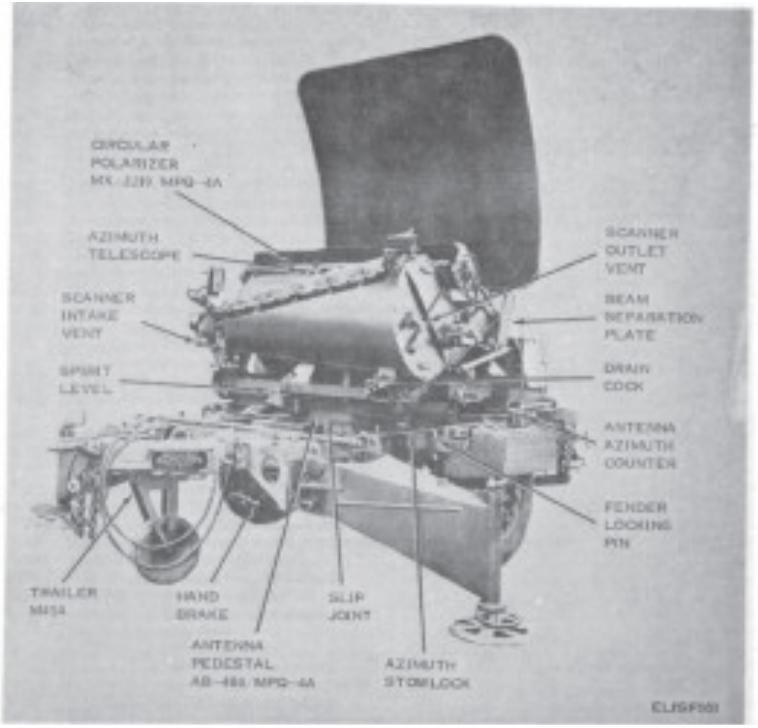
Cyclotron proposal

- board approved spending $100k from university general funds
  - almost immediately back-pedalling started
  - March 1938 – recommend getting funds from 3 or 4 private donors
- planning and preparations (and financial waffling) went on until summer 1939
  - NIMBY-ism concerning the location (biologists)
  - architectural progress was slow due to technical nature of the building
  - technical plans promised by Lawrence were not supplied (they did not exist)
  - cost reviews by new principal
  - etc
- meanwhile events were unfolding in Europe .....

World War II

- in September, 1939 the cyclotron was immediately put on hold
  - principal of McGill asked General MacNaughton (NRC president) if it had military value
  - MacNaughton supported the cyclotron but could not think of any military applications
  - decision to reconsider after the war

- Foster stayed at McGill doing radar work but soon (1941) headed to MIT where the real action was (and double the salary)
  - other members of the microwave antenna group included Alvarez, Purcell, and Dicke
  - Foster used his experience with optics to invent the “Foster Scanner” (capable of tracking a single bullet for 3 km)
  - he was awarded the US Medal of Freedom for his contributions



- While at MIT he returned to Montreal every two weeks to see family and deliver lectures at McGill (and smuggle radar components)

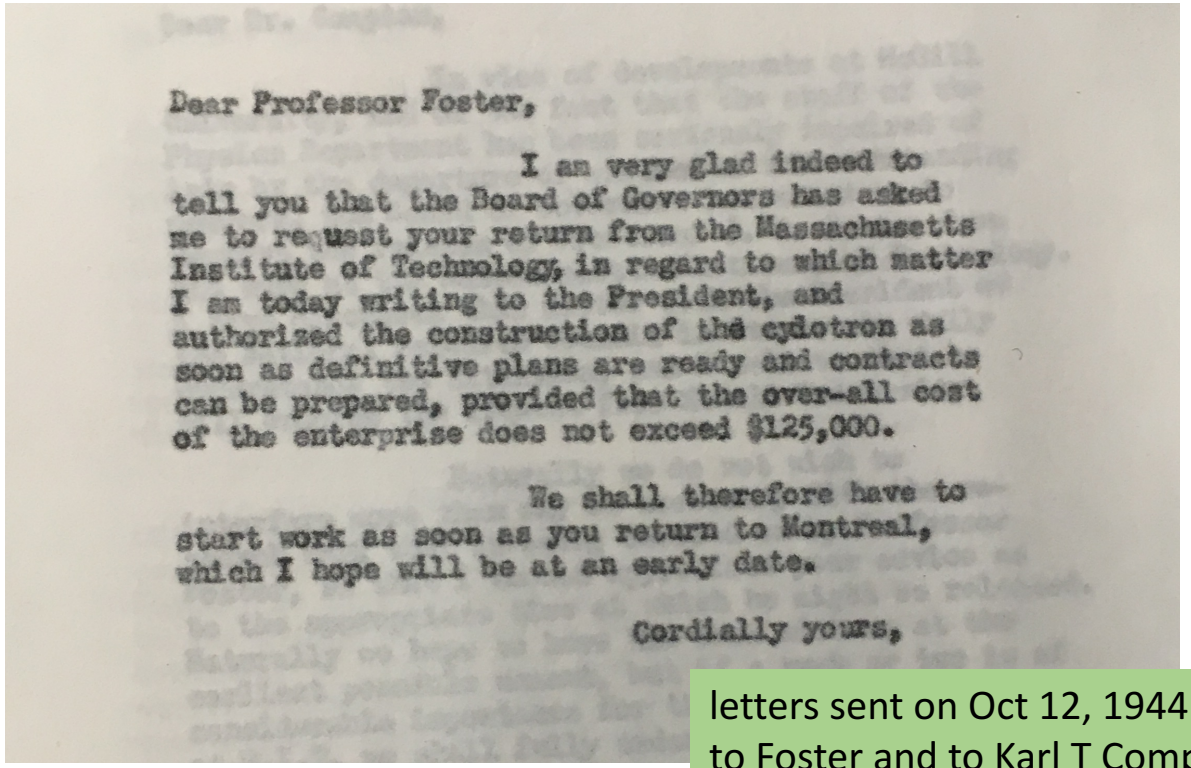
World War II – return from MIT

by 1944 McGill was desperate to get Foster back

- three faculty had retired

- students were in the army or doing graduate work elsewhere

- private money was flowing into McGill (thanks to J.W. McConnell)

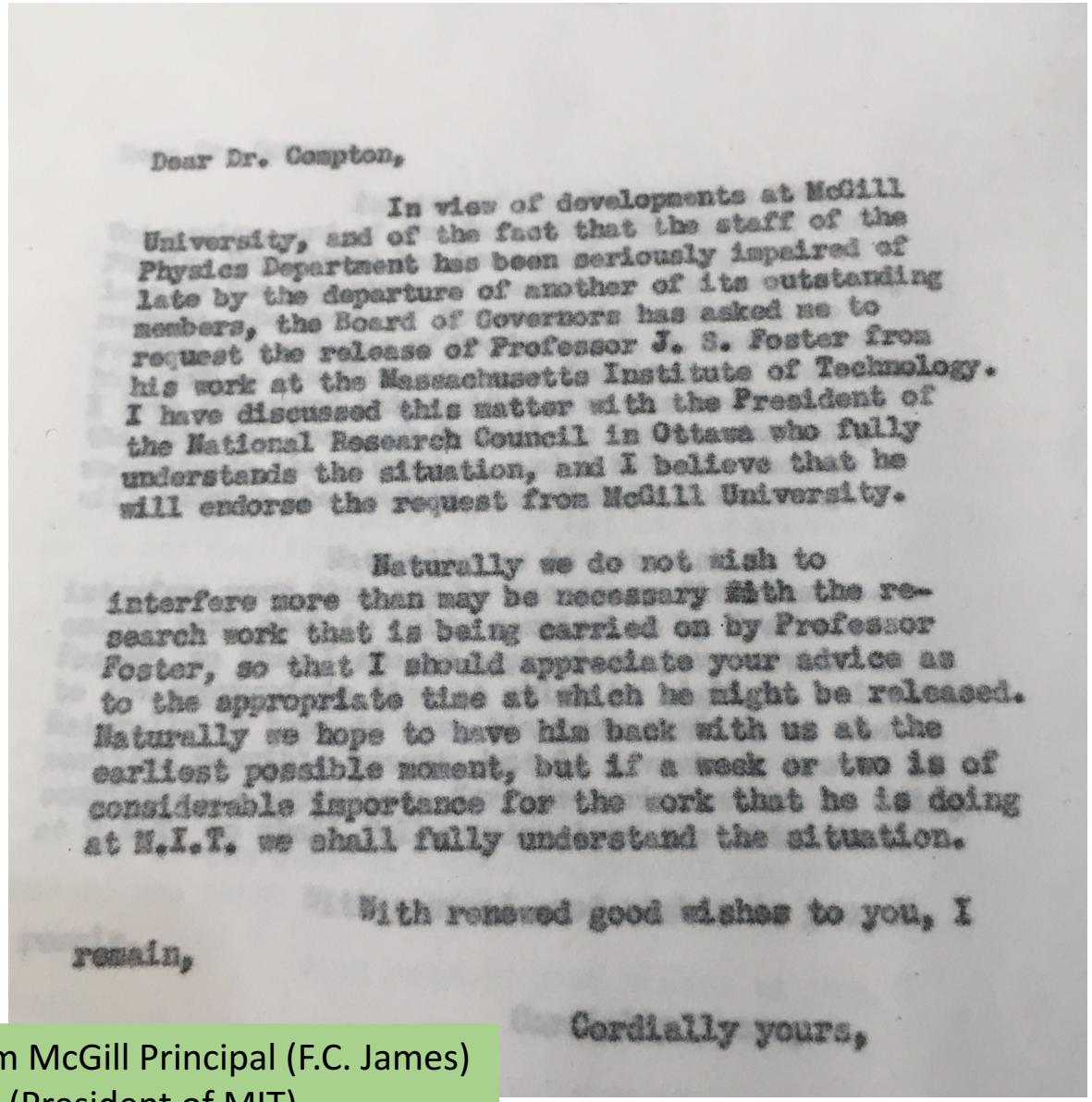


Dear Professor Foster,

I am very glad indeed to tell you that the Board of Governors has asked me to request your return from the Massachusetts Institute of Technology, in regard to which matter I am today writing to the President, and authorized the construction of the cyclotron as soon as definitive plans are ready and contracts can be prepared, provided that the over-all cost of the enterprise does not exceed $125,000.

We shall therefore have to start work as soon as you return to Montreal, which I hope will be at an early date.

Cordially yours,



Dear Dr. Compton,

In view of developments at McGill University, and of the fact that the staff of the Physics Department has been seriously impaired of late by the departure of another of its outstanding members, the Board of Governors has asked me to request the release of Professor J. S. Foster from his work at the Massachusetts Institute of Technology. I have discussed this matter with the President of the National Research Council in Ottawa who fully understands the situation, and I believe that he will endorse the request from McGill University.

Naturally we do not wish to interfere more than may be necessary with the research work that is being carried on by Professor Foster, so that I should appreciate your advice as to the appropriate time at which he might be released. Naturally we hope to have him back with us at the earliest possible moment, but if a week or two is of considerable importance for the work that he is doing at M.I.T. we shall fully understand the situation.

With renewed good wishes to you, I remain,

Cordially yours,

letters sent on Oct 12, 1944 from McGill Principal (F.C. James) to Foster and to Karl T Compton (President of MIT)

World War II – return from MIT

-NRC was in the business of nuclear physics thanks to the Anglo-Canadian effort at the Montreal Labs and Chalk River Nuclear Laboratories

John Cockcroft lobbied C.J. Mackenzie (NRC) to obtain support for the cyclotron and suggested it be an ‘outstation’ of the Chalk River operation

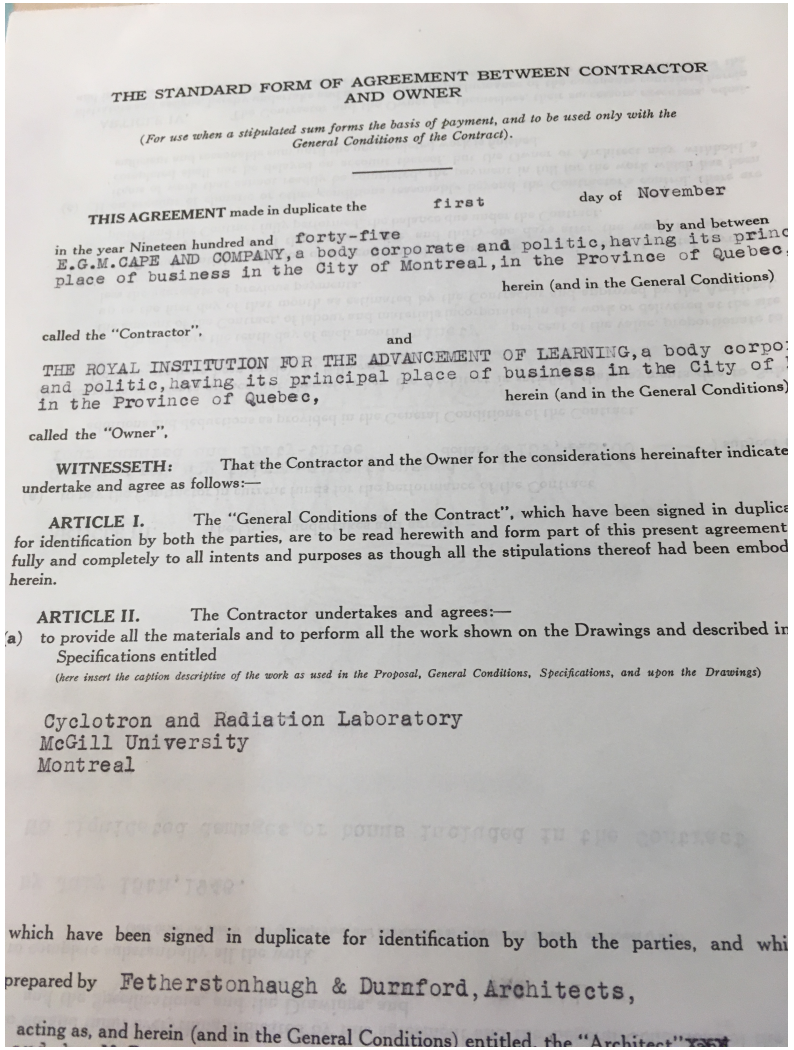
Foster was not amused, but returned to Montreal to re-engage

Cyclotron Redux

- Foster revised the proposal to incorporate arguments for increased energy - 25 MeV (eventually raised to 100 MeV)
- stressed that the cyclotron would continue McGill ‘tradition of excellence’ in nuclear physics (despite a 40-year lapse)
- with a combination of McGill and NRC support, the project was approved ($125 k authorized by McGill governors in 1944)
- October 1946 convocation included honorary degrees for Bohr and Lawrence and an “official opening” of the lab

JS Foster, N Bohr, J Anderson, FC James, EO Lawrence

Cyclotron Redux



THE STANDARD FORM OF AGREEMENT BETWEEN CONTRACTOR AND OWNER

(For use when a stipulated sum forms the basis of payment, and to be used only with the General Conditions of the Contract).

THIS AGREEMENT made in duplicate the first day of November

in the year Nineteen hundred and forty-five by and between E.G.M.CAPE AND COMPANY, a body corporate and politic, having its princ place of business in the City of Montreal, in the Province of Quebec herein (and in the General Conditions)

called the "Contractor",

and

THE ROYAL INSTITUTION FOR THE ADVANCEMENT OF LEARNING, a body corpo and politic, having its principal place of business in the City of in the Province of Quebec, herein (and in the General Conditions)

called the "Owner",

WITNESSETH: That the Contractor and the Owner for the considerations hereinafter indicate undertake and agree as follows:—

ARTICLE I. The "General Conditions of the Contract", which have been signed in duplica for identification by both the parties, are to be read herewith and form part of this present agreement fully and completely to all intents and purposes as though all the stipulations thereof had been embod herein.

ARTICLE II. The Contractor undertakes and agrees:—

(a) to provide all the materials and to perform all the work shown on the Drawings and described in Specifications entitled

(here insert the caption descriptive of the work as used in the Proposal, General Conditions, Specifications, and upon the Drawings)

Cyclotron and Radiation Laboratory
McGill University
Montreal

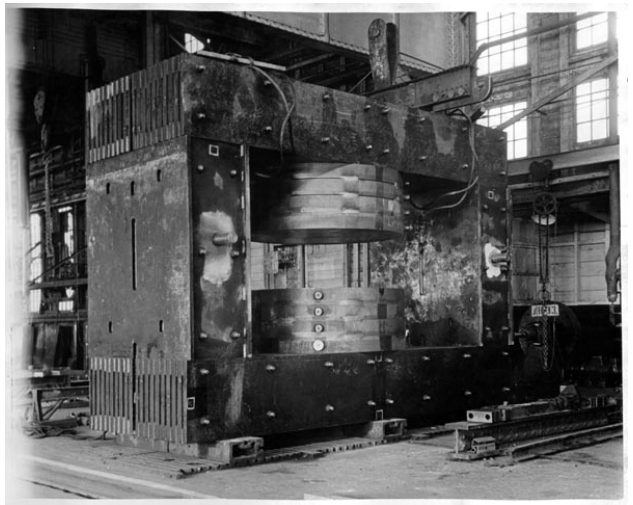
which have been signed in duplicate for identification by both the parties, and whi

prepared by Fetherstonhaugh & Durnford, Architects,

acting as, and herein (and in the General Conditions) entitled, the "Architect"

lab in 1947
(cyclotron vault is under the earthen mound with the ventilator)

later enlarged (1962) to add a fourth floor and a beam hall for experiments using the extracted beam



November 1945 – construction of the lab starts

Cyclotron Redux

cost of construction up to 1949 is stated as $350,000

much of the savings came from using graduate-student labour

Department of Physics

McGILL UNIVERSITY
PRINCIPAL'S ROOM
RECEIVED
MAY 31 1946

May 30, 1946

Dr. F. Cyril James,
Principal and Vice-Chancellor,
McGill University.

Dear Dr. James:

The following men wish to work on the construction of the cyclotron during the next four months at the rate of $125 per month for full time.

Anderson, D. A.	half time	$62.50 per mo.	$250.00
Bartholomew, W. F.	full time	125.00 per mo.	500.00
Fraser, J. S.	half time	62.50 per mo.	250.00
Henry, W. H.	full time	125.00 per mo.	500.00
Hone, D. W.	half time	62.50 per mo.	250.00
Mathison, J. F.	full time	125.00 per mo.	500.00
Stephens-Newsham, L. G.	full time	125.00 per mo.	500.00
Turner, T. E.	full time	125.00 per mo.	500.00
Warren, Ross	full time	125.00 per mo.	500.00
		Total	$3,750.00

This amount is saved from estimates on the Cyclotron and does not represent additional cost.

Yours faithfully,

J. S. Foster,
Macdonald Professor of Physics.

JF/FD

...real Daily Star.

...REAL, SATURDAY, MAY 10, 1947

HA. 5101
Connecting All Depts.
WANT

McGill's Mighty Atom-Smasher

This is the atom-smasher nearing completion at McGill University, and it weighs a mere 300 tons. The cylinders contain five miles of aluminum ribbon. Between the poles of the nation's biggest magnet will be placed a vacuum chamber in which atoms will be bombarded with electron bullets with, of course, incomprehensible velocity.

Canada's Only Cyclotron Ready for Initial Trials Soon

Gen. McNaughton Announces Federal Grant Of $85,000 Will Be Sought for Research

FIVE miles of aluminum bus bar, in which there is a central passage allowing for the flow of cooling water, have been installed in the mighty McGill 300-ton atom-smasher in preparation for the initial trials shortly.

The long aluminum ribbon with a hole in it is one of the outstanding features of Canada's only cyclotron which will be used to keep the Dominion in the van of atomic research.

The cyclotron was inspected today by Gen. A. G. L. McNaughton, chairman of the Atomic Energy Control Board, who announced yesterday that Parliament would be asked to approve an $85,000 grant to McGill to assist in paying for

Cyclotron → Synchrocyclotron

the cyclotron equation no longer works
as the mass increases due to relativity
- the effect becomes important for energies greater than 25 MeV

$$v = \frac{qBR}{m} \qquad E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

a solution to the problem was found by E. McMillan (1945) and applied to the 184-inch cyclotron at Berkeley: reduce the frequency as particles gain energy – use a rotating condenser

beam is now structured – no longer CW

lower current as well

15 μs bursts

400 bursts/s

4 nA

TABLE I

STATUS OF SYNCHROCYCLOTRONS IN THE UNITED STATES AND EUROPE

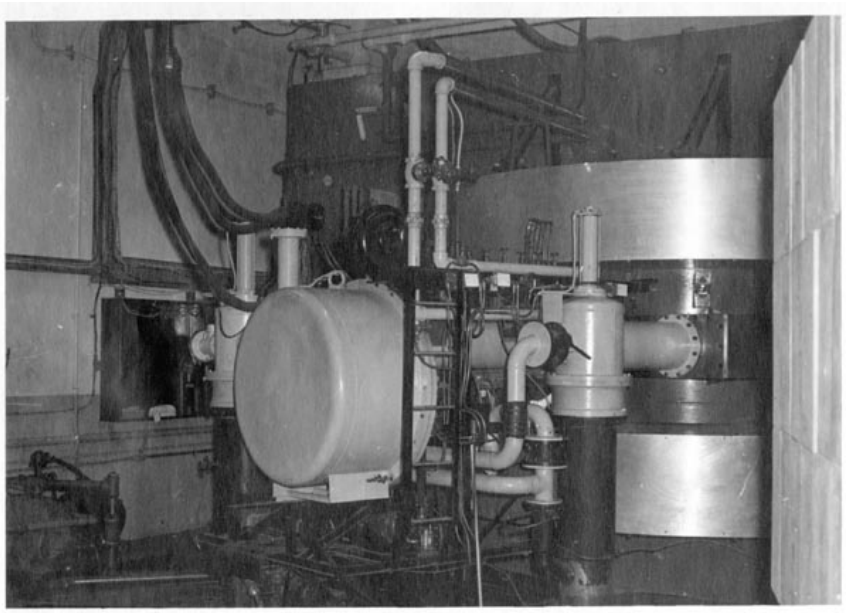
Synchrocyclotrons in Operation

Location and (Supervisor):	Pole Diam.: (in.)	Particle-Energy: (M.e.v.)	Magnet Weight: (tons)	Magnetic Field: (kg.)	Pulse Rate: (c/s)	Av. Beam Current: (μa)	Approx. Cost: (excl. bldg.)	Date First Operation:
(United States)								
1. Univ. of Calif. (E. O. Lawrence)	184	p—350 d—200 α—400	4,300	15.0	60	0.75	—	Nov. 1946
2. Univ. of Rochester (S. W. Barnes)	130	p—240	1,000	17.0	100	0.1	—	Dec. 1948
3. Harvard Univ. (R. B. Holt)	95	p—130	700	16.5	50–200	0.1	$750,000	May 1949
4. Columbia Univ. (J. R. Dunning and E. J. Booth)	164	p—385	2,400	17.4	30–100	0.1	—	Mar. 1950
(Foreign)								
5. Amsterdam, Holland (C. J. Bakker)	71	d— 28	210	13.7	2,000	25.0	—	Sept. 1949
6. Harwell, England (T. G. Pickavance)	110	p—175	670	16.8	100	1–2	£300,000	Dec. 1949
7. McGill Univ. (J. S. Foster)	82	p—100	260	16.4	200	0.2	$200,000	June 1950
Synchrocyclotrons under Construction								
(United States)								
8. Univ. of Chicago (H. L. Anderson)	170	(p—450)	2,200	18.6	50–360	—	$2,500,000	—
9. Carnegie Inst. Tech. (E. C. Creutz)	141.7	(p—440)	1,500	20.5	300	—	$2,000,000	—
(Foreign)								
10. Upsala, Sweden (The Swedberg)	90.5	(p—200)	720	22.0	500	—	3 M Sw. Kr.	—
11. Univ. of Liverpool (H. W. B. Skinner)	156	(p—400)	1,640	18.0	—	—	—	—

M. S. Livingston Ann. Rev. Nucl. Sci. vol 1 1952

starting in ~ 1950, the cyclotron was a productive engine for research

- 70 new isotopes were identified
- internal targets were bombarded, producing neutron-deficient isotopes
- complementary to the neutron-rich isotopes produced in reactors

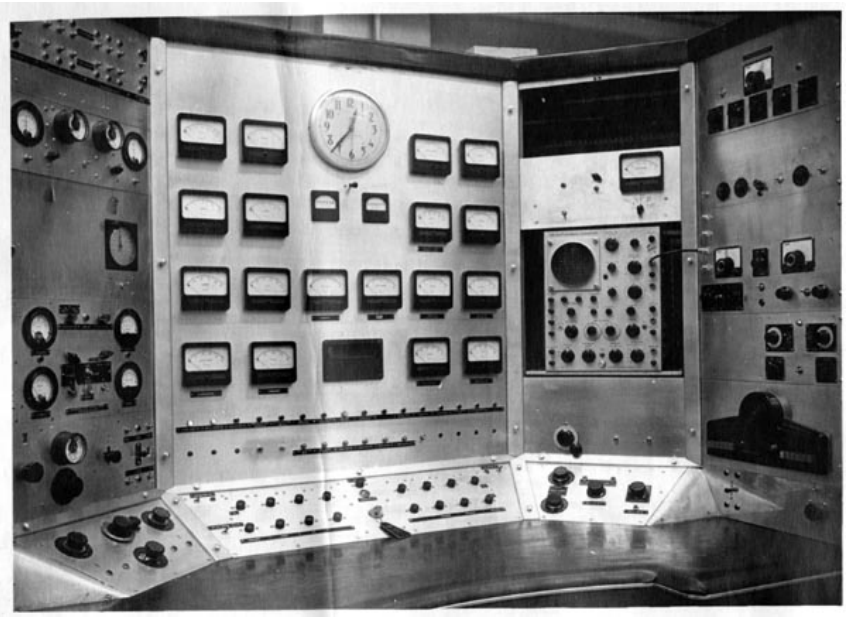


in 1960 an external beam was commissioned, allowing reaction studies

- beta-delayed proton emission is arguably the most important discovery made at the lab

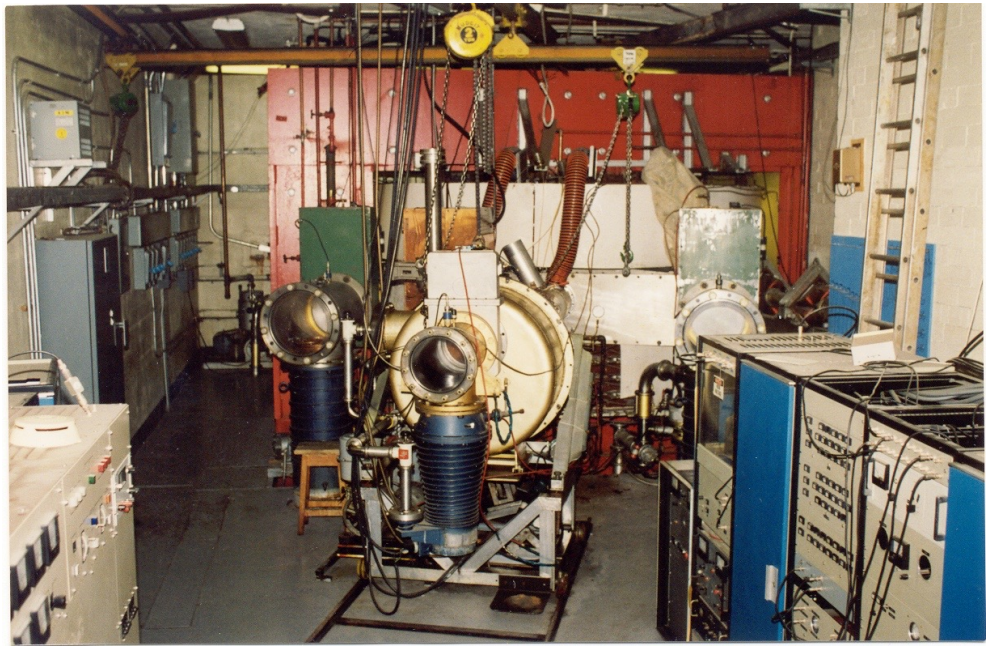
between 1948 and 1968 about 125 MSc and PhD degrees were obtained

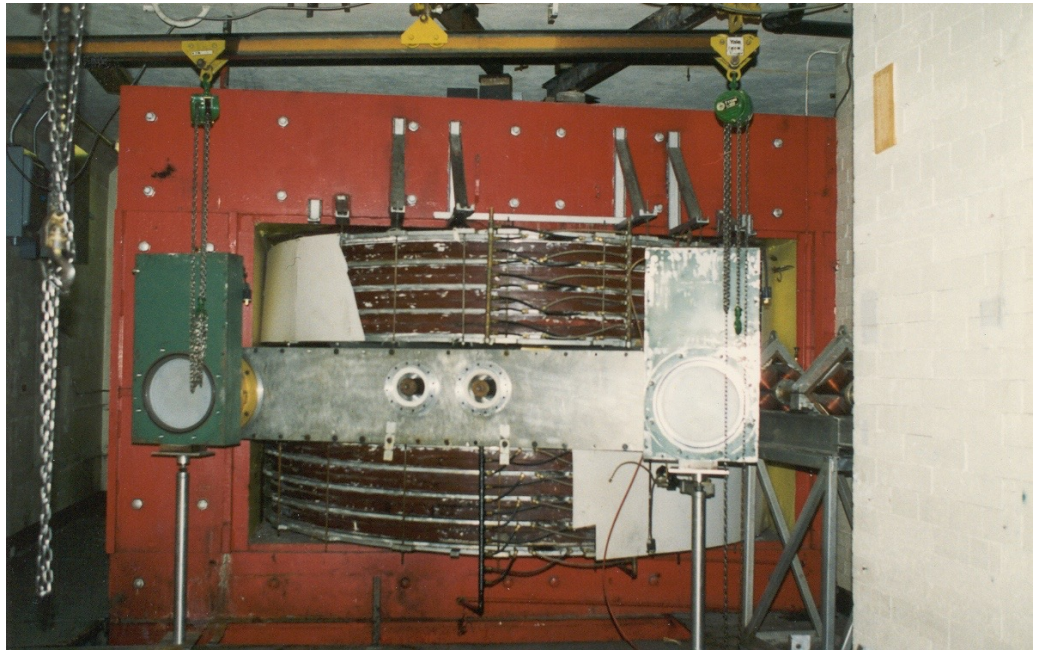
in 1964 the lab was named for Foster shortly before his death



Foster Theses

Aikman, Edward P.	M.Sc.	33-
Aikman, William E. P.	Ph.D.	35-
Alcock, Norman Z.	Ph.D.	49-
Anderson, Donald A.	Ph.D.	49-
Badior, Mark A.	M.Sc.	54-
Bell, Robert E.	Ph.D.	48-
Bernstein, Hyman	M.Sc.	56-
Bloom, Myer	M.Sc.	50-
Brannen, Eric	Ph.D.	46-
Breckon, Sydney W.	Ph.D.	51-
Brunton, Donald C.	Ph.D.	48-
Carruthers, James A.	Ph.D.	49-
Carter, Alfred L.	Ph.D.	58-
Chalk, Mary L.	Ph.D.	28-
Clark, Eric N.	Ph.D.	51-
Cloutier, Joseph A.	Ph.D.	55-
Cloutier, Joseph A.	M.Sc.	53-
Crawford, Gerald J.	Ph.D.	54-
Dahlstrom, Carl E.	Ph.D.	53-
Dewdney, John W.	M.Sc.	52-
Din, Ghias ud	M.Sc.	59-
Dodds, John W.	Ph.D.	49-
Douglas, Donald G.	Ph.D.	49-
Eadie, Frank S.	Ph.D.	52-
Eadie, Frank S.	M.Sc.	49-
Kappen, Collaparambil	Ph.D.	59-
Epp, Edward R.	Ph.D.	55-
Feeny, Harold Francis	M.Sc.	40-
Flower, Louis G.	M.Sc.	54-
Foster, Leigh C.	Ph.D.	56-
Geldart, Lloyd Philip	Ph.D.	41-
Girdwood, Barbara M.	M.Sc.	46-
Girdwood, Barbara M.	Ph.D.	48-
Gransden, Max M.	Ph.D.	51-
Green, Ralph E.	Ph.D.	56-
Groves, Trevor K.	M.Sc.	53-
Gunton, Robert C.	Ph.D.	47-
Guptill, Ernest W.	Ph.D.	46-
Hargrove, Clifford K.	M.Sc.	57-
Harkness, Harold W.	Ph.D.	30-
Haslam, Robert N.	Ph.D.	33-
Heard, Jack F.	Ph.D.	32-
Henriksen, Arne	Ph.D.	53-
Henry, William H.	Ph.D.	51-
Hilborn, John W.	Ph.D.	54-
Hilborn, John W.	M.Sc.	51-
Hone, David W.	Ph.D.	51-
Hopkins, Nigel J.	Ph.D.	52-
Hopkins, Nigel J.	M.Sc.	49-
Horton, Cyril A.	Ph.D.	37-
Hunt, John W.	Ph.D.	56-
Hunten, Donald M.	Ph.D.	50-
Huq, M. Shamsul	M.Sc.	56-
Jackson, Ray W.	Ph.D.	50-
Johnson, Frederick A.	Ph.D.	52-
Jones, Donald C.	Ph.D.	37-
Kennedy, John Edward	M.Sc.	42-
Keys, John D.	Ph.D.	51-
Langstroth, George C.	Ph.D.	30-
Link, William T.	Ph.D.	57-
Lorrain, Paul	Ph.D.	47-
Lorrain, Paul	M.Sc.	41-
Maclure, Kenneth C.	Ph.D.	52-
Maclure, Kenneth C.	M.Sc.	50-
Martin, William M.	Ph.D.	51-
Mathison, James F.	Ph.D.	56-
McKay, Kenneth Gardiner	M.Sc.	39-
Michel, Walter	Ph.D.	48-
Millar, Charles H.	Ph.D.	47-
Moody, Harry J.	Ph.D.	55-
Moon, James H.	Ph.D.	50-
Moore, Robert B.	M.Sc.	59-
Morrison, Wesley A.	Ph.D.	48-
Munn, Allan M.	Ph.D.	47-
Neamtan, Samuel M.	Ph.D.	37-
Panter, Shraga F.	Ph.D.	36-
Pepper, Thomas P.	Ph.D.	48-
Perlman, Martin M.	Ph.D.	55-
Perlman, Martin M.	M.Sc.	51-
Piggott, Carmen I.	Ph.D.	53-
Pounder, Elton R.	Ph.D.	37-
Rao, C. Kanaka D.	M.Sc.	58-
Rotenberg, Avrahm B.	Ph.D.	41-
Rowles, William	Ph.D.	28-
Rowles, William	M.Sc.	26-
Scott, Donald Burton	Ph.D.	40-
Sellen, John M.	M.Sc.	51-
Shugar, David	Ph.D.	40-
Skarsgard, Harvey M.	Ph.D.	55-
Snell, Arthur H.	Ph.D.	33-
Stephens-Newsham, Lloyd	Ph.D.	48-
Telford, William M.	M.Sc.	41-
Thomas, George M.	Ph.D.	58-
Thomas, George M.	M.Sc.	56-
Thornton, Robert L.	Ph.D.	33-
Tilley, Donald E.	Ph.D.	51-
Turner, Terry E.	Ph.D.	48-
Van Steenbergen, Arie	Ph.D.	57-
Voyvodic, Louis	Ph.D.	48-
Walker, Laurence Richard	Ph.D.	39-
Warren, F.G. Ross	Ph.D.	48-
Weaver, Ralph S.	M.Sc.	59-
Whitehead, Andrew B.	Ph.D.	57-
Whitehead, Andrew B.	M.Sc.	55-
Wolfson, Joseph L.	Ph.D.	48-
*Campbell, Herbert N.	M.Sc.	30-
*Fraser, John S.	Ph.D.	49-
*MacDonald, James L.	M.Sc.	28-
*McRae, Duncan R.	Ph.D.	30-
*Reeve, Herbert A.	M.Sc.	31-
*Telford, William M.	Ph.D.	49-
ster, J. .		
*Danby, Gordon T.	Ph.D.	56-





all good things come to an end

- the lab was shut down in the late 1980s
(as part of the scaling back of nuclear physics in Canada)

- the cyclotron was dismantled

- the McGill profs became users of other machines

(part of) the building remains but has been re-purposed

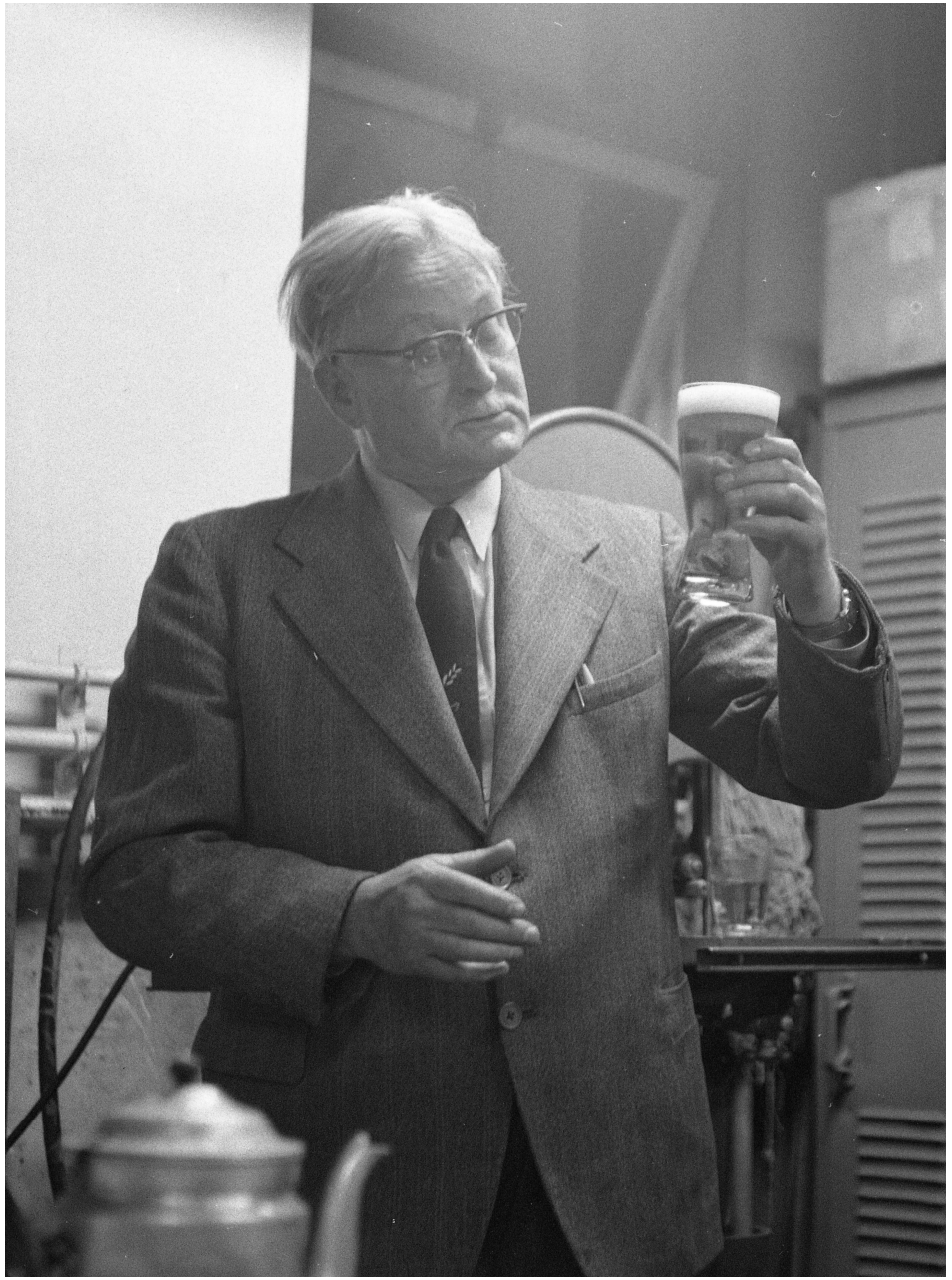
John Stuart Foster

- extraordinary career and lasting legacy

- endowed with scientific and organizational gifts

- blessed with good luck; a knack for being in the right place at the right time

- brought nuclear physics back to McGill



Extras

Robert L Thornton PhD 1933

- went to Berkeley in 1933
- co-author of first paper where ‘cyclotron’ name was used
- built cyclotrons at U Michigan (1935) and WUSL (late 30s)
- returned to Berkeley (1942) to assist in Calutron development
- worked on Manhattan project in Oak Ridge
- declined offer to direct CRNL
- returned again to Berkeley (1945) – promoted to professor
- served as assistant director (1954) and associate director (1959) of UCRL

First beam of 184-inch cyclotron, November 1, 1946; foreground, left to right, R. Thornton, Ernest Lawrence, Ed McMillan, and James Vale

Arthur H Snell PhD 1933

1851 Exhibition Scholarship (England-Canada) held at University of California, Berkeley, 1930-37; Research Assoc., Univ. of Calif. 1937-38; Research Instructor, Univ. of Chicago, 1938-42; Chief, Cyclotron Group, Manhattan Project (Chicago) 1942-44; Group Leader, Oak Ridge National Laboratory, 1944-48; Director, Physics Division, ORNL, 1948-57; Director, Thermonuclear Div., ORNL 1958-67; Assistant Director, ORNL, 1957-70; Associate Director, ORNL, 1970-71. Consultant, ORNL; Member, Board of Directors, Oak Ridge Institute of Nuclear Studies, 1959-62. Chairman, Subcommittee on Nuclear Instruments and Techniques, National Academy of Science-National Research Council, 1954 -61.

Radioactive Decay of the Neutron*

ARTHUR H. SNELL, FRANCES PLEASONTON, AND R. V. MCCORD
Oak Ridge National Laboratories, Oak Ridge, Tennessee
March 6, 1950.

Adjacent articles in Phys Rev. 78

Radioactive Decay of the Neutron

J. M. ROBSON
Atomic Energy Project, National Research Council of Canada, Chalk River, Ontario, Canada
March 13, 1950