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ISIS Neutron and Muon Source

ISIS Muons Update (The Secret Diary of ISIS Muons, Aged 35½)

Peter Baker

Plan of talk

- ISIS Muons today
- Recent work
- Forthcoming developments
- Muons at ISIS-II

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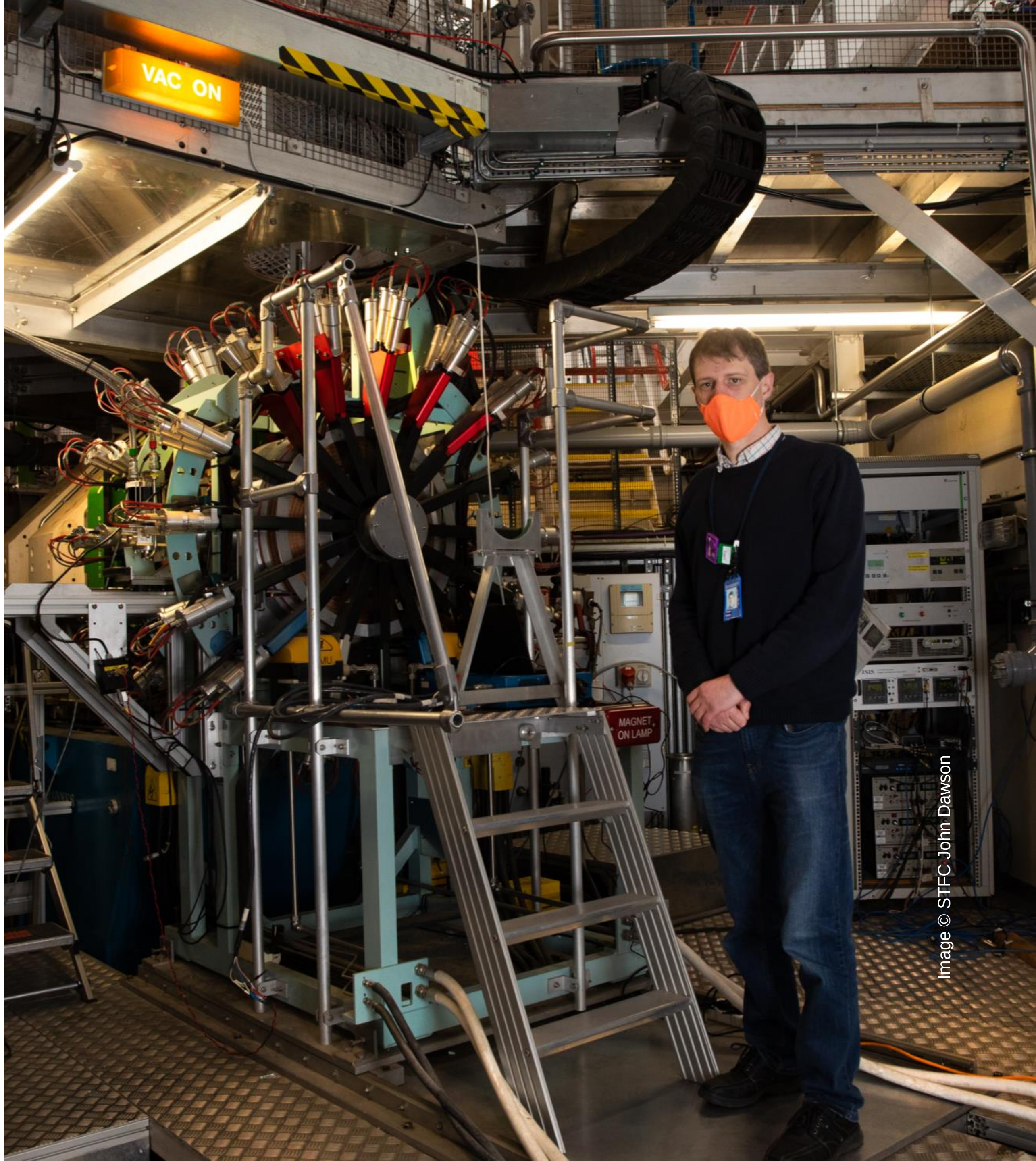
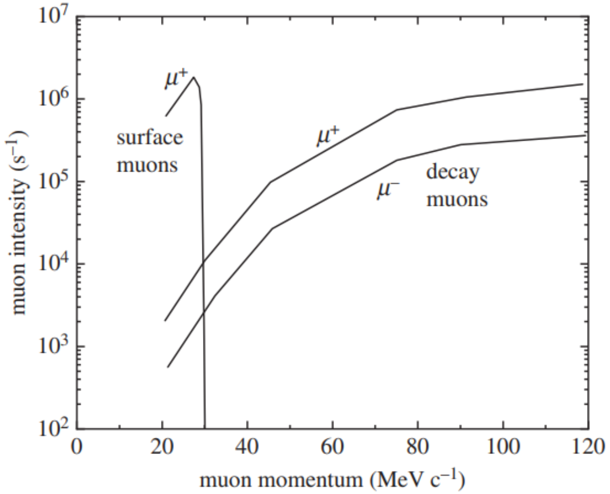
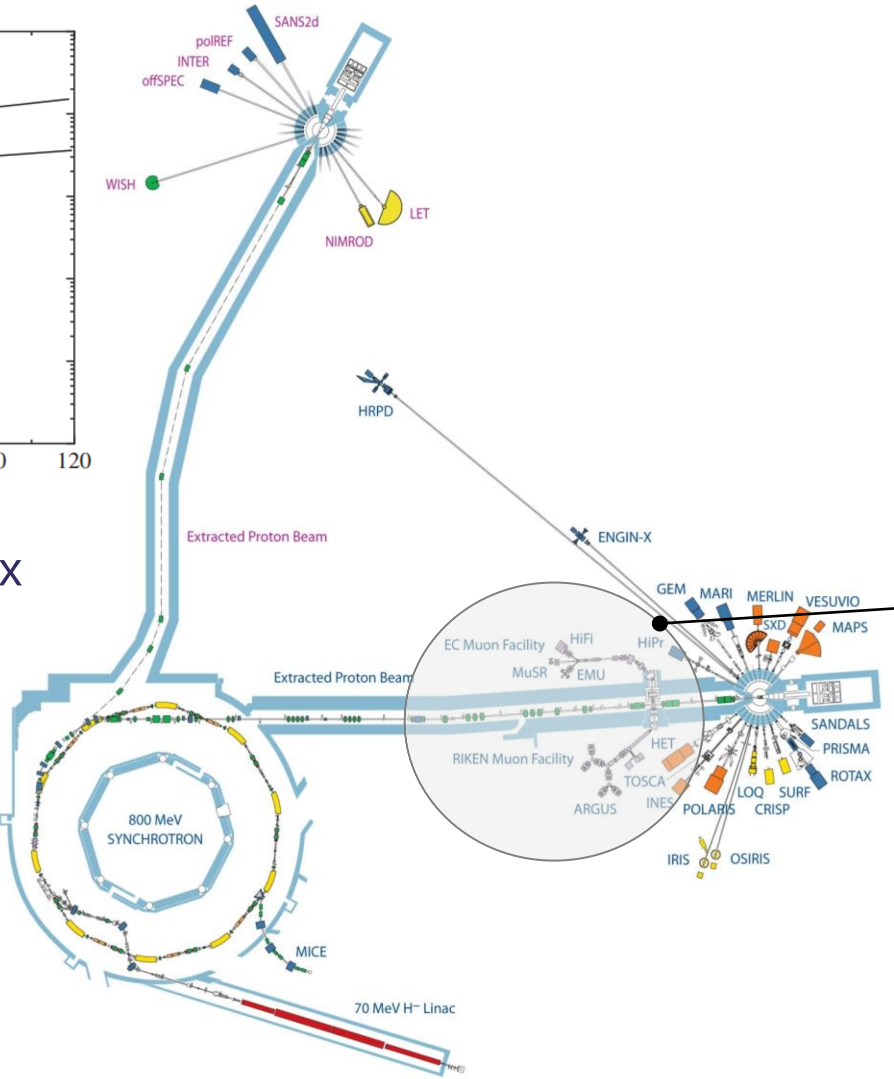


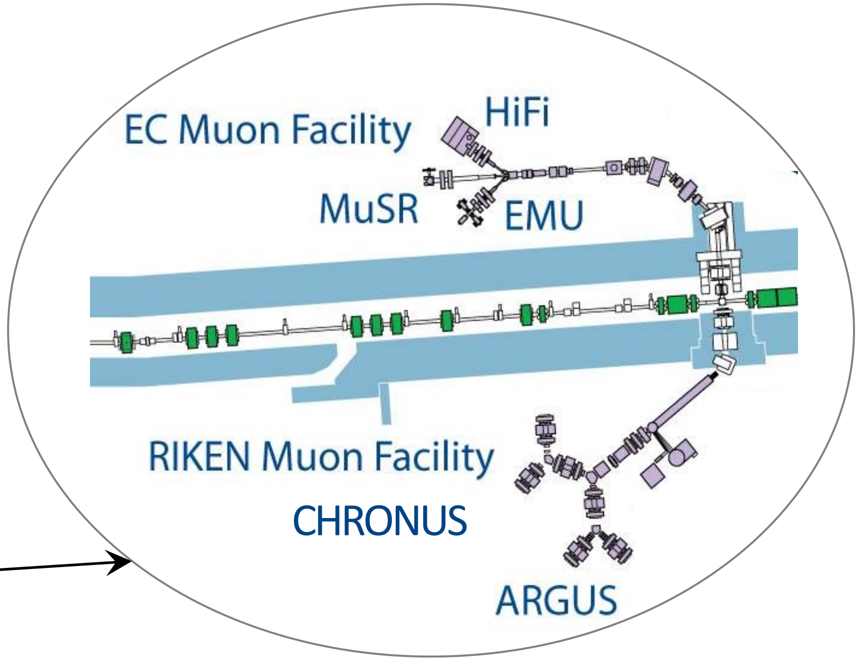
Muons at ISIS

Hillier et al, 2019 Muons at ISIS. Phil. Trans. R. Soc. A 377: 20180064.



RIKEN-RAL muon flux





EC Muons Surface muon beamline

μ+ only ~28 MeV/c

Flux at instruments ~ $2x10^6$ total

RIKEN-RAL: Decay channel

μ+ or μ- 15 – 90 (120) MeV/c

Flux at instruments (see left)

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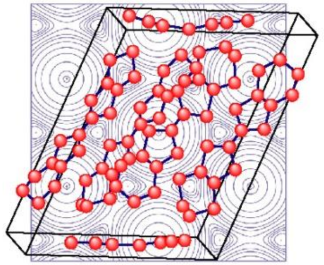
Science with ISIS muons

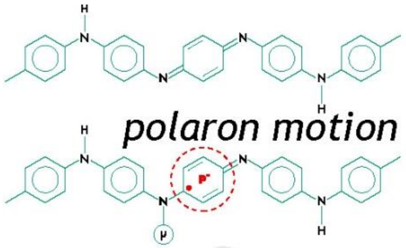
Passive probes of superconductors, magnets, molecular dynamics, charge transport

Active probes of semiconductors, proton conductors, light particle diffusion in metals

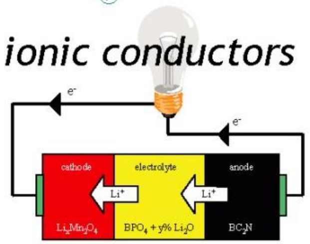
superconductors



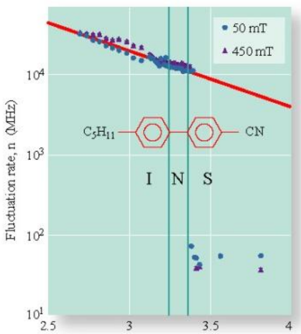
polaron motion



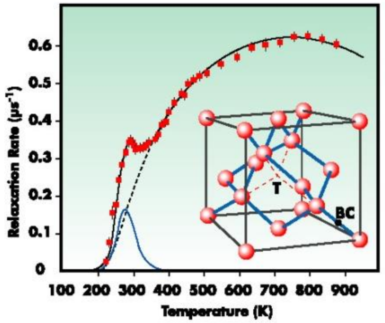
ionic conductors



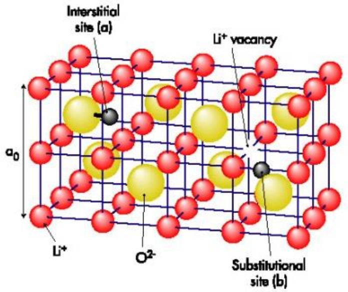
molecular dynamics



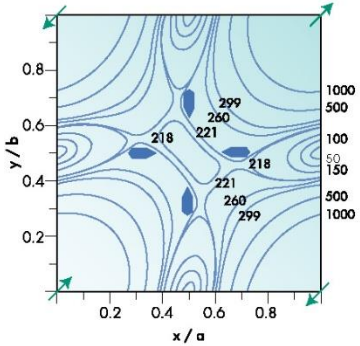
semiconductors



proton conductors



magnetism



Electronic irradiation

Elemental Analysis

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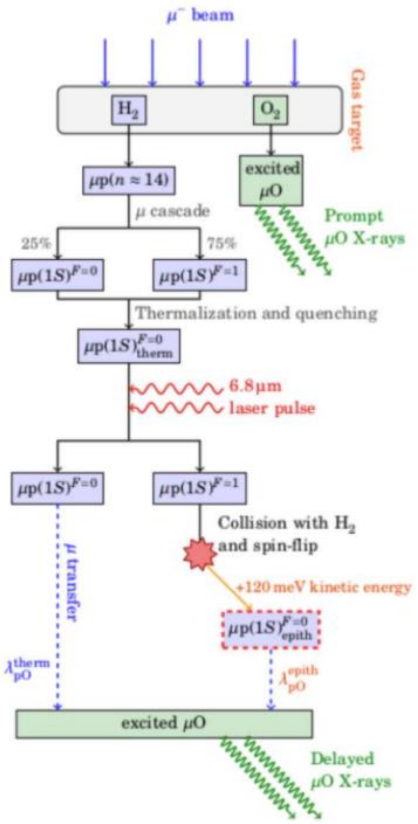
Recent additions to science programme

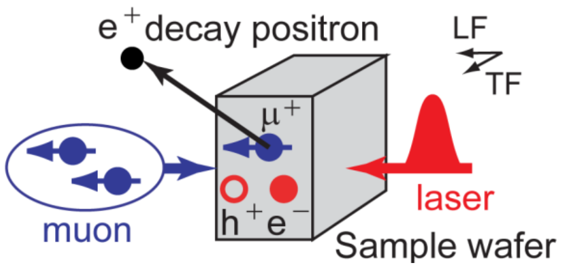
FAMU experiment

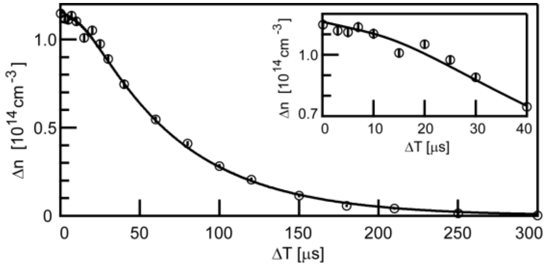
- Determining proton Zemach radius using hyperfine splitting in muonic hydrogen
- About to start data collection
- Led by A. Vacchi (INFN and Udine)



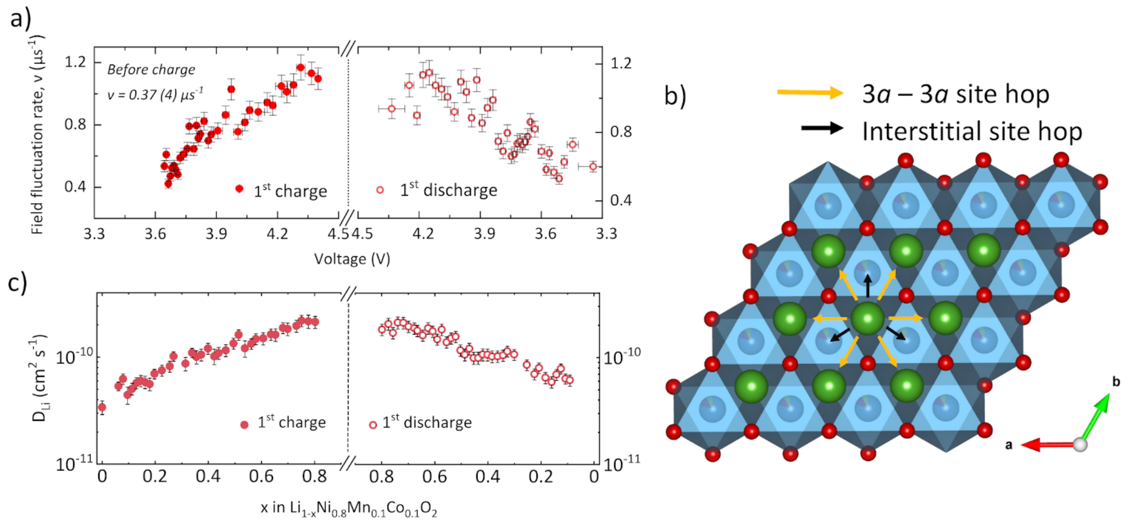
Energy materials developments

- Photoelectron dynamics in Si





- Li⁺ motion in cell during cycling



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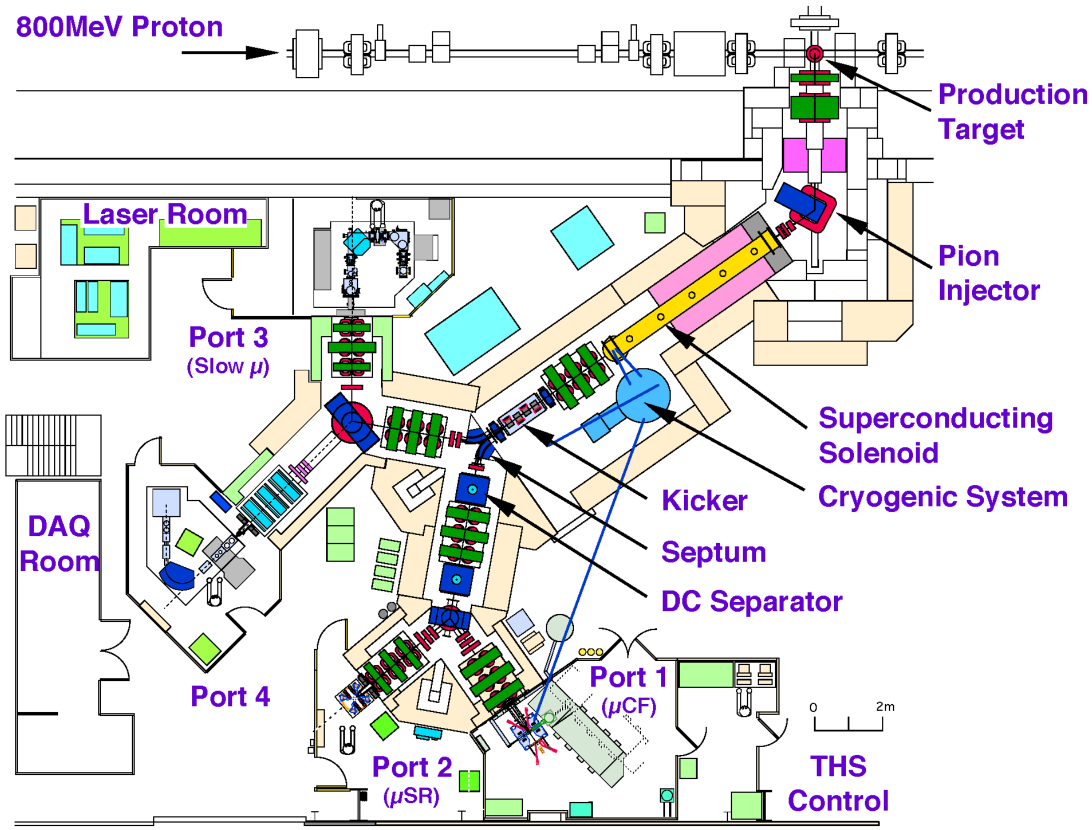
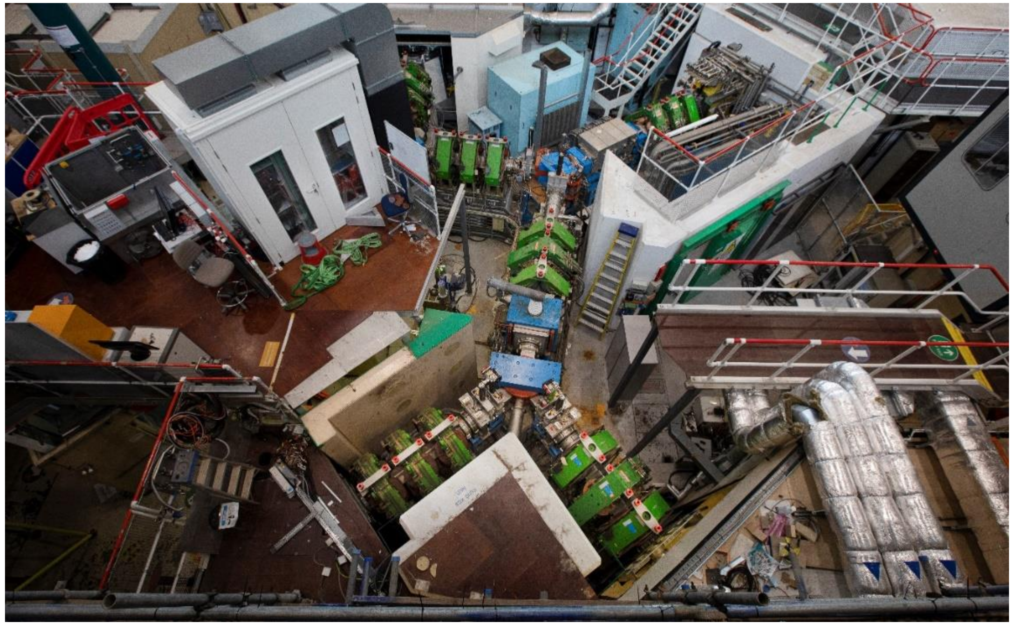
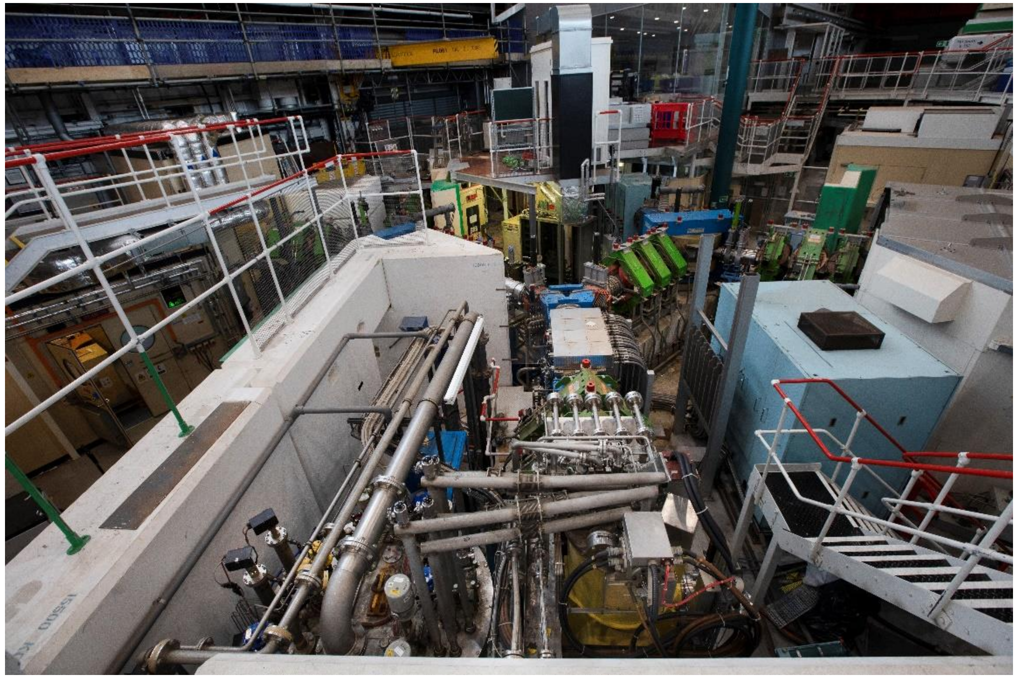
Future of RIKEN-RAL muon beamlines

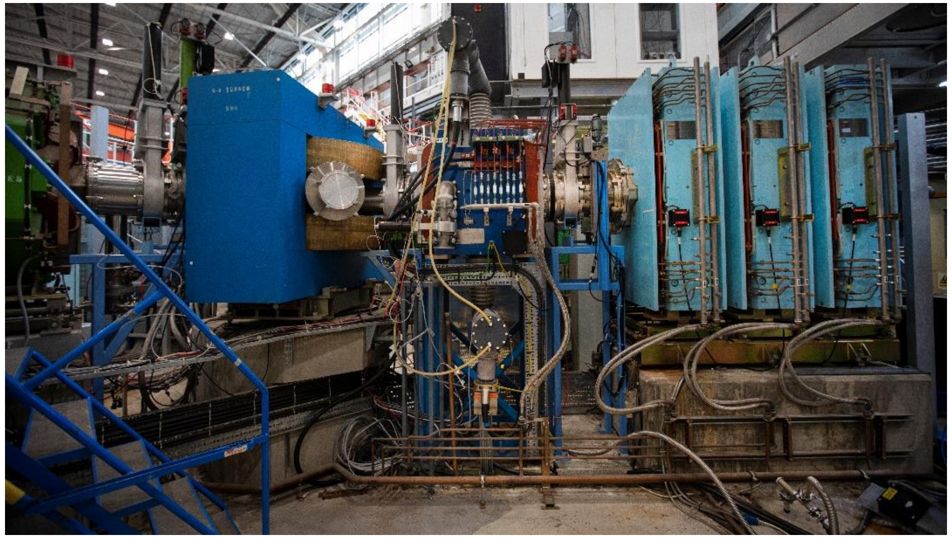
- Refurbished during present ISIS long shutdown
  - Cooling water
  - Power supplies
  - Vacuum
  - Sample Environment
  - Instruments
- Plan to replace
  - Solenoid
  - Front end quadrupoles
  - Additional slits



Refurbishment work







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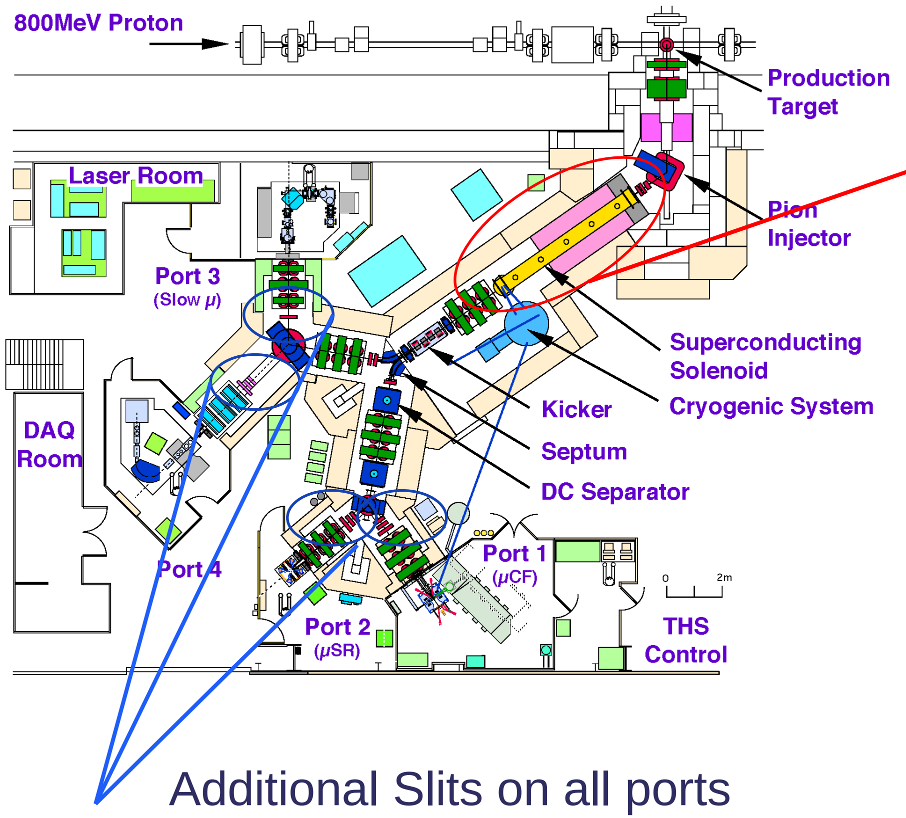
RIKEN Future Projects



Replace Solenoid

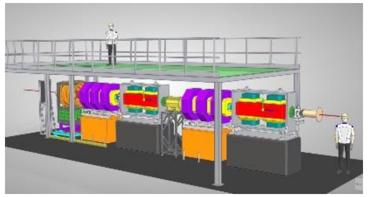
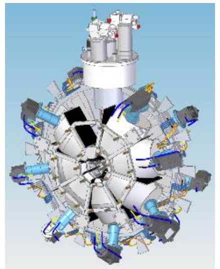
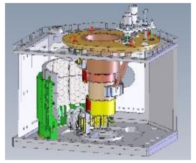
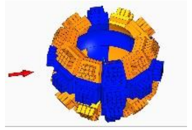
- Feasibility study complete
- Cryogen-free option
- Big reduction in support and power consumption

Additional Slits on all ports

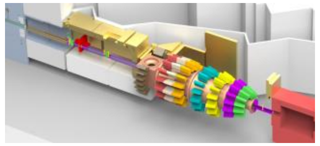
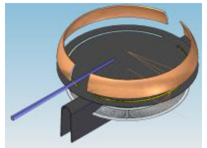
- Better beam spot definition
- Reduced background from the lead collimator

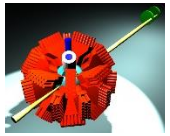
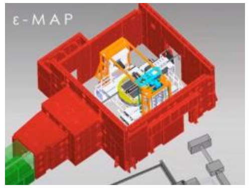
ISIS Endeavour programme

- Programme of 9 new or upgraded instruments
- Going through Government-level financial approval process
- Hope to formally start projects next financial year
- Upgrade to MuSR beamline and instrument hopefully starting immediately after approval

ENDEAVOUR
INSTRUMENTATION FOR THE FUTURE

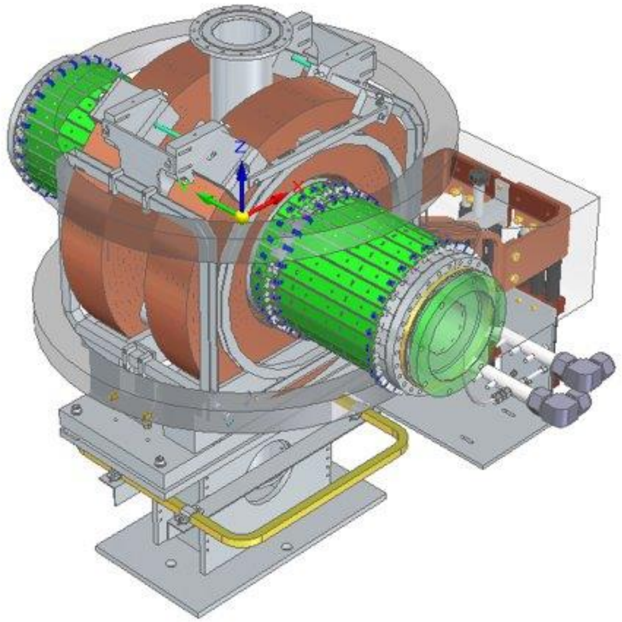



Super-MuSR

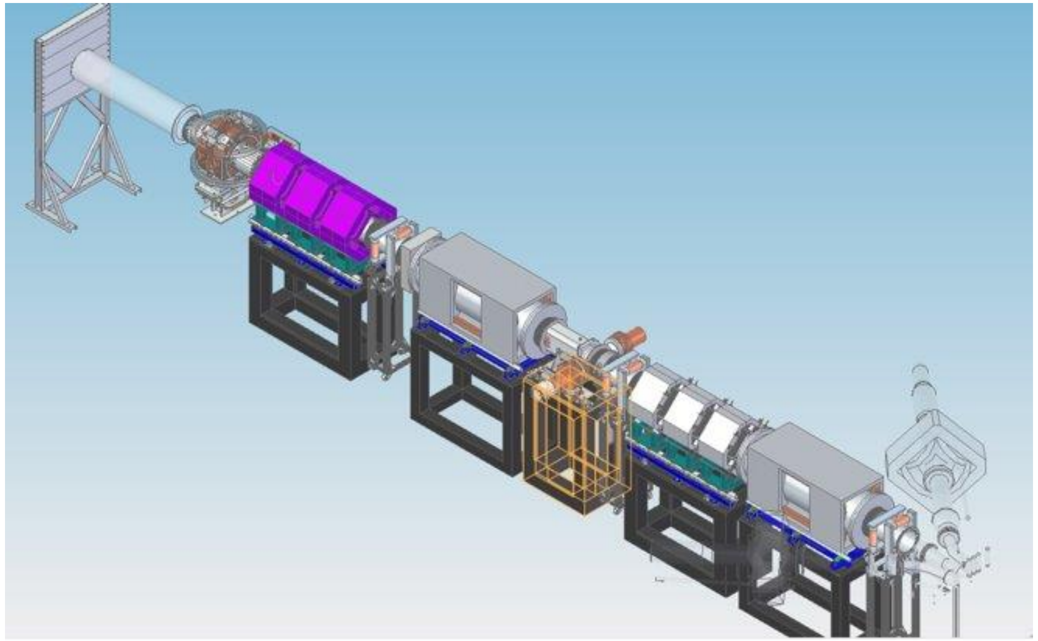
Instrument improvements for 20x rate improvement

- Use full muon flux and maximise information per muon
- New transverse magnet and cruciform with flypast tube



Beamline improvements to improve time resolution >10x

- Pulse slicing reduces uncertainty in muon arrival time
- Spin rotators allow higher fields for superconductor experiments



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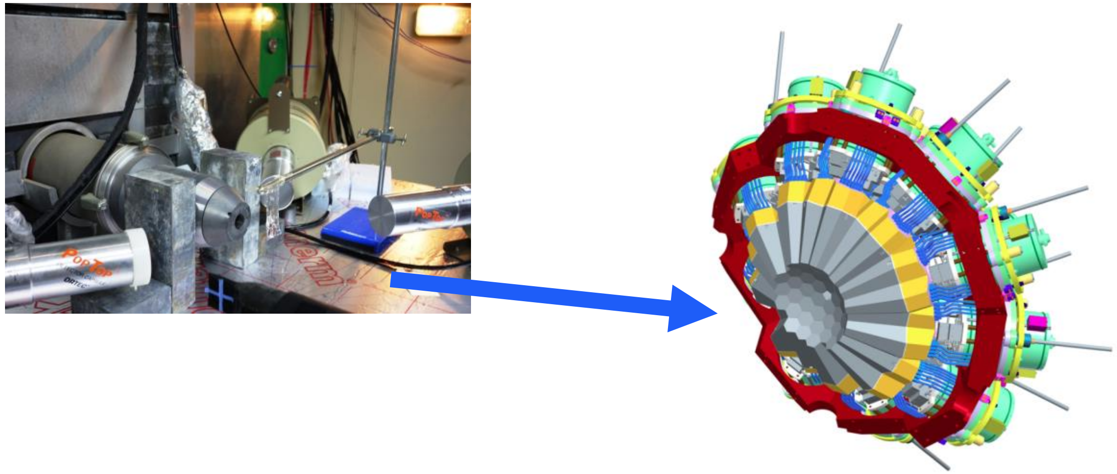
Upgrades beyond Endeavour

MuX: Elemental analysis



The AGATA 1π array. Drawing made by STFC Daresbury in ~2008.

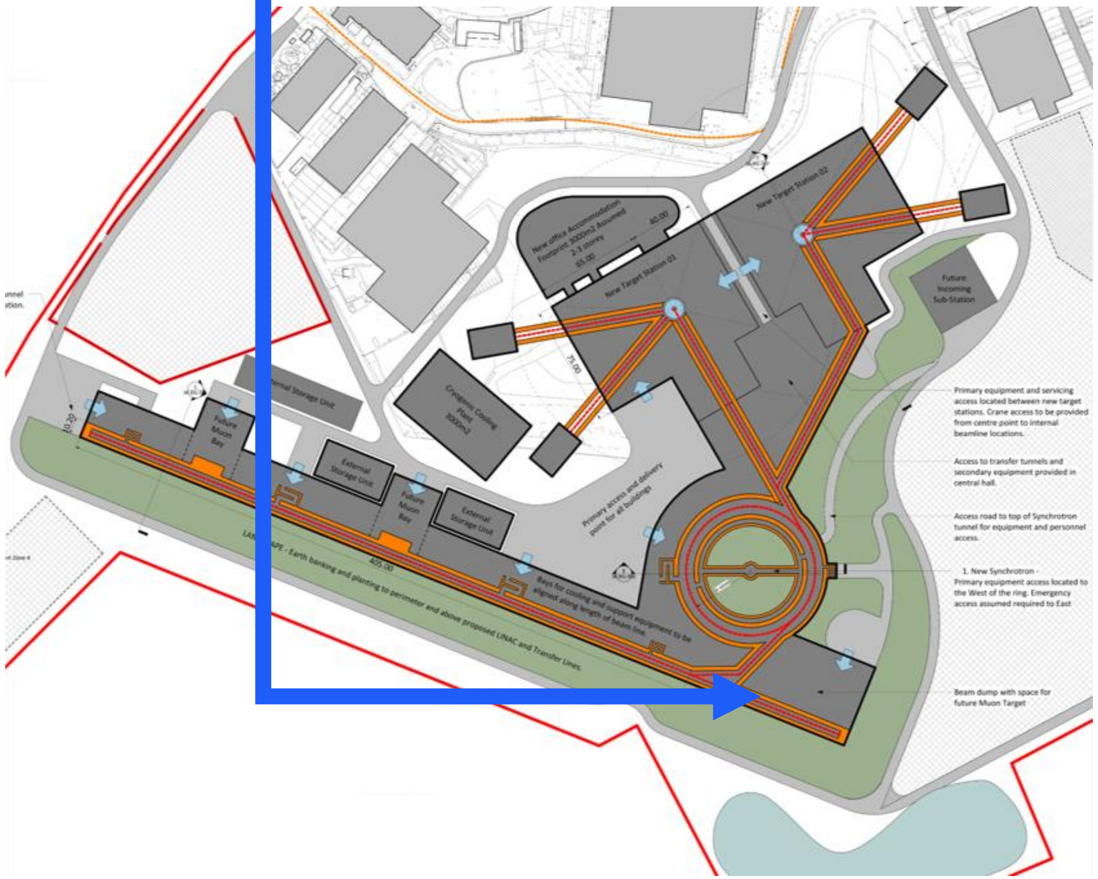
- Big cultural heritage programme using negative muons
- Huge opportunities with better instrumentation

Upgrading existing instruments

- Super-MuSR detector electronics can give 2-3x improvements on other instruments
- ‘Super-EMU’:
  - Bending beam to reduce spot size at sample position
  - Possibly another pulse slicer

Muons at ISIS-II

- ISIS making plans for ISIS-II (Dean Adams’ talk)
- Development work already funded
- Muon production within the plan and already exploring options
- Opportunities for new science with a more powerful and better optimized muon source



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What do we want? Muons!

Spin-polarized (>95%) μ^+, E~4MeV

- Most of present science programme
- Instrumentation well-established

Unpolarized μ^+ & μ^-, variable E~1-50MeV

- Elemental analysis
- Tomography
- Developing instrumentation

Spin-polarized μ^+ & μ^-, variable E~1-50MeV

- Applied pressure measurements
- μ^-SR for things μ^+SR isn't good at
- Instrumentation well-established

Spin-polarized μ^+ (& μ^-?), E~10keV

- Surface science (big area)
- One cold μ^+ source in the world
- Hard to produce efficiently

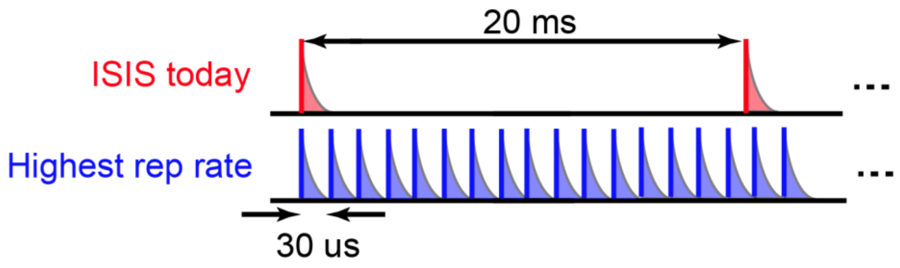
When do we want them? As often as possible

Separate target(s) after Linac: kHz

- Easier to design instruments with more options and capabilities
- Higher instrument duty factor
- New and probably better type of pulsed muon source
- Active beam components might need to involve RF

Intermediate target: 10’s Hz

- Harder to design instruments to deal with instantaneous rate but technology nearly ready
- Already exists at J-PARC (MW) and ISIS (~100kW)
- Easier to design active beamline components like pulse slicers similar to near future equipment



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How do we make them? Targets!

- How can existing target designs be improved?
- Intermediate targets at ~1MW already operating at PSI and J-PARC
  - Are there opportunities to improve these further? e.g. HiMB at PSI
- Dedicated targets following the linac would be lower power and should offer more flexibility for optimization
  - What is the best scheme for making the muons we want from one or more targets?
  - Designing target along with the muon capture scheme for it is vital

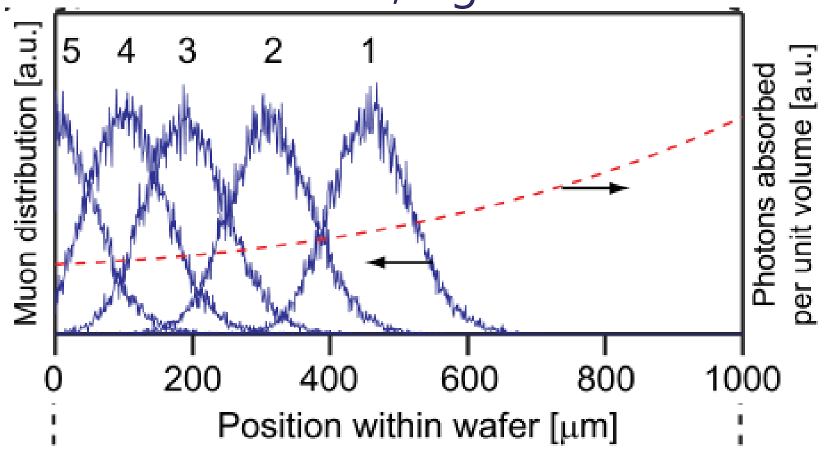
How do we get them to the beamlines?

- Different beam optics are best suited to the different sorts of muon beams we want to provide
- HiMB shows one way to improve this but there are others
- If we can dedicate beamlines coming off the target(s) to particular types of muons we can maximize the value of the extracted protons
  - J-PARC already do this to some extent
  - Coupled to different target designs for the different muon beams this could extend the advantage

Low-energy muons today

- PSI moderation is ~10^{-4} efficient to get ~10^4 μ^+/s on the sample
- RIKEN-RAL → J-PARC approach ionizing muonium has same or lower efficiency

Surface muons, e.g. ISIS HIFI



Solid Ar film on Si wafer

Figure adapted from K. Yokoyama et al., Appl. Phys. Lett. 118, 252105 (2021).

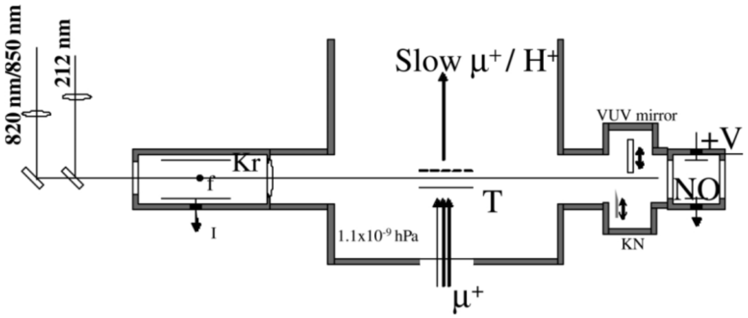


Figure adapted from P. Bakule, et al. Spectrochimica Acta Part B: Atomic Spectroscopy 58, 1019 (2003).

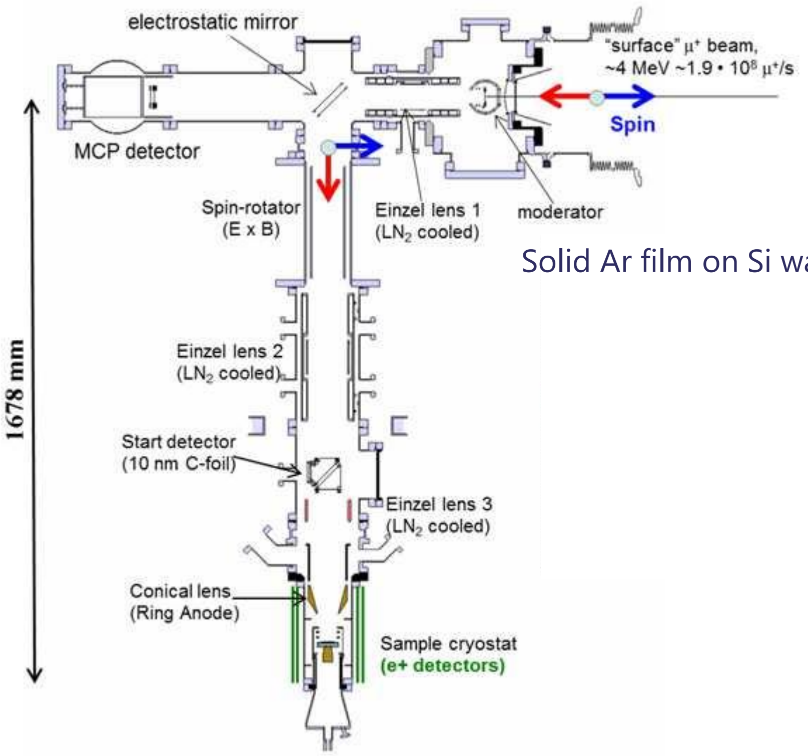


Image taken from https://www.psi.ch/en/low-energy-muons/experimental-setup

Low-energy muons, PSI LEM

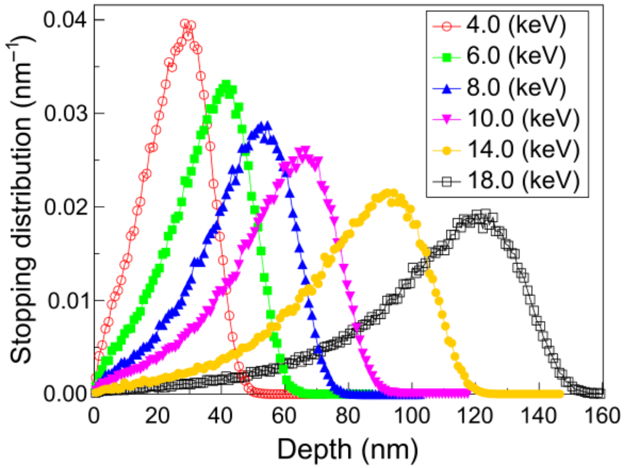


Figure adapted from T. Prokscha, et al. Phys. Rev. Applied 14, 014098 (2020).

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Low-energy muons for ISIS(-II)

- To get ~10^4 μ^+/s at the sample at ISIS today needs ~10^{-2} efficiency
- muCool experiment at PSI has demonstrated ~10^{-3} efficiency
  - Retains spin polarization
  - Shrinks beam spot from cm^2 to mm^2
- Continuous beams ≠ pulsed beams
- Could this scheme be improved?

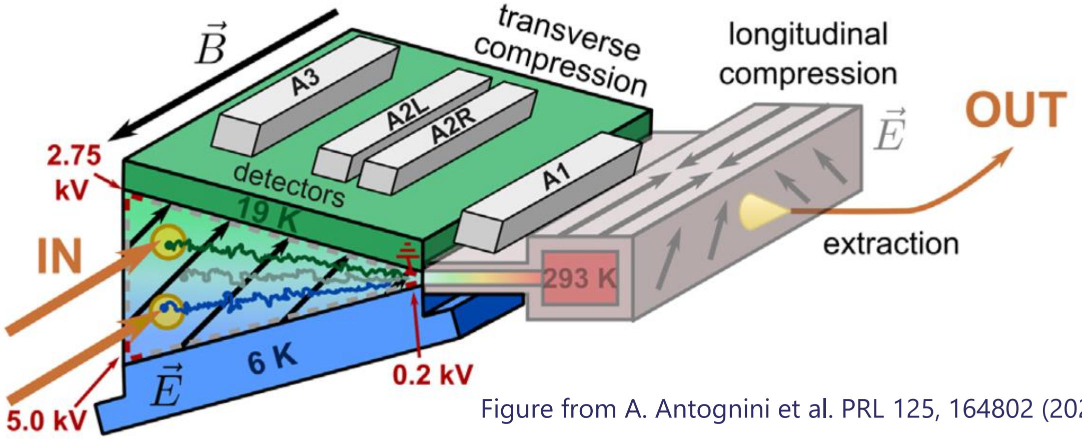

Figure from A. Antognini et al. PRL 125, 164802 (2020).

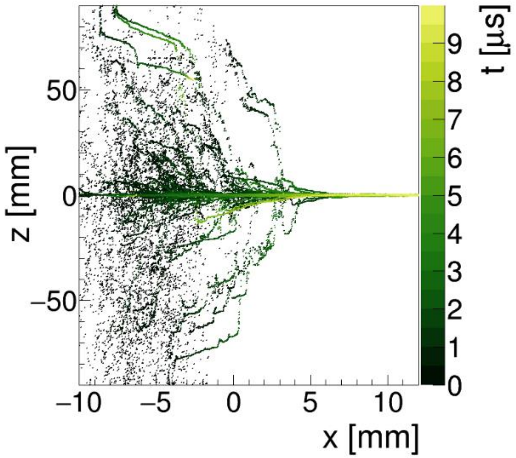

Figure from I. Belosevic, DISS. ETH. NO. 26394 (2019).

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Conclusions

- ISIS muons now finishing off a series of refurbishments
  - Better performance and reliability
- Upcoming projects will improve performance and sustainability
  - Super-MuSR improving data rate and resolution by an order-of-magnitude
  - RIKEN solenoid replacement will ‘pay for itself’ in reduced electricity & support
- Thinking hard about how to make ISIS-II a great muon source
- Really slow muons (~keV) offer massive scientific potential and perhaps only one step away from such a beam at ISIS
- Keen to collaborate on projects of mutual interest

Thank you for your attention!

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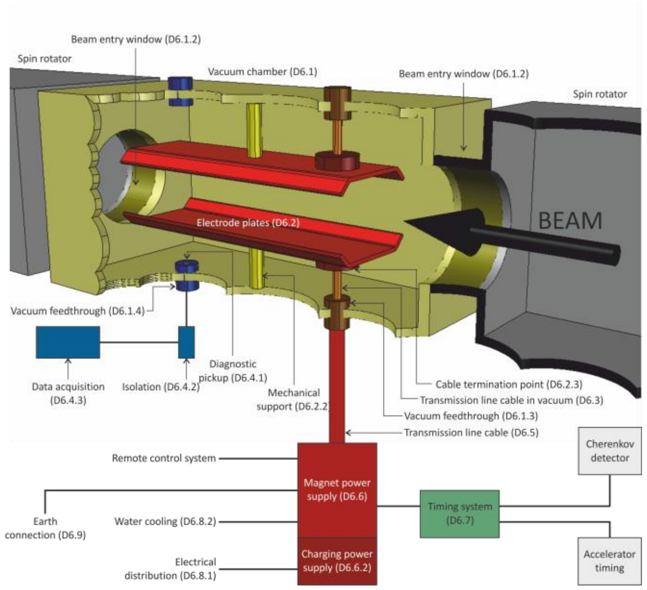
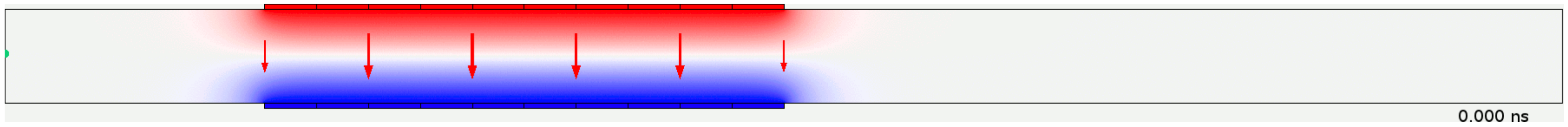
Thank you

isis.stfc.ac.uk @ISISNeutronMuon STFC

Increased resolution by pulse slicing

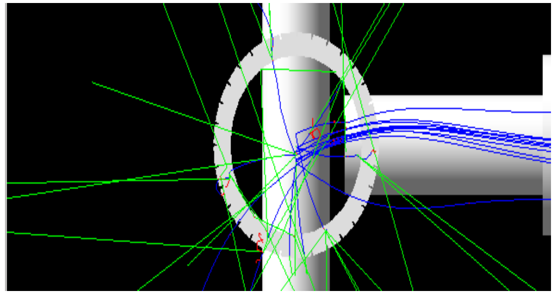
- 100ns incoming muon pulse width is primary limit on ISIS time resolution
- Slicing the pulse increases the time resolution to 10-20ns – reducing uncertainty in muon arrival
- Prototype power supplies already exceeding this goal and offering control over wider pulse widths
- Engineering design work for slicer plates is largely complete and now focussed on HV feed throughs to ensure HV pulse shape maintained





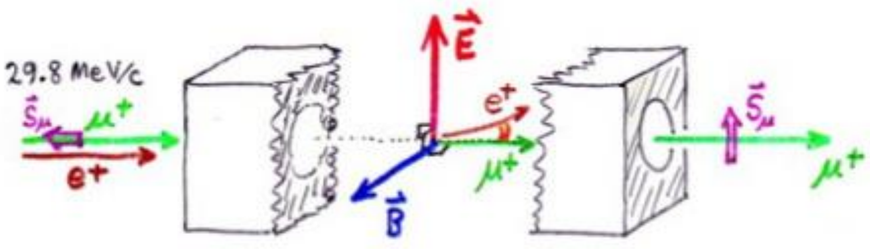
Increasing field range using spin rotation

Problem



- TF experiments need magnetic field perpendicular to muon spins
- Beam is deflected in perpendicular field
- Practical field limit is just above the present resolution limit – would limit benefit of slicer

Solution



- Rotating muon spins in flight prevents deflection in TF along beam axis
- Long established at TRIUMF and PSI
- Collaborating with PSI on spin rotator design and construction

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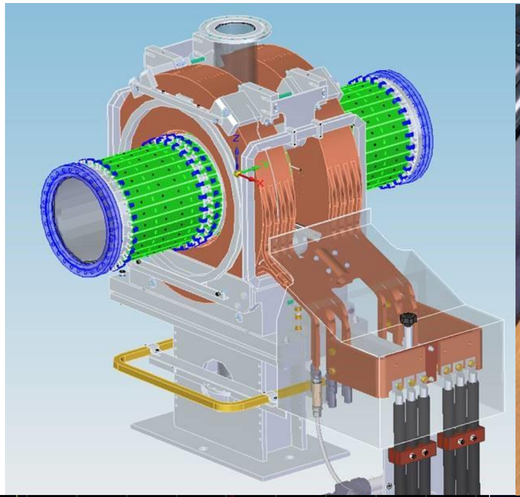
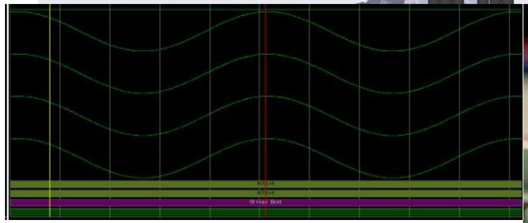
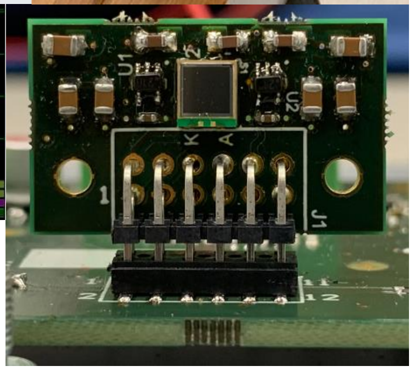
Increasing counting rate with detectors

- Current instrument limited by number of detectors and their recovery time
- Aiming to count 20x more decay positrons than today
  - Too difficult to make 20x more detectors
- Improving the recovery time allows us to use ~10x more detectors with each counting ~2x as many positrons
  - Change from hardware discriminators to digitizing detector output
- Both detectors and digitizers are being prototyped at the moment with STFC Technology and Nuclear

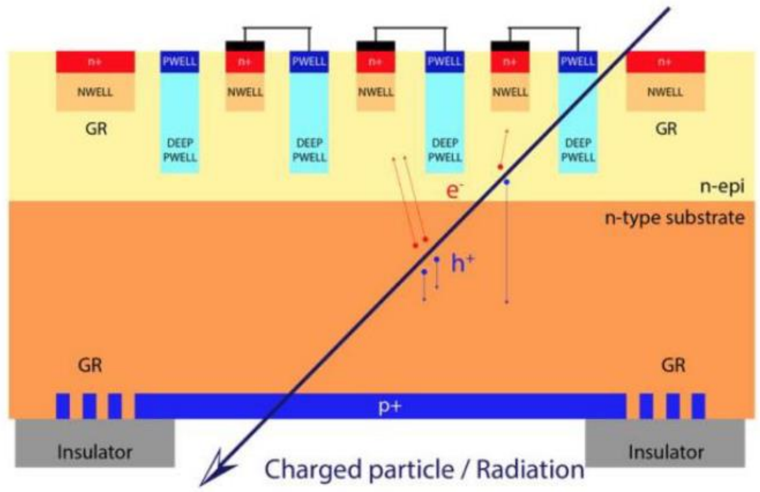


Beyond Super-MuSR: Si-pixel detectors

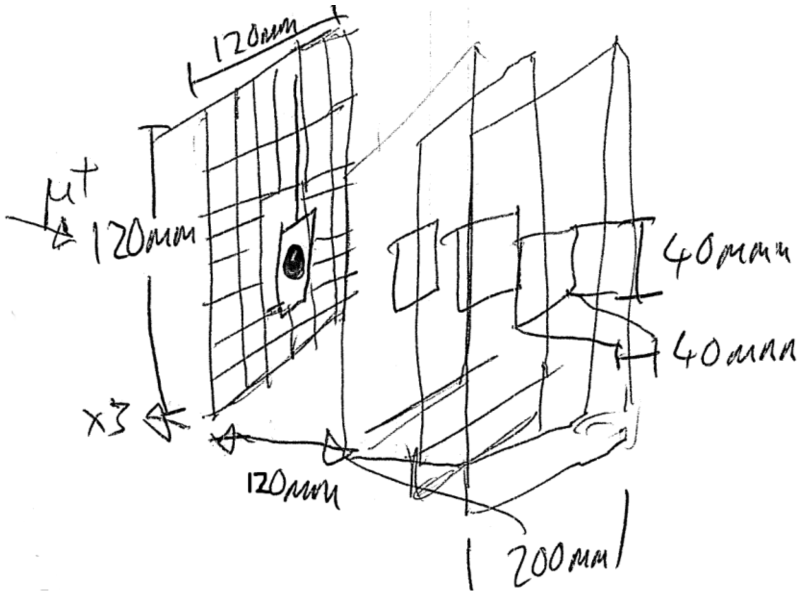
"Up to about 10 years ago, silicon sensors were not considered mainstream MIP timing detectors. Presently, they are considered the most likely (only?) solution for 4D trackers."
– Nicolo Cartiglia, Position Sensitive Detectors Conference 2021

- Position sensitive detector in silicon
- Electronics can be in the same silicon
- Provide information on:
  - Position – >~50μm
  - Counting – <THz/cm^2, often <GHz/cm^2
  - Timing – >30ps
- Can't have all the best performance characteristics at the same time
- Also need some other characteristics specific to muon experiments
- R&D is very expensive so hope to find already developed systems suitable for us
- What do we really need?



Positron tracking

- Aim: Track positrons out of sample
- Benefits: Sample/BG separation, multiple samples, imaging samples, better field dependence
- How precisely do we need to know positron source? – 1mm for BG removal?
- Endcap designs are also possible
- What else would we like to specify?



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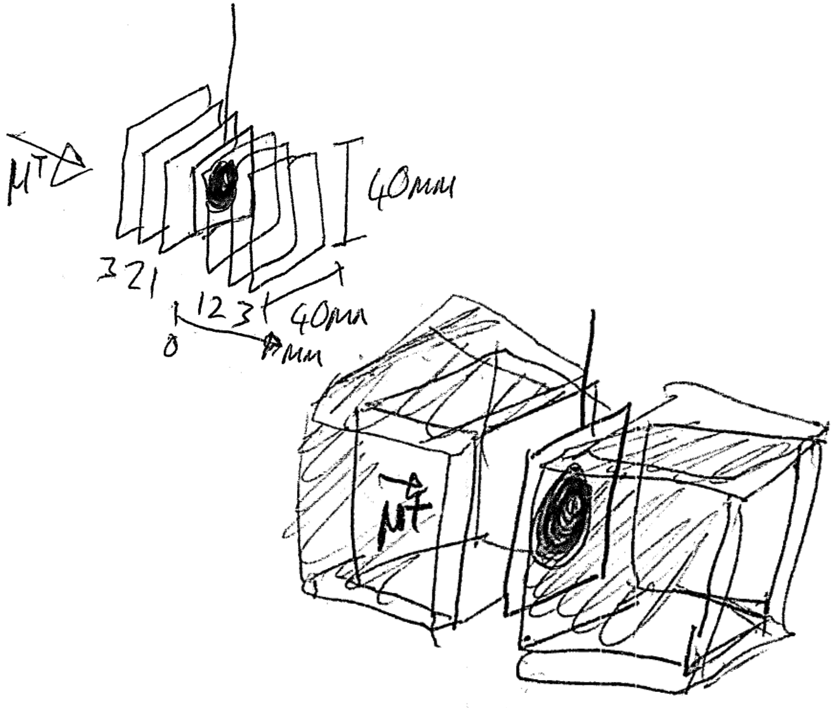
Muon and positron tracking

- Aim: Track muons into sample and match positrons emitted
- Benefits: Beat muon pulse width + benefits of positron tracking
- Rate will be limited by scattering of muons through muon counter limiting precision in where they stop
- Would need new sample environment to get detectors close enough
- What else would we like to specify?



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