# The ISIS Neutron and Muon Source

C. T. Rogers on behalf of the ISIS team

UKRI Science and Technology Facilities Council
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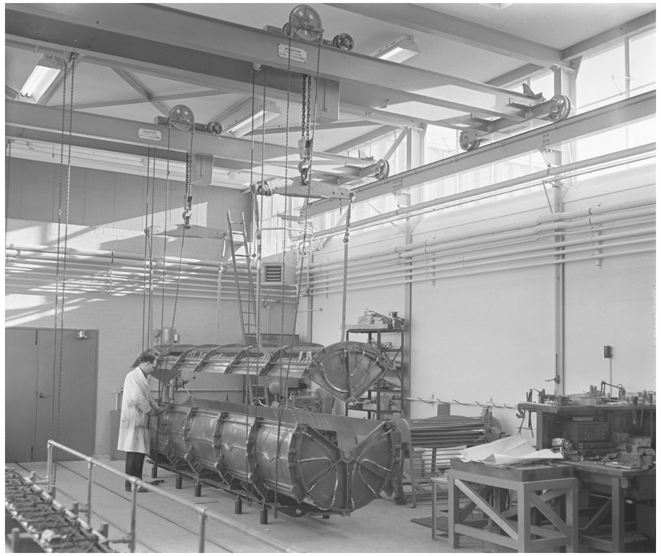
# ISIS

- Neutrons provide unique insight into the atomic structure of matter
  - Scattering
  - Diffraction
  - Spectroscopy
- Muons enable study of magnetic and atomic properties
  - μ spin resonance spectroscopy
  - μ X-ray studies
- Secondary particles generated by firing **pulsed** proton beam onto target
- What is the source of these protons? What are the performance limits?
- How are they used?

# ISIS – Celebrating its 40th (70th Anniversary)

- ISIS opened by Maggie Thatcher in 1984
- Some linac sections date back to the Proton Linear Accelerator built at Harwell in 1950s

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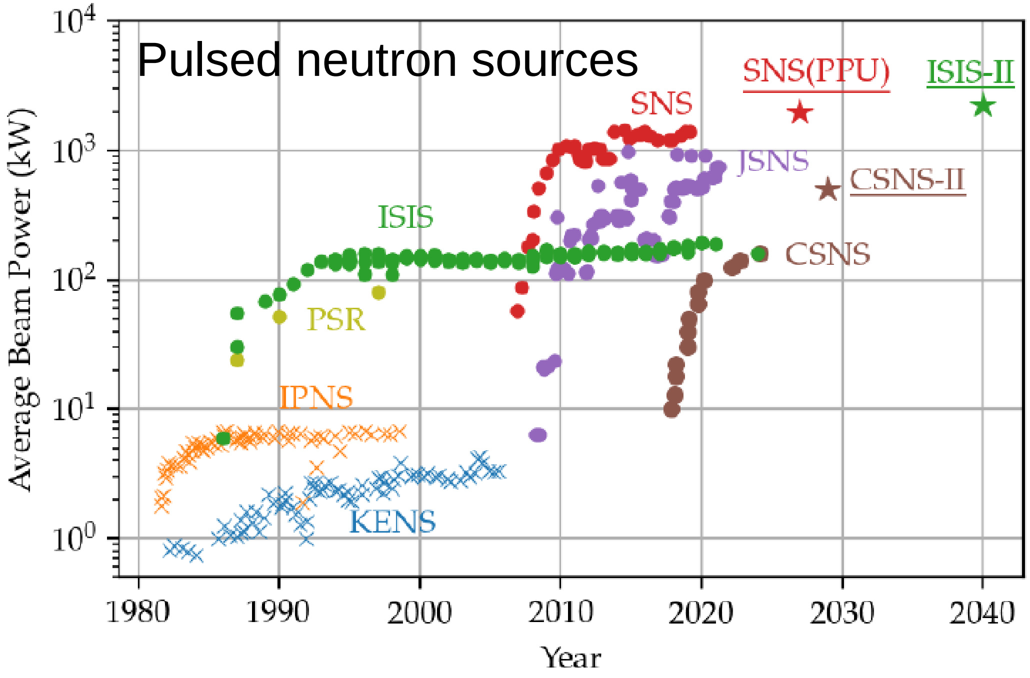
# ISIS in the international context

- ISIS is a pulsed source
  - Important for applications
- Makes neutrons and muons
- Number of secondaries characterised by beam power
  - Hides details of energy, number of protons and target/beam geometry
- ISIS was most powerful pulsed proton source in world
  - Around 200 kW average power @ 50 Hz repetition rate
  - Around 30 GW peak power

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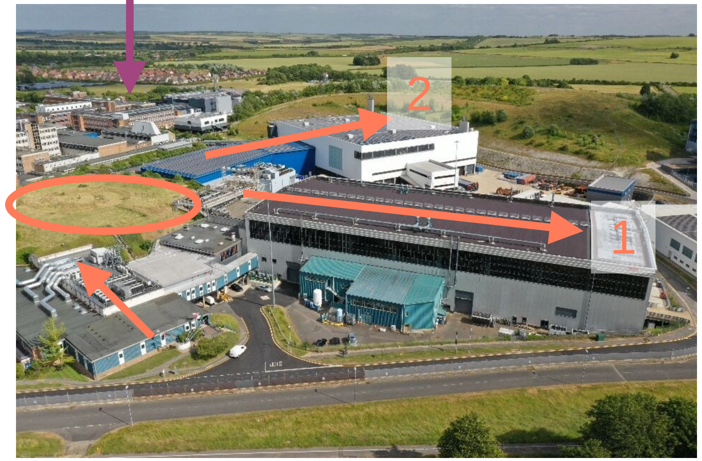
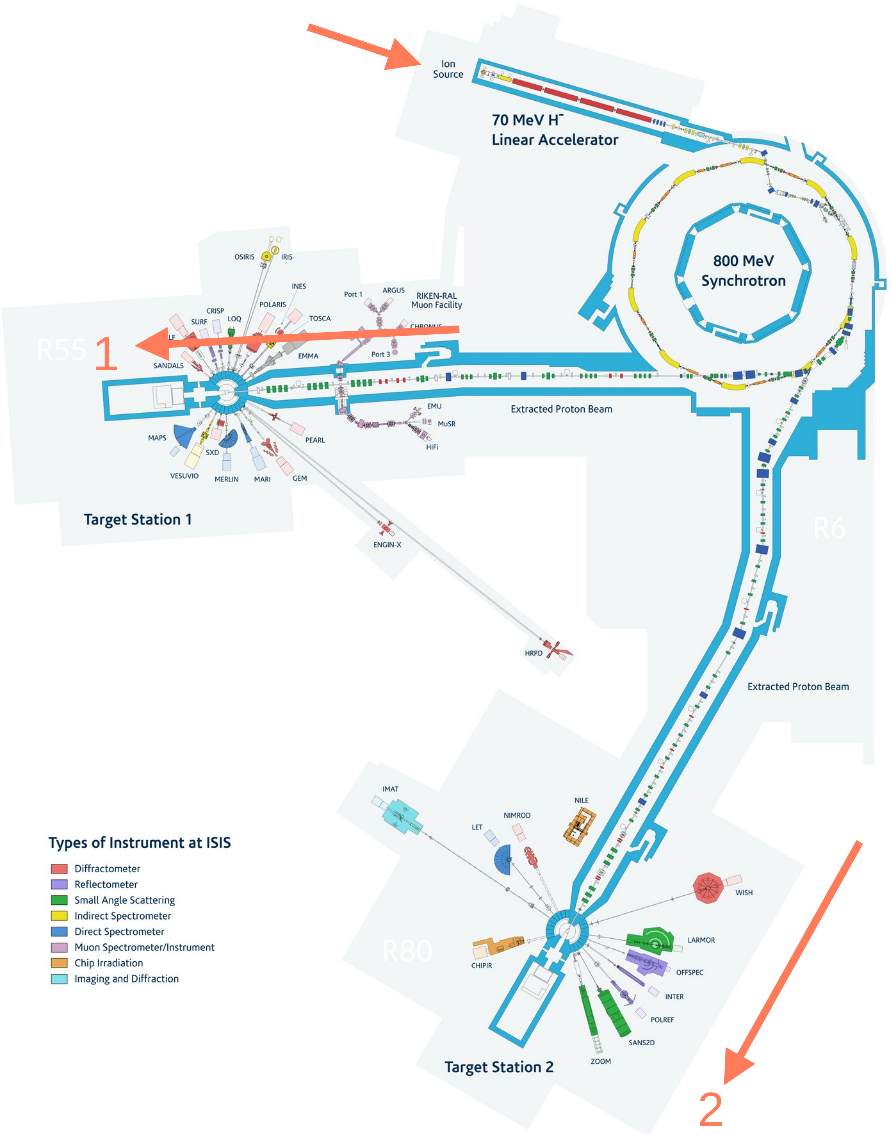
# The ISIS Facility

- H- ion source
- RFQ
- Linac to 70 MeV
- Charge-exchange injection
- Acceleration to 800 MeV
- Delivery to muon and neutron targets

We are here




Start here

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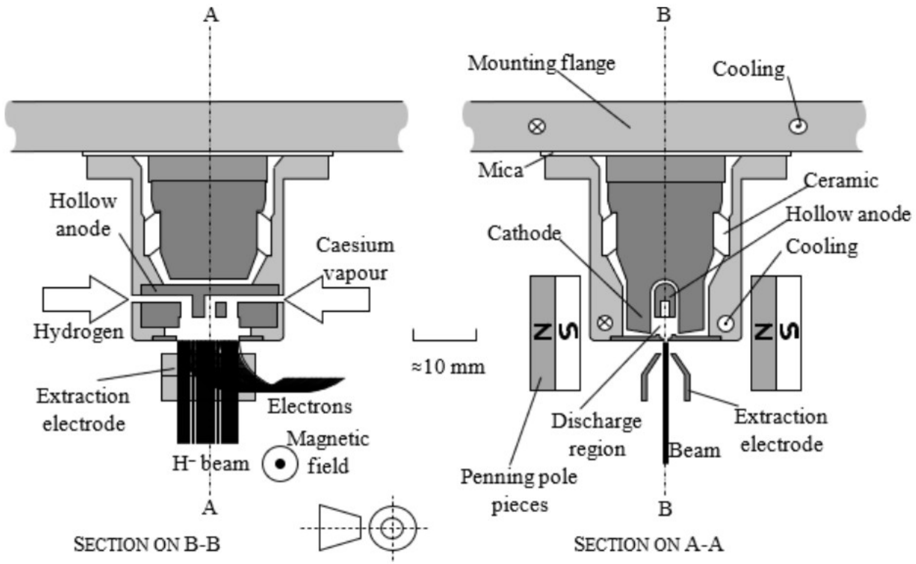
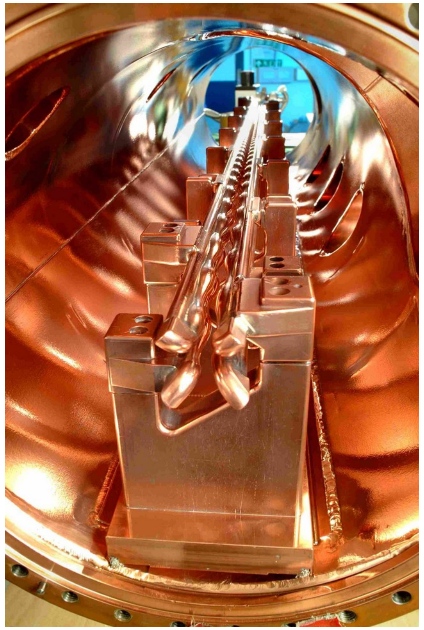
# Ion Source

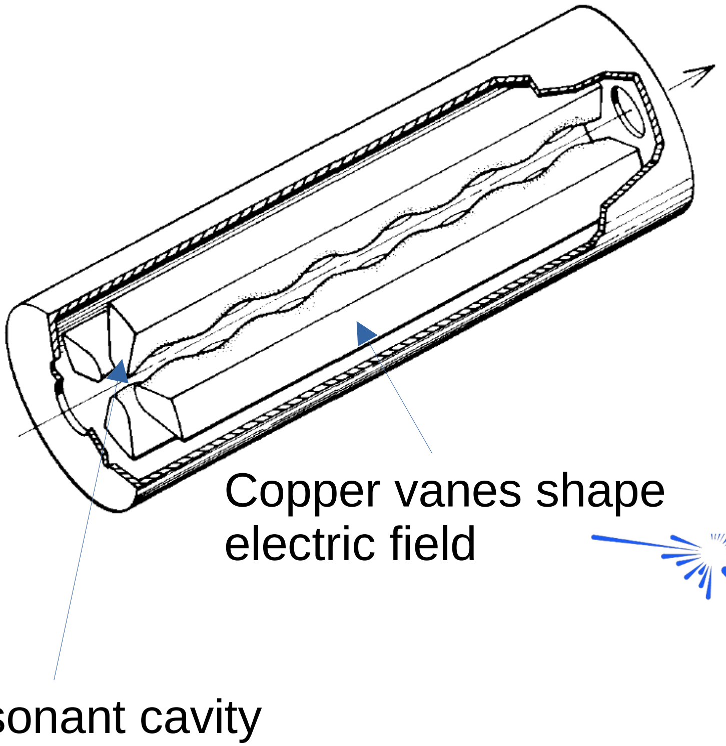
- It all starts with **H**$^-$ ions
  - Proton + two electrons
- Discharge through Hydrogen gas
  - 220 µs pulse
- Molybdenum cathode/anode
- Steering magnet plus bias voltage to filter e$^-$



# Radio Frequency Quadrupole

- Radio frequency quadrupole provides acceleration, focusing and bunching
  - Copper cavity resonator
- Copper vanes shape electric field profile
  - Combined acceleration and transverse focusing
- Oscillation period matched to proton velocity
  - Accelerate 35 to 665 keV
  - Contain beam despite intense space charge forces






RF Quadrupole Beam Dynamics
Design Studies Crandall et al, Linac79

# Why RF?

$$\oint_{\partial \Sigma} \mathbf{E} \cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t} \iint_{\Sigma} \mathbf{B} \cdot \mathrm{d}\mathbf{S}$$

- Maxwell’s law tells us we need either massive (non-physical) voltage
- Or a changing field – RF
- Successive RF cavities must be phased so that incident particles always see correct voltage
- Off-energy, early and late particles are contained by “phase stability”

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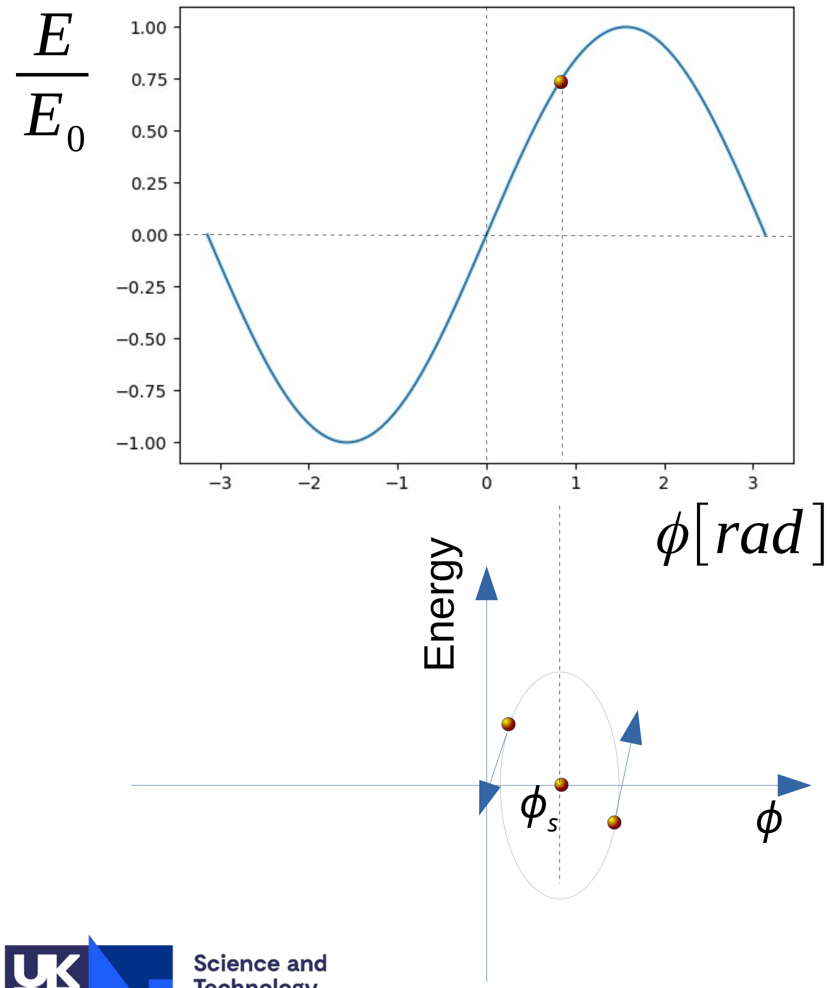
RF Quadrupole Beam Dynamics Design Studies Crandall et al, Linac79

# Phase stability




- Phase cavities so that a "synchronous" particle always crosses at phase $\phi_s$
- Particle crossing at phase $\phi$ relative to synchronous particle
- Particle arriving early & fast
  - Gets smaller energy kick
  - Ends up relatively slower
- Particle arriving late & slow
  - Gets bigger energy kick
  - Ends up relatively faster
- Phase stability!

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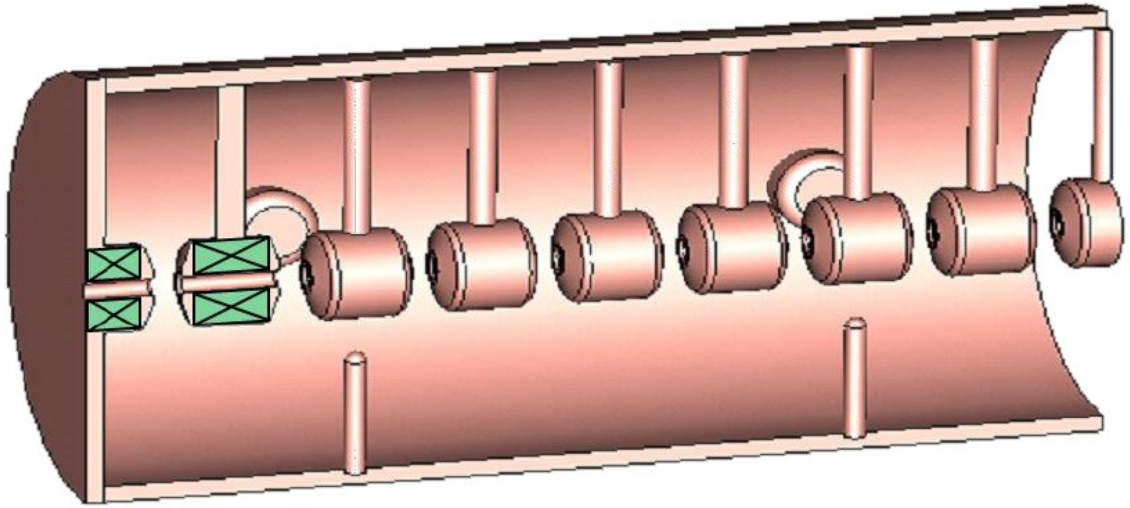
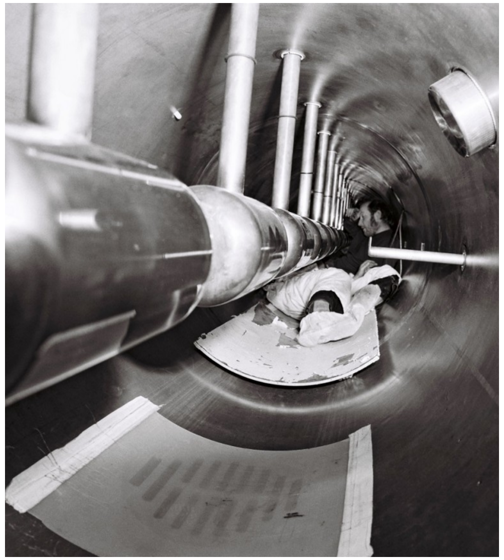
# Linac

- Acceleration to 70 MeV in four Drift Tube Linac "tanks"
- Successive gaps provide electric field
- Distance between gaps matched to velocity
- Quadrupoles give transverse focus





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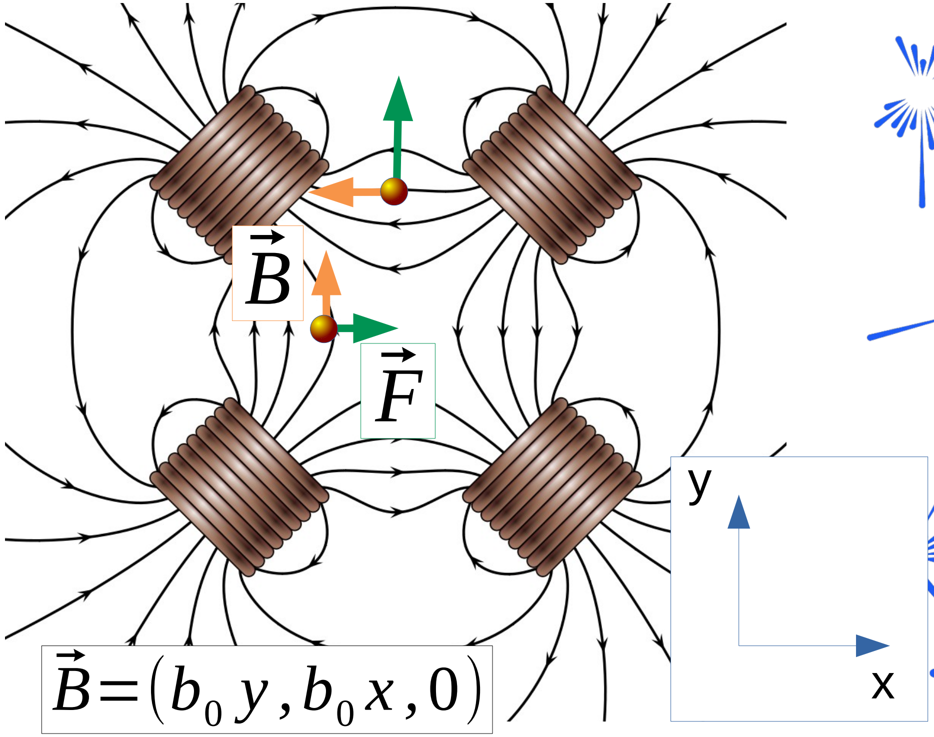
# Transverse focusing

- Use quadrupoles magnets for beam containment
- Field stronger away from beam centre
  - Like a spring or pendulum
  - Simple harmonic motion
- "F" quad focuses in x and defocuses in y
- "D" quad focuses in y and defocuses in x
  - Overall focussing by alternating "F" and "D"
  - Just reverse the polarity




$$\vec{B}=(b_0 y, b_0 x, 0)$$

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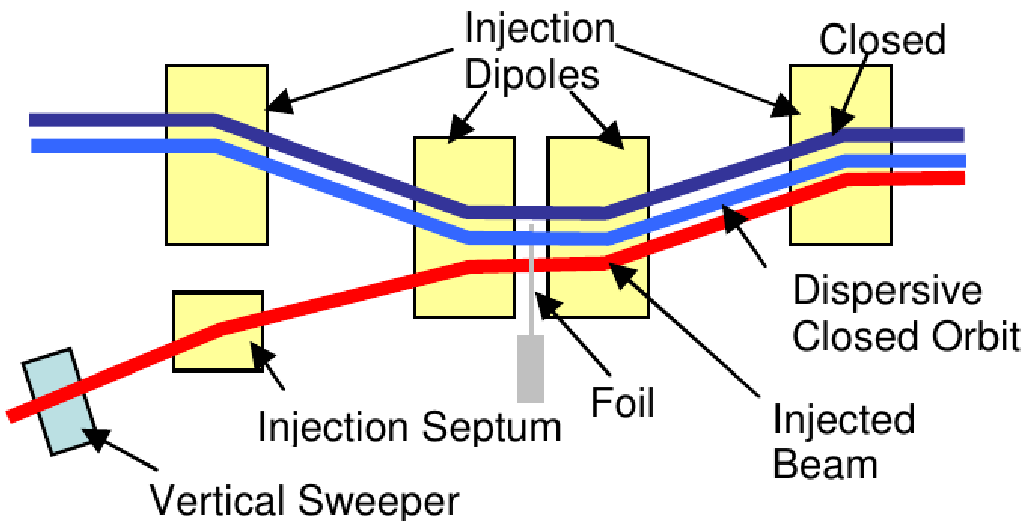
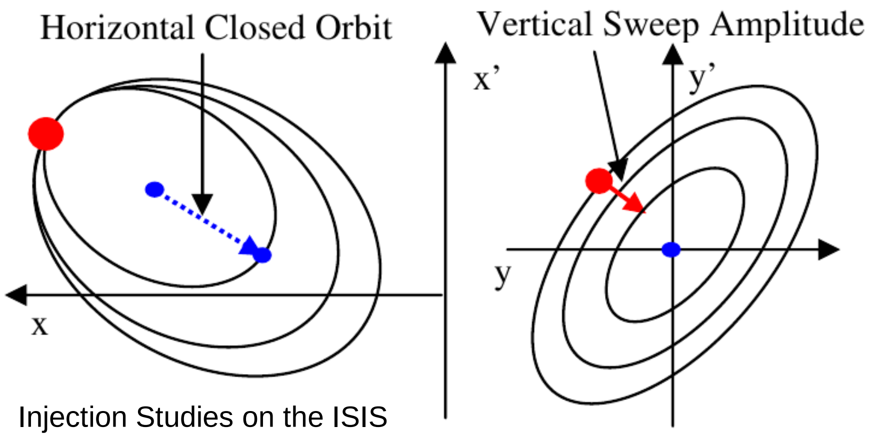
# Injection

- Seek to bring H- beam into the synchrotron ring
- H- pulse is very long
  - ~ 220 μs
- Synchrotron ring is rather short
  - ~0.544*c* μs
- How to inject the beam?
  - Pulses overlap – 130 turns!
- Fundamental theorem → Liouville's theorem
  - Position-momentum (phase) space is incompressible
  - Phase space trajectories cannot cross
- Phase space volume occupied by beam → emittance
- When the laws of physics say "no", we cheat

# Charge Exchange Injection




Injection Studies on the ISIS Synchrotron, B. Jones, D. Adams, C. Warsop,

- Accelerate and inject H- on top of circulating proton beam
  - H- and protons pass through a dipole at different angles → merge
  - Pass H- through a thin Carbon foil
  - H- are ionised leaving protons
- Sweeping dipoles enable build up of different beam shapes
  - “Painting”

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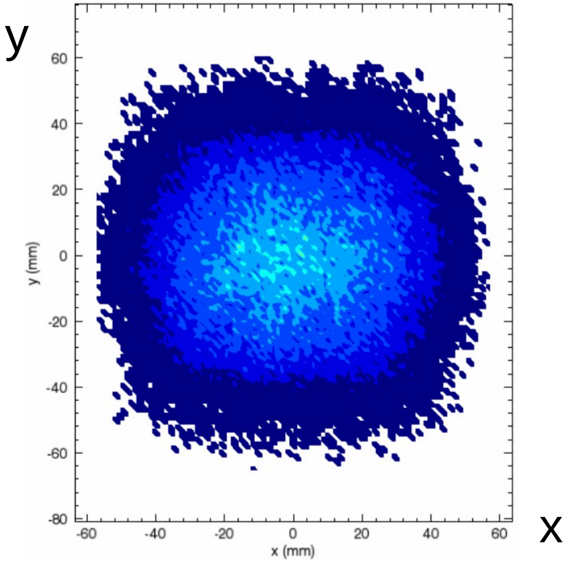
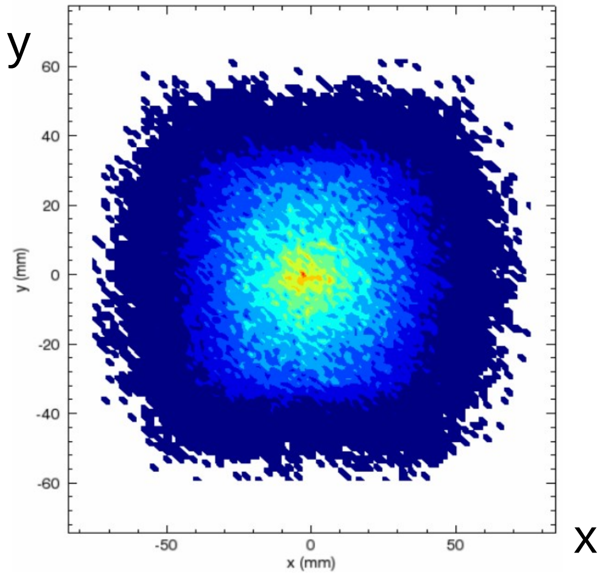
# Painting




- Why paint the beam?
  - Self-voltage of beam tends to repel particles
  - Limits achievable current
- Beam which is strongly peaked in the middle has bigger self-voltage
  - Causes diffusion of beam from centre to edge
  - Emittance growth
  - Loss

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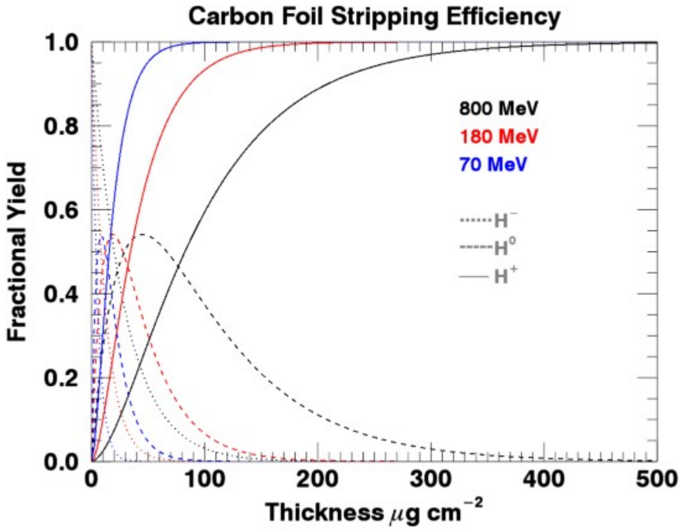
# Foil heating

- Foil heating and damage limits intensity
- Thickness optimised for stripping
  - Even a small inefficiency → unacceptable loss
- R&D to develop new foils
  - $Al_2O_3$ foil decommissioned
  - Replaced with Carbon foils
- Corrugated foils under study

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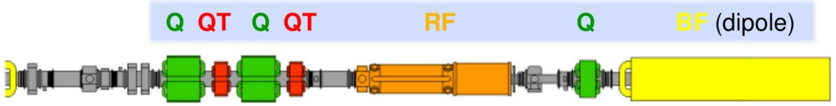
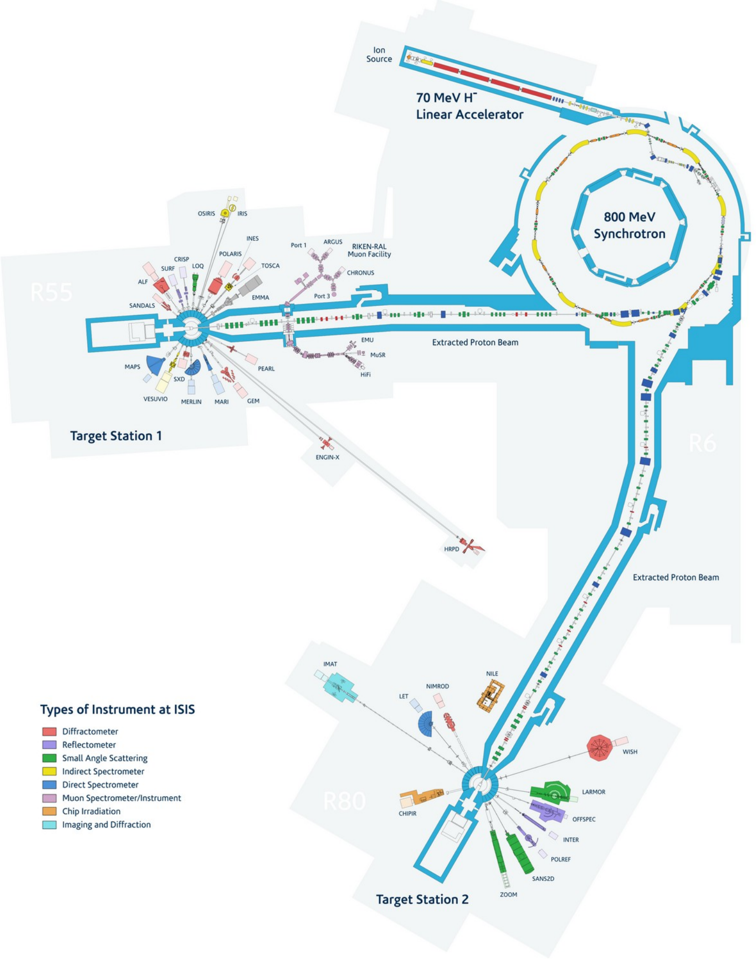
# Synchrotron

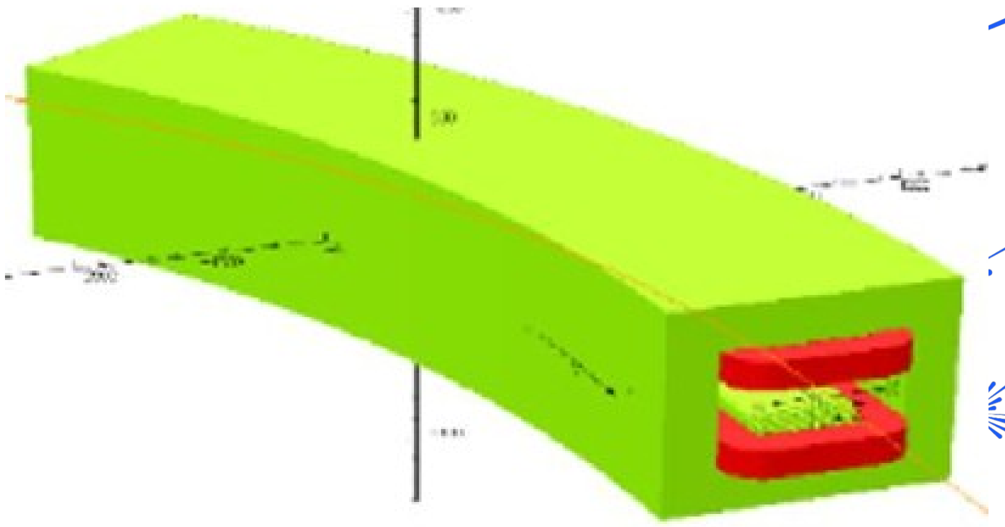
- Accelerate in Rapid Cycling Synchrotron
  - RF cavities provide acceleration
  - Ramp dipoles to maintain constant beam trajectory
  - Ramp quadrupoles to maintain constant focusing




| | |
|---|---|
| **Circumference** | 163 m |
| **Energy Range** | 70 – 800 MeV |
| **Repetition Rate** | 50 Hz |
| **Intensity** | ~3x10$^{13}$ ppp |
| **Beam Power** | ~200 kW |
| **RF System (2 bunches)** | h=2, 1.3 – 3.1 MHz, $V_{pk}$ ~160 kV/turn<br>h=4, 2.6 – 6.2 MHz, $V_{pk}$ ~80 kV/turn |
| **Tunes** | $Q_x$, $Q_y$ = 4.31, 3.83 (programmable) |
| **Extraction** | Single turn, vertical |
| **Losses** | Inj: 2%, Trap: <3%, Acc/Ext < 0.5% |

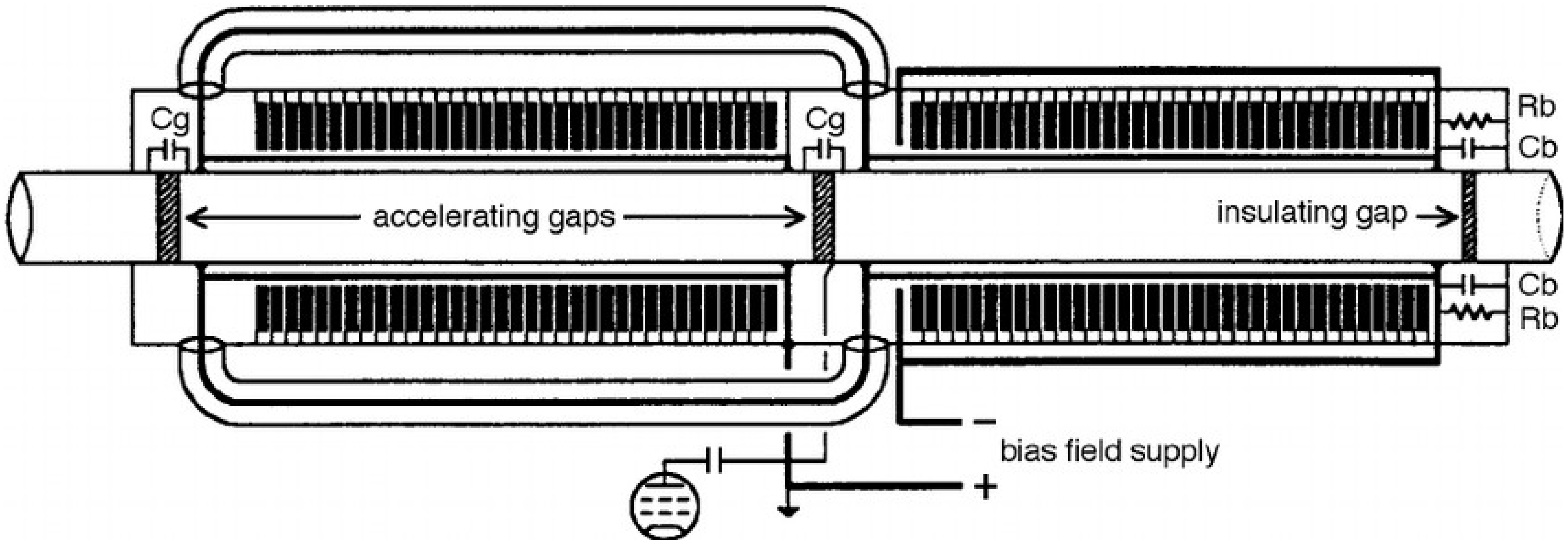


# Synchrotron Magnets



- Dipoles laminated to reduce eddy currents
- Quadrupoles provide most of the focusing
- Weak quadrupole gradient across the dipoles for focusing
- Sextupoles installed for chromaticity correction – but never used

# Synchrotron RF




- RF cavity must oscillate synchronously with ring time-of-flight
  - Capacitative gap oscillating with inductive ferrite
  - Two RF cavity oscillations per beam circulation
  - Frequency swing from 1.3 – 3.1 MHz
- Frequency swing achieved by tuning Ferrite inductance using applied magnetic field

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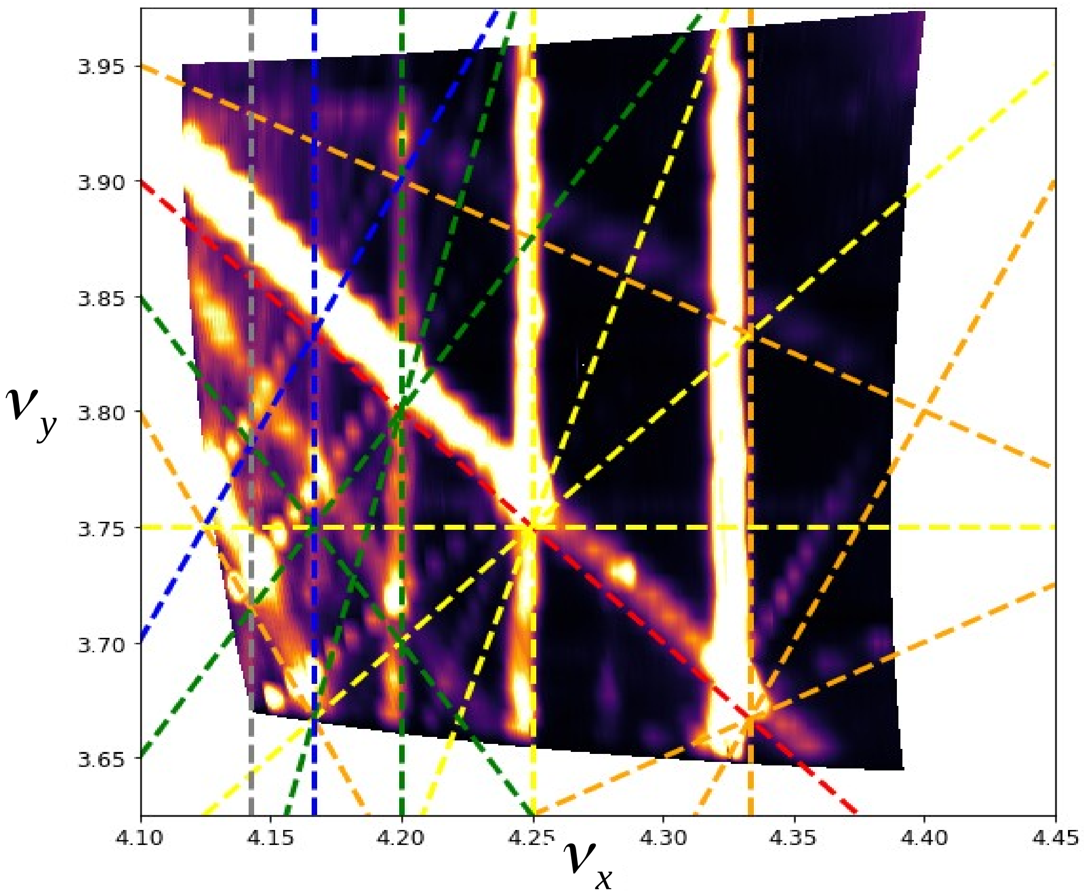
# Beam Instrumentation

- Beam instrumentation essential for beam operation
  - Identify issues before they cause loss
  - Identify beam loss quickly and protect the machine
  - Validation and optimisation
- Beam Instrumentation mostly non-destructive
  - Ionisation chambers identify secondaries caused by loss
  - Beam position monitors – capacitative wall current monitor
  - DC Current Transformer – measure wall current
  - Residual gas ionisation monitor – measure ions arising from residual gas interaction with beam

# Synchrotron – Resonances

- Characterise oscillations by frequency
  - "Tune" **Q** number of oscillations per turn
    - Horizontal
    - Vertical
- Resonances where tune is fraction
  - Q ~ m/n where m, n are fractions
- Optimise tune to avoid resonances
  - Tweak quadrupole currents

ISIS Synchrotron (measured)

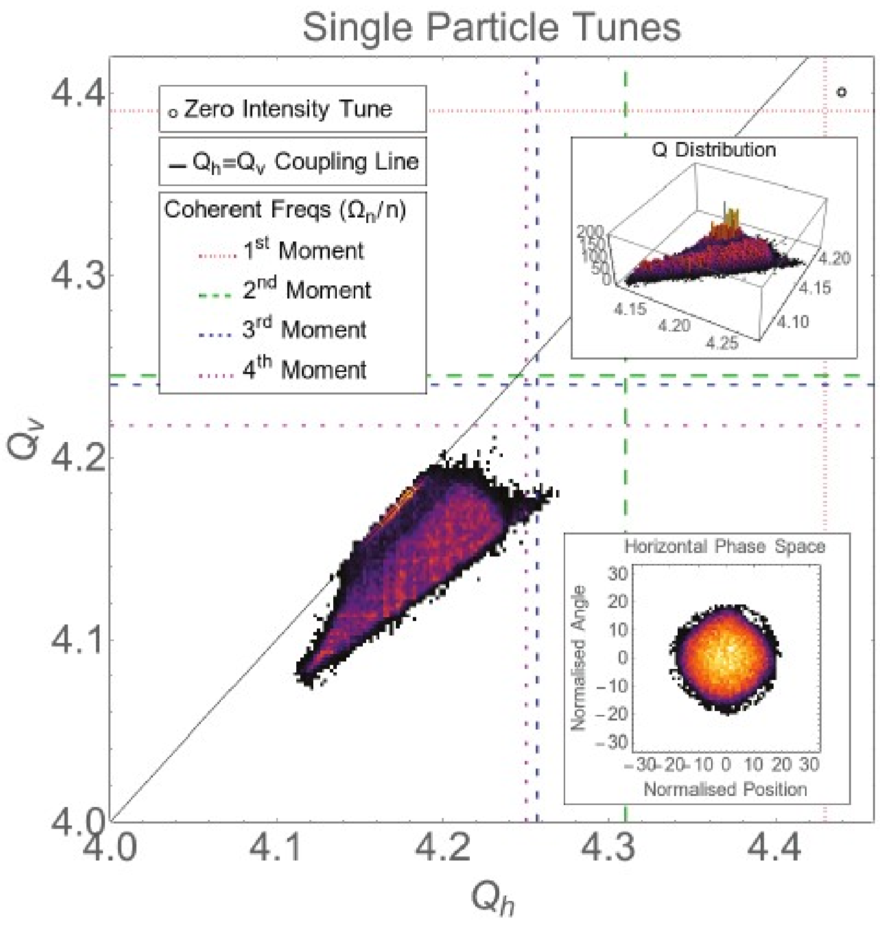



Bad transmission (hot)

Good transmission (cold)

# Synchrotron – Space Charge

- Space charge causes defocusing
  - Strength of defocusing varies across beam
  - Causes tune spread
- Fundamental limit for charge at injection

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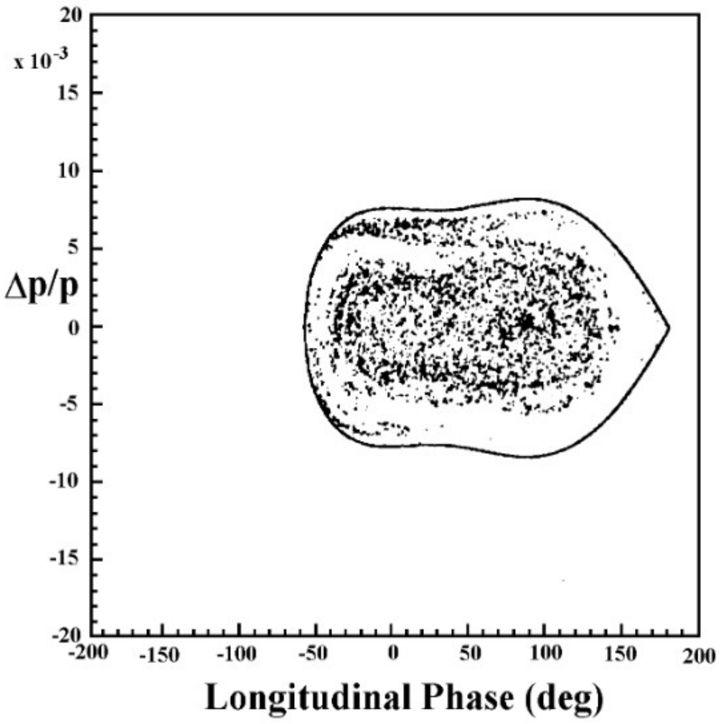
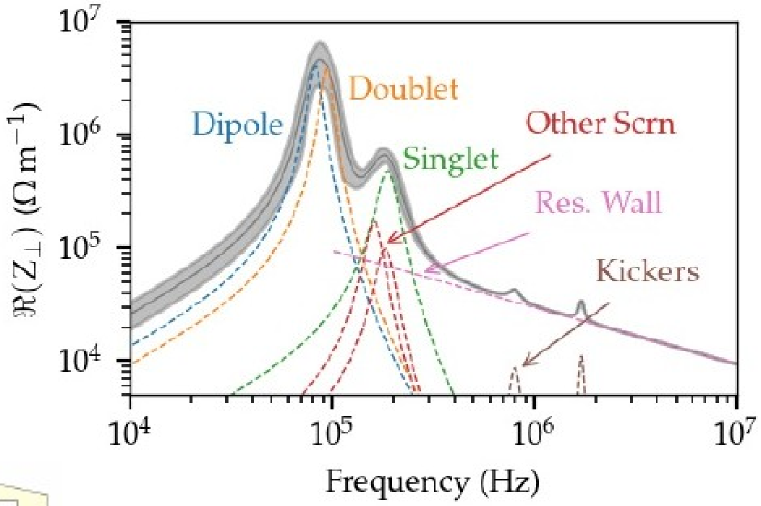
# Second harmonic cavities

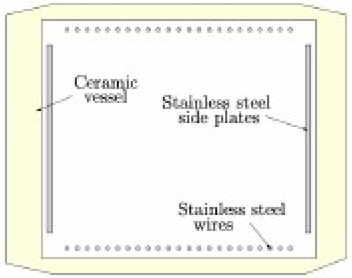
- Use higher harmonic in RF system
- Modify stable area in momentum-phase
- Flatten and lengthen the bunch
    - Reducing instantaneous charge i.e. tune dilution

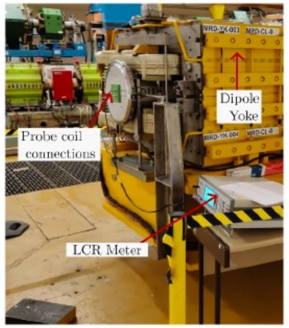


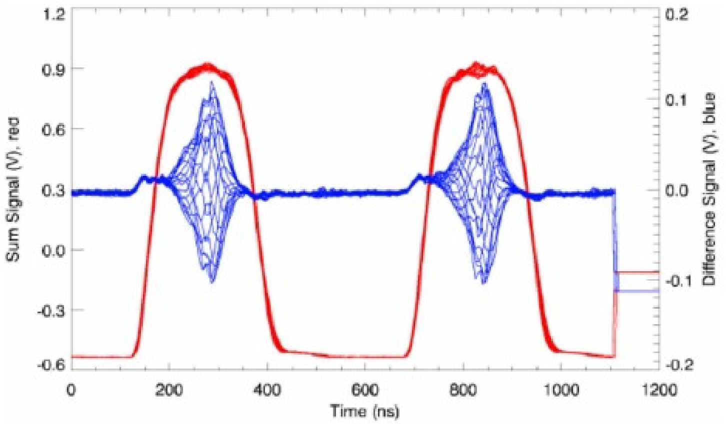
# Synchrotron - Wakefields

- Passage of beam induces EM oscillations
- Can build up over many turns
- Causes beam loss
- Characterise frequency of EM noise
  - Impedance
- Resonances with beam → loss

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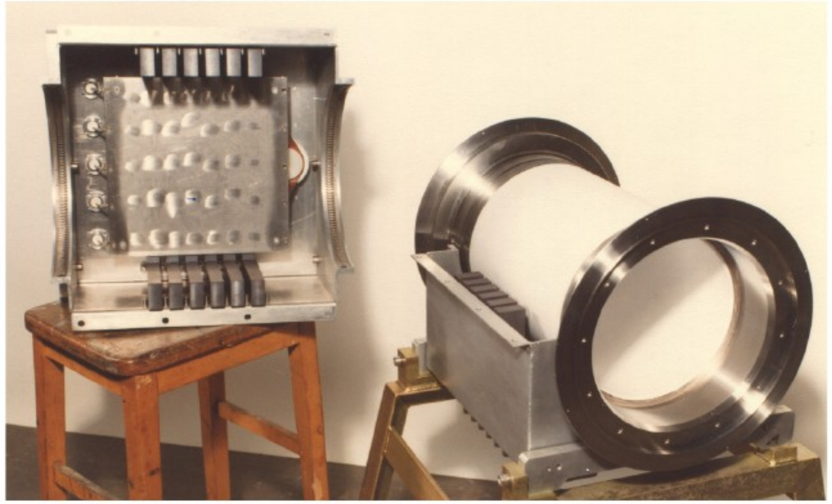
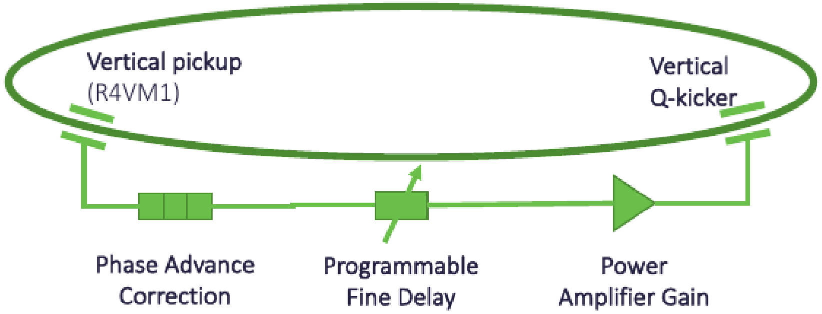
# Damping System

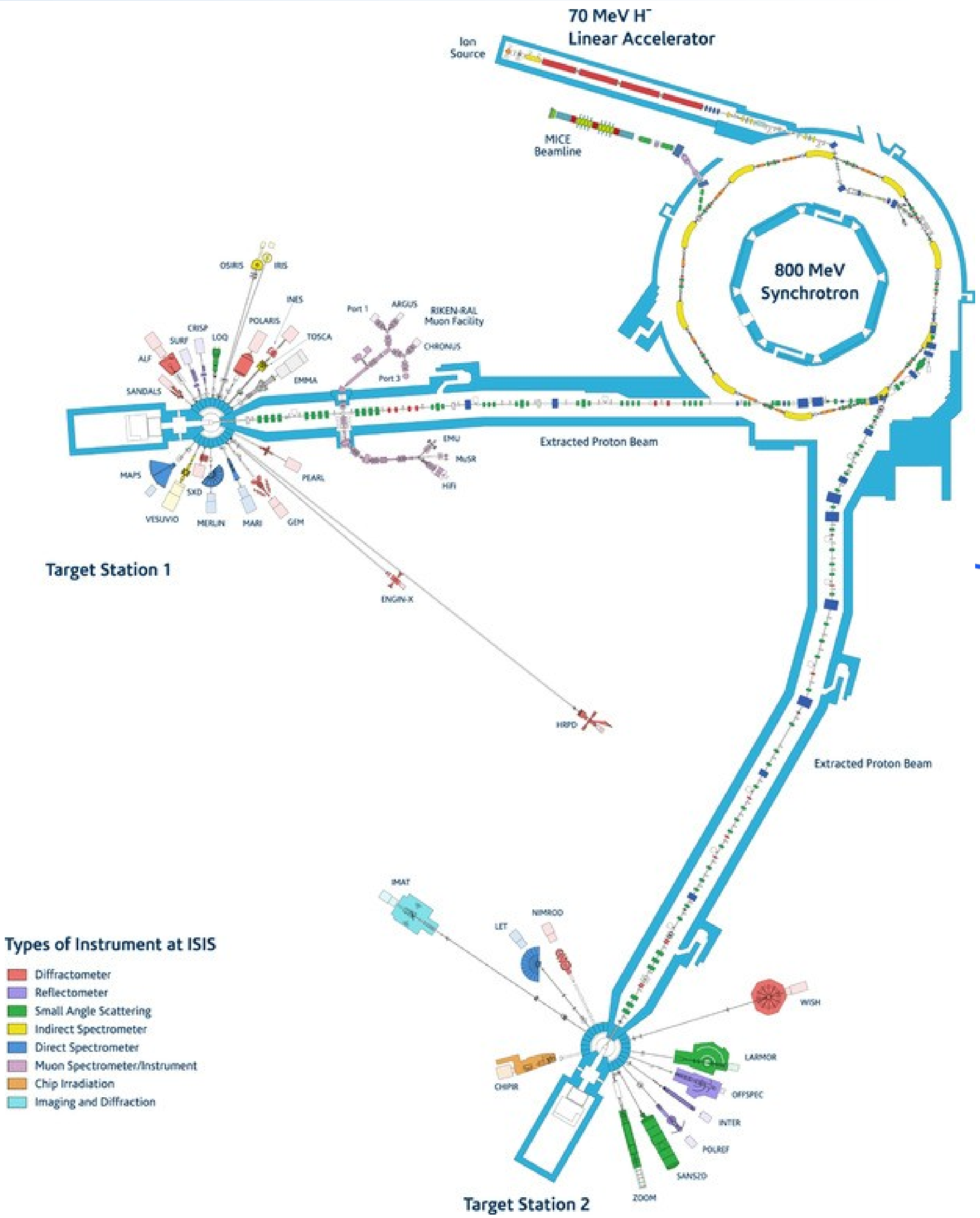
- Damping system under development
- Fast pulsed dipole
  - Kick in anti-phase with wakefield excitation
- Pick-up and feedback circuit
- Significant reduction in loss seen in tests
- Moving to production
  - Challenging to achieve





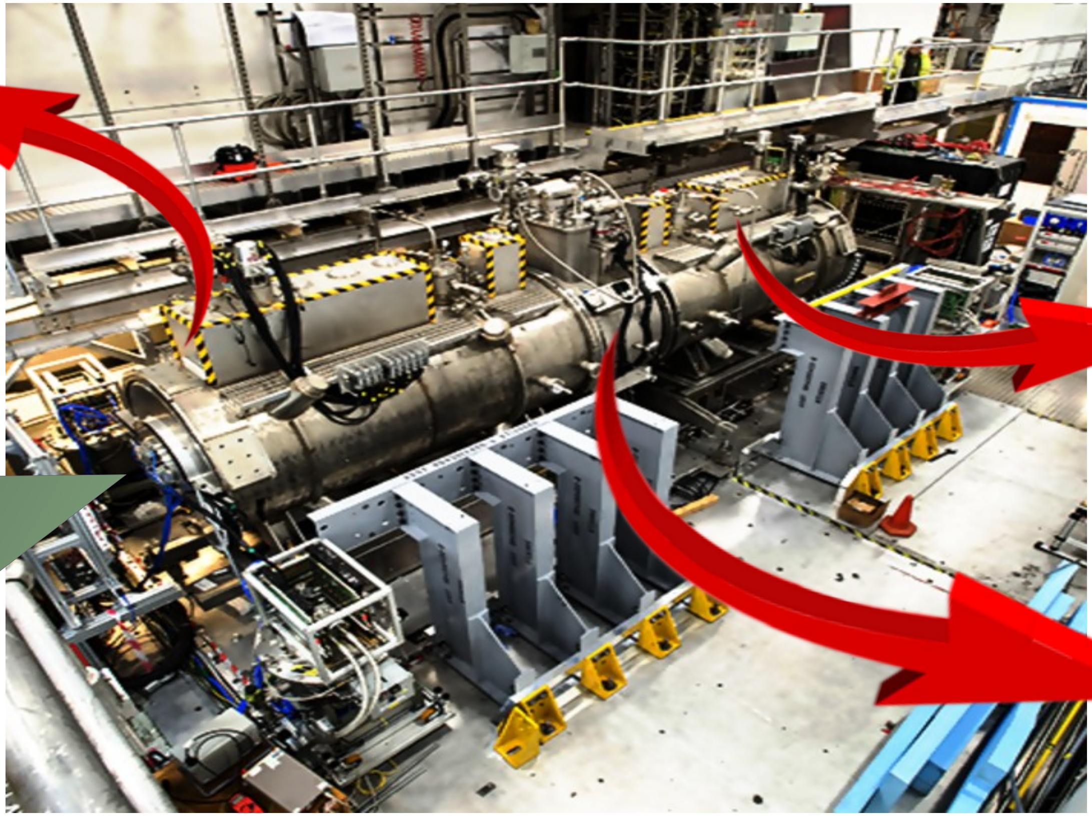
# Extracted Proton Beams

- MICE beamline (decommissioned)
- Two EPBs
- Two neutron targets
- Muon target



# Muon Ionization Cooling Experiment

**Measure** muon position and momentum upstream



Beam

**Measure** muon position and momentum downstream

**Cool** the muon beam using LiH, $LH_2$, or polyethylene wedge absorbers

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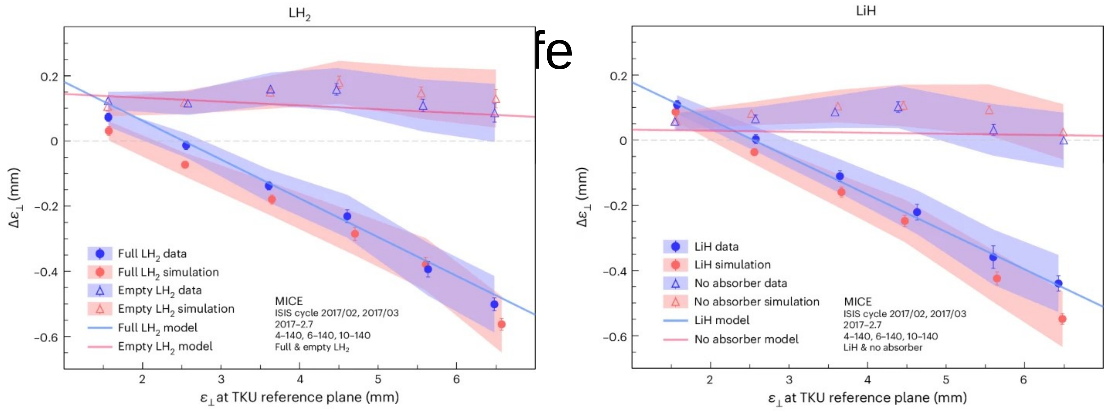
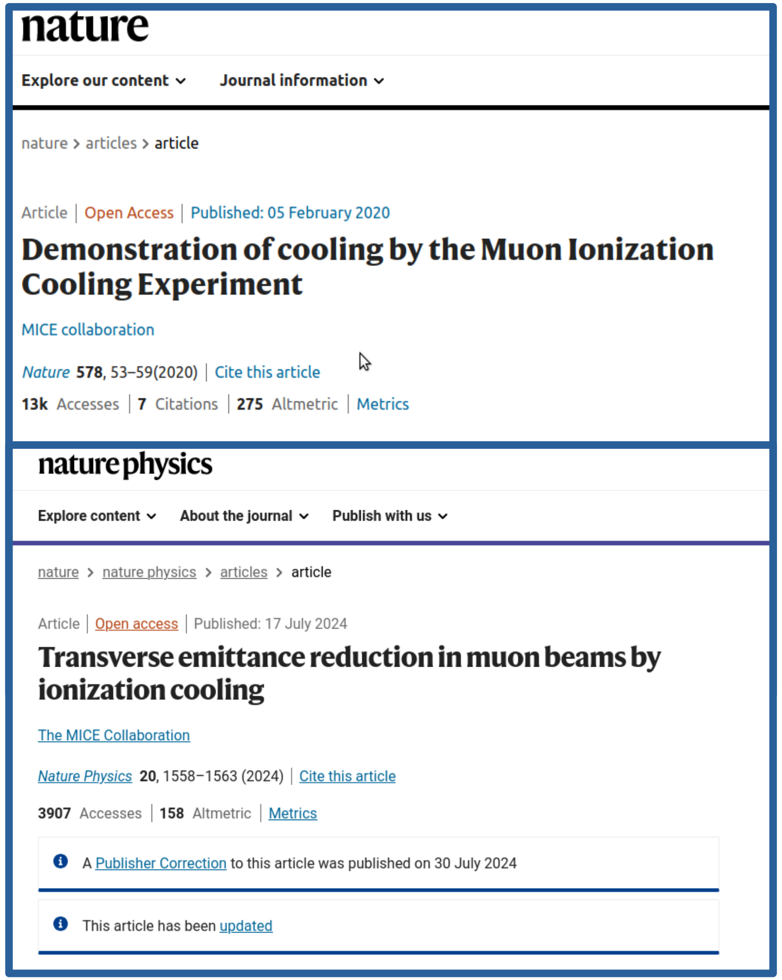
# MICE - Results

- Muon ionisation cooling was demonstrated by MICE
  - Muons @ ~140 MeV/c
  - Transverse cooling only
  - No re-acceleration
  - fe

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**Demonstration of cooling by the Muon Ionization Cooling Experiment**

MICE collaboration

*Nature* **578**, 53–59(2020) | Cite this article

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The MICE Collaboration

*Nature Physics* **20**, 1558–1563 (2024) | Cite this article

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A Publisher Correction to this article was published on 30 July 2024

This article has been updated

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# Inside Target Station 1

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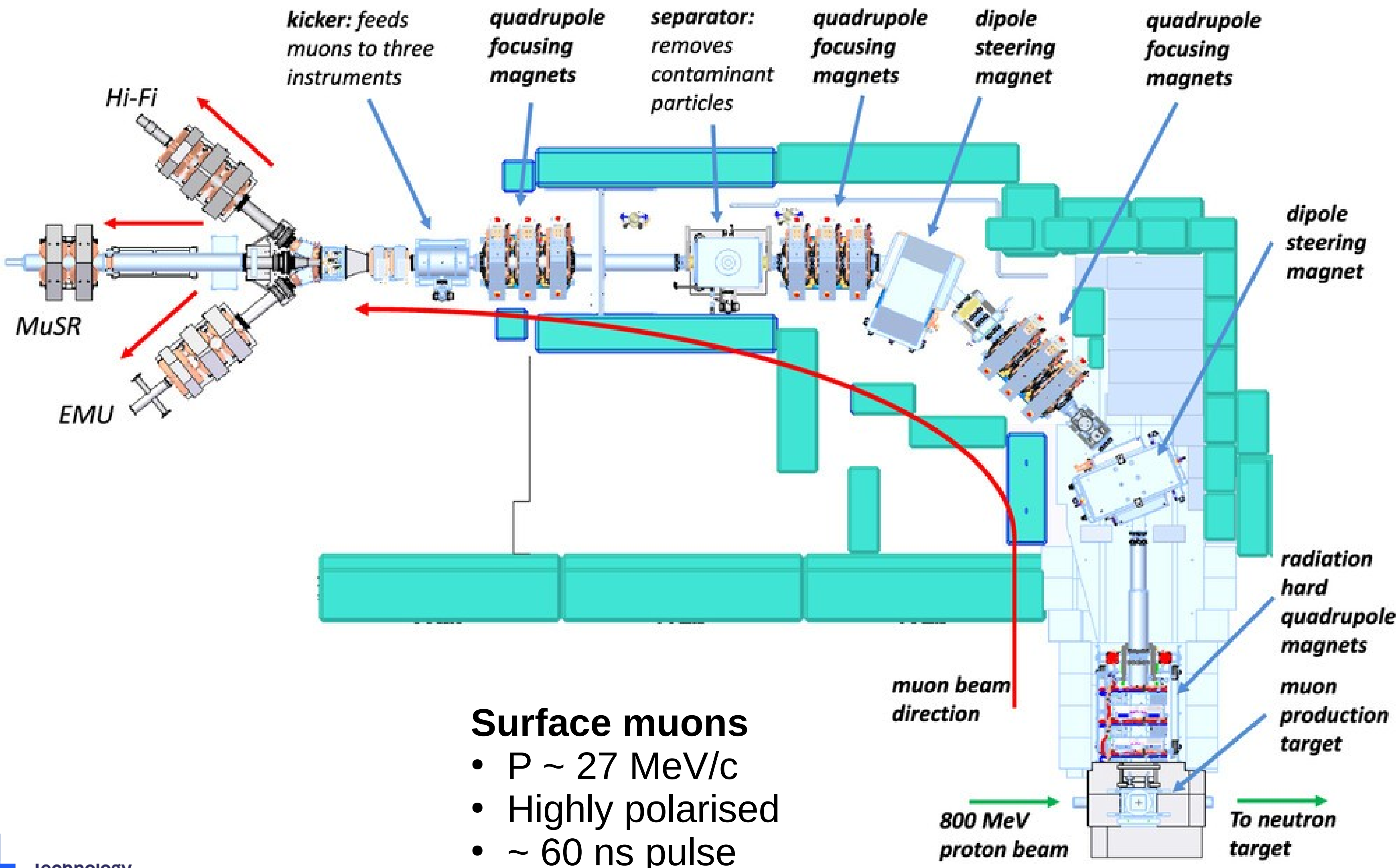
Inside Target Station 2

# Muon Target




**Surface muons**
- P ~ 27 MeV/c
- Highly polarised
- ~ 60 ns pulse

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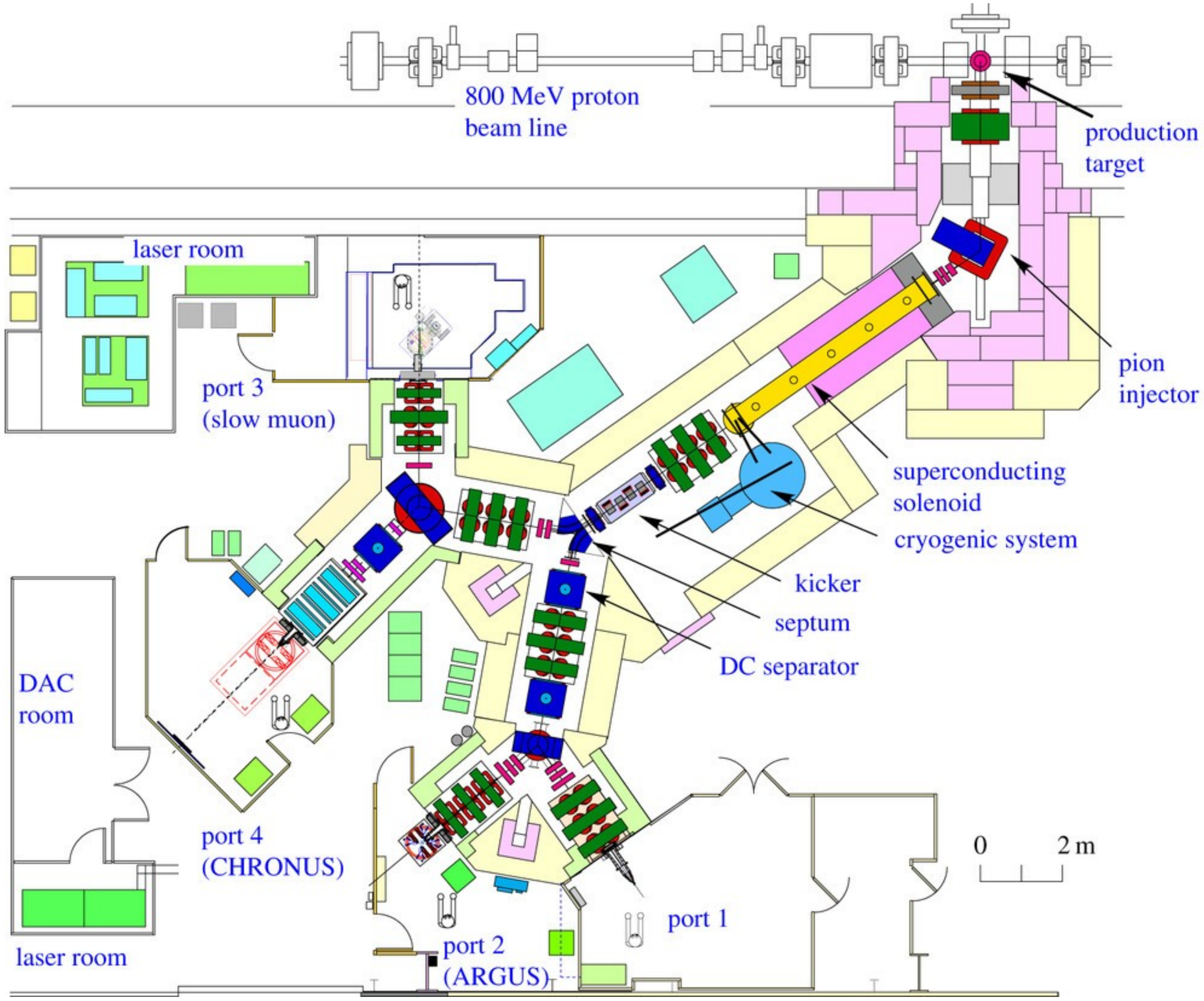
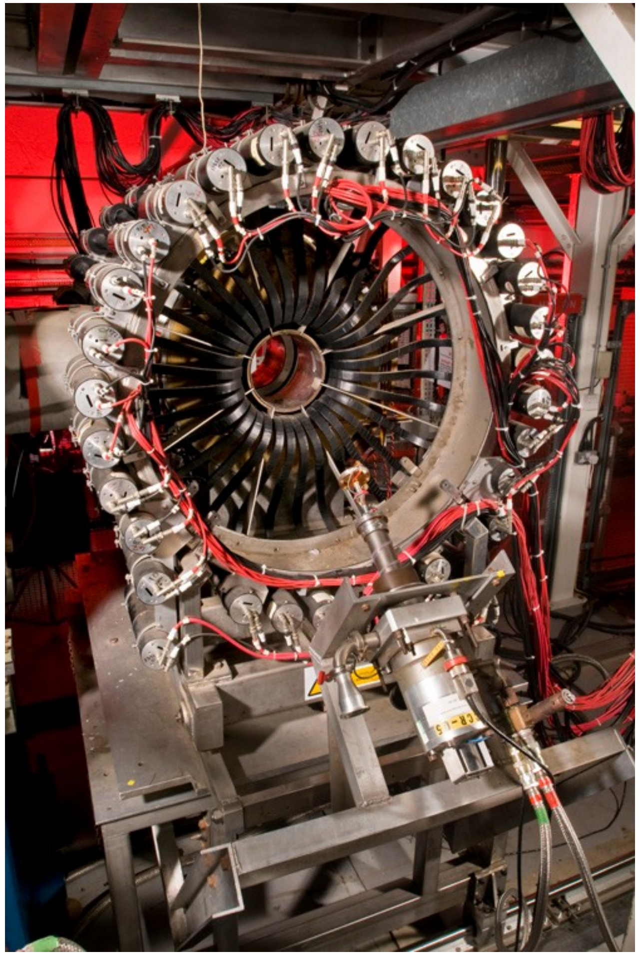
# Rikken-RAL

- Pion decay-in-flight
- 17 MeV/c to 120 MeV/c

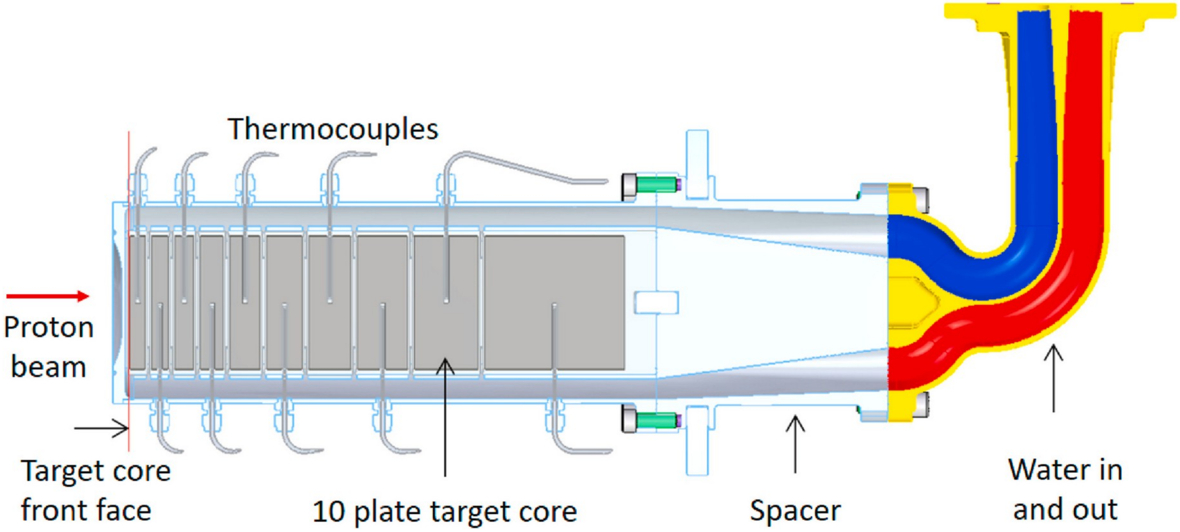


# μSR

- Muons stop in sample
- Spin rotates in magnetic field
- Count forwards and backwards decays
  - Simple scintillator slabs
- Oscillation frequency → magnetic field

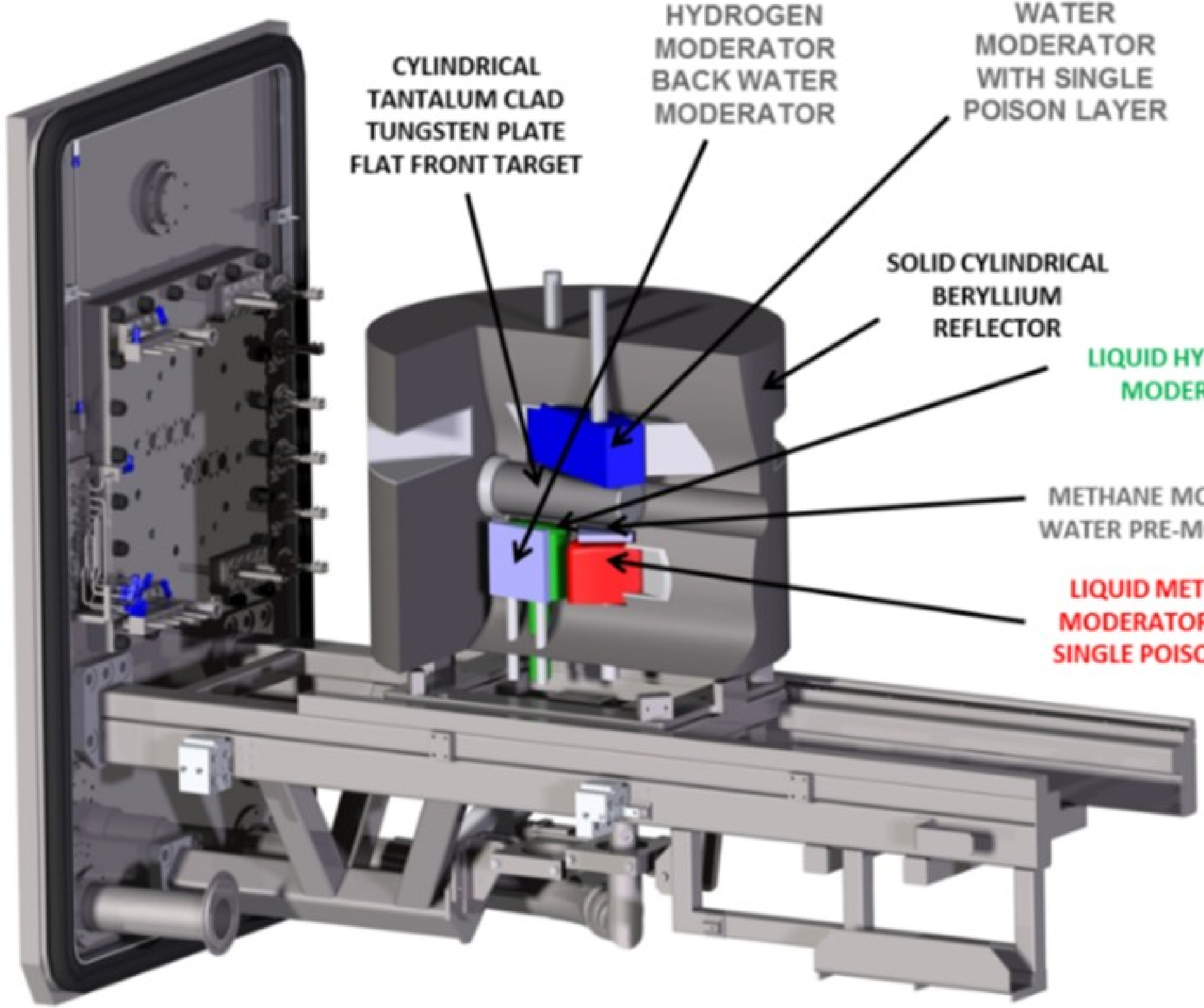


# Neutron Target




- Two neutron targets
- Energy deposited → speeding car hitting the target *every second*
- Tantalum-clad Tungsten
- Water cooled
- Surrounded by neutron reflectors and moderators

# TS1 Target assembly

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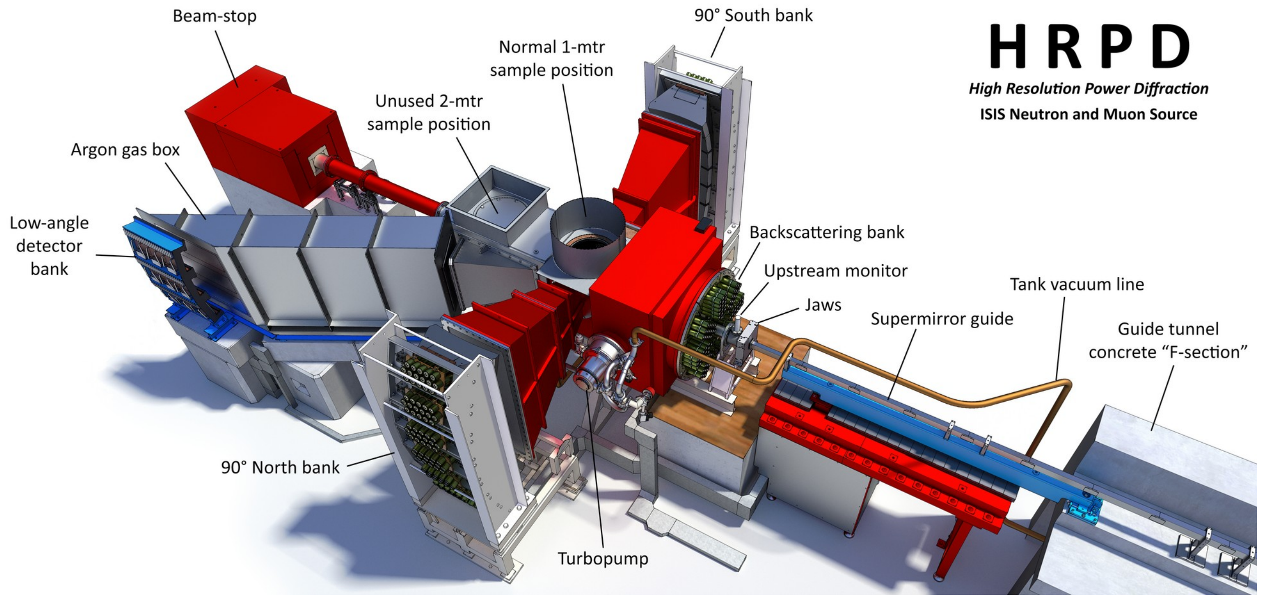
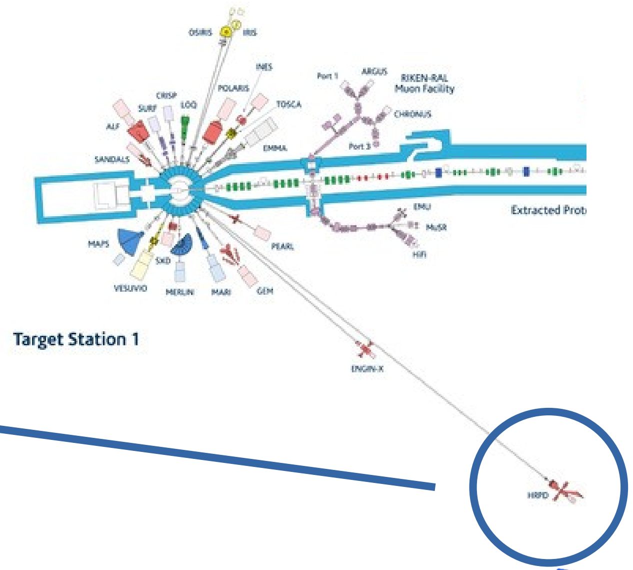
# Instruments - HRPD




https://epubs.stfc.ac.uk/manifestation/47807502/STFC-AAM-2020-063.pdf

- High Resolution Powder Diffractometer – HRPD
- Neutron wavelength → time-of-flight
- Bragg scattering: $\lambda_{hkl} = 2\, d_{hkl} \sin \theta_o$

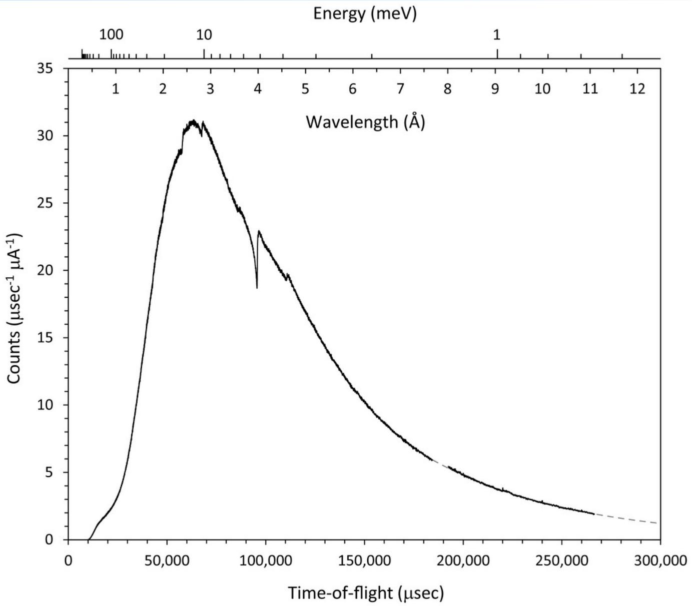
Neutron wavelength

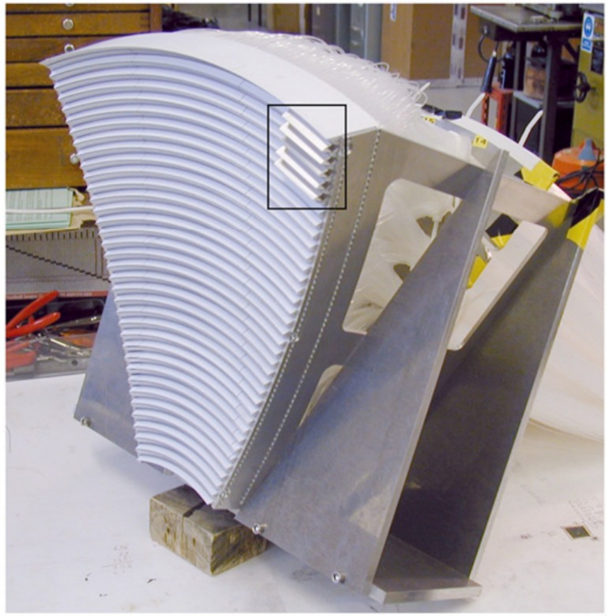
Crystal structure size

Scattering angle

# Instruments - HRPD

- Resolution driven by
  - Flight path uncertainty
  - Timing uncertainty
  - Angular uncertainty
- Long flight path → minimise uncertainty
- Detectors optimised for neutron detection
  - $He_3$ tubes
  - ZnS scintillating fibre



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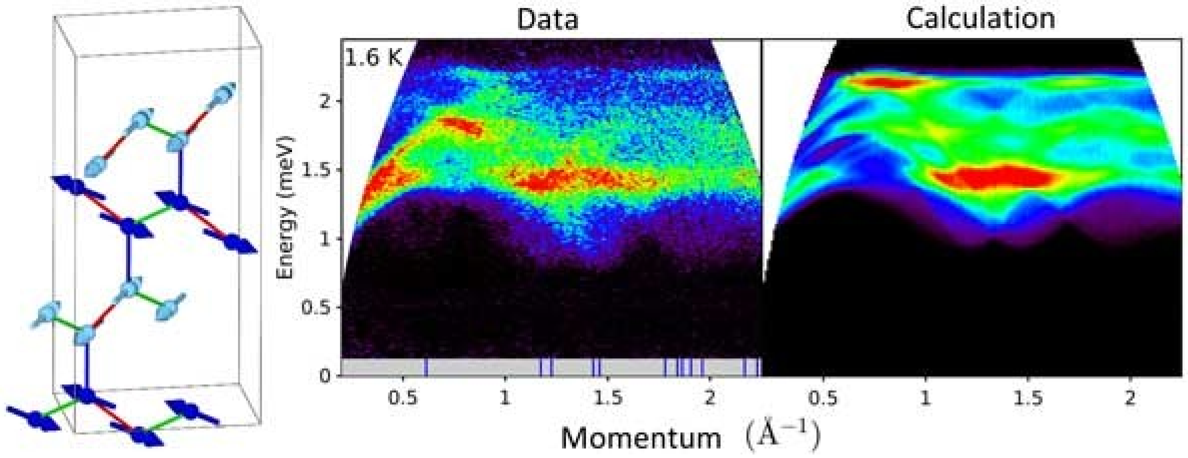
# Science - Magnetism

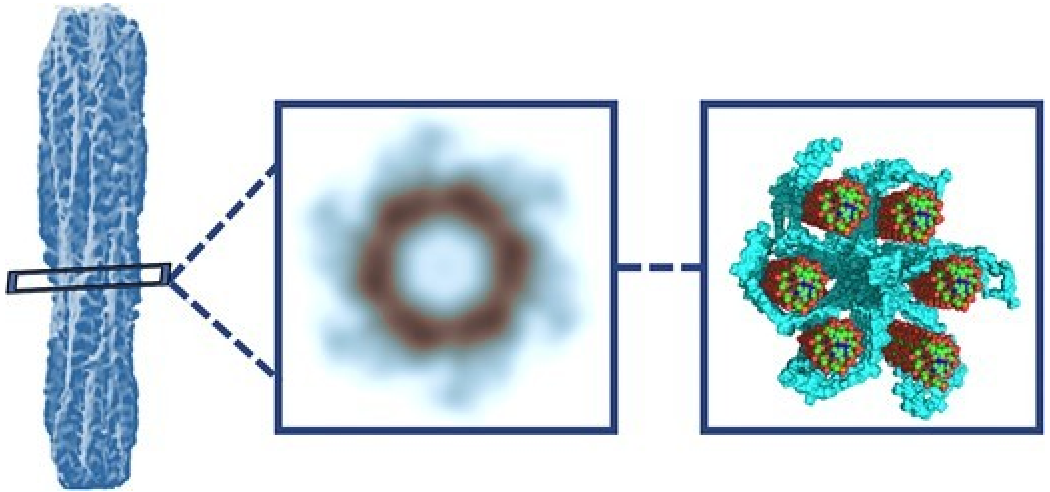
- Novel magnetic material $Na_2PrO_3$
- Magnetic moments aligned along different directions for different atoms
- Magnetic properties uncovered by
  - Neutron diffraction
  - Inelastic neutron scattering




Compass-model physics on the hyperhoneycomb lattice in the extreme spin-orbit regime, R Okuma et al, Nature Communications, 2024

# Science – DNA shaping

- Studying protein Hfq
- Looking at structure to understand how it can fold DNA
- Combined study using ISIS, ILL, electron microscopy



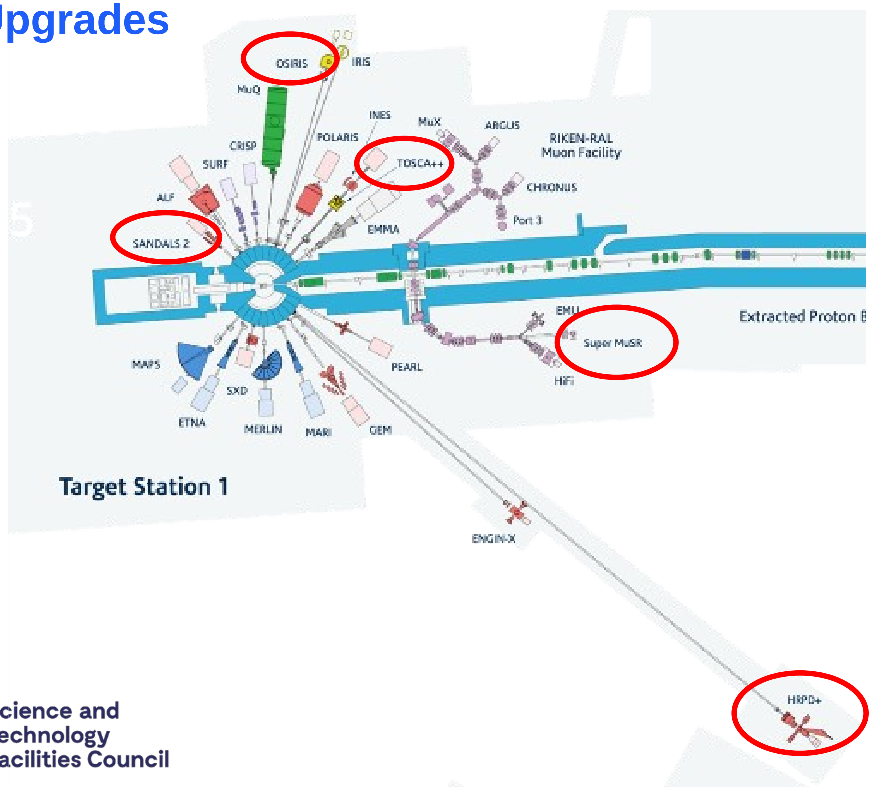
Amyloid-like DNA bridging: a new mode of DNA shaping, F. Wien et al, Nucleic Acids Research, Volume 53

# The Endeavour Programme

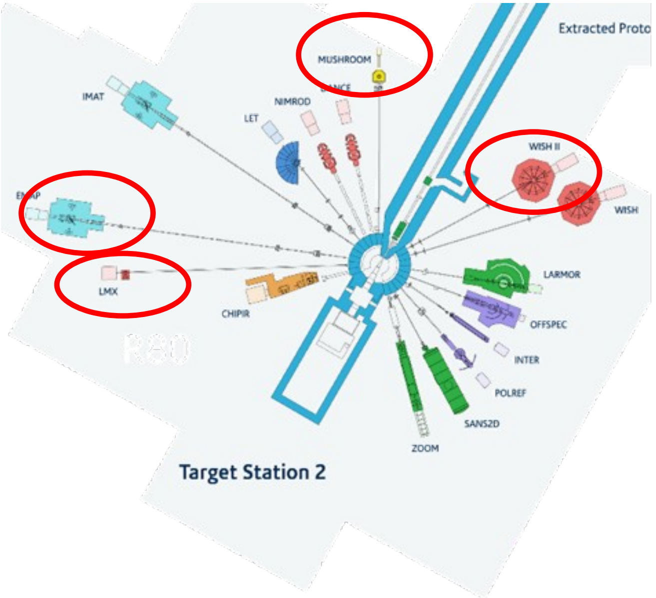
**Endeavour is a £93 million programme that will deliver four new instruments and five significant instrument upgrades between 2023 - 2033.**

The program will significantly boost the facility's capacity and capability, enabling researchers to tackle some of the most critical and transformative science challenges of the 21st century, including climate change and Net Zero, advanced engineering, quantum technologies and healthcare.

## 5 Major Upgrades




## 4 New Instruments

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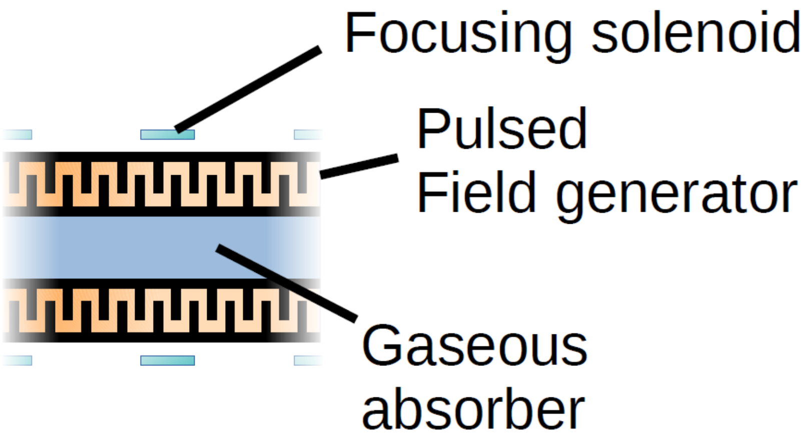
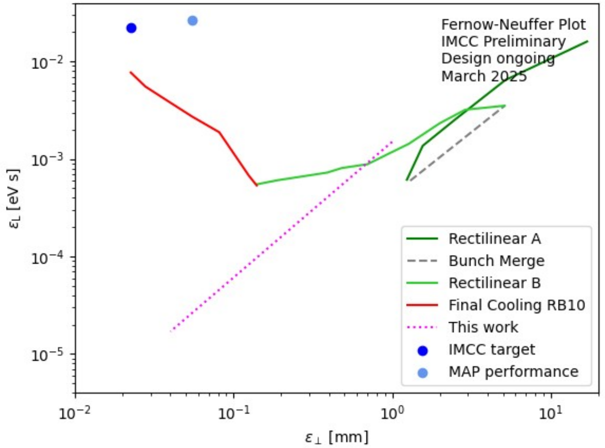
**Find out more about Endeavour**

# Slow muons

- Preliminary investigation of slow muon beam line
- Deliver ultra-low emittance $\mu^+$
- Very low energy (~ keV)
- High trapping efficiency
- Interesting for muon collider

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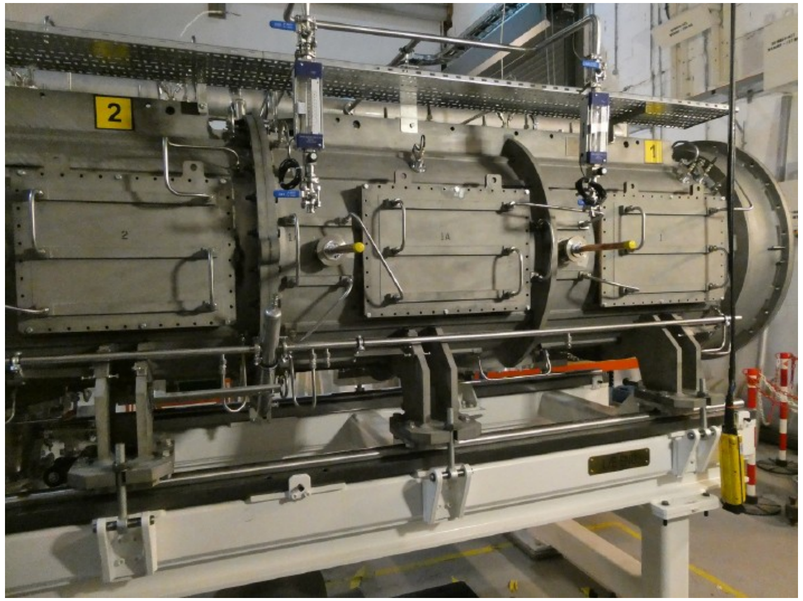
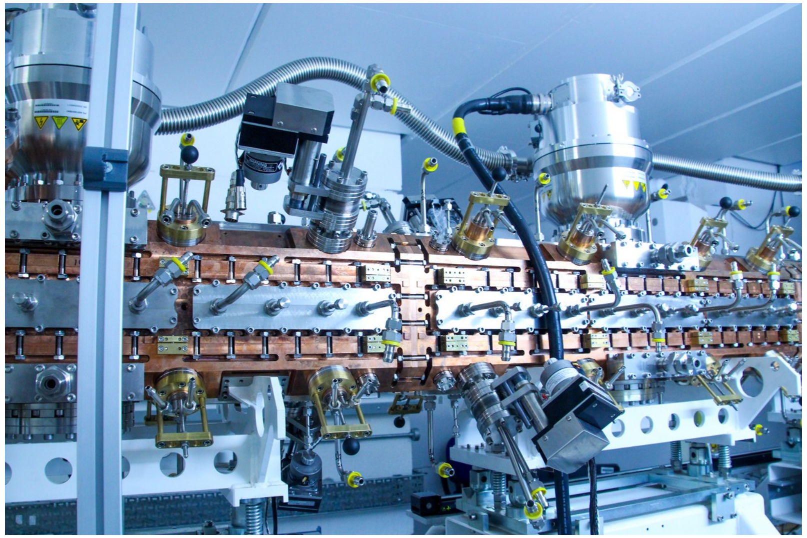
# Linac development

- Tank 4 Upgrade
  - New DTL tank installed in ISIS beamline in 2022
  - Replace old Tank 4 build in 1970s
- Front End Test Stand
  - Test stand for RFQ to 3 MeV
  - Test fast/slow chopper for clean beam production
- MEBT upgrade
  - Improved transport to Tank 1
  - Chopper for more efficient injection into synchrotron



# ISIS-II

- Neutron drought coming
  - ILL planned closure in 2030s
  - Even with ESS facility, reduction in neutron availability across Europe
- ISIS-II upgrade studied for multi-MW upgrade to ISIS
- Three options considered
  - Linac & accumulator ring
  - Synchrotron
  - FFA

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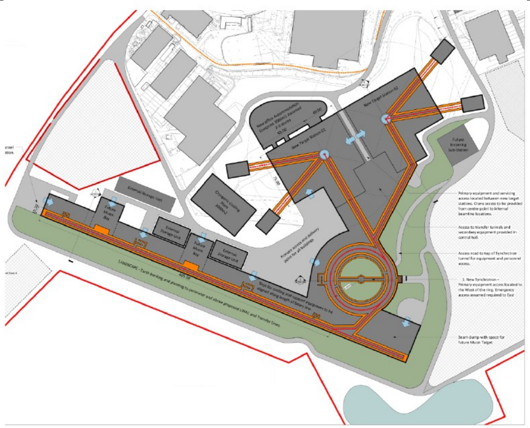
SCIENCEINSIDER | EUROPE

## Europe on course for a neutron drought

Billion-Euro accelerator won't make up the shortfall, experts say

14 MAR 2016 · BY EDWIN CARTLIDGE



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**Science and Technology Facilities Council**

**Neutron Science and Facilities**

**An Update to the 2017 Strategic Review**

June 2020

The concept of an ISIS II short pulse facility is exciting, and it has the potential to be very complementary to other sources. Continued exploration is strongly encouraged as a long-term option. Detailed analysis of the proposal is outside the scope of the current review, but the concept demonstrates visionary forward thinking and could create an exciting technical challenge to engage the whole UK community in.

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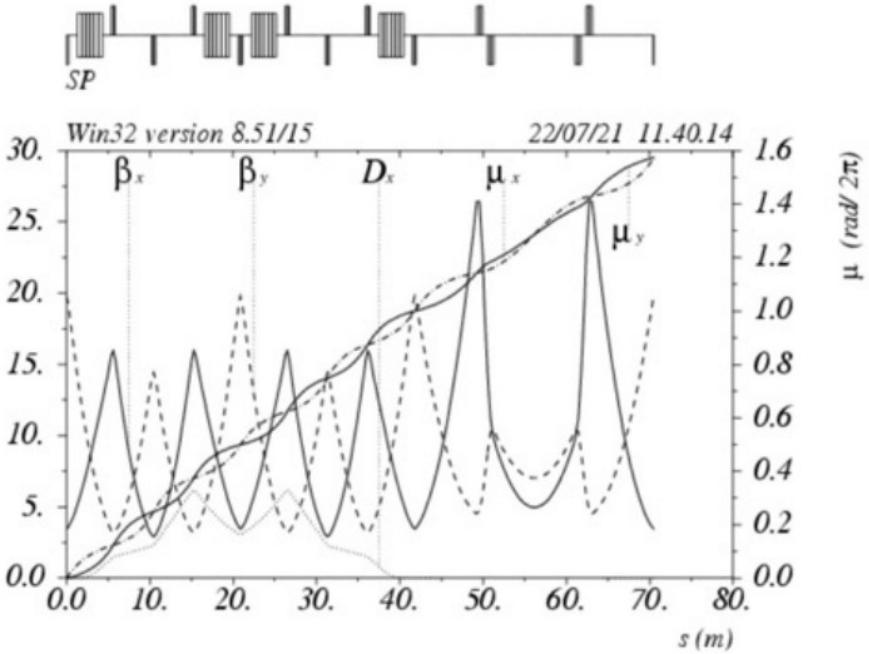
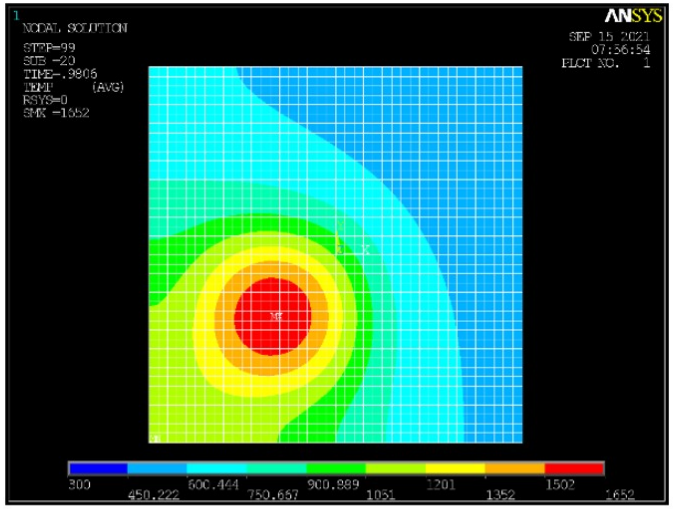
# Conventional Ring

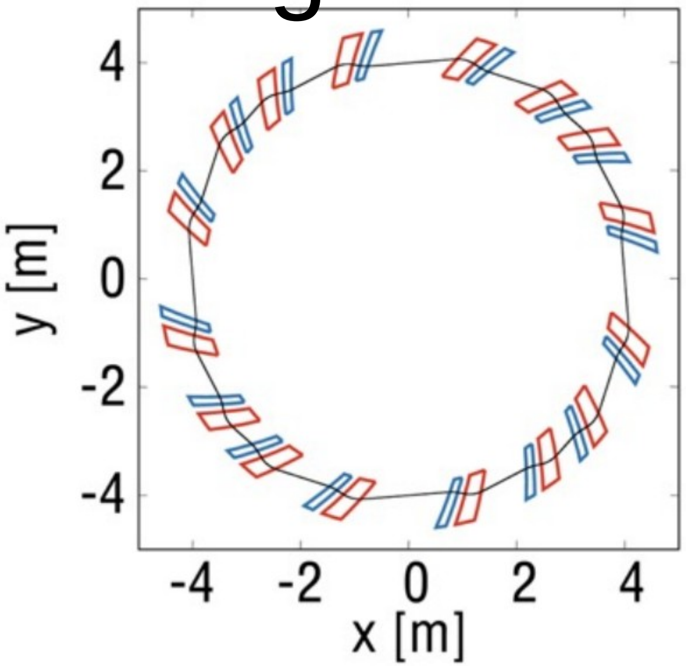
- Conventional ring concept  either:
    - Accumulator Ring + linac (SNS)
    - Synchrotron (JPARC/Fermilab)
- Technical challenges
    - Injection foil heating
    - Loss must be reduced x10 compared to ISIS
    - Target power

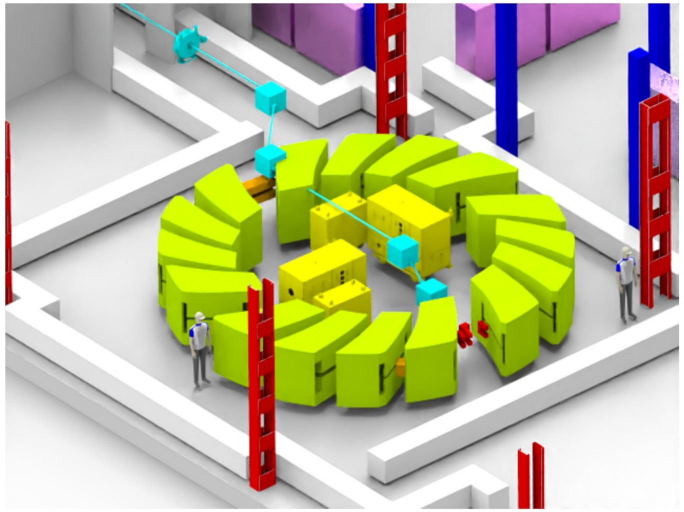


# Fixed Field Alternating Gradient Ring

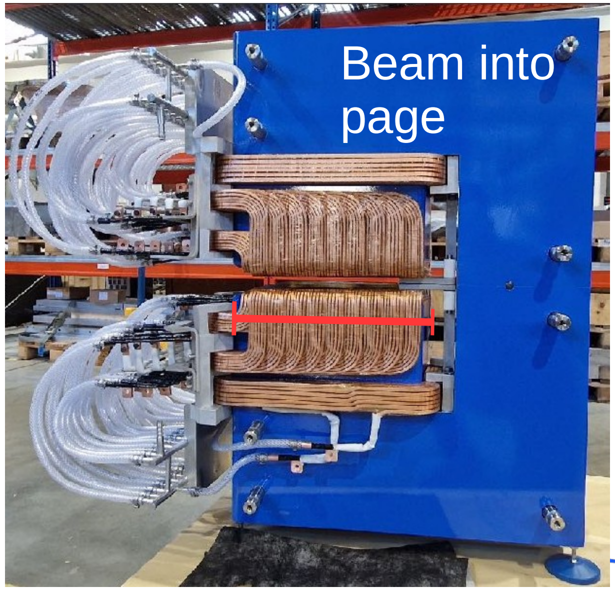
- FFA → modified synchrocyclotron
  - Fixed field like cyclotron
  - Variable frequency RF like synchrotron
- Bending (dipole) ramps with radius
  - Much more compact than cyclotron
- Focusing strength (quadrupole) ramps with radius
  - Keep tune constant
- Advantages
  - More acceleration cycles per second
  - Access to superconducting magnets
- But no high intensity experience
- Synergy with LhARA phase II

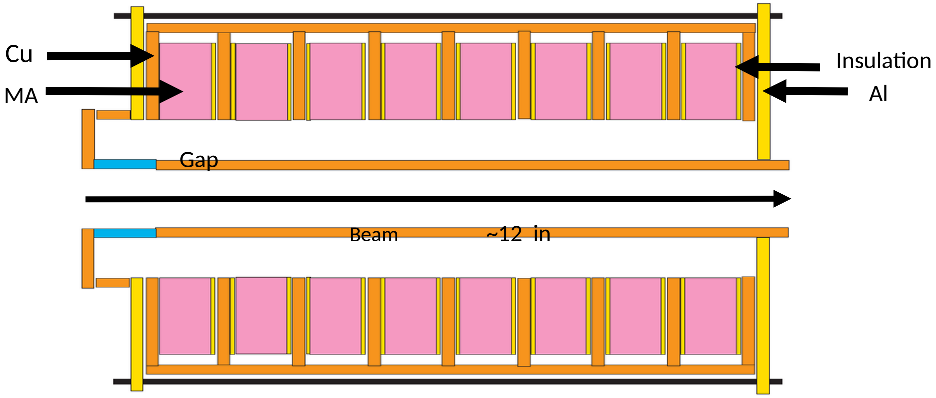


# FFA R&D

- Optics design for FFA with variable working point
  - Changable gradient → variable tune
- Prototype (normal conducting) magnet
  - 1/3 scale
- Prototype ferrite/magnetic alloy core
  - Much wider than ISIS cavities
- CDR delivered March 2025 for prototype ring

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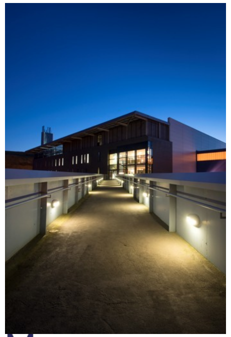
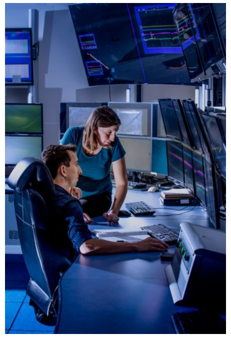
# Conclusions

- ISIS has been operating for more than 40 years
- Some major components are more than 70 years old
- High intensity rapid cycling synchrotron
  - Loss Limited
- Delivers broad range of exciting science
- Studies for an upgrade are underway






Muon

# Thanks

- Contributions from across ISIS
  - Accelerator
  - Target
  - Instruments
  - Science teams