UNIVERSITY OF BIRMINGHAM | COLLEGE OF ENGINEERING AND PHYSICAL SCIENCES

Applications in nuclear physics and nuclear industry

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CYCLOTRON FACILITY

NNUF National Nuclear User Facility

EPSRC Engineering and Physical Sciences Research Council

Overview

- Overview of the Birmingham Cyclotron facility
- Details of the new neutron source — HF-ADNeF
- User requirements sought for neutron source
- Detector testing — AIDA
- Detectors — Nuclear Physics
- Detectors — Positron Imaging Centre (PIC)
- Summary

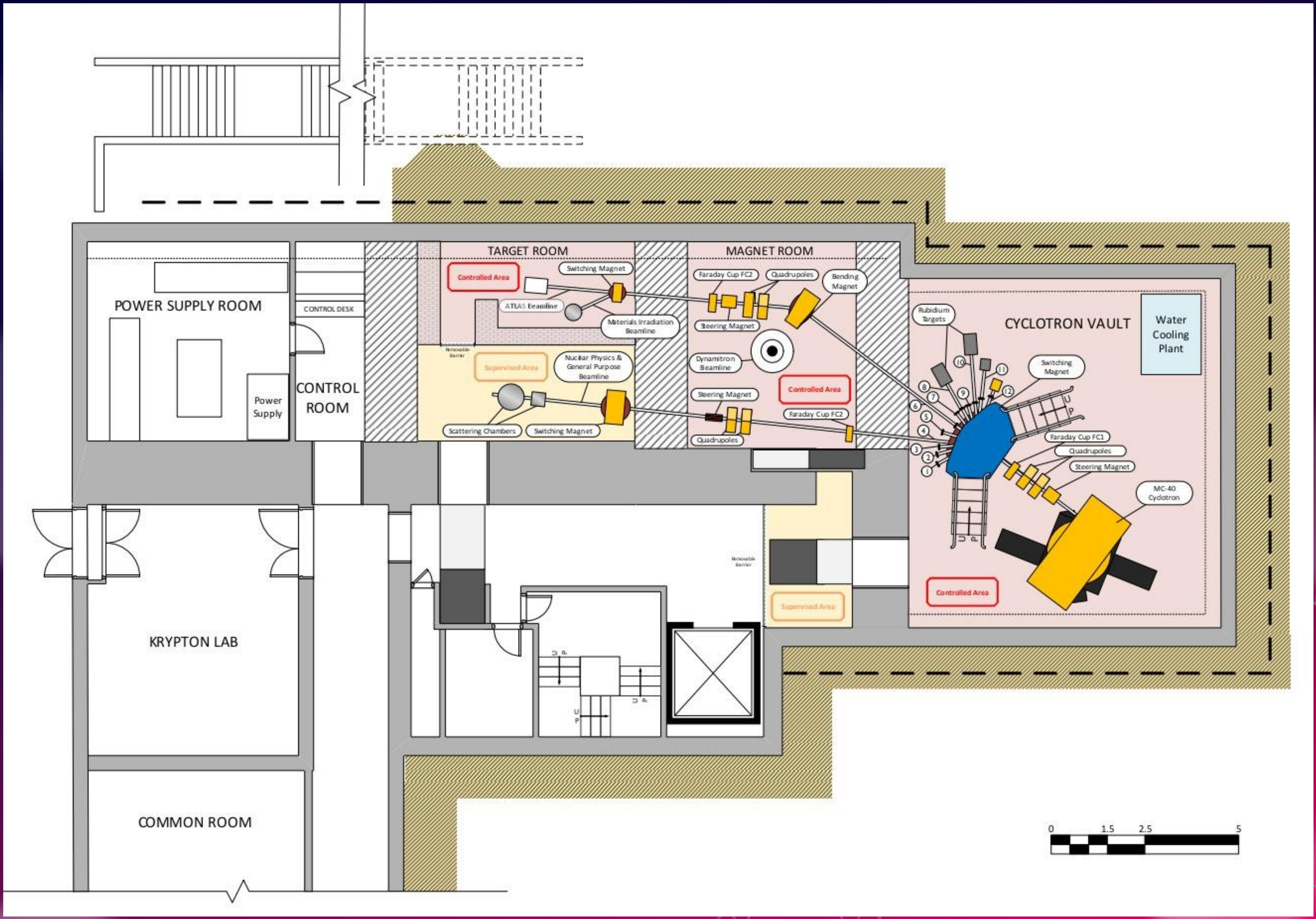
Current facility — the MC40 cyclotron

Energies and ions routinely available.

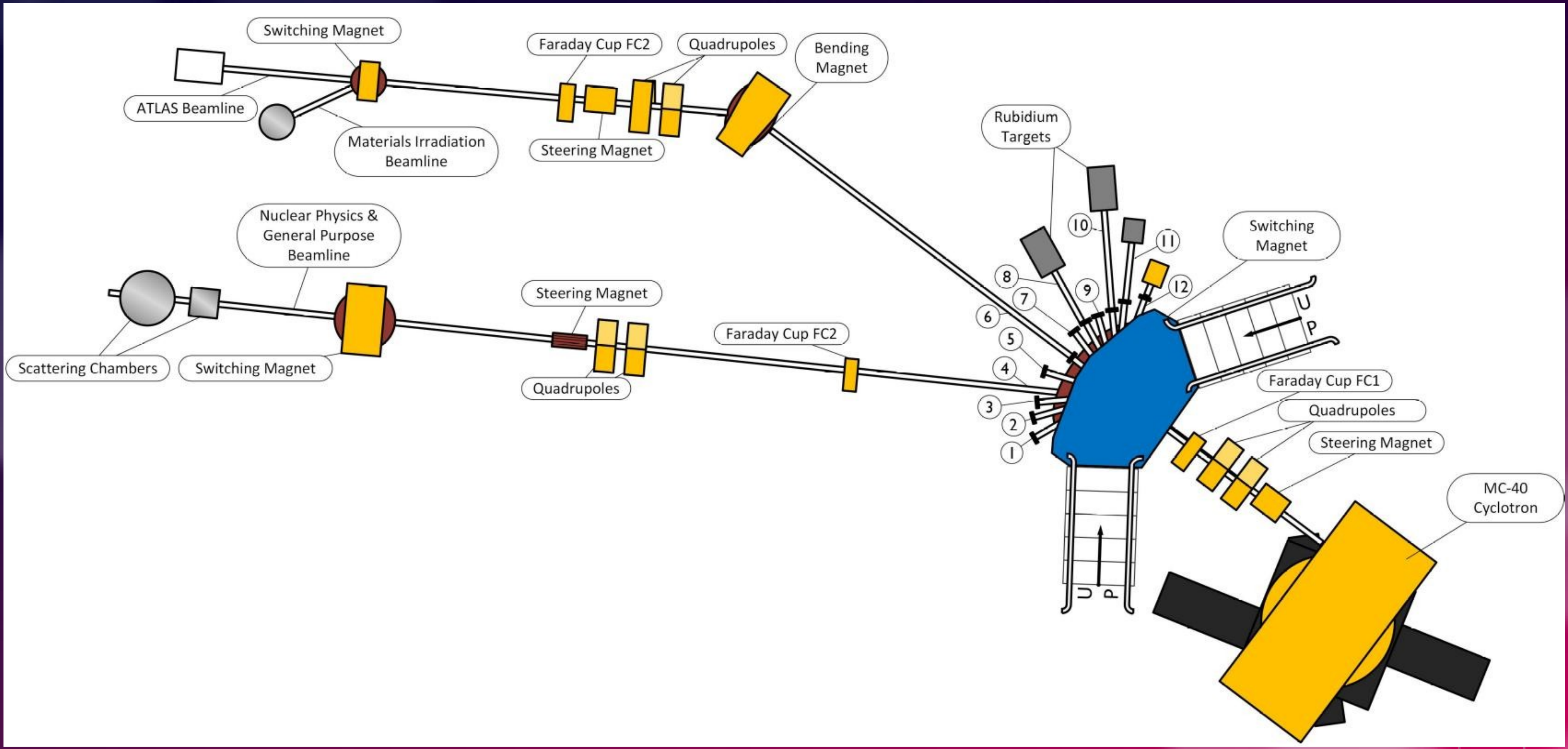
Beam ion	Energy (N=1)	Energy (N=2)
Protons (^{1}H)	10.8-40 MeV	2.7-10 MeV
Deuterons (^{2}H)	---	5.4-20
Helium-3 (^{3}He)	33-50 MeV	8-28 MeV
Helium-4 (^{4}He)	---	10.8-40 MeV

Nitrogen and oxygen beams have also been accelerated for nuclear physics.

The Birmingham Cyclotron Facility



The Birmingham Cyclotron Facility



MC40 cyclotron uses – overview

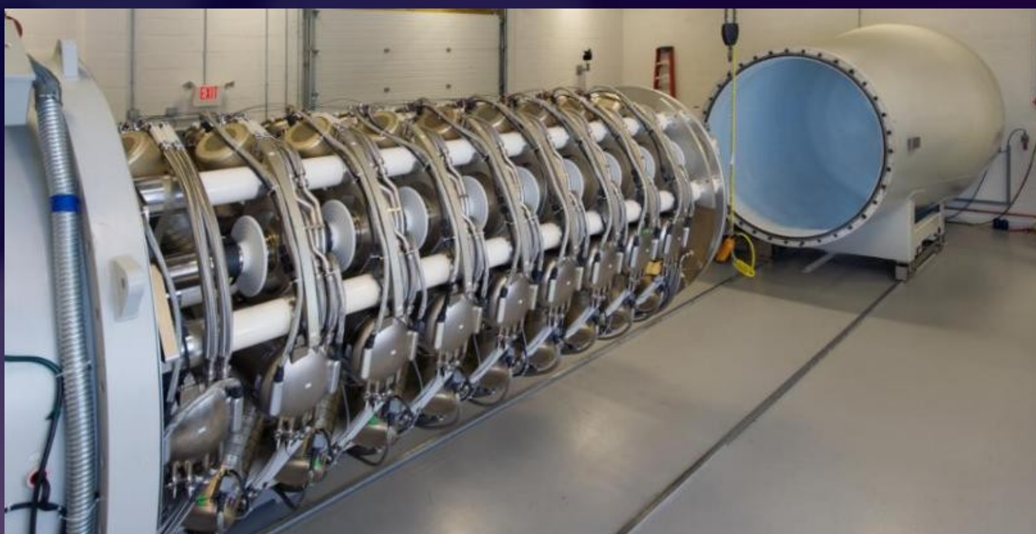
- Applications
  - Medical isotope production for imaging
  - PEPT, tracking particles through industrial equipment
  - Activating thin layers for tribology – the study of wear/friction
- Studies of radiation effects and damage for materials
  - Investigating how nucleons damage materials, e.g. steels used in nuclear power plants
  - Testing radiation hardness of component for the Large Hadron Collider ATLAS experiment @CERN and AIDA
  - Irradiating space electronics

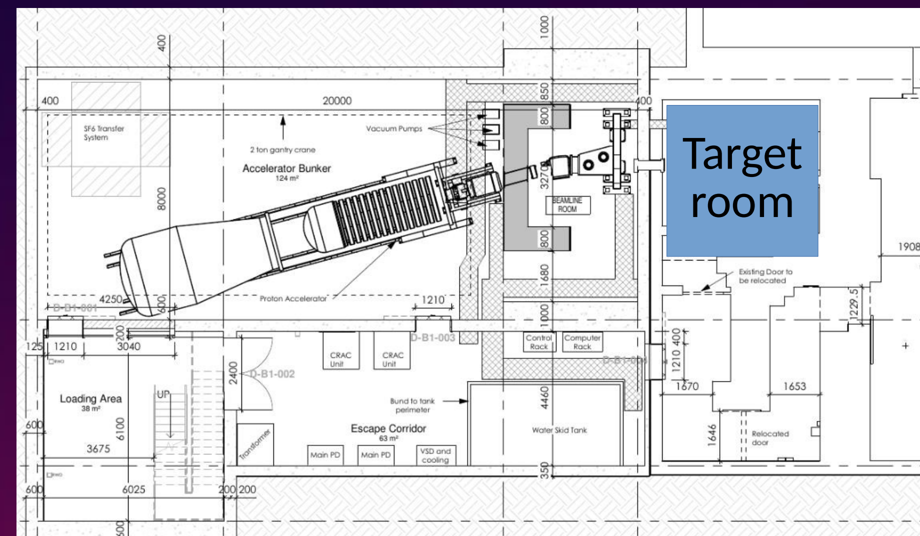
- Making isotopes for radiation standards at the National Physical Laboratory
- Curiosity driven nuclear physics research into the origin of the isotopes.
- Training the next generation of experimentalists — a hands on facility in the UK

The Birmingham MC40 Cyclotron Facility, by David Parker and Carl Wheldon, Nuclear Physics News, **28** issue 4 (2018) 15, https://doi.org/10.1080/10619127.2018.1463021.

HF-ADNeF — High-Flux Accelerator Driven Neutron Facility

A £10M project for a national user facility funded by EPSRC and UoB through the NNUF (National Nuclear User Facility) to underpin fission and fusion research for both academic and industry users.





Hyperion: A single-ended electrostatic accelerator. Easily achievable levels >30 mA protons specified. Energies of ~0.4-2.6 MeV.

Now sold by Neutron Therapeutics as part of accelerator BNCT facilities, including a high power Li target → fast neutrons at $>1.8 \times 10^{11}$ n/cm^2/s.

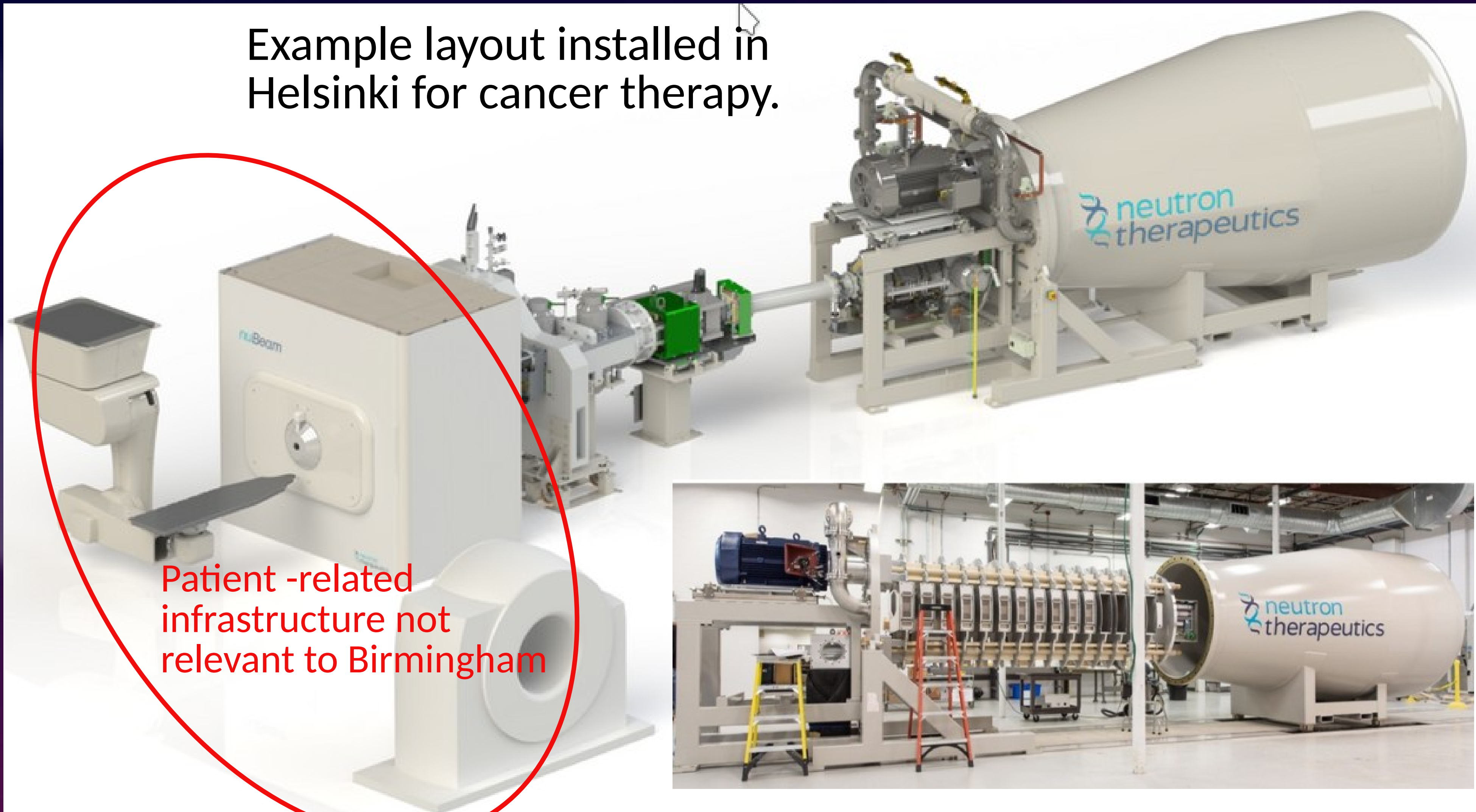
A dual beam facility is planned with cyclotron beams to study, e.g., He embrittlement.

Neutrons are produced using a cooled, rotating, lithium target and the ^{7}Li(p,n)^{7}Be reaction ($Q = -1.64$ MeV, i.e. $E_{thresh} = 1.88$ MeV).

Direct proton beams are possible for, e.g., damage studies.

The new facility – neutron therapeutics machine

Example layout installed in Helsinki for cancer therapy.



Patient -related infrastructure not relevant to Birmingham

Figures from: https://www.neutrontherapeutics.com/ and https://www.d-pace.com/

Accelerator-driven neutron facility

Phase 1 (2020-2021)

Building and hardware procurement

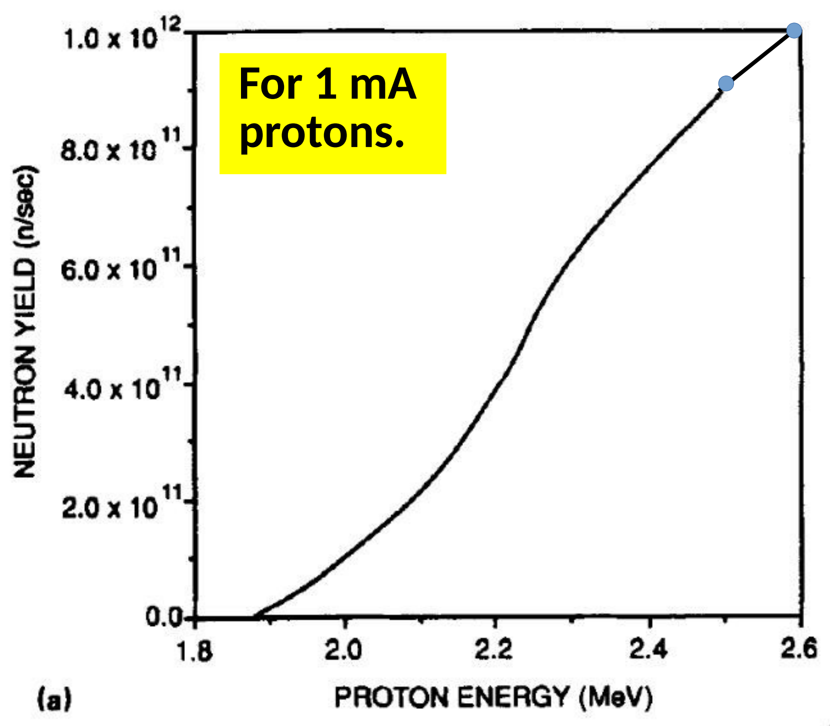
Accelerator delivery and installation

Phase 2 (2022)

Work-up to 30 mA protons

Fast neutron flux of 1.8×10^{11} n/cm^2/s

Thermal flux of 6×10^9 n/cm^2/s.



Phase 2 (2023)

Fast neutron flux of **1×10^{12} n/cm^2/s** matching the now decommissioned Imperial reactor.

Achieving a 10^{18} integrated neutron fluence required operation for 11.5 days.

Phase 3 (2023 onwards)

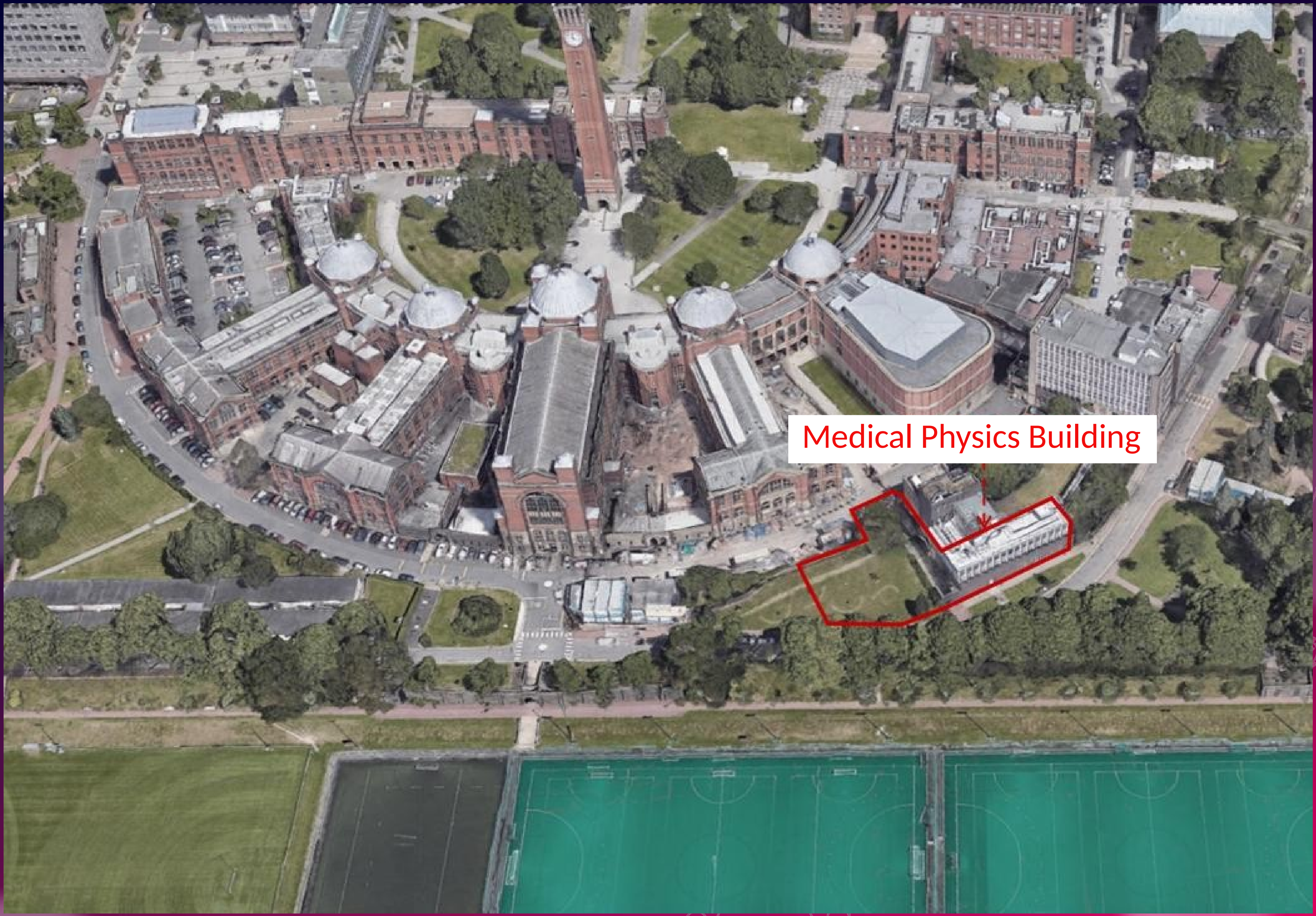
Develop deuteron beam with enhancement of flux to 5×10^{12} n/cm^2/s.

Achieving a 10^{18} integrated neutron fluence required operation for 4 days.

Dual beam facility with cyclotron.

Figure from: J.C. Yanch *et al.*, Medical Physics **19** 709 (1992).

The new facility



The new facility

Artists impression before the build

How it looks today

Broad applications

- Nuclear materials research under neutron irradiation.
- Nuclear fission and fusion data, e.g. neutron capture cross section data.
- Nuclear waste management — understanding the long term effects of radiation on material characteristics.
- High power target development.
- Medical physics, from radiobiology to boron neutron capture therapy developments.
- Industrial and space research on the effect of radiation.
- Nuclear Metrology — calibrated and controllable neutron source availability and testing new radiation monitoring systems.
- Nuclear physics — the neutron spectrum is close to that in stellar environments.

User requirements

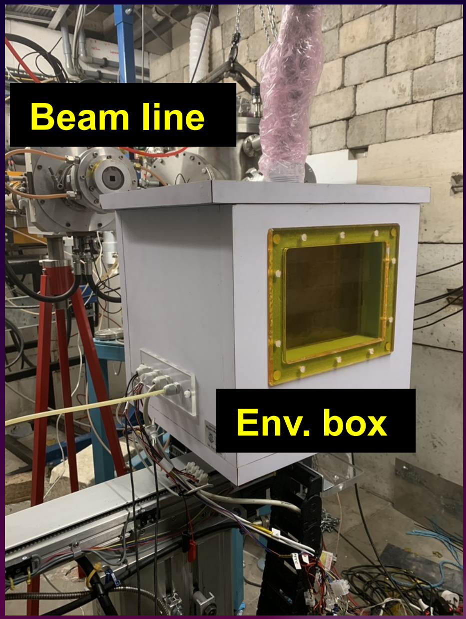
- Funds can be requested as part of research grants to gain access.
- There is a pot of money for user access to NNUF facilities over the next three years administered by Oxford.
- Cyclotron beam time, on the same model, is being made available to stimulate research ideas, and test proof concept *etc*.

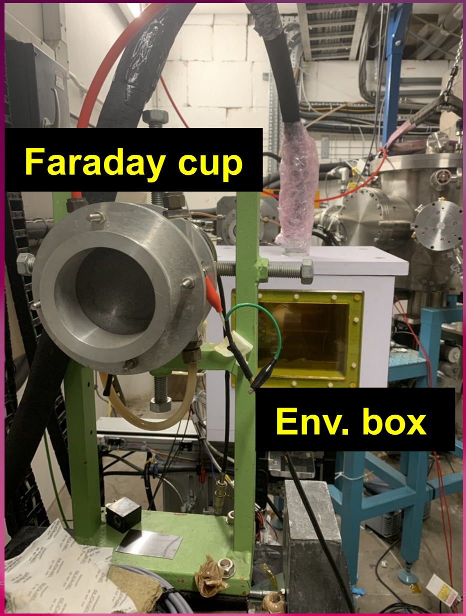
End station possibilities

Users are invited to come and talk to us now as user requirements are being captured as part of the design process.

MC40 high intensity irradiation line

- Initially developed by Birmingham, Liverpool and Sheffield through STFC support for UK ATLAS Upgrade, then AIDA2020 Transnational Access facility (2015 – 2020)
- Designed to reach fluence expected at the HL-LHC (few 10^{15} 1 MeV n_{eq}/cm^2) within one day of irradiation
- Typical beam parameters: 27 MeV protons, 100 – 400 nA
- **Experimental set-up:**
  - Environment controlled box on an XY-axis scanning system for uniform irradiation of samples at low temperature
  - Liquid nitrogen evaporative cooling system, typically = −27C during irradiation (-40C possible)
  - Dry N2 is used to keep low humidity, typically RH = ~10% during irradiation
- Faraday cup used to measure beam current





AIDA — Advanced European Infrastructure for Detectors at Accelerators

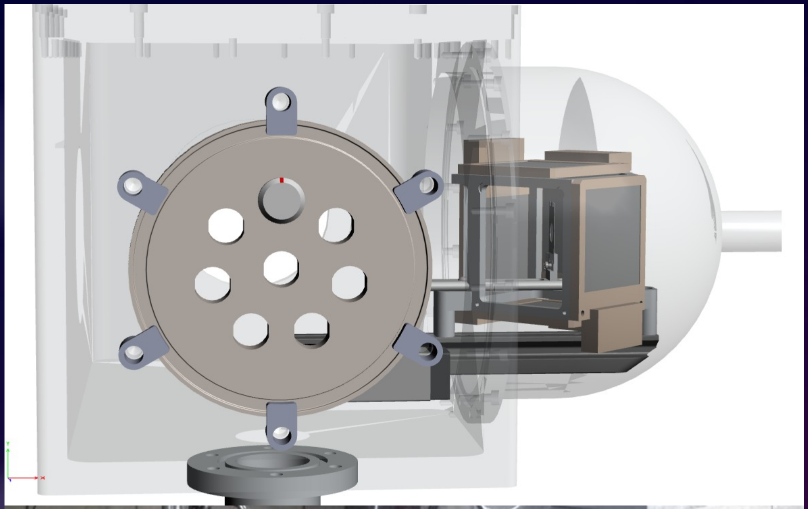
AIDA 2020 Transnational access

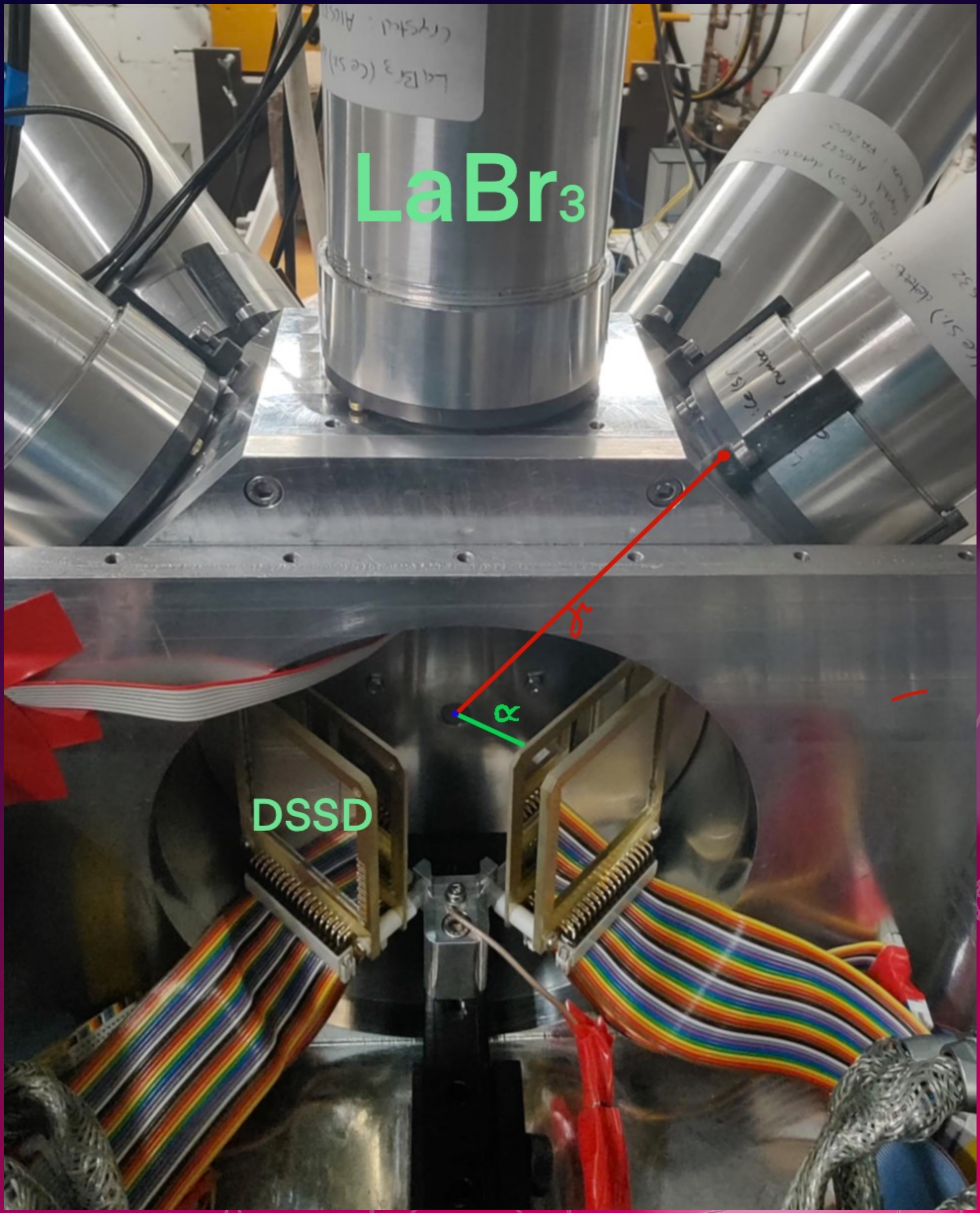
- 300 hours of beam time delivered to 12 projects with a total of 41 users
- Samples irradiated included: silicon sensors and readout ASIC, flex circuits, glass scintillators, glues foams, GanFET transistors, micromegas
- Users base: ATLAS, LHCb, EIC, ESS

New: EURO-LABS

- New Translation Access funding, 2022 – 2026
- Proposal in preparation
- Similar amount of beam time and projects planned as during AIDA2020
- Planned upgrade of the experimental setup to reach fluence of 10^{17} 1 MeV n_{eq}/cm^2 within one day of irradiation
- To meet the requirements for development of detectors for future high energy physics experiments

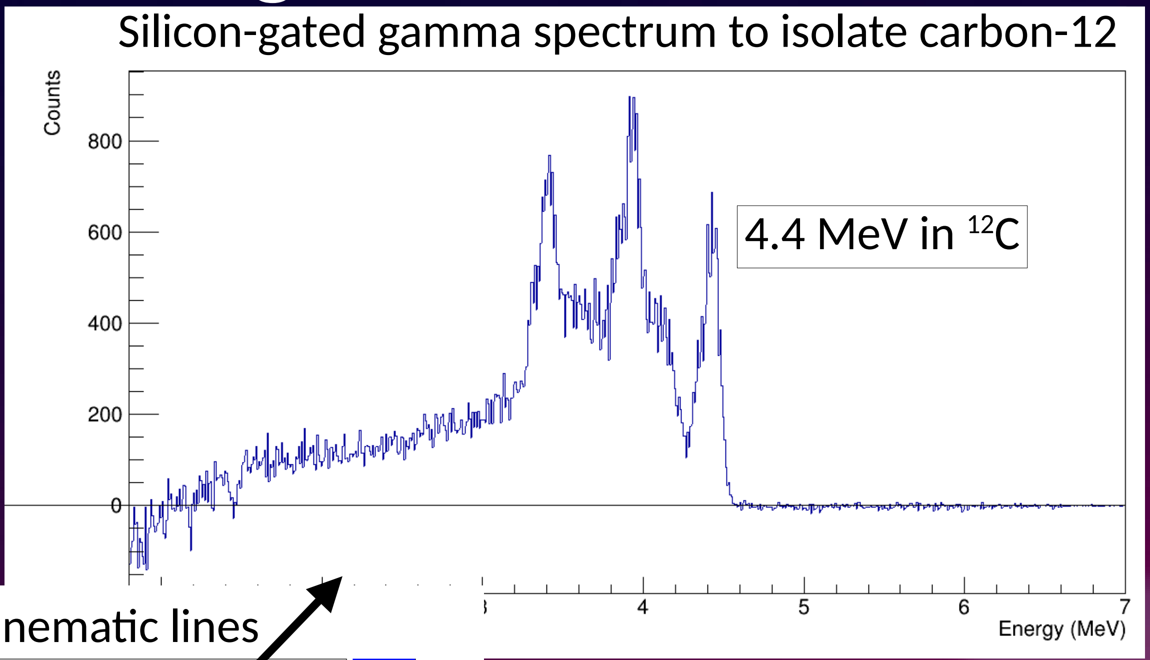
Nuclear physics — particle-gamma coincidences

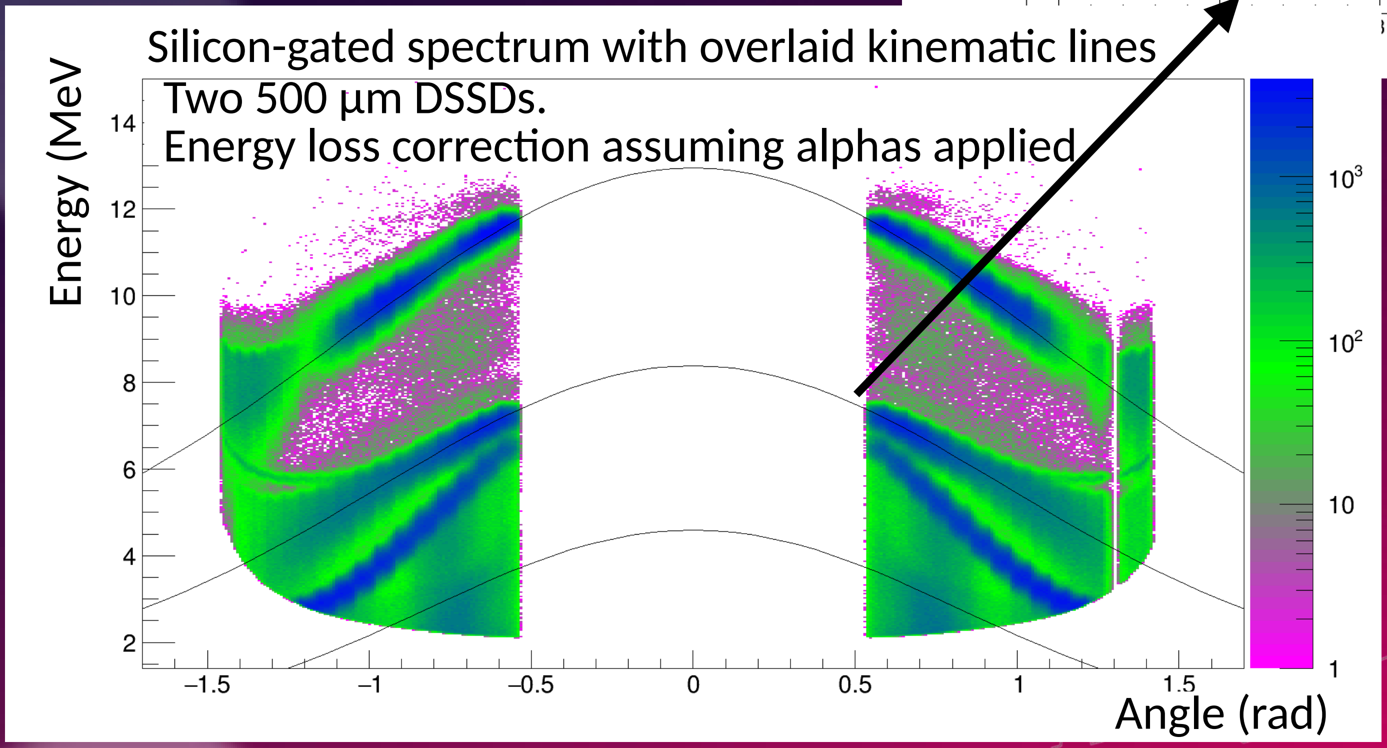




Nuclear physics — particle-gamma coincidences

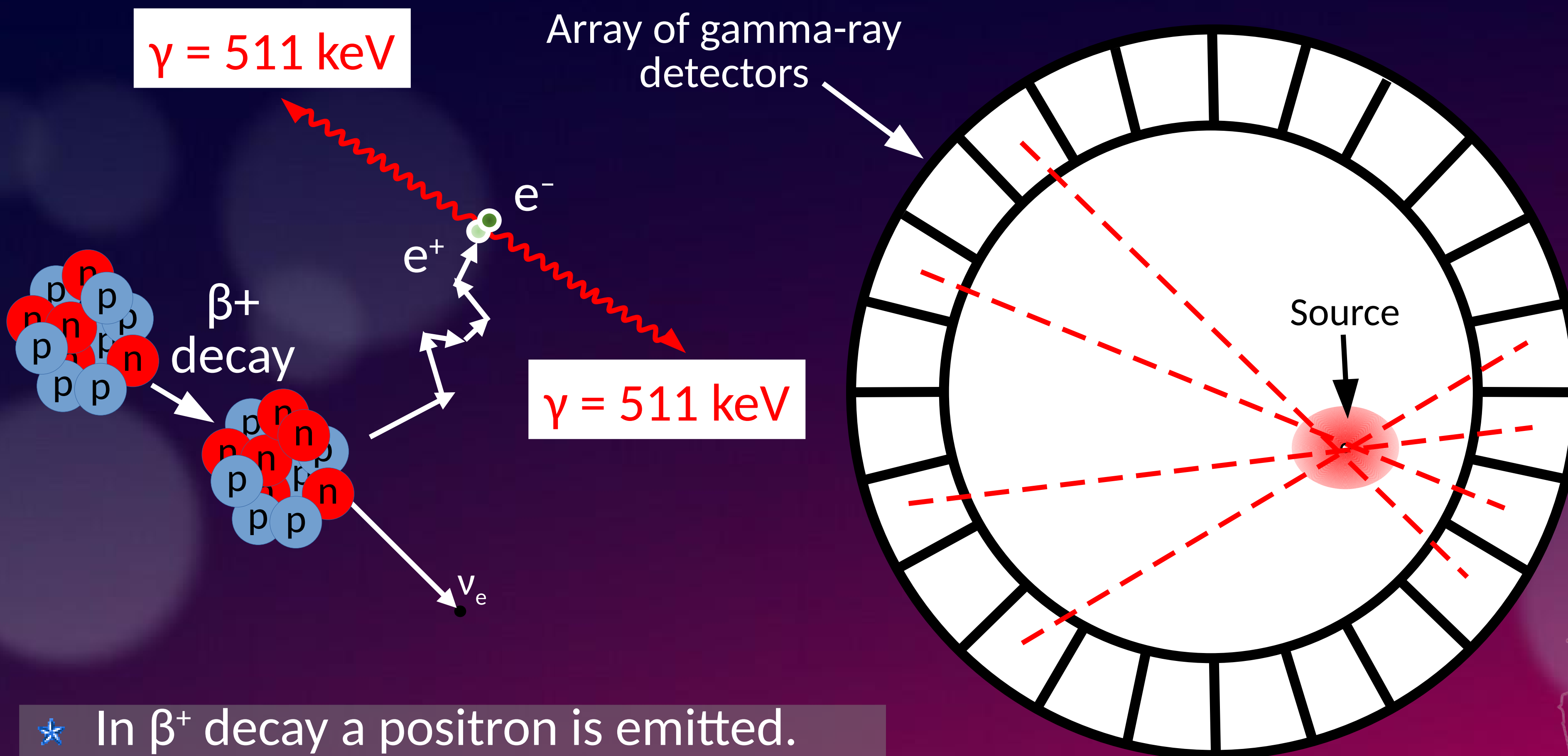
- Particle-gamma coincidences are a powerful tool to study weakly populated states and decay branches.
- DSSDs provide a large number of pseudo pixels for relatively few electronics channels.





- Micron W1 detectors are the 'work-horse' detector type at Birmingham.
- Multiple hits with similar energies can lead to increase background. → M-C simulation to optimise geometry.

PIC — Positron Emission Particle Tracking (PEPT)



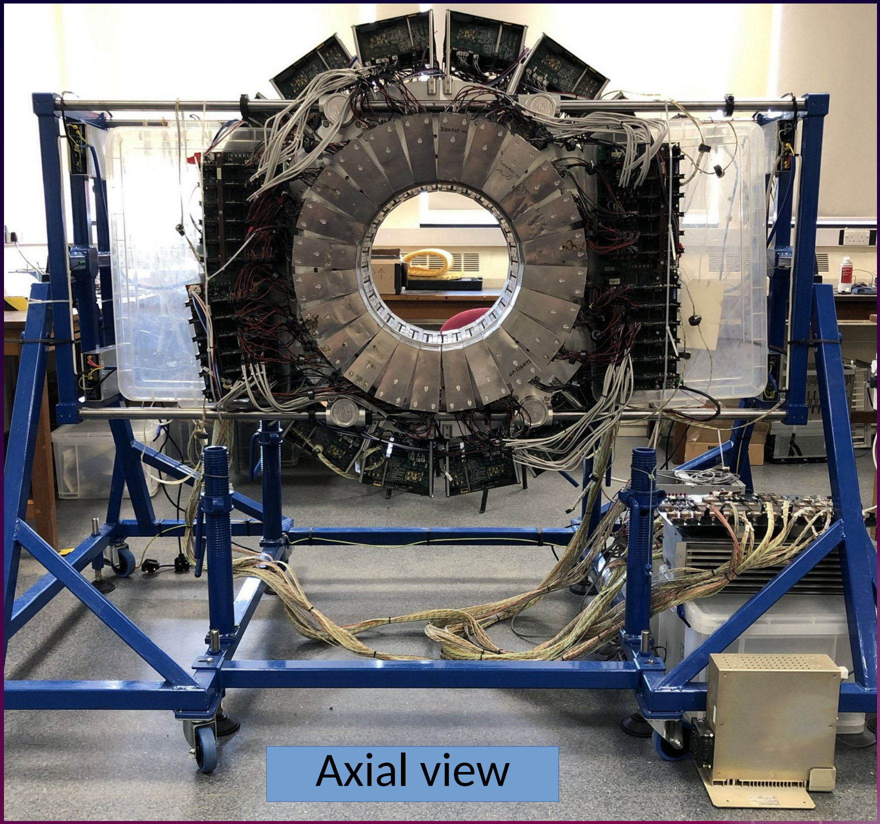
- In β^+ decay a positron is emitted.
- This loses energy and then annihilates with an electron.
- Two back-to-back gamma rays are produced.

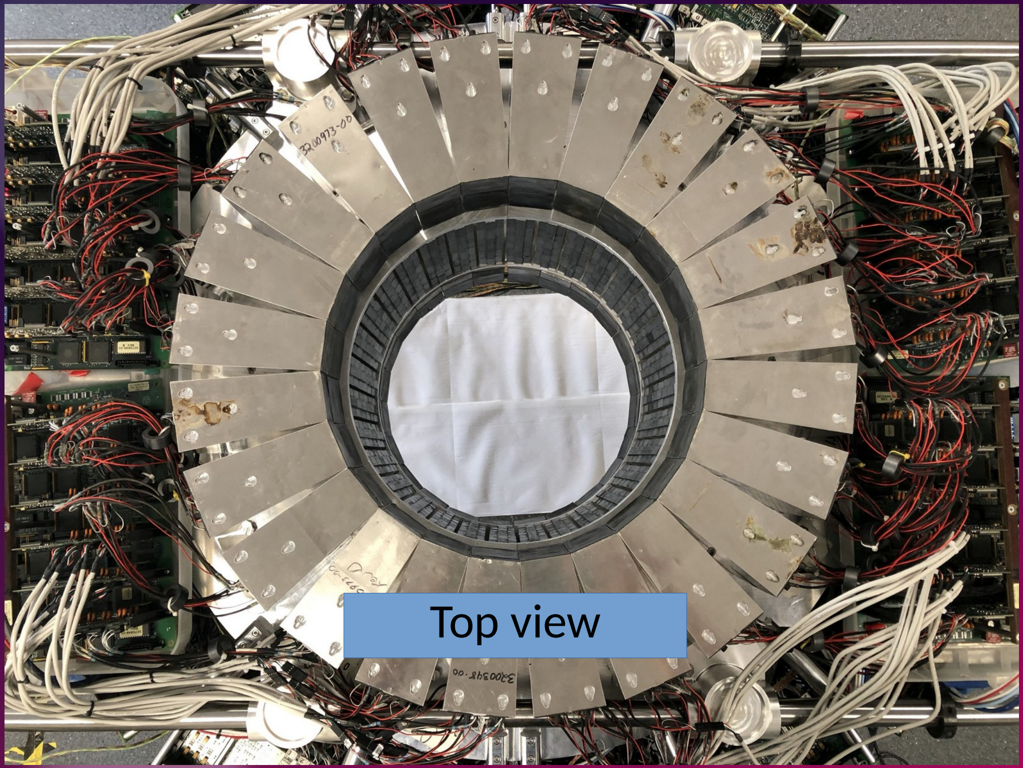
What are the most common PET isotopes?

^{18}F, ^{15}O and ^{11}C.

Positron Imaging Centre — SuperPEPT

- New large field-of-view array.
- Sub-millimetre position resolution.
- Real-time particle tracking.
- High data rate.
- Ideal for studying flow inside complex systems

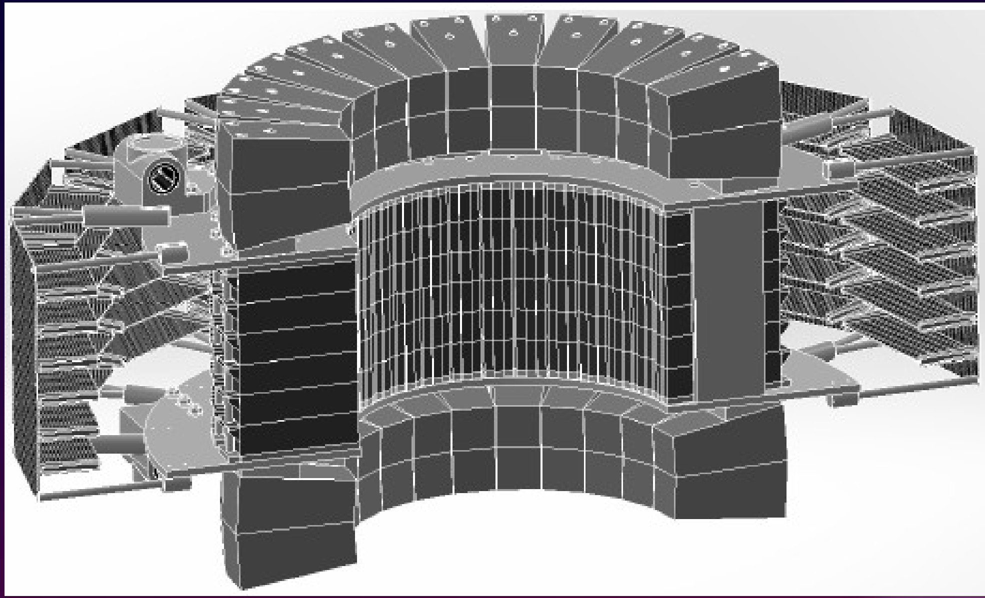




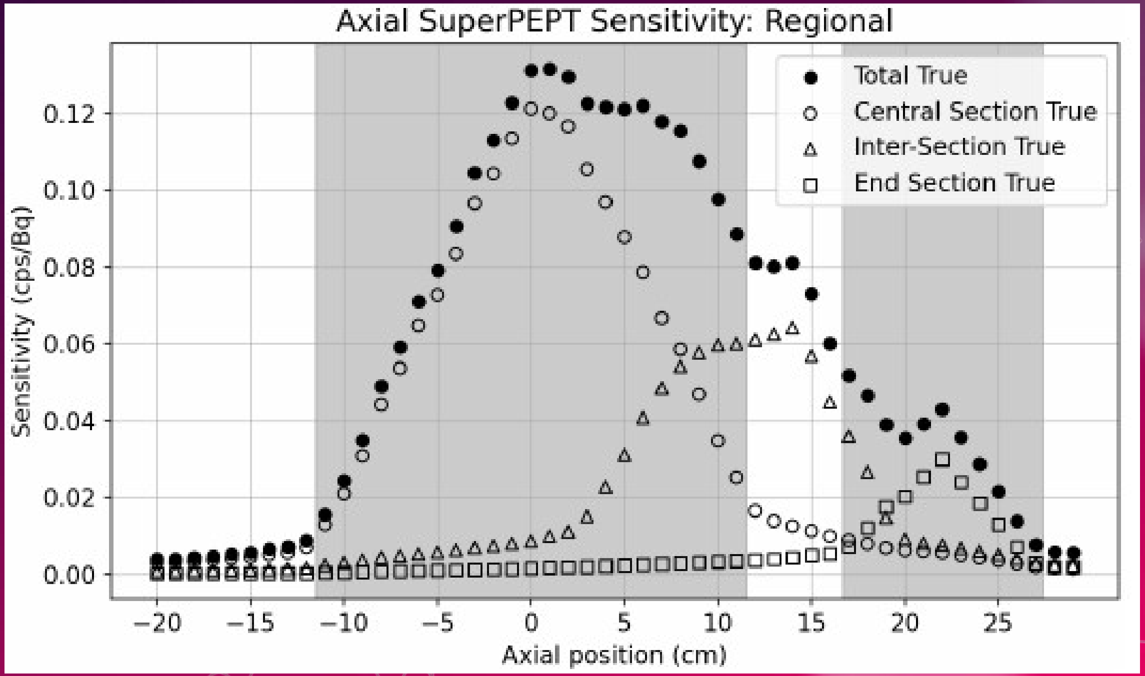
(Right) 8x8 segmented BGO detectors.

Positron imaging Centre — SuperPEPT

- Currently two of the three sections have been tested. The central section and one side section.
- Dimensions: inner diameter: 40 cm, axial length: 54.5 cm.
- Absolute sensitivity, measured in counts per second per becquerel is shown below.



- Typical coincidence rate of 1.7 MHz (much higher rates are possible).
- For fast moving source, e.g. a rotating ^{18}F source moving at 900 RPM, an RMS position error (in 3-dimensions) of <1 mm can be achieved.



Summary

- The new facility offers a wealth of possibilities both for fission, fusion and other fields.
- The lifetime of these accelerators can be 50 years.
- Applications and blue skies research comfortably coexist.

https://www.birmingham.ac.uk/research/activity/nuclear/about-us/Facilities.aspx

Thanks for contributions to slides:

- Prof. Tzany Kokalova, Dawid Hampel (PIC)
- Dr Laura Gonella (AIDA)
- Pedro Santa Rita Alcibia (Si-$LaBr_3$ set-up)

The HF-ADNeF team:

- Dr Ben Phoenix technical specialist for accelerators.

  (Thanks to Ben for providing many of the pictures in today's talk.)

- Prof. Martin Freer (PI), Prof. David Parker and Prof. Stuart Green

Thanks for your attention.

The End

Birmingham's other accelerator…

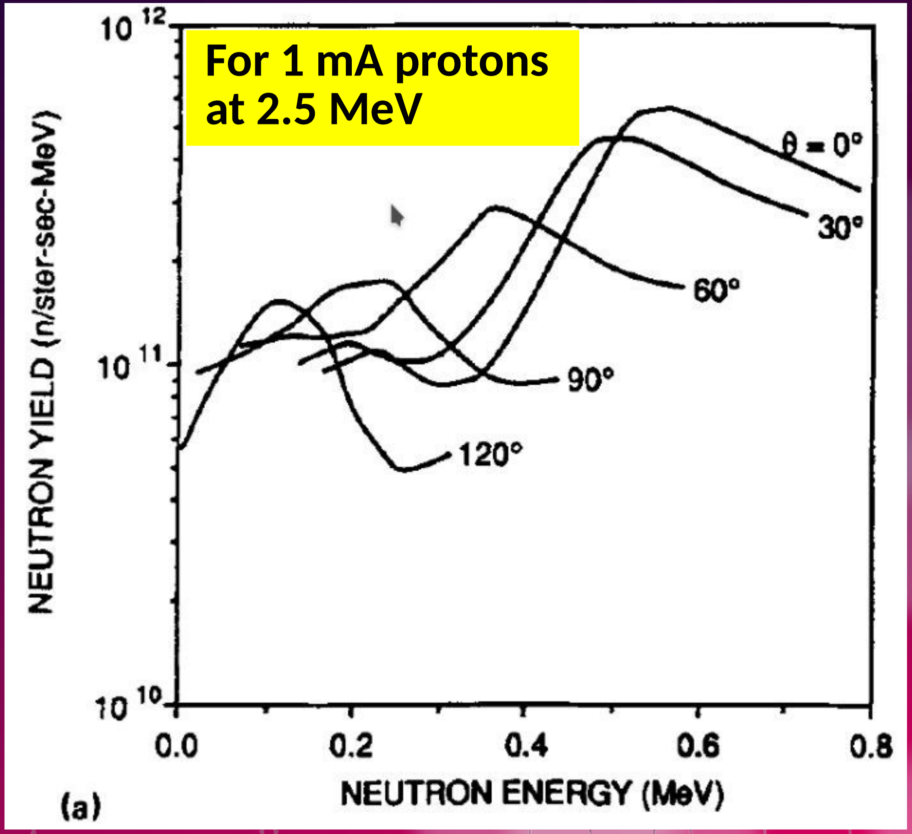
- **RDI 3MV Dynamitron (1970 – 2019) 49 years!**
- A low energy accelerator, for protons up to 3 MeV.
- This was high current machine (1 mA) for nuclear physics, BNCT and later materials damage studies.
- High neutron fluxes were produced from protons on a lithium target.
- This machine is being decommissioned. The new HF-ADNeF machine is a horizontal accelerator!

Neutron production

Neutrons are produced using a cooled, rotating, lithium target and the $^{7}Li(p,n)^{7}Be$ reaction (Q = –1.64 MeV).

E_{beam} = 1.8-2.6 MeV

Neutron energy spectrum as a function of angle

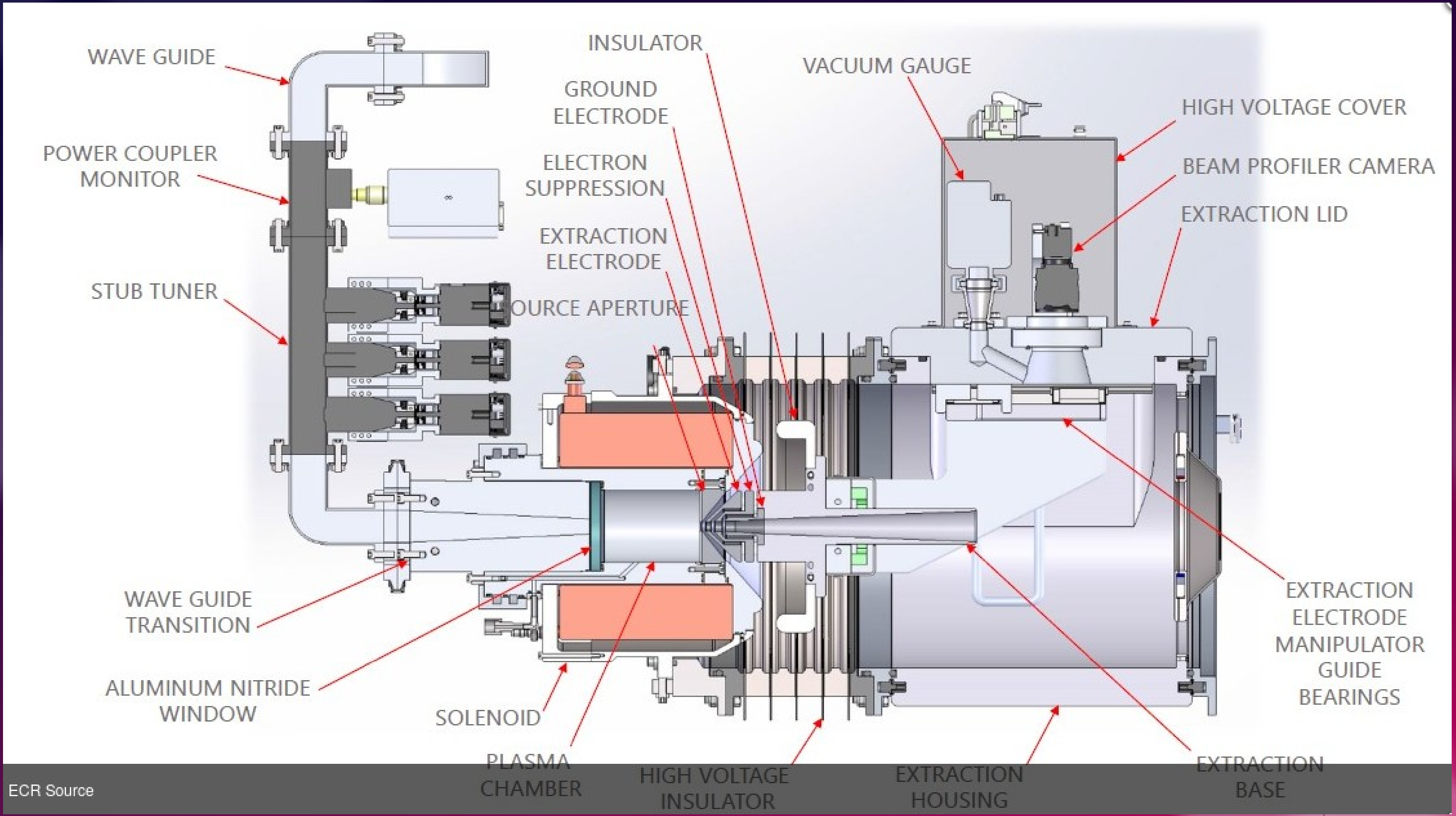


Due to the build-up of radioactivity from the ^{7}Be ($t_{1/2}$ = 53.22 days) target (resulting in 478 keV gamma 10% of the time) changes will be performed robotically.

Figure from: J.C. Yanch *et al.*, Medical Physics **19** 709 (1992).

Ion source for HF-ADNeF

ECR source to create positive ions.

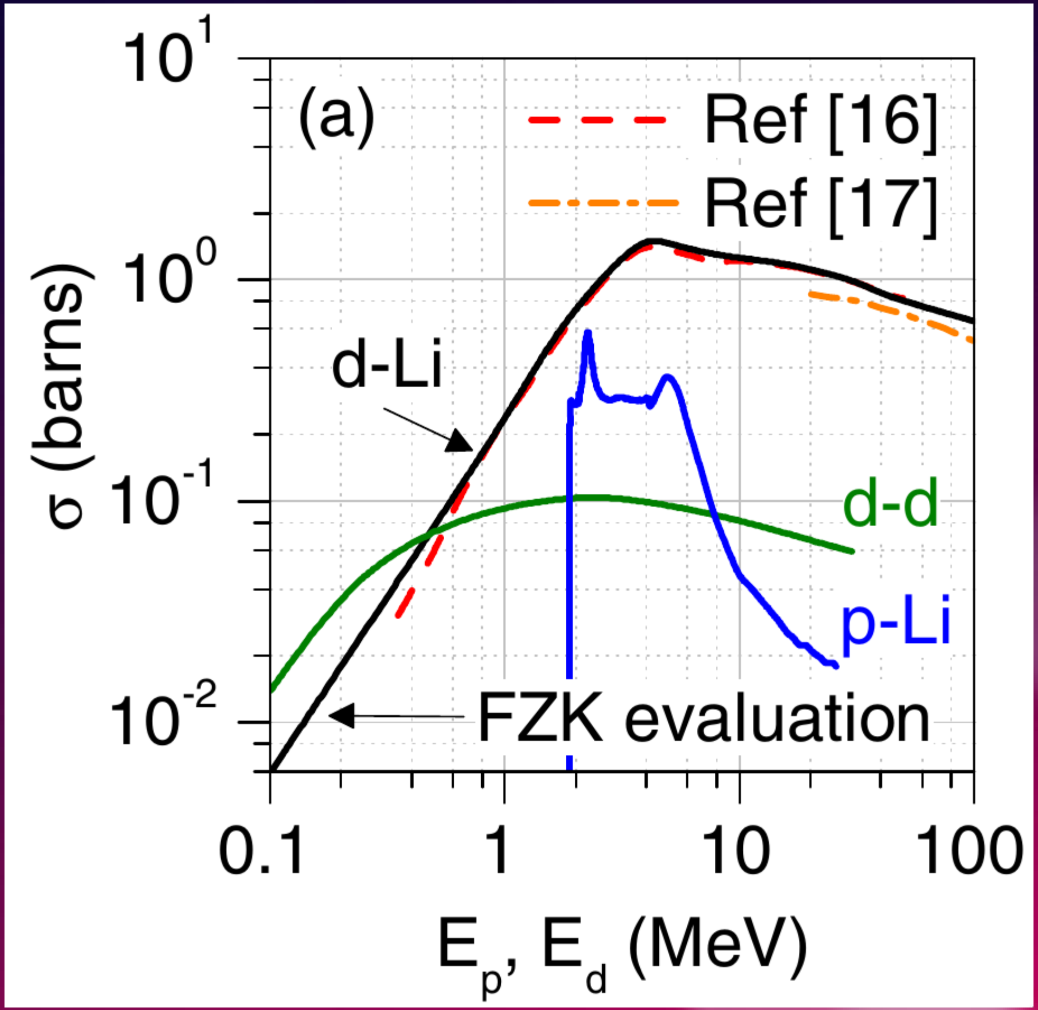


ECR Source

https://www.d-pace.com/

Possible HF-ADNeF upgrades in the future

Possible future up-grade to both current (>50 mA) and the use of deuteron beams.

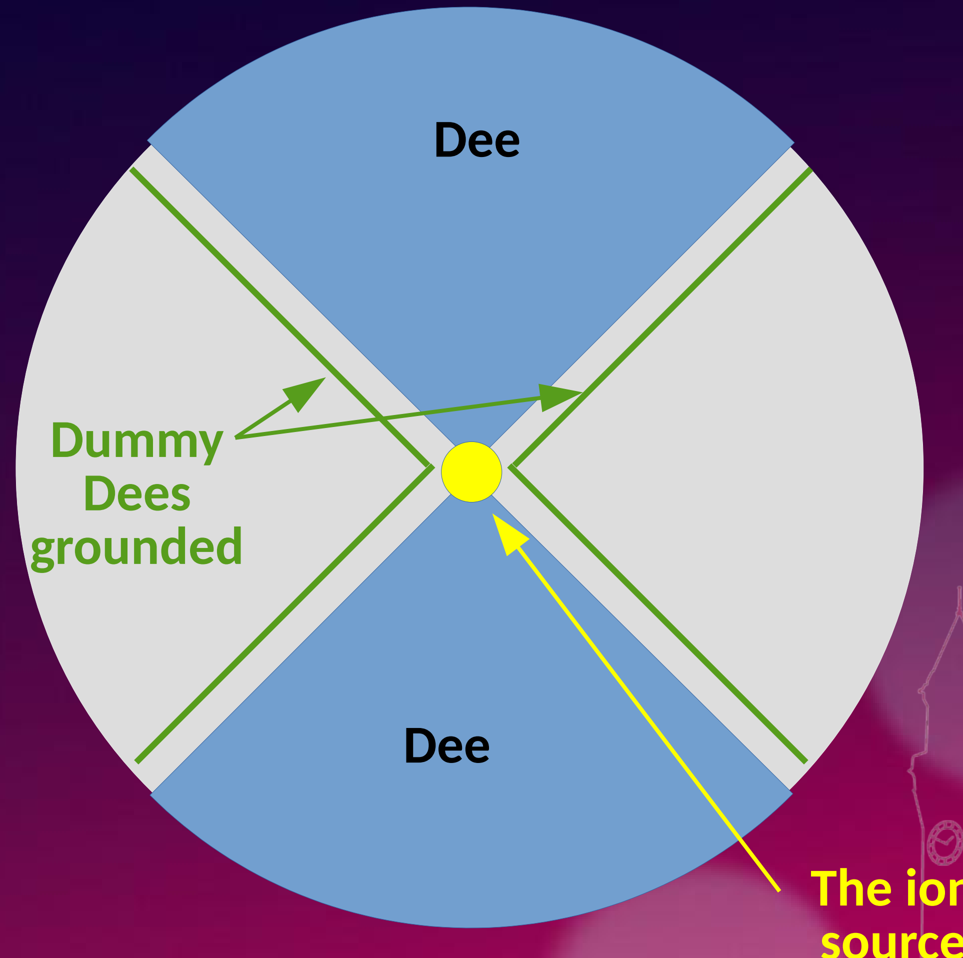


J. Davis, *et al.*, Plasma physics and controlled fusion **52**.4 (2010) 045015.

The MC40 cyclotron

A Scanditronix MC40 cyclotron.

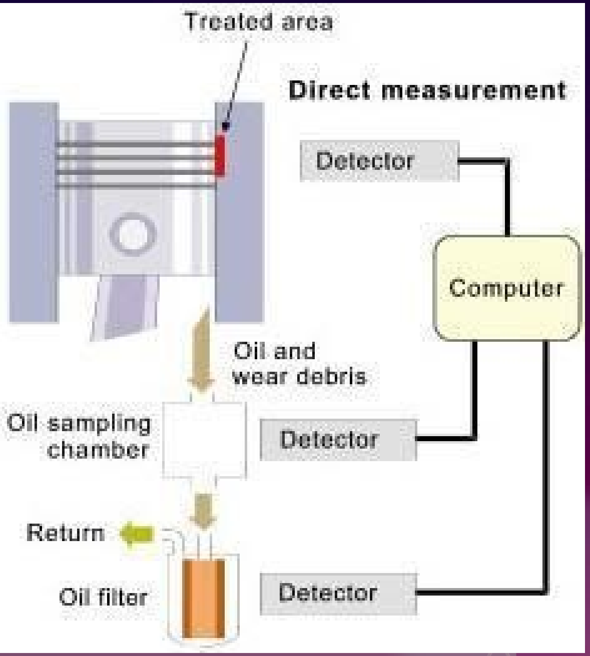
From 2002-2004 it was transferred from Minneapolis, USA. Originally installed 1988, run occasionally from 1991-2001.



Thin-layer activation

For measuring **wear** on components (especially automotive parts, for R&D):

- Irradiate surface with beam to create long-lived radionuclide in well-defined surface layer (typically ~ 50 µm deep).
- Subsequently monitor surface removal by detecting gamma-rays either from remaining layer or from wear debris.



Steel:

- $^{56}Fe(p,n)^{56}Co$ (77 days, 0.85 MeV and 1.24 MeV gammas).
- $^{56}Fe(d,n)^{57}Co$ (270 days, 0.122 MeV gammas).

Can activate different surfaces with each for simultaneous studies.

Aluminium:

- $^{27}Al(^{3}He, 2\alpha)\,^{22}Na$ (2.7 yrs, 0.511 MeV & 1.27 MeV gammas)

Diamond-like carbon (DLC) coatings

- $^{12}C(^{3}He, 2\alpha)^{7}Be$ (53 days, 0.47 MeV gamma).