Science and Technology Facilities Council

ISIS Neutron and Muon Source

The ISIS Linac and accelerators at RAL

IOP Particle Accelerator and Beams and History of Physics Groups Meeting on the History of UK Particle Accelerators

Alan Letchford

7th March 2023

Alternative title:

Proton Linacs on the RAL site 1952 - 2023

Science and
Technology
Facilities Council

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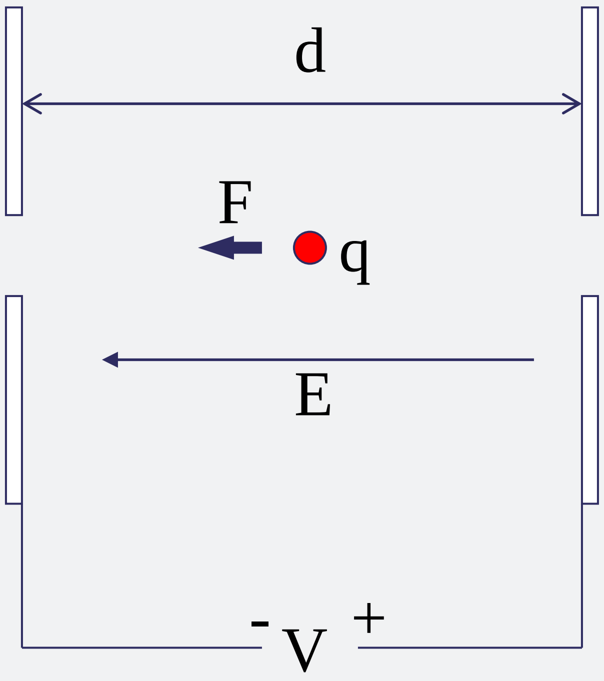
CONTENT

- A brief introduction to RF Linear Accelerators
- The Proton Linear Accelerator (PLA) at Harwell 1952 – 1957
- The PLA at Rutherford High Energy Laboratory 1957 – 1969
- The NIMROD synchrotron at RHEL/RL 1963 – 1978
- The ISIS Neutron and Muon Source at RL/RAL 1978 – 2023
- The future ...

Electrostatic accelerator

The very simplest linac is just a potential difference between two electrodes:



$$\vec{E} = \frac{V}{d}$$

$$\vec{F} = \vec{E}q$$

Total energy gain is just the potential difference times the charge

$$\Delta W = V|q| \quad \text{eV}$$

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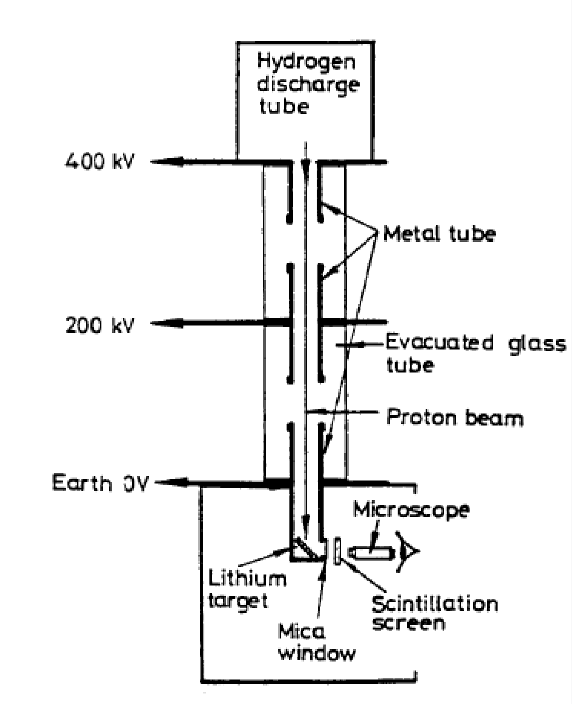
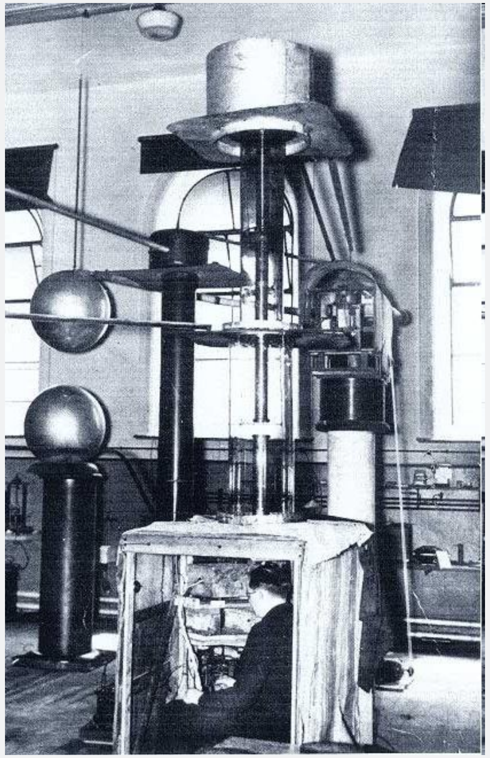
Cockcroft-Walton Accelerator

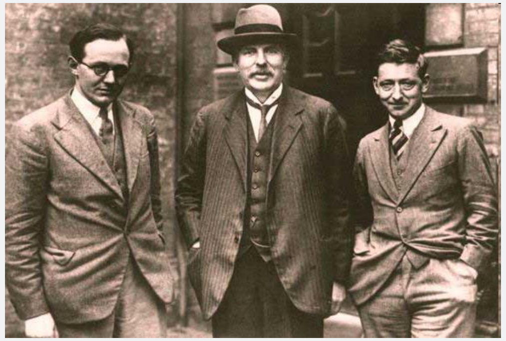
The first successful accelerator was a simple electrostatic gap driven by a voltage multiplier from which it takes its name.





The first 'atom smasher' at the Cavendish Lab

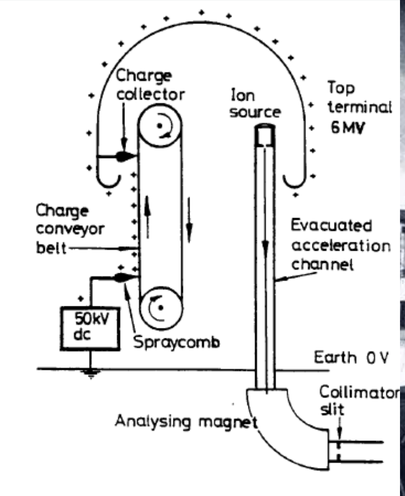
The eponymous voltage multiplier



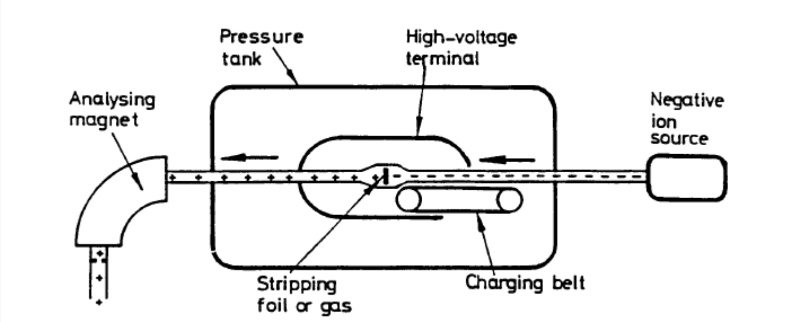
Cockcroft and Walton with Rutherford

Van de Graaff accelerator

The C-W circuit becomes inefficient above a certain practical limit. A Van de Graaff generator can produce larger voltages but at the cost of mechanical complexity.



Simple Van de Graaff accelerator



The tandem V de G accelerator uses the electric field twice by changing the sign of the particle charge in the HV terminal

20MV tandem V de G accelerator and the tower for the NSF at Daresbury

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RF Linacs

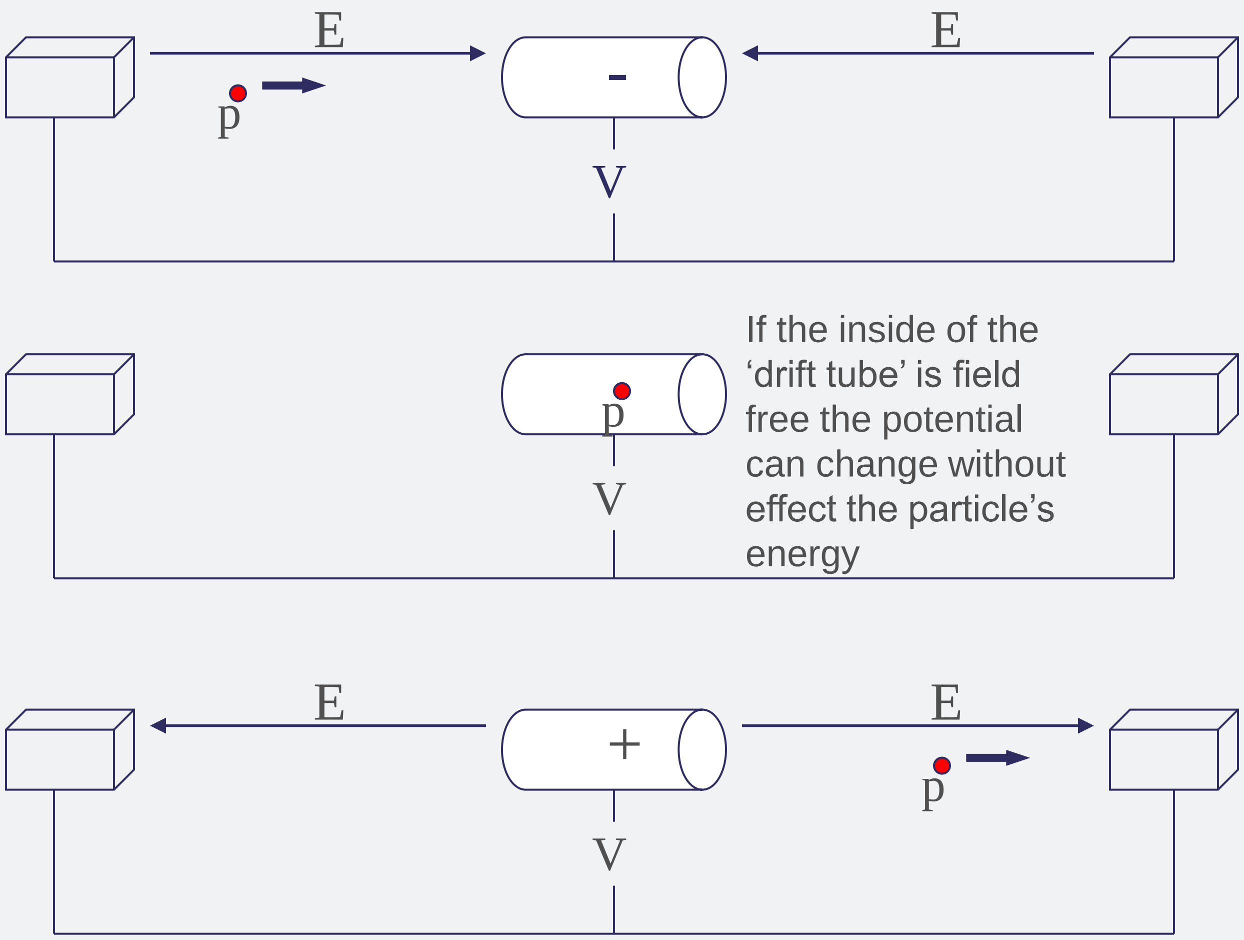
The tandem Van de Graaff accelerator has two desirable features which lead on to the development of RF linacs:

- The accelerating potential is used more than once.
- Both the particle source and the ‘target’ are at ground potential.

In the tandem V de G the particle charge is inverted in the HV terminal to utilise the same electric field in both directions. This is not always possible or desirable.

An alternative method first proposed by Ising (1924) and realised by Wideröe (1928) is to change the potential of the HV terminal while the particles are within it.

The Wideröe Linac



If the inside of the ‘drift tube’ is field free the potential can change without effect the particle’s energy

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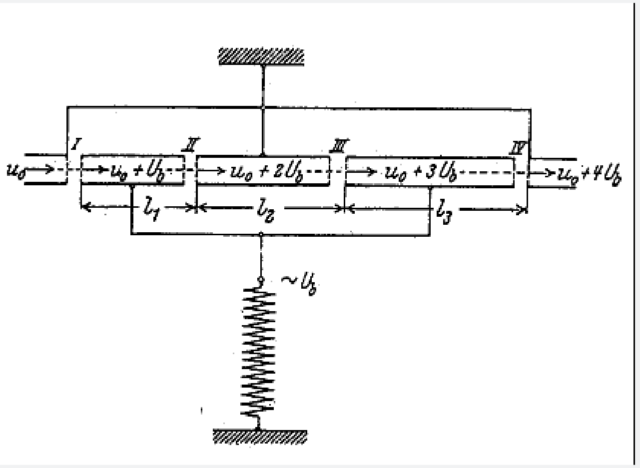
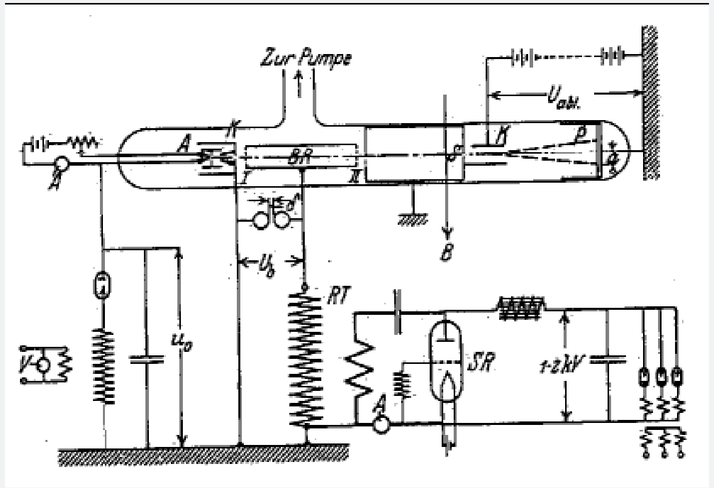
The Wideröe Linac



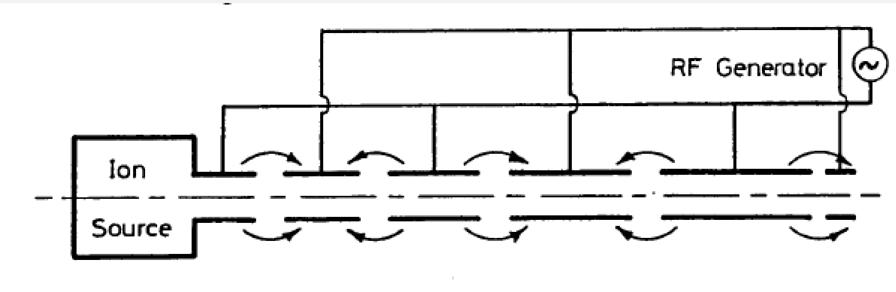


Wideröe’s original proposal …

…and his first linac.

He achieved 50kV of acceleration with a single 25kV source oscillating at 1MHz.

Any number of drift tubes can be connected together to multiply the source voltage many times.



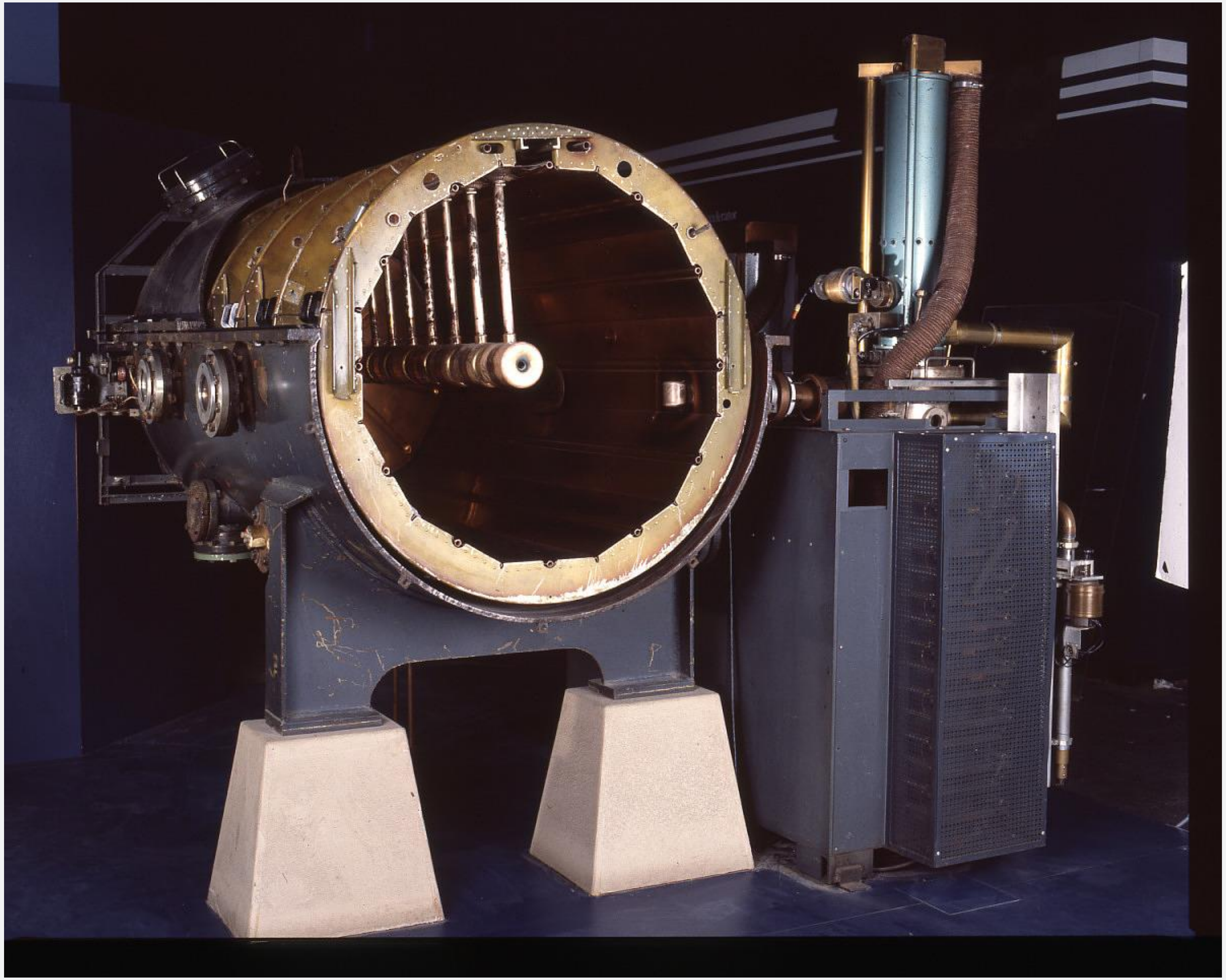
The Wideröe Linac

The distance between successive gaps is related to the RF wavelength.

For relativistic particles high frequencies are needed:
$f = 1\text{MHz}, \lambda = 300\text{m}$
$f = 100\text{MHz}, \lambda = 3\text{m}$
$f = 10\text{GHz}, \lambda = 30\text{mm}$

A practical linac using this principle needs RF power at ~100 MHz or more. It wasn't until after World War II that such RF power sources were available having been developed for radar and other systems.
At these higher frequencies Wideröe's structure with connected drift tubes becomes difficult to drive and inefficient in power. A variation using resonant RF cavities, due to Alvarez (1947), is the method used – in a wide range of guises - in virtually all RF linear accelerators today.

The Alvarez Linac



The first RF proton Linac is built at Berkeley in 1947. 30 MeV

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AERE Harwell

What is today the Harwell Campus started life as RAF Harwell in 1937.

In the Second World War the first British forces to land in continental Europe on D-Day left from RAF Harwell on 5th June 1944.

A Horsa glider leaving RAF Harwell for Normandy.

UKRI Science and Technology Facilities Council

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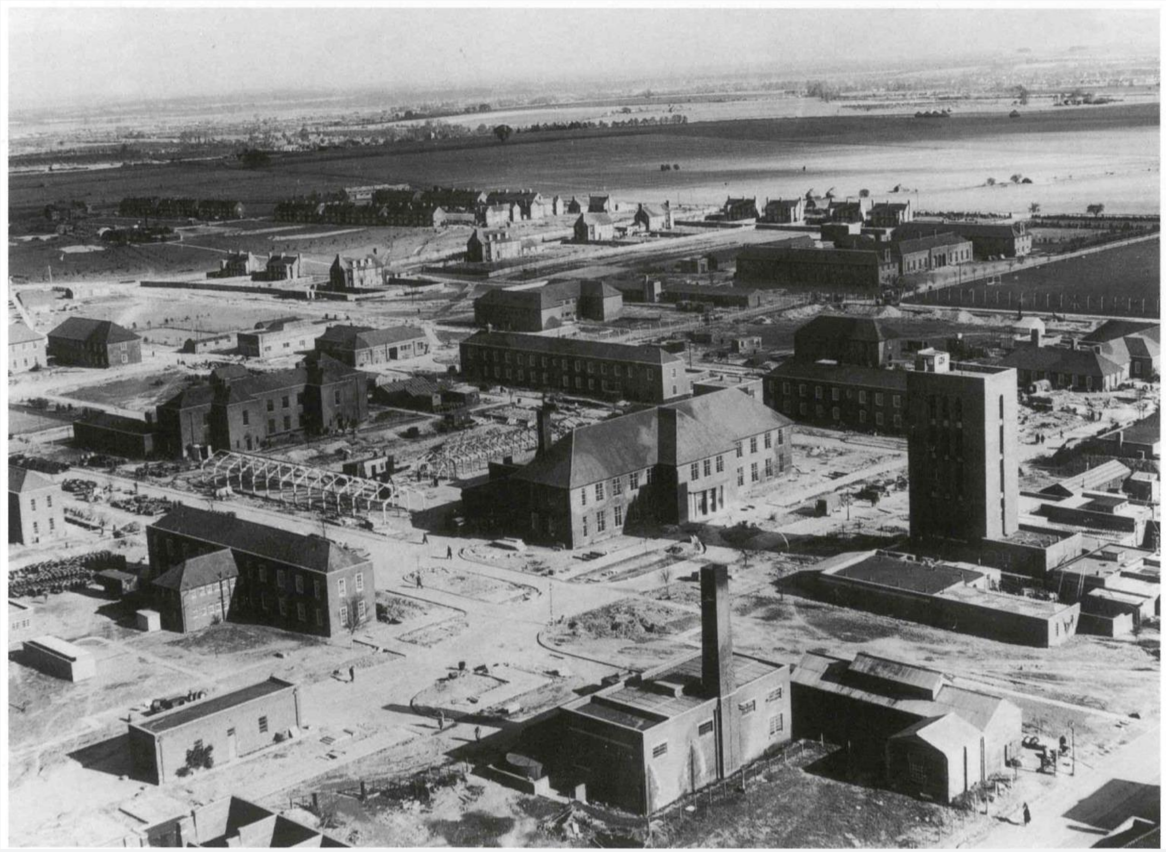
AERE Harwell

Following the second world war Harwell became the UK’s Atomic Energy Research Establishment in 1946. Although this included civil use, at this time ‘Atomic Energy’ primarily meant the UK’s independent nuclear deterrent.



AERE Harwell in 1947

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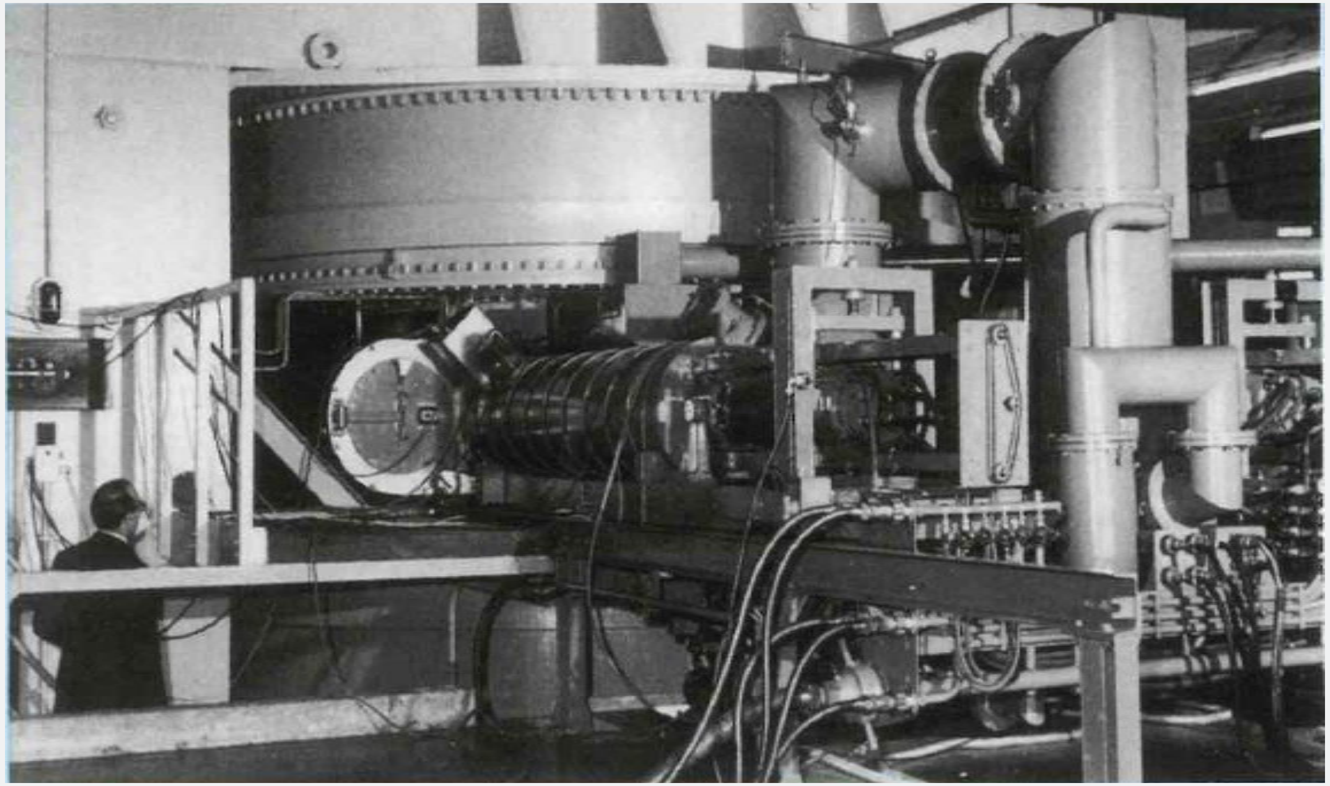
AERE Harwell

In 1951 all work on the nuclear deterrent was moved to the Atomic Weapons Establishment in Aldermaston. Harwell continued work on atomic power and high energy physics.



The 110” Harwell cyclotron

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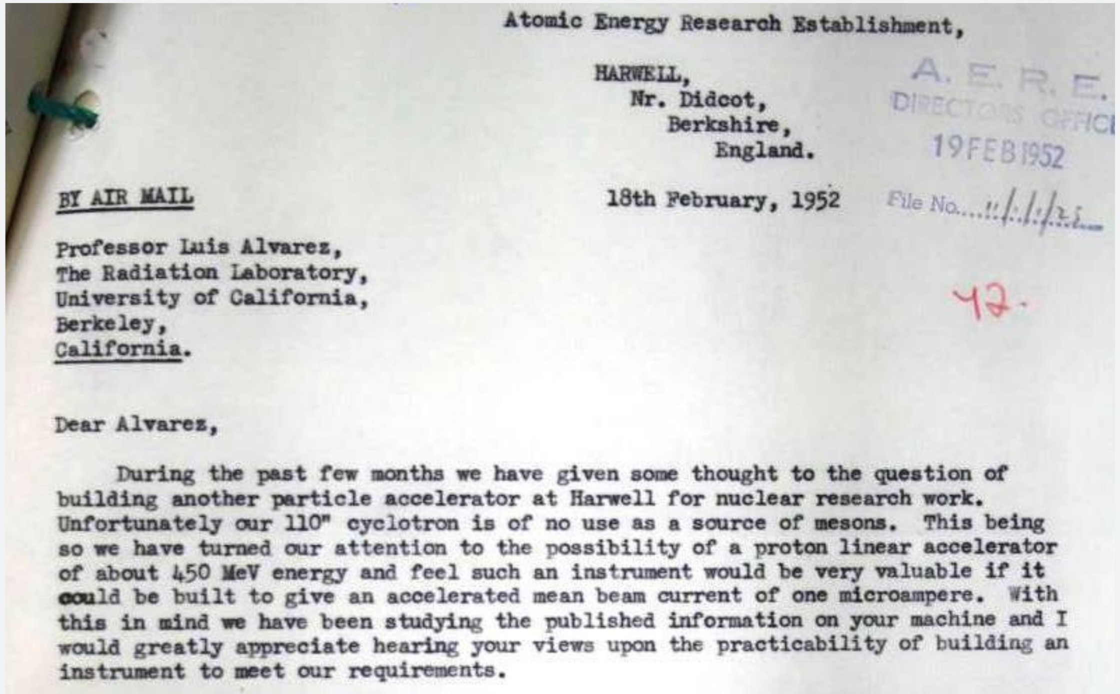
The Proton Linear Accelerator (PLA) is born

In 1952 the decision was taken to proceed with a design study for a 500 MeV proton linac for nuclear research.



Atomic Energy Research Establishment,

HARWELL,
Nr. Didcot,
Berkshire,
England.

A.E.R.E.
DIRECTOR'S OFFICE
19 FEB 1952
File No. ...

BY AIR MAIL

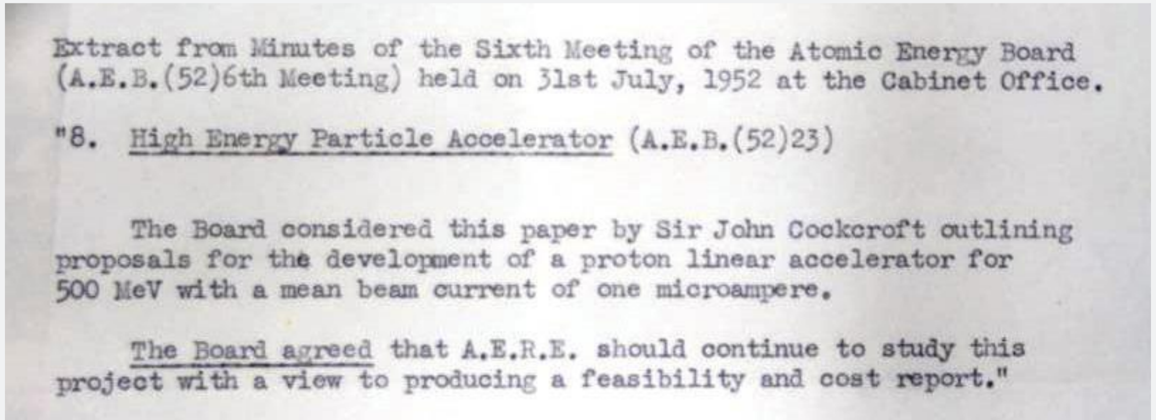
18th February, 1952

42.

Professor Luis Alvarez,
The Radiation Laboratory,
University of California,
Berkeley,
California.

Dear Alvarez,

During the past few months we have given some thought to the question of building another particle accelerator at Harwell for nuclear research work. Unfortunately our 110" cyclotron is of no use as a source of mesons. This being so we have turned our attention to the possibility of a proton linear accelerator of about 450 MeV energy and feel such an instrument would be very valuable if it could be built to give an accelerated mean beam current of one microampere. With this in mind we have been studying the published information on your machine and I would greatly appreciate hearing your views upon the practicability of building an instrument to meet our requirements.



Extract from Minutes of the Sixth Meeting of the Atomic Energy Board (A.E.B.(52)6th Meeting) held on 31st July, 1952 at the Cabinet Office.

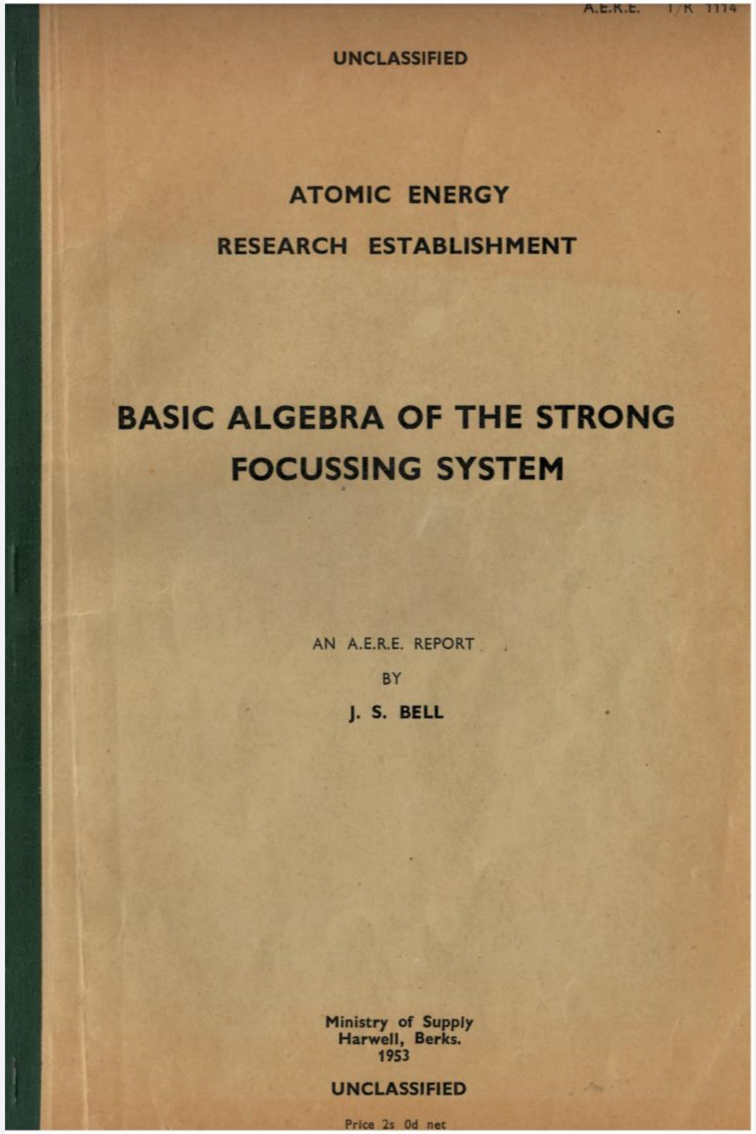
"8. High Energy Particle Accelerator (A.E.B.(52)23)

The Board considered this paper by Sir John Cockcroft outlining proposals for the development of a proton linear accelerator for 500 MeV with a mean beam current of one microampere.

The Board agreed that A.E.R.E. should continue to study this project with a view to producing a feasibility and cost report."

The PLA design study

Between 1953 and 1957 a series of internal design studies by AERE and external studies by the Metropolitan-Vickers Electrical Company were conducted.


A.E.R.E. T/R 1114

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ATOMIC ENERGY
RESEARCH ESTABLISHMENT

BASIC ALGEBRA OF THE STRONG FOCUSSING SYSTEM

AN A.E.R.E. REPORT
BY
J. S. BELL

Ministry of Supply
Harwell, Berks.
1953

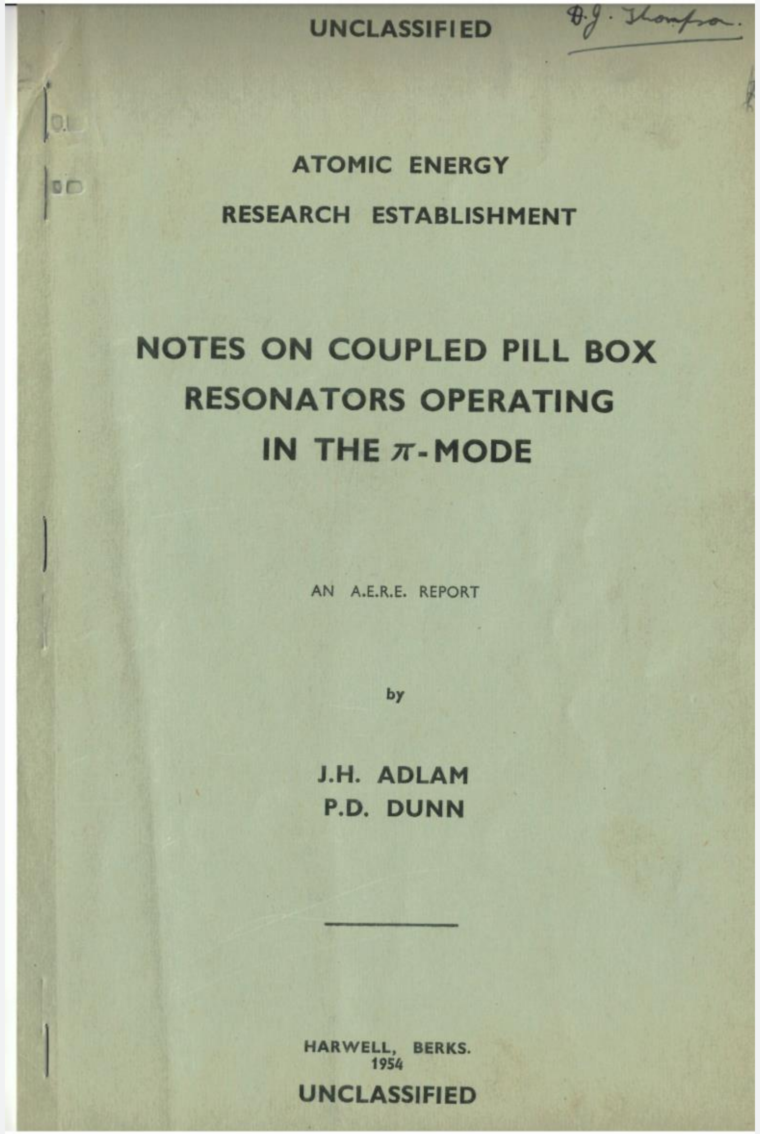
UNCLASSIFIED

Price 2s 0d net

In 1953 strong focussing by alternating gradient quadrupoles was still quite a new idea.

AERE design study

A lot of this stuff was very new and had to worked through from first principles by hand.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ATOMIC ENERGY
RESEARCH ESTABLISHMENT

NOTES ON COUPLED PILL BOX
RESONATORS OPERATING
IN THE π-MODE

AN A.E.R.E. REPORT

by

J.H. ADLAM
P.D. DUNN

HARWELL, BERKS.
1954
UNCLASSIFIED

Science and Technology Facilities Council

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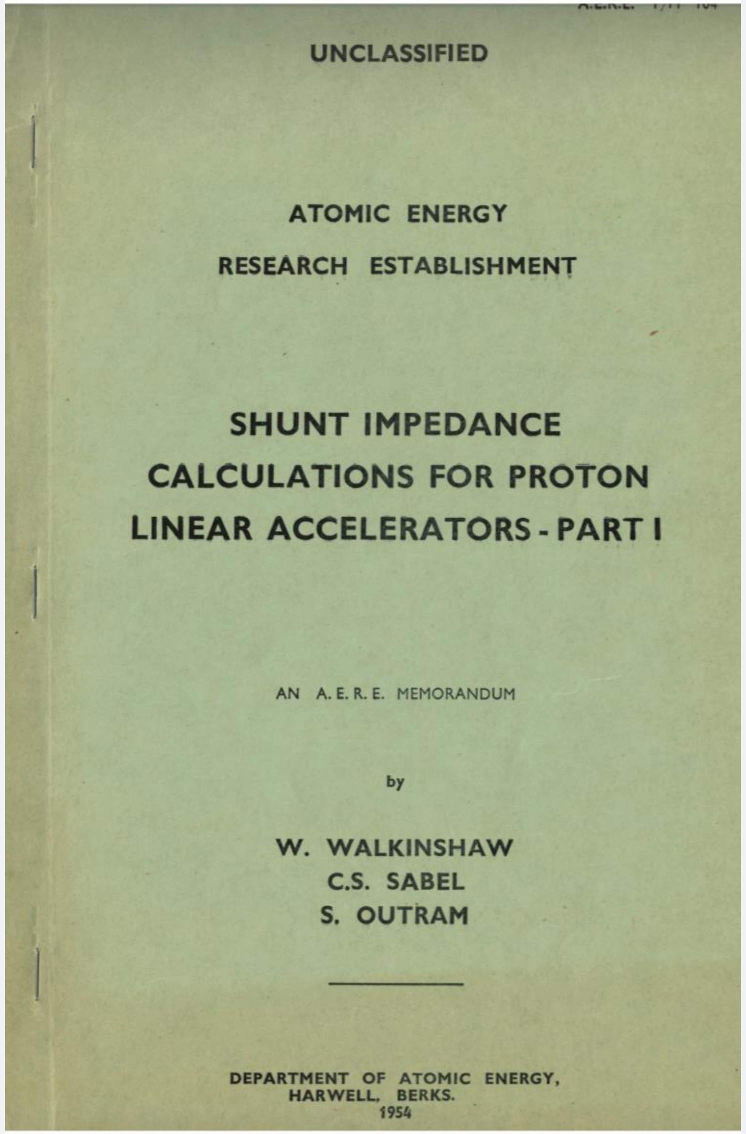
AERE design study



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RESEARCH ESTABLISHMENT

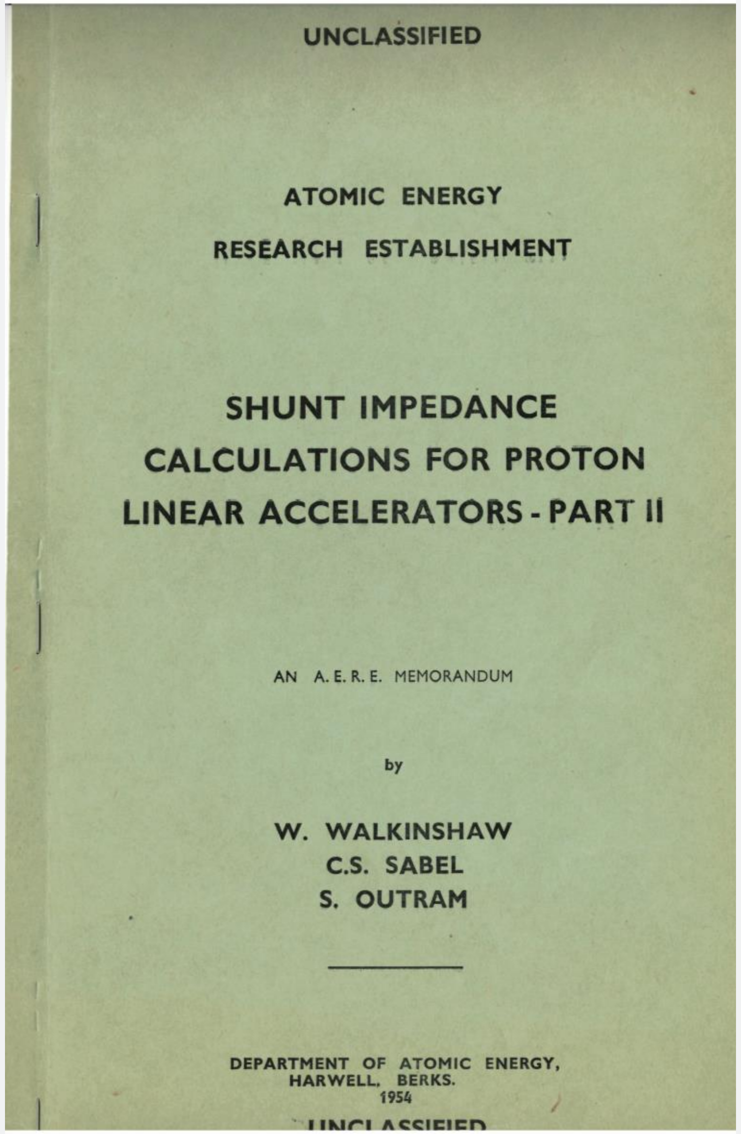
SHUNT IMPEDANCE CALCULATIONS FOR PROTON LINEAR ACCELERATORS - PART I

AN A. E. R. E. MEMORANDUM

by

W. WALKINSHAW
C.S. SABEL
S. OUTRAM

DEPARTMENT OF ATOMIC ENERGY,
HARWELL, BERKS.
1954



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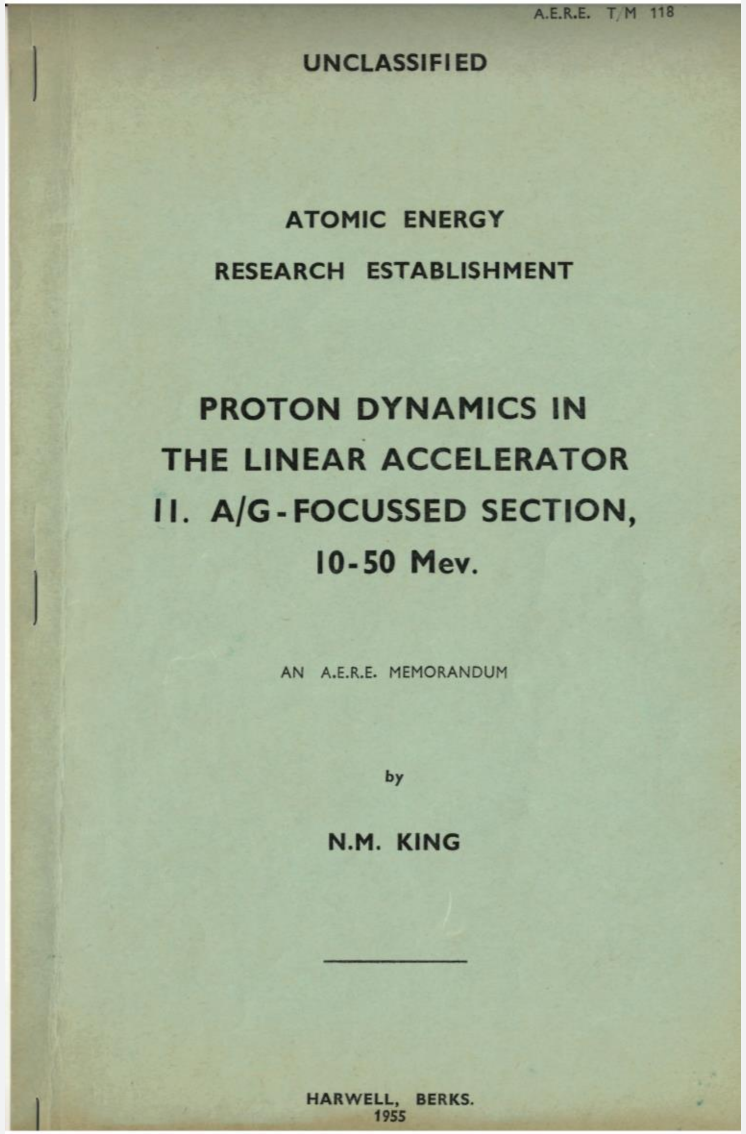
ISIS Neutron and Muon Source

AERE design study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ATOMIC ENERGY
RESEARCH ESTABLISHMENT

PROTON DYNAMICS IN
THE LINEAR ACCELERATOR
II. A/G-FOCUSSED SECTION,
10-50 Mev.

AN A.E.R.E. MEMORANDUM

by

N.M. KING

HARWELL, BERKS.
1955

In 1955 they were already talking about a 50 MeV linac instead of the full 500 MeV. Budget constraints and changing priorities are nothing new.
Plus ça change, plus c'est la même chose.

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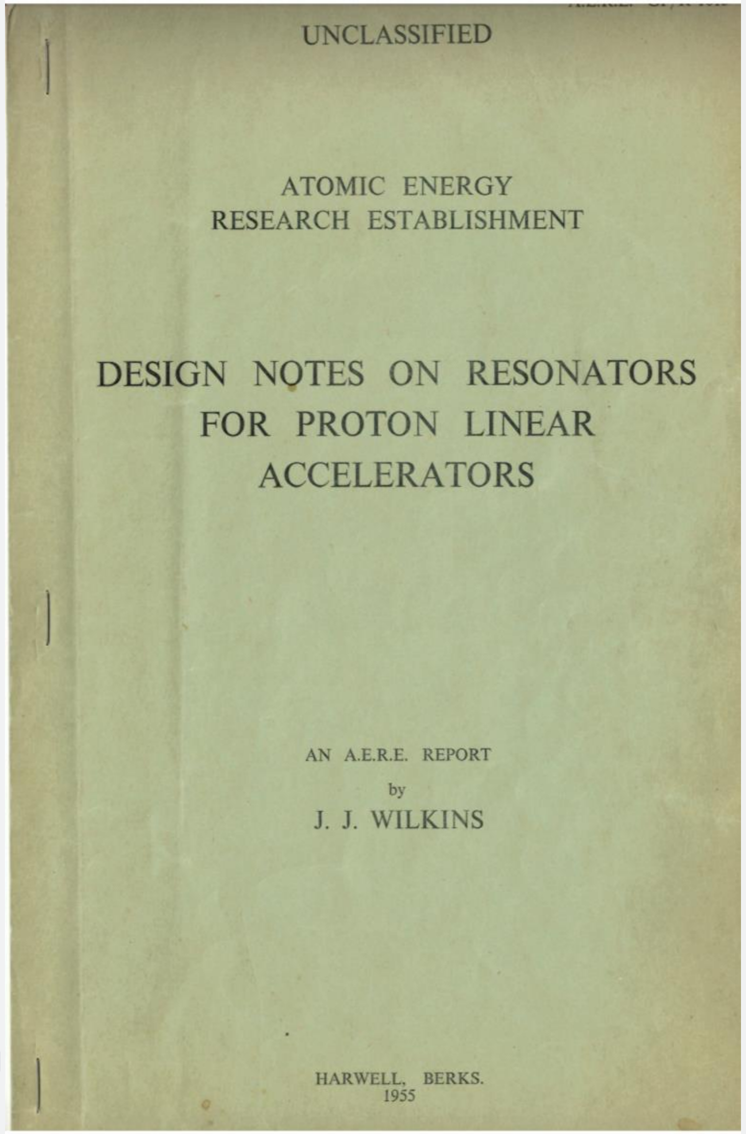
AERE design study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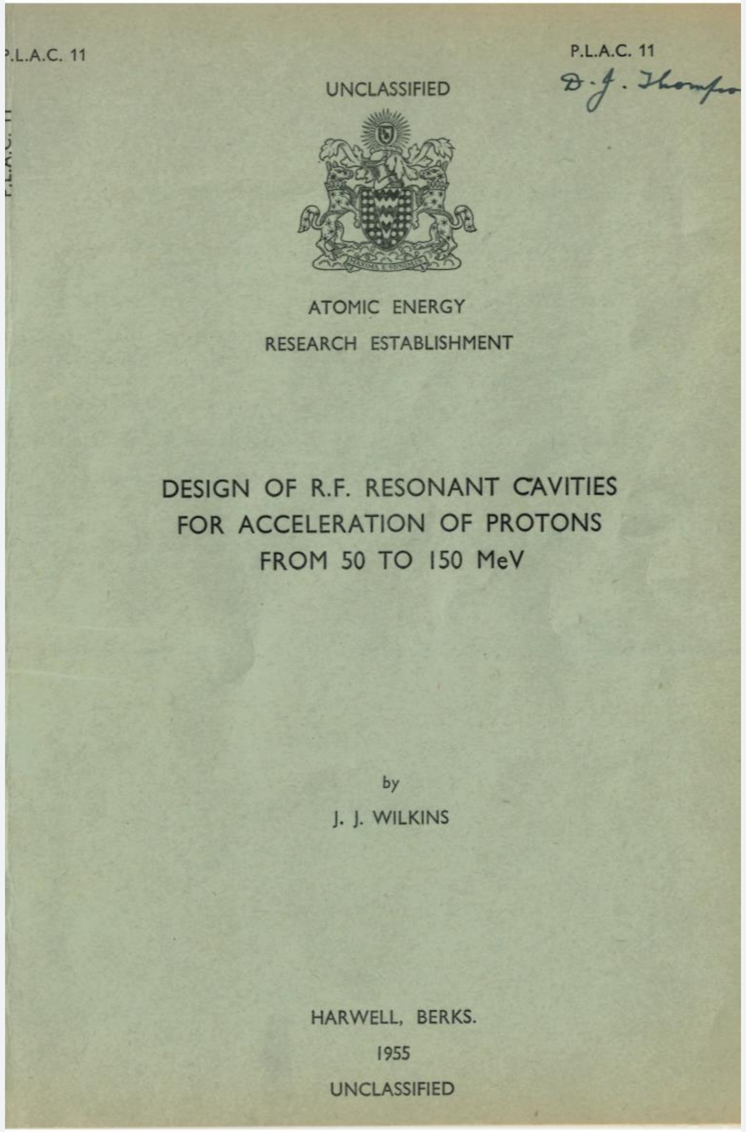
ATOMIC ENERGY
RESEARCH ESTABLISHMENT

DESIGN NOTES ON RESONATORS
FOR PROTON LINEAR
ACCELERATORS

AN A.E.R.E. REPORT
by
J. J. WILKINS

HARWELL, BERKS.
1955


P.L.A.C. 11

P.L.A.C. 11

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ATOMIC ENERGY
RESEARCH ESTABLISHMENT

DESIGN OF R.F. RESONANT CAVITIES
FOR ACCELERATION OF PROTONS
FROM 50 TO 150 MeV

by
J. J. WILKINS

HARWELL, BERKS.
1955
UNCLASSIFIED

But they hadn't given up on going to higher energies.

The fundamentals of much of what we do today when designing linacs can be found in these reports.

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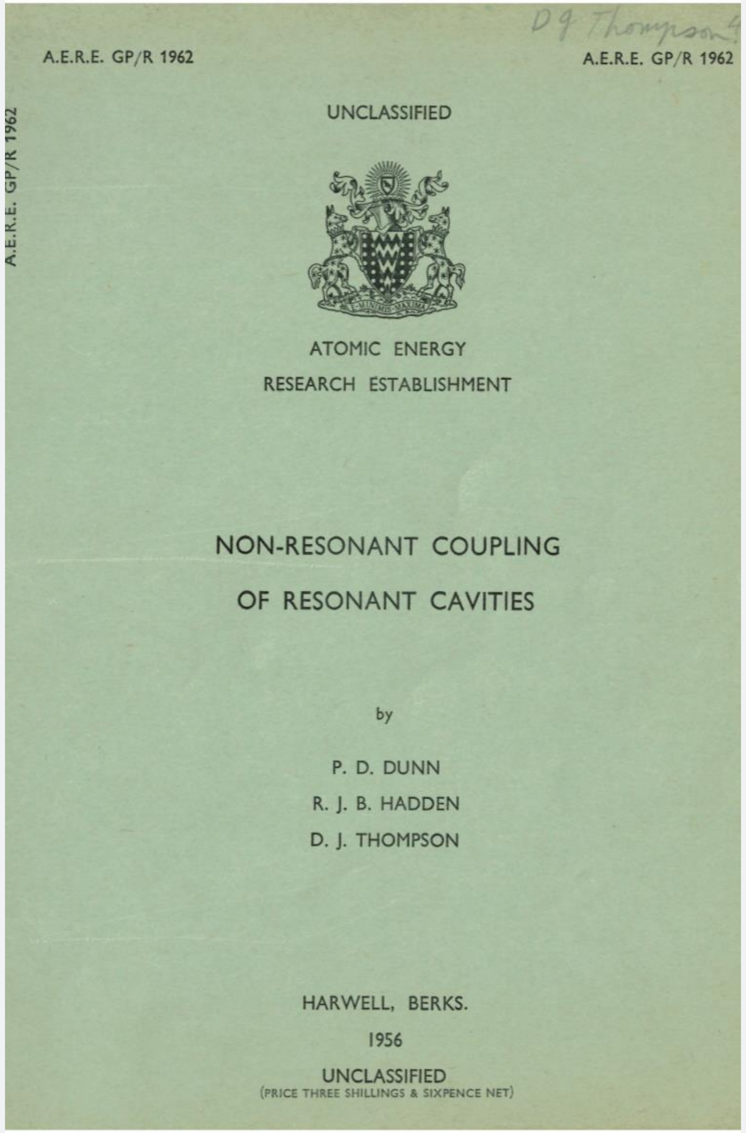
AERE design study



A.E.R.E. GP/R 1962   A.E.R.E. GP/R 1962

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ATOMIC ENERGY
RESEARCH ESTABLISHMENT

NON-RESONANT COUPLING
OF RESONANT CAVITIES

by

P. D. DUNN
R. J. B. HADDEN
D. J. THOMPSON

HARWELL, BERKS.
1956
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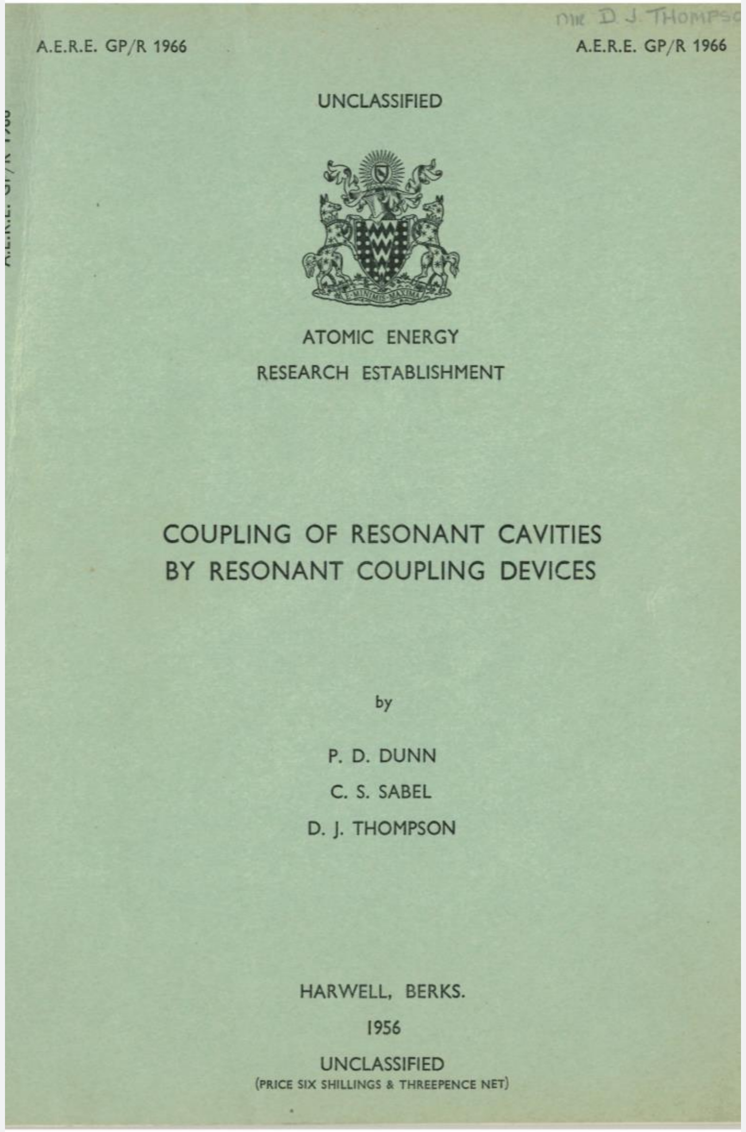
(PRICE THREE SHILLINGS & SIXPENCE NET)



A.E.R.E. GP/R 1966   A.E.R.E. GP/R 1966

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RESEARCH ESTABLISHMENT

COUPLING OF RESONANT CAVITIES
BY RESONANT COUPLING DEVICES

by

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C. S. SABEL
D. J. THOMPSON

HARWELL, BERKS.
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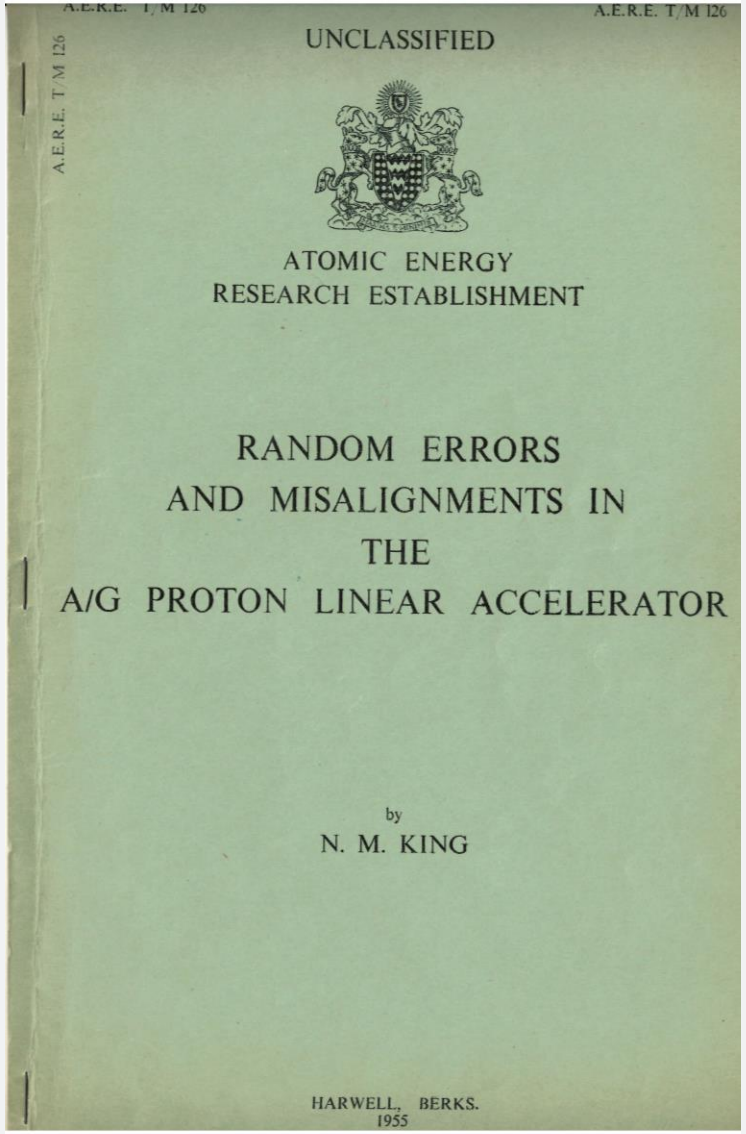
A.E.R.E. T/M 126 A.E.R.E. T/M 126

A.E.R.E. T/M 126

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ATOMIC ENERGY
RESEARCH ESTABLISHMENT

RANDOM ERRORS
AND MISALIGNMENTS IN
THE
A/G PROTON LINEAR ACCELERATOR

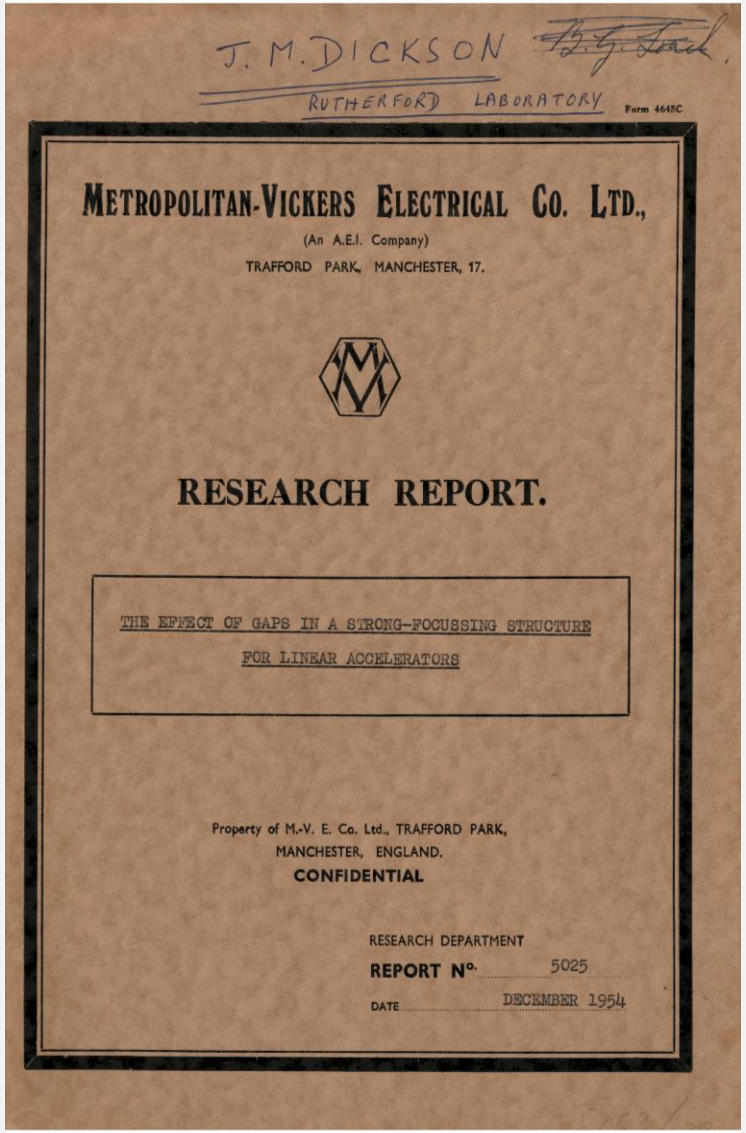
by
N. M. KING

HARWELL, BERKS.
1955

Despite being almost 70 years ago, all the elements of a modern design study can be found here.

Metropolitan-Vickers design study

In parallel to the basic physics studies carried out at AERE, studies into how to actually build the linac were carried out by industry.



J. M. DICKSON

RUTHERFORD LABORATORY

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TRAFFORD PARK, MANCHESTER, 17.

RESEARCH REPORT.

THE EFFECT OF GAPS IN A STRONG-FOCUSSING STRUCTURE FOR LINEAR ACCELERATORS

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CONFIDENTIAL

RESEARCH DEPARTMENT

REPORT N°. 5025

DATE DECEMBER 1954

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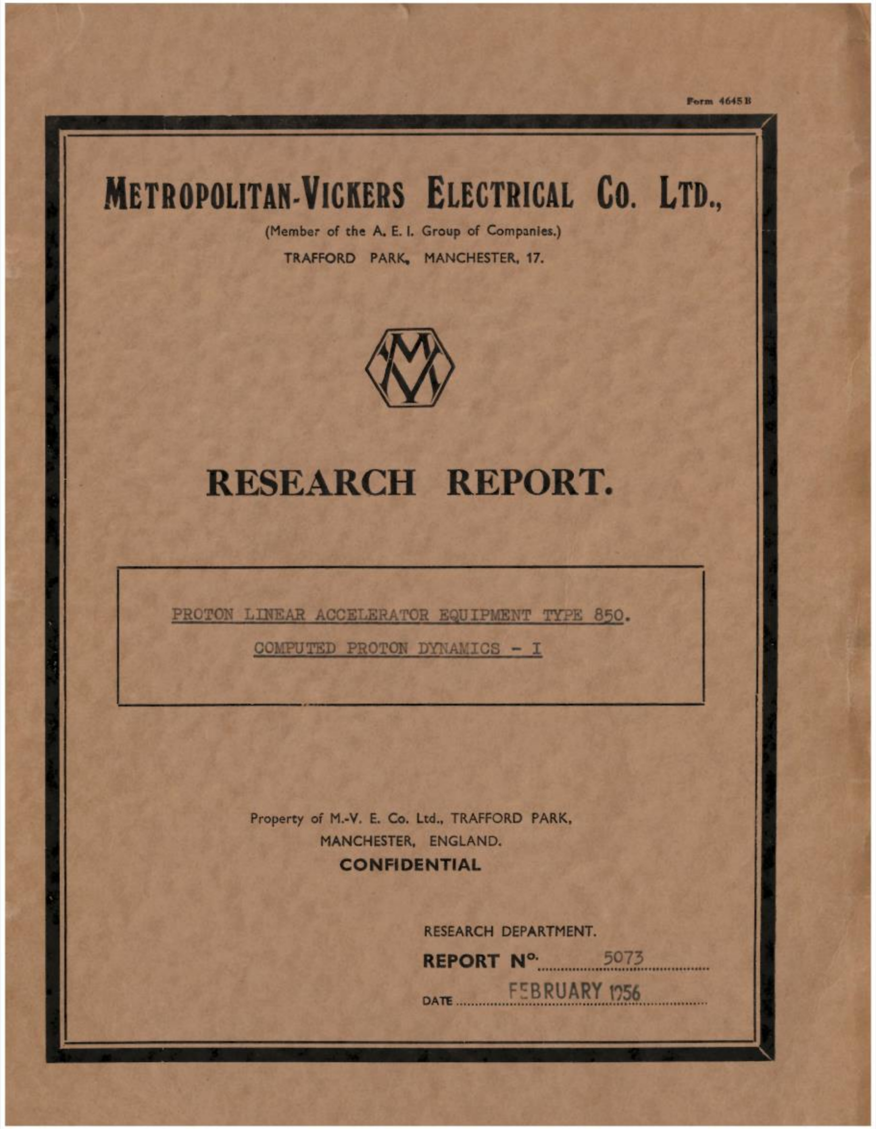
Metropolitan-Vickers design study



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RESEARCH REPORT.

PROTON LINEAR ACCELERATOR EQUIPMENT TYPE 850.

COMPUTED PROTON DYNAMICS - I

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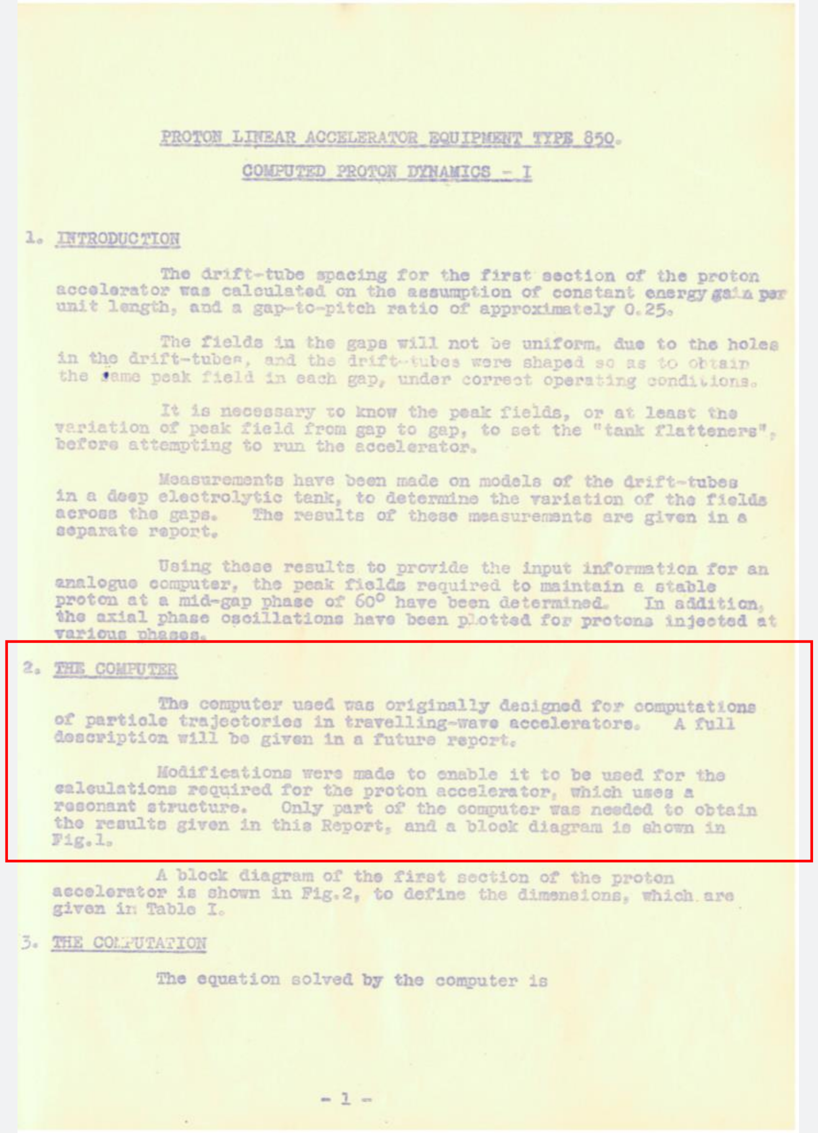
REPORT No. 5073

DATE FEBRUARY 1956



PROTON LINEAR ACCELERATOR EQUIPMENT TYPE 850.

COMPUTED PROTON DYNAMICS - I

1. INTRODUCTION

The drift-tube spacing for the first section of the proton accelerator was calculated on the assumption of constant energy gain per unit length, and a gap-to-pitch ratio of approximately 0.25.

The fields in the gaps will not be uniform, due to the holes in the drift-tubes, and the drift-tubes were shaped so as to obtain the same peak field in each gap, under correct operating conditions.

It is necessary to know the peak fields, or at least the variation of peak field from gap to gap, to set the "tank flatteners", before attempting to run the accelerator.

Measurements have been made on models of the drift-tubes in a deep electrolytic tank, to determine the variation of the fields across the gaps. The results of these measurements are given in a separate report.

Using these results to provide the input information for an analogue computer, the peak fields required to maintain a stable proton at a mid-gap phase of 60° have been determined. In addition, the axial phase oscillations have been plotted for protons injected at various phases.

2. THE COMPUTER

The computer used was originally designed for computations of particle trajectories in travelling-wave accelerators. A full description will be given in a future report.

Modifications were made to enable it to be used for the calculations required for the proton accelerator, which uses a resonant structure. Only part of the computer was needed to obtain the results given in this Report, and a block diagram is shown in Fig.1.

A block diagram of the first section of the proton accelerator is shown in Fig.2, to define the dimensions, which are given in Table I.

3. THE COMPUTATION

The equation solved by the computer is

- 1 -

"The computer used was originally designed for computations of particle trajectories in travelling-wave accelerators. A full description will be given in a future report.

Modifications were made to enable it to be used for the calculations required for the proton accelerator, which uses a resonant structure. Only part of the computer was needed to obtain the results given in this report, and a block diagram is shown in Fig. 1"

Metropolitan-Vickers design study

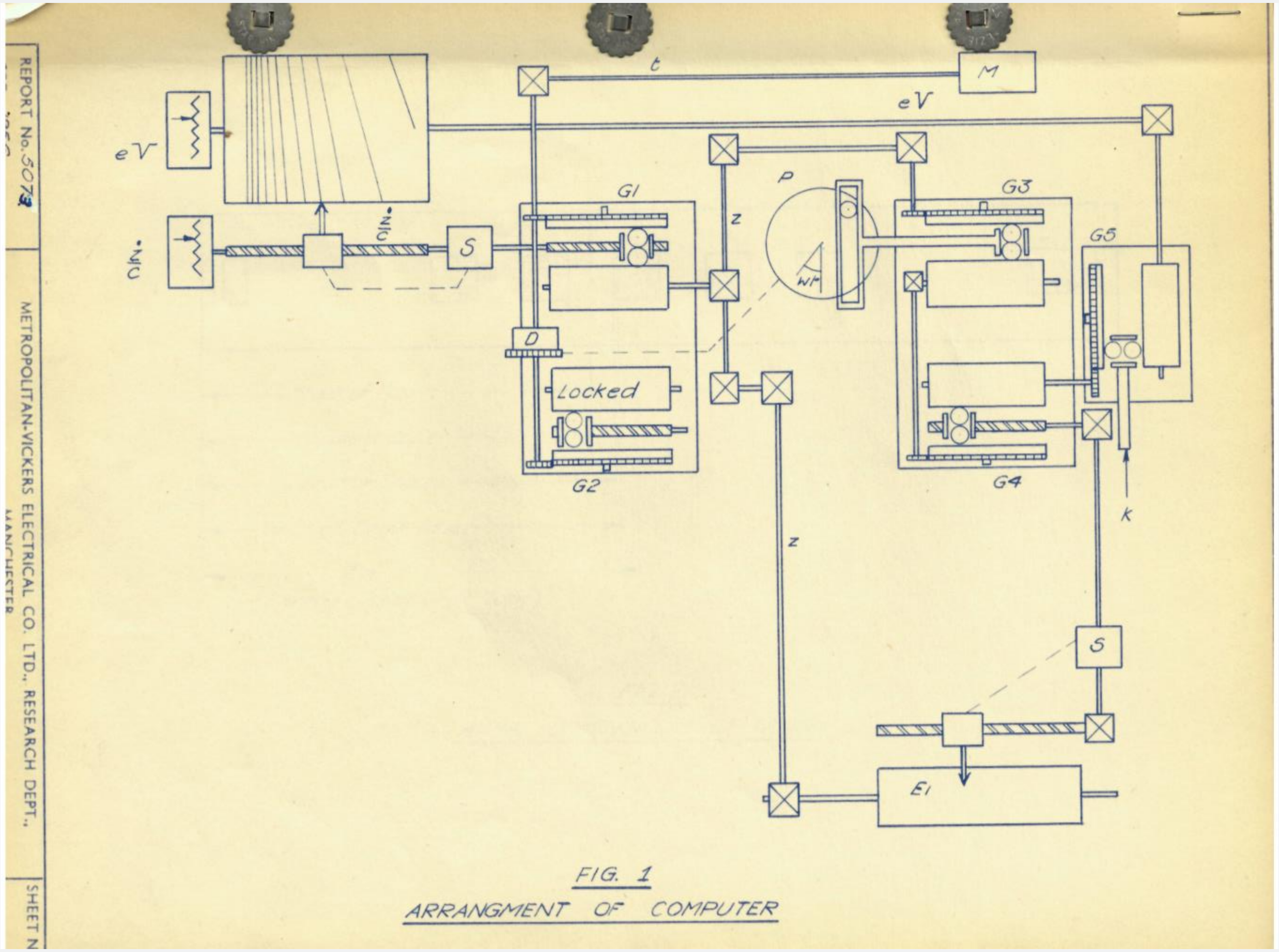


FIG. 1
ARRANGMENT OF COMPUTER

The ‘computer’.

No vector processing pipeline, high speed cache or GPU in sight.

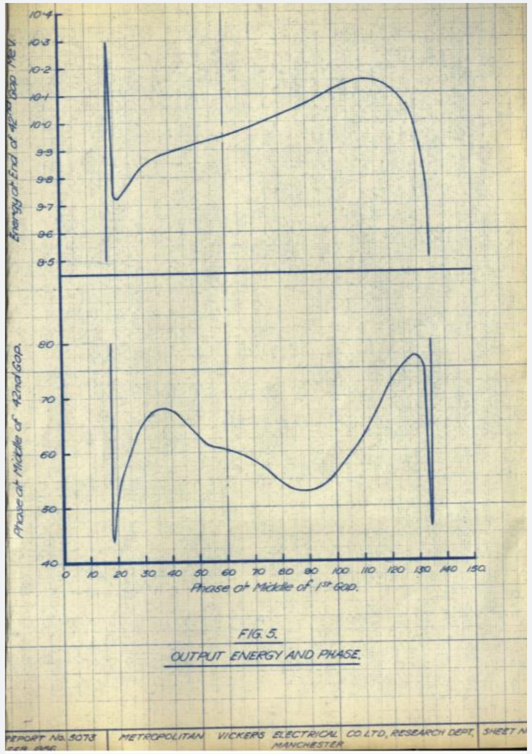


FIG. 5.
OUTPUT ENERGY AND PHASE.

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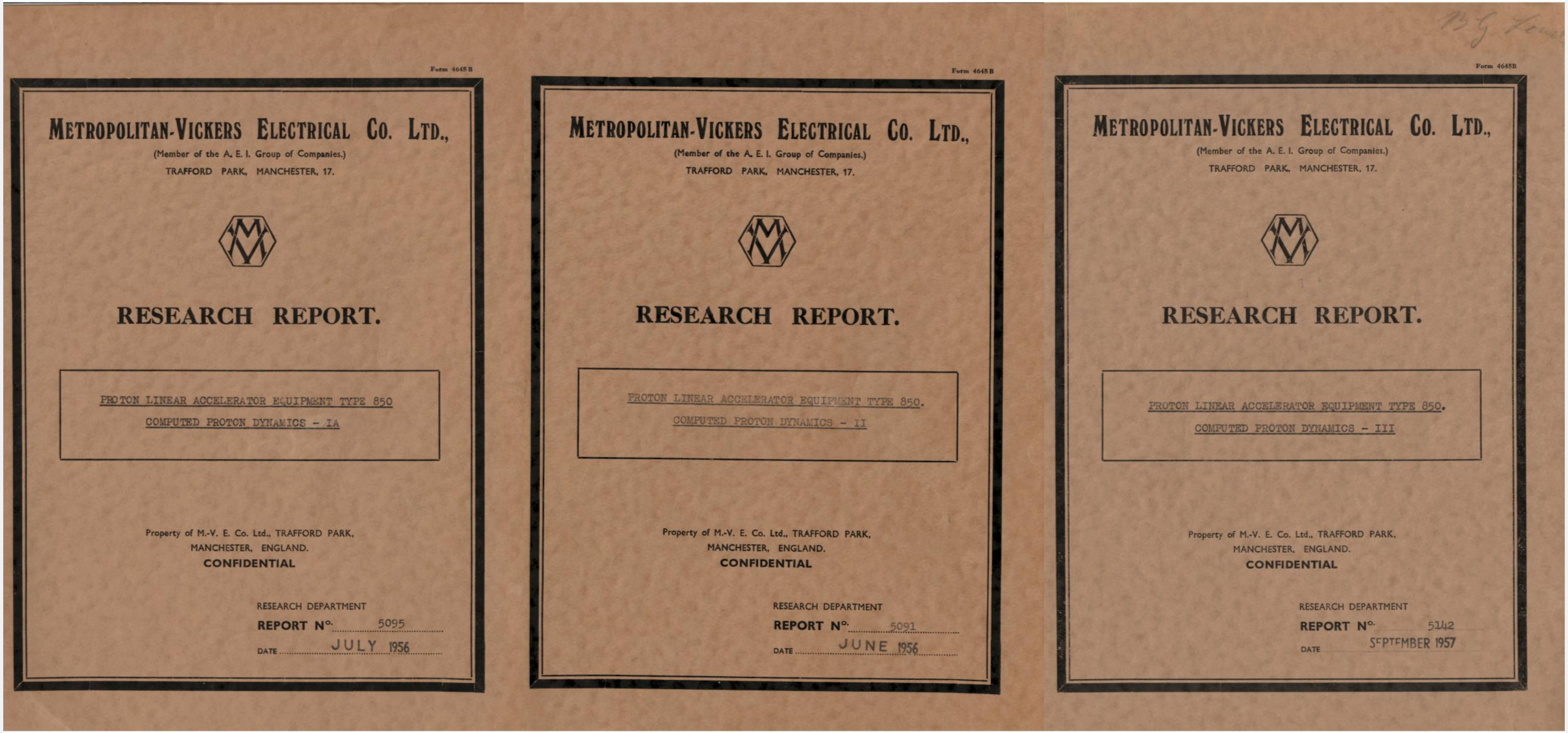
Metropolitan-Vickers design study



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RESEARCH REPORT.

PROTON LINEAR ACCELERATOR EQUIPMENT TYPE 850
COMPUTED PROTON DYNAMICS - IA

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REPORT No. 5095
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PROTON LINEAR ACCELERATOR EQUIPMENT TYPE 850.
COMPUTED PROTON DYNAMICS - II

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PROTON LINEAR ACCELERATOR EQUIPMENT TYPE 850.
COMPUTED PROTON DYNAMICS - III

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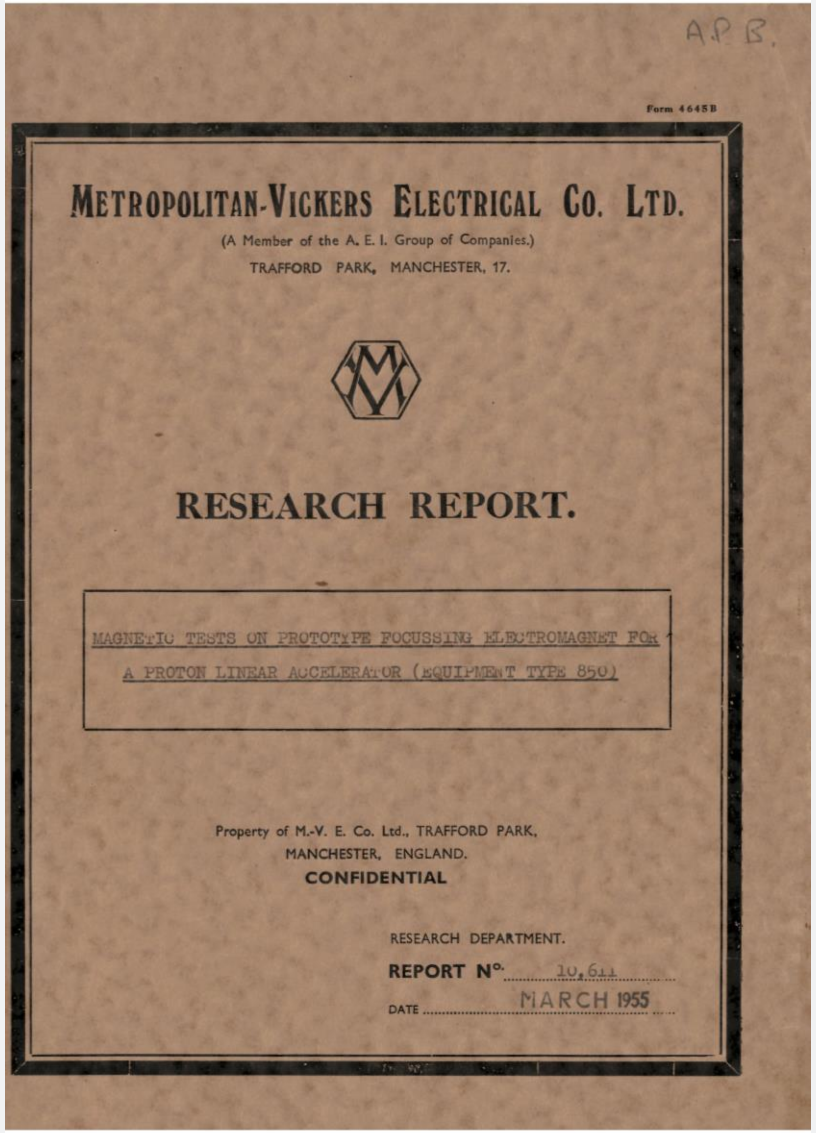
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RESEARCH REPORT.

MAGNETIC TESTS ON PROTOTYPE FOCUSSING ELECTROMAGNET FOR A PROTON LINEAR ACCELERATOR (EQUIPMENT TYPE 850)

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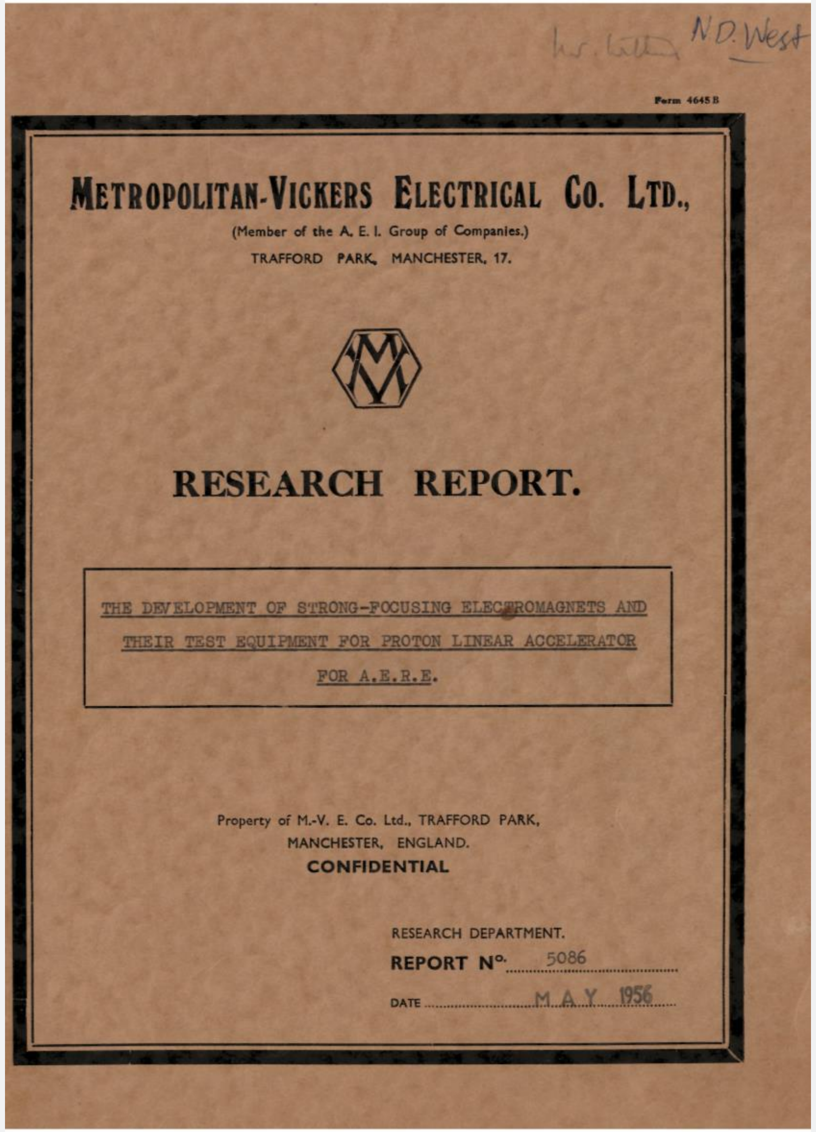
RESEARCH DEPARTMENT.
REPORT No. 10,611
DATE MARCH 1955


N.D. West

Form 4645B

METROPOLITAN-VICKERS ELECTRICAL CO. LTD.,
(Member of the A. E. I. Group of Companies.)
TRAFFORD PARK, MANCHESTER, 17.

RESEARCH REPORT.

THE DEVELOPMENT OF STRONG-FOCUSING ELECTROMAGNETS AND THEIR TEST EQUIPMENT FOR PROTON LINEAR ACCELERATOR FOR A.E.R.E.

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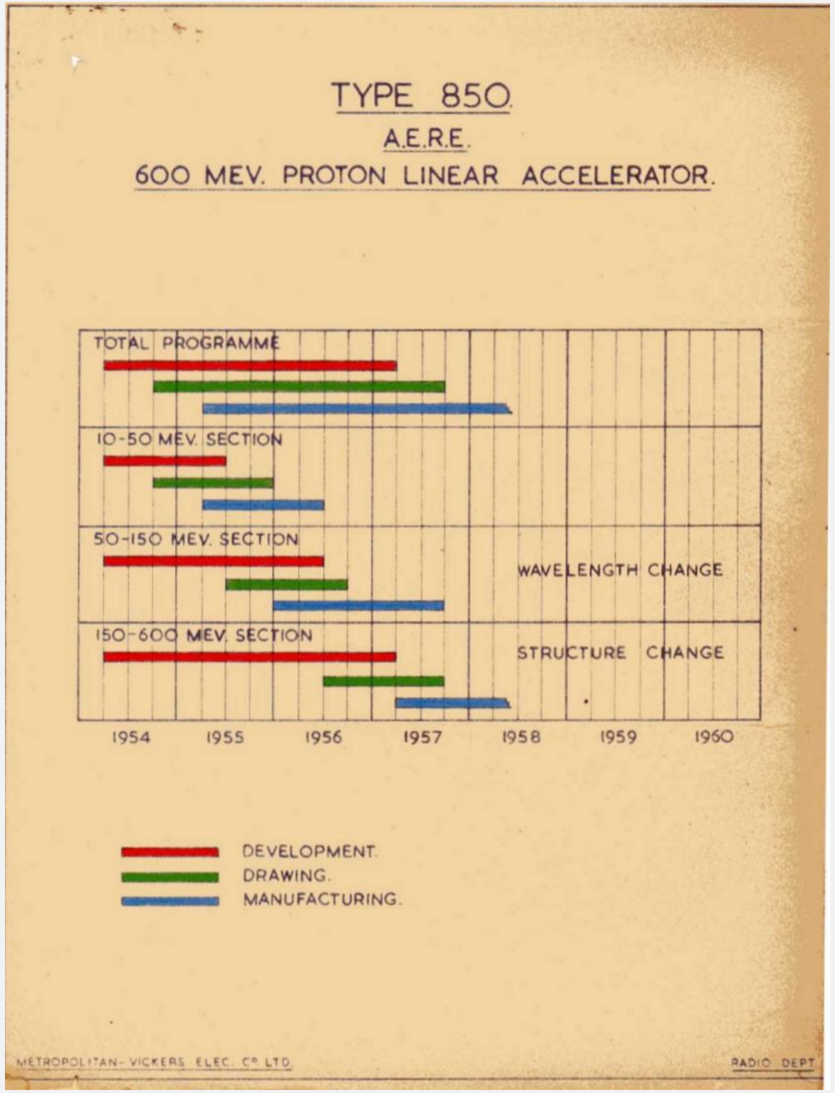
CONFIDENTIAL

RESEARCH DEPARTMENT.
REPORT No. 5086
DATE MAY 1956

Fig.1. Magnetic test on proton accelerator drift tube

Previously crude grid focussing had been used. To achieve strong AG focussing required electro-magnets and it wasn’t clear that such things could even be made to work.

Metropolitan-Vickers design study



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The PLA arrives at AERE

Circa 1956.

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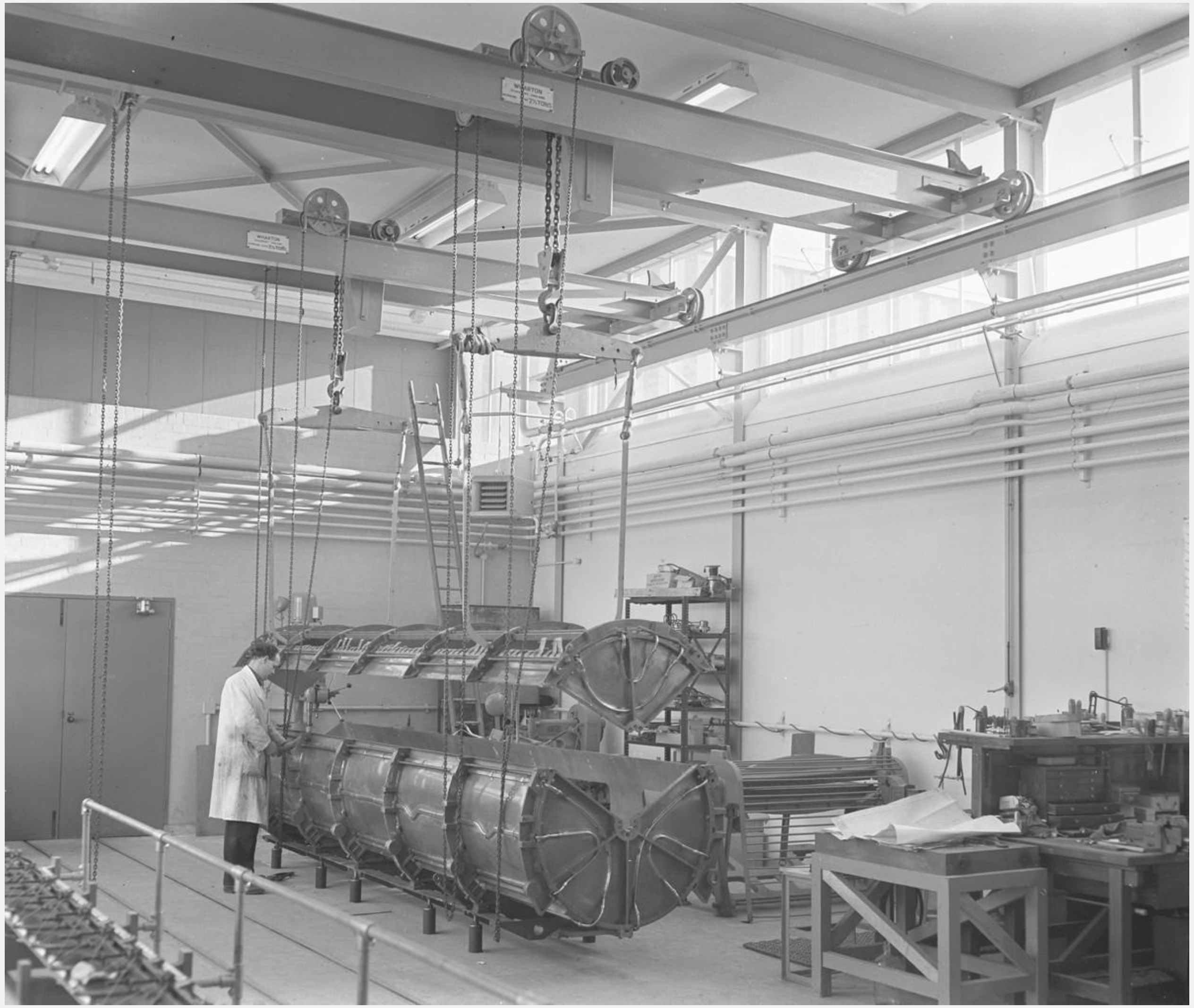
ISIS Neutron and Muon Source

The PLA arrives at AERE



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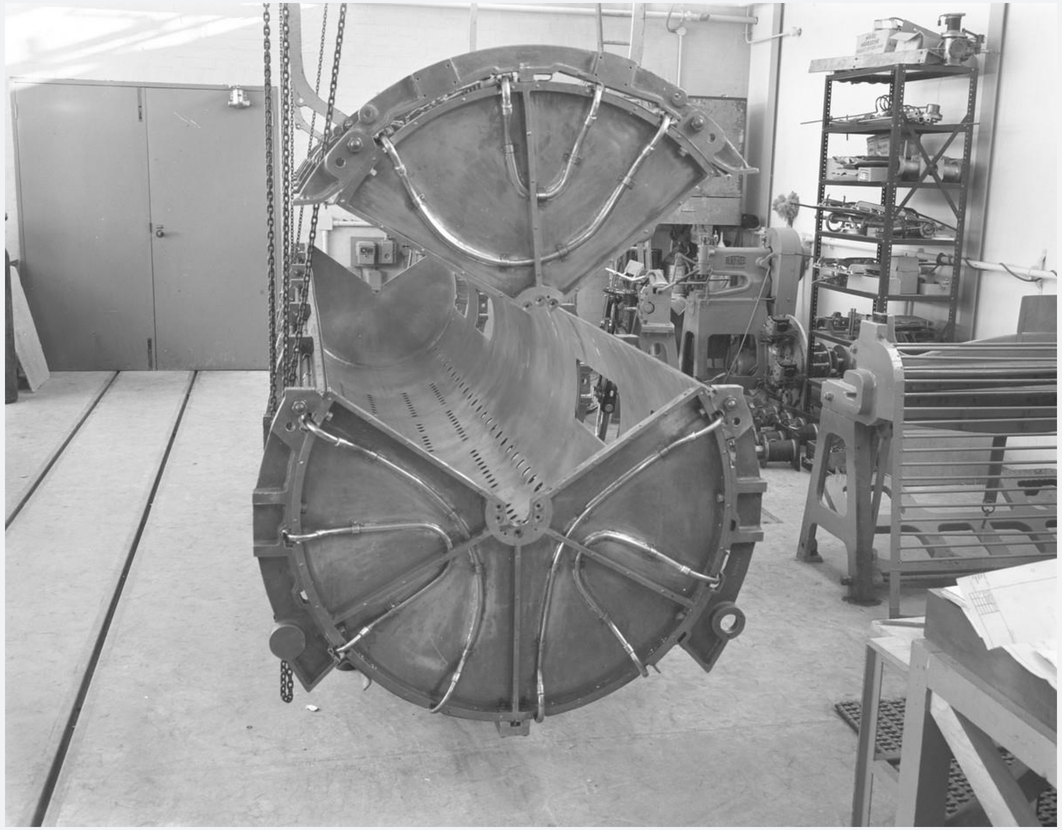
The PLA at AERE



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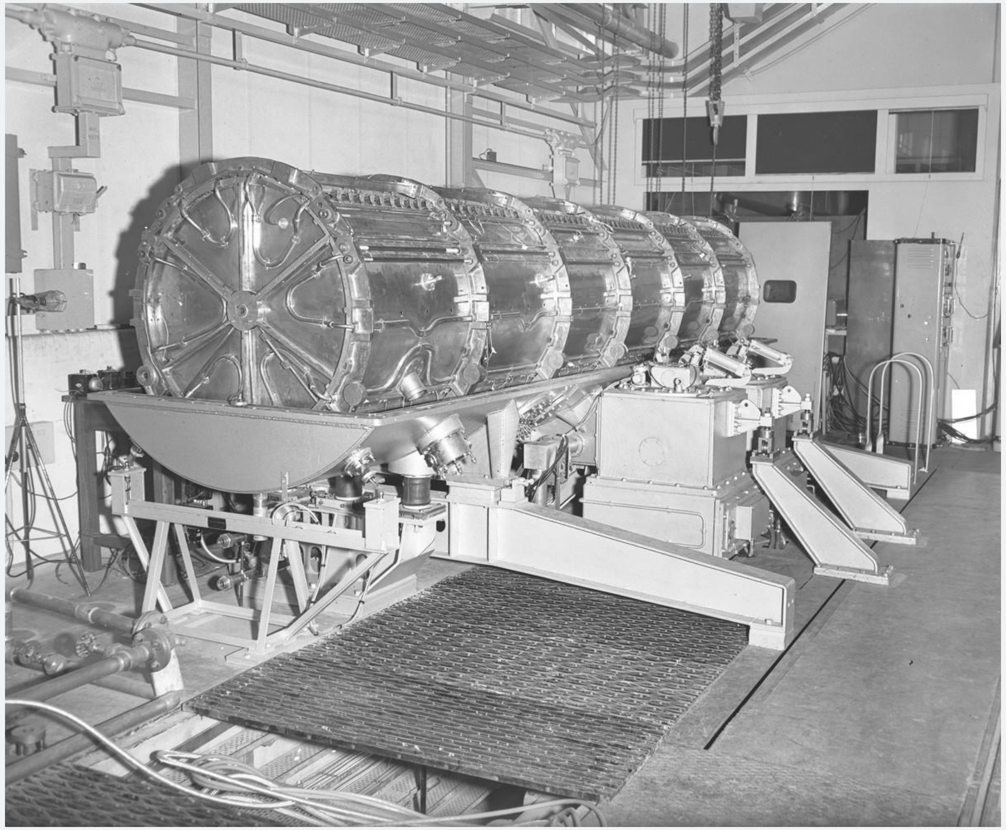
The PLA at AERE



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The Rutherford High Energy Laboratory

In 1957 the Rutherford High Energy Laboratory (RHEL), operated by the National Institute for Research in Nuclear Science (NIRNS), was created to take over the high energy physics activities of AERE. Harwell continued its atomic energy research under the auspices of the United Kingdom Atomic Energy Authority (UKAEA).

John Cockcroft breaking ground on the new RHEL site.

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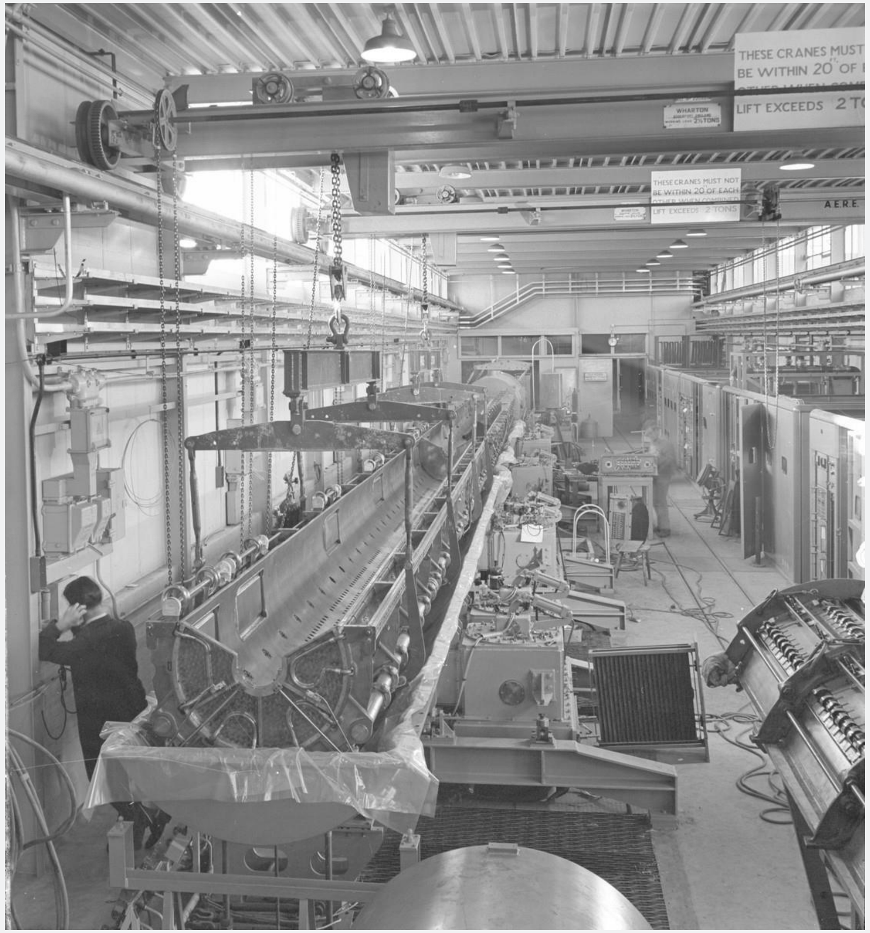
The PLA at RHEL



RHEL took on the task of completing the PLA.

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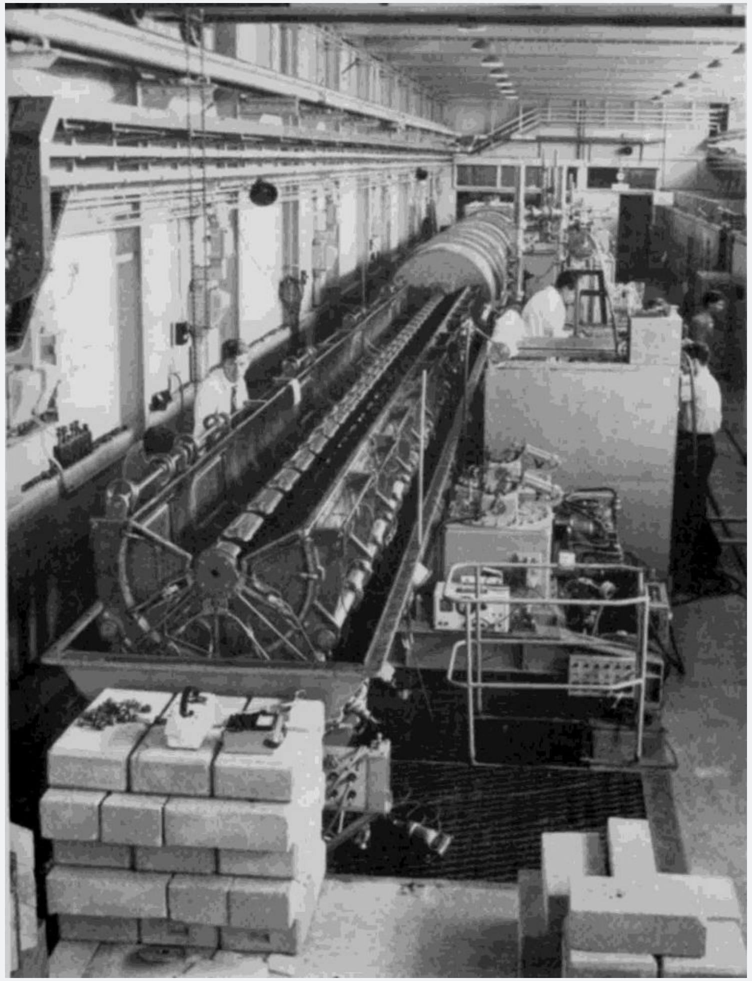
The PLA at RHEL



The PLA produced first beam at 30 MeV in 1959. Tank 3 at 50 MeV was commissioned in 1962

The PLA at RHEL

The PLA was operated for nuclear physics experiments until 1969.

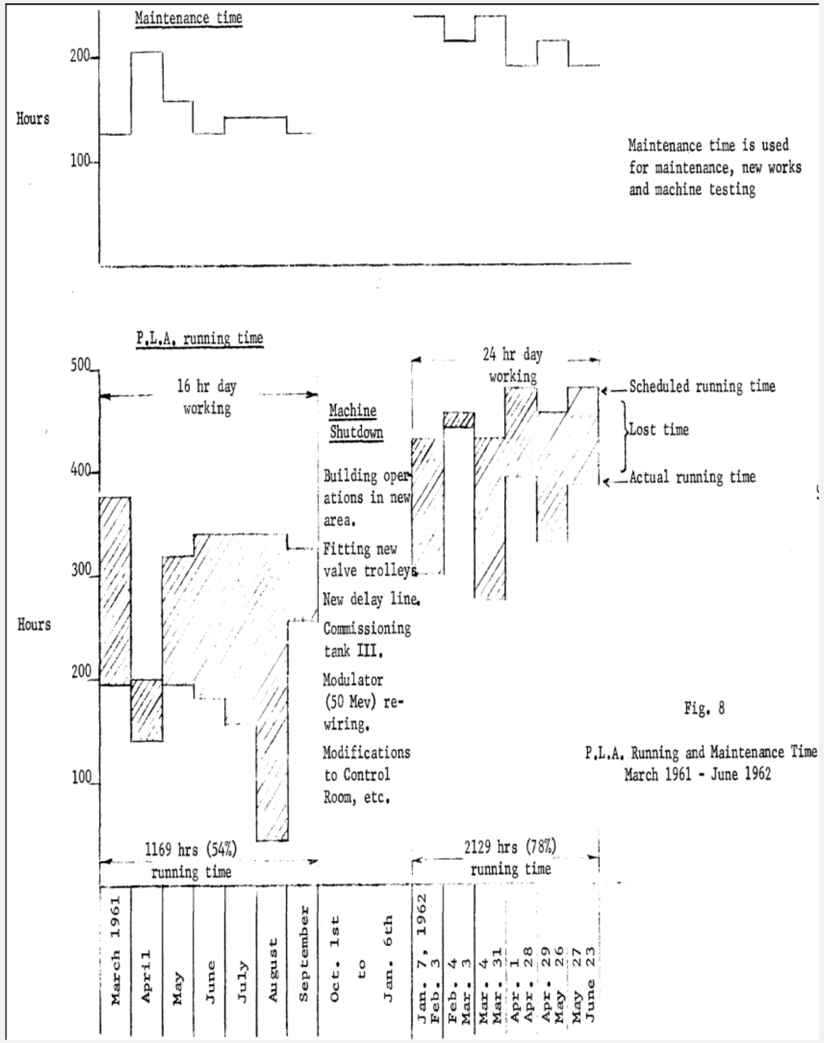


Fig. 8

P.L.A. Running and Maintenance Time March 1961 - June 1962

Early PLA availability date from 1962.

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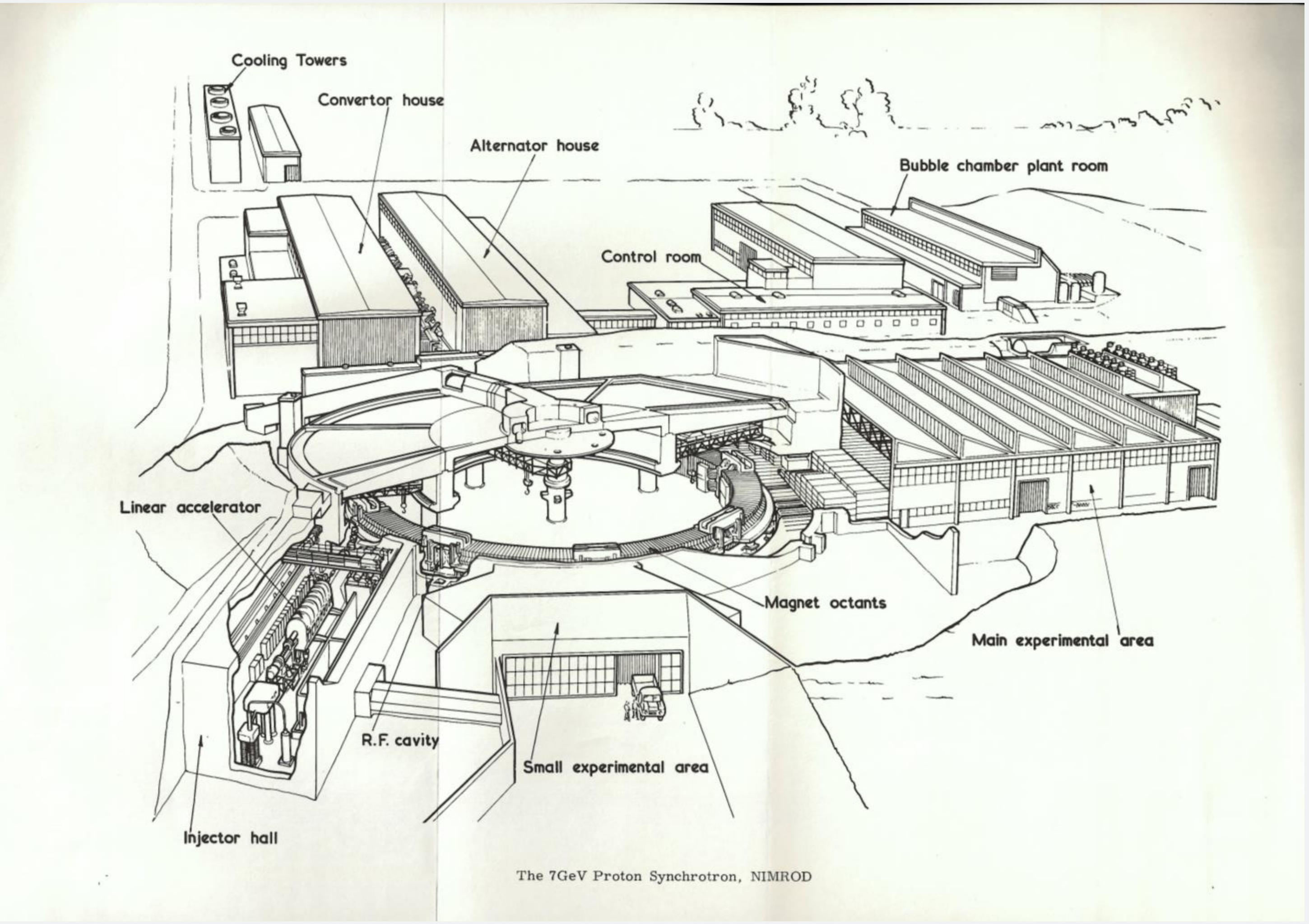
The NIMROD synchrotron

As well as the PLA, RHEL was responsible for constructing the Nimrod 7 GeV synchrotron. Construction started in 1957 with first beam in 1964.



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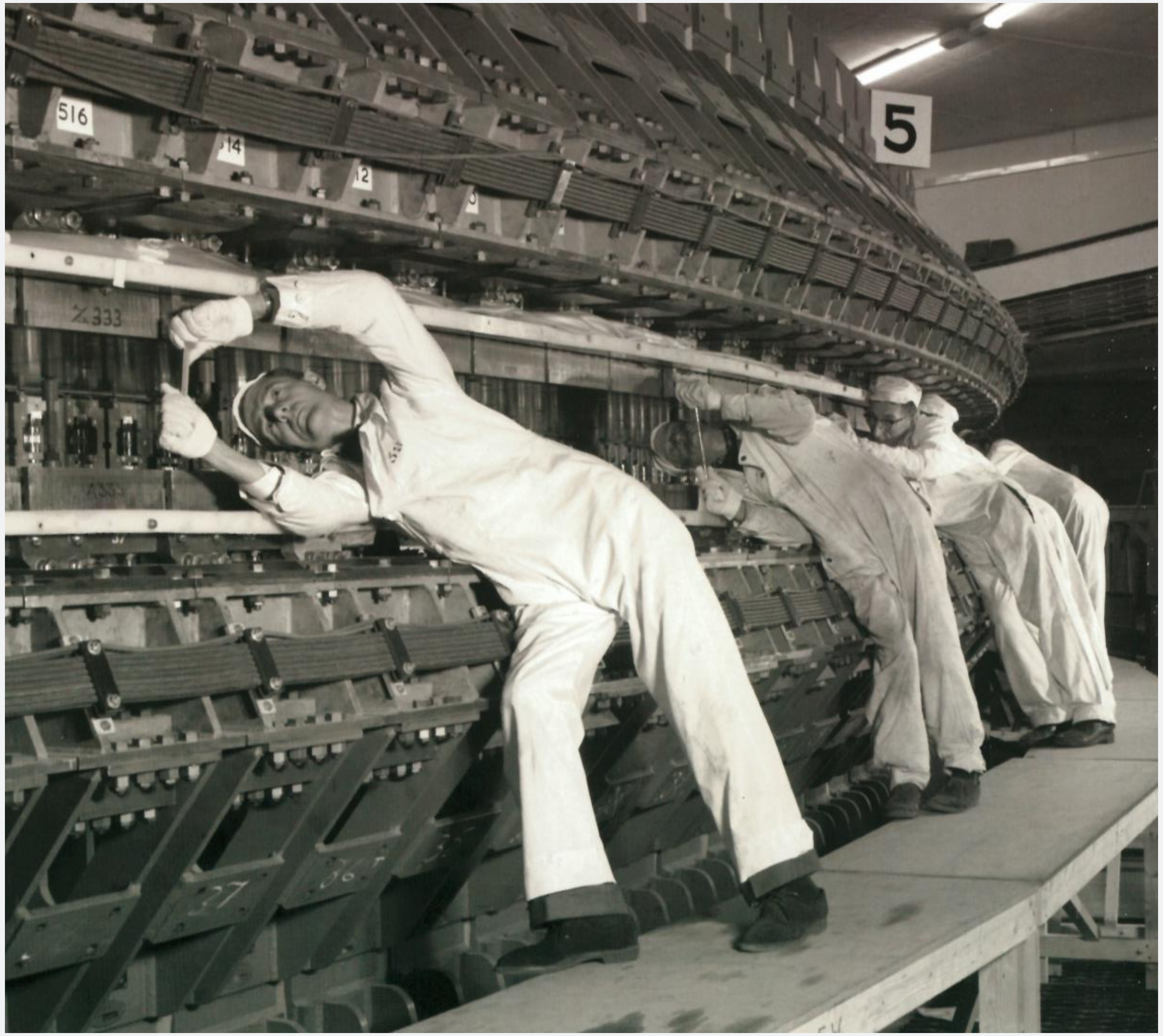
The NIMROD synchrotron

Nimrod was a weak focussing synchrotron which ultimately limited its performance.



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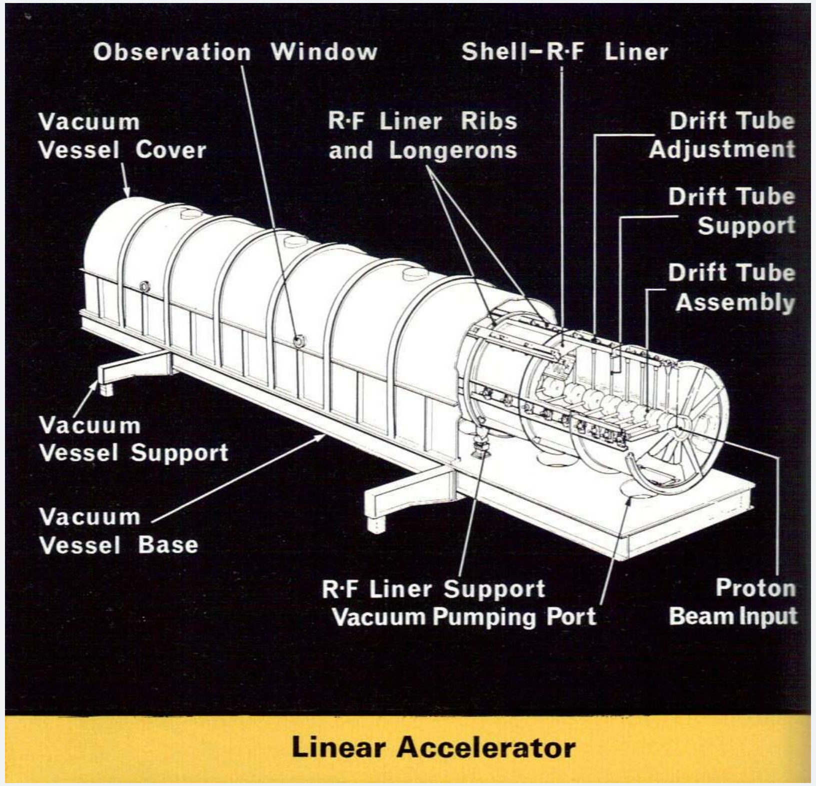
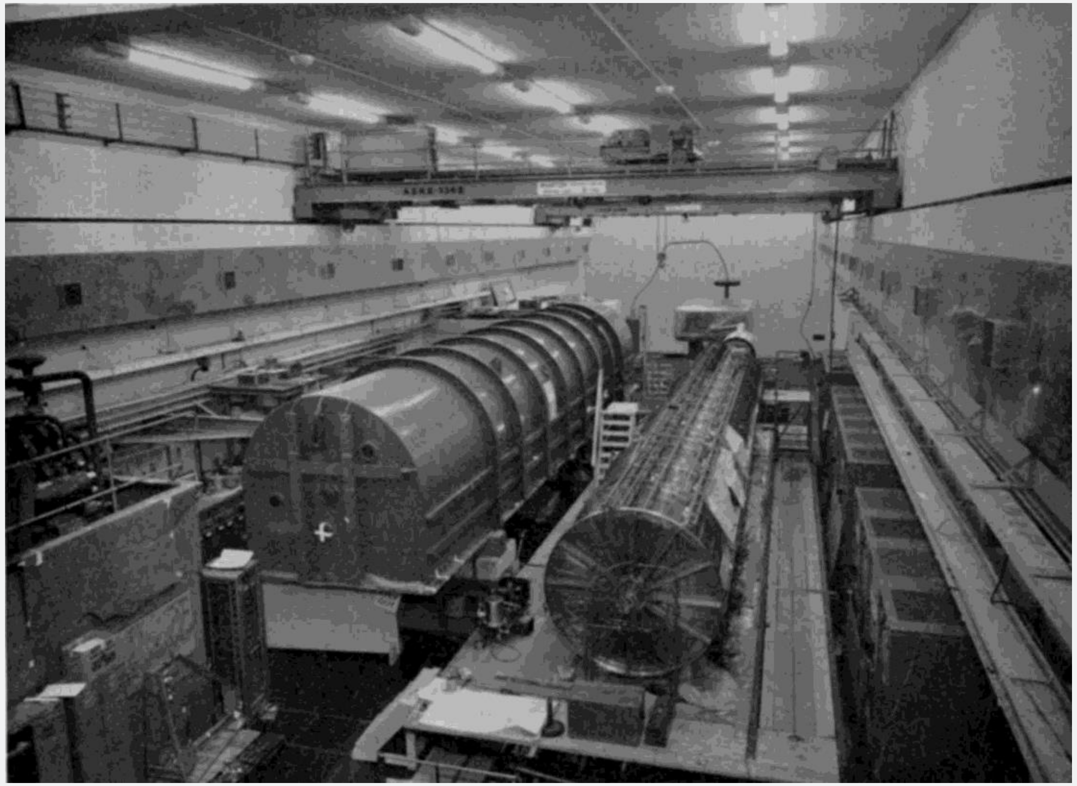
The NIMROD Injector

Nimrod had a single tank 15 MeV injector and 500 keV Cockcroft-Walton pre-injector.





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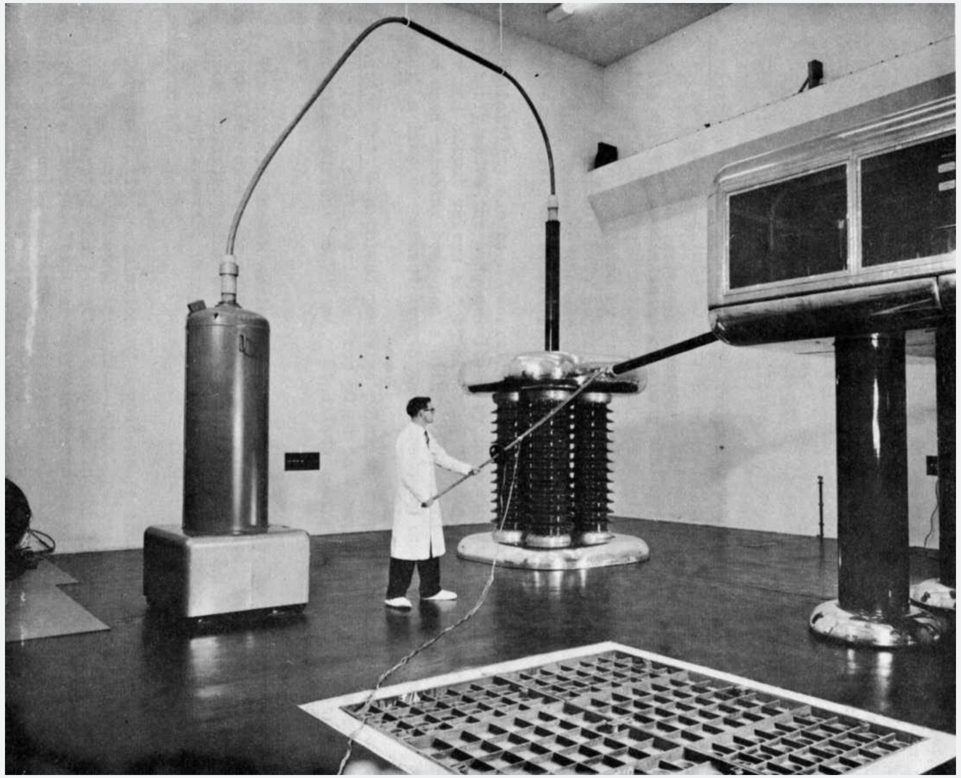
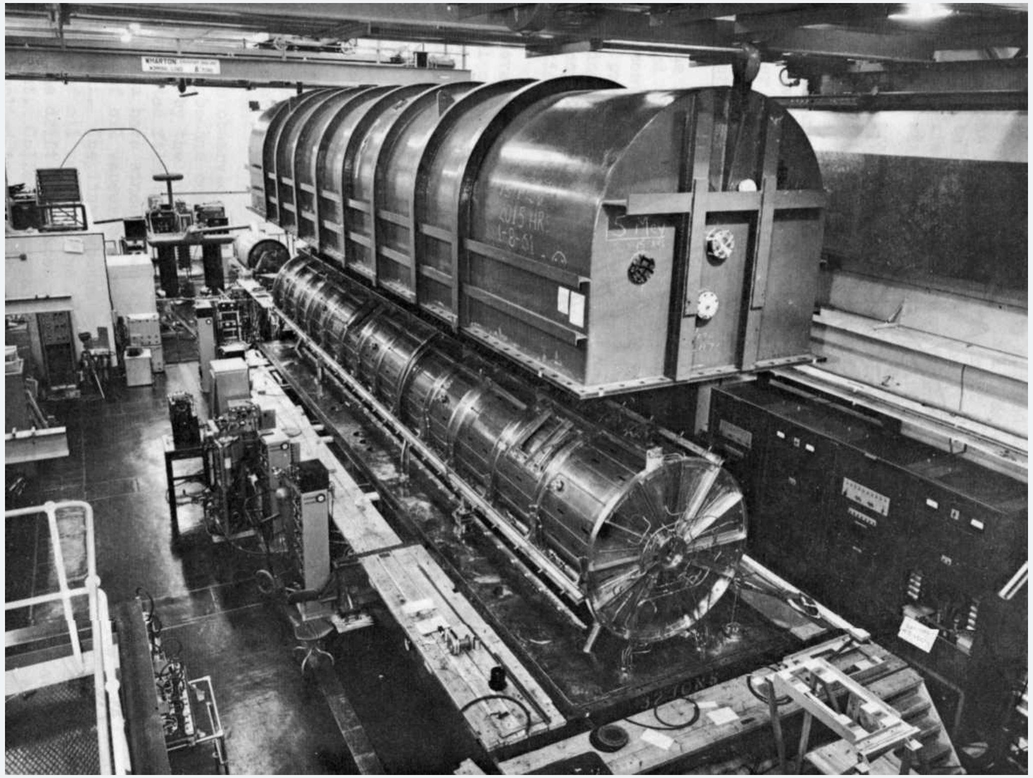
The NIMROD Injector

The 15 MeV injector was based heavily on the design of the PLA.





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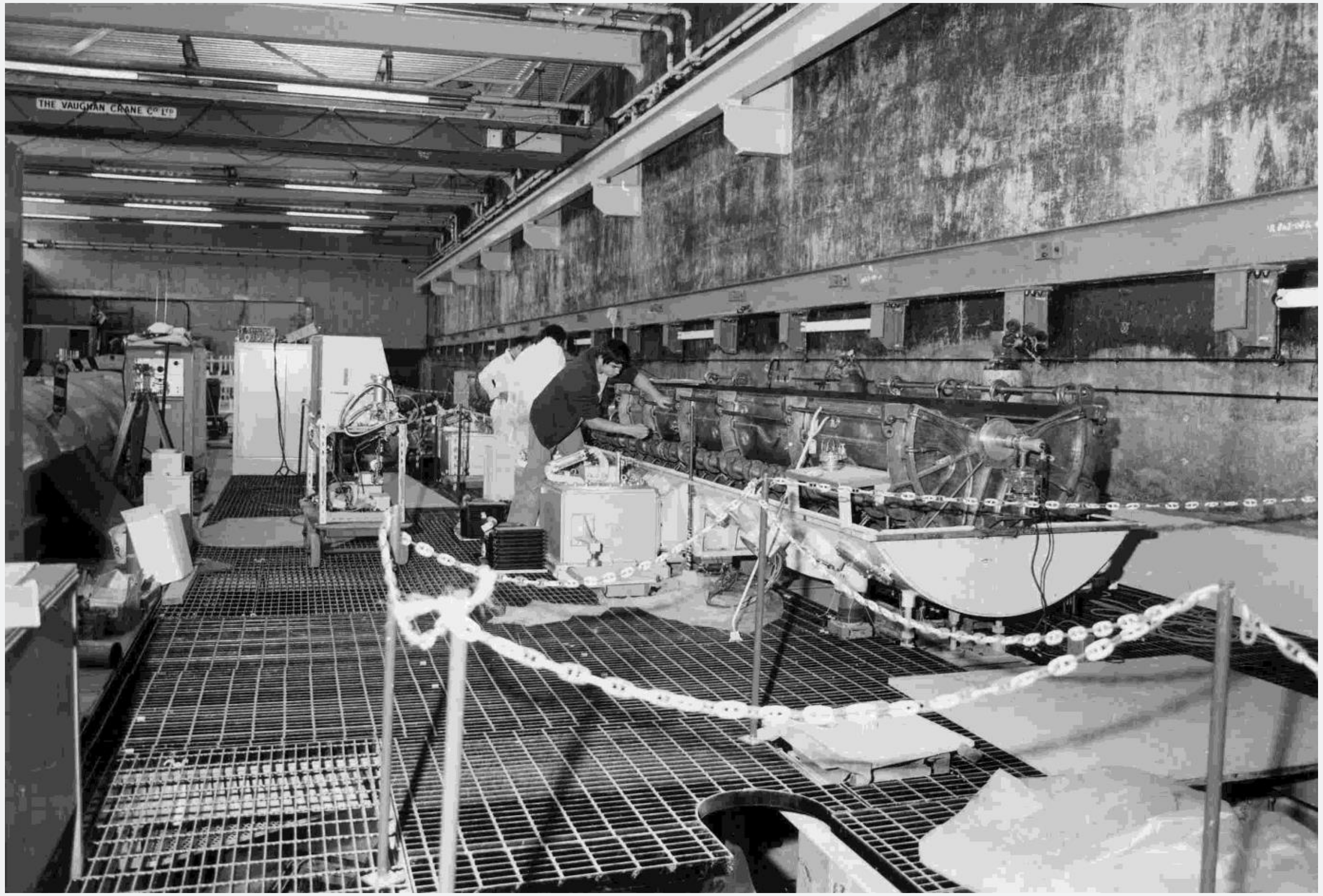
The NIMROD Injector Upgrade

In 1972 a 70 MeV injector upgrade was approved. It would re-use Tanks 2 (30 MeV) and 3 (50 MeV) from the PLA together with a new 665 keV pre-injector, Tank 1 (10 MeV) and Tank 4 (70 MeV).



PLA Tank 3 being installed in the new Nimrod injector.

The NIMROD Injector Upgrade

The 70 MeV linac delivered its first beam in 1976.

Meanwhile it had been decided to close Nimrod in 1978 so the new linac was never used for Nimrod.

Note that by then parts of the 'new' injector were already 20 years old.

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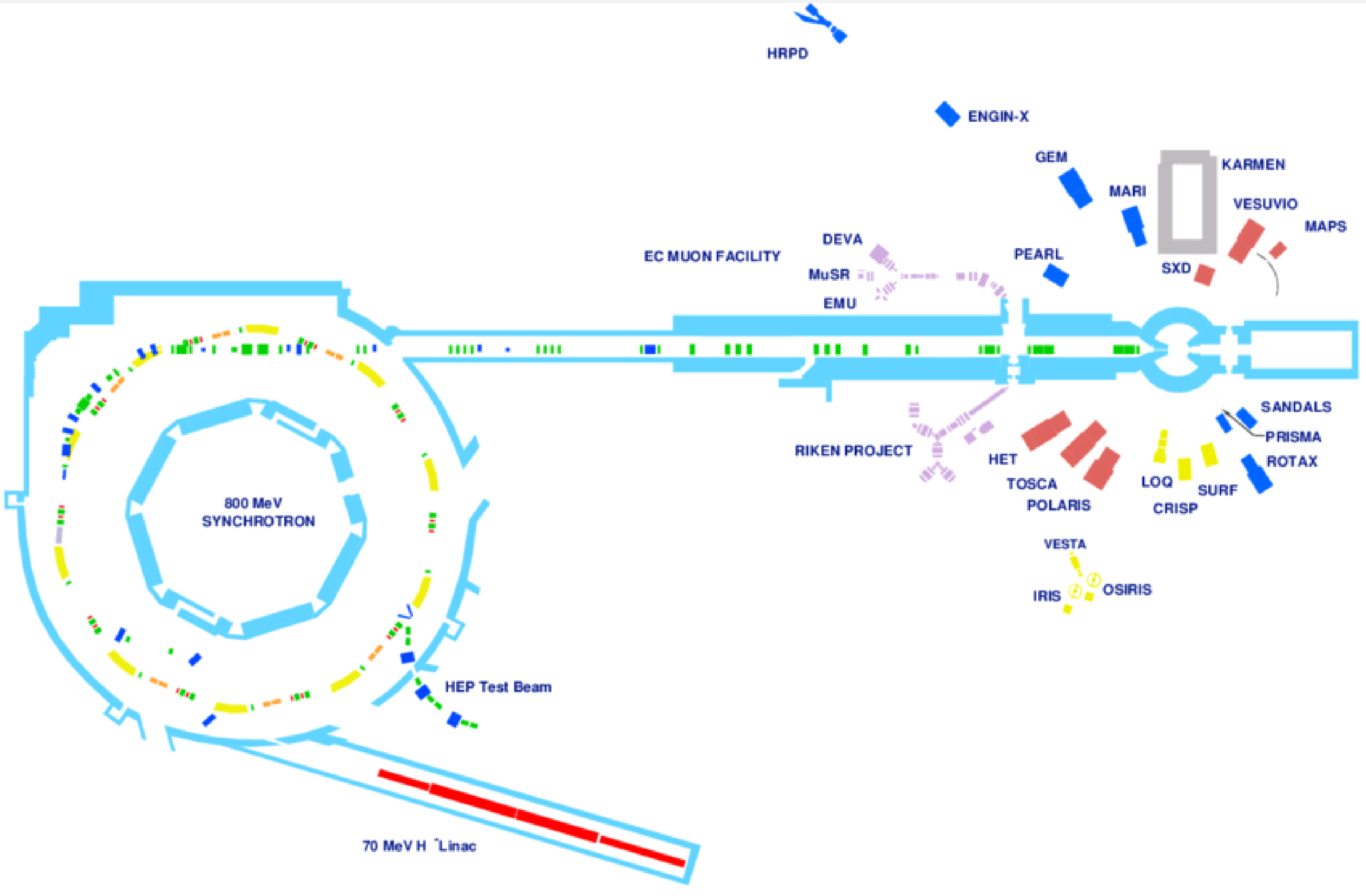
The ISIS Pulsed Spallation Neutron Source

Following the closure of Nimrod approval was given to build the ISIS neutron source. Based around an 800 MeV rapid cycling synchrotron it would re-use much of the infrastructure and some equipment from Nimrod.



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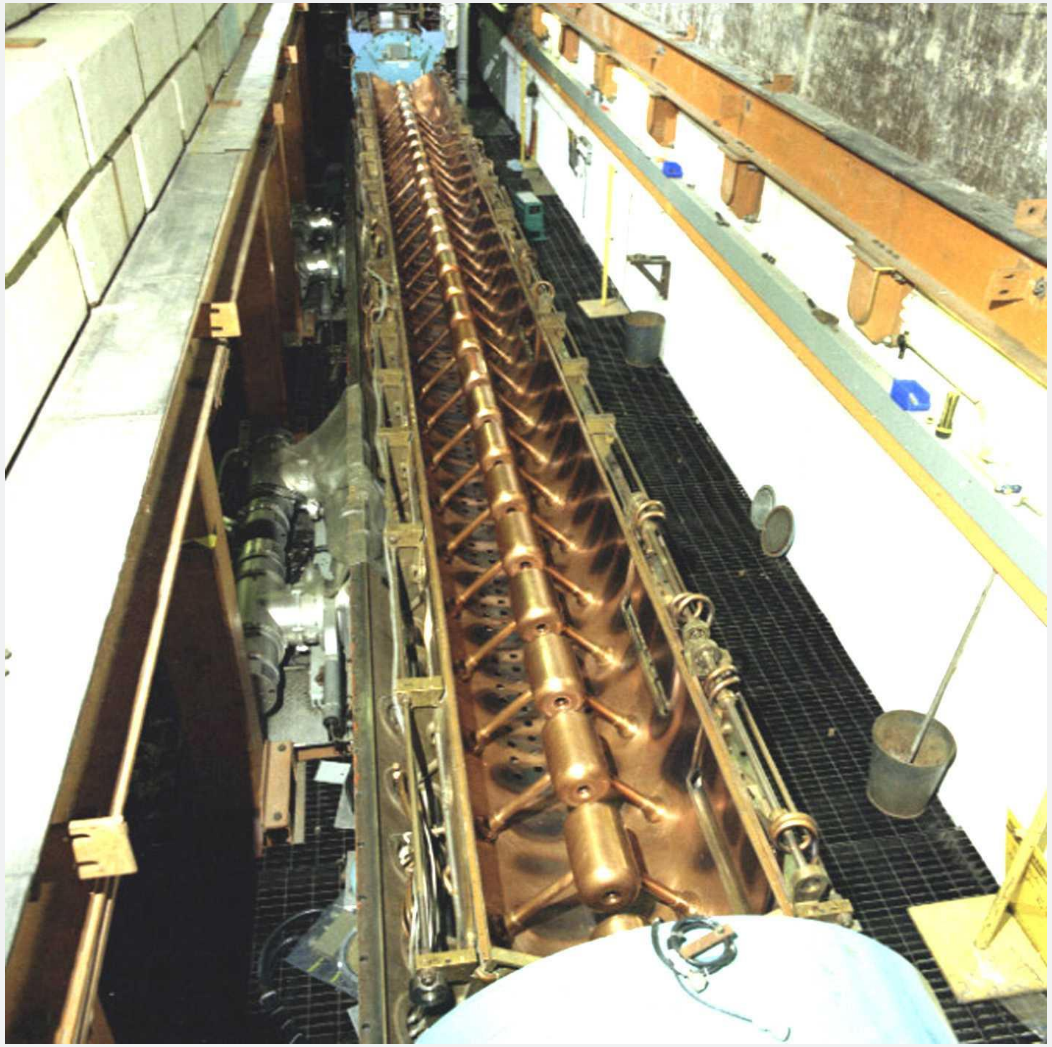
The ISIS Pulsed Spallation Neutron Source

ISIS was relatively cheap due to this recycling. It is also part of the reason for the name: ISIS is the Egyptian goddess of resurrection.

The ISIS strong focussing, rapid cycling synchrotron in the hall originally built for Nimrod.

The ISIS 70 MeV Linac

The ISIS injector using the old new Nimrod injector was upgraded from a 1 pps proton linac to a 50 pps H- linac.



ISIS produced its first neutrons in 1984.

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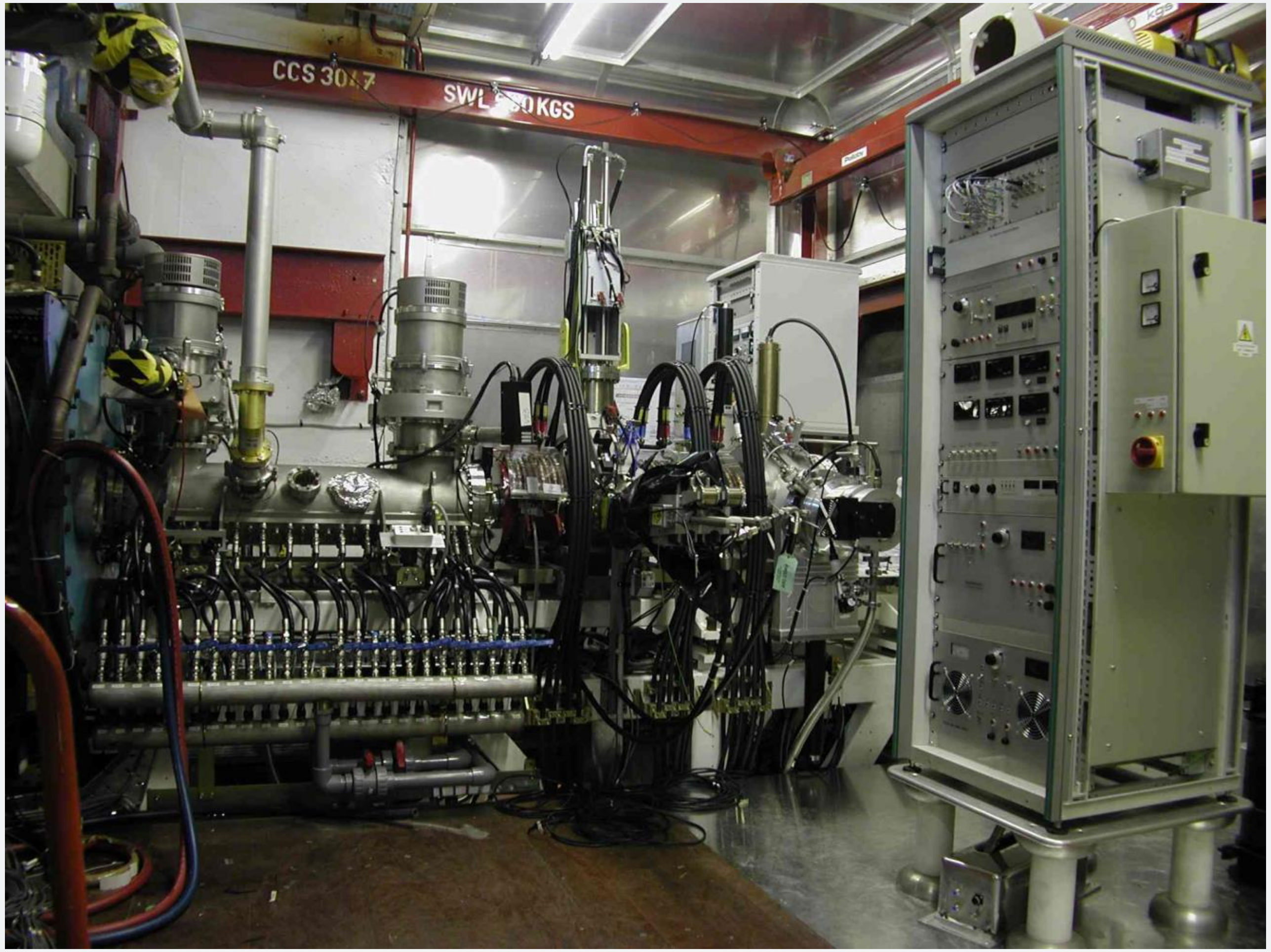
The ISIS Pre-injector Upgrade

In the mid 1990s a decision was taken to replace the aging and somewhat unreliable 665 keV Cockcroft Walton pre-injector.

The ISIS Pre-injector Upgrade

The pre-injector was replaced with a 665 keV Radio Frequency Quadrupole (RFQ) in 2004. The RFQ was still quite a new technology so significant offline testing was performed.



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Tank 4 replacement

Tank 4 is one of the 'new' tanks made in the 1970s. It is made in a much more recognisably modern way compared to the 1950s Tanks 2 & 3.

Some of the internal welds cracked at the time of manufacture.

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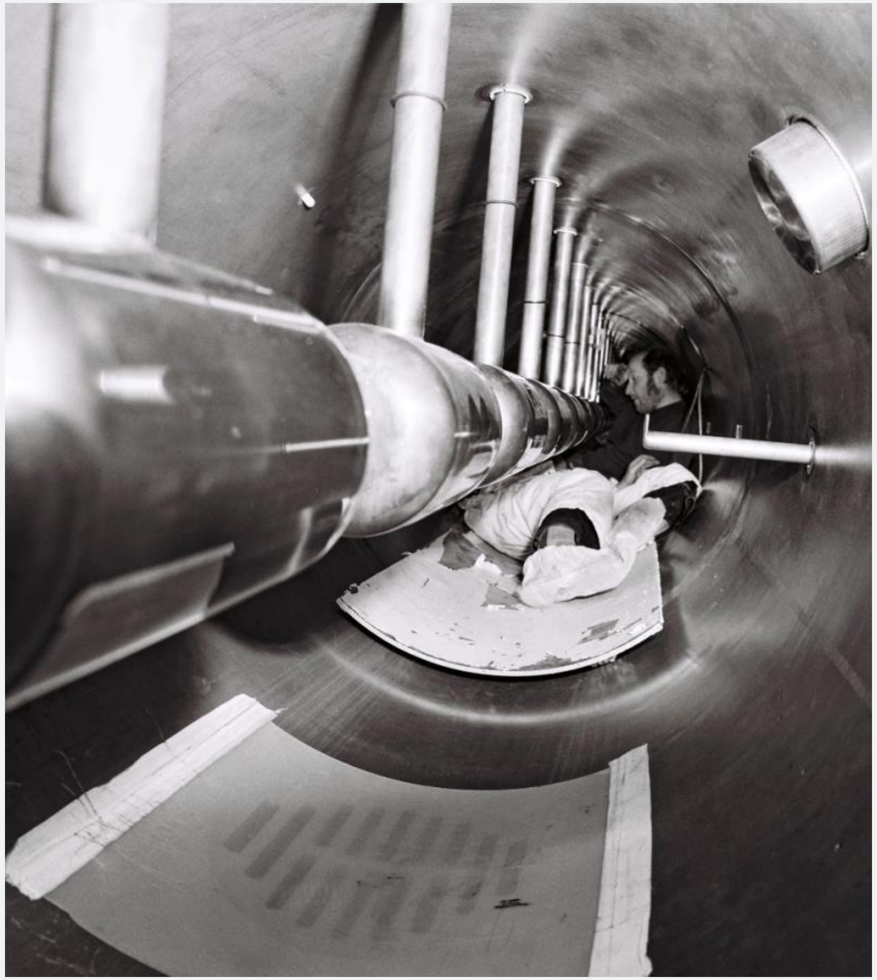
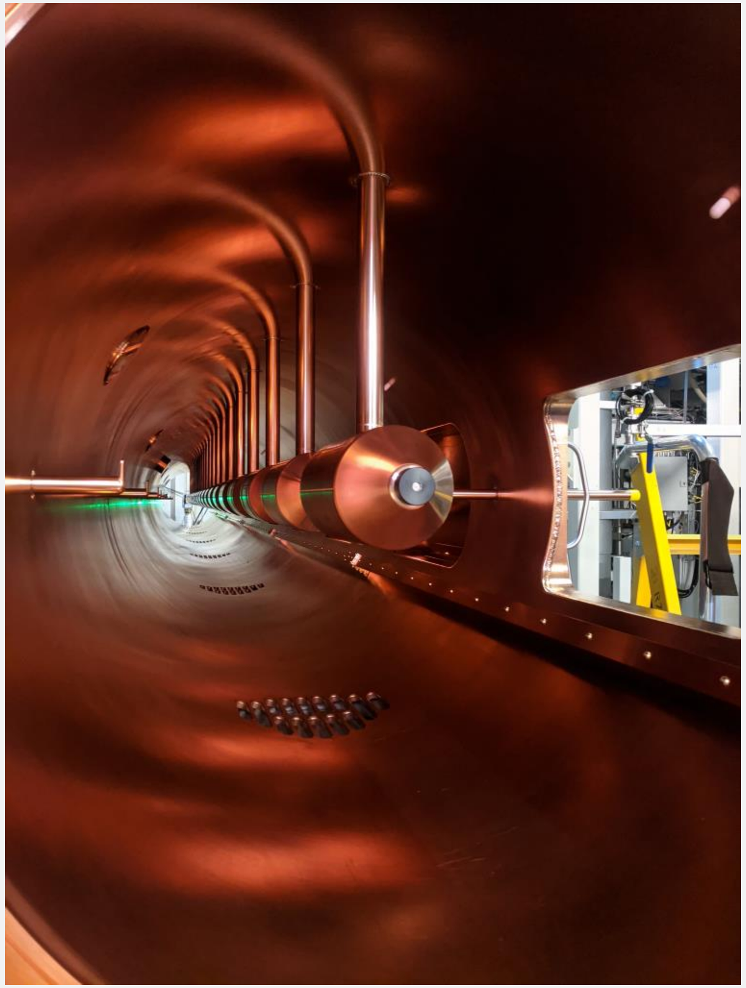
Tank 4 replacement

Patches were fitted over the vacuum leaks which allowed several decades of operation but eventually the leaks became too bad with no reasonable means of repair.



Tank 4 replacement

A brand new tank was designed, constructed and tested offline. With essentially the same beam dynamics but improved engineering and lower power requirements.



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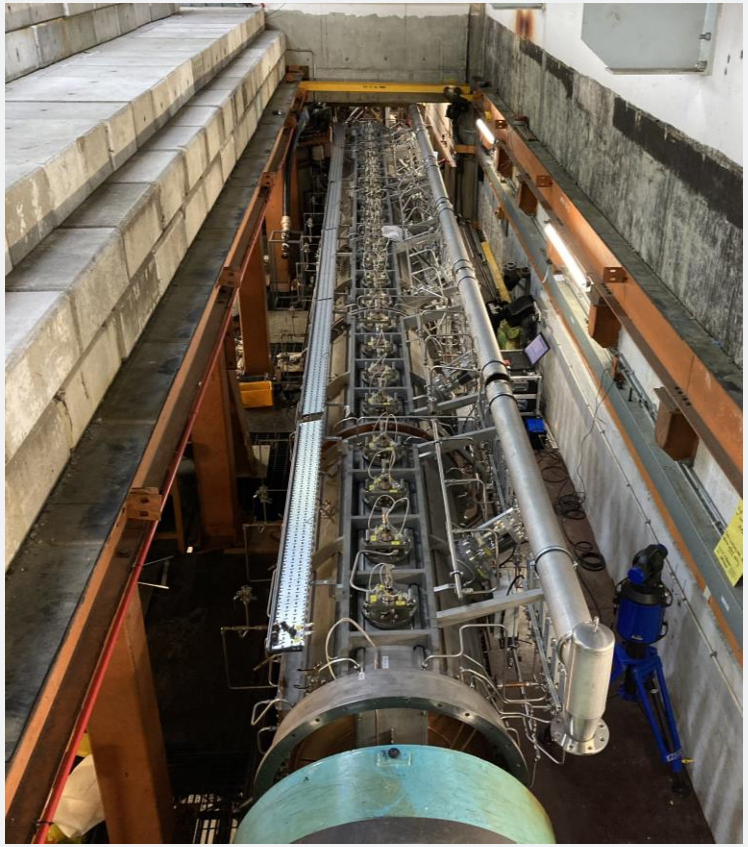
Tank 4 replacement

The new tank was installed and commissioned in the linac in 2022. First operational beam was delivered in early 2023.



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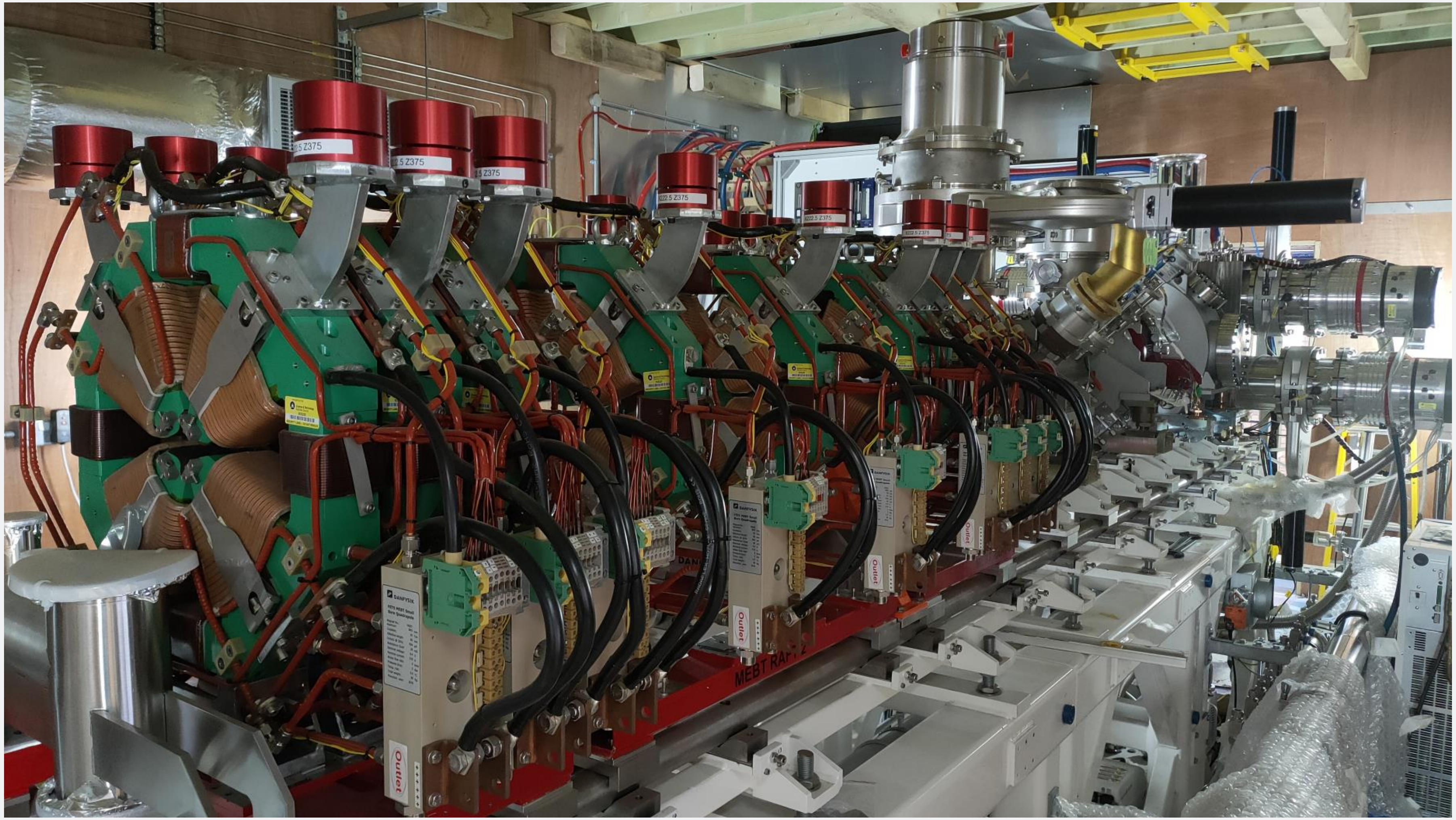
The Future

A new Medium Energy Beam Transport and RF driven ion source which will further improve performance and reliability are currently being constructed and tested.



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Summary

- The ISIS Linac can trace its lineage directly back to the very earliest days of accelerators in the UK

- In the 1950s scientists and engineers at AERE Harwell began designing one of the few Alvarez type RF proton linear accelerators anywhere in the world at the time.

- Designed with pen and paper and an analogue computer, as of 2023 Tanks 2 & 3 of that linac are still operational after nearly 70 years of use.

- Other newer equipment has failed or been replaced while the old tanks keep on going.

- The method of construction makes the old technology almost endlessly repairable.

- Upgrades to the ISIS Linac are being planned on the assumption that the facility will operate for another 10 – 20 years by which time the ex-PLA tanks will be approaching 90 years old.