Alta Cyclotron Services

A University of Birmingham business

The Birmingham MC40 Cyclotron

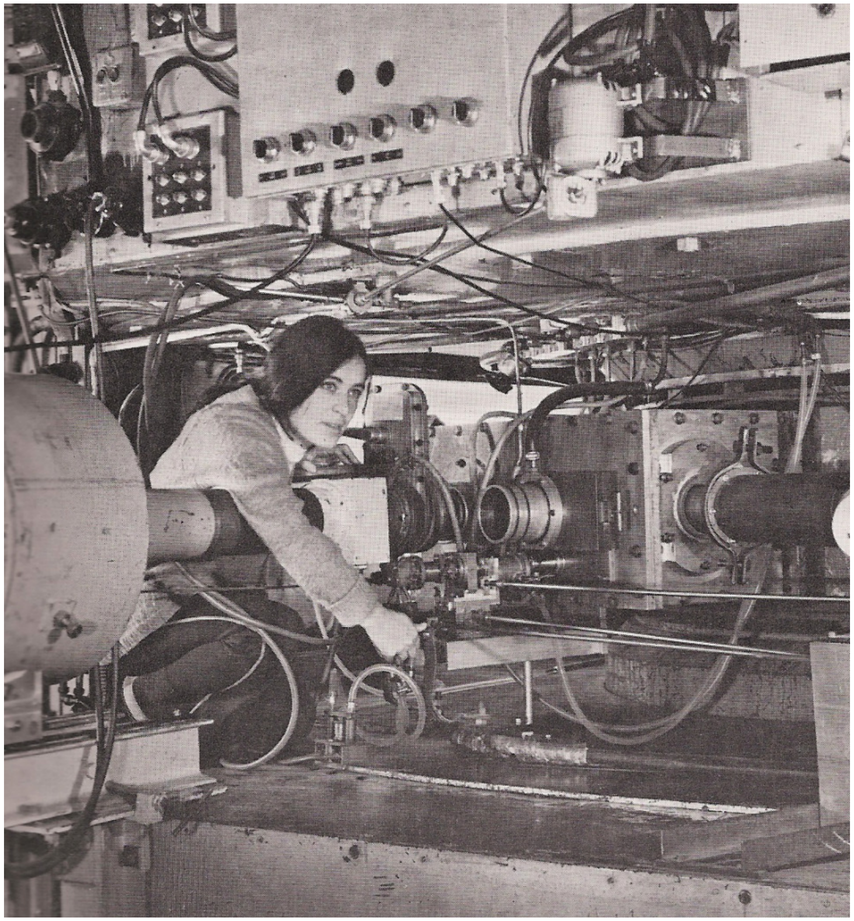
David Parker

University of Birmingham

- Quick History
- Technical description
- Applications
- More on transfer from Minneapolis

History of accelerators at Birmingham

- 60” Nuffield cyclotron (1948-1999) 10MeV p, 40MeV α



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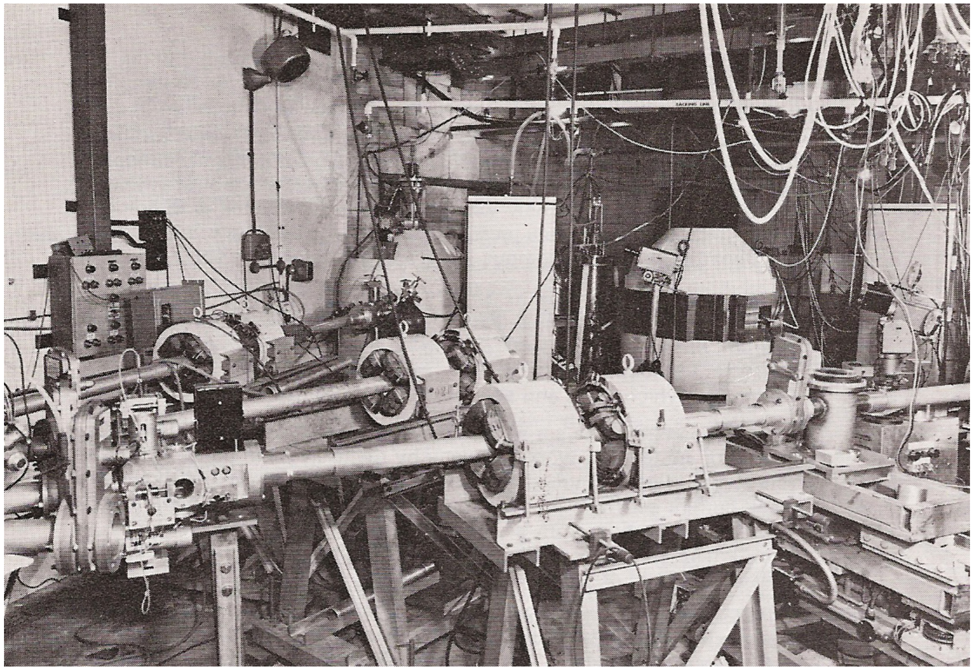
  (axially injected polarised beams) 12MeV d, 24 MeV α, 33MeV ^{3}He



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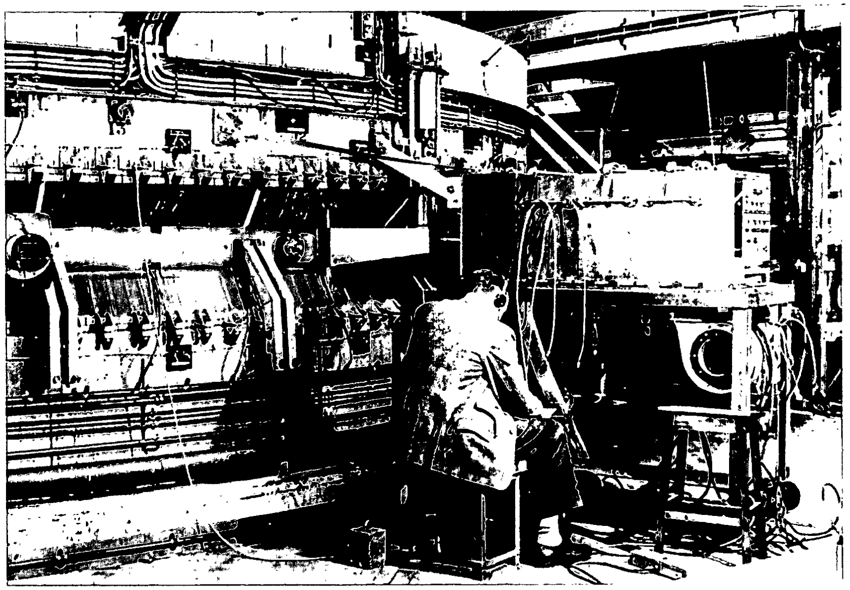
- 1GeV proton synchrotron

  (1953-1967)

  (overtaken during construction

  by Brookhaven Cosmotron)



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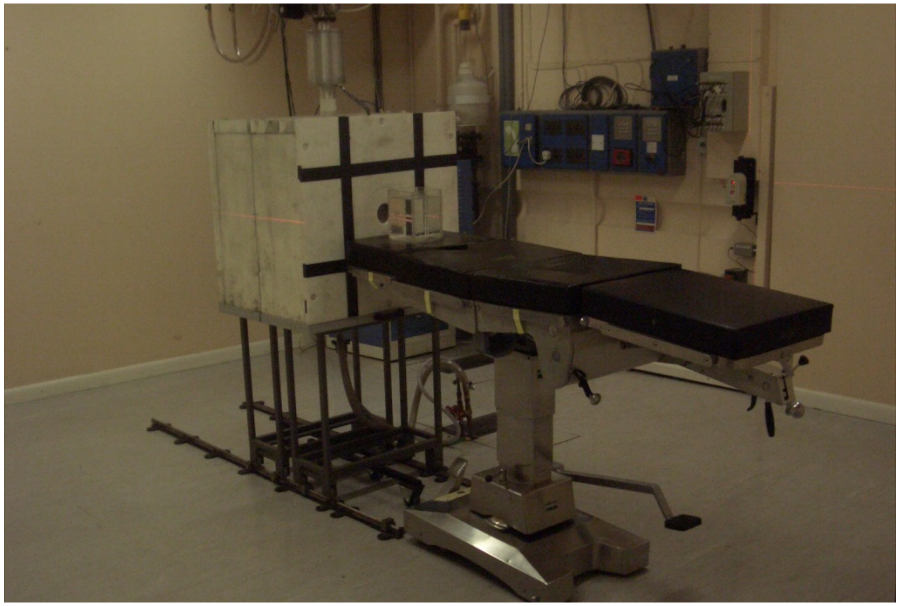
- 1GeV Proton synchrotron (1953-1967)

- RDI 3MV Dynamitron (1970 - 3MeV p on Li for BNCT



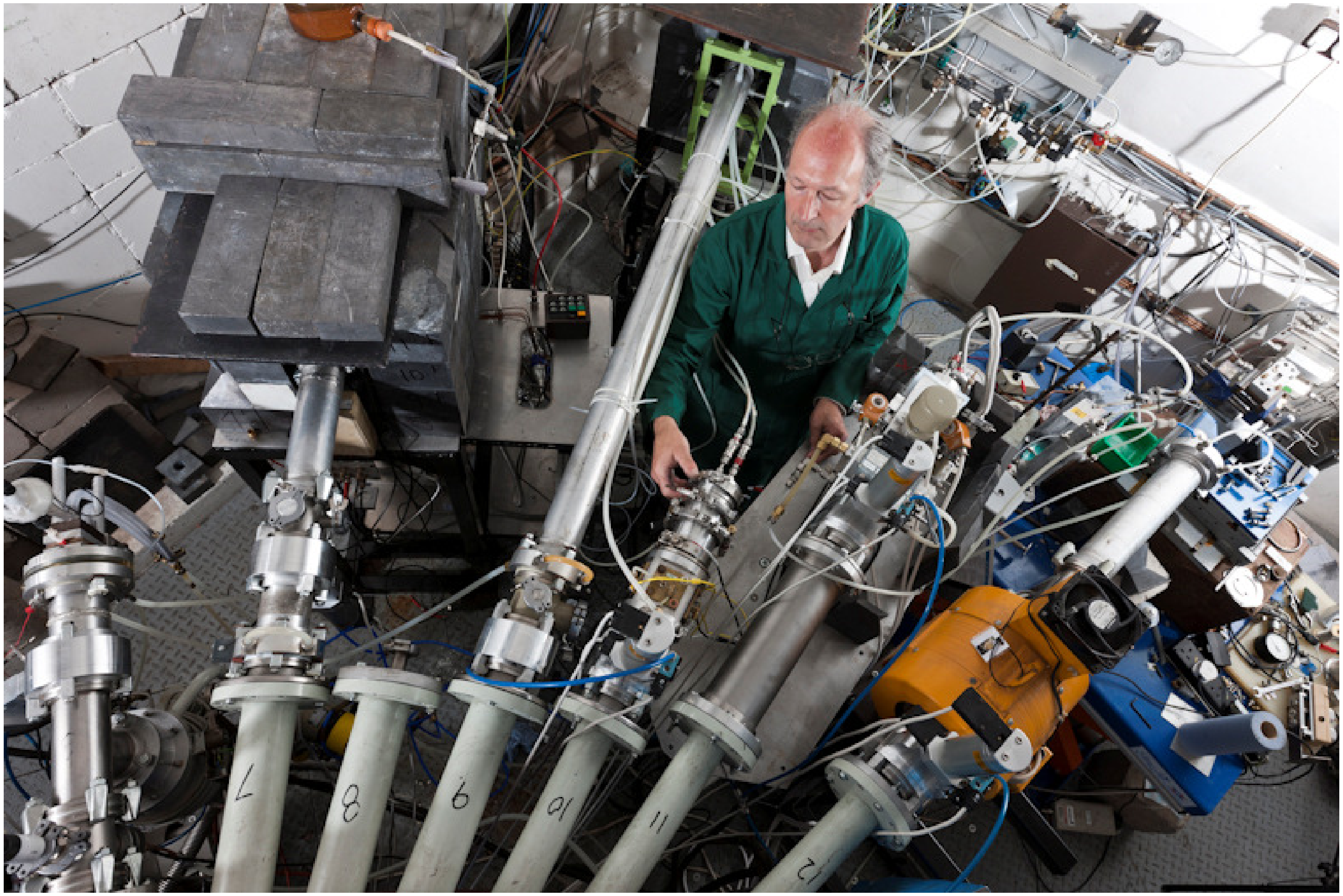
The MC40 cyclotron

is the third cyclotron to be operated at the University of Birmingham

In 2002-2004 transferred from Minneapolis

to Birmingham

In 2005 we added a 12-way switching magnet (blue) [ex Vivitron]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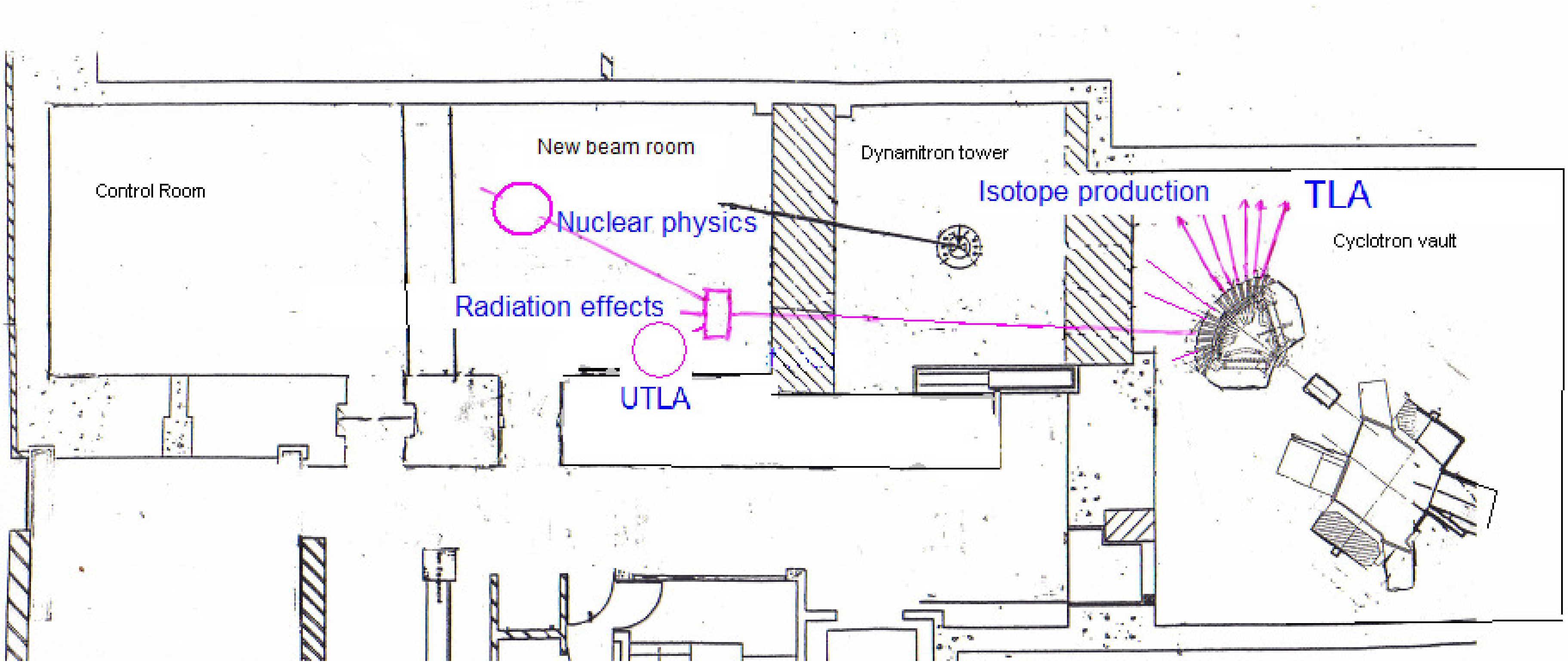
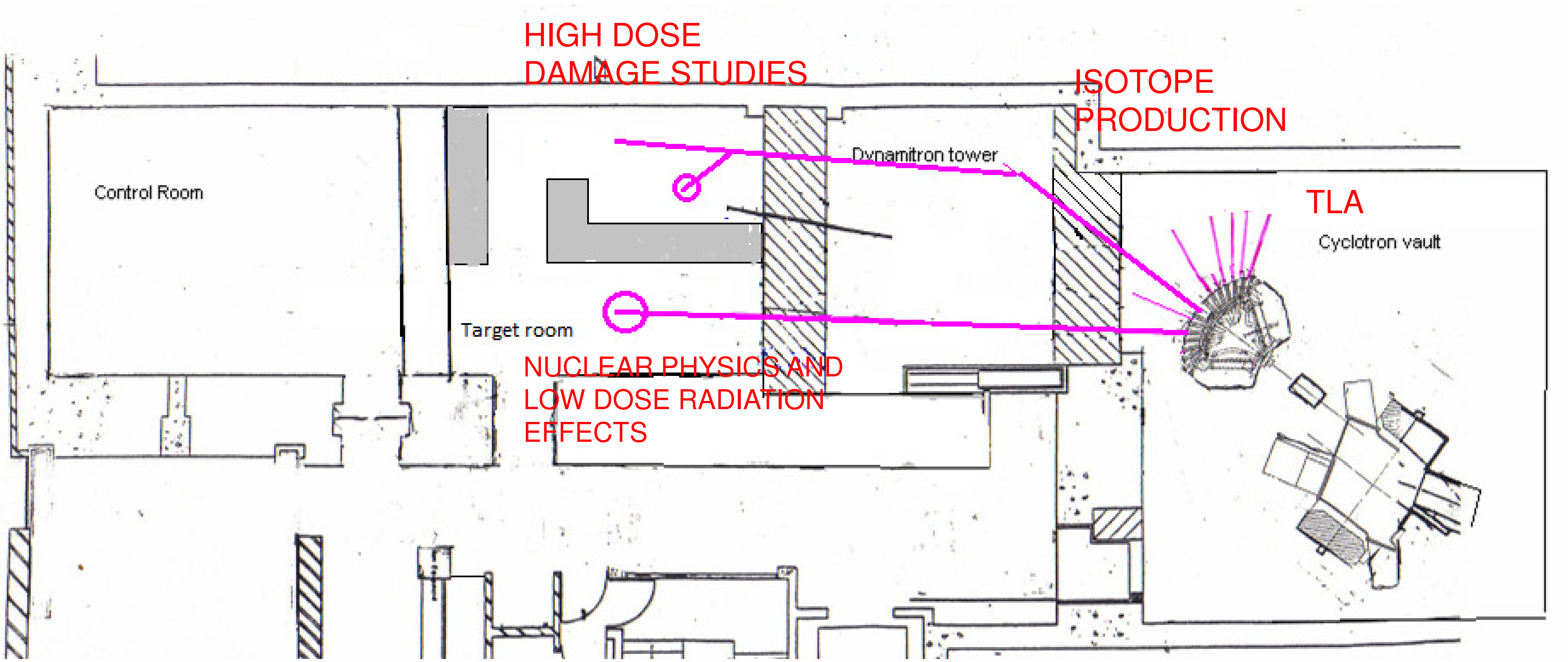
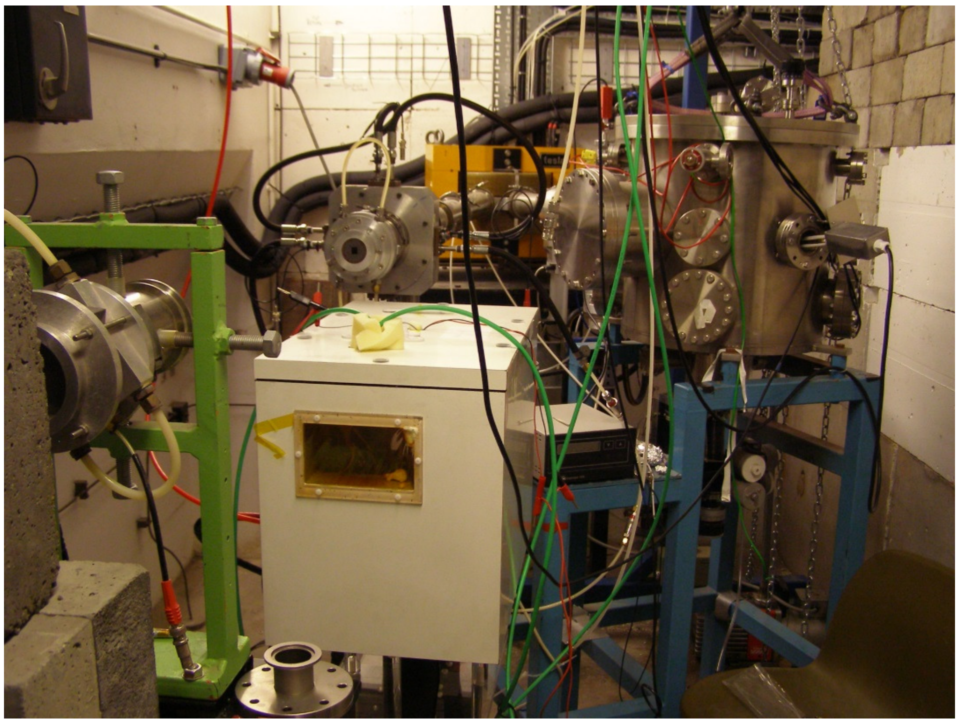
Initially one beam line ran into the adjacent room (past Dynamitron accelerator) and was used for studying radiation effects (e.g. space electronics)

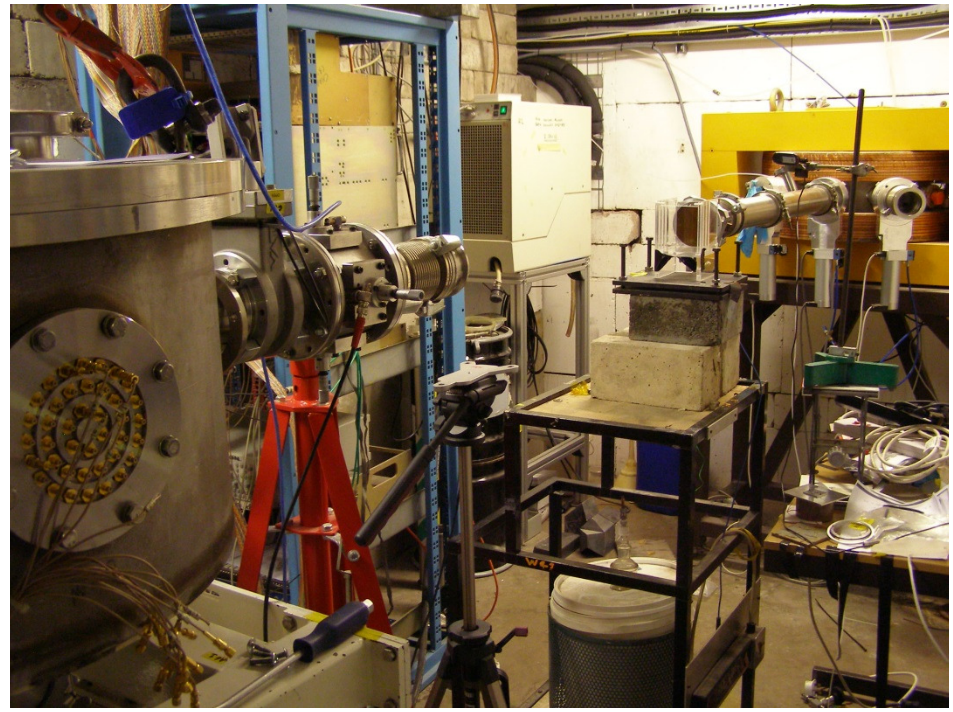


More recently, we were asked to provide high dose-rate damage studies (LHC ATLAS group and metallurgy) so extended a second beam-line into a specially shielded area.



High current irradiation cell:
ATLAS line on left,
Metallurgy chamber on right





Low current irradiation line:
Radiobiology, space applications upstream,
Nuclear physics scattering chamber downstream.

Cyclotron equations for particle mass m, charge q in magnetic field B (assuming uniform B, invariant mass)

Velocity v related to radius r via $\frac{mv^2}{r} = qvB$

(hence constant angular velocity $\omega = \frac{v}{r} = \frac{qB}{m}$)

At extraction radius R, kinetic energy is

$$E = \frac{1}{2} m v_R^2 = \frac{1}{2} m \left(\frac{qB}{m} \right)^2 R^2 = \frac{R^2}{2} \frac{q^2}{m} B^2$$

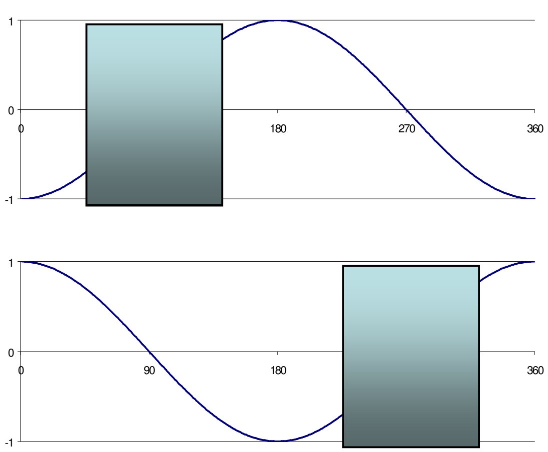
With R=53 cm, B_{max}= 1.8 T, maximum energies are

protons	40 MeV
deuterons	20 MeV
alphas	40 MeV
$^3He^{2+}$	53 MeV

Acceleration is provided by rf voltage on two 90^{o} dees

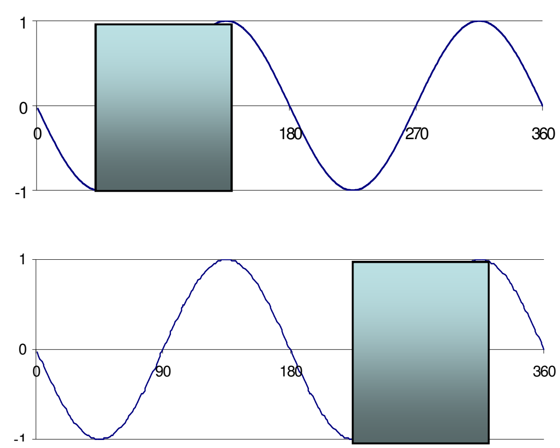
Accelerating frequency = N x orbital frequency where N=harmonic number (N=1,2)

N=1



or

N=2



In this way we can double the range of orbit frequencies with the same rf system

40 MeV protons, *N*=1, requires 26.6 MHz

rf system tuneable between 14.2 and 28 MHz (was originally designed to go down to 13 MHz but rf stubs were cut down because of limited headroom in Minneapolis)

protons	N=1	11-39 MeV
	N=2	3 - 9.5 MeV
deuterons	N=2	5.5-19.5 MeV
$^{4}He^{2+}$	N=2	11-39 MeV
$^{3}He^{2+}$	N=1	33-54 MeV
	N=2	13-27 MeV

Also 46 MeV $^{14}N^{4+}$ and 70 MeV $^{14}N^{5+}$ for nuclear physics

Cyclotron is used for

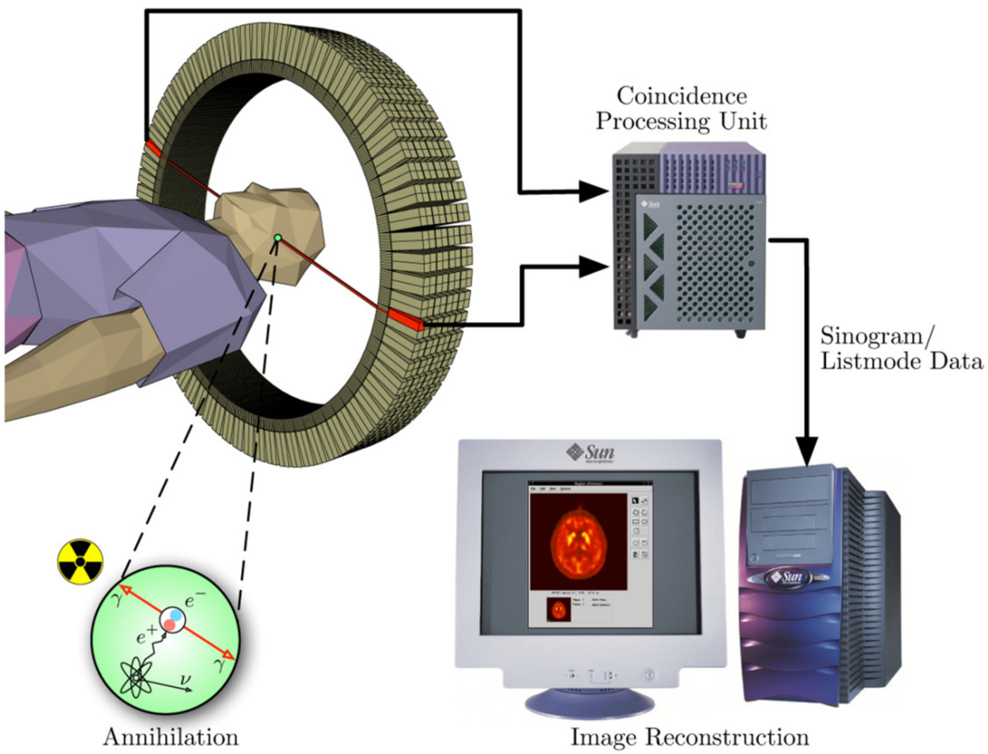
- Producing positron emitting nuclides for Engineering PET [NOT FDG]
- Producing ^{81}Rb for ^{81m}Kr generators
- Thin Layer Activation
- Other isotope production:
    - ^{69}Ge for labelling oil
    - ^{62}Zn supplied to St Thomas' Hospital London
    - Various irradiations for NPL
- Radiation effects studies:
    - Radiobiology + dosimetry (proton imaging)
    - Space electronics etc
    - ATLAS components
    - Metallurgy of nuclear materials
- Nuclear physics

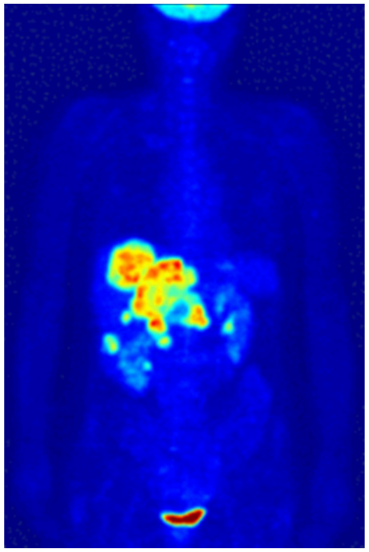
Positron emission tomography (PET):

Mapping concentration of radioactively-labelled fluid

PET scanner consists of rings of many small detectors, operating in coincidence to detect the pairs of back-to-back γ-rays from positron annihilation.

After detecting millions of such events a 3D tomographic map of tracer concentration can be reconstructed



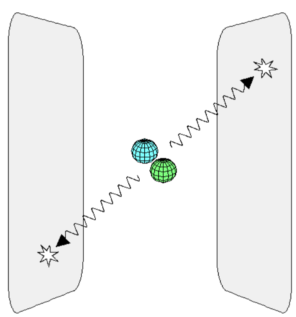


Gamma rays are penetrating – can observe labelled fluid inside process vessels

But PET is slow – requires detection of ~ million coincidence pairs

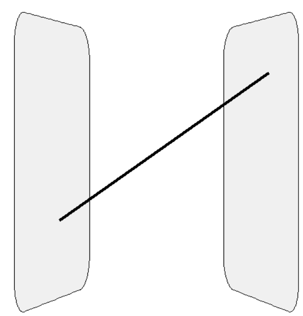
For fast dynamic information use **Positron emission particle tracking (PEPT):**

Introduce a single labelled particle, and locate it frequently



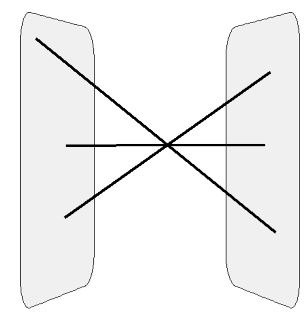
Detection

Detection of gamma rays using two large position sensitive detectors.



Reconstruction

Two rays detected in coincidence define line along which particle lies.



Particle Location

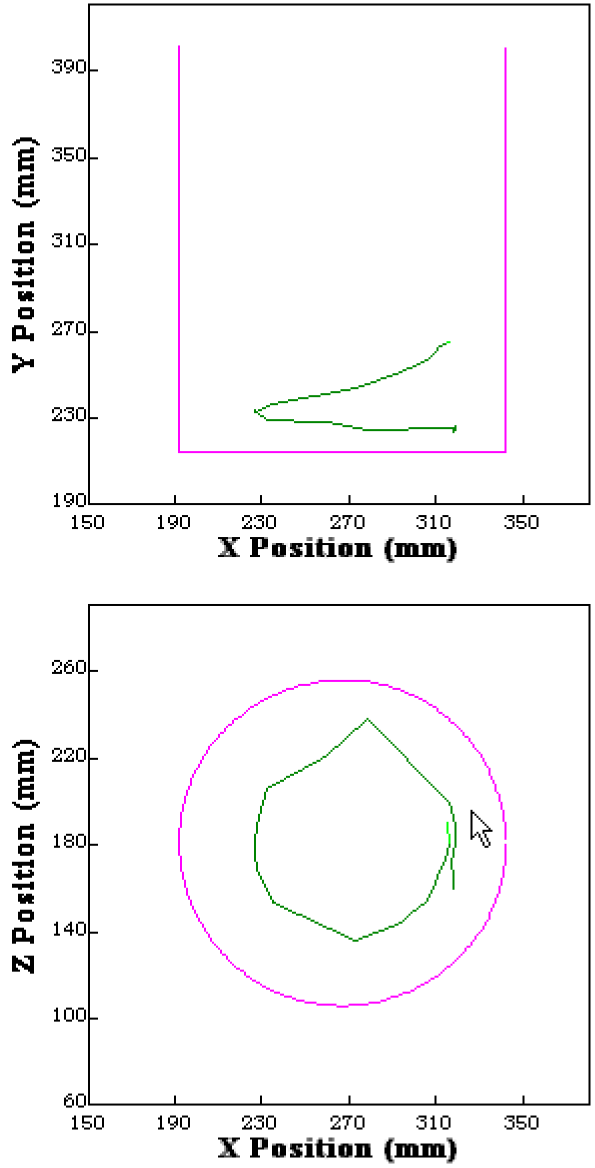
After several events, tracer can be located via triangulation.

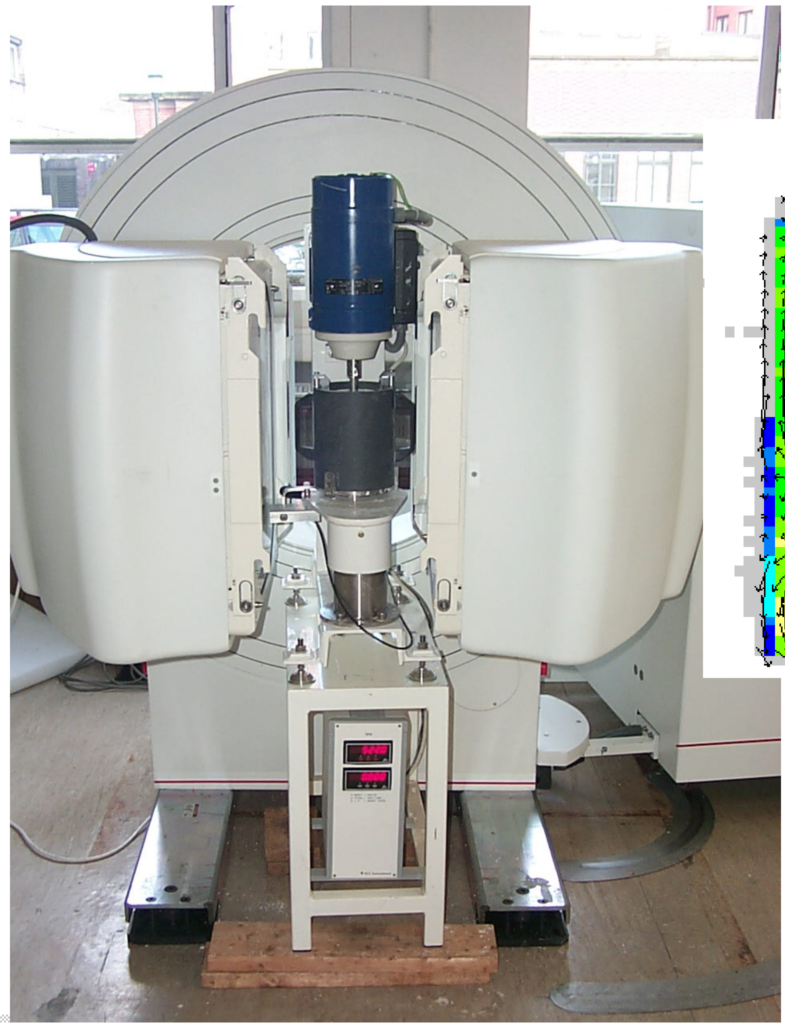
Currently labelling tracer particles down to 100µm diameter

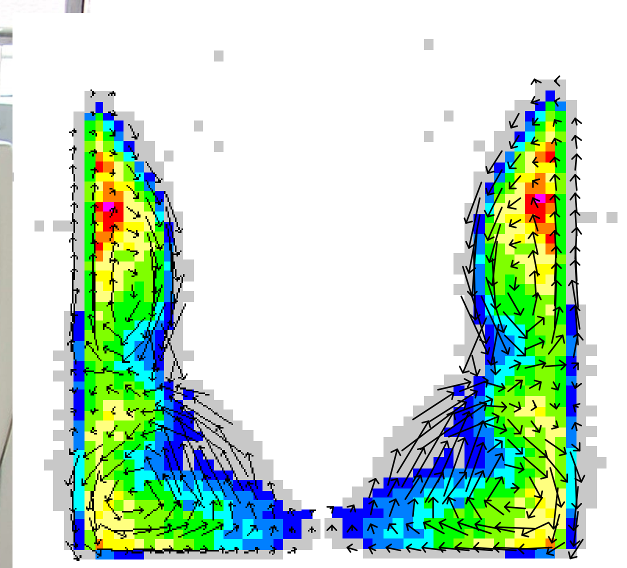
Can locate tracer particle to within 1mm every 1ms

Positron emission particle tracking (PEPT)

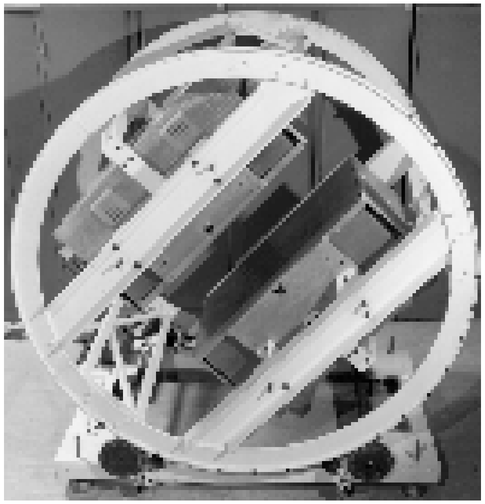
Label a single particle (grain of sand, etc) with positron-emitter (usually ^{18}F from ^{3}He on natural oxygen) and track it as it moves inside equipment





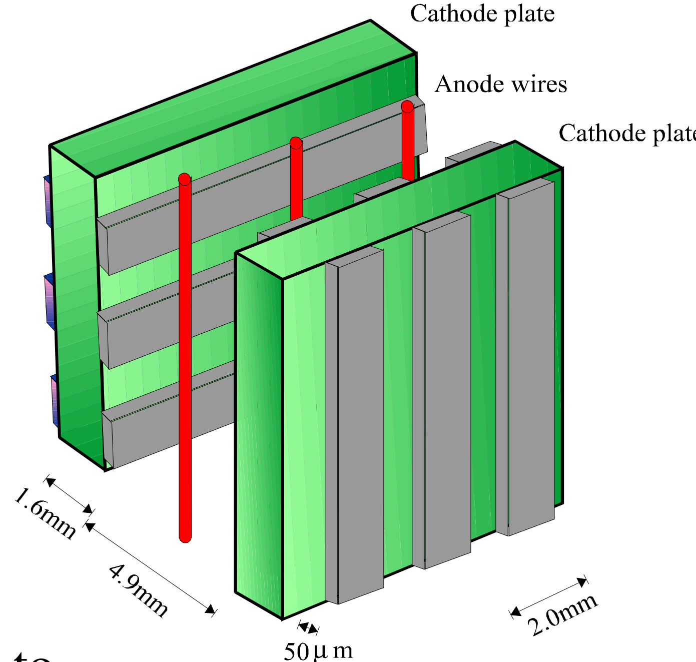


Original Birmingham Positron Camera



Hawkesworth et al, PSD1 1987

- Originally designed to image lubricant in operating jet engine
- Operational 1984
- Pair of gas filled MWPCs, sensitive area 600x300mm^2



- Cathode planes have 50μm lead strips
- Delay line readout
- Each chamber contains a stack of 20 such assemblies
- Total quantum efficiency for 511keV photons 7%

- Spatial resolution 8mm FWHM (+long tails)

Useful count rate limited to around 3000 events/s due to

dead time in readout

random coincidences (resolving time 12.5ns)

"New" Birmingham Positron Camera

Parker et al, PSD5 1999

•Installed summer 1999
•Commercially available medical system (ADAC Forte)
•Cost £0.3M
•Pair of gamma camera heads on rotating gantry; separation 250-800mm

Each head contains NaI(Tl) crystal 590x470x16mm^3,
55 PMTs each connected to its own ADC;
single board computer

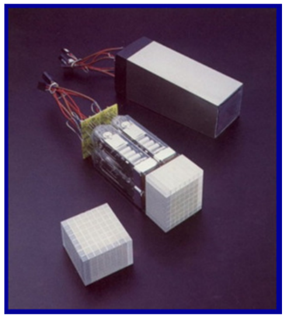
	Old camera	New camera
Spatial resolution	8mm	4-6mm
Singles sensitivity	7%	23% total/16% photopeak
Energy resolution	None	15% FWHM
Resolving time	12.5ns	7.5ns
Max true coincidence rate	5kcps	100kcps

Third generation Birmingham systems

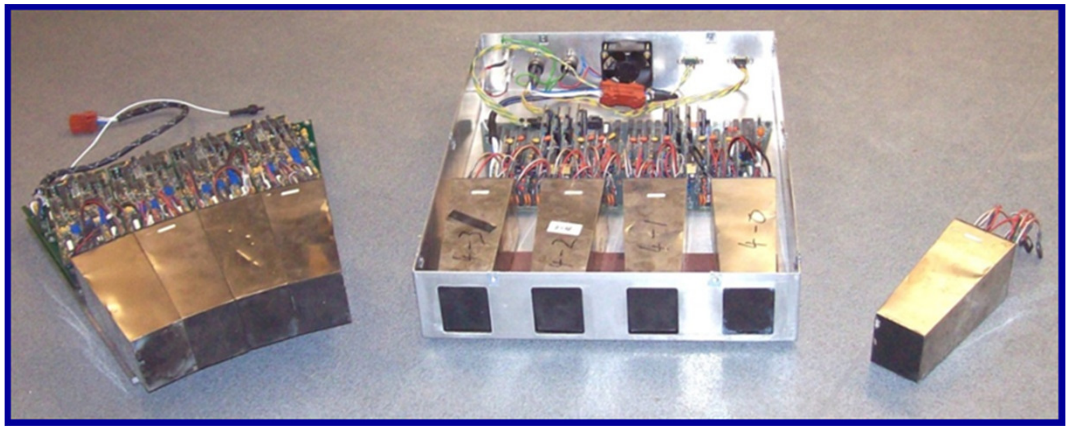
developed from redundant medical PET scanners

Leadbeater et al, PSD7-9

Since 2002 PIC has acquired
6 complete PET scanners
and components from two others
(all based on segmented BGO blocks)



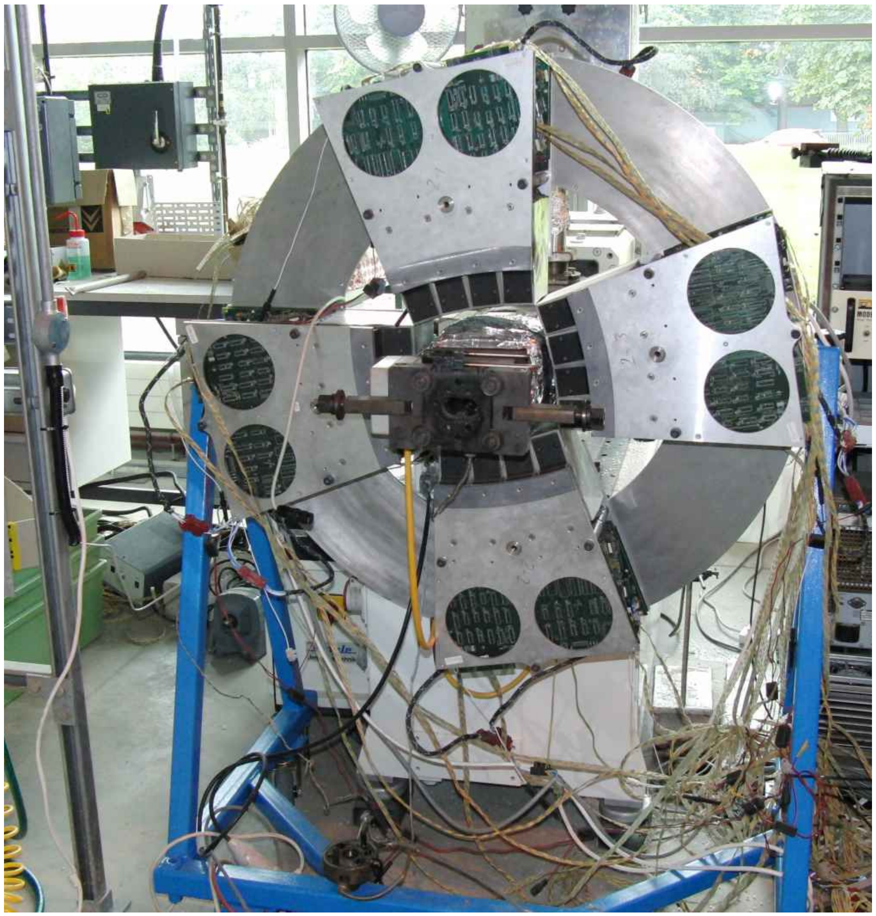
These are inherently modular, and can in principle be reconfigured in different geometries for PEPT.



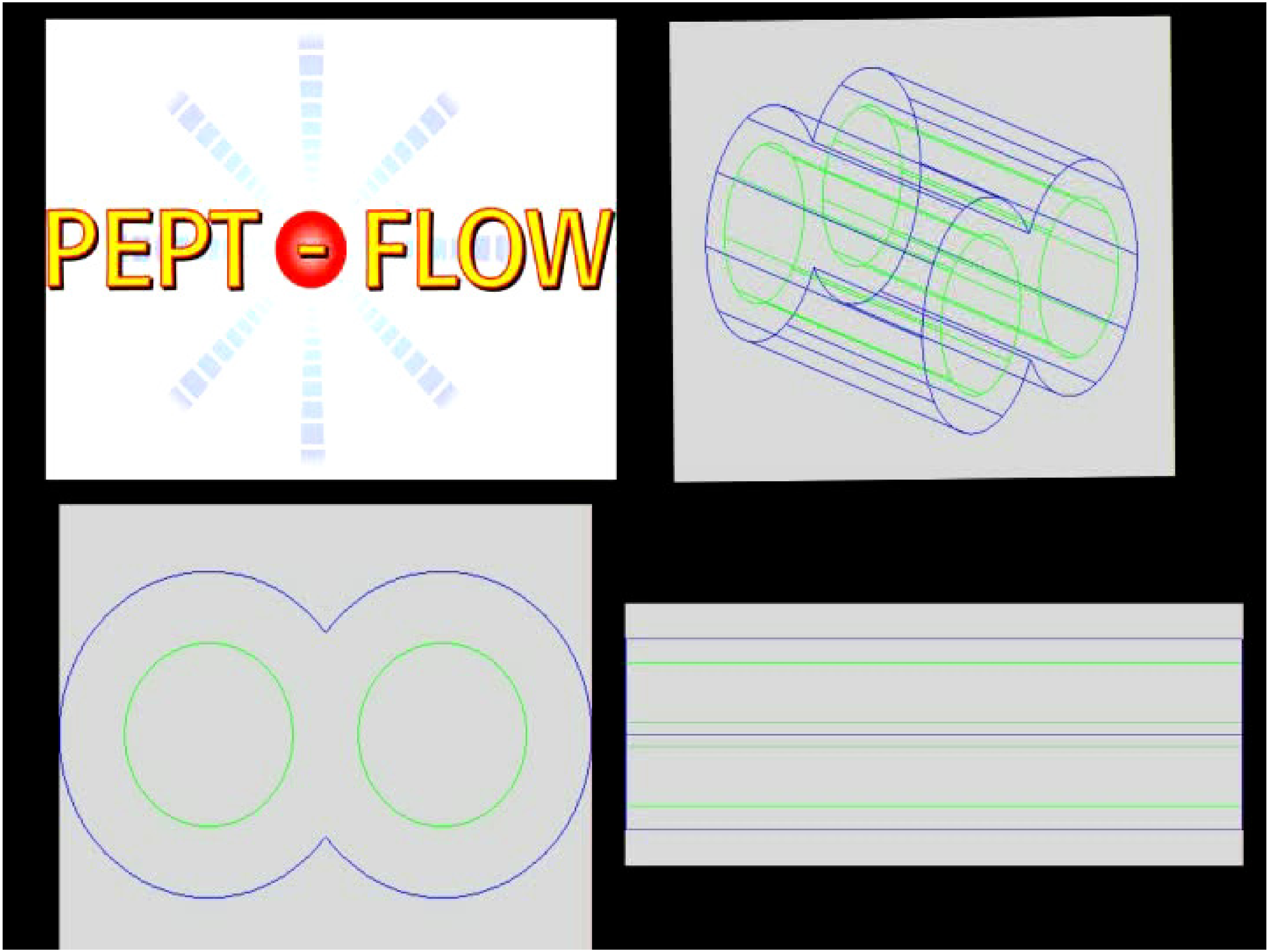
Can operate at >1Mcps, sensitivity often non-uniform

Twin Screw Extrusion of Polymers

Modular camera installed on Modified Leistritz 27mm TSE



Screw Elements in FOV

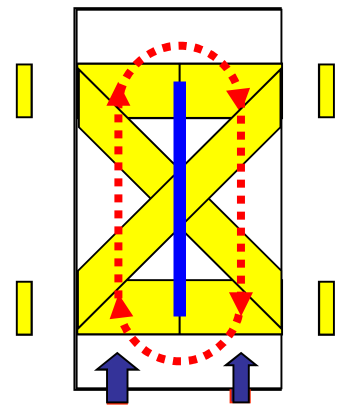

PEPT - FLOW

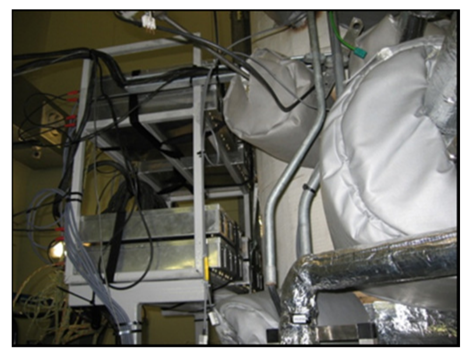
On-plant PEPT study : BP, Hull

(240km from Birmingham)

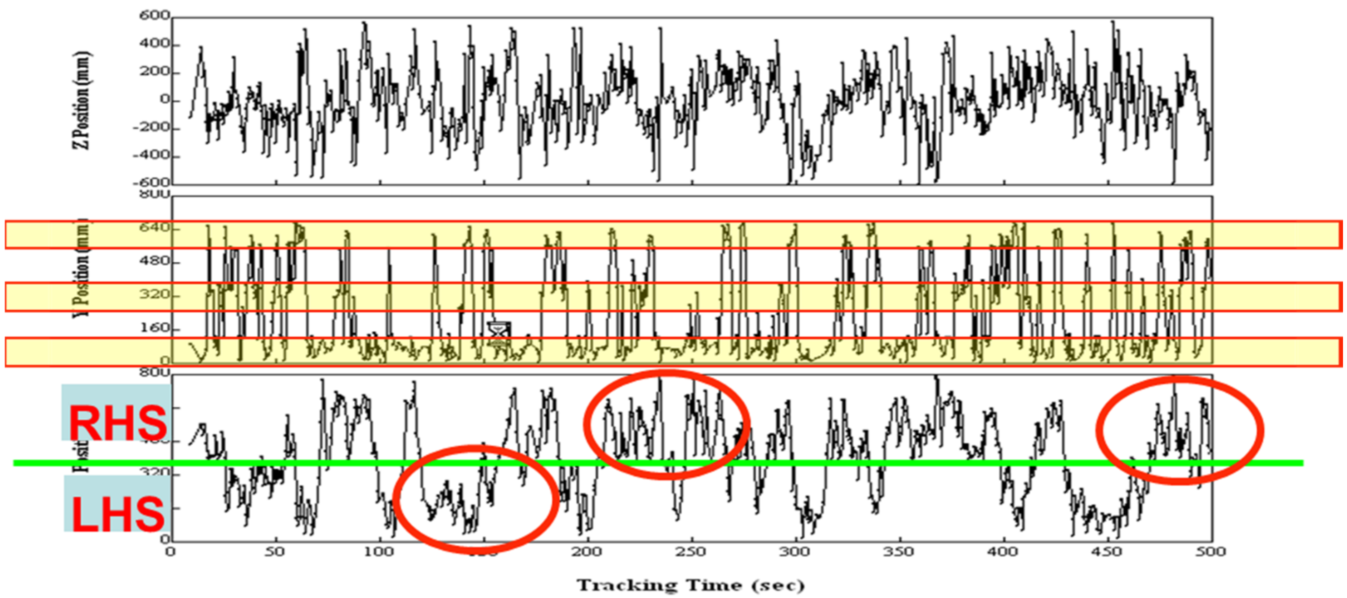
750mm diameter fluidised bed, with central dividing baffle + different air supplies each side of baffle

4 banks of detectors (detector separation 1.2m) give FOV shown

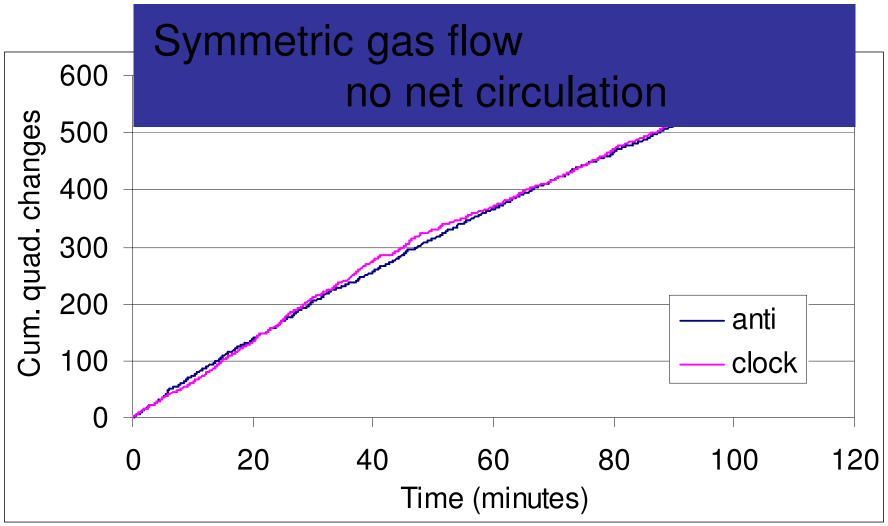


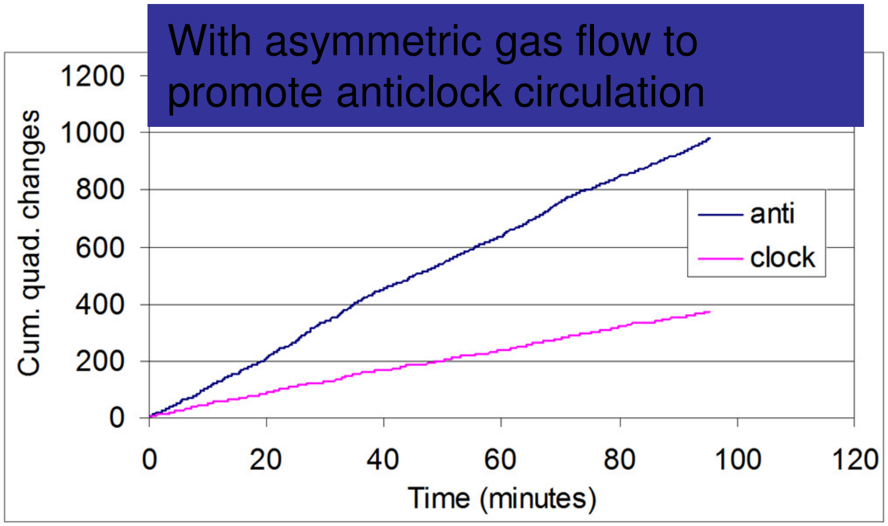


Data

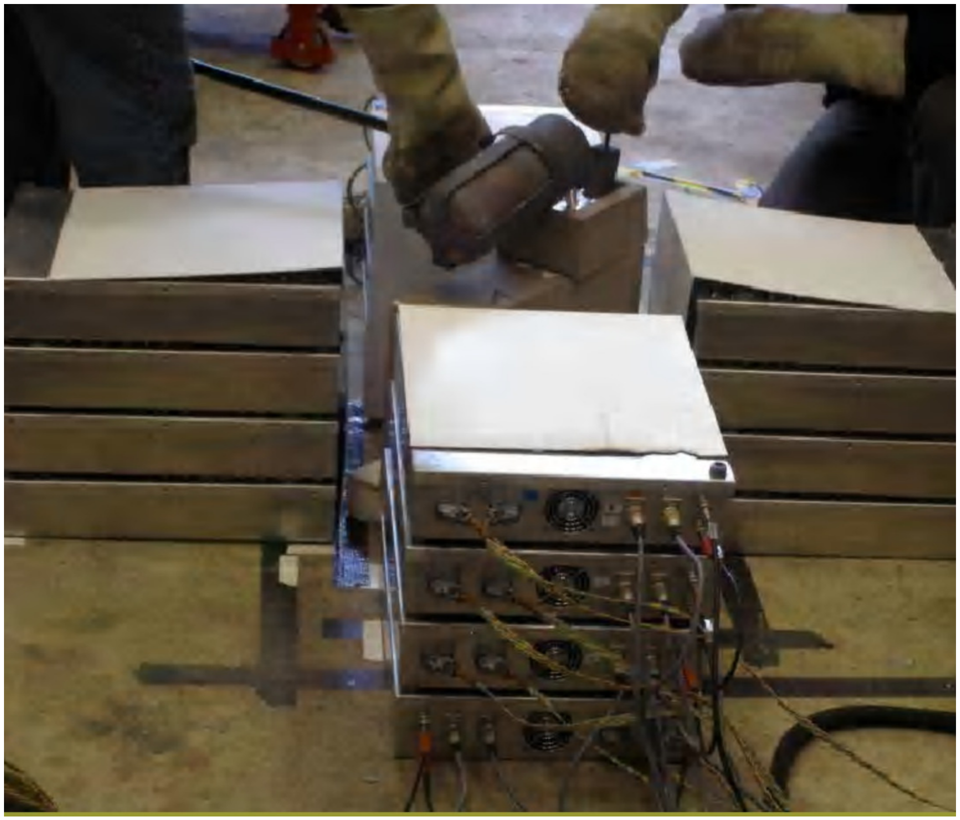


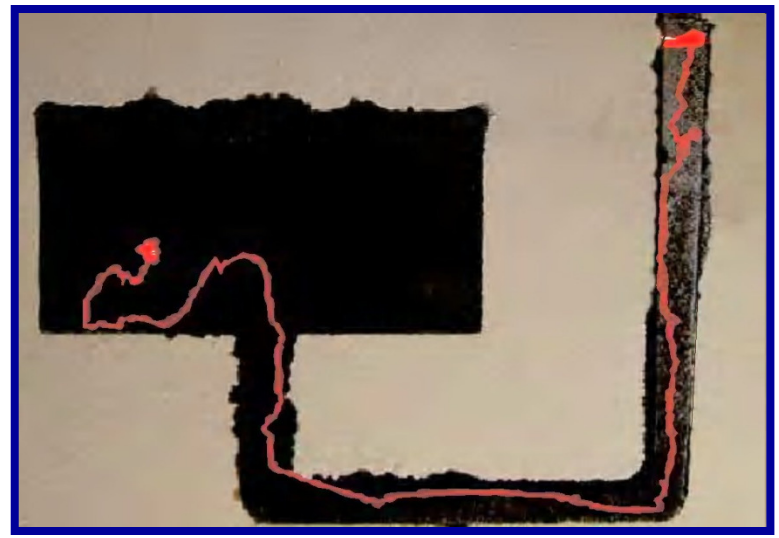
Analysis in terms of movement between four quadrants



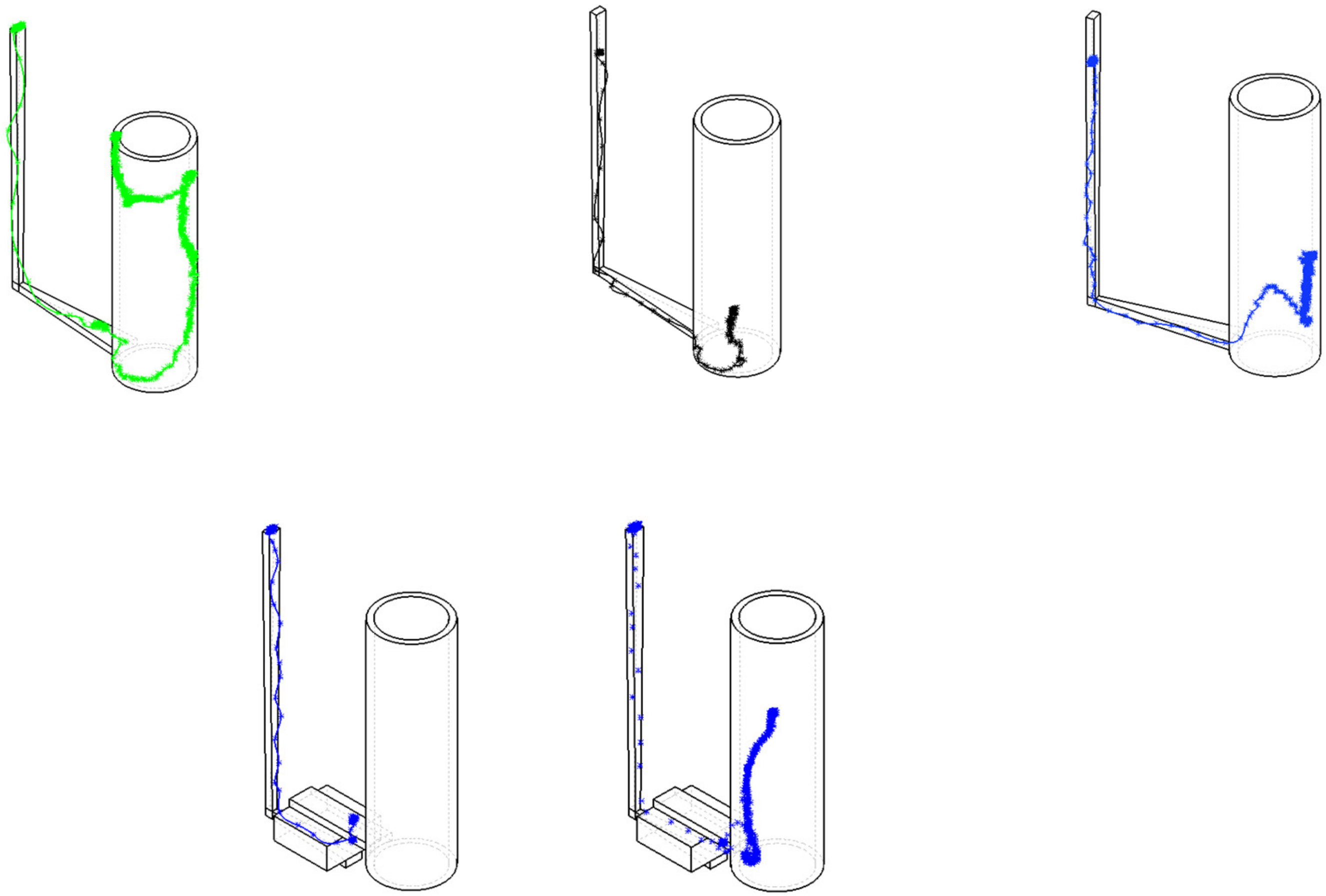


Casting of liquid metal:
PEPT tracking of small alumina inclusion

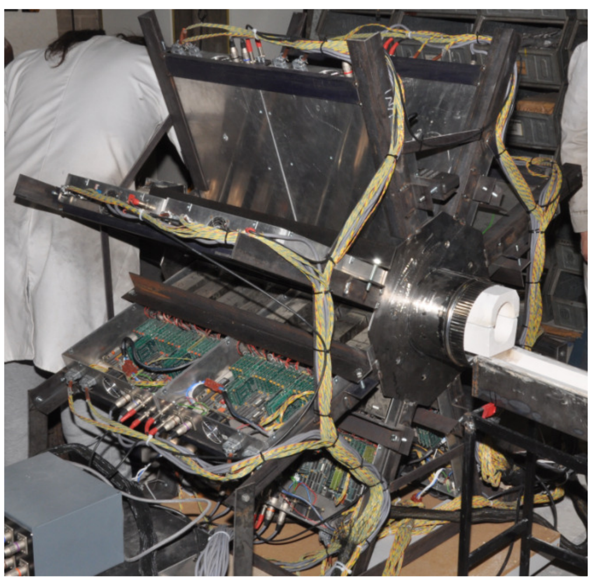


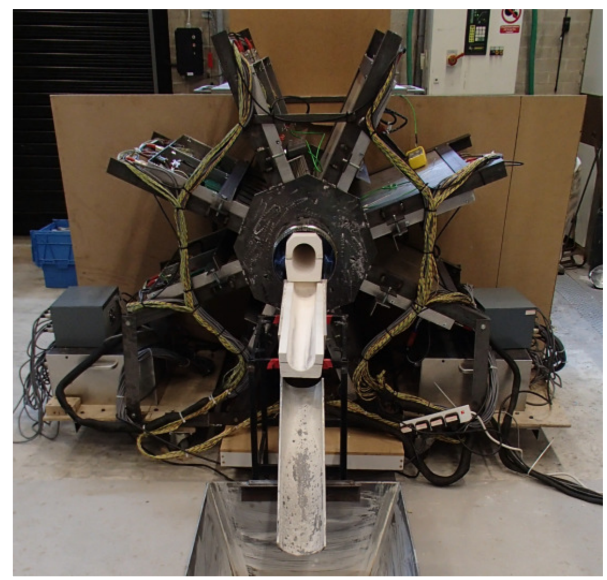


Examples of tracks obtained with entrained alumina particles of size range 63-100 µm

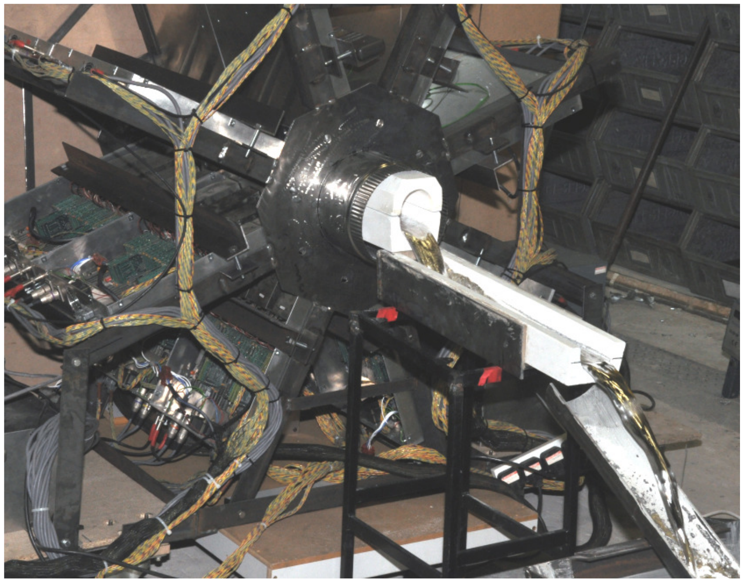


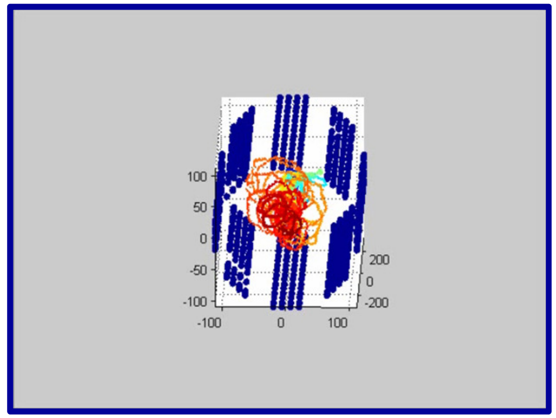
Examples of the use of PEPT to study filtration of liquid metal using ceramic foam filters.
In (a) the alumina particle has become trapped in a 30 ppi filter.
In (b) the alumina particle has passed through a 20 ppi filter.

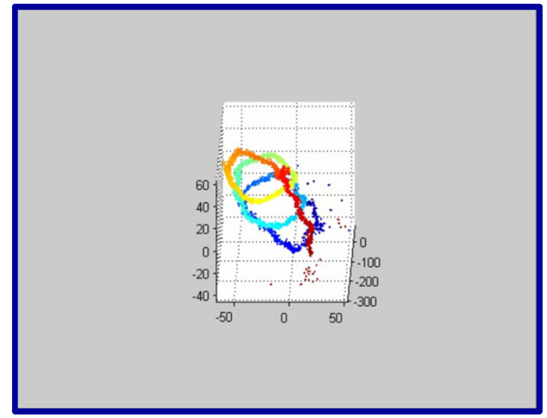




Modular Camera – Metal Casting



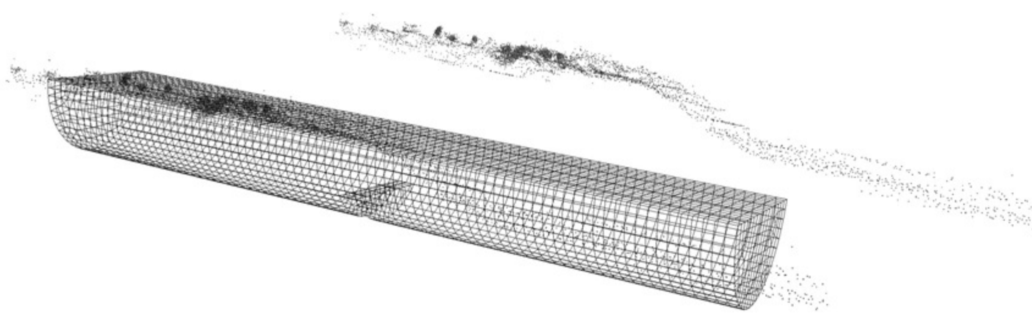




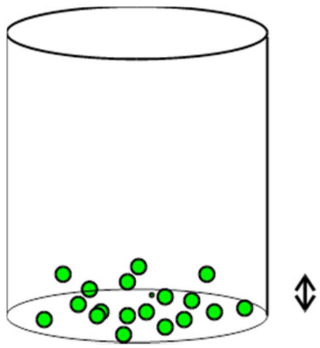
Virtual particles after 2 seconds of simulation time

The simulation showed particles rising as they approached the baffle and falling immediately after it. The simulation also showed approximately 2% of particles adhering to the baffle face and the tendency for particles to resist entering the boundary layer.

Particle positions for eight particles from the final experiment

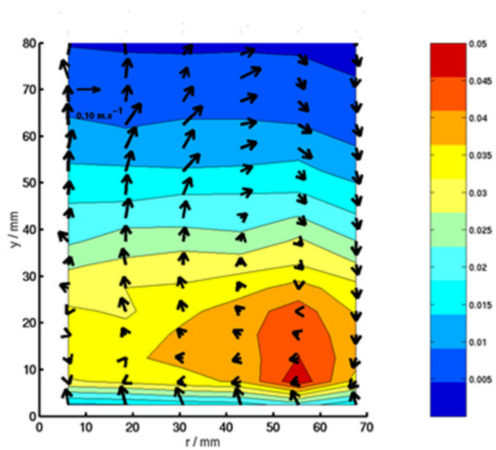


Granular Physics



Especially vibrofluidised granular gases:

- Convection
- Segregation
- Scaling laws



PRL 111, 038001 (2013) PHYSICAL REVIEW LETTERS week ending 19 JULY 2013

Thermal Convection and Temperature Inhomogeneity in a Vibrofluidized Granular Bed: The Influence of Sidewall Dissipation

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[2]*Multi Scale Mechanics (MSM), MESA +, CTW, University of Twente, Post Office Box 217, 7500 AE Enschede, The Netherlands*
(Received 16 February 2013; published 16 July 2013)

Using a vertically vibrated, fully three-dimensional granular system, we investigate the impact of dissipative interactions between the particles in the system and the vertical sidewalls bounding it. We find that sidewall dissipation influences various properties of the bed including, but not limited to, the spatial distribution of granular temperatures, the functional form of velocity distributions, and the strength of convection. Simple, monotonic relationships are observed for all the aforementioned properties, including a striking linear relationship between convection strength and wall dissipation. We conclude that sidewall effects are not limited to the vicinity of the walls themselves, but extend into the bulk of the system and hence must be considered even in relatively wide, three-dimensional systems. We also propose the possibility of using the alteration of sidewall material as a method of "tuning" certain system parameters in situations where changing the bulk properties or driving parameters of a granular system may be undesirable.

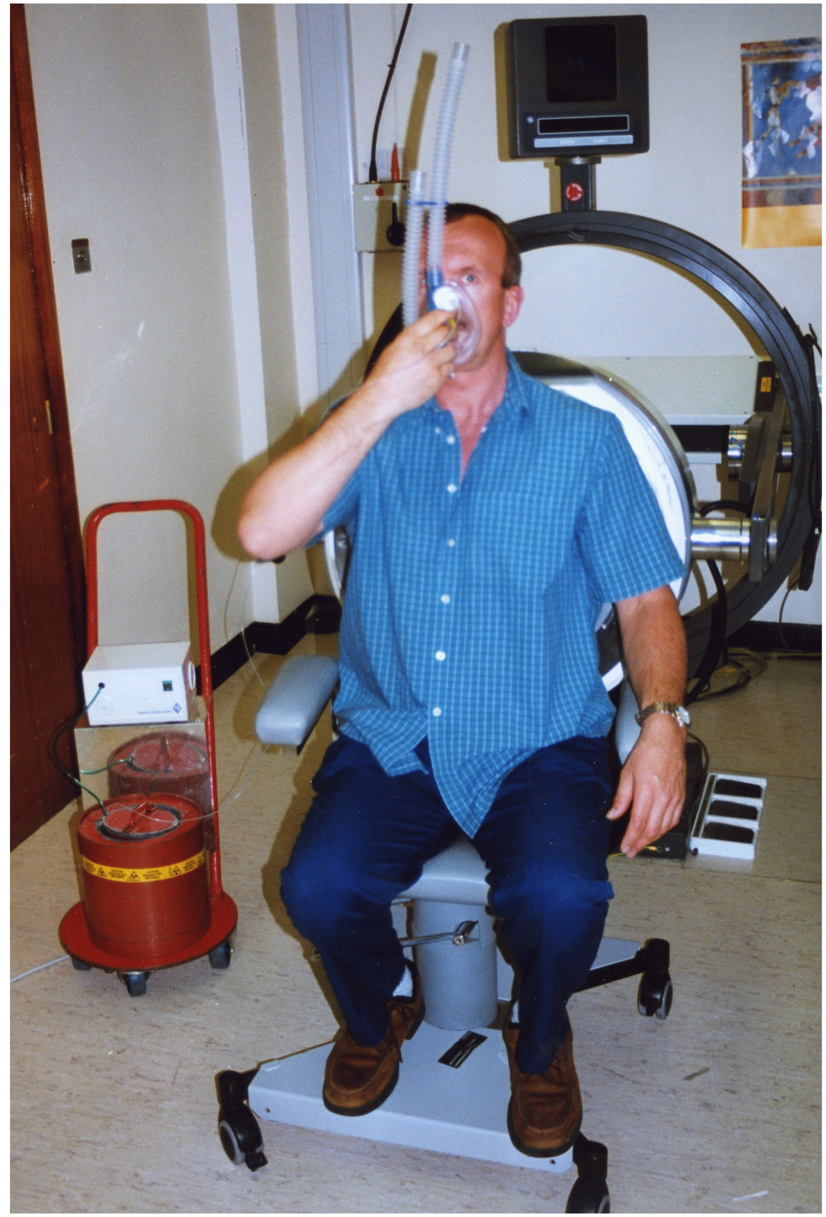
DOI: 10.1103/PhysRevLett.111.038001 PACS numbers: 45.70.Mg, 47.20.Bp, 81.05.Rm

^{81}**Rb** (4.6 h)

Parent of ^{81m}Kr (gas), which decays (13s) to g.s. emitting 190 keV gamma

(Parent/daughter generator)

^{81m}Kr used for imaging lung function using gamma camera



^{81}Rb production

Using the technique developed at MRC Cyclotron Unit (Hammersmith):

- Irradiate target containing ^{82}Kr gas (6 bar pressure) with 29 MeV protons (30μA)
- ^{81}Rb is produced and deposits on walls of target
- At end of irradiation, recover ^{82}Kr gas cryostatically
- Then elute ^{81}Rb from target: 3 x 40ml transferred to dispensing room.
- Finally evacuate target ready for reuse.

Currently making approx 65 generators per week – fairly stable

^{81}Rb Production statistics

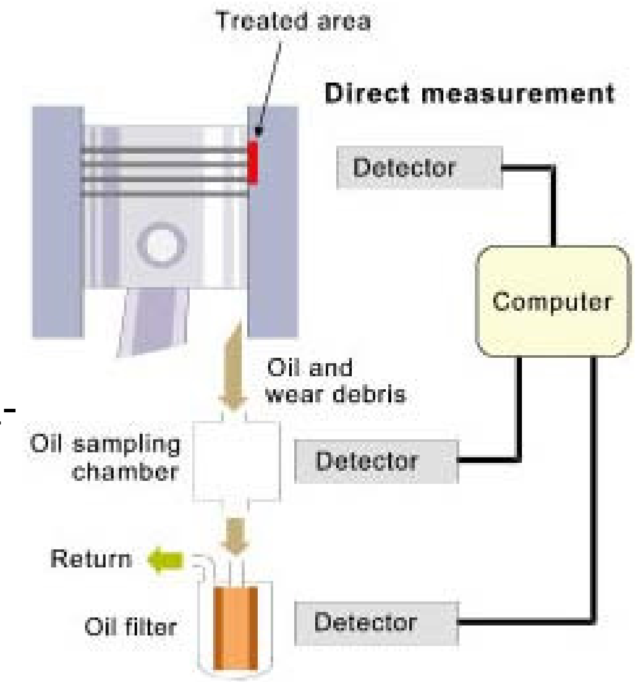
Started ^{81}Rb production in March 2006
5 evenings per week, 50 weeks per year

To end of Sept 2014, attempted production on 2116 days,
of which 2045 were successful (97% success rate)

Have produced over 28k generators

Thin Layer Activation

For measuring **wear** on components
(especially automotive parts, for R&D):
irradiate surface with beam from accelerator to create
long-lived radionuclide in well-defined surface layer
(typically ~ 50μm 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)
- Might activate different surfaces with each for simultaneous studies

Aluminium

- Best probably $^{27}Al(^{3}He, 2\alpha)\,^{22}Na$ (2.7 years, 0.511 MeV and 1.27 MeV gammas)

Diamond-like carbon (DLC) coatings

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

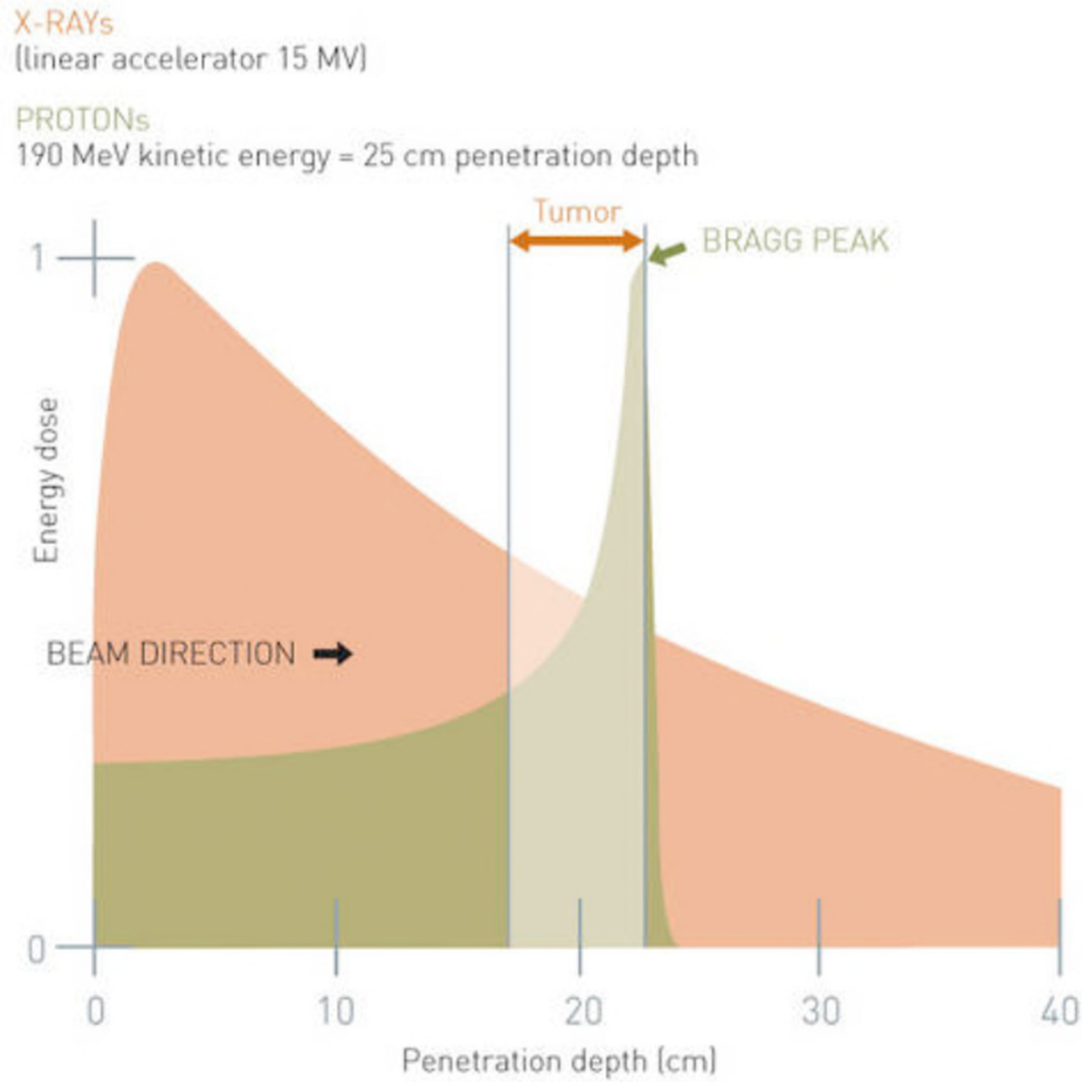
PRaVDA

Seeing and Treating Cancer with Protons

- University of Lincoln*
- University of Birmingham*
- University of Liverpool*
- University of Surrey*
- University of Cape Town
- University of Warwick
- University Hospital Birmingham NHS Foundation Trust*
- University Hospital Coventry and Warwickshire NHS Trust*
- National Research Foundation (NRF) - iThemba LABS, SA*
- United Lincolnshire Hospitals NHS Trust
- The Christie NHS Foundation Trust

- ISDI: Image Sensor Design and Innovation Ltd
- aSpect Systems GmbH
- Elekta AB (Publ)
- Advanced Oncotherapy Plc

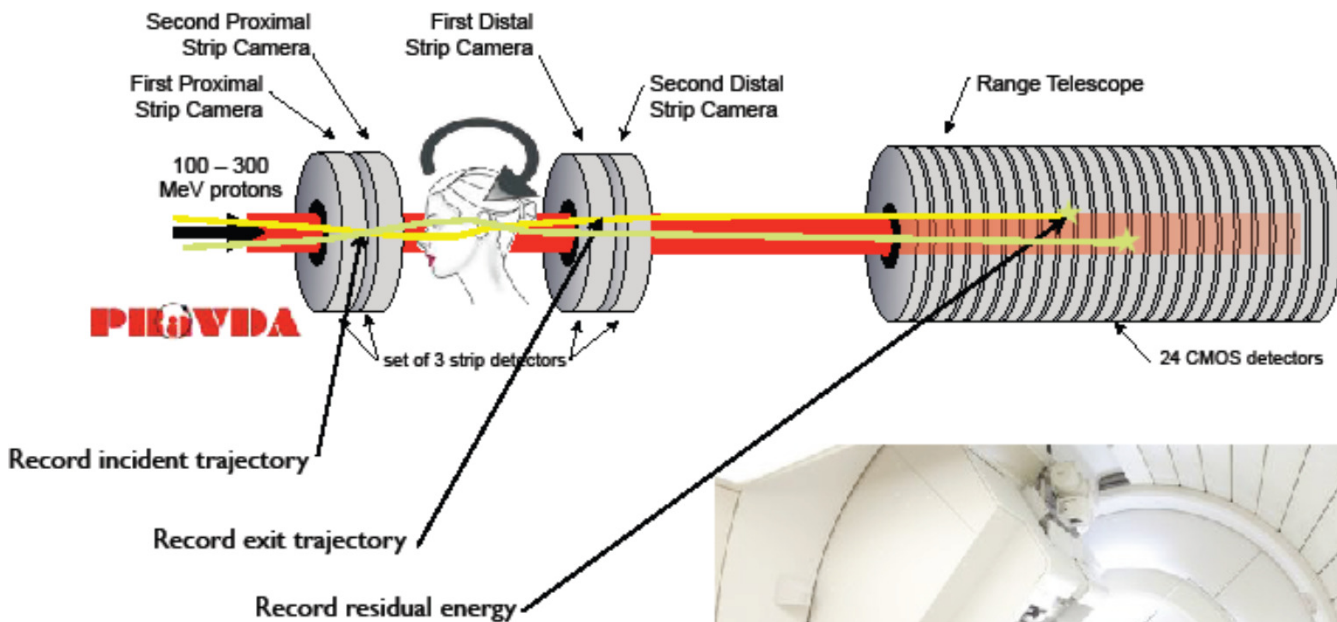
Funded by
wellcome trust
Grant Number 098285



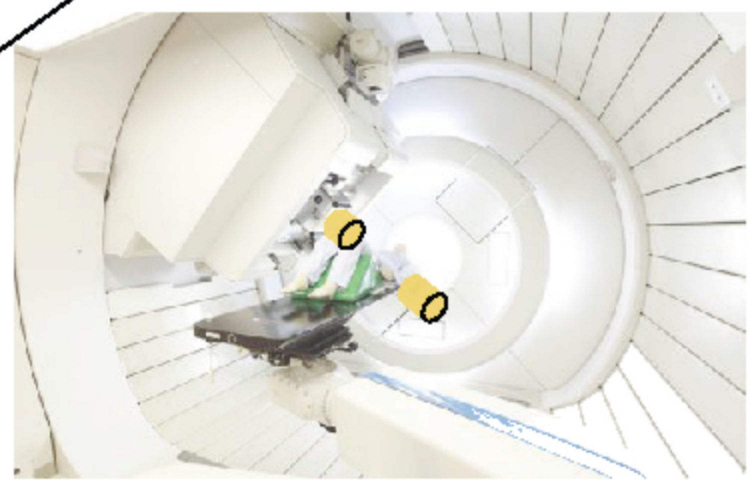
Local dose curve when protons penetrate the body. The clear increase in effect at the end of the proton path (Bragg Peak) compared with X-rays substantiates the considerable advantages of protons in the treatment of deep tumors.

System Overview

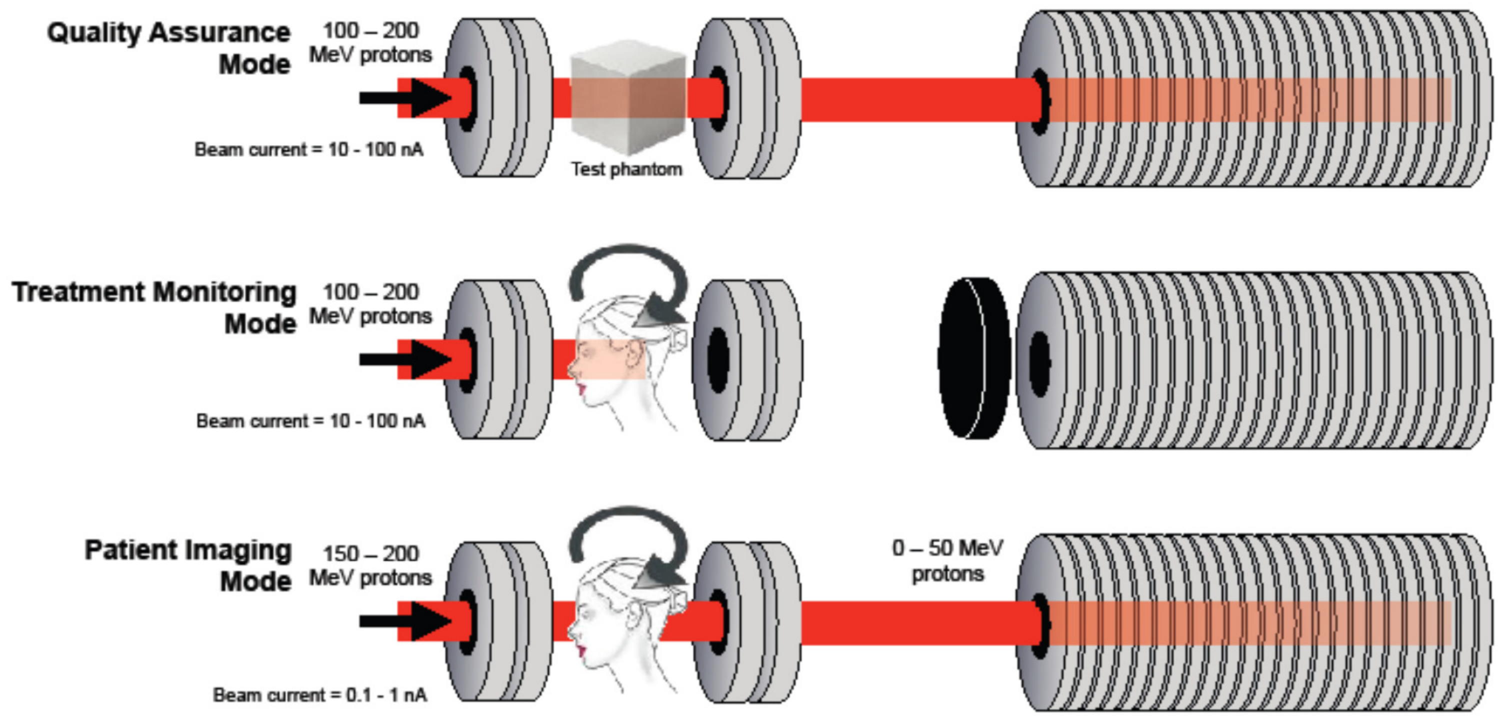
UK Patent Application Number **1410188.5**.



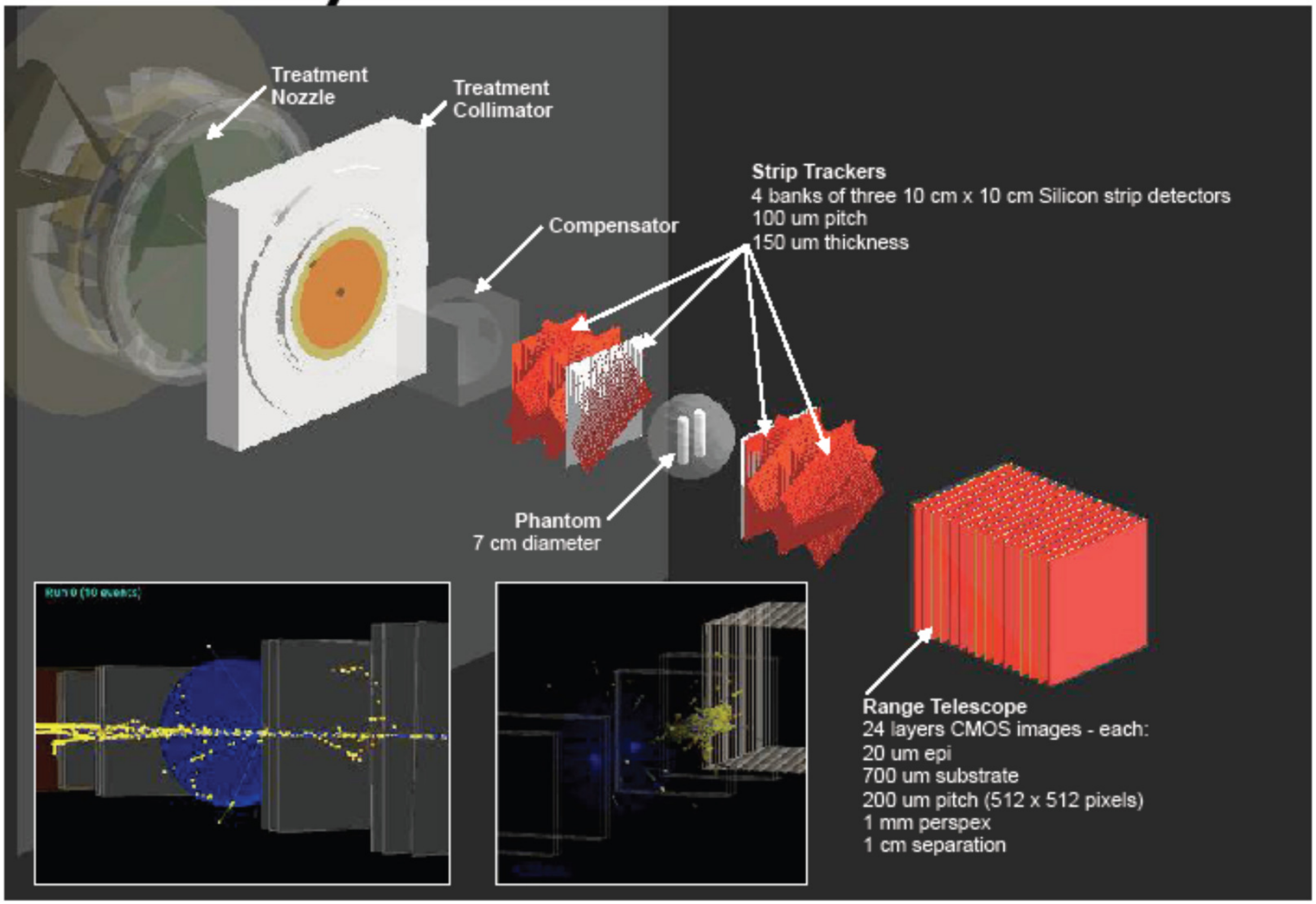
Repeat many times ....



Operational Modes

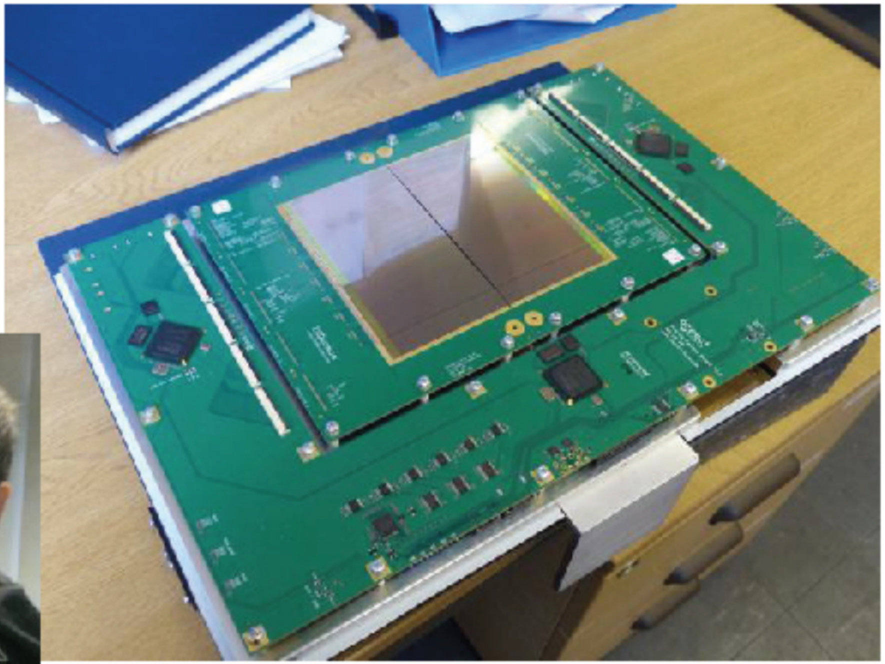


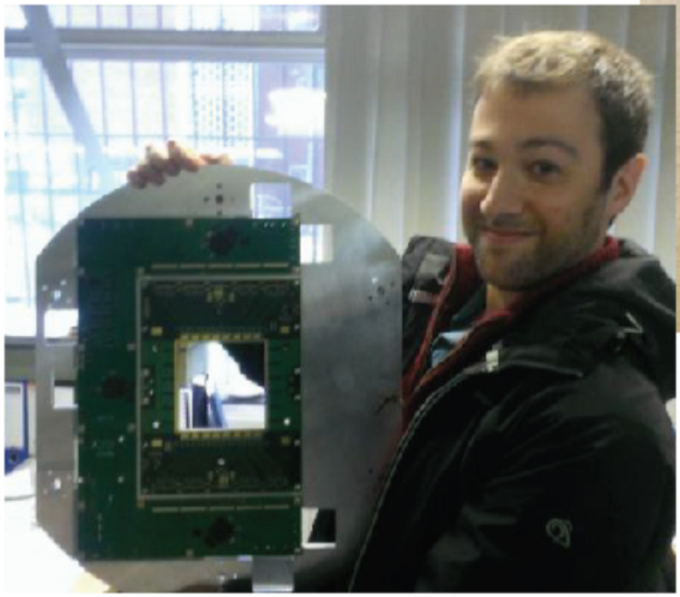
Extensive Physics Model



Geant4 model of PRaVDA instrument

Specified and designed complex DAQ





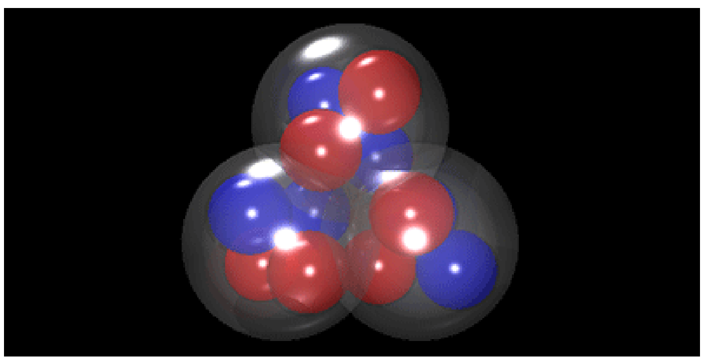
Nuclear Physics

(mainly training students)

Phys Rev C90 (2014) 024302 ^{4}He(^{14}N, states in ^{18}F c.n.

Phys Rev C90 (2014) 014319 ^{12}C(^{3}He,^{3}He)3α states in ^{12}C

PRL 113 (2014) 012502 ^{12}C(^{4}He,3α)^{4}He Triangular state in ^{12}C



Cyclotron is used for

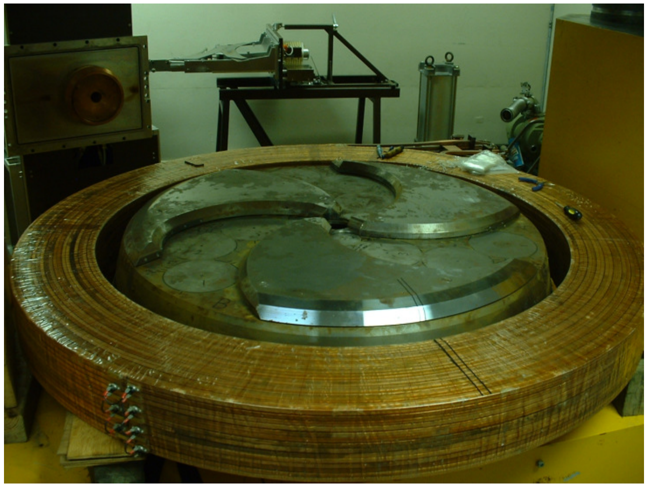
- Producing positron emitting nuclides for Engineering PET [NOT FDG]
- Producing ^{81}Rb for ^{81m}Kr generators
- Thin Layer Activation
- Other isotope production:
    - ^{69}Ge for labelling oil
    - ^{62}Zn supplied to St Thomas' Hospital London
    - Various irradiations for NPL
- Radiation effects studies:
    - Radiobiology + dosimetry (proton imaging)
    - Space electronics etc
    - ATLAS components
    - Metallurgy of nuclear materials
- Nuclear physics


SCANDITRONIX


SCANDITRONIX


SCANDITRONIX

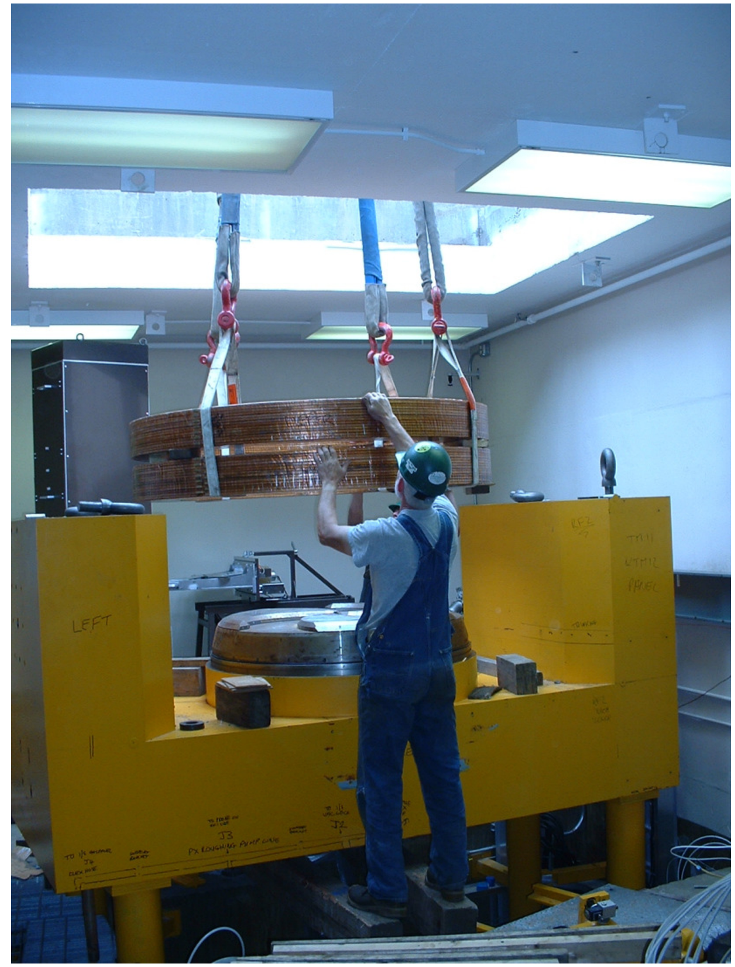

SCANDITRONIX




SCANDITRONIX
LEFT

Lifting : Saturday 8th June 2002


HANG OUT ON A CORNER




LEFT

Cyclotron was packed into 56 crates
- 3 40 foot containers + 2 20 foot containers

Travelled by rail to Montreal and thence by sea to Liverpool where it arrived on 24th July 2002

After clearing customs, arrived in Birmingham 20-23 August

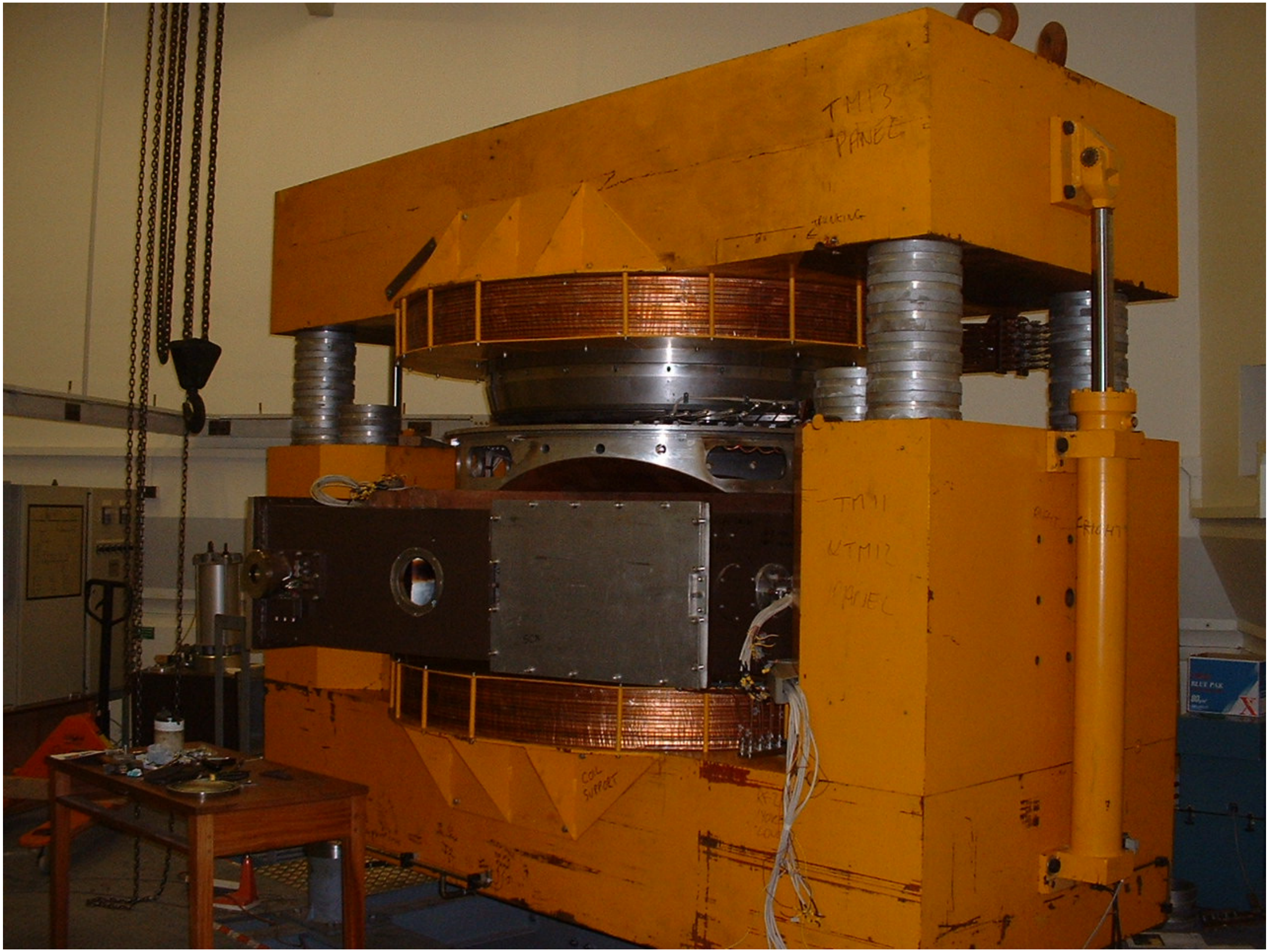
“Active components” were packed in Type A drums and sent air freight

Construction of new supporting floor complete February 2003


Ring Road Medical School
Ring Road North
South West Campus
ALLEY'S TRANSPORT
STUDLEY, WARKS ENGLAND.
01527 852408
01527 853298
TOP


SWL
6T


NO LOAD


TM13 PANEL
COIL SUPPORT
BLUE PAK

Cyclotron has been operational since early 2004

p 11-39 MeV and 3-9 MeV (N=2)
d 5.5-19.5 MeV
α 11-39 MeV
^{3}He 33-54 MeV and < 27 MeV

Also 46 MeV $^{14}N^{4+}$ and 70 MeV $^{14}N^{5+}$

for nuclear physics