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Muon Beam Lines

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ISIS

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

Muon Production - physics

- High energy protons colliding with nuclei, to form pions
- Nuclear reactions such as

  $p^+ + p^+ \rightarrow p^+ + n + \pi^+$

  $p^+ + n \rightarrow n + n + \pi^+$

  $p^+ + p^+ \rightarrow p^+ + p^+ + \pi^0$

  $p^+ + n \rightarrow p^+ + n + \pi^0$

  $p^+ + n \rightarrow p^+ + p^+ + \pi^-$
- Requires proton energy > 280 MeV
- Full production rate for energy 500-1000 MeV

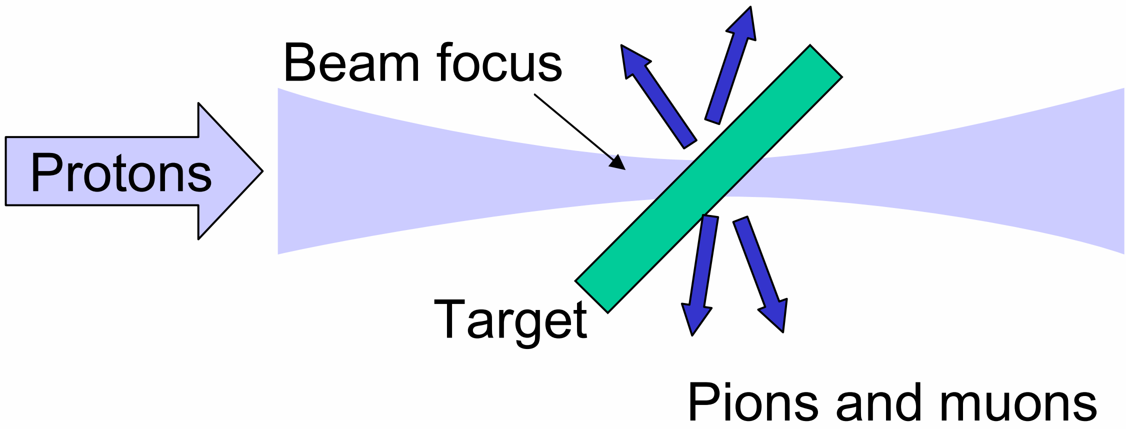
  ISIS 800 MeV, PSI 590 MeV
- Also double pion production $p^+ + p^+ \rightarrow p + p + \pi^+ + \pi^-$ etc at higher energy

- 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 or radiation.
- Most protons (> 95%) do not produce pions and pass through with little energy loss, so can be used for other purposes (neutrons).



Muons and Pions

- Some pions escape from the target
  - Capture into beam line, allow to decay in flight
  - Momentum of muon relative to pion determines polarisation
  - both 'forward' and 'backward' decays can be used
  - Select both initial pion momentum and final muon momentum

    'Decay' muon beam line

    High momentum muons to penetrate pressure cells etc.

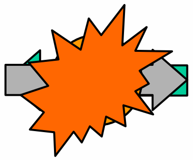
    Final polarisation of the muon beam ~ 80%

- Some pions stop within the target material
  - Decay to muons which escape into the beam line
  - Pions at rest mean muons collected in one direction are all polarised
  - 'Surface' muon beam line - simpler design

    More intense beam but low momentum muons mean thin windows
  - Fully polarised muon beam

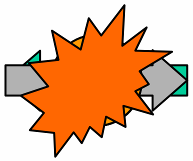
Pion decays

- 'Surface' muons from pions at rest (in the production target)



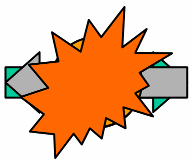
p_μ=27MeV/c E_μ=4MeV

- 'Forward' muons from pions in flight



$p_\mu > p_\pi$ High energy

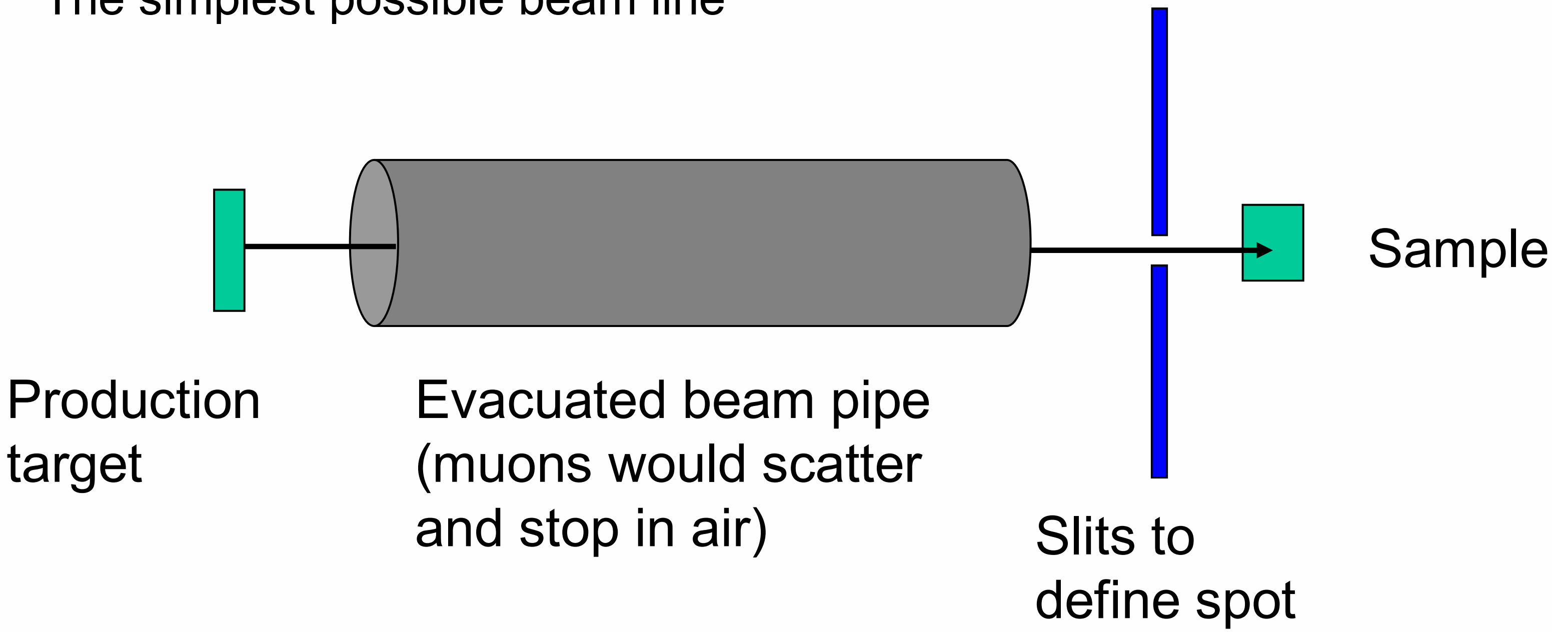
- 'Backward' muons from pions in flight



$p_\mu < p_\pi$ High energy

Beam Line design 1

- The simplest possible beam line



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

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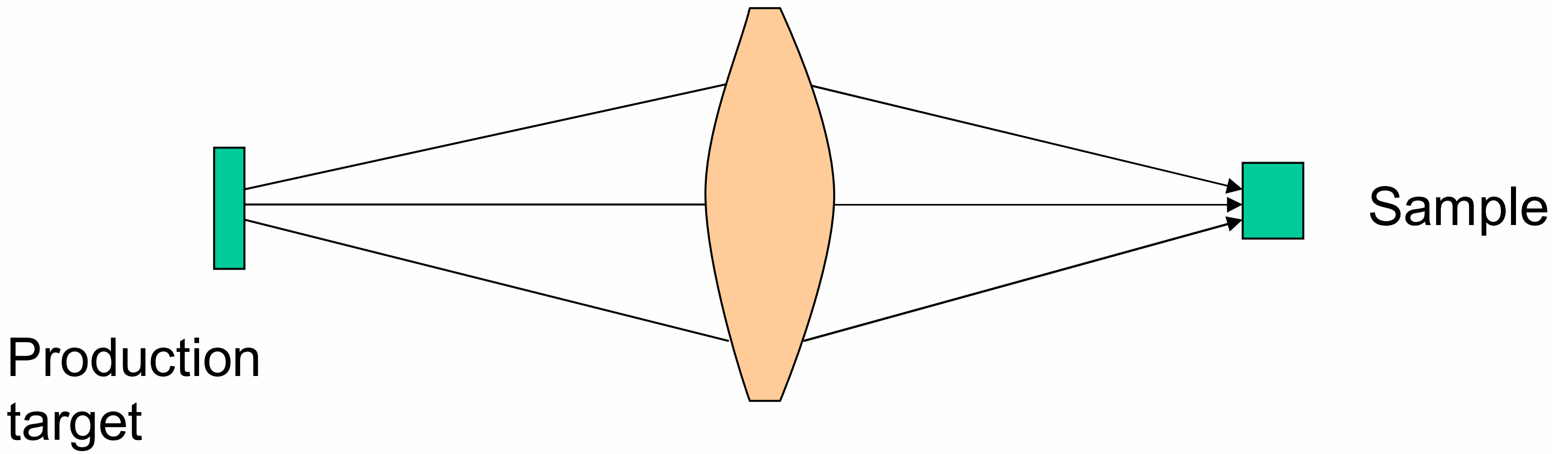
Muon Shutters

- Need to be able to stop the beam at the sample position to change the sample
  - Do not want to switch off the whole accelerator
  - Some radiation from target even with proton beam off
- Shutter required which will stop all particles coming down the beam line.
- Beam with direct view of the target - 1m thick steel block (as in neutron instruments) to stop neutrons, gamma rays, etc.
  - Large motor and gearbox to raise/lower. Slow.
- Clean muon beam with momentum 27MeV/c - 5cm thick lead plate
  - Simple compressed air cylinder. Fast operation.

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

Beam line design 2

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

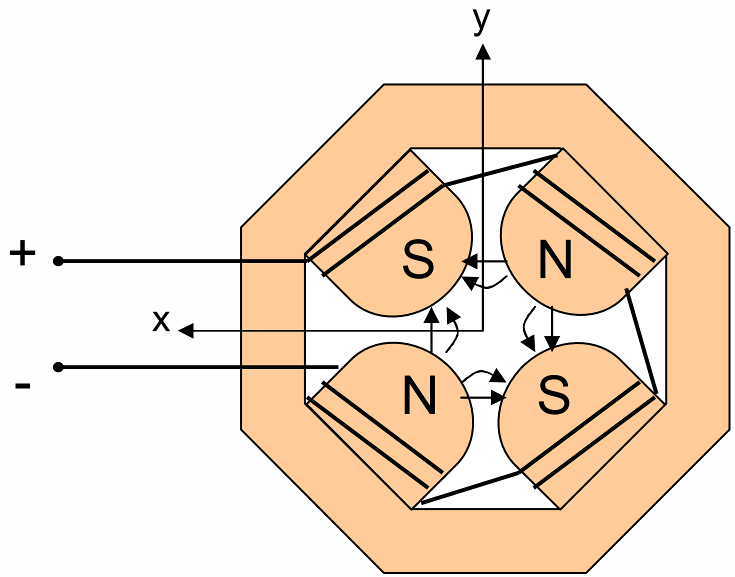


- Usually use more than one lens:
  - First lens close to source to capture large solid angle
  - Sample close to last lens to give smaller beam spot
- Still transmits many other particles ñ these are poorly focused if the wrong momentum
- Straight-through path for neutrons

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 beam through the same angle at any position off axis
- Field Gradients give deflection varying with position ñ focusing possible
- Quadrupole magnet

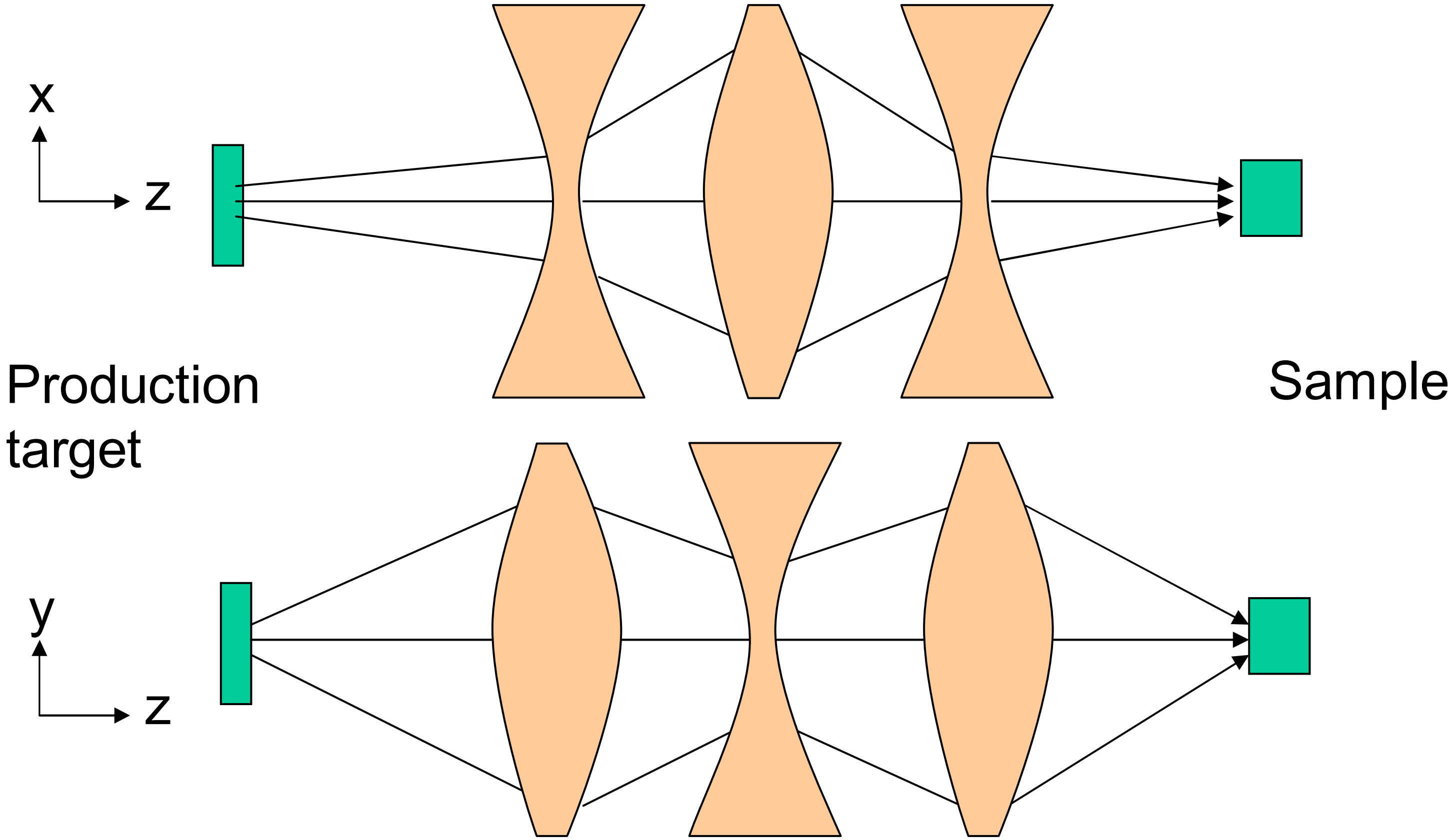
- Beam in +z direction (into screen)
- Along axis, B=0 and no deflection
- Displaced in +x direction
  - B along +y and F in -x direction
  - Focusing (convex lens)
- Displaced in +y direction
  - B along -x and F in +y direction
  - Defocusing (concave lens)



- Canít focus both axes simultaneously!

Practical muon lenses

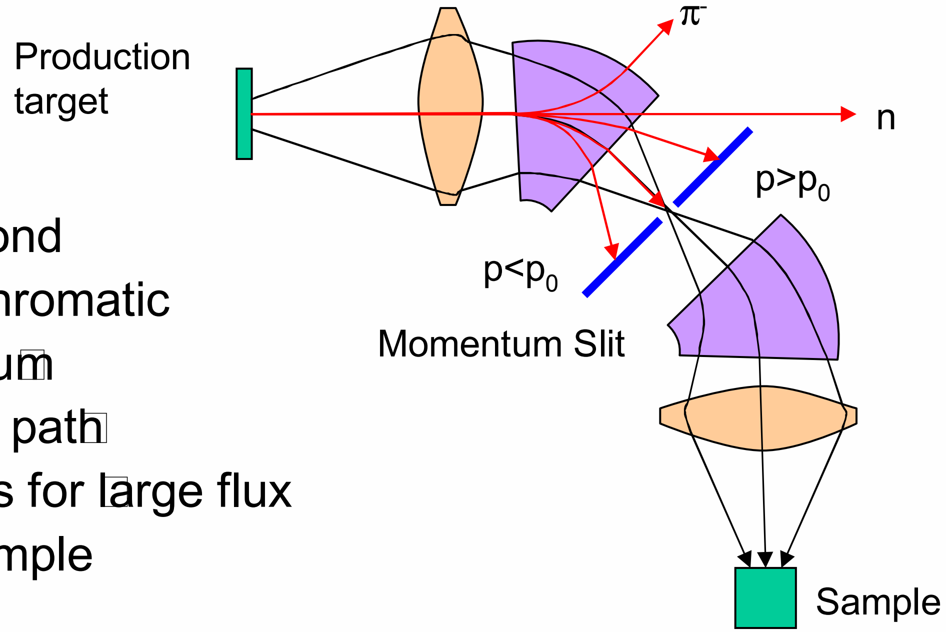
- For focusing on both axes we use a Doublet or Triplet
- Doublet gives different magnification in x and y
- Triplet can preserve image shape



Beam line design 3

- 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

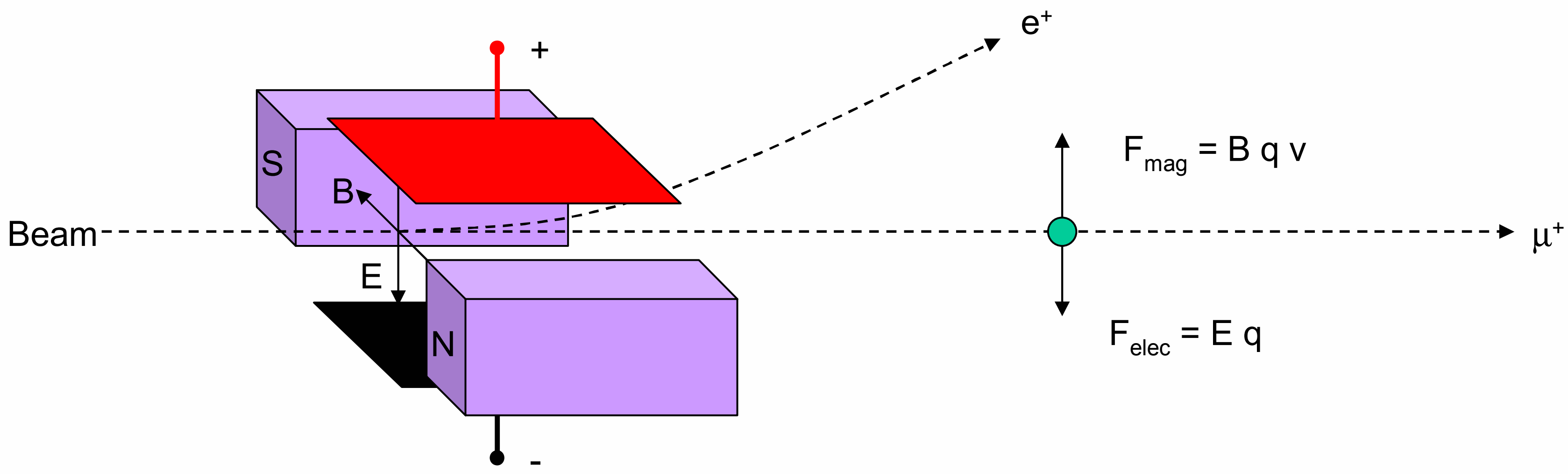
    can open momentum slits for large flux

    but same spot size at sample

- Problem - still passes positrons if they have the same momentum

Beam line design 4

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



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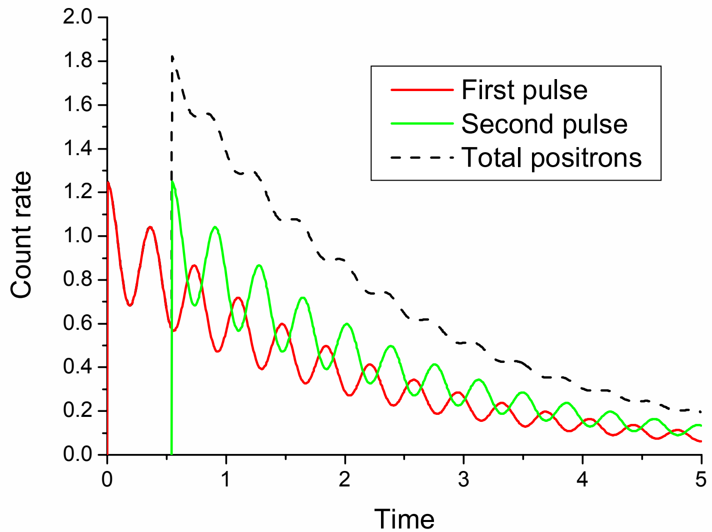
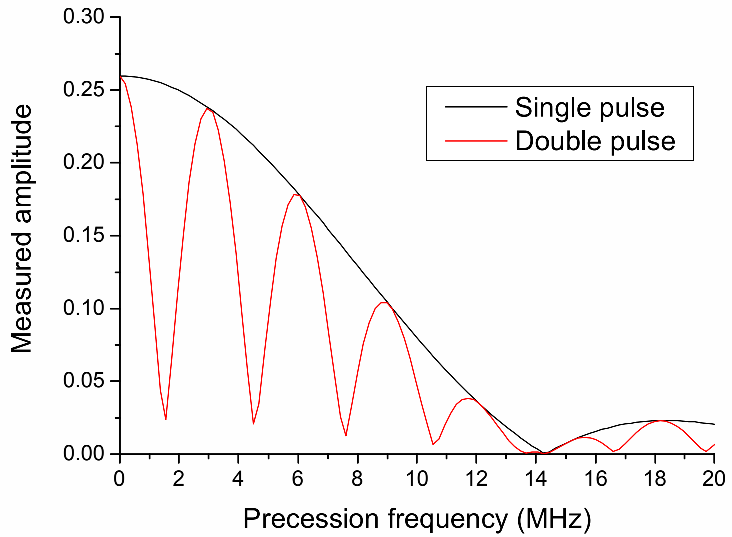
Beam line design 5

- 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

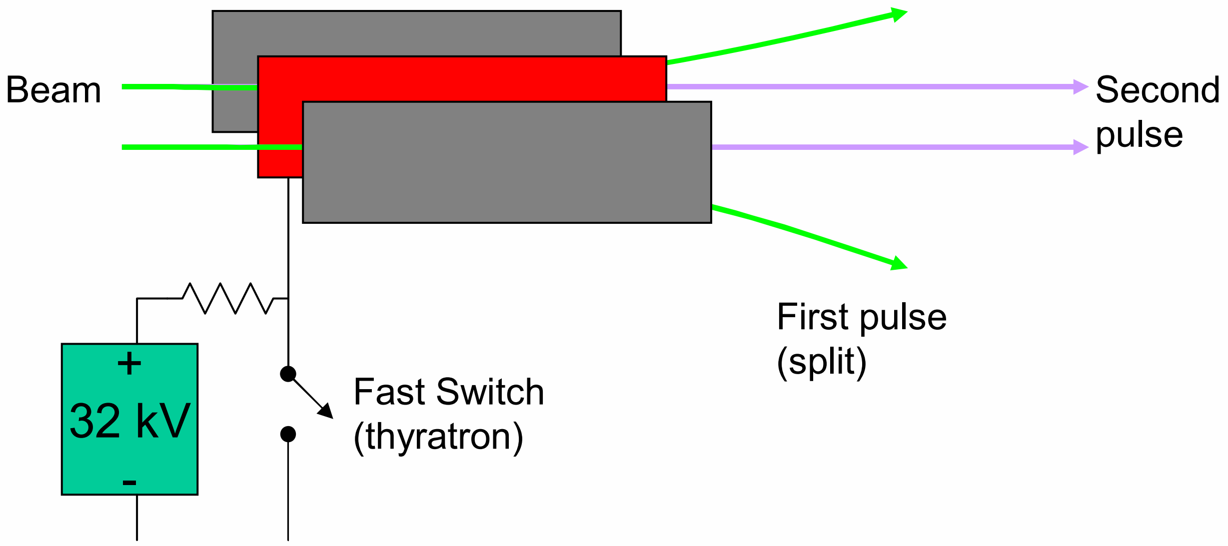
  Must remove one pulse.





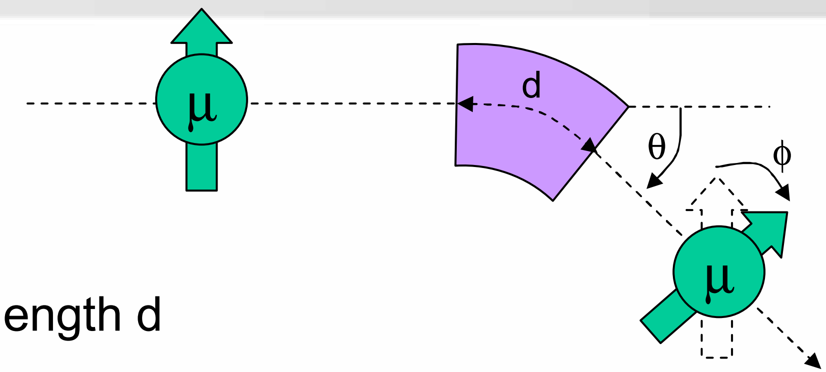
The Kicker

- First used 'UPPSET' electrostatic kicker to throw away one pulse
- Improved design - divert the second pulse elsewhere - 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 - MORE at PSI

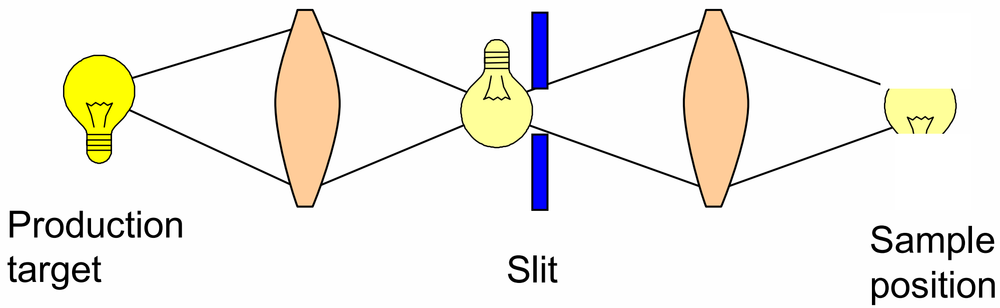
Spin Rotation



- For a magnetic bend of field B and path length d
  - Deflection $\theta = d\ B\ e / p$
  - Spin precession $\phi = B\ \gamma t = d\ B\ g\ e / 2p$
  - 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 DEVA
- 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

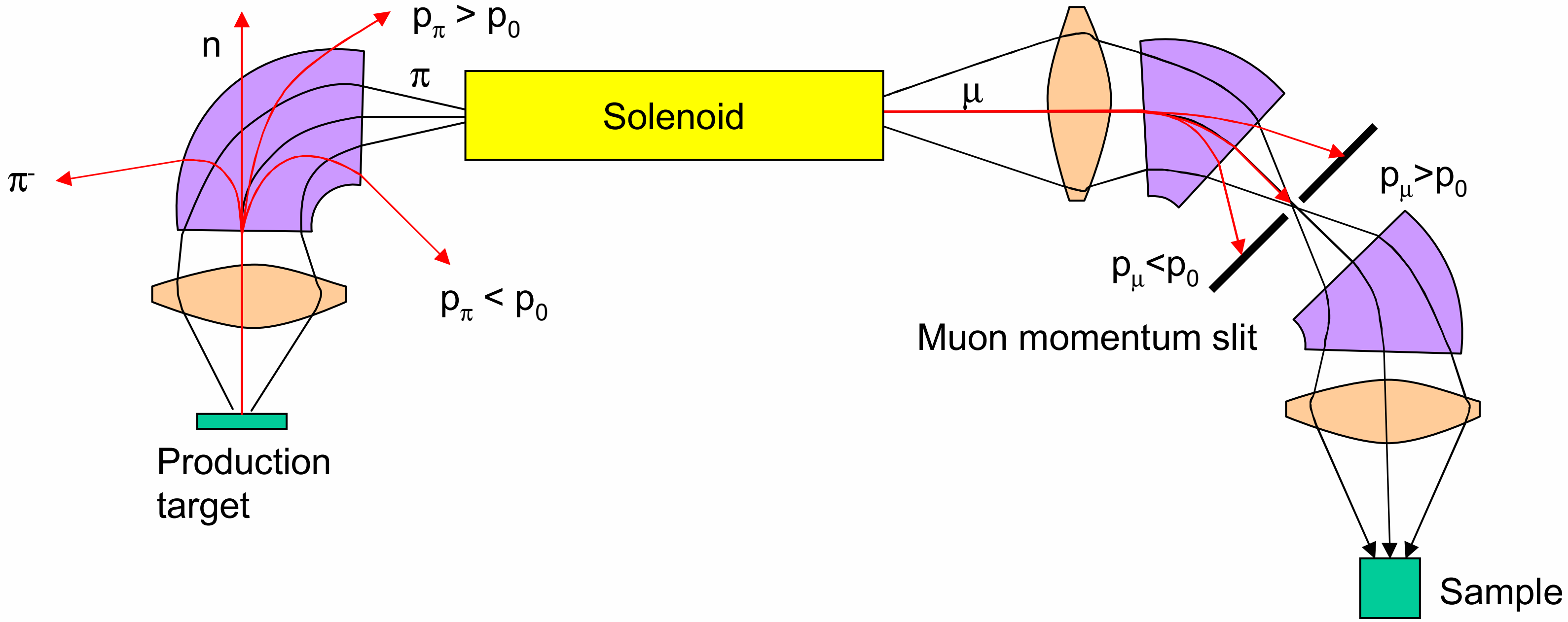
Beam line design 6

- 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



Decay beam line

- Pions decay to muons at different positions along the beam
  - 100MeV pions decay over a mean path length 5.5m
- Must keep the muons in the same path although different momentum
- Solenoid (high longitudinal field) where the particles spiral round the field lines
- Inject pions into solenoid, selecting initial momentum for decay
- Exit of solenoid is muon source. Select final momentum and focus onto sample

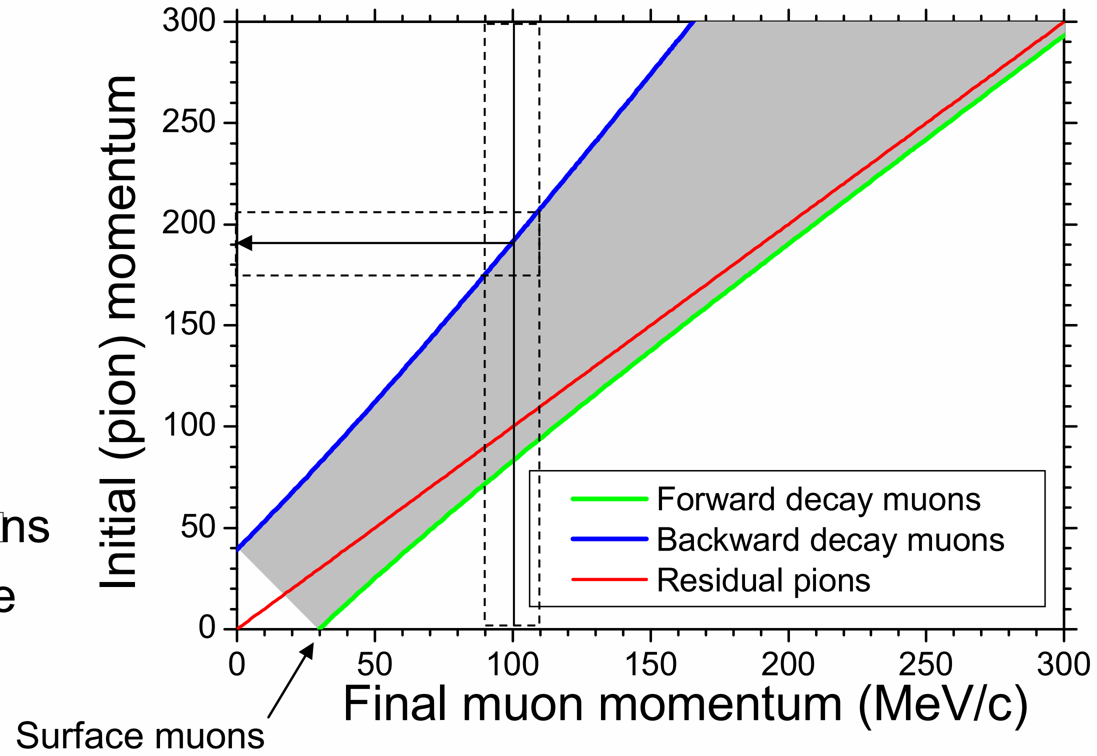


Decay muon beam tuning

- We can use either 'backward' or 'forward' muons
- Backward muons are easier to separate from remaining pions (or muons formed before initial momentum selection)

- Select muon energy
- Tune muon section of beam
- Look up required pion energy
- Tune pion section

- Continuum of muon energies between forward and backward
- Actual energy of muons and pions optimised for flux at the expense of some polarisation



Positive and Negative Muons

- Most muon experiments use positive muons produced in the decay of positive pions
- Negative muons are also produced, from negative pions
  - Lower yield of π^- than π^+ from positive proton beam striking positive nuclei
  - No 'surface' μ^- because any negative pion coming to rest in matter is rapidly captured by a nucleus and reacts with it
- Negative muons are also captured into orbits around nuclei
  - Muonic X-rays emitted as muon cascades down to 1s level, characteristic of the elements present
  - Very strong coupling between muon and nuclear spin
  - Muon lifetime reduced by capture reactions ñ greater effect for larger nuclei
- Can use the same decay beam line to produce a negative muon beam
  - Reverse the fields in all the bending magnets (and quadrupoles)

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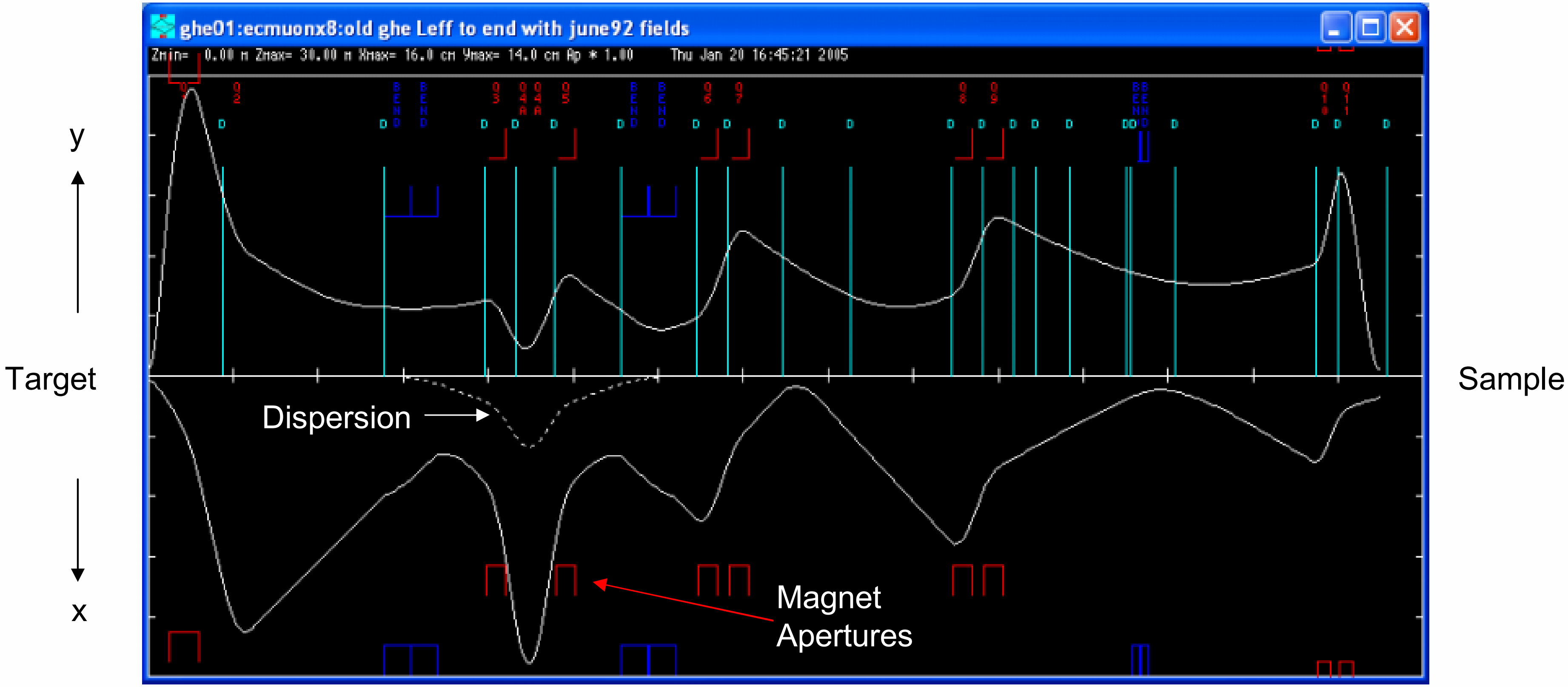
Continuous and Pulsed beams

- Continuous beam (eg. PSI)
  - DC, or any time structure << τ_μ
- Each muon counted into the sample and its positron counted out
- Rate limited if two muons in sample at once ñ also depends on time range measured
- Background from stray positrons or muons which fail to be counted in
- Can use veto counters to reduce effective spot size, and exclude positrons (no separator may be needed)
- Precession frequency range depends on timing accuracy of detectors (500 MHz +)
- Can remove muon counter and just measure positrons giving average polarisation (ALC) at higher rate

- Pulsed beam (eg. ISIS)
  - pulse length << τ_μ and spacing >> τ_μ
- Start signal from accelerator at average position of muon pulse, just count positrons out
- Rate limited only when detectors saturate close to t=0 (segmented)
- Background usually low, time range longer (> 10 τ_μ)
- Must use collimation or ìfly-pastî for small samples, and positron-free beam
- Precession frequency range limited by pulse width (10 MHz)
- Time dependent polarisation always available ìfor freeî

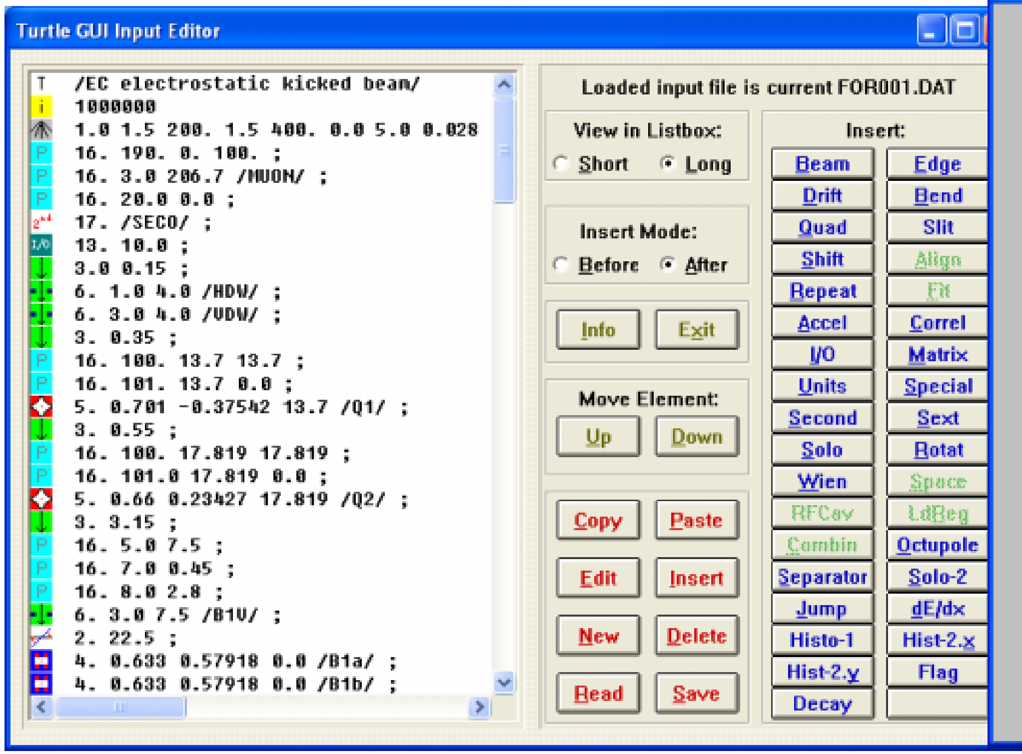
Designing a beam line

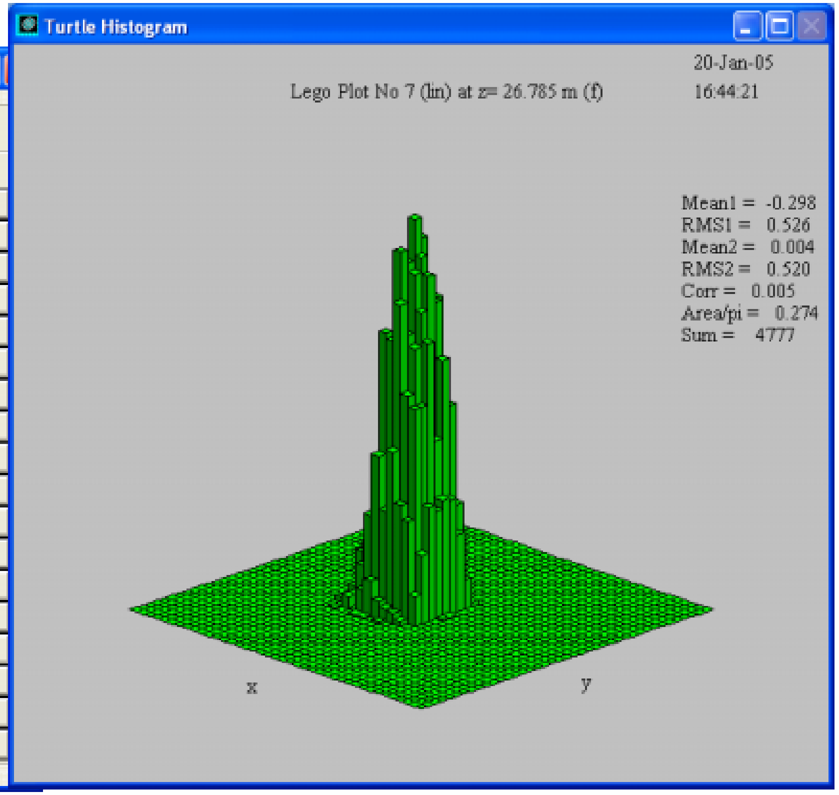
- Computer calculation of the focusing effect of all elements - TRANSPORT
- 'Transfer matrix' method to first or second order - fast calculation
- Finds required fields to focus the beam correctly and best locations for slits
- Plots beam envelopes along the beam line



Designing a beam line

- Computer calculation by ìray tracingî 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

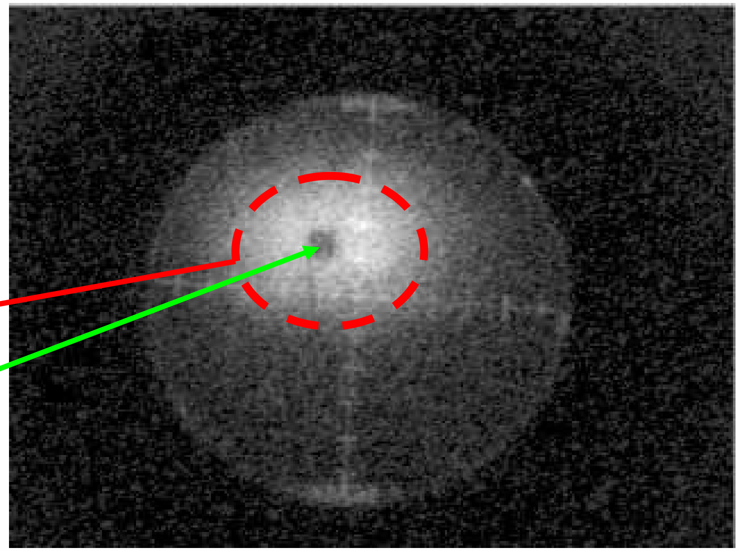




Monitoring the beam line

We may need to check the performance of the beam line or adjust the focusing, separator voltage, etc:

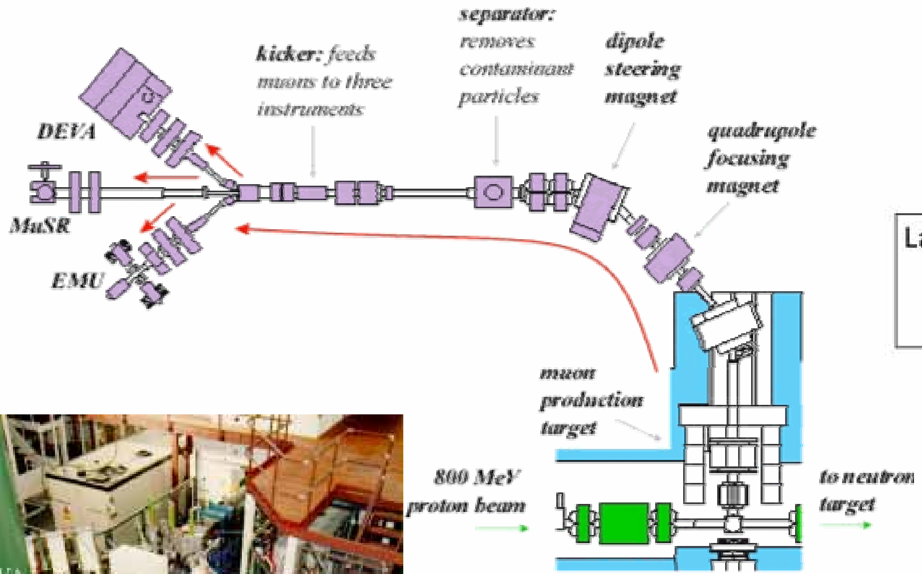
- Measure rates of muons arriving at instrument
  - using either a large sample plate or small fly-past sample at centre
- Standard samples for beam steering and spot size measurements
  - combination of materials giving different relaxation signals
- Slit Counters ñ thin strip of scintillator along the edges of the slits
  - measure muons hitting edge of slit, can adjust slit and measure profile
  - also confirm correct kicker timing
- Beam Camera for direct spot imaging at the sample position
  - plate of scintillator viewed by a sensitive CCD camera

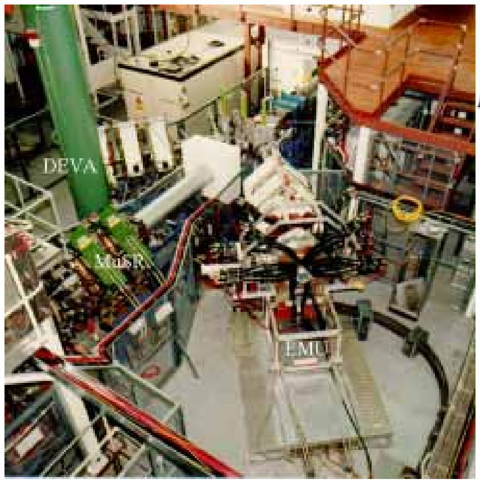


Beam Spot
Marker (sample holder)

The ISIS muon beam lines today

South side (EC Muons)





North side (RIKEN)