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The Muon Beamline at ISIS

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Introduction

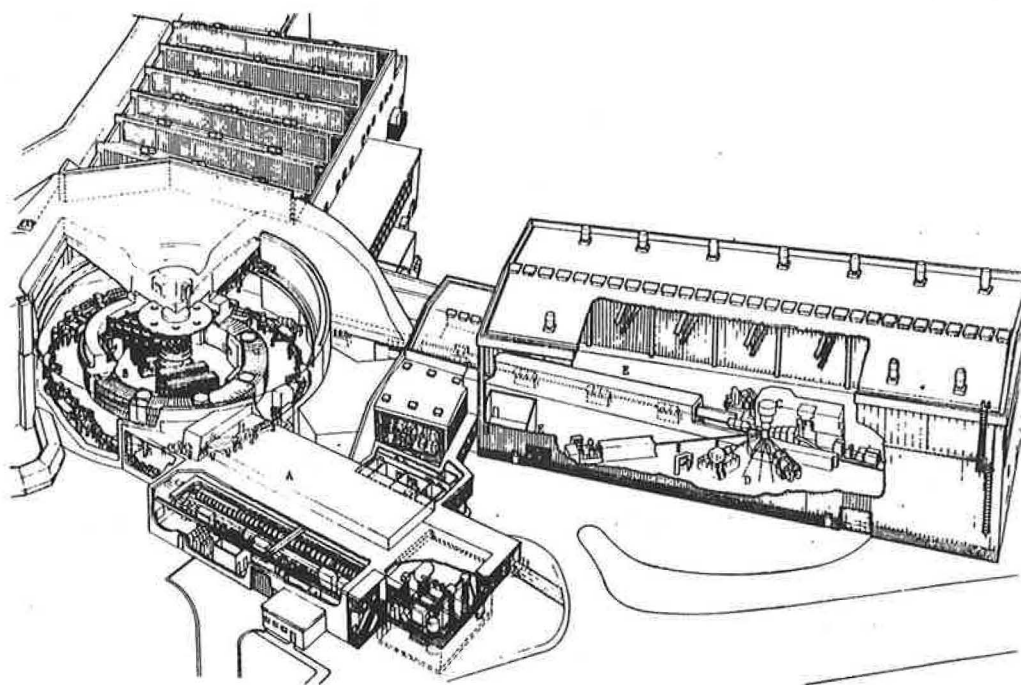


Figure 1. *The ISIS facility*

The original pulsed surface muon facility was established at the Rutherford Appleton Laboratory's ISIS in 1987. The facility was then upgraded in 1993 from a single beam line and spectrometer to a triple beam facility with three spectrometers working independently.

The layout of ISIS is shown above in figure 1. The linear accelerator A injects negatively charged hydrogen ions of 70 MeV into the synchrotron using an injection scheme known as multi-turn injection. After stripping off the electrons the synchrotron accelerates these protons to 800 MeV, using RF cavities operating at twice the fundamental harmonic. In this way two proton bunches are accelerated during each machine cycle, so that upon extraction using fast magnetic kickers, two pulses are directed from the synchrotron B along the extracted proton beam channel to the spallation neutron target C. This target consists of uranium or tantalum plates in which the protons are stopped producing approximately 30 (15) neutrons / proton in the case of uranium and tantalum respectively. These fast MeV

neutrons are moderated to low energies in an ensemble of four moderators surrounding the target. Each moderator acts as a source for several neutron instruments, D.

A plan of the ISIS experimental hall is shown below in Figure 2 indicating the respective locations of the neutron beams, the KARMEN neutrino facility and the muon beam line complex.

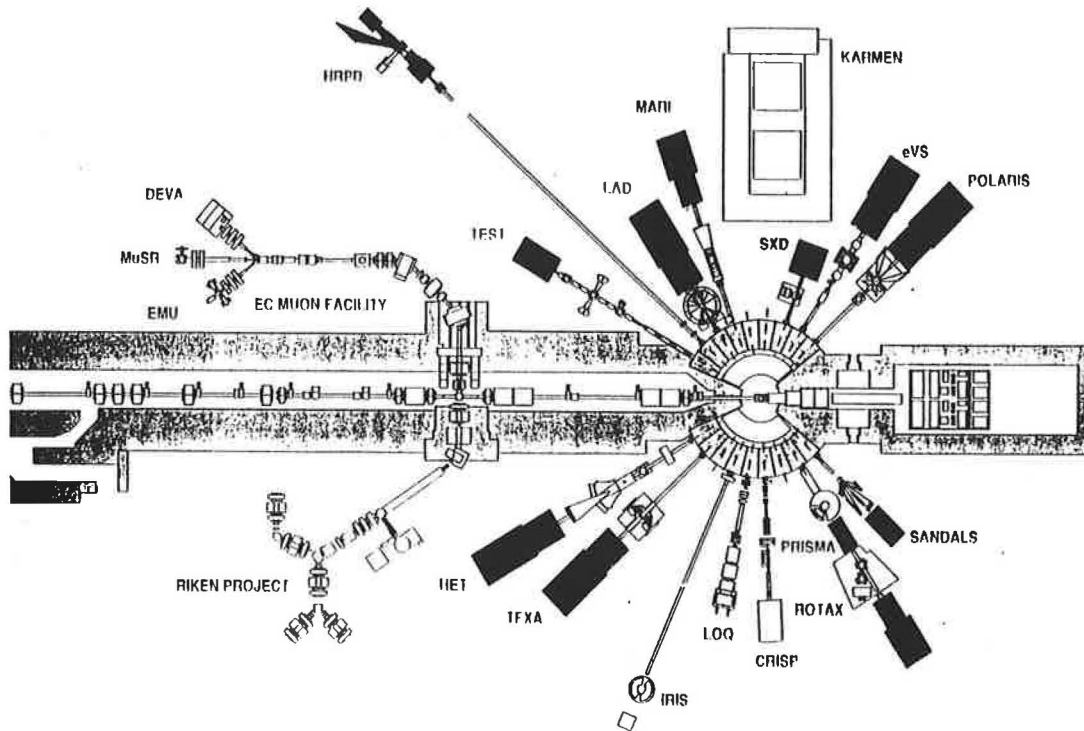
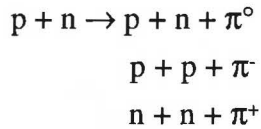
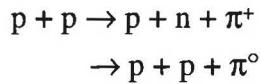


Figure 2. ISIS Experimental Hall

The ISIS muon beams are produced from thin graphite targets, (marked E in Figure 1), located some 20m upstream of the neutron production target. These graphite targets are edge cooled at the base and oriented at 45° to the proton beam such that the south side muon facility views the backward face. The thickness of the intermediate graphite target is limited by two factors (i) the loss in neutron intensity must be acceptable to other users of the facility and (ii) neutron backgrounds arising from the muon production target must be kept at a reasonable level around the neutron scattering instruments and in KARMEN. By 1994 the thickness of muon targets will be variable from 5mm to 10mm in the proton beam. It should be noted that the time structure of the proton pulses, while of no significance to the thermalized neutron beams, is important in the case of the muon facility, where the muon pulses reflect this time structure (70ns FWHM wide pulses, separation 340ns.)

Muon Production

All muon facilities rely upon the production of π mesons as the parents of the muons and hence require proton accelerators of an energy well beyond the energy threshold for single pion production in the typical reactions given below.



The energy threshold for these reactions is around 180 MeV proton kinetic energy but sizeable production cross sections are achieved only at energies well beyond this threshold, typically above 500 MeV, the energy of the meson factory at TRIUMF. PSI produces 590 MeV protons, while ISIS has an extraction energy of 800 MeV. Increasing the kinetic energy from 500 MeV to 800 MeV has little effect on the production cross sections for low energy pions, but enhances the production of higher momentum pions and allows the onset of double pion production.

The pions are produced from targets inserted into the proton beam. Those targets most commonly used are carbon or beryllium of low Z, to maximise pion production while minimising multiple scattering of the proton beam itself.

The charged pion mass is 139.56 MeV in contrast to the 0.5 MeV, 938.2 MeV masses for the electron and proton respectively. The pion is short lived with a lifetime of 26.03 ns and decays via the following reaction.



The muon mass (105.65 MeV) is such that in the two body decays above, which occur at rest i.e. stopped pion, the muon has a unique energy and momentum (29.79177 MeV/c) arising from the zero neutrino mass and conservation of momentum and energy in the decay process. Precise measurements of this muon momentum have placed upper limits on the muon neutrino mass which are consistent with zero mass.

The pion itself has zero spin or angular momentum, so that as a consequence of the negative helicity (longitudinal spin) of the neutrino in pion decay, the emergent muons in any particular direction must be fully longitudinally polarised. This fact forms the basis of the production of polarised muons in a so called 'surface' or 'Arizona' muon channel where the parent pions are at rest before decay. Those pions which stop in the actual target in which they were produced, provide muons which are close to the full muon momentum in the decay process only if they stop at or close to the surface of the target facing the muon channel, hence the expression 'surface' muon beam. By this means very intense beams of fully polarised positive muons may readily be produced. Negative pions on the other hand upon stopping in the target are rapidly captured from their orbits around the target nuclei, producing pionic disintegration of the nucleus concerned. Because of this a surface muon beam is not capable of producing polarised surface muons of negative charge.

Transport of muons to the experimental areas

Muons, unlike neutrons, are charged particles and hence can be deflected in magnetic and electric fields. Magnetic fields in a typical muon beam line are generated by and used in quadrupole magnets for focusing the muon beam, and in bending magnets which are used to select a particular momentum for the transmitted muons. Electrostatic fields are used to deflect the muon beam, either independently or in combination with magnetic fields

Non relativistically the force on a particle of mass m , velocity v , charge e , passing through a magnetic field B perpendicular to its path is given by

$$\text{Force} = Bev \text{ in a direction perpendicular to } B \text{ and } v$$

The particle executes a circular path of radius R in the field such that

$$Bev = \frac{mv^2}{R}$$

so that the deflection angle in passing through the field ϕ is proportioned to $\frac{Be}{mv}$ i.e.
proportional to $\frac{1}{p}$

Therefore the magnetic fields required in quadrupoles and bending magnets are proportional to the momentum of the particles concerned. Similar considerations for electrostatic deflections show that these are proportional to $p\beta$ of the particles concerned. In general, deflecting devices based upon electrostatic fields are suitable only for low particle momenta and velocities, higher momentum particles are more efficiently deflected using magnetic fields.

The primary task of a muon beam line is to collect and transmit as many of the muons produced in the target as is possible within the typical aperture constraints of the various elements in the beam-line. A quadrupole magnet if used as a horizontally focusing device is of necessity vertically defocusing and so these must be used in pairs (quadrupole doublet) or in three (triplet) to produce net focusing in both directions.

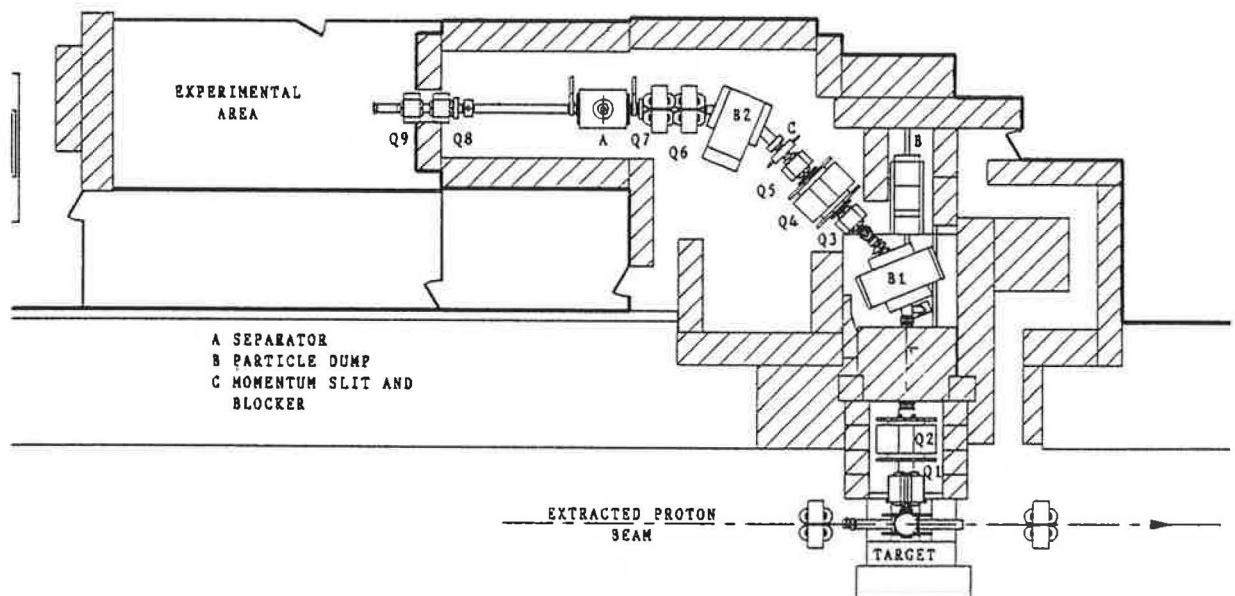


Figure 3. Layout of the muon beamline, with quadrupole magnets marked *Q* and bending magnets *B*

In a pulsed beam of muons such as the ISIS facility, special care must be taken to remove contaminant particles other than muons in the beam. These are principally positrons in a positive surface muon beam. Because their velocity is close to the velocity of light, in contrast to $\beta = 0.24c$ for surface muons, they are readily removable using a crossed

magnetic field / electric field separator, marked A in figure 3. At ISIS the unseparated beam consists of positrons and muons in the ratio 1.4 : 1, but in normal operation, with fields of 100kV in the separator, this ratio becomes 0.05 : 1.

Positron elimination from the ISIS muon beam

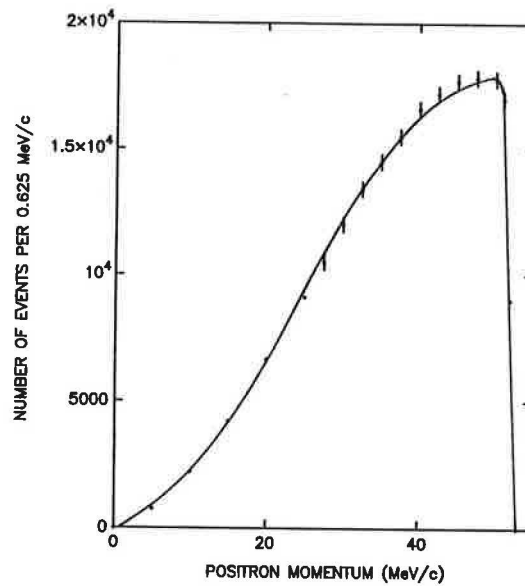


Figure 4. Momentum spectrum of positrons from muon decay

The muon beam line is set at a surface muon momentum of 26.5 MeV/c transmitting all positively charged particles of this momentum. Therefore, besides the surface muons themselves, positrons exist in the beam line some of which arise from the decay of π^0 produced in the target and the subsequent materialisation of electron positron pairs in the reactions:



Because the π^0 lifetime is short (0.83×10^{-16} secs), these positrons are prompt and reflect precisely the time structure of the proton pulses. If all of the positrons were prompt, they would not pose such a serious problem in a pulsed muon facility, however, a sizeable

fraction (~ 50%) of the contaminant positrons arise from the decay of muons in the target with a decay time constant of 2.2 μ secs.

The momentum spectrum of positrons from muon decay is shown above in the Michel spectrum (Figure 4) where it is clearly evident that many e^+ are produced in this decay at a momentum of 26.5 MeV/c and which are therefore transmitted by the beam line. These must be eliminated in such a beam as they simulate exactly the muon decays in the sample.

The cross field electrostatic separator is a device which consists of a vertical electric field between horizontally disposed electrodes, and a horizontal magnetic field generated by auxiliary coils. In such a device, particles of momentum p (GeV/c) and velocity β (V/c) are deviated vertically by an angle $\Delta y'$ (mr) given by the expression.

$$\Delta y' (\text{mr}) = \frac{\ell}{p} \left[\frac{\epsilon_0}{\beta} - 300 B \right]$$

where ℓ is length in m, ϵ_0 the electric field gradient in Mv/m and B the field in T

For particles such as surface muons ($p = 0.0265$ GeV/c, $\beta=0.24$) it can be arranged that $\Delta y' = 0$ when $\frac{\epsilon_0}{\beta} = 300B$. This being the case the muons are transmitted through the device without deviation. For positrons $\beta = 1$ and a vertical deviation occurs which for 100kv applied to the device, is sufficient to remove them from the beam. This device essentially acts as a velocity selector.

Typical values used at ISIS are 100 kv over the 13 cm gap of the separator cancelled by a magnetic field of 106.9 Gauss. This produces a vertical deviation for positrons of 92mr.

Incidentally this device induces a polarisation rotation of the muon given by $\phi = \frac{eB\ell}{\beta\gamma}$ where e is the charge in the muon and $\gamma = 1 / \sqrt{1 - \beta^2}$

For 100kv $\phi = 6.6^\circ$ at surface momentum pointing upwards from the direction of travel of the muons. Given sufficient electric field gradient and length, $\pi/2$ rotation can be achieved resulting in a transformation of longitudinal polarisation to transverse. Such a capability is useful for high transverse field experiments and for full flexibility of the facility. Such $\pi/2$ rotation would require 454 kv generated over two cross field separators each 1.5m long.

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Creation of three independent beam lines

The electrostatic kicker is a crucial part of the new (post June 1993) muon facility and is situated immediately after quadrupoles Q8 and Q9. It contains three electrodes, an outer, grounded pair and a thin central anode. The potential of this anode can be reduced from 32kV to zero in 100ns between the two muon pulses. Therefore, under normal working conditions, the first pulse experiences an electrostatic field on either side of the anode. This gives rise to an equal division of the muon pulse and a right or left deflection of 3.8° to the septum magnets, situated 2.15m downstream of the kicker. Each deflected beam is deviated by a further 36.2° by the septum magnets to produce a total deflection between these beams of 80° . The second muon pulse experiences no electrostatic field and therefore is transmitted through the space between the septum magnets.

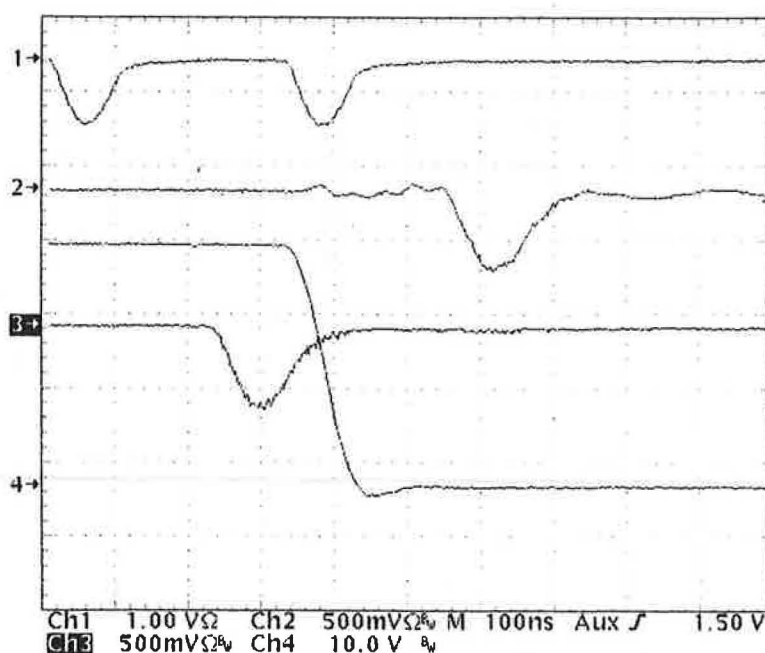


Figure 5. Oscilloscope traces showing the action of the E-field kicker on the double pulse of muons

Area B. MuSR. After passing through the septum magnets the muon beam passes through a large aperture quadrupole doublet, Q10B and Q11B, which is sufficient to form a simultaneous horizontal and vertical waist at the end of the MuSR beam. The original 32 detector "DIZITAL" spectrometer is situated at the end of this beam line. It can be rotated through 90° from longitudinal to transverse geometry and fields of up to 2000 gauss can be applied. It will support a variety of sample environment equipment, (dilution refrigerator, "orange" cryostat, closed cycle refrigerator and furnace) covering a temperature range of 35mK to 800K.

At the sample position the maximum dimensions (FWHM) of the muon beam are 15mm in the horizontal (x) direction by 8mm in the vertical (y) direction. The horizontal dimension can be modified by the x-slits, situated at X in figure (6), to give a muon spot of 7mm in the x direction and 8mm in the y direction, but with a 50% reduction in intensity.

The positrons, generated by the muon decay in the sample, are detected by one of the 32 scintillators surrounding the sample position. These are arranged in two groups of 16 either forward and backward or right and left of the muon beam depending upon the orientation of the instrument. The light from a scintillator is carried back to a photomultiplier tube through a Plexiglas light guide. Signals are then transmitted electronically to the data acquisition electronics in the back of the MuSR cabin.

Contact - Sue Kilcoyne

Area C. EMU. EMU is optimised for experiments with magnetic fields applied along the beam direction (longitudinal geometry). A water cooled Helmholtz pair delivers up to 4000 gauss longitudinal field, while for calibration purposes, a pair of saddle coils are incorporated to produce a vertical 100 gauss transverse field at the sample. The sample environment is provided by a closed cycle refrigerator (10K to 320K) or by a helium cryostat with a base temperature of 1.4K.

As a result of the kicker operation EMU receives 50% of the muons in the first of each double pulse but in a noticeably broader beam: with the x-slits wide open the FWHM dimensions of the muon spot size is 27mm horizontally by 10mm vertically, this can be reduced to 9mm horizontally by 10mm vertically but with a 75% decrease in count rate.

As in MuSR the positrons are detected by 16 counters in the forward direction and 16 in the backward direction, and the signals from the photomultiplier tubes are passed back to the counting electronics in a similar fashion to that described above.

Contact - Steve Cottrell

Further reading

1. *Commissioning of the Rutherford Appleton Laboratory pulsed muon facility.* G H Eaton et al. Nuclear Instruments and Methods in Physics Research A269 (1988) 483
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4. *Development of the Pulsed Muon Facility at ISIS.* G H Eaton, C A Scott and W G Williams. Proceedings of μ SR 93 to be published in Hyperfine Interactions (1994)
5. *Fast E-field switching of a pulsed surface muon beam: the commissioning of the European muon facility at ISIS.* G H Eaton, M A Clarke-Gayther, C A Scott, C N Uden and W G Williams. New Nuclear Instruments and Methods in Physics Research A342 (1994) 319

