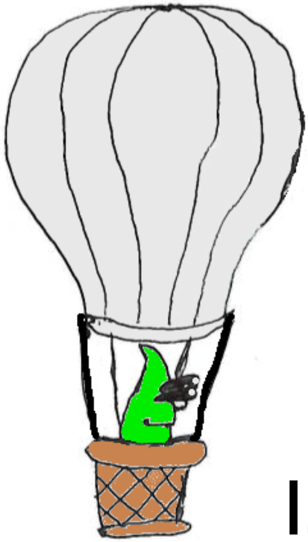
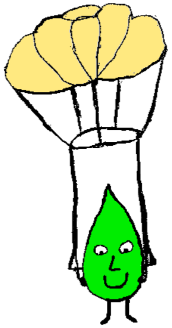


Making Muons

Peter Baker

ISIS Pulsed Neutron and Muon Source



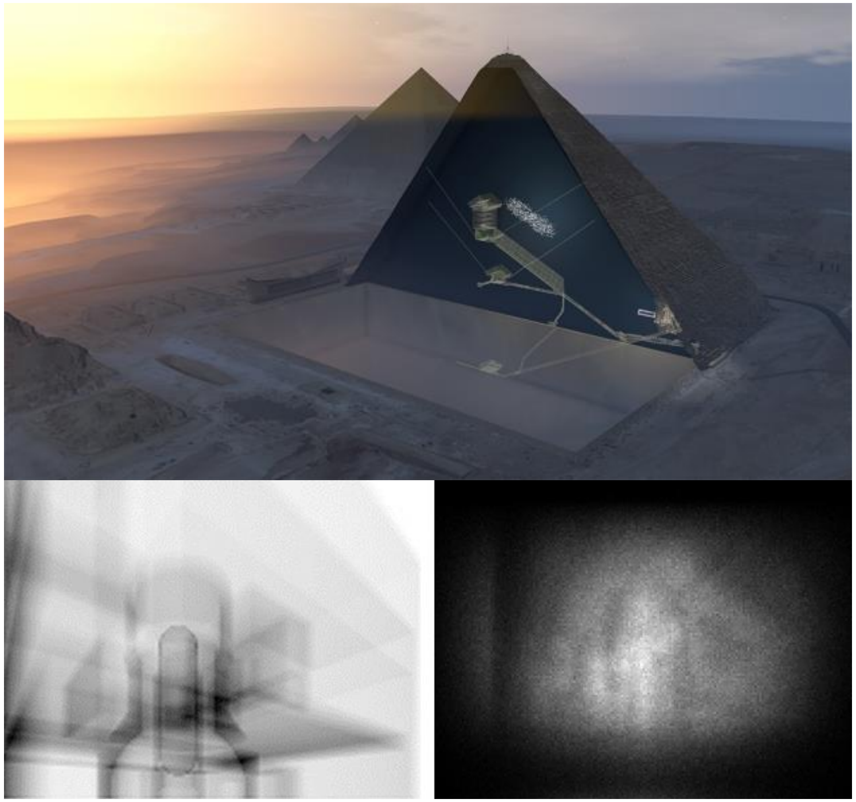
With thanks to James Lord for diagrams

Everyone’s local muon source

Everyone’s local muon source

- Muons made 15km above Earth’s surface
- Flux ~ 1 $cm^{-1}min^{-1}$
- Energy ~ 4 GeV
- Stopping range ~ 20 m
- Distribution of directions
- No polarization

Everyone's local muon source



- Muons made 15km above Earth's surface
- Flux ~ 1 $cm^{-1}min^{-1}$
- Energy ~ 4 GeV
- Stopping range ~ 20 m
- Distribution of directions
- No polarization
- Useful for a limited number of samples!

Making Muons
(in a useful manner)

Peter Baker

ISIS Pulsed Neutron and Muon Source

What do we want?

1. Positive or negative muons
2. Low contamination with other particles
3. Muons hitting the sample
4. Muons stopping in our sample (well-defined and suitable energy)
5. Few muons missing the sample
6. High spin polarization (if needed)
7. Useful time structure for experiment
8. Lots of muons!

How do we get it? (Plan of talk)

- Particle accelerators
- Muon production targets
- Getting the muons to the sample
  - Focussing
  - Bending
  - Selecting the right particles
  - Manipulating the beam
- Planning and designing
- Monitoring to check it works
- Future possibilities

PARTICLE PHYSICS AND PARTICLE ACCELERATORS

Pion production – physics

Lower energy

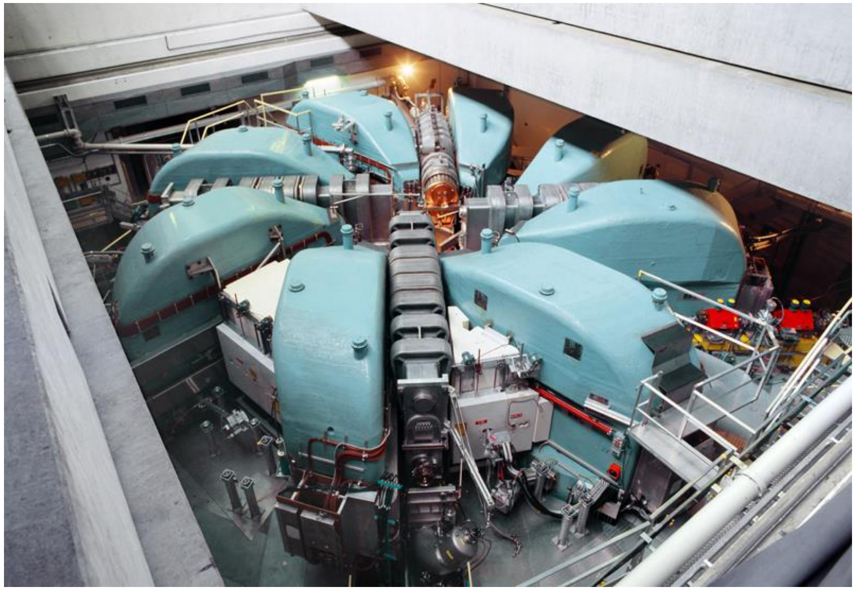
- Single pion production
  - $p^+ + p^+ \rightarrow p^+ + n + \pi^+$
  - $p^+ + n \rightarrow p^+ + p^+ + \pi^-$
- Needs $E_p > 280$MeV
- Maximum production 500MeV < E_p < 1GeV
  - MuSIC: 392MeV
  - TRIUMF: 520MeV
  - PSI: 590MeV
  - ISIS: 800MeV

Higher energy

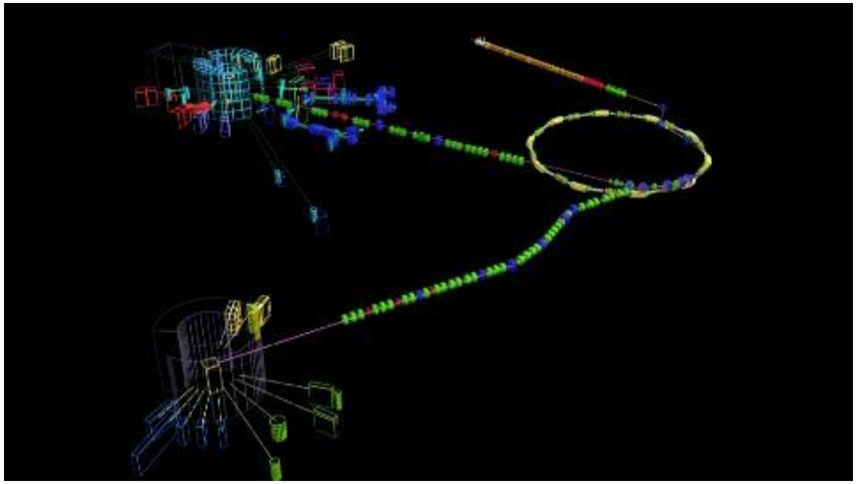
- Double pion production
  - $p^+ + p^+ \rightarrow p + p + \pi^+ + \pi^-$
- Needs $E_p > 600$MeV
- Production increases up to E_p ~1.5GeV
  - J-PARC: 3GeV

Particle accelerators

Cyclotrons (quasi-continuous)



Synchrotrons (pulsed)



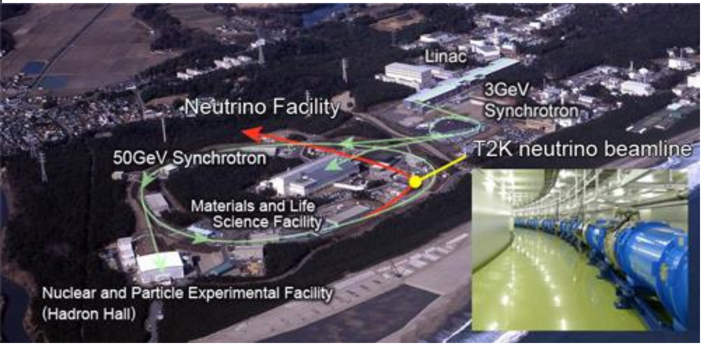
Muon sources of the world

ISIS, Oxfordshire, UK

Paul Scherrer Institute,
Zurich, Switzerland

MuSIC, Osaka, Japan

TRIUMF, Vancouver, Canada



J-PARC, Ibaraki, Japan

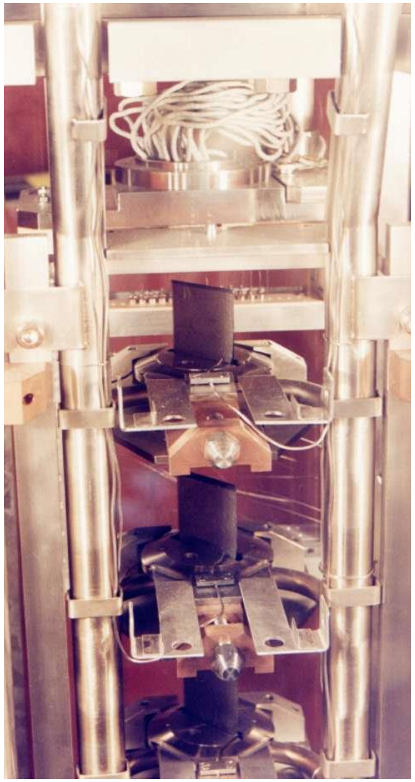
Continuous and pulsed beams

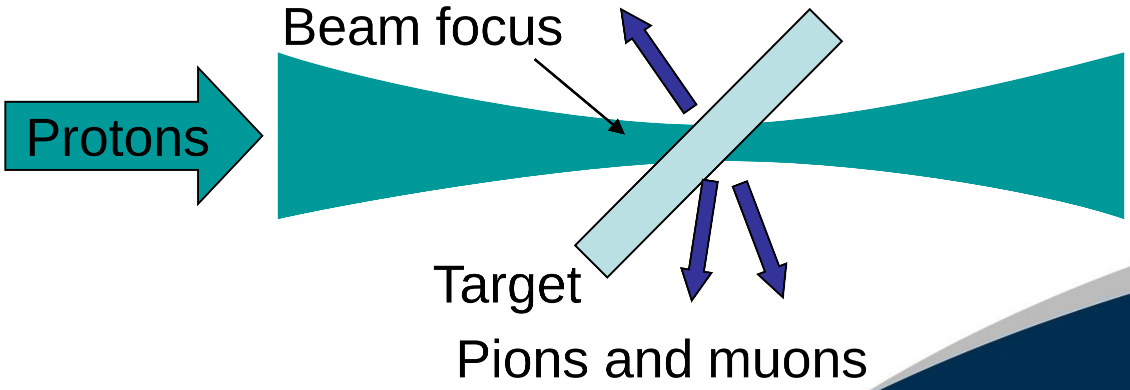
	Continuous (e.g. PSI)	**Pulsed** (e.g. ISIS)
Beam structure	Effectively DC (structure << τ_μ)	Pulse << τ_μ, spacing >> τ_μ
Counting system	Each muon counted in, each positron counted out	Average start time from accelerator, count positrons
Rate limit (time-differential)	When two muons in sample (~20 million/hour)	A few counts per detector per pulse (~150 million/hour)
Integral counts	Just count positrons with 100% duty factor	Always gives time-differential signal with 0.01% duty factor
Background	If second muon not detected (Measure to ~5τ_μ without tricks)	Mostly cosmic rays (Measure to > 12τ_μ routinely)
Small samples	Can use veto counters to exclude muons missing sample	Either collimate or use 'fly-past'
Frequency range	Limited by detectors and electronics (500MHz – >10GHz)	Limited by pulse width (~10MHz)

MUON PRODUCTION TARGETS

Muon Production Targets – I

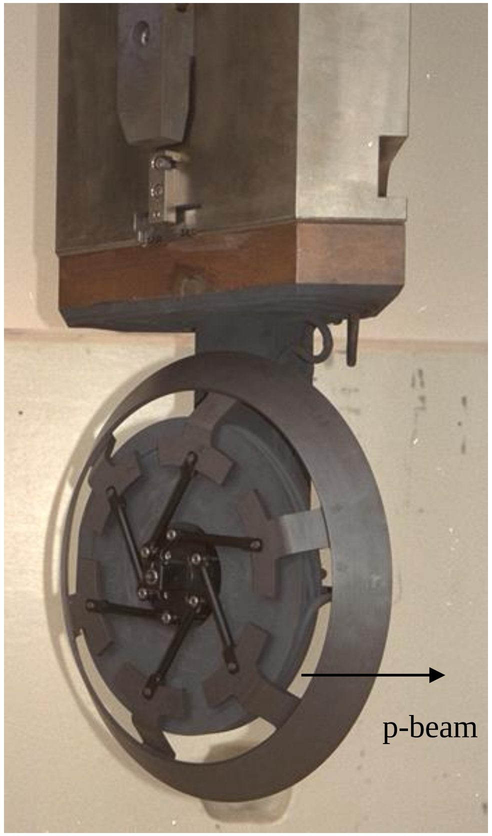
- Material: Low atomic number and high melting point
  - High atomic number gives more neutrons by spallation and more scattering of the beam
- Usually Graphite, sometimes Beryllium
- Beams and therefore targets are in vacuum
- ISIS target heated to ~600°C, cooling by conduction to the edge and radiation
- Rotating targets necessary for effective cooling at higher power sources (see next slide)
- Most protons (> 95%) pass through with little energy loss, so can be used to make neutrons



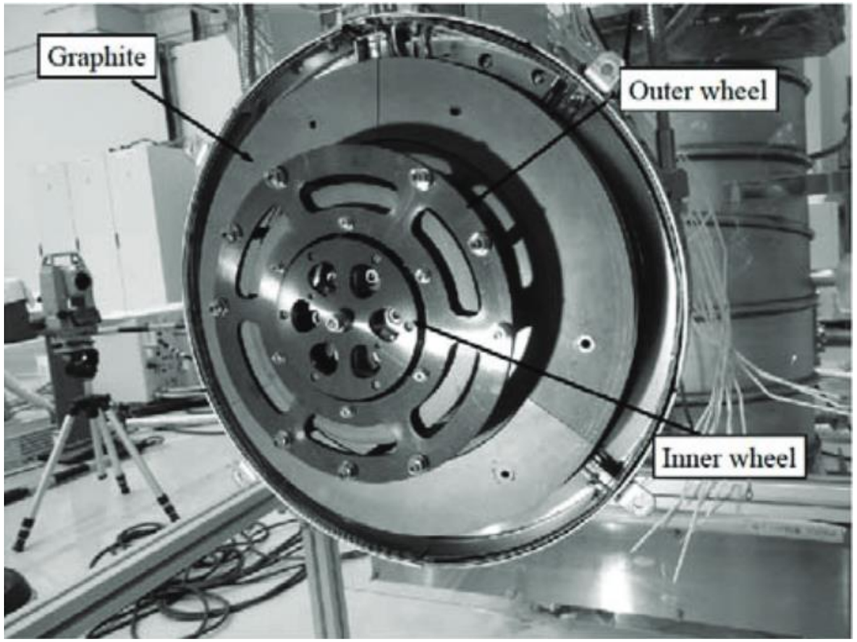


Muon Production Targets – II

PSI rotating wheel

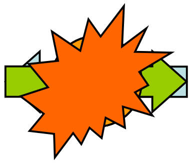


J-PARC rotating wheel



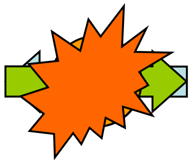
Different pion decays – I

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



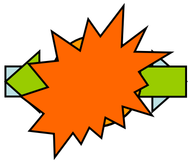
p_μ=27MeV/c E_μ=4MeV

- “Forward” muons from pions in flight



$p_\mu > p_\pi$ High energy

- “Backward” muons from pions in flight



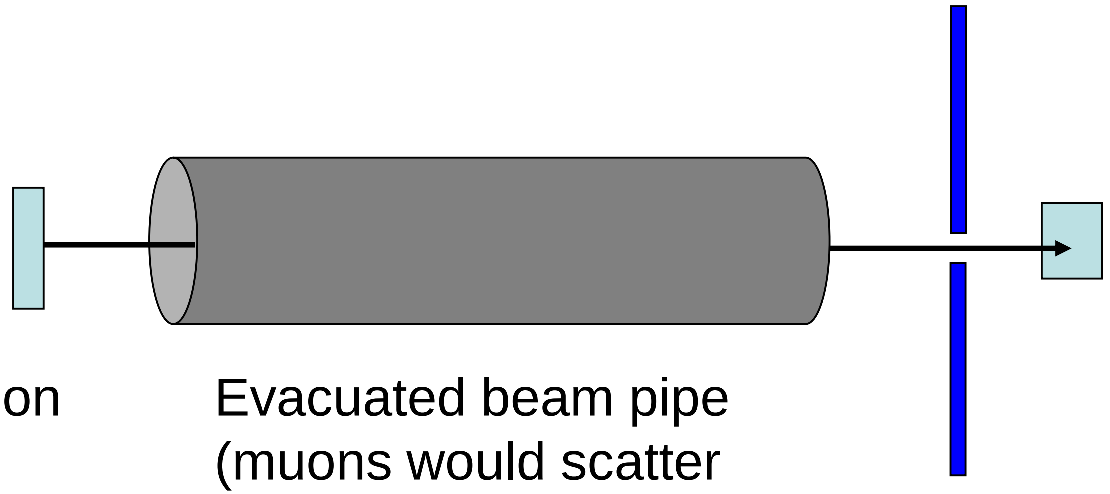
$p_\mu < p_\pi$ High energy

Different pion decays – II

- “Surface” muons from pions at rest (in the target)
  - Muons decay into the beamline
  - Muons collected in one direction are 100% polarized
  - Allows for simple beamline design but limits thickness of windows (and other material) before the sample
  - Final spin polarization >95%
- “Forward” and “Backward” muons from pions in flight
  - Needs a more complicated and lengthy beamline (£/CHF/$/¥)
  - Choice of momentum can be made for experiments allowing pressure cells etc. to be used
  - Negative muons available
  - Final spin polarization ~ 80%

BEAMLINE COMPONENTS

Simplest possible beamline



Sample

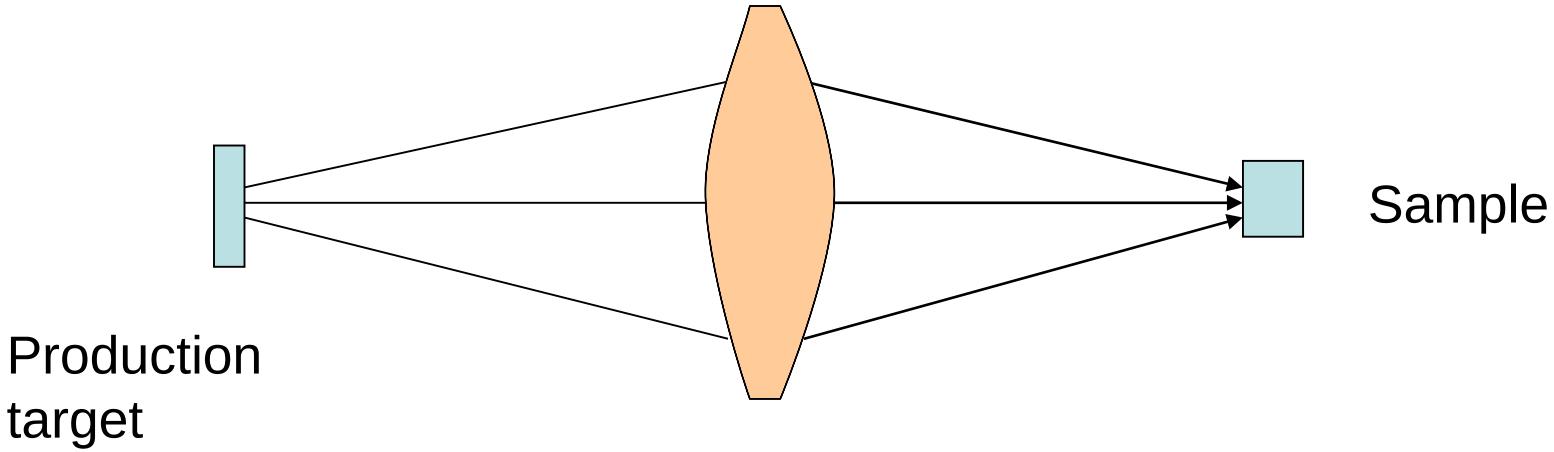
Production target

Evacuated beam pipe (muons would scatter and stop in air)

Slits to define spot

- Main problem – low muon flux
- Other problems – other particles transmitted and high radiation level at the sample

Add focussing

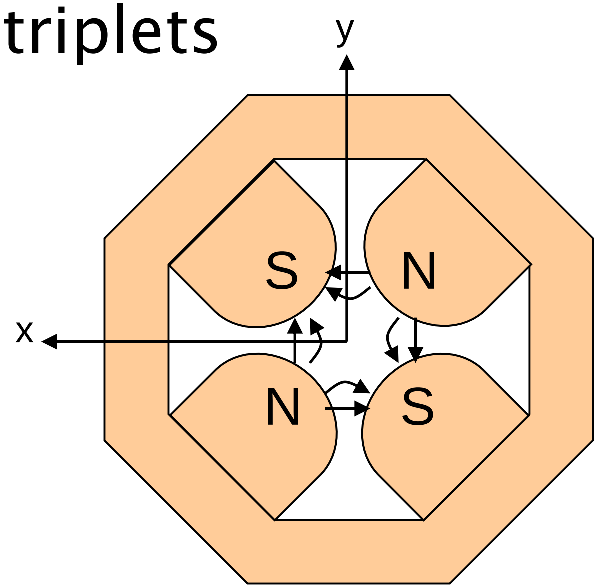


- Really needs more than one lens
  - First lens close to the source to capture large solid angle
  - Last lens close to the sample to give a small beam spot
- Still transmits many other particles – poorly focussed if they have the wrong momentum
- Neutrons still go through
  - Unless blocked on axis

Electromagnetic lenses

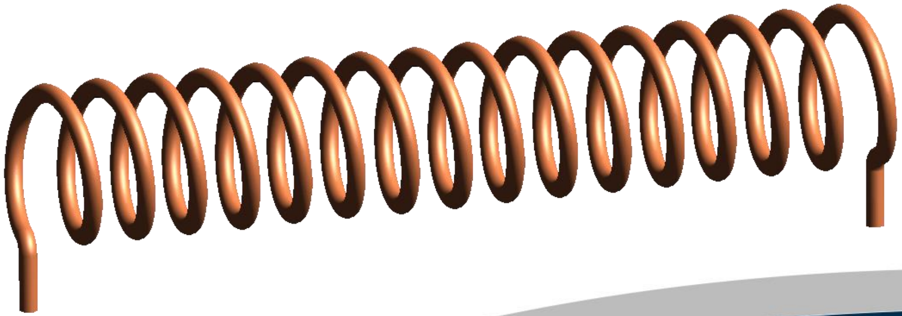
Quadrupoles (£)

- No deflection on axis
- Focussing (x) and defocussing (y)
- Therefore need doublets or triplets

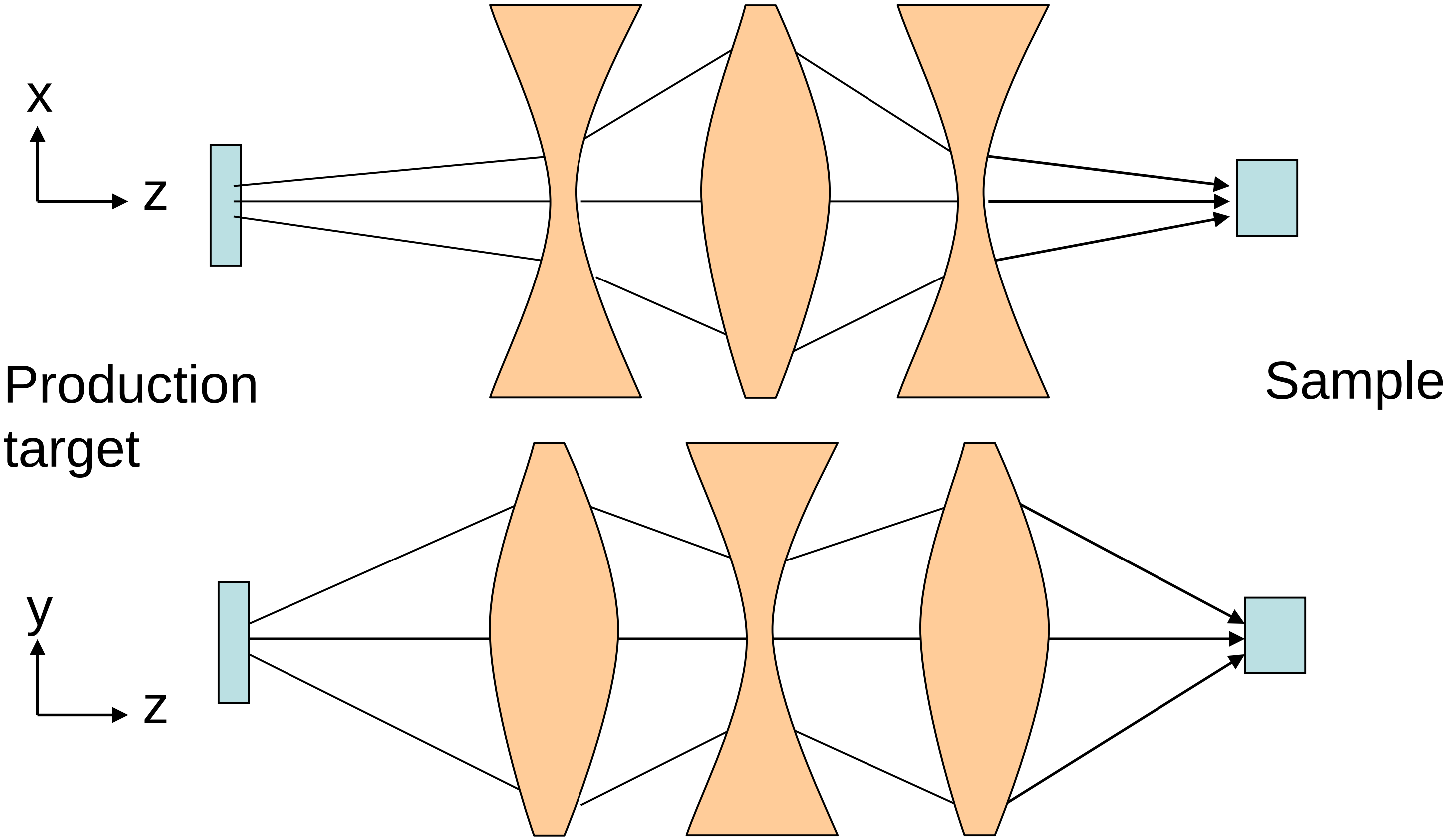


Solenoids (£££)

- Able to focus both axes simultaneously
- Can also be built with bends for steering

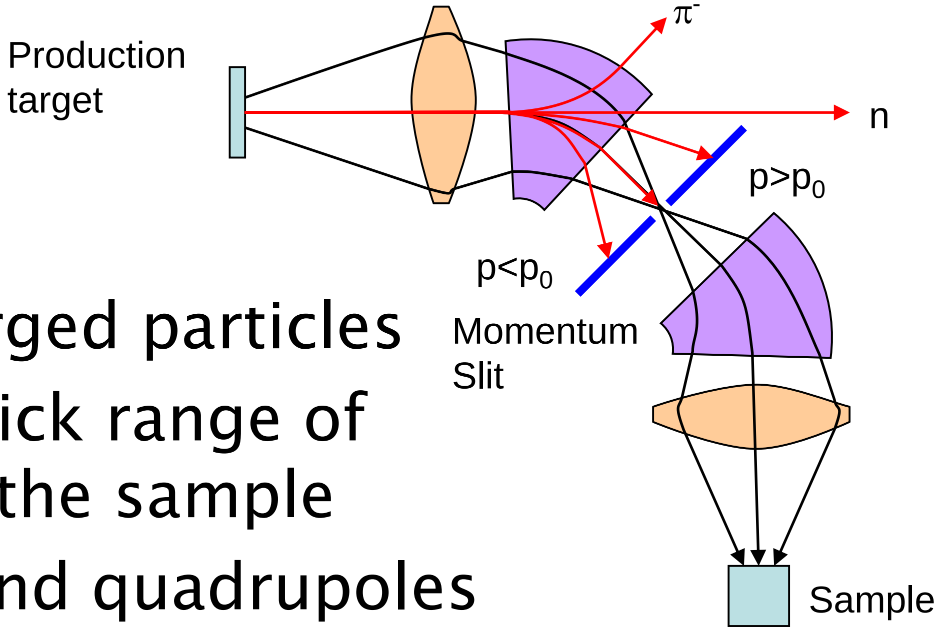


Focussing with quadrupoles



- Doublets give different x and y magnification
- Triplets preserve image shape

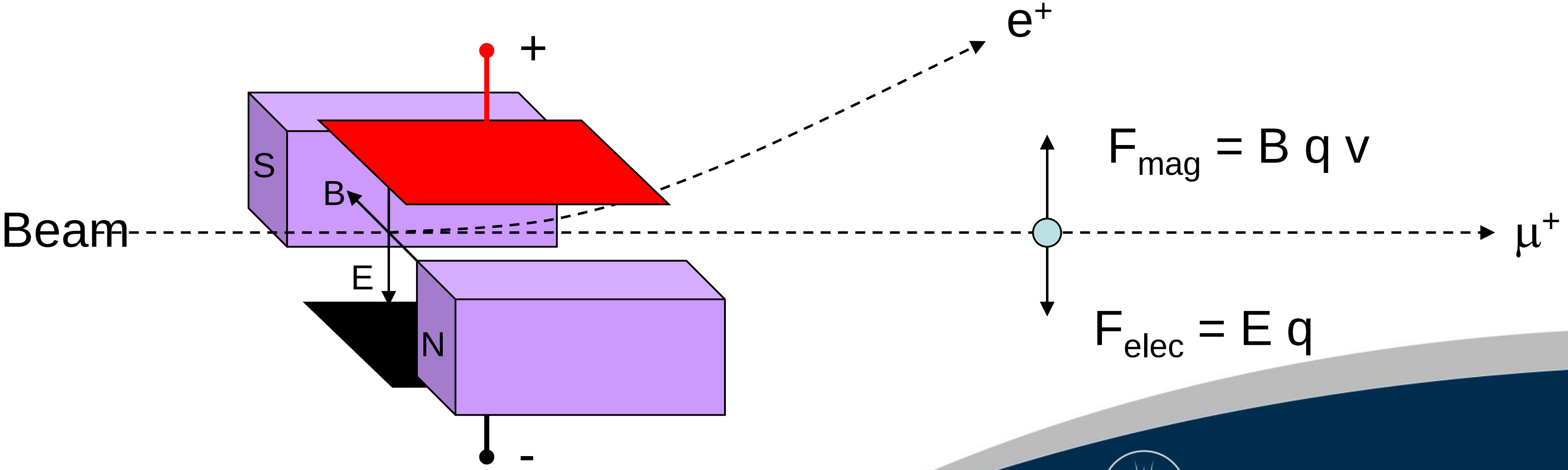
Adding corners



- Use dipole magnets to bend the beam
- Removes wrongly/uncharged particles
- Momentum slit used to pick range of momenta transmitted to the sample
- Combining two dipoles and quadrupoles can give an achromatic beam
- Still lets other particles through if they have the same momentum and charge

Cleaning the beam – Separator

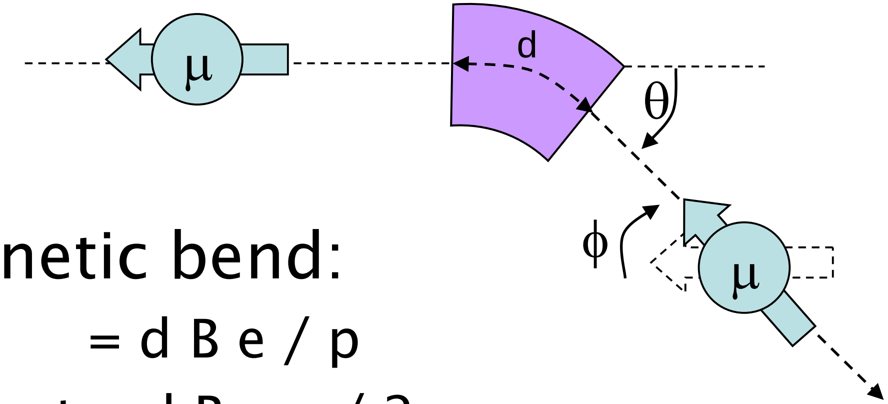
- Magnetic parts of the beamline only select momentum
- Need to separate surface muons (p=27 MeV/c, v=0.24c) from positrons with p=27 MeV/c (but v ≈ c)
- Use perpendicular E and B fields chosen to balance forces for particles with correct velocity



$F_{mag} = B\,q\,v$

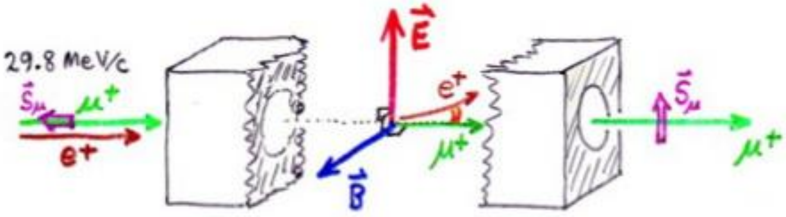
$F_{elec} = E\,q$

Spin rotation – I



- Muons going round a magnetic bend:
  - Deflected by: $\theta = d\,B\,e\,/\,p$
  - Spin precession of: $\phi = B\,\gamma\,t = d\,B\,g\,e\,/\,2p$
  - Exact match for $g = 2.0$, but muon $g = 2.00233$
  - Spin follows momentum unless there are many turns (like muon storage rings used to measure g-2)
- Electrostatic deflection leaves the spin unchanged but rotates the momentum
  - ISIS kicker gives 4° horizontal spin rotation for EMU and HiFi

Spin rotation – II



- A separator with crossed electric and magnetic fields rotates the spin without changing the momentum
  - ISIS separator gives 6˚ rotation (vertical)
- Using higher fields and/or longer path length gives bigger rotation
  - Ideal case is 90˚, but diminishing returns beyond 70˚
  - Useful for higher transverse fields because muons enter the sample along the field direction
  - Rotation of ~45˚ allows simultaneous measurement of longitudinal and transverse relaxation rates

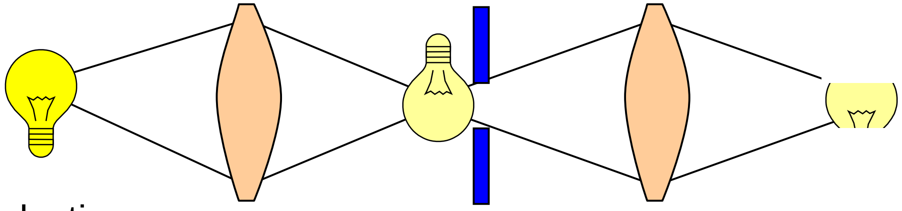
Controlling spot size

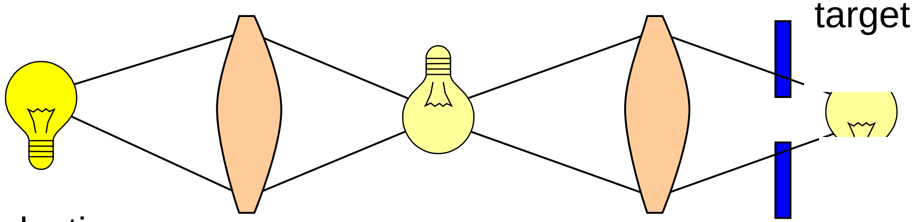
Local collimation

- Lead near instrument
- Need to stop muons and their decay positrons from hitting detectors

Remote collimation

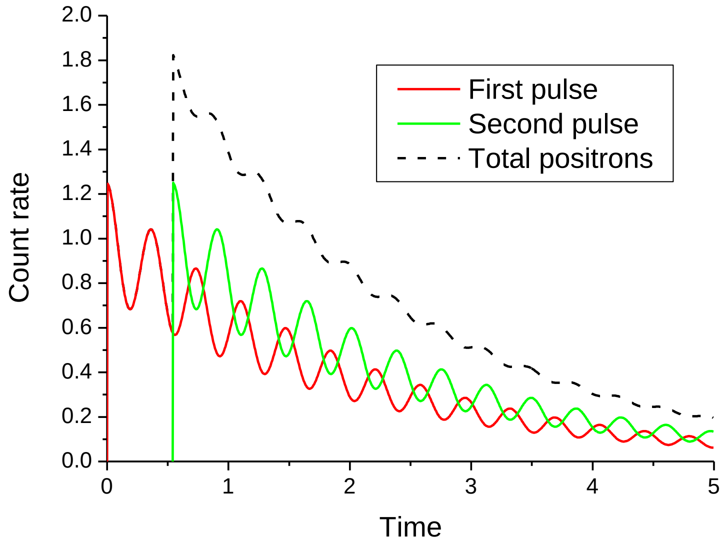
- Metal slits at a focal point earlier in beamline
- Positrons can't reach detectors

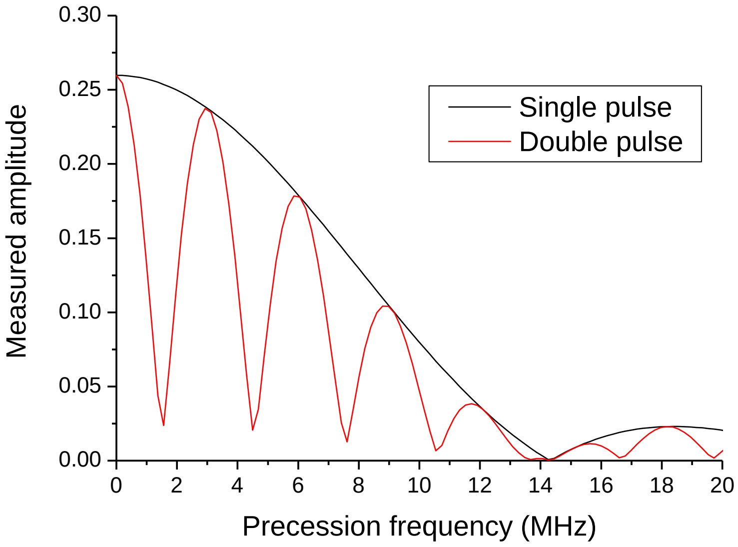




Dealing with pulsed beams

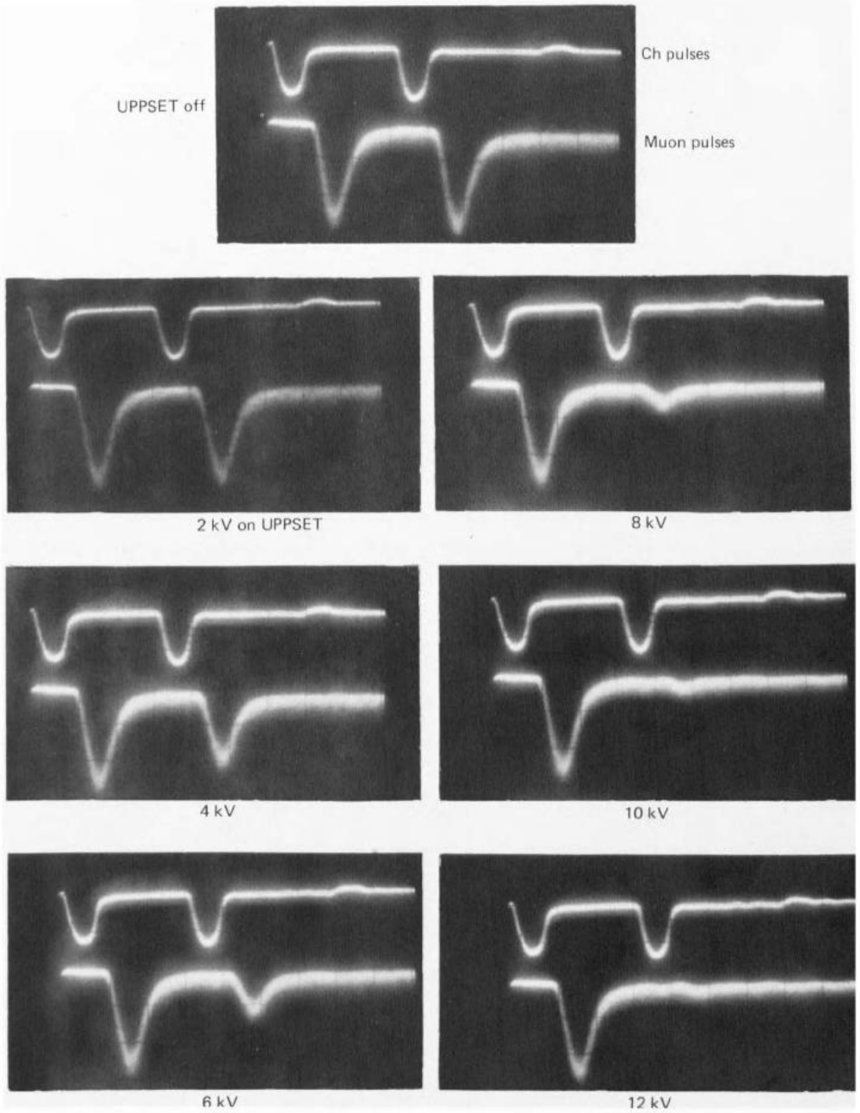
- Synchrotrons like ISIS normally output pairs of proton pulses
  - ISIS separation 330ns @ 50Hz (with 1 pulse in 5 missing)
- Separation normally less than muon lifetime so the spectra overlap, complicating data
- Need to separate pulses





Historical interlude

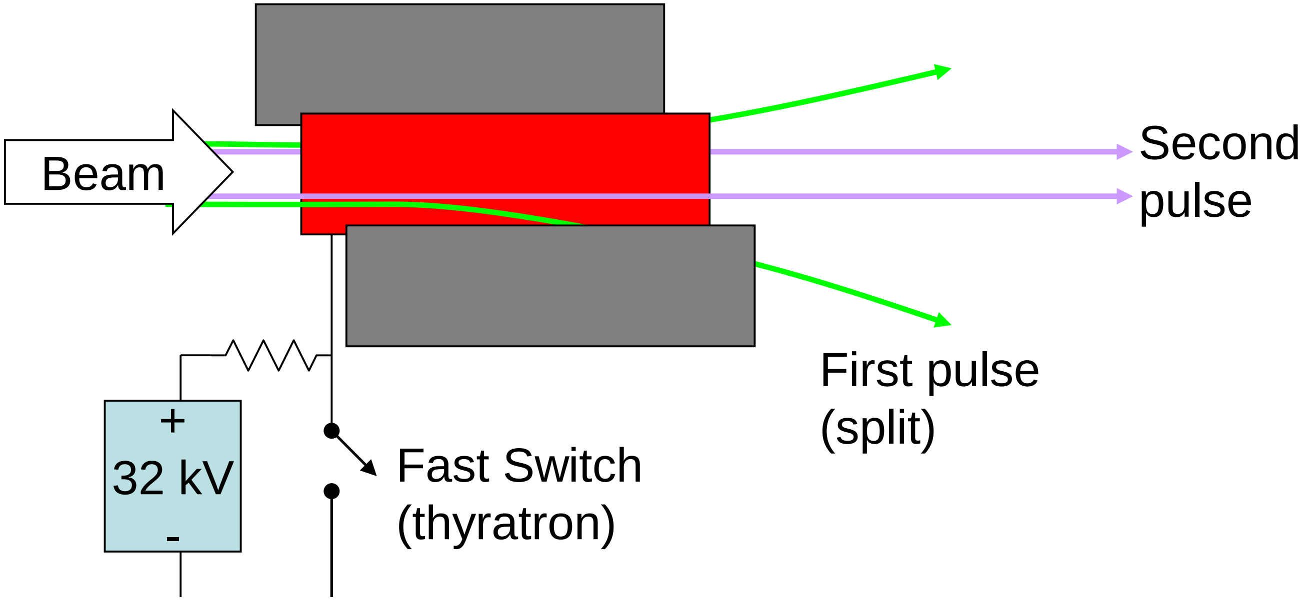
- Simplest way to separate pulses is to discard one
- This is how ISIS first did it (30 years ago)
- Device was called UPPSET (Uppsala, Pulse Eliminator and Trimmer)
- Removed the second pulse before it reached the MuSR instrument (then the only one)

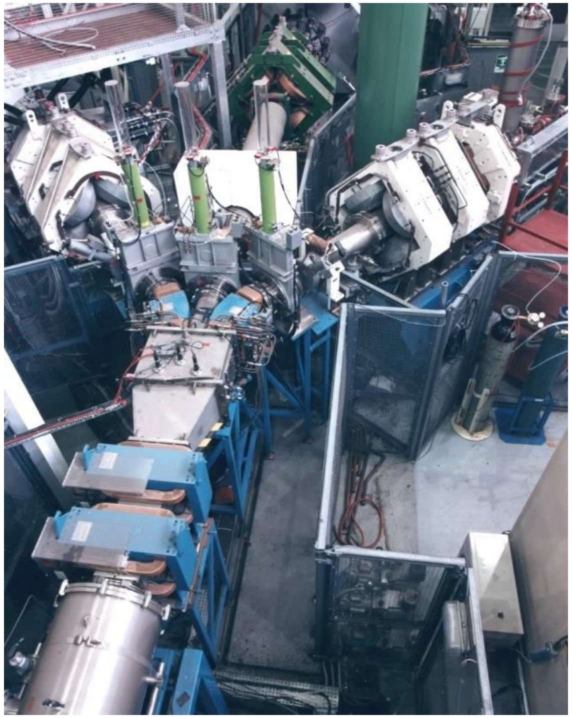


A. I. Borden *et al.*, Nucl. Inst. and Methods A **292**, 21-29 (1990)

A modern kicker

- Why not throw away the pulse into instruments that can use it?



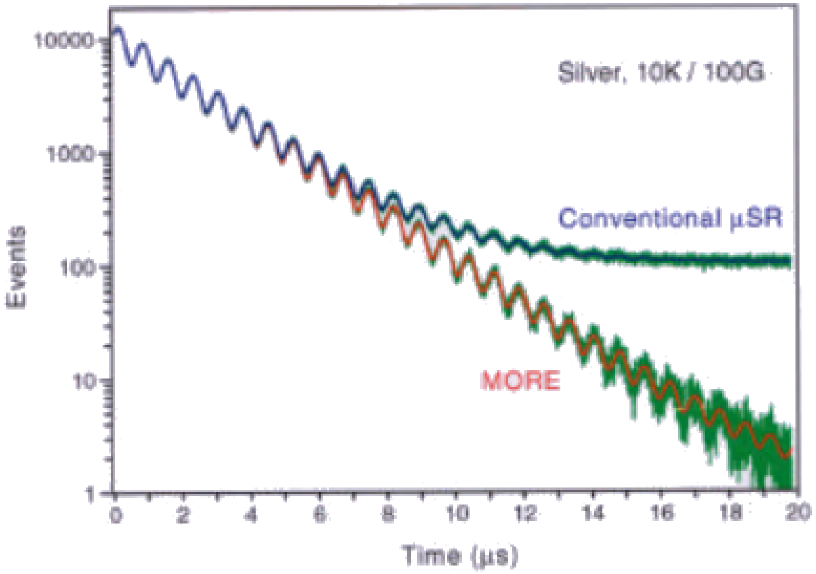


- ISIS south-side kicker is electrostatic
- RIKEN kicker is electromagnetic, better for high momentum muons

Other uses for kickers

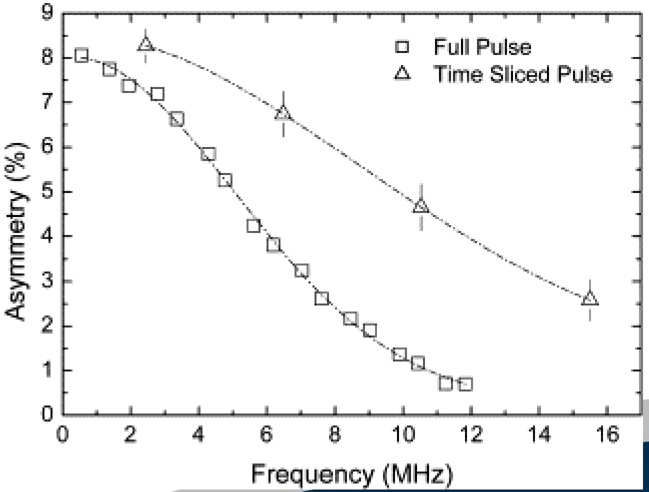
Continuous source: Background reduction

- PSI have the MORE (muons on request) system to reduce background counts



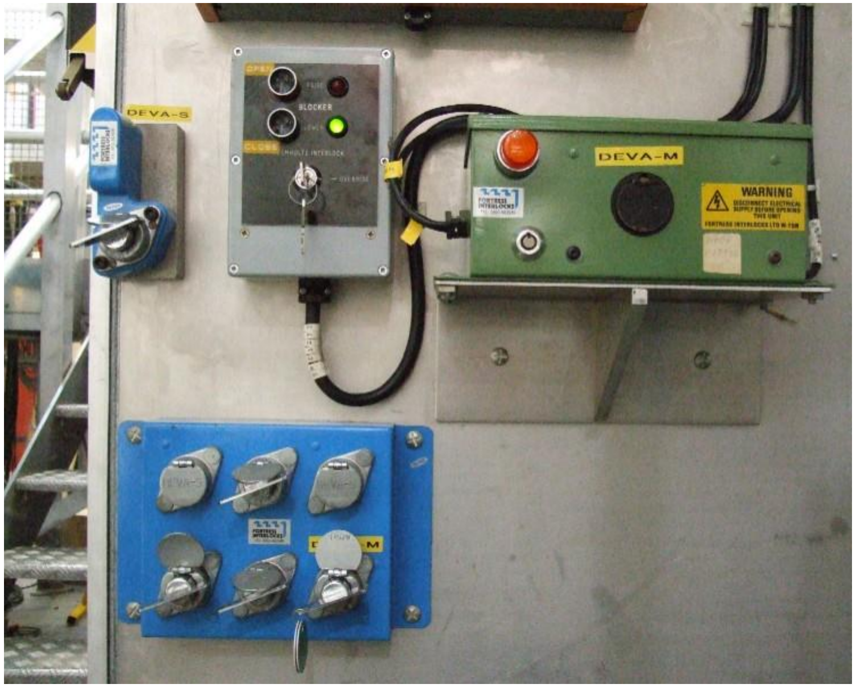
Pulsed source: Increased frequency resolution

- ISIS and later J-PARC have demonstrated pulse slicing to narrow the muon pulses



Shutters for muons

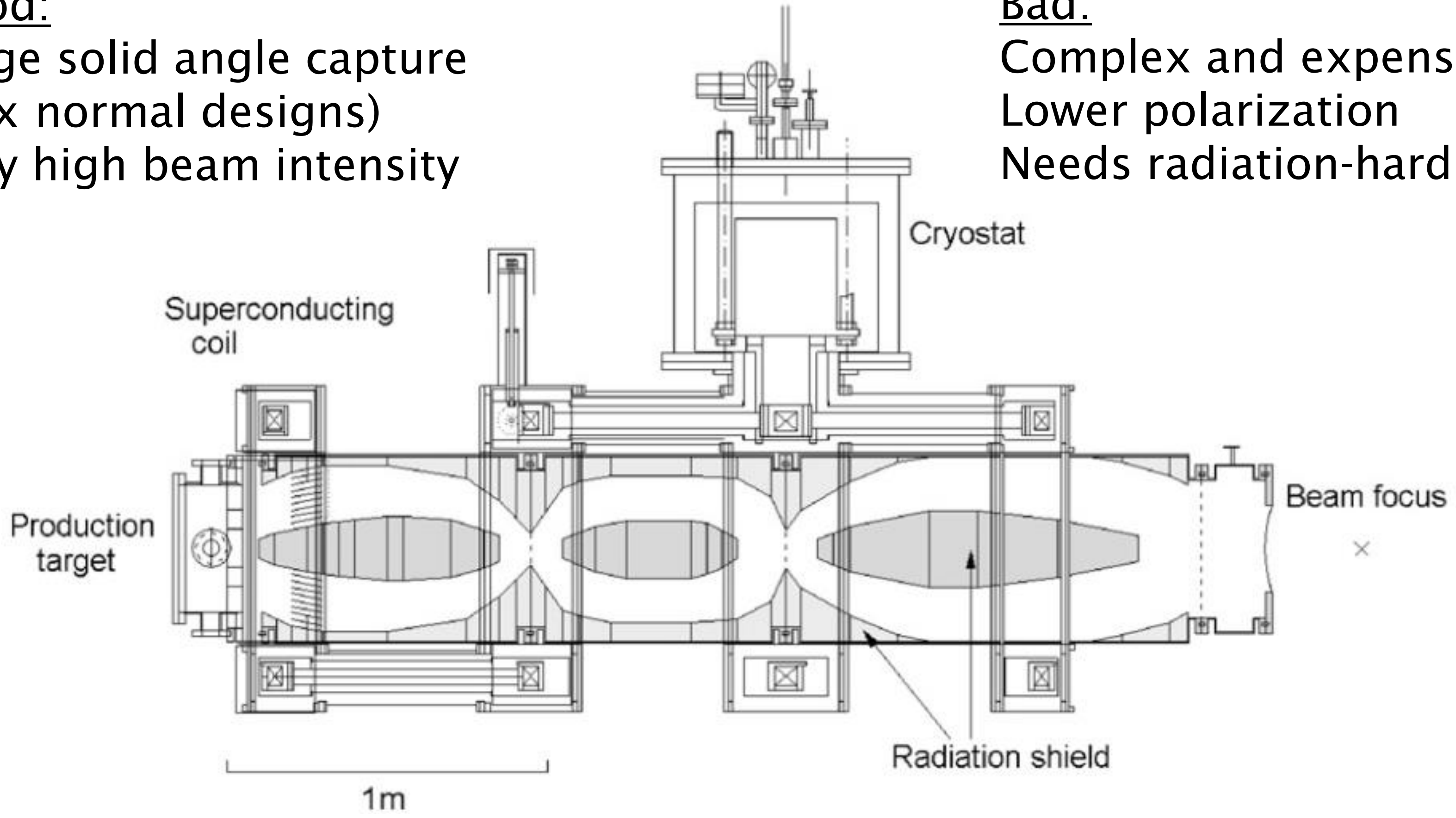
- Being able to stop the muon beam is quite important
  - Safe sample changes
  - Not switching off the accelerator frequently
- Surface muons stopped by 5cm lead plates
  - Neutrons need ~1m of steel
- Also have interlock systems to prevent people meeting muons



Dai-Omega beamlines

Good:
Large solid angle capture
(20x normal designs)
Very high beam intensity

Bad:
Complex and expensive
Lower polarization
Needs radiation-hard SC



e.g. H. Miyadera et al.,
Nucl. Phys. B **149**, 351-353 (2005)

PUTTING IT ALL TOGETHER

Beamlines for decay and surface muons

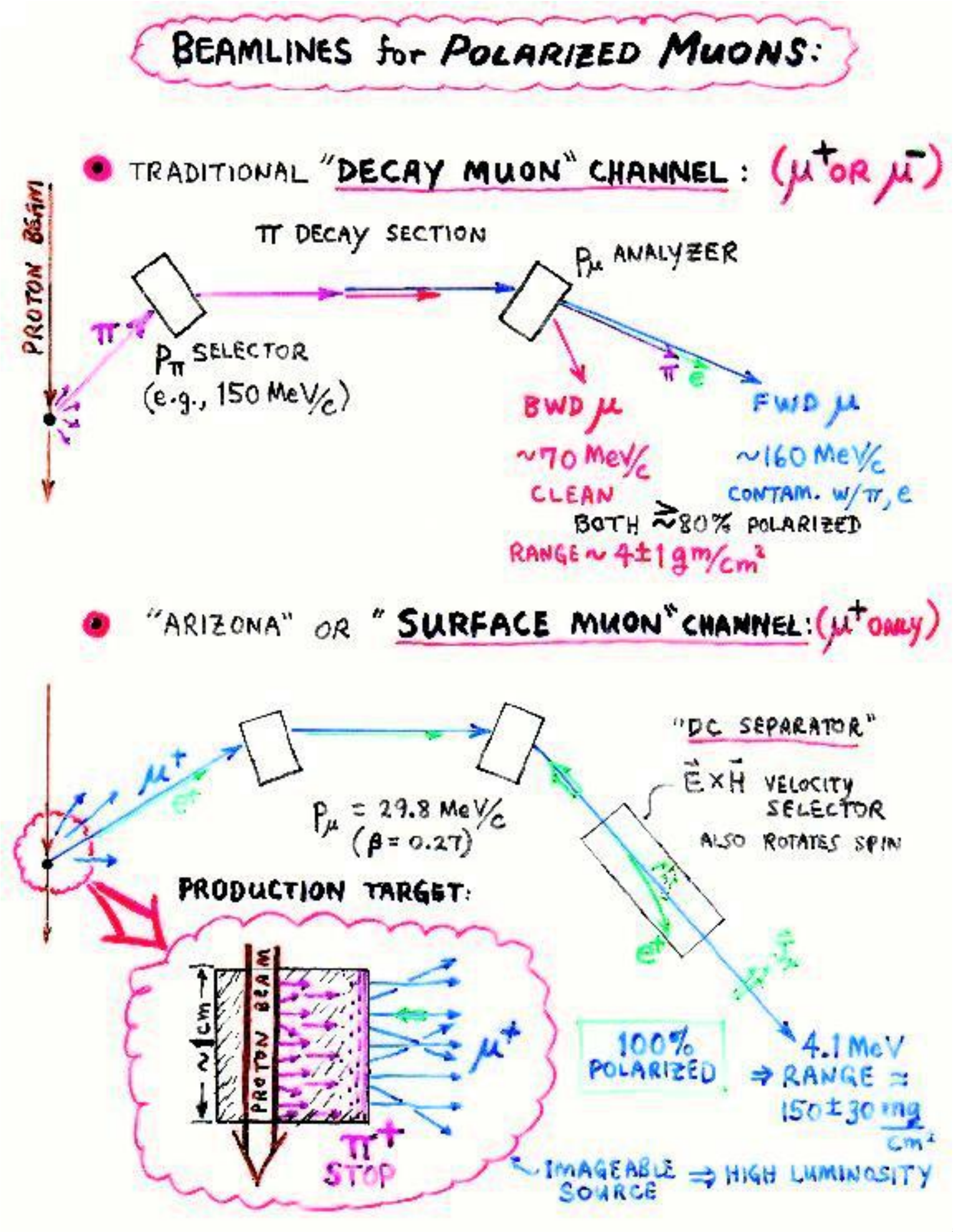
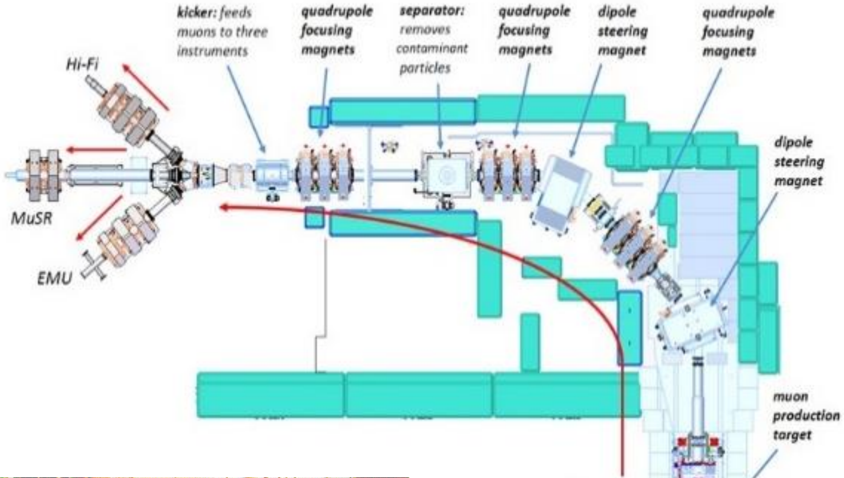
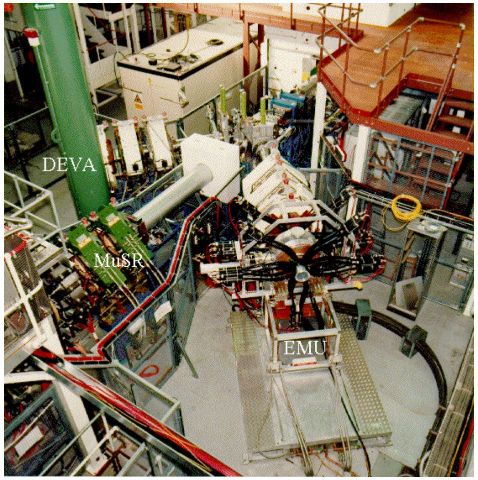


Figure from Jess Brewer

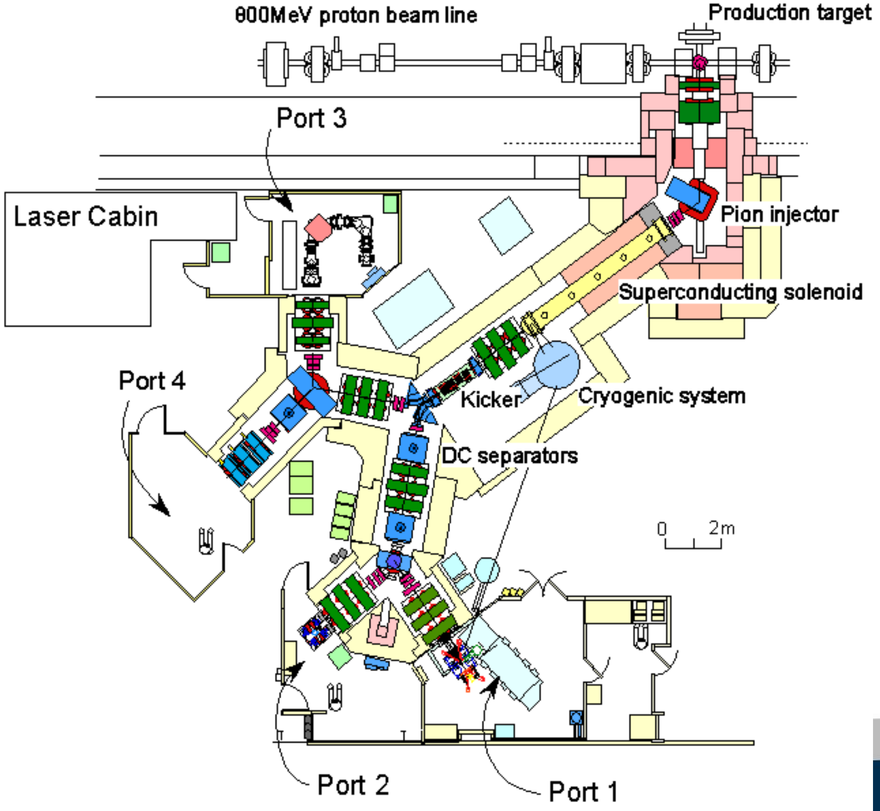
Examples from ISIS

South side (Surface muons only)



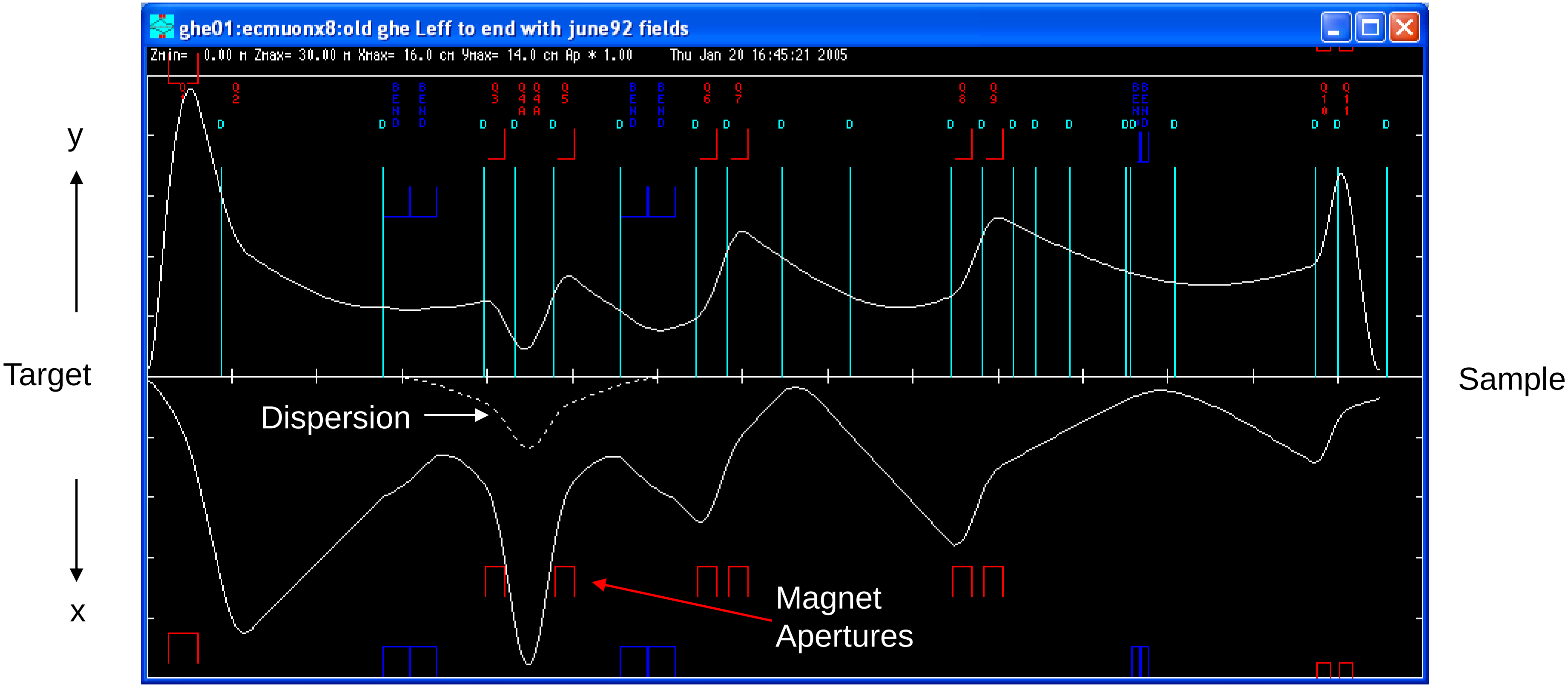


North side (Surface/decay muons)



PLANNING AND DESIGNING BEAMLINES

Designing a beamline – I

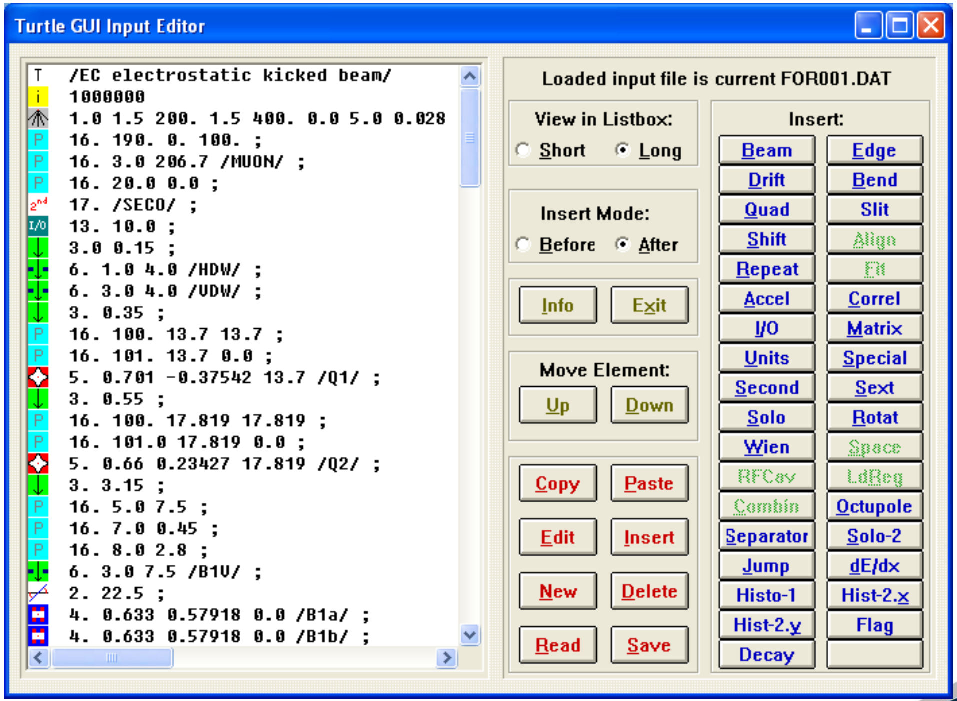


```
ghe01:ecmuonx8:old ghe Leff to end with june92 fields
Zmin=  0.00 m Zmax= 30.00 m Xmax= 16.0 cm Ymax= 14.0 cm Ap * 1.00      Thu Jan 20 16:45:21 2005
```

- Use a program such as TRANSPORT to calculate focussing effect of elements – fairly quick calculation
- Plots beam envelope along beamline

Designing a beamline – II

- Use a ray-tracing program such as TURTLE to work out paths of individual muons
- Slower calculation but more realistic and able to provide flux at sample and where other muons stop

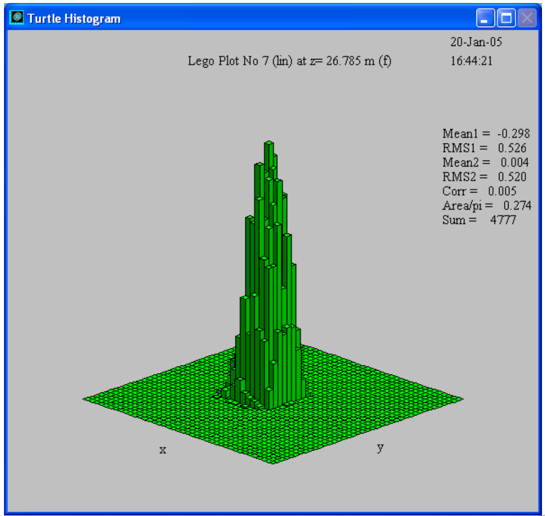


```
T   /EC electrostatic kicked beam/
i   1000000
    1.0 1.5 200. 1.5 400. 0.0 5.0 0.028
P   16. 190. 0. 100. ;
P   16. 3.0 206.7 /MUON/ ;
P   16. 20.0 0.0 ;
2nd 17. /SECO/ ;
I/O 13. 10.0 ;
    3.0 0.15 ;
    6. 1.0 4.0 /HDW/ ;
    6. 3.0 4.0 /VDW/ ;
    3. 0.35 ;
P   16. 100. 13.7 13.7 ;
P   16. 101. 13.7 0.0 ;
    5. 0.701 -0.37542 13.7 /Q1/ ;
    3. 0.55 ;
P   16. 100. 17.819 17.819 ;
P   16. 101.0 17.819 0.0 ;
    5. 0.66 0.23427 17.819 /Q2/ ;
    3. 3.15 ;
P   16. 5.0 7.5 ;
P   16. 7.0 0.45 ;
P   16. 8.0 2.8 ;
    6. 3.0 7.5 /B1V/ ;
    2. 22.5 ;
    4. 0.633 0.57918 0.0 /B1a/ ;
    4. 0.633 0.57918 0.0 /B1b/ ;
```

Loaded input file is current FOR001.DAT

View in Listbox: ○ Short ● Long

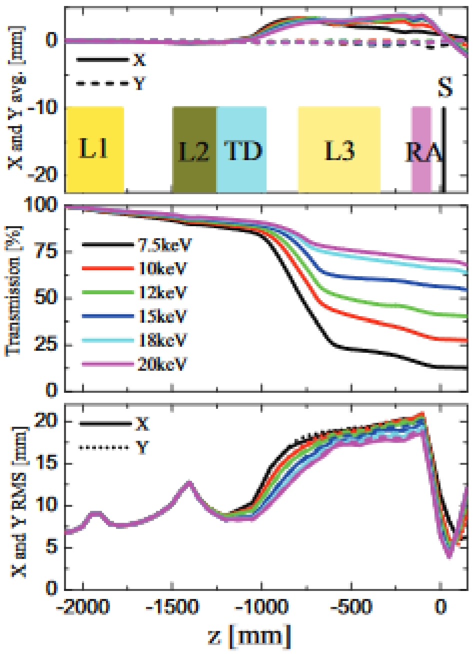
Insert Mode: ○ Before ● After



Mean1 = -0.298
RMS1 = 0.526
Mean2 = 0.004
RMS2 = 0.520
Corr = 0.005
Area/pi = 0.274
Sum = 4777

Designing a beamline – III

- Monte-Carlo simulation programs such as GEANT4 can calculate beam transport too
- Most computationally intensive
- Best suited to modelling individual components or special cases



e.g. Modelling of PSI LEM beamline and implementing a spin rotator

Z. Salman *et al.*, Phys. Procedia **30**, 55 (2012)

BEAMLINE MONITORING

How to monitor your beamline

In the beamline itself

- Ideal case (£££) is measuring beam profile at several points
- Normally have some intermediate counters on slits or other apertures
- Tuning the beamline magnet currents and E-fields to see what comes out is most common way to work out how optimal the set-up is

At the instrument

- How many muons come out?
  - On big plate/small sample
- What shape is the beam?
  - Camera or reference samples
- How far do the muons penetrate?
  - Stopping in metal foils in front of haematite or quartz
- How big is the signal as a function of frequency?

These are routine activities at muon facilities

FUTURE POSSIBILITIES

How to do things better?

Pulsed sources

- Higher pulse frequency (~20kHz ideal vs ~50Hz)
- Pulse slicing to increase frequency resolution
- Higher solid angle beam capture for higher flux

Continuous sources

- Higher fluxes could give very small beam sizes for tiny samples (< mm)
- Tracking muons and positrons could beat the ‘1 muon at a time’ limit

Accelerators

- FFAGs and LINACs may provide better sources for muon production in future

Conclusions

- There are plenty of muons in the sky but you need a huge sample to use them
- Different sorts of particle accelerator are best suited to different sorts of muon experiment
- Transporting muons is well-understood and computer simulation can aid beamline design
- Plenty of scope for future improvements!