The Liverpool 156-inch synchrocyclotron

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of LIVERPOOL

Artifical disintegration

To penetrate deep into the centre of matter requires beams of high energy particles. At first, until 1932, these came from natural (radioactive) sources but it became clear that artificially accelerated beams would be the next step in disintegrating atomic nuclei.

Cockcroft and Walton built the first machine that could do this in April 1932, but a much more powerful and versatile machine become available within a few months.

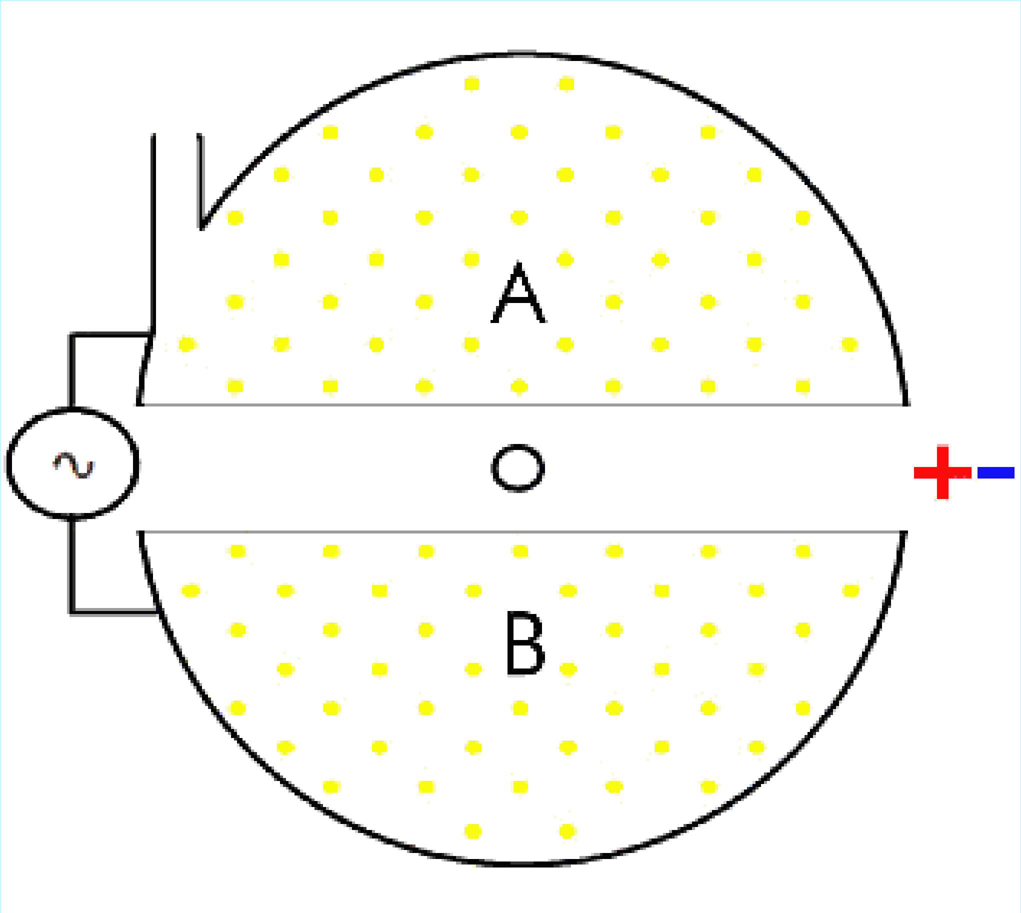
This was the cyclotron, which had first been made operational by Ernest Lawrence at Berkeley in January 1931 and performed its first disintegration in September 1932.

Cyclotron

Essentially, the limitation of other accelerators such as the Cockcroft-Walton machine, the Van de Graaff accelerator, and the linear accelerator was that the acceleration was done by an electrostatic field in a single operation. However, the cyclotron allowed repeated acceleration by using a spiral path produced by accelerating charged particles across a gap between two D-shaped electrodes and the pole pieces of a large magnet.

An electric field alternating at a constant frequency saw the particles increasing in energy with every cycle, with a corresponding increase in the radius of orbit. However, each cycle took the same amount of time, ensuring that the particles maintained the same frequency of rotation as the oscillating field.

The cyclotron



James Chadwick, c 1935

James Chadwick, at Cambridge, saw the importance of the cyclotron for nuclear physics and tried to persuade Rutherford to build one.

His failure to do this led to him leaving Cambridge in 1935. Liverpool saw the opportunity and took him on as their new Head of Department with the promise of whatever money he needed to build his machine.

Chadwick's cyclotron

Chadwick's 37-inch cyclotron took four years to construct – in the basement of the George Holt Building – and produced its first beams in July 1939. Unfortunately World War II intervened and a large part of the research programme had to be diverted to the war effort, specifically the capture cross-sections of neutrons in uranium and plutonium.

Chadwick, Otto Frisch, Joseph Rotblat and other members of the Liverpool team spent the latter years of the war working on the Manhattan Project, to which they had contributed much crucial information.

The synchrocyclotron

The very significant contribution of Chadwick and Liverpool to the war effort was rewarded with the offer to the Department of a more advanced research machine. This was a synchrocyclotron, which significantly upped the energy available for collisions and transformed the device from a nuclear physics to a particle physics machine (from a few MeV to around 400 MeV).

Previously, particle physics discoveries were made with cosmic rays and other natural sources, using random events captured in cloud chamber photographs or using photographic emulsions.

Now, it was possible to direct beams at targets with enough energy to initiate particle physics events, under controlled conditions and for precision experiments to be made.

The synchrocyclotron

The limitation of the original type of cyclotron was that the accelerating particles increased in mass due to the relativistic effect, which then caused them to slow down.

The synchrocyclotron overcame this by using a synchronized RF field to compensate for the increased mass, the key component being a rotating condenser. It also eliminated one of the Dees because the unlimited number of cycles the particles could take meant that the strong electric field of the cyclotron wasn't required. The condenser and the single dee formed a tuned capacitor-inductor circuit.

Chadwick started the process of designing and constructing the new machine at Liverpool but he did not stay to see it completed. He left to become Master of Caius College, Cambridge in 1948.

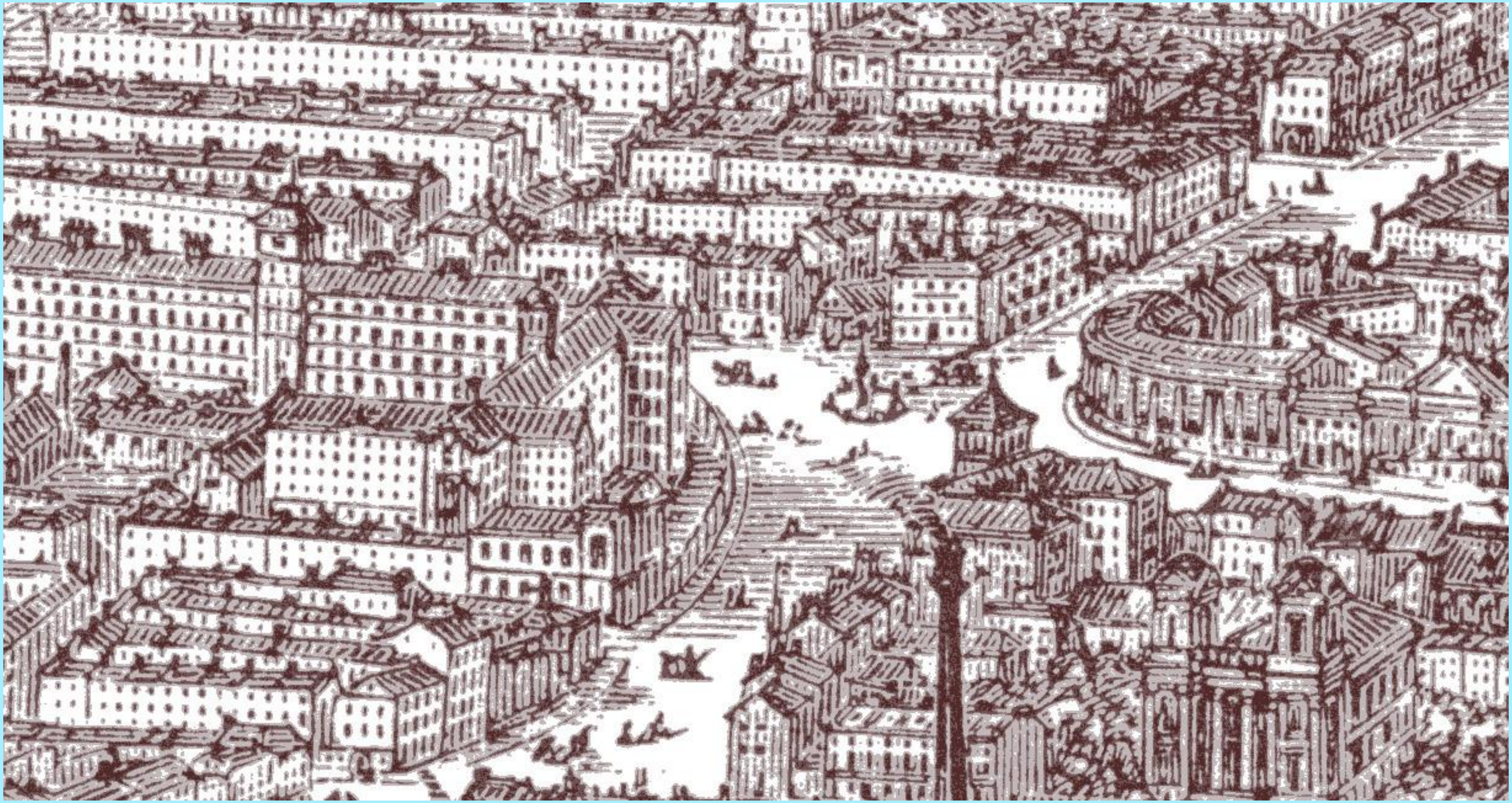
Plans for the construction

Plans were drawn up to build the machine on land obtained on lease near the RC Cathedral, then under construction on Mount Pleasant.

Joseph Rotblat, who was temporarily in charge during Chadwick’s absence, claimed that he got the idea of building underground in the cathedral mound after a visit to the catacombs in Rome, clerics there pointing to the massive crypt in the then unfinished cathedral.

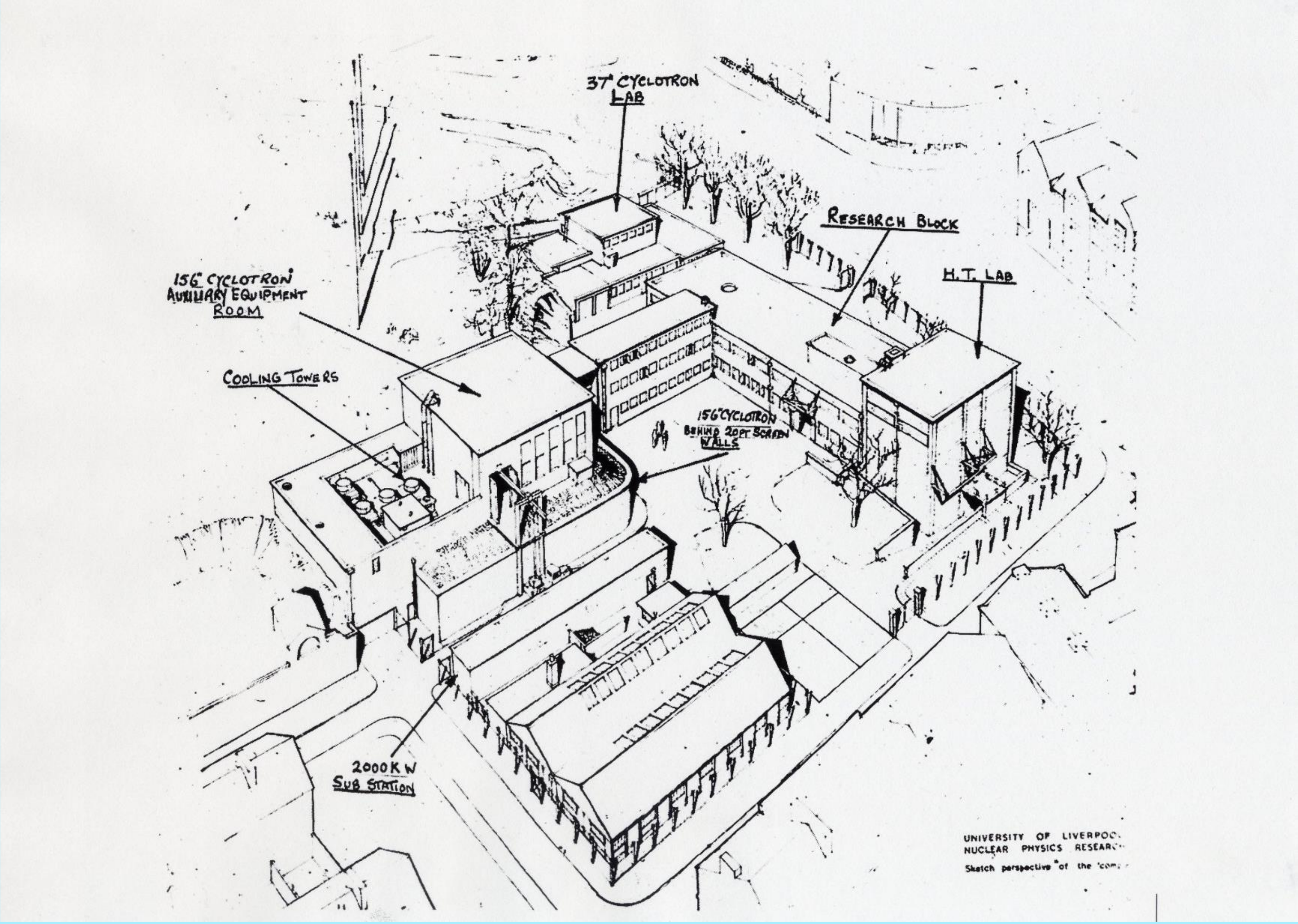
A whole new building complex, the NPRL, was constructed on the site.

NPRL occupied by workhouse to 1931 (centre left)

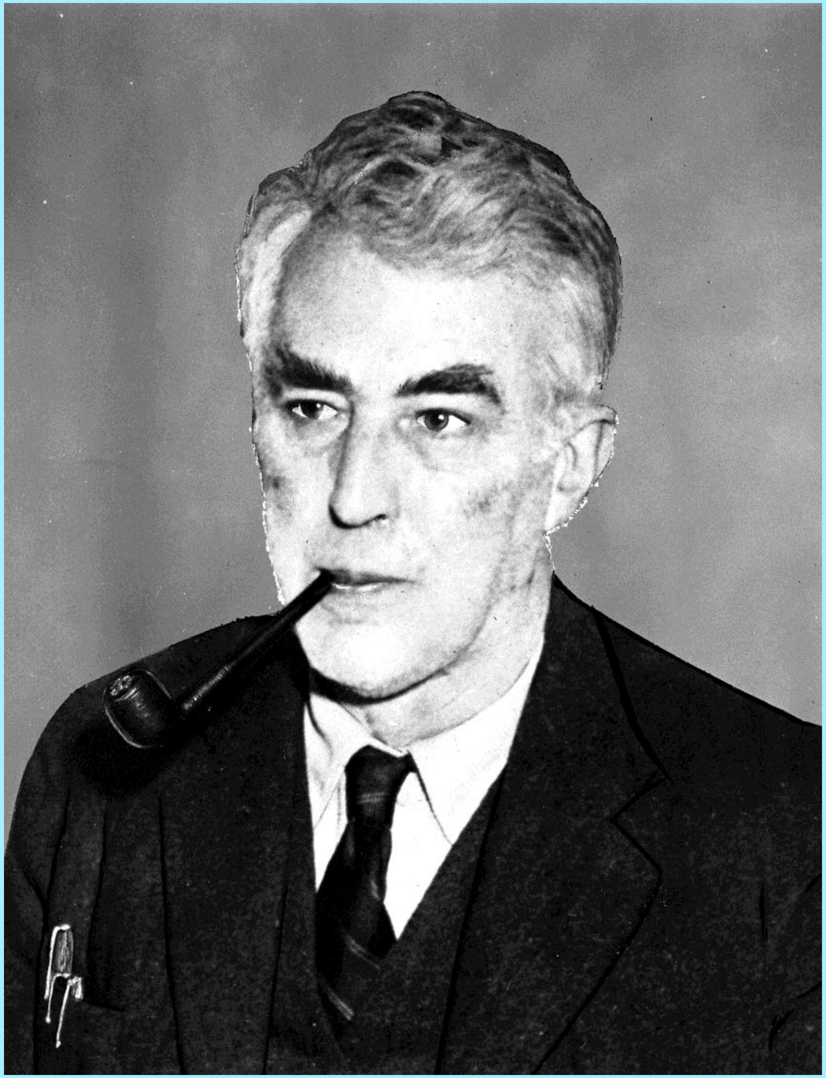


Workhouse 1930

NPRL


37" CYCLOTRON LAB
RESEARCH BLOCK
H.T. LAB
156" CYCLOTRON AUXILIARY EQUIPMENT ROOM
COOLING TOWERS
156" CYCLOTRON BEHIND 20FT SCREEN WALLS
2000KW SUB STATION
UNIVERSITY OF LIVERPOO
NUCLEAR PHYSICS RESEAR
Sketch perspective of the 'com

H. W. B. Skinner



After Rotblat himself left Liverpool to concentrate on the field of nuclear medicine in London, Chadwick was replaced by Herbert Skinner who arrived as Head of Department, from Harwell in 1949, and took the main responsibility for the construction.

Mike Moore at the controls of the 37 inch cyclotron

Much of the technical work was organized by Mike Moore, who had come from Metro-Vick to fit the magnet of the original cyclotron in 1936, before being hired by Chadwick on a permanent basis.

NPRL

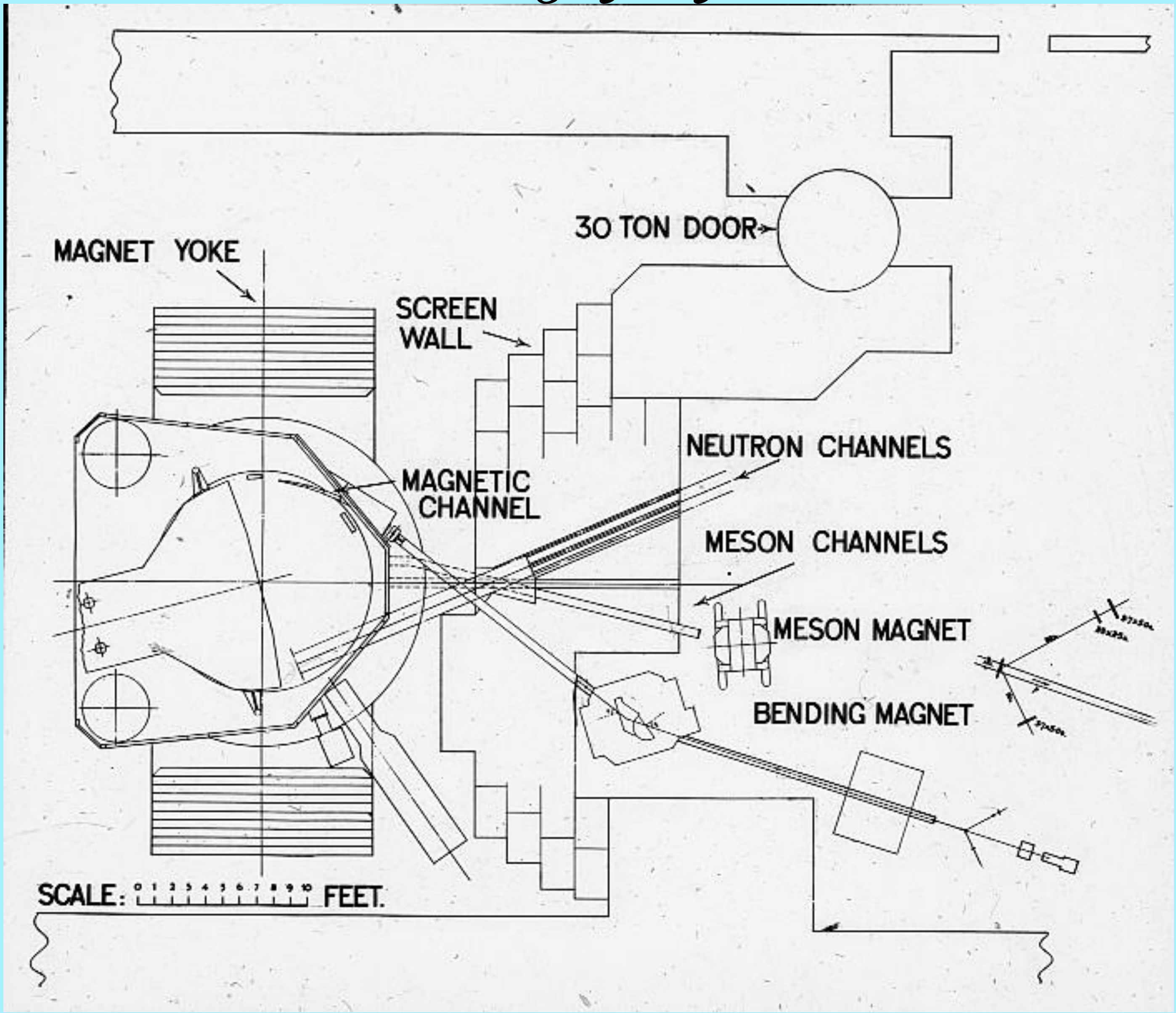
The site

The site

NPRL, completed 1952

NPRL

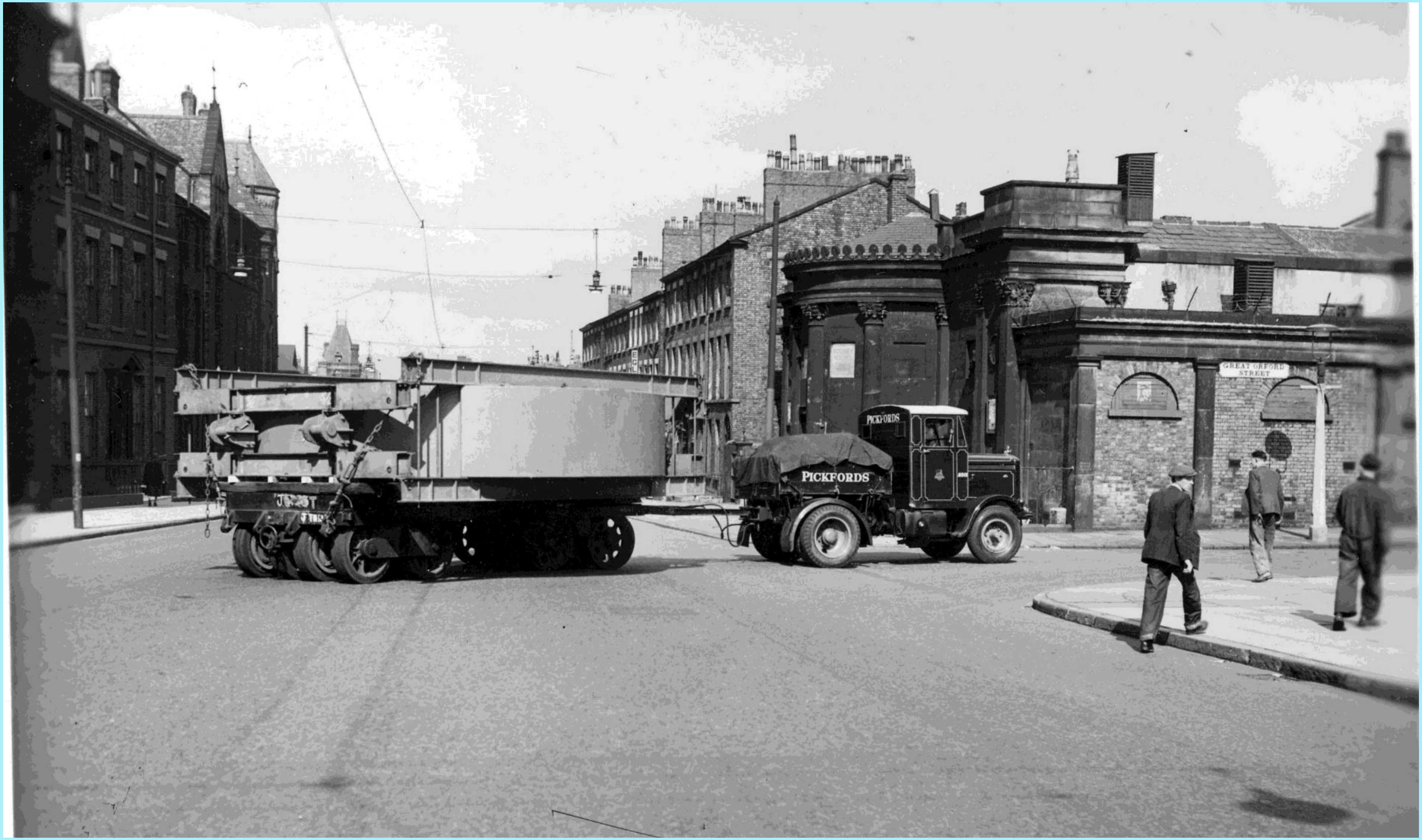
Drawing of layout



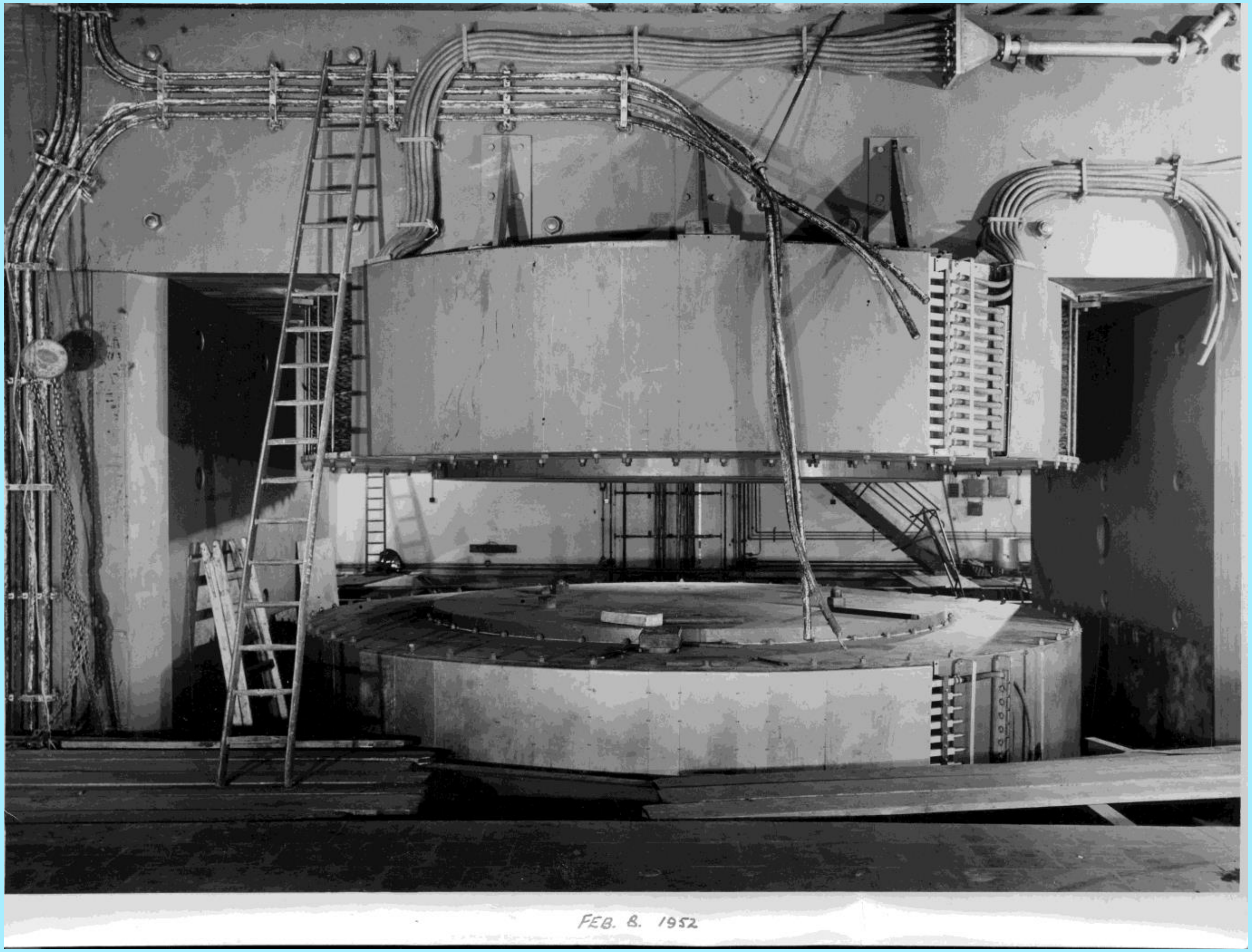
Installation of magnet


METROVICK
MAGNET COIL FOR 156 INCH CYCLOTRON
FOR LIVERPOOL UNIVERSITY
FROM
METROPOLTAN-VICKERS ELECTRICAL CO. LTD.
TRAFFORD PARK, MANCHESTER 17.
CXV625

Delivery, Mount Pleasant

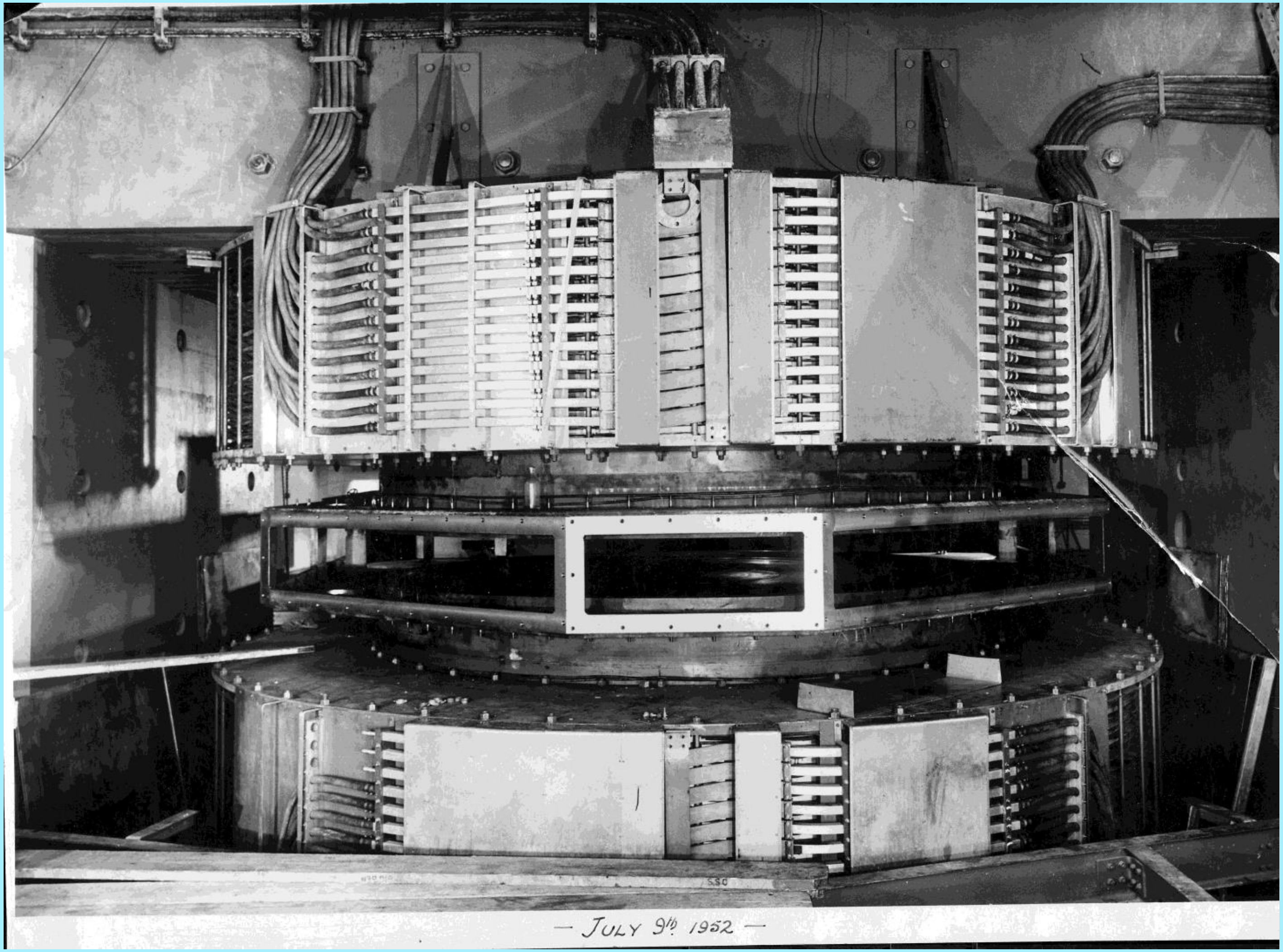


156-inch synchrocyclotron



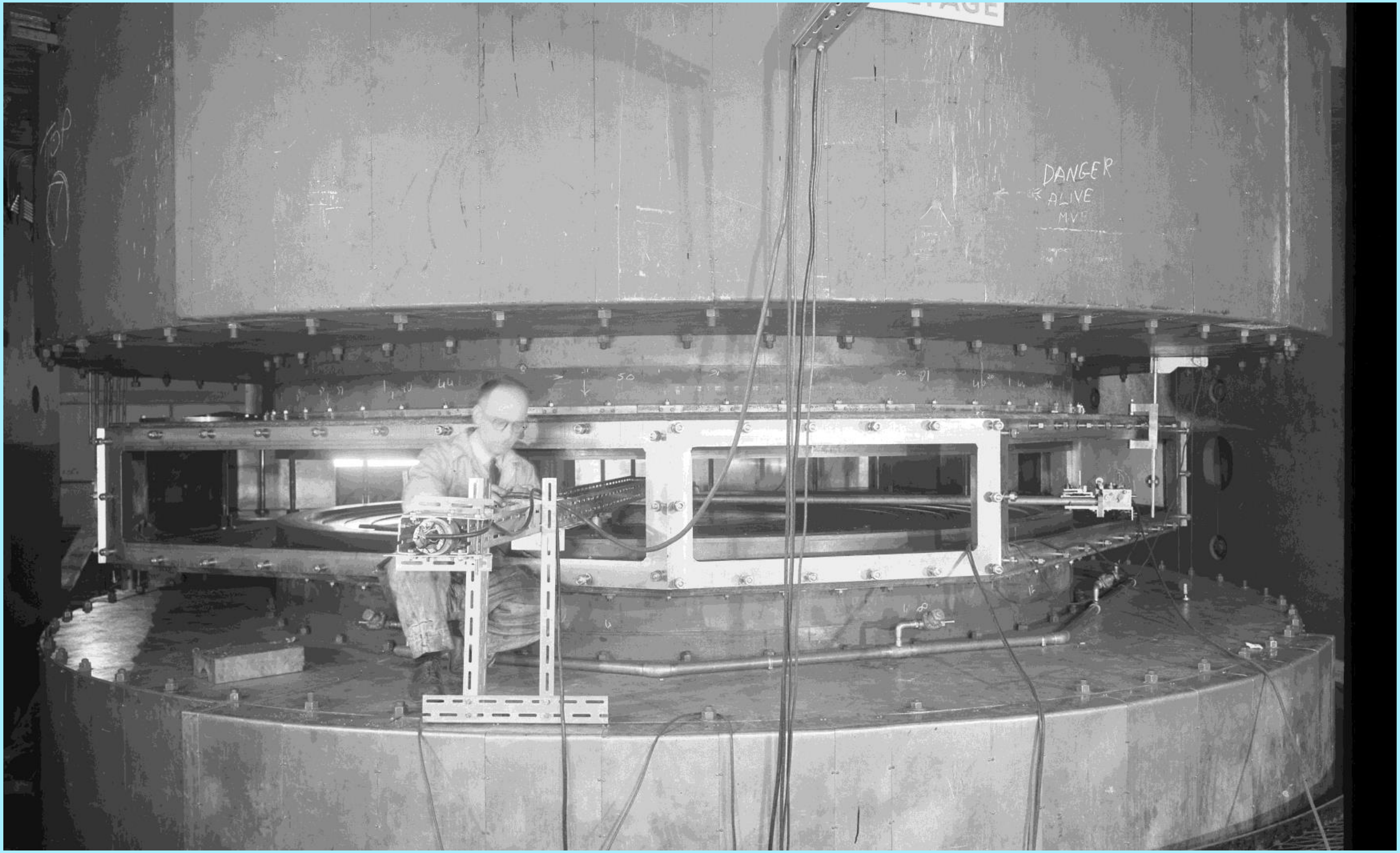
FEB. 8. 1952

156-inch synchrocyclotron

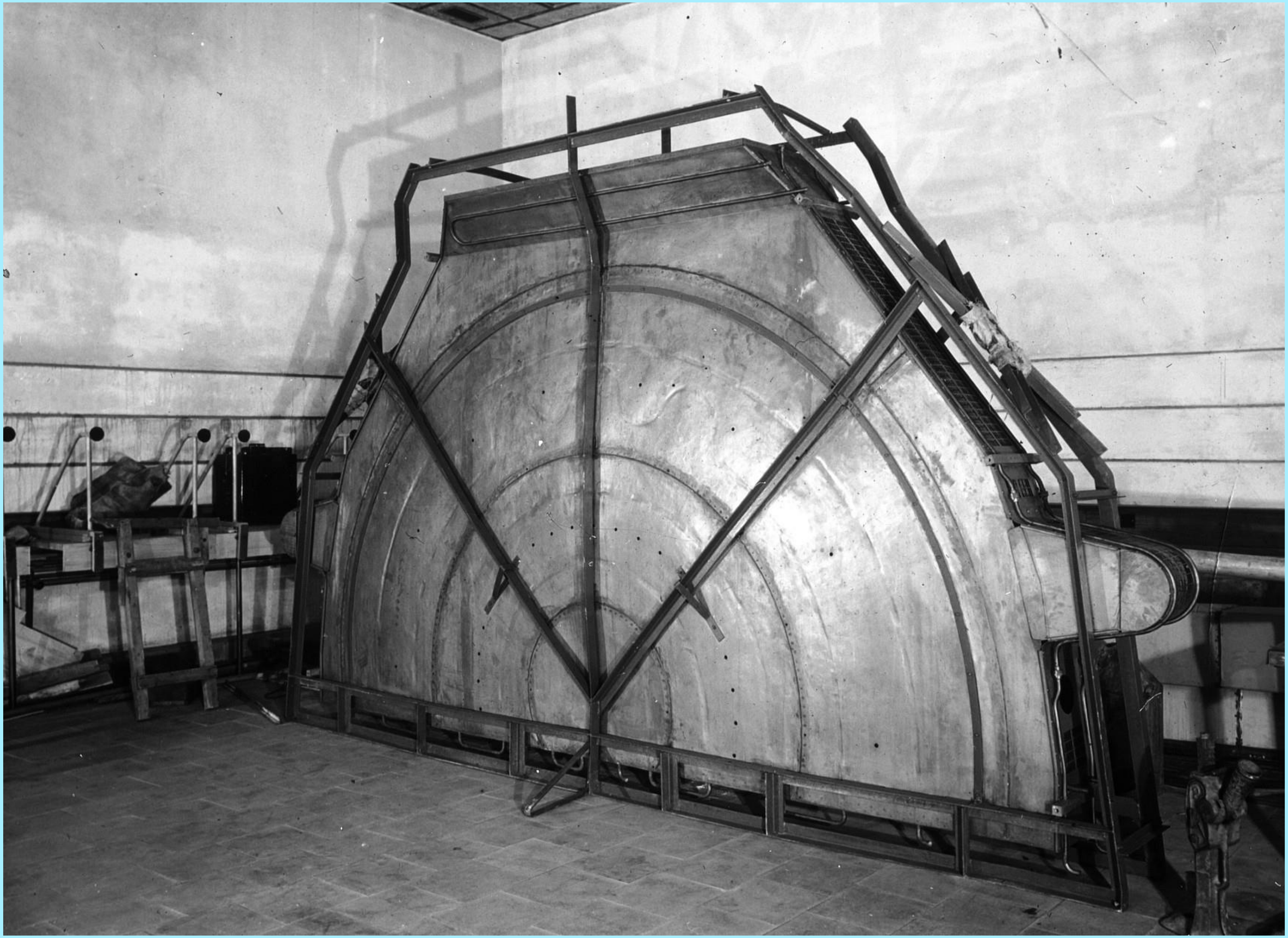


— JULY 9th 1952 —

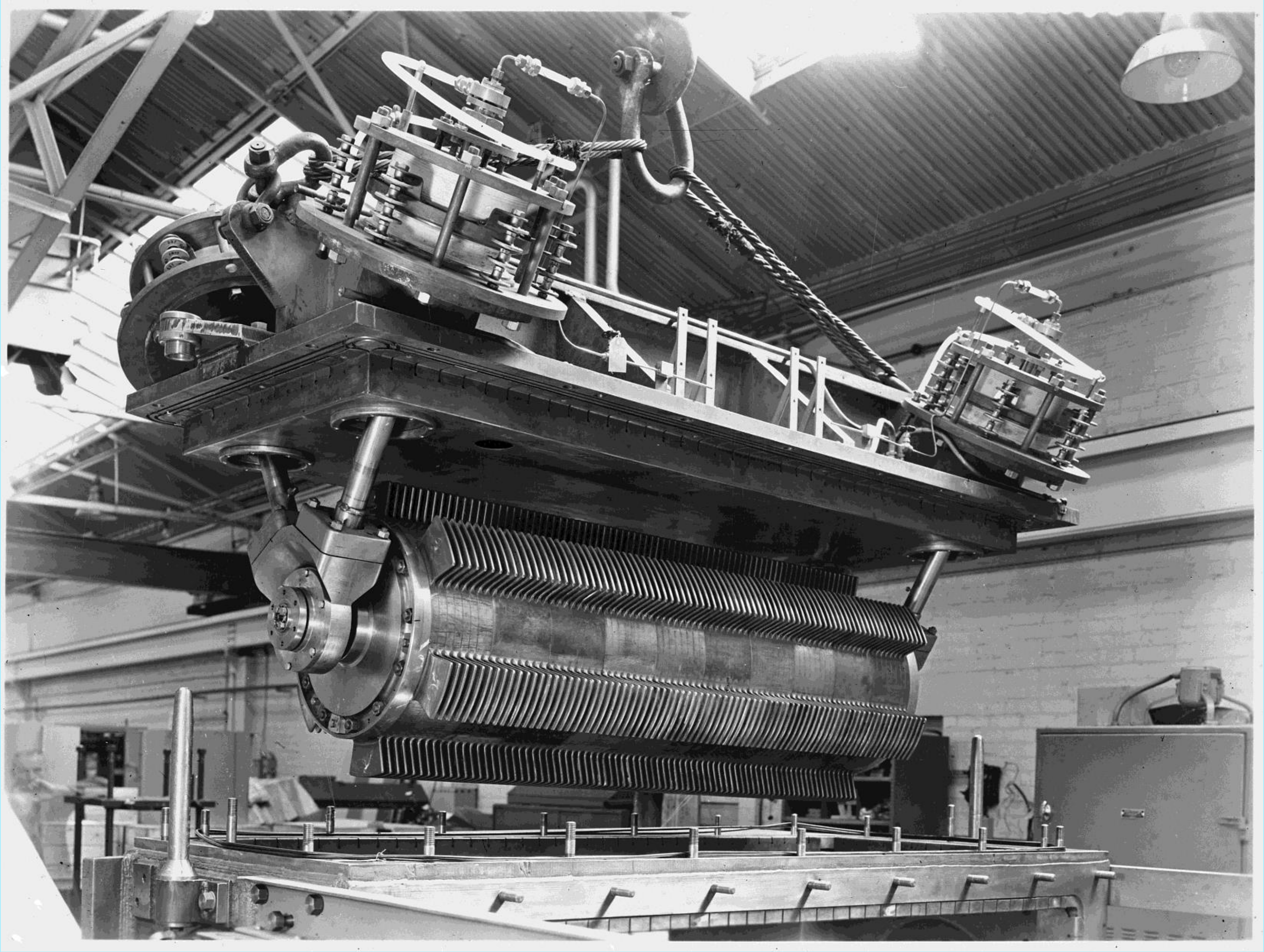
156-inch synchrocyclotron



Dee

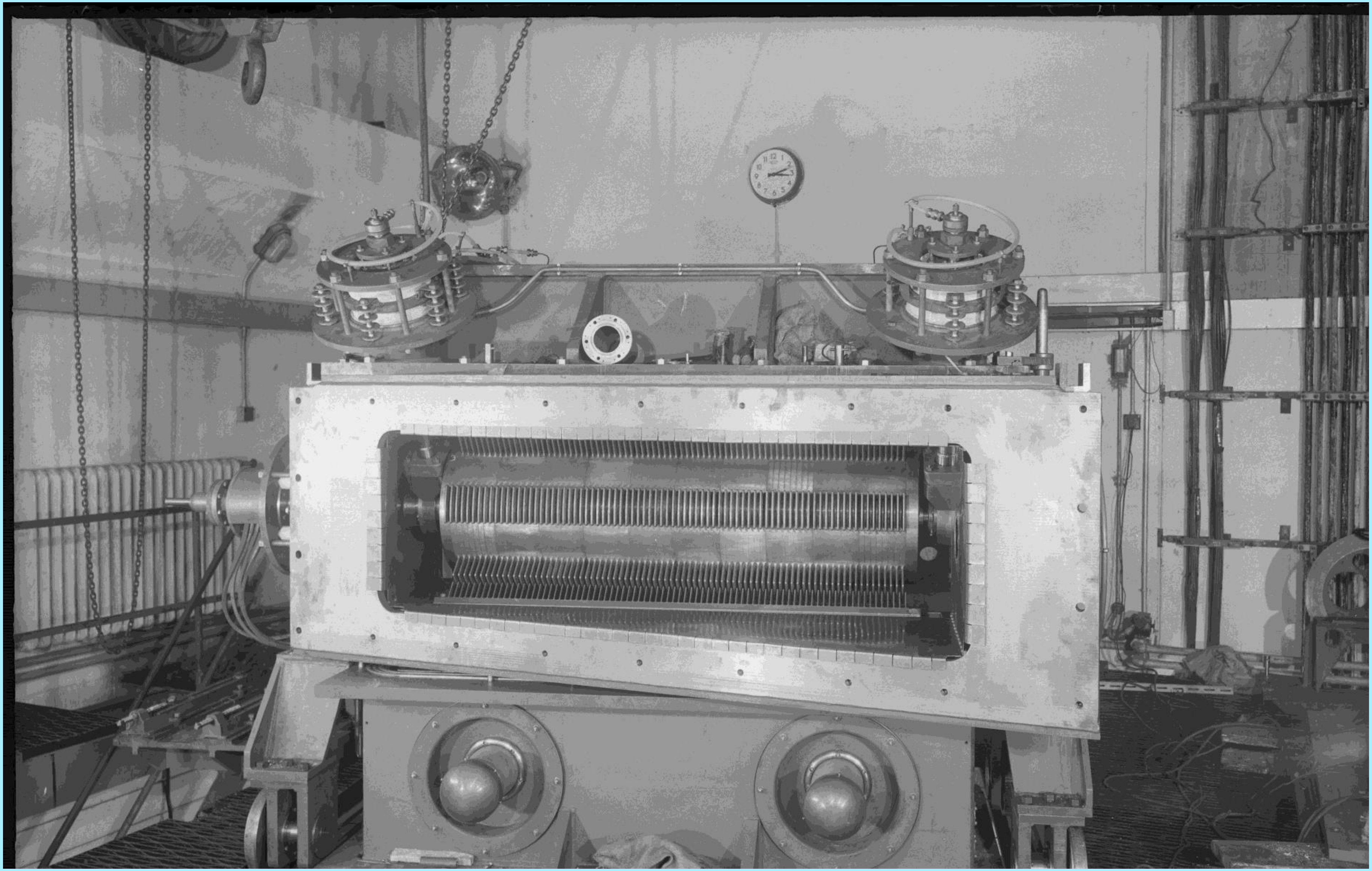


Rotating condenser at factory

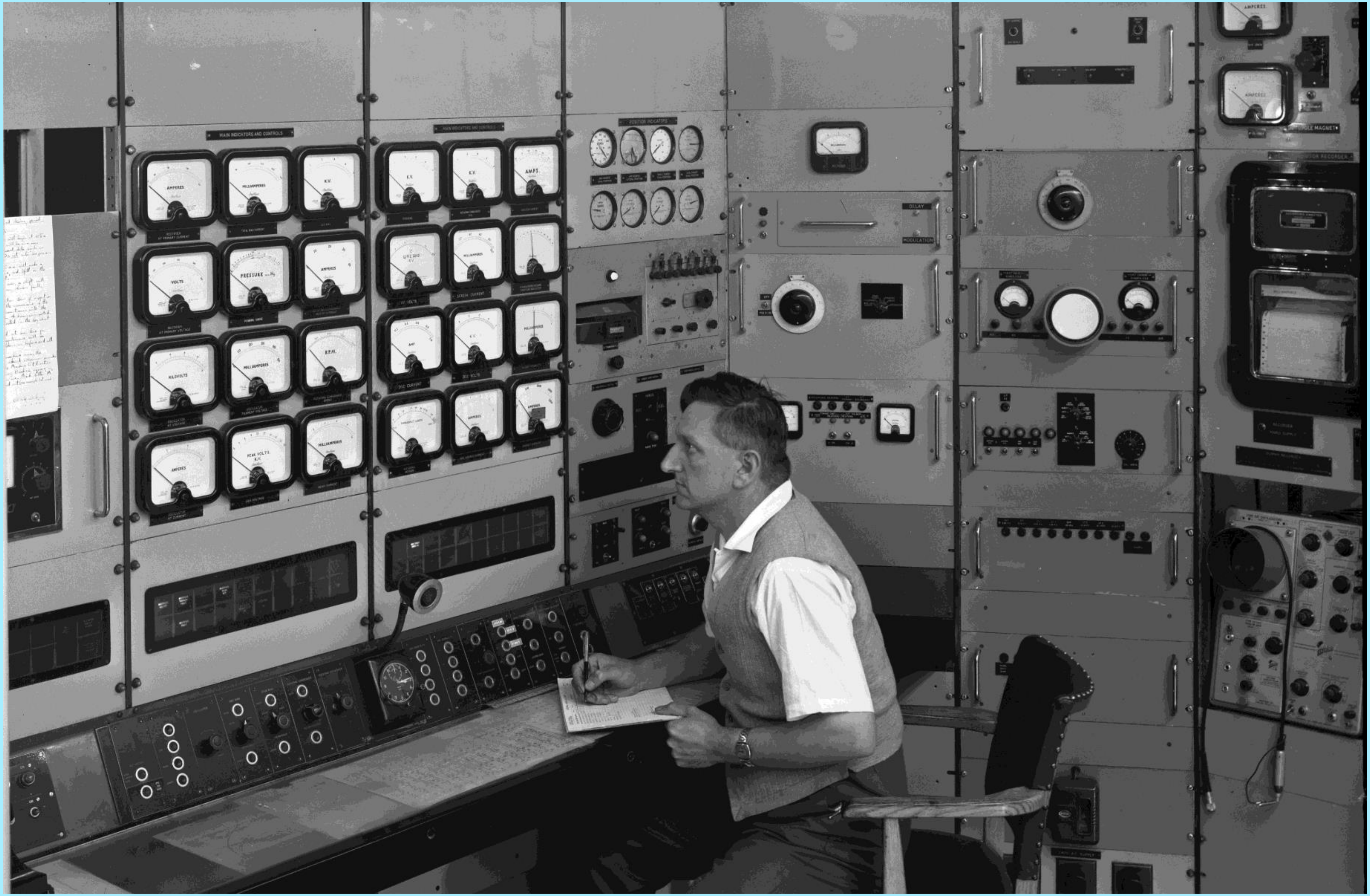


Rotating condenser bearing repair

Rotating condenser



Bert Chesters in the Control Room



Extraction of the beam, April 1954

Several different centres started constructing synchrocyclotrons at approximately the same time in the late 1940s and early 1950s. and most took a long time to commission. Liverpool's produced its first circulating beam in April 1954, but the key thing was to extract the beam, so that experiments could be set up outside the apparatus.

Here, Liverpool scored a notable first with a method for the extraction of a beam of protons in December 1954. Nontrival theory by Ken Le Couteur (using an early electronic computer ar Rothamsted to solve coupled differential equations) was put into practice by Albert Crewe and John Gregory. They extracted up to 10 % of the proton beam, immediately nullifying one of advantages of the alternative linear accelerator system. Other labs including CERN followed the Liverpool method. Unfortunately, Crewe was poached by competitors at Argonne Lab in Chicago.

Panofsky ratio, 1955

The Liverpool machine was the most powerful in Europe (designed for 383 MeV beam), used in research and training for CERN after its foundation in 1954.

Subjects investigated included the longitudinal polarization of electrons from β-decay, and the forward-backward asymmetry of electrons from a polarized radioactive nucleus, in addition to asymmetries and polarization in the decay of pions and muons.

Panofsky ratio, 1955

In 1955 rival Liverpool teams, led by Jim Cassels and Alec Merrison, measured the Panofsky ratio (a good example of precision measurement)

This measures the probabilities between the emission of a neutral pion plus neutron emission or of a gamma ray plus neutron following the capture of a slow negative pion by a proton.

Theory said close to 2, but early results suggested it nearer 1.

Panofsky ratio, 1955

The Liverpool measurements converged on values in the region 1.5 to 1.6. The explanation of the discrepancy was ultimately found in the violation of parity conservation, put forward by Lee and Yang in 1956.

Nonconservation of parity

Nonconservation of parity confirmed at Washington early in 1957 (Wu et al) using Co^{60} cooled to very low temperatures.

Created an ideal opportunity for exploiting the power of the Liverpool synchocyclotron.

The nature of the weak force, 12 October 1957

In a classic experiment in two parts, John Holt’s group at Liverpool showed that charge conjugation was also violated.

They also used the direction of the spin of positive muons to determine the spin of the neutrinos emitted in β-decay, from which they established that the β-decay couplings were V (vector) and A (axial vector) rather than S (scalar) and T (tensor), as had been previously supposed.

The nature of the weak force, 12 October 1957

In the first part, the team (Culligan, Frank. Holt, Kluyver and Massam) used pions from the beam to hit a carbon target. This produced muons, which decayed to positrons, which then produced polarized photons.

The result was that the spins of the positrons were aligned preferentially to the direction of motion.

This was a result of huge significance to the developing theory of the weak interaction, determining its specific mathematical nature.

At the time it was supposed that beta-decay couplings combined a scalar and a tensor term. If this was so, the positrons produced by positive muon decay would have spins aligned in the opposite direction to the direction of motion.

The nature of the weak force, 12 October 1957

The experiment required a huge electromagnet and led to an amusing episode, recounted to me by David Edwards, who was there.

The team knew they had competition from many laboratories, including Washington. The experiment was done in a hurry over three days, working day and night. When they finally obtained the results they wanted, it was 3.00 in the morning.

At that moment, they realised they didn’t know which way round the magnet was wired, and so couldn’t fix the interpretation.

The nature of the weak fore, 12 October 1957

Arguments erupted over whether a north-seeking pole was a magnetic north pole, or whether Fleming’s left-hand rule or right-hand rule should apply. The arguments persisted even when they tested the magnet with a small laboratory compass.

Eventually, one member of the team went outside and pointed the compass at the pole star, saying, ‘Look, that’s north!’ However, the compass was actually pointing south. The strong magnetic field had changed its orientation.

This meant that, rather than scalar-tensor, the weak couplings were actually vector minus axial vector.

The nature of the weak force, 12 October 1957

Today, the V – A theory is the foundation for all theoretical discussions of the weak force.

It is amusing that a result of such profound theoretical significance required not only one of the most powerful and sophisticated research machines of its time but also the techniques of ancient navigation!

Violation of charge conjugation, 1958

In an extension of this experiment, the team (Culligan, Frank and Holt) used both positive and negative muons, decaying to positive and negative electrons, which produced opposite polarizations.

This meant that charge-conjugation symmetry (*C*) was violated alongside parity (*P*).

Further results along these lines were the violation of combined *CP* (Brookhaven, 1964) and explicit *T* or time-reversal symmetry (CP Lear, with Liverpool involvement, 1986). It is now believed that only the combined *CPT* resists violation.

The closure of the synchrocyclotron

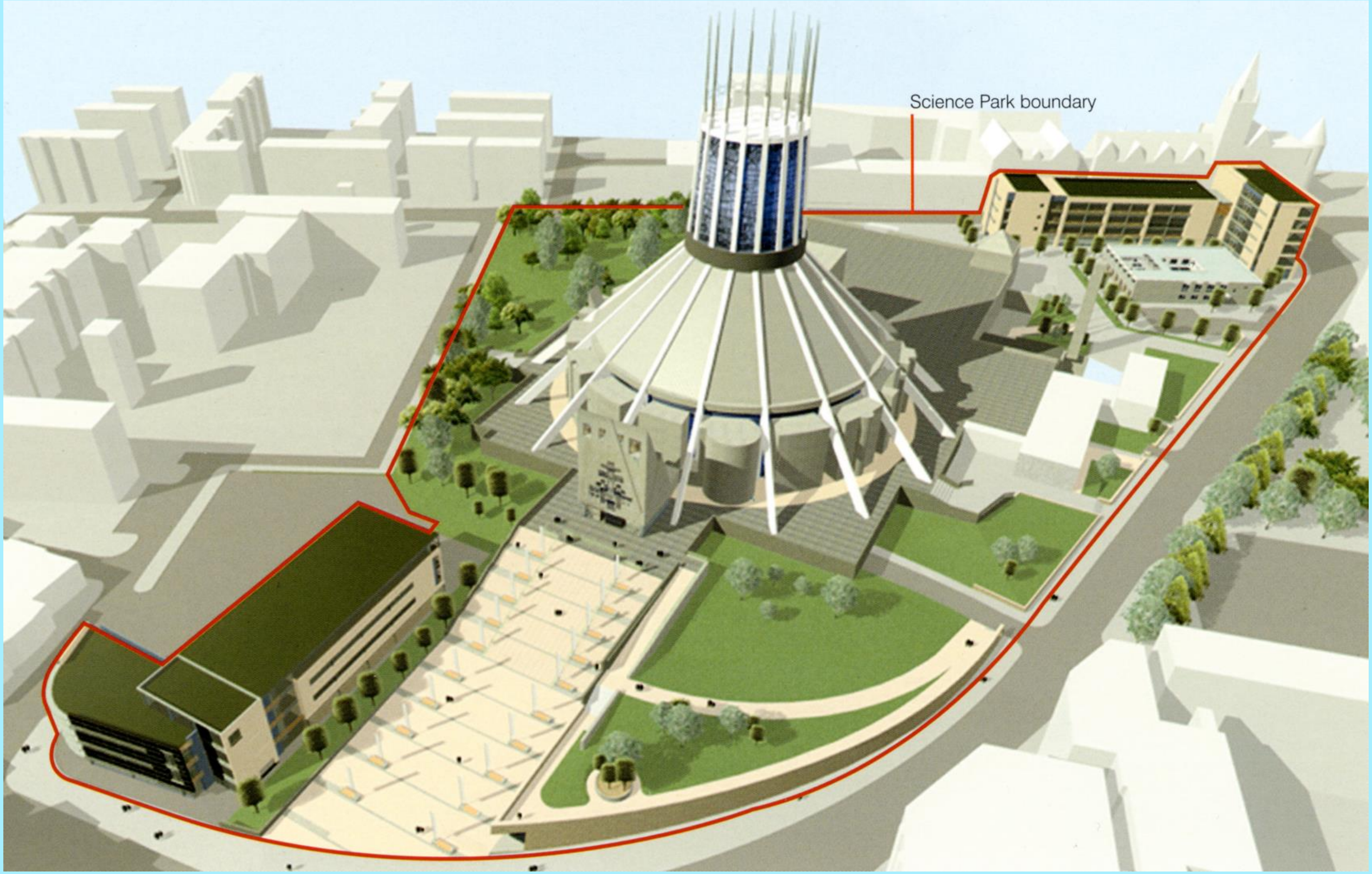
The synchrocyclotron continued in operation until 1968. In one of the later experiments (1968), pions from the synchrocyclotron allowed the determination of the neutron-neutron scattering, contributing to knowledge of the real nucleon-nucleon force (the strong interaction).

The closure of the synchrocyclotron

Ultimately, the synchrocyclotron turned out to be a dead end – a solution to an immediate problem rather than a route to future development. The single linear magnetic field restricted the energy which such a machine could produce. Single magnets just could not be built big enough to satisfy the increasing energy requirements. The future lay in the radial arrangement of multiple magnets, as used now at CERN.

Of course, cyclotrons and even synchrocyclotrons are still used, especially in medical applications, but not in the energy range needed for particle physics.

The lease was till 1975 but the Cathedral construction began 1965 – the only science park with a cathedral



Disposal

Disposal started a year after shutdown and took approximately 2 years (1969-1971). Many of the parts, of course, were radioactive – usually at low level. These were dealt with in collaboration with the local authority. Inactive waste was recycled for other use. The high activity waste required the collaboration of the AEA and was mostly buried at Drigg.

The pole pieces which had low radioactivity went to a lab in Zurich. The miles of cable and other copper metal scrap went to a landfill site near Otterspool.

Of the Liverpool machine only the rotating condenser and its frame still exist – in the Liverpool City Museum.

The End

1957

Culligan, G.; Frank, S. G. F.; Holt, J. R.; Kluyver, J. C.; Massam, T.

Nature (1957), 180, 751-2

A high degree of longitudinal polarization of the muon-decay positrons was observed. Positrons produced in the p-m-e decay sequence were passed through 2 scintillation counters into a Pb plate producing bremsstrahlung quanta. These passed through an Fe cylinder which was magnetized alternately parallel and antiparallel to the direction of the quanta. These were then detected by a NaI crystal. The transmission of the Fe core was greater when the north pole was toward the positron source, showing that the positrons were predominately "right-handed", i.e., with spins pointing in the direction of motion.

1957

Nature 180, 751 - 752 (12 October 1957)

Longitudinal Polarization of the Positrons from the Decay of Unpolarized Positive Muons

G. CULLIGAN, S. G. F. FRANK, J. R. HOLT, J. C. KLUYVER* & T. MASSAM
Nuclear Physics Research Laboratory, University of Liverpool. Sept. 18.
*Present address: C.E.R.N., Geneva, Switzerland.

It is now well known that parity is not conserved in weak Fermi interactions, and that this generally results in longitudinal polarization of the spins of the emitted particles. Very strong polarizations of the muons emitted in pion decay, and of the electrons emitted in beta decay, have already been detected. The experiment reported here was aimed at detecting longitudinal polarization of the positrons emitted in the decay of unpolarized muons.

Longitudinal Polarization of the Electrons from the Decay of Unpolarized Positive and Negative Muons

- G. Culligan, S. Frank, J. R. Holt
- Physics 1959

The polarization of electrons from the decay of unpolarized positive and negative muons has been detected by the method of transmission of bremsstrahlung through magnetized iron. It is shown that the positrons have positive helicity and the negatrons negative helicity, thus providing a clear demonstration of violation of invariance under charge conjugation. It follows on the basis of the two component neutrino theory that the neutrino associated with the decay of the pion has negative helicity and the anti-neutrino positive helicity. The agreement of this with recent results for the neutrino in β-decay lends support to this theory and confirms the law of conservation of leptons.