Muon Beam Lines

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The Objectives

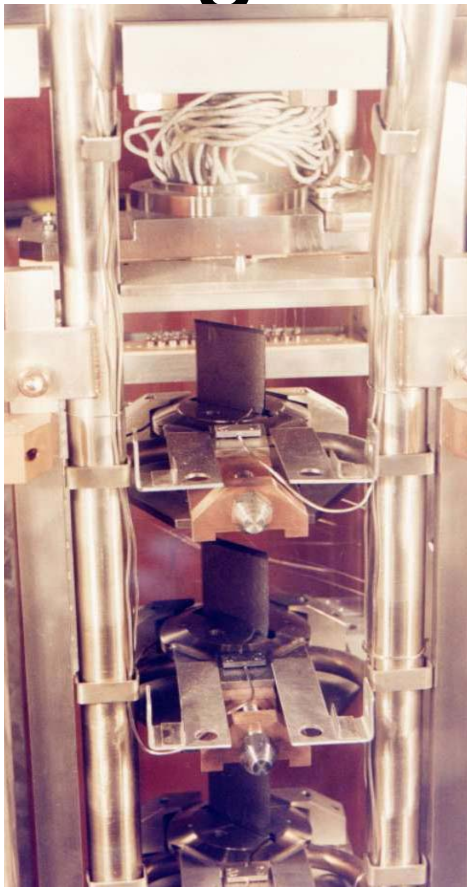
- Deliver muons to a sample
- Small spot size (match sample size)
- Well defined energy (penetration depth)
- Intense beam
- High polarisation
- Low contamination with other particles (background counts)

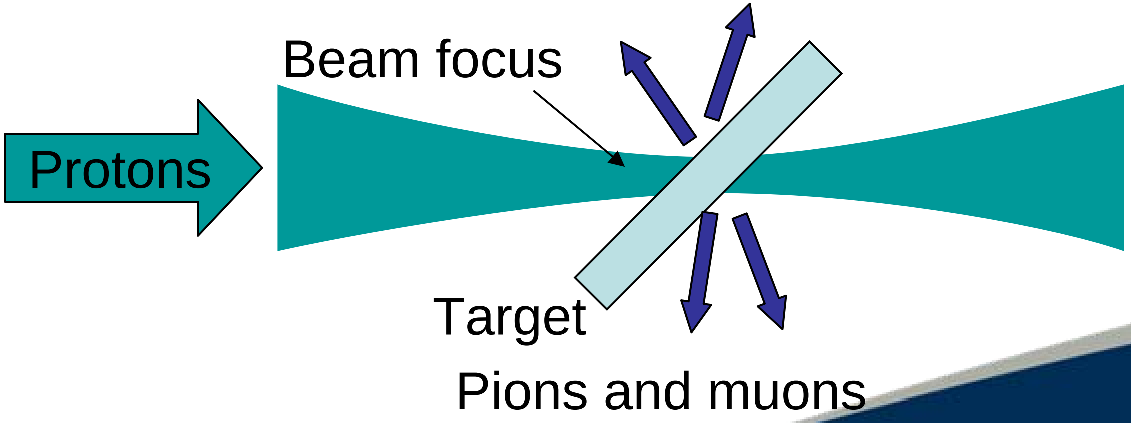
Muon Production - physics

- High energy protons colliding with nuclei, to form pions
- Nuclear reactions such as
  - $p^+ + p^+ \rightarrow p^+ + n + \pi^+$
  - $p^+ + n \rightarrow p^+ + p^+ + \pi^-$
- Requires proton energy > 280 MeV
- Full production rate for energy 500-1000 MeV
  - ISIS 800 MeV, PSI 590 MeV
- Also double pion production $p^+ + p^+ \rightarrow p + p + \pi^+ + \pi^-$ etc at higher energy
- Pions then decay to give muons: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (lifetime 26ns)
  - This decay gives the muon polarisation: 100% polarised opposite to momentum, in the rest frame of the pion

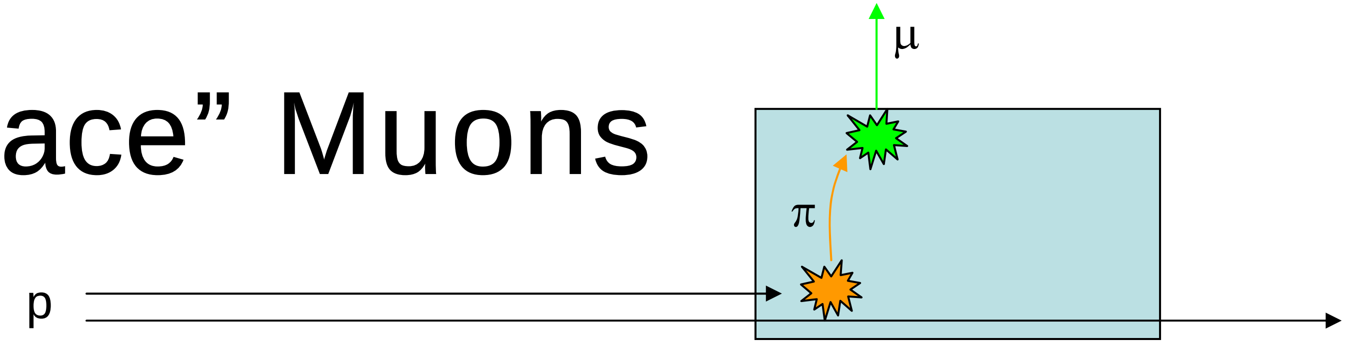
Muon Production - Targets

- Material must have a low atomic number and high melting point
  - High atomic number gives more neutrons by spallation and more scattering of the beam
- Usually Graphite, sometimes Beryllium.
- Beams are in vacuum. ISIS target heated to ~600°C, cooling by conduction to the edge and radiation.
- Most protons (> 95%) do not produce pions and pass through with little energy loss, so can be used for other purposes (neutrons).





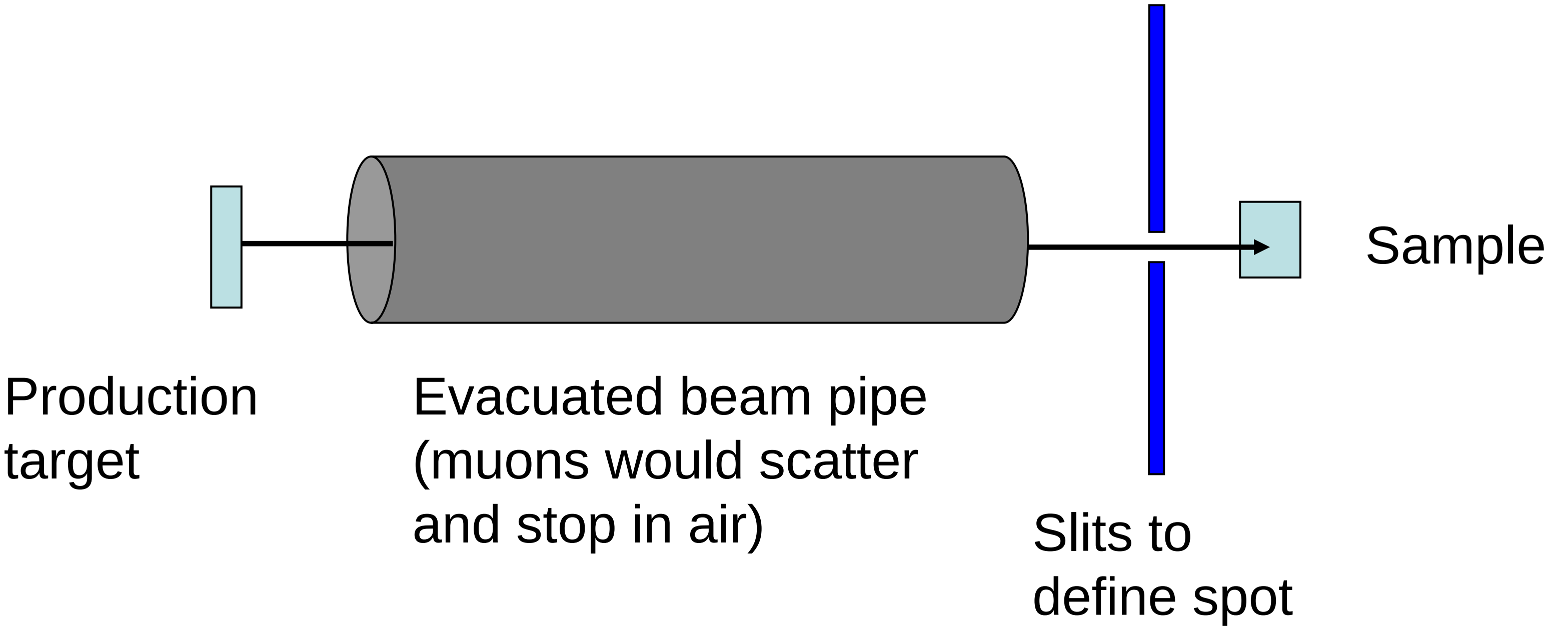
"Surface" Muons



- Some pions stop within the target material
- Each pion decays to a muon (E=4.1MeV, p=29MeV/c, 100% polarisation parallel to momentum) and a neutrino
- Muons formed close to the target surface can escape
- Some of these muons collected into the beam line
- Polarisation 100% for parallel beam at sample

Beam Line design 1

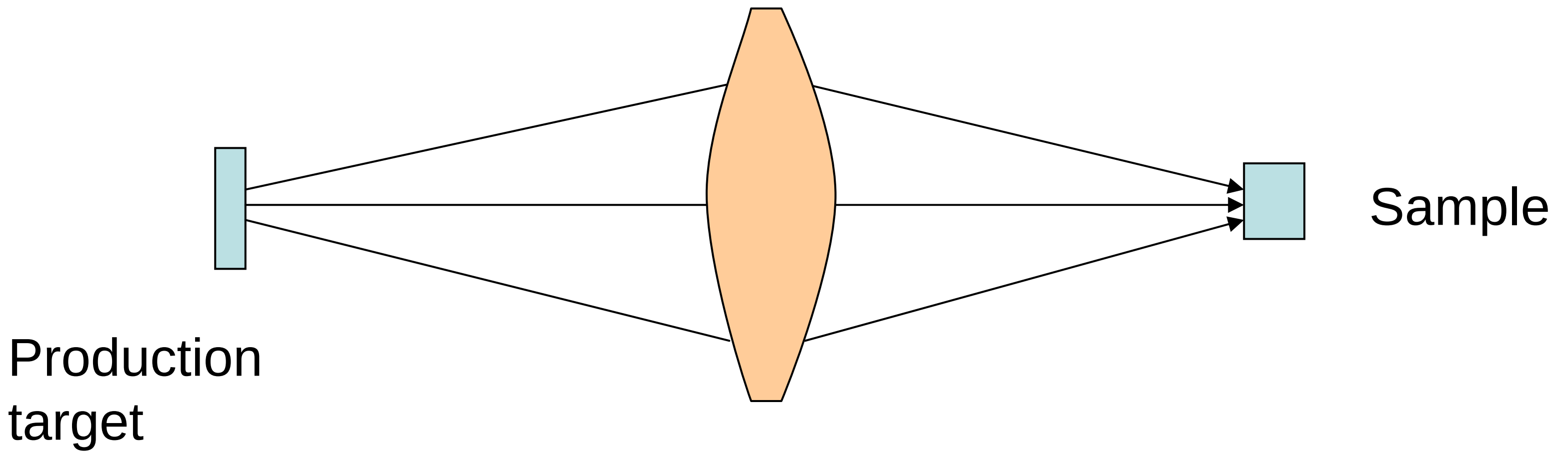
- The simplest possible beam line



- Main problem – Low muon flux
- Additional problems – other particles transmitted, high radiation level at sample

Beam line design 2 - focusing

- Use a lens to focus the muons and give larger flux

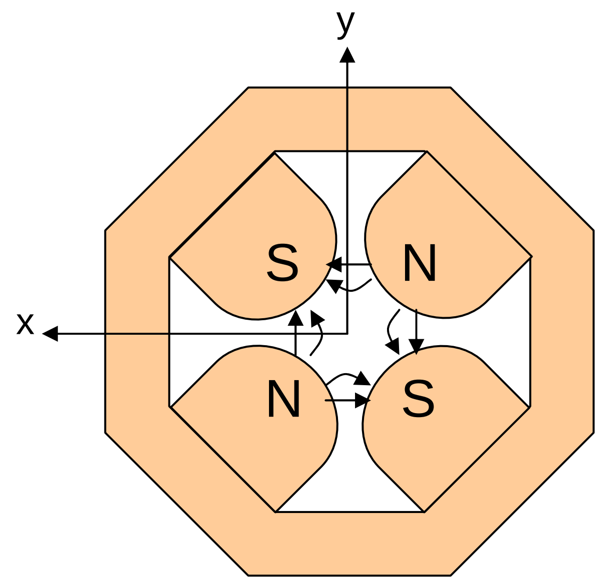


- Usually use more than one lens:
  - First lens close to source to capture large solid angle
  - Sample close to last lens to give smaller beam spot
- Still transmits many other particles – these are poorly focused if the wrong momentum
- Straight-through path for neutrons (could be blocked, e.g. Dai-Omega)

Practical muon lenses

- Muons deflected in transverse magnetic (or electric) fields
  - Deflection $\theta = d\,B\,q\,/\,p$ or $\theta = d\,E\,q\,/\,p\,v$
- Uniform field bends the whole beam through the same angle
- Field Gradients give deflection varying with position – focusing possible

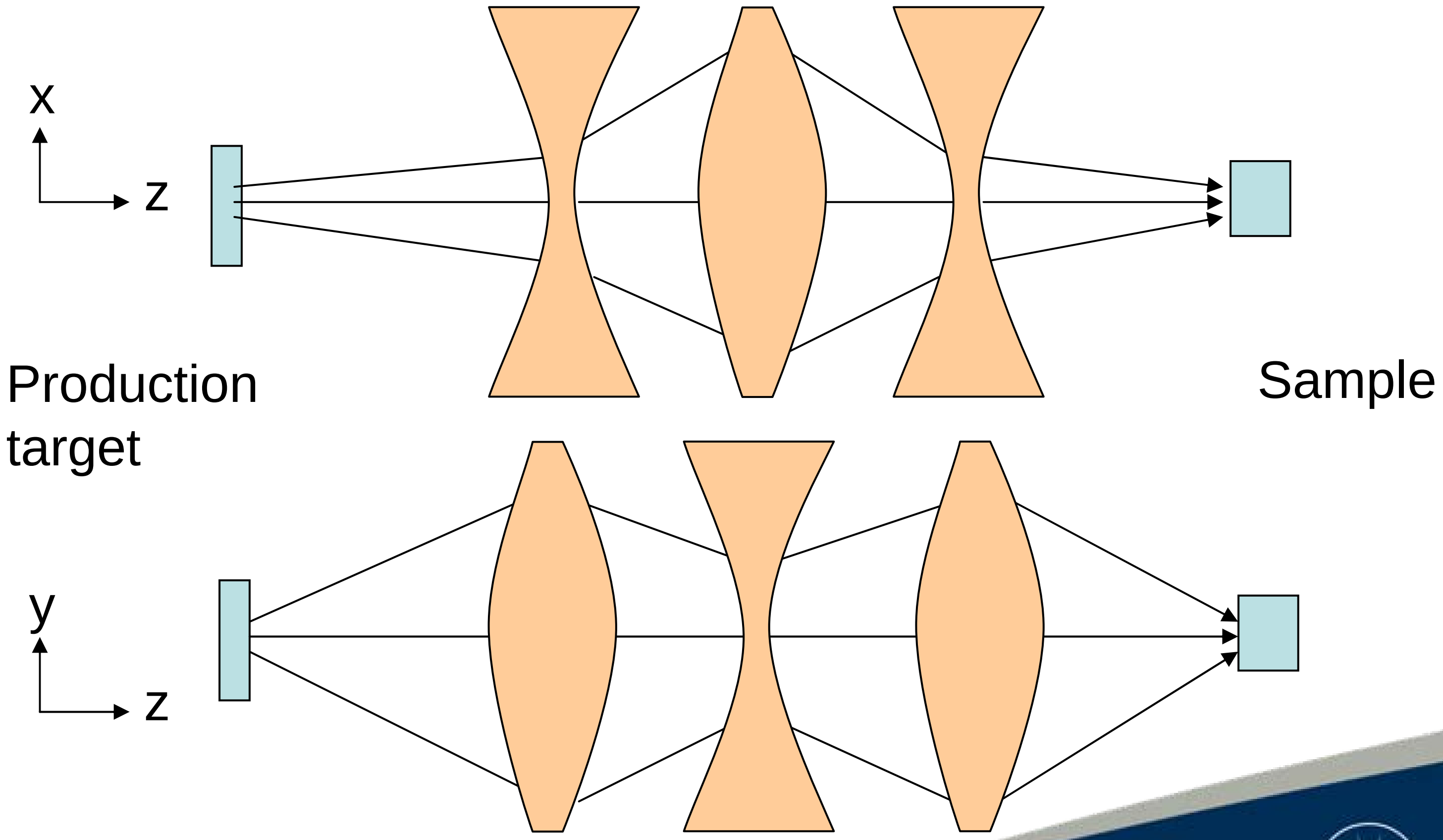
- Quadrupole magnet
  - Along axis, B=0 and no deflection
  - Focusing in x direction (convex lens)
  - Defocusing in y (concave lens)
- Can't focus both axes simultaneously (but Solenoids can do this)



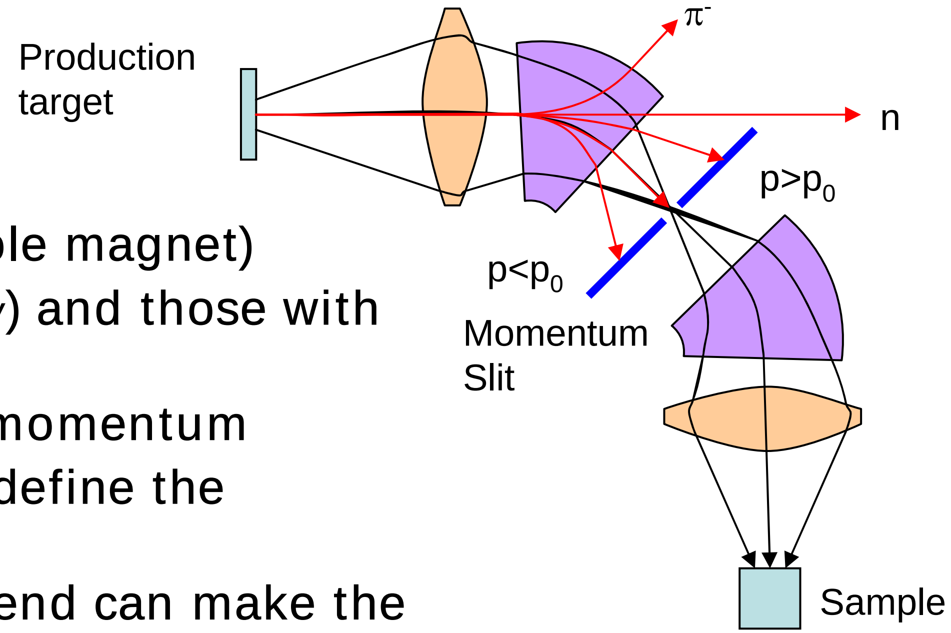
- Generally use electromagnets
  - Allow tuning of beam by varying current
- Focusing strength depends on momentum

Practical muon lenses

- For focusing on both axes we use a Doublet or Triplet
- Doublet gives different magnification in x and y
- Triplet can preserve image shape



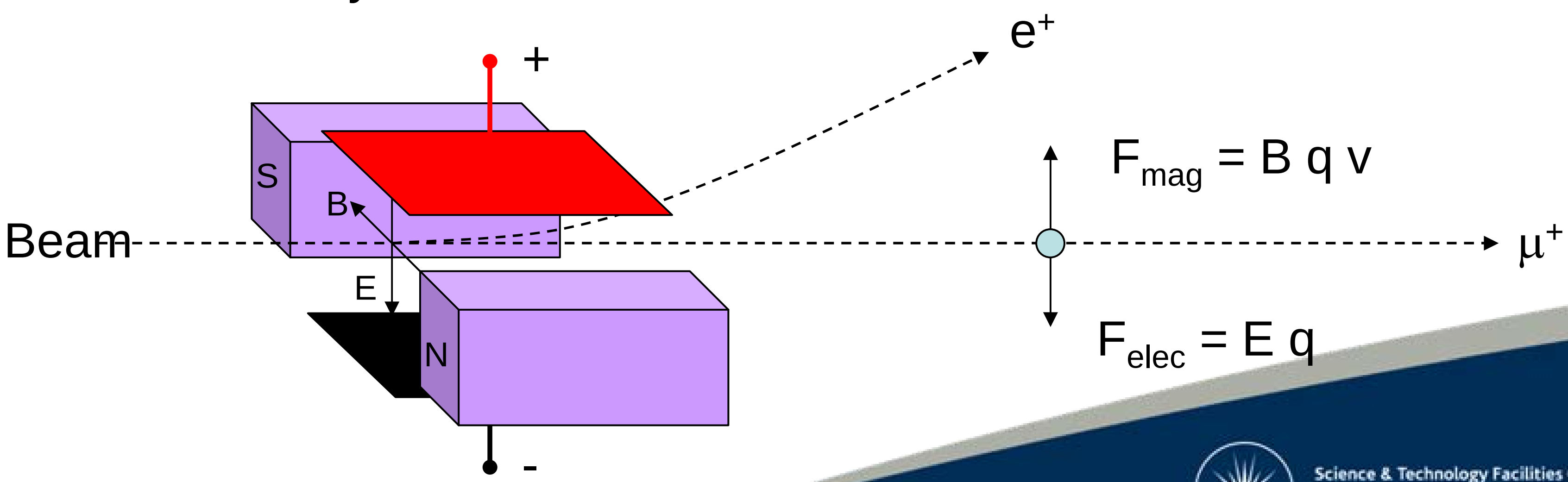
Beam line design 3 - bends



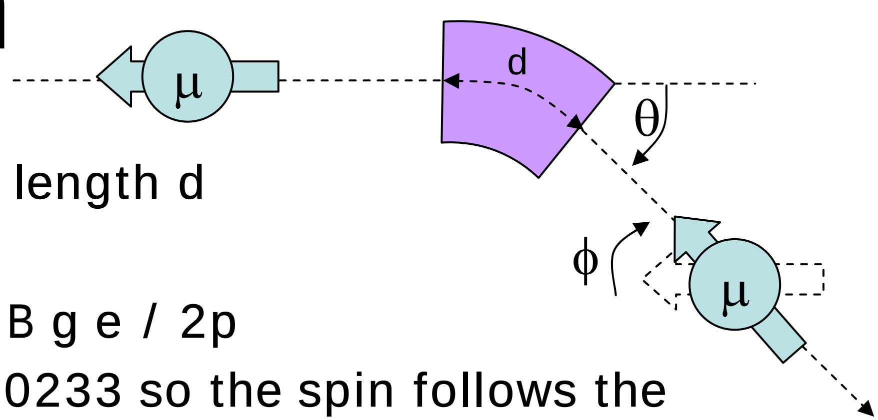
- Include a Bend (uniform field, dipole magnet)
- Excludes uncharged particles (n , γ) and those with wrong charge (π^-, e^-)
- Separates particles with different momentum
  - use Slits at a suitable point to define the momentum range passed
- More quadrupoles and a second bend can make the beam Achromatic
  - particles of any momentum are returned to the same path
  - can open momentum slits for large flux but keep same spot size at sample
- Problem – still passes positrons if they have the same momentum

Beam line design 4 - Separator

- Magnetic beam line selects momentum only
- Need to separate out surface muons (p=27 MeV/c and v = 0.24 c) from positrons with p=27 MeV/c (but v ≈ c)
  - these arise from muon decay in the target and have the same time structure as the positrons from the sample
- Use a Crossed field separator
- Electrostatic and magnetic forces cancel only for particles of the correct velocity



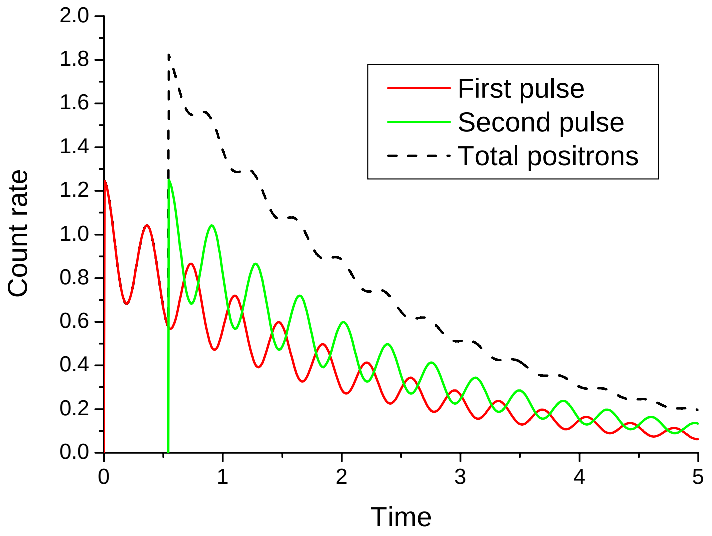
Spin Rotation

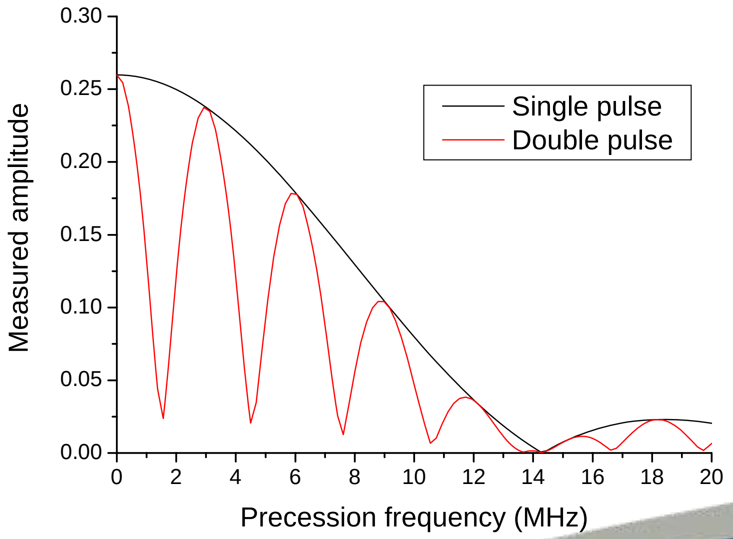


- For a magnetic bend of field B and path length d
  - Deflection $\theta = \quad d\,B\,e\,/\,p$
  - Spin precession $\phi = B\,\gamma\,t = \quad d\,B\,g\,e\,/\,2p$
  - Exact match for g=2.0. Muon g=2.00233 so the spin follows the momentum along any simple magnetic beam line.
  - Muon storage rings can measure (g-2) after many turns
- Electrostatic deflection leaves the spin unchanged but rotates the momentum
  - ISIS kicker gives 4° horizontal spin rotation for EMU and HiFi
- A crossed field device rotates the spin without changing the momentum
  - ISIS separator gives 6° rotation (vertical)
- Higher fields and/or longer path length give a “spin rotator” ideally 90°
  - useful for transverse field experiments, muons enter sample along field
  - ~45° allows simultaneous measurement of longitudinal and transverse relaxation rates

Beam line design 5 - Pulses

- ISIS produces a double proton pulse, separation 330ns (repeated at 50Hz)
- Muon lifetime 2.2μs
- Therefore the muon decay spectra overlap
- Transverse precession signals can interfere and cancel
  - Must remove one pulse.





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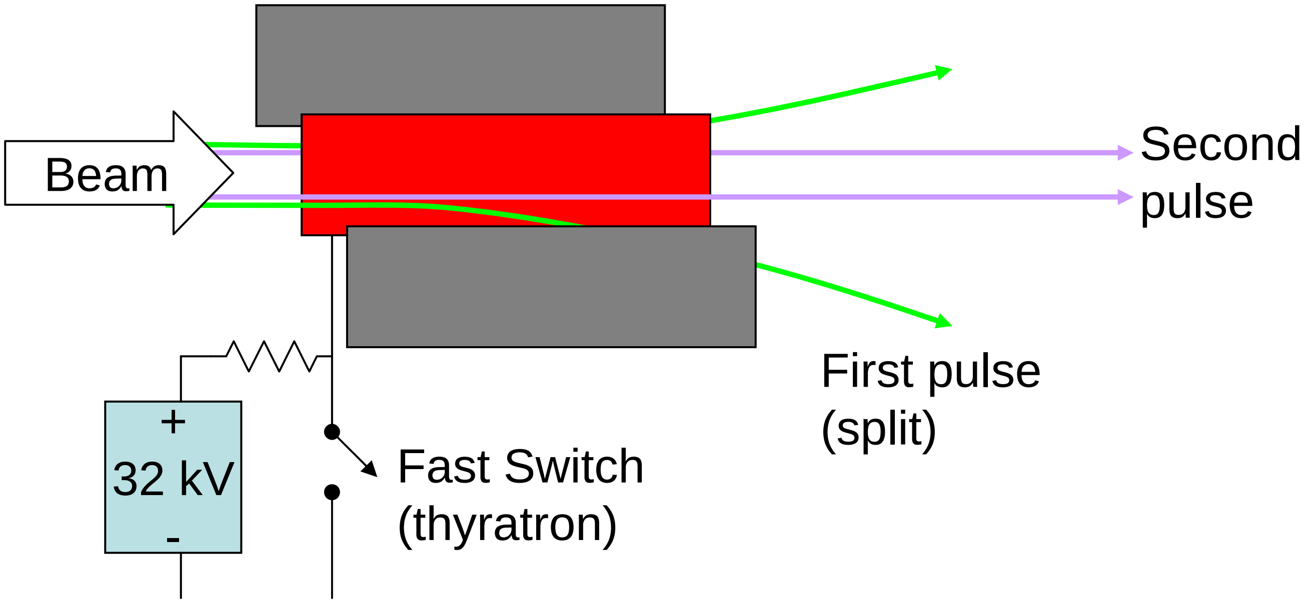
The Kicker

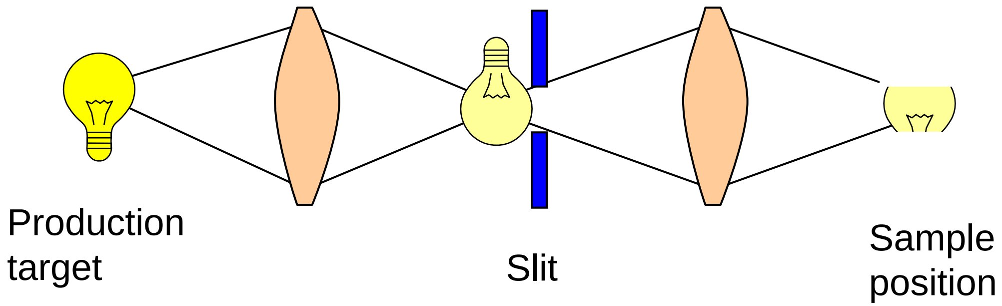
- First used “UPPSET” electrostatic kicker to throw away one pulse
- Improved design – divert one pulse into a second (and third) instrument – EC electrostatic kicker
- RIKEN uses a magnetic kicker, better for high momentum muons



- Also useful for
  - Slicing pulses for higher frequency response
  - Lower background at continuous sources such as MORE at PSI

Beam line design 6 – Spot Size

- The muon spot is the image of the production target – often too large
- We could use collimators near the sample
- Unwanted muons stop in the collimator and decay as normal
  - These positrons must be stopped from reaching the detectors while not blocking those from the sample. Difficult to achieve in practice
- Solution – Remote collimation
  - Intermediate focus earlier in the beam line
  - Slits at that point reduce the spot size
  - Positrons from the slits cannot reach the detectors
  - Slits imaged onto the sample



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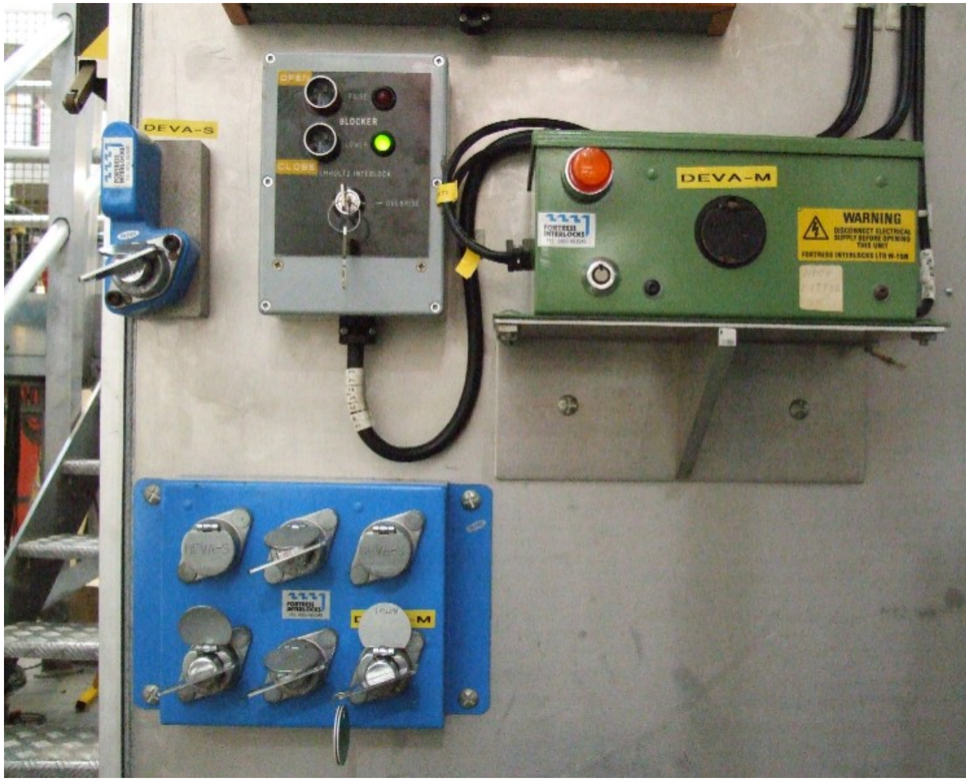
Muon Shutters

- Stop beam to change sample
  - Can't turn off accelerator if other instruments running
- Neutrons need 1m thick steel block
- Surface muon beam stopped by 5cm lead plate lifted by compressed air cylinder

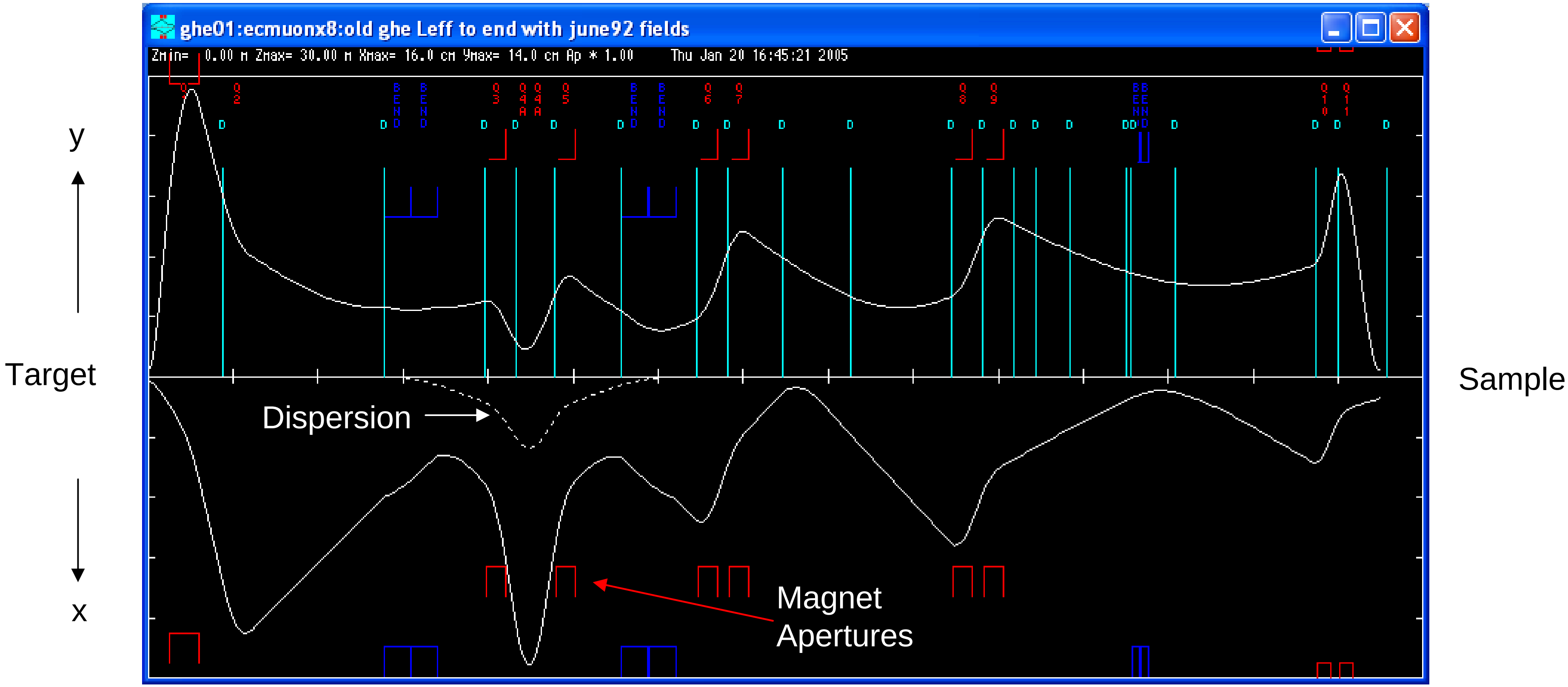
- Interlock system
  - prevents shutter being opened unless area is searched and locked.
  - stops beam if any problem eg. "Beam Off" button
  - In addition the interlocks may control some of the beam line magnets.



Continuous and Pulsed beams

	Continuous (eg. PSI)	Pulsed (eg. ISIS)
Beam structure	DC, or $<< \tau_\mu$	Pulse $<< \tau_\mu$, Spacing $>> \tau_\mu$
Counting	Each muon counted in and positron counted out	Average start signal from accelerator, just count positrons
Rate limit	When 2 muons in sample	Count rate per detector element close to t=0
Integral counts	Can remove muon counter for high rate	Time dependent polarisation always available
Background	If 2nd muon not detected	Usually low, measure to $>10\ \tau_\mu$
Small samples	Can use veto counters	Must use collimation or fly-past
Frequency response	Limited only by detectors and electronics (500MHz+)	Limited by pulse width (10 MHz)

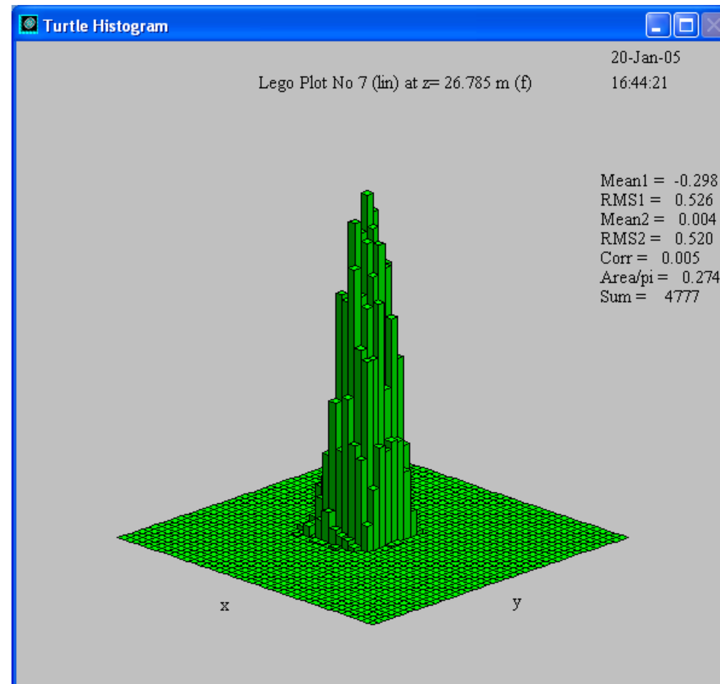
Designing a beam line

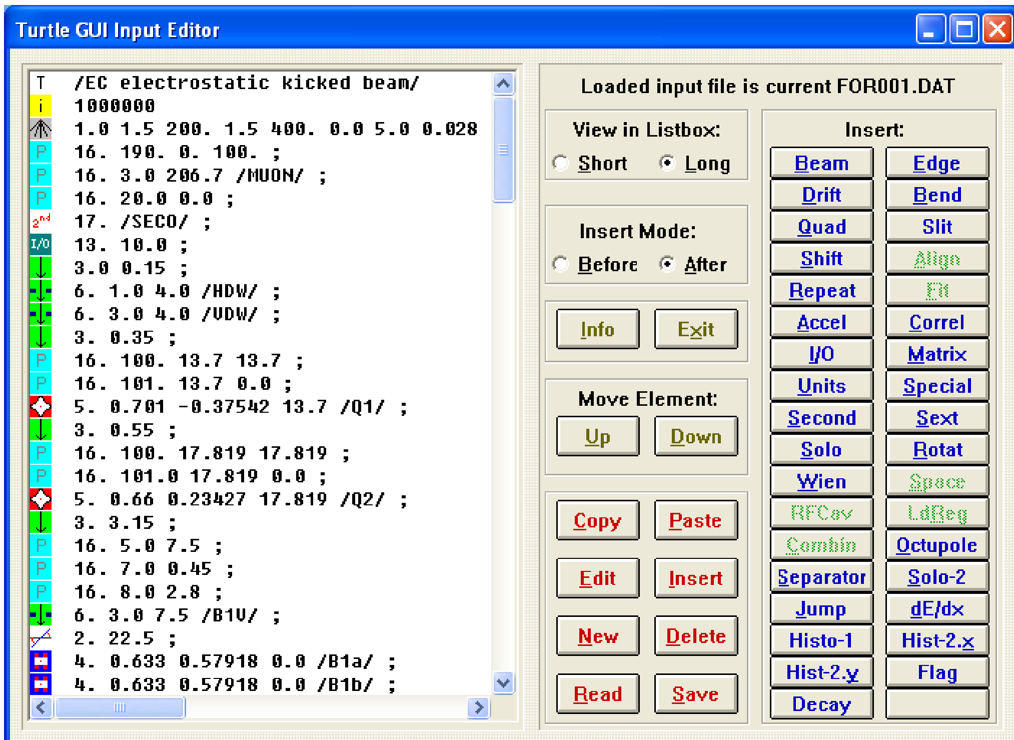


- Computer calculation of the focusing effect of all elements – TRANSPORT
- “Transfer matrix” method to first or second order – fast calculation
- Finds required fields to focus the beam correctly and best locations for slits
- Plots beam envelopes along the beam line

Designing a beam line

- Computer calculation by “ray tracing” individual muons – TURTLE
- More computer time needed – was slow on old computers
- High order corrections and arbitrary apertures included
- Calculate flux at sample and identify where other muons are being stopped





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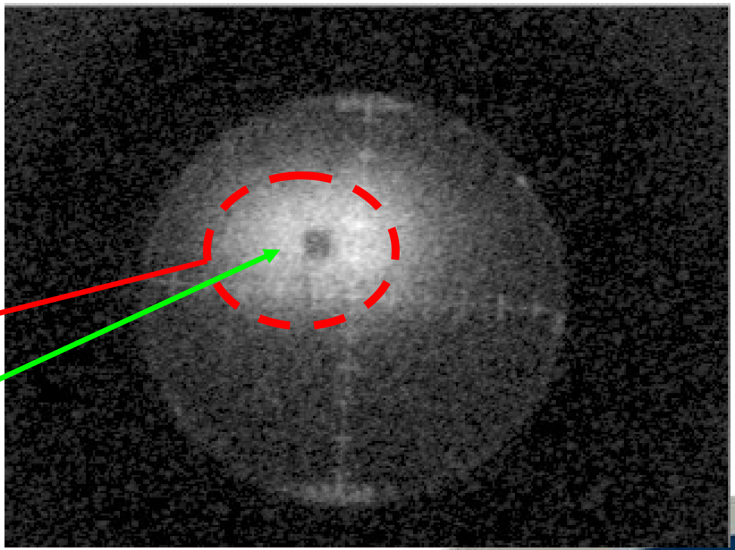
Monitoring the beam line

- Rates of muons counted in the instrument
  - large sample plate or small fly-past sample
- Standard samples for beam steering and spot size measurements
  - combination of materials giving different relaxation signals
- Slit Counters
  - thin strip of scintillator along the edges of the slits

- Beam Camera for direct spot imaging at the sample position
  - plate of scintillator viewed by a sensitive CCD camera

Beam Spot

Marker (sample holder)



The ISIS muon beam lines today

South side (EC Muons)

North side (RIKEN)