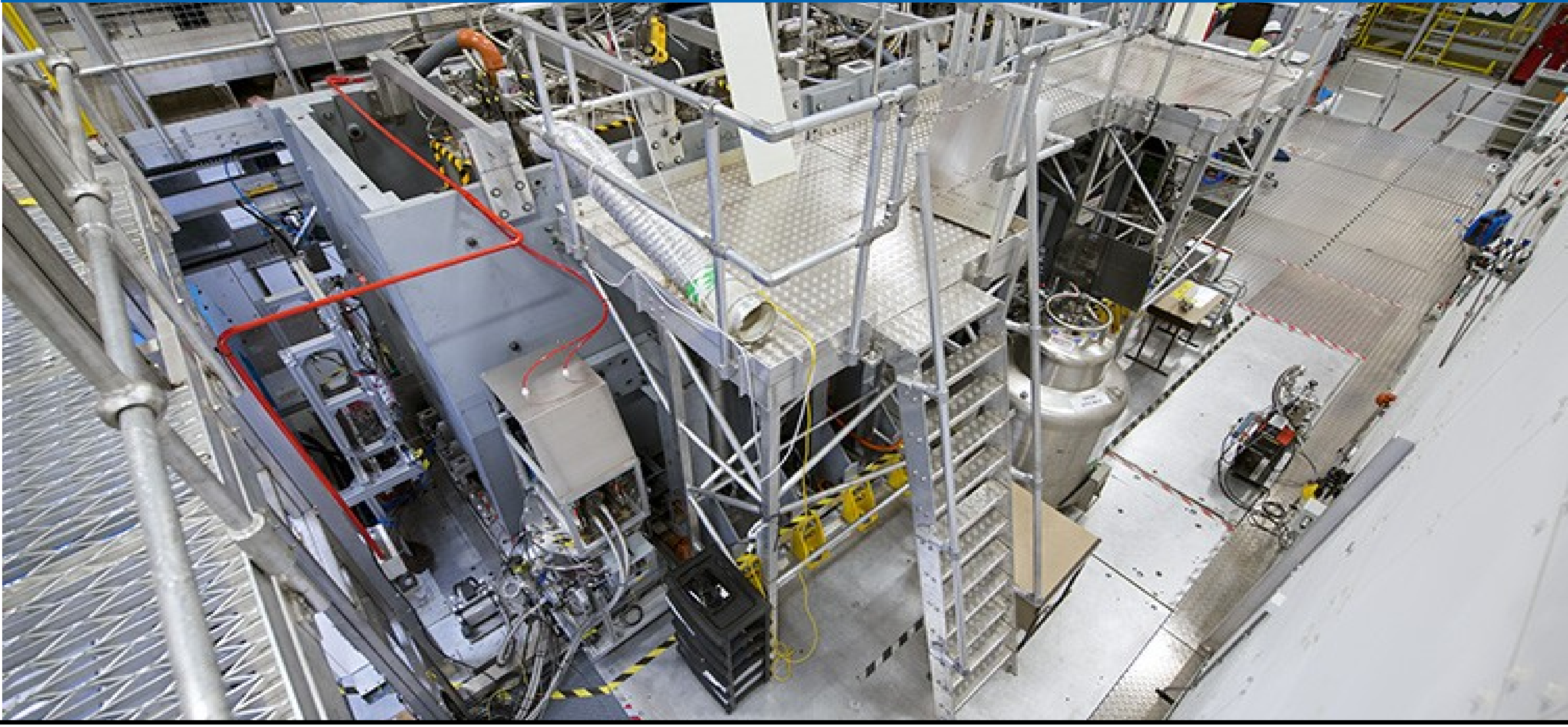
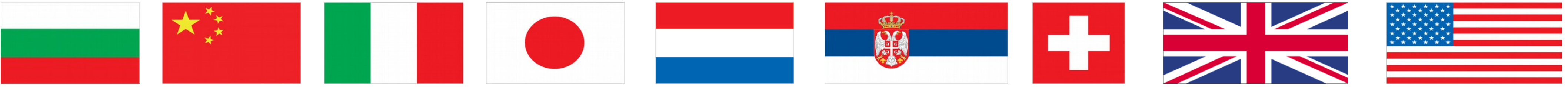
MICE

Muon Ionization Cooling Experiment





Steve Boyd / Warwick

Liverpool 2019

- MICE motivation
- A little light beam physics
- Muon ionisation cooling
- MICE design and data-taking
- Preliminary results from MICE
- The Future of MICE

- Accelerators were first built in the 1920’s/30’s to accelerate protons/ions and electrons for fundamental research

- **Hadron accelerators**
  - Discovery machines e.g. LHC
    - Messy hadronic environment
  - High $\sqrt{s}$
- **Lepton machines**
  - Precision machines e.g. LEP
  - Relatively lower $\sqrt{s}$
- **Secondary particle accelerators**
  - pions, kaons, neutrinos e.g. NUMI

Lepton machines

Circular Machines

✓ Accelerate beam in many turns
✓ Can use a single injection many times

✗ are limited by synchrotron radiation losses

$$\Delta E \propto \left(\frac{E}{m}\right)^4$$

Large for electrons

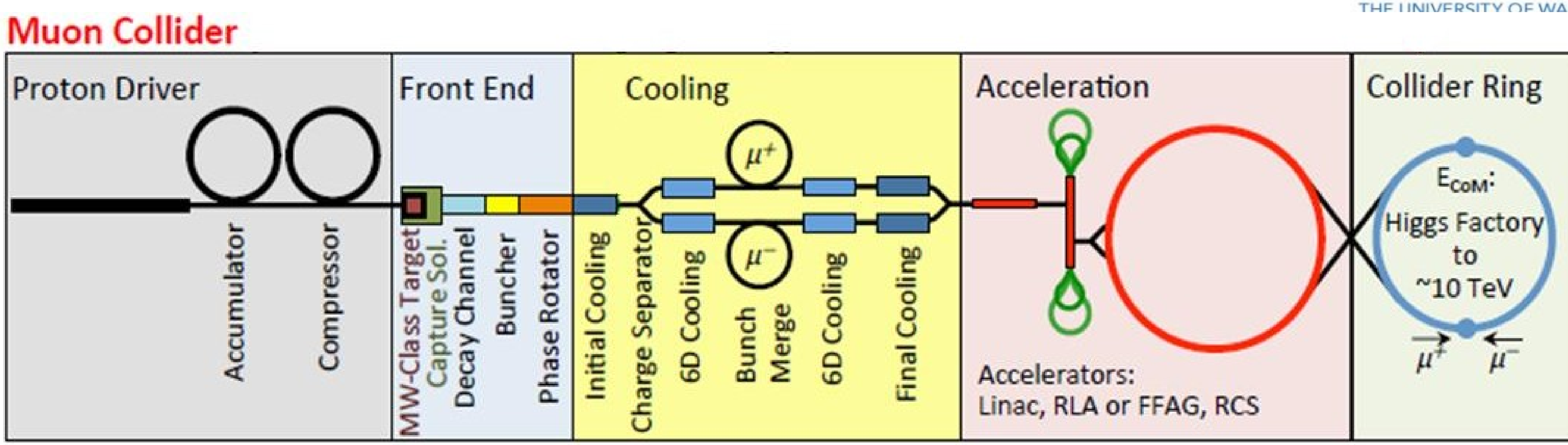
Linear Machines

✓ Almost no radiation loss

✗ Have to achieve energy/ luminosity in a single pass

✗ Limited by available RF

1. Muon colliders

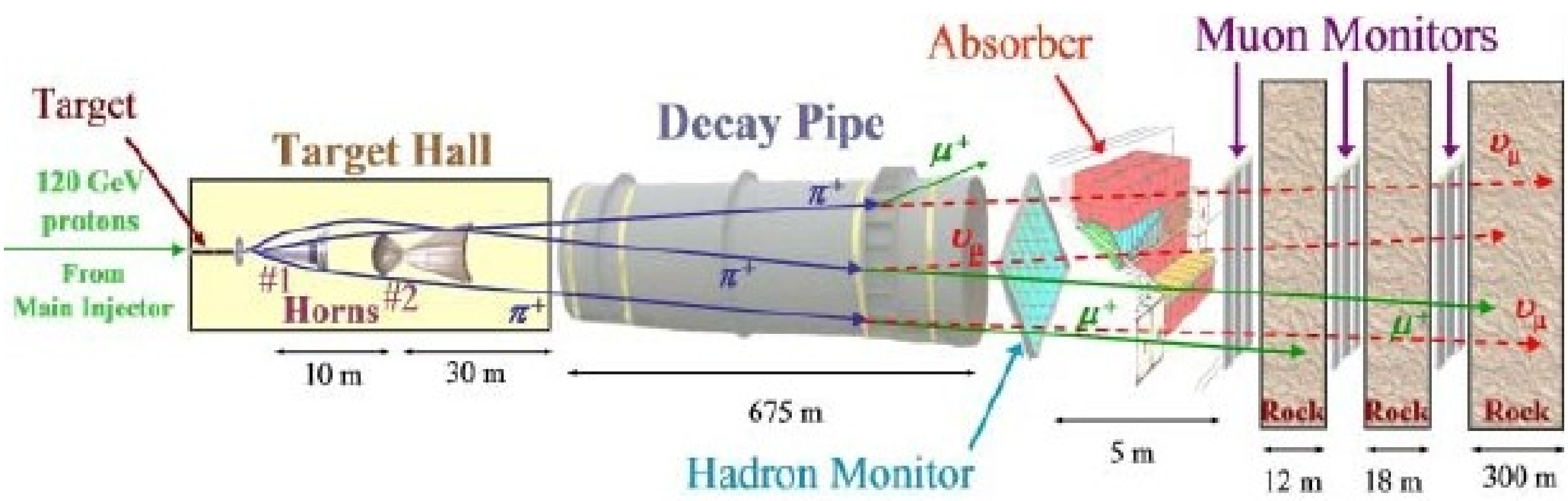


- MW-class proton driver
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV
- Collisions
- Critical issues
  - High initial beam size
  - Short muon lifetime

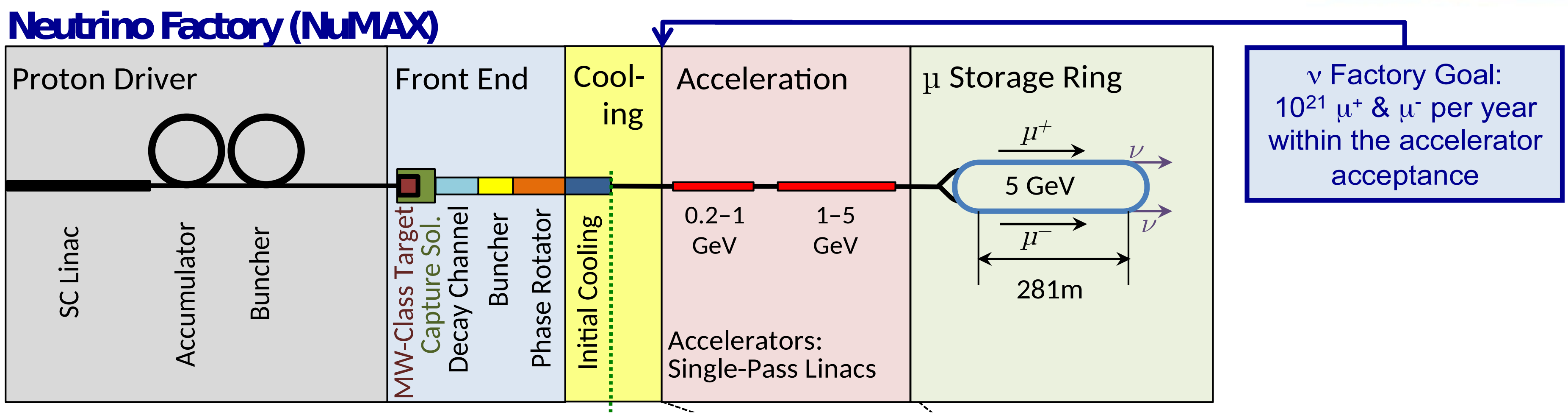
- muon mass is 200 x electron mass so synchrotron radiation is not a large problem
- can operate at higher √s with circular machines
- Higgs factories

Neutrino Beams

- Most accelerator-based neutrino oscillation experiments are based on the same basic design
- Make pions from proton/low-Z interactions
- Pions decay, emitting a muon (typically) and neutrino
- Muons are removed leaving only the neutrino
  - Neutrino flux is hard to simulate – systematic uncertainty O(5-10%)
  - One of the largest systematic errors in neutrino experiments



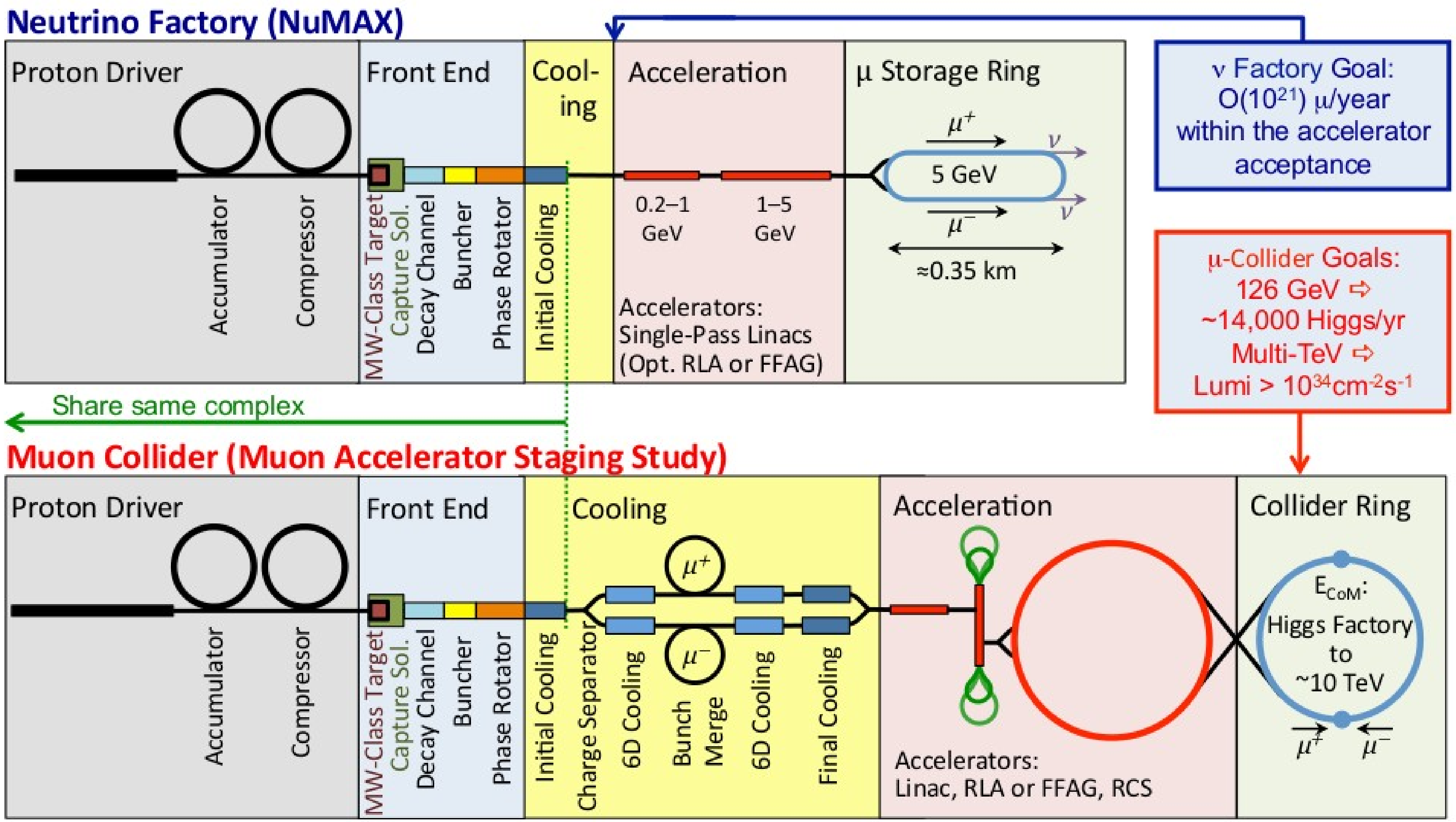
2. Neutrino Factories



- MW-class proton driver
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to GeV
- Muons decay in storage ring
- Critical issues
  - High initial beam size
  - Short muon lifetime

- Flux precisely known
- Precision measurements of neutrino oscillation parameters including CP phase
- Precision cross section studies (although neutrino energy is not known on an event-by-event basis)

Comparisons

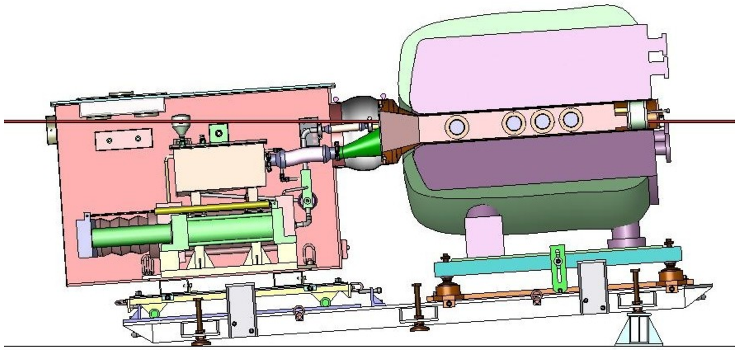


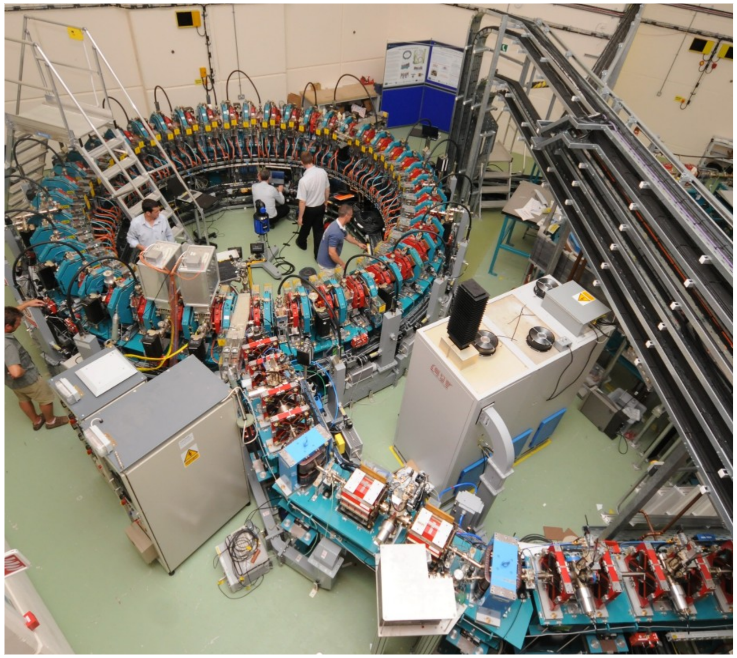
Systems for both facilities are essentially identical up to the initial cooling section

Accelerator R&D

WARWICK
THE UNIVERSITY OF WARWICK

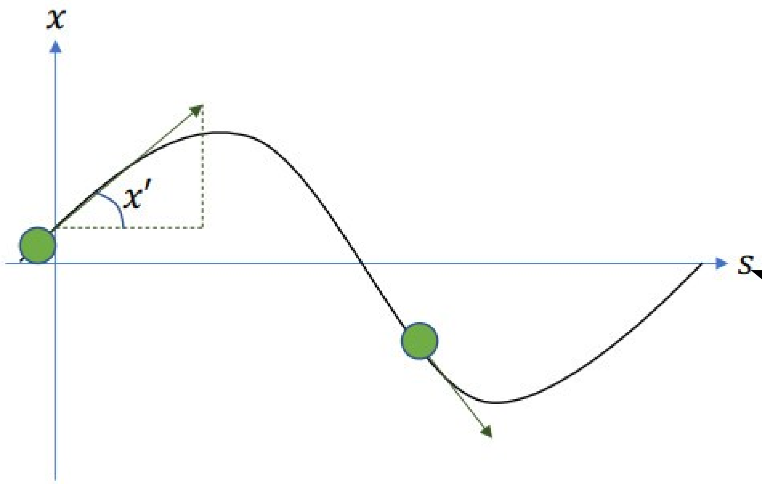
- MERIT
  - Demonstrated principles of high power proton targetry
- EMMA
  - Demonstrated fast acceleration using Fixed-Field Alternating Gradient (FFAG) accelerators
- MUCOOL
  - Cavity R&D for ionisation cooling
  - Demonstrated operation of cavities at high voltage in magnetic fields
- MICE
  - Ionisation Cooling

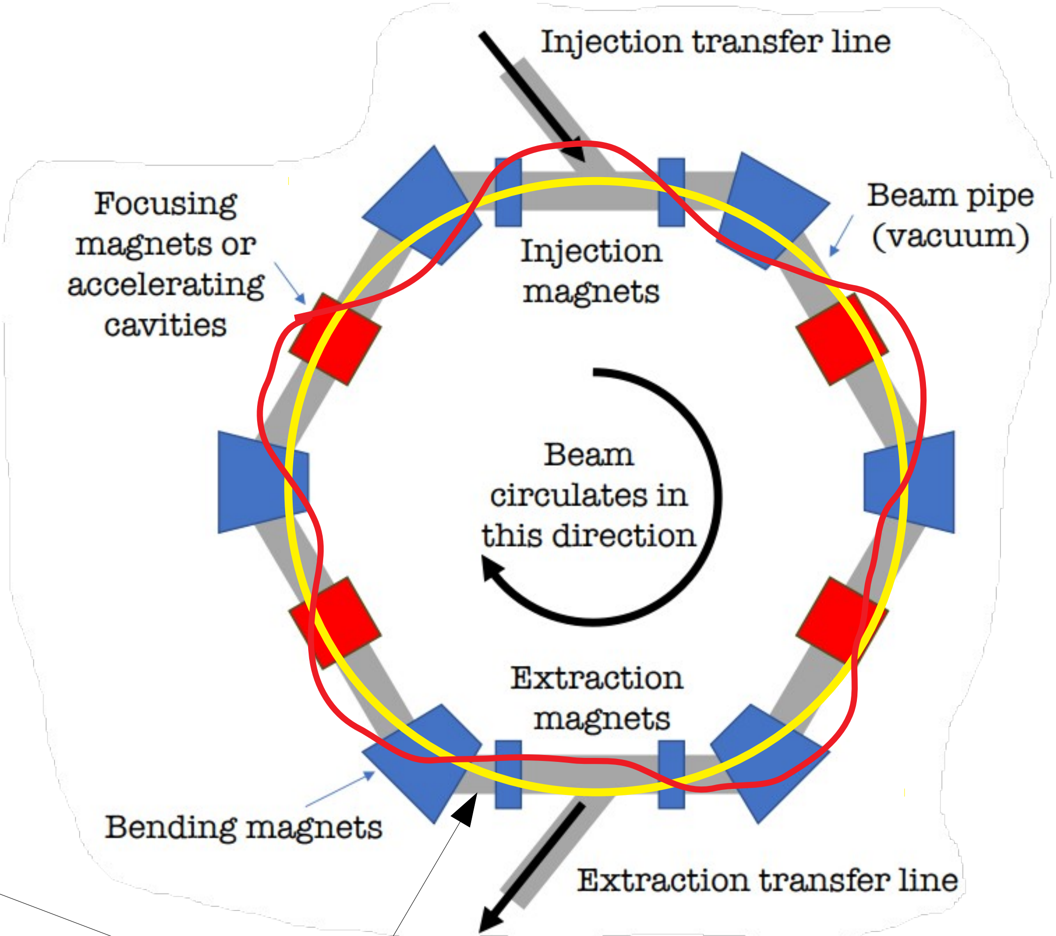




A bit of beam physics

- Particle motion is controlled by magnetic fields
- A single particle will typically exhibit *betatron oscillations* around an ideal reference orbit

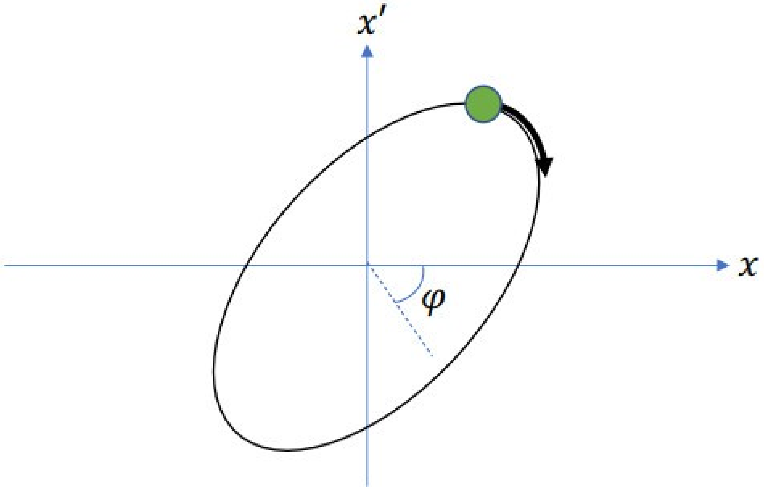


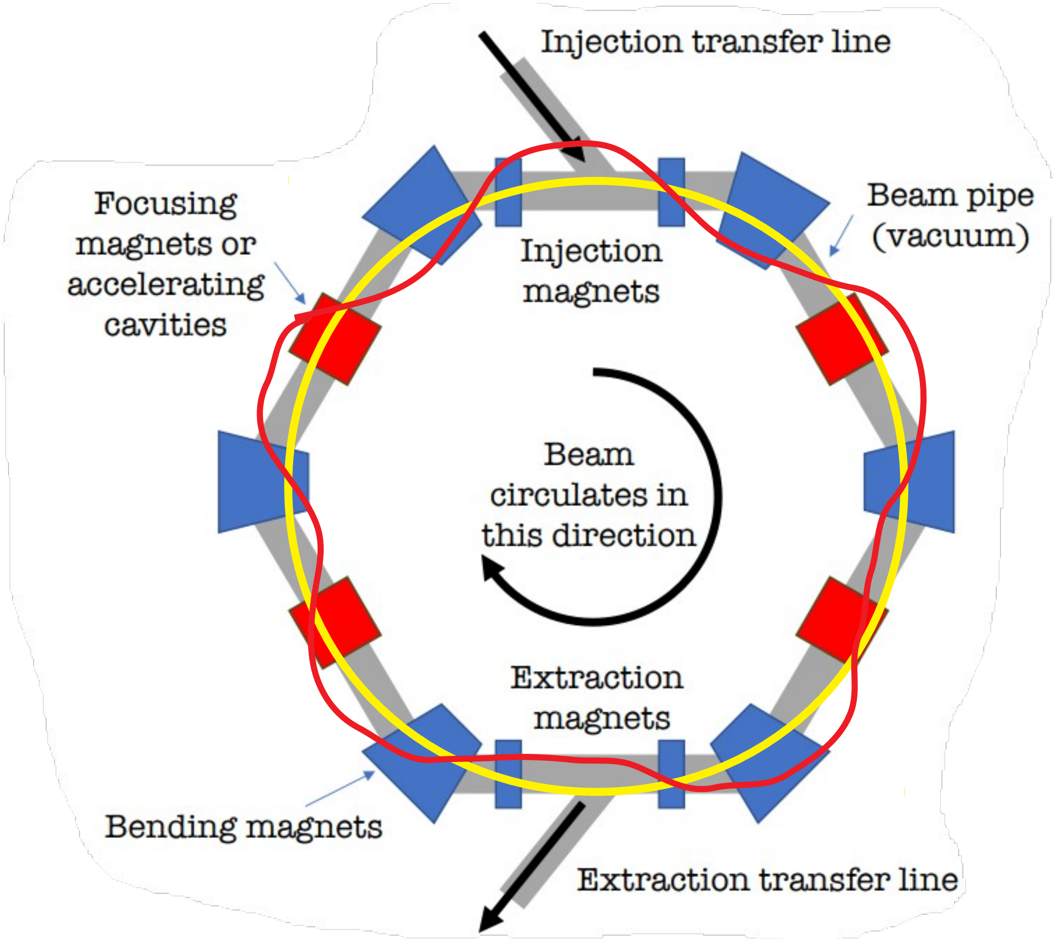


Reference orbit

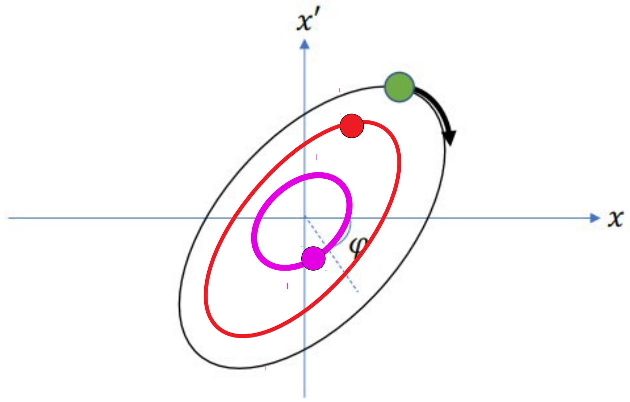
Beam Concepts

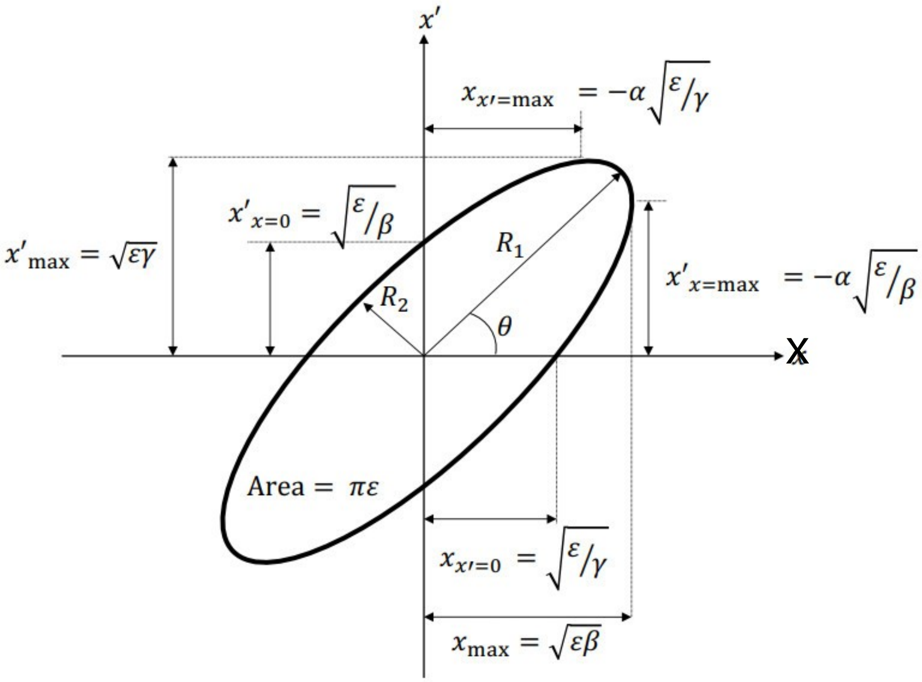
- particle path does not have to close in one orbit
- particle moves around an ellipse in phase space (x,y,z,p_x,p_y,p_z) as the particle makes turns around the ring
- Different ellipse at each point around the ring.





Beam concepts



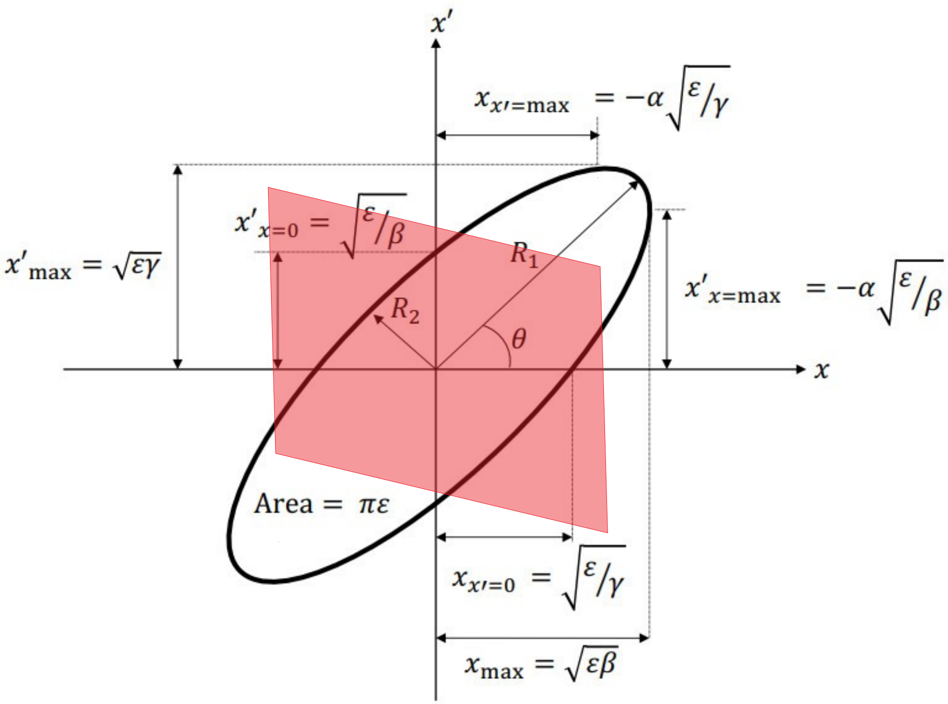


- Particles with different initial conditions lie on different ellipses
- RMS ellipse of all particle ellipses (the *machine ellipse*) is defined by the *Twiss parameters*
  - α → related to beam convergence
  - β → related to beam shape and size
  - ε → *emittance* of the beam

$$Area = \pi\,\epsilon = \pi R_1 R_2$$

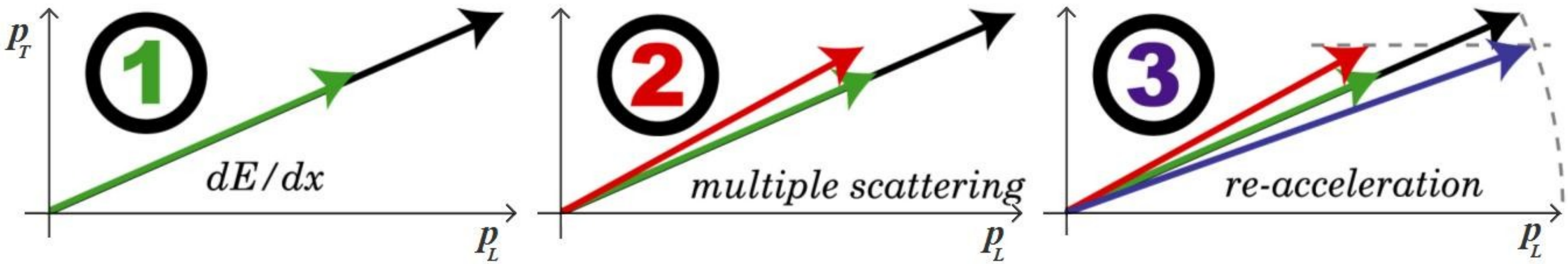
- volume of the beam in phase space
- conserved under conservative forces (Liouville's theorem)

Beam concepts



- Different parts of an accelerator have different apertures which only particles within a certain volume in phase space will enter
- Act of decreasing the beam emittance is called *beam cooling*
- Generally used to squeeze emittance to maximise transmission and/or interaction rates
- A number of different cooling techniques are available, but are too slow to work on the timescale of the muon lifetime
- MICE was designed to test the concept of *ionisation cooling* for muons

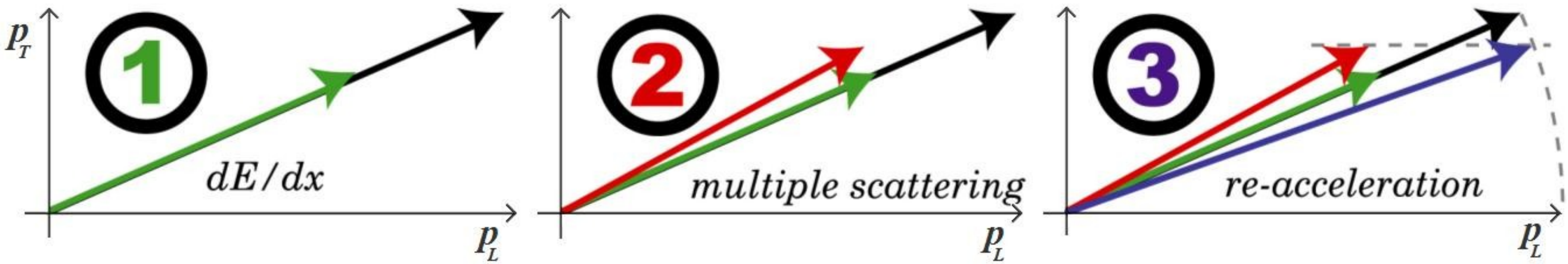
Ionisation Cooling



- Fast cooling achieved through ionisation energy loss in an absorber
- Followed by re-acceleration to replace lost momentum
- Stochastic effects limit emittance loss
- Multiple scattering increases beam emittance
- Tight focus and low-Z absorber material limits relative effect of scattering

$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\, MeV)^2}{2\beta^3 E m_\mu X_0}$$

Ionisation Cooling

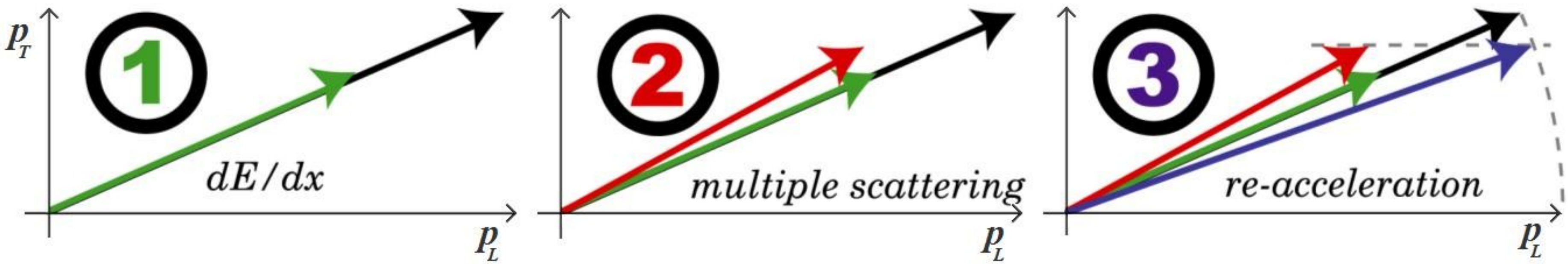


- Fast cooling achieved through ionisation energy loss in an absorber
- Followed by re-acceleration to replace lost momentum
- Stochastic effects limit emittance loss
- Multiple scattering increases beam emittance
- Tight focus and low-Z absorber material limits relative effect of scattering

$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\,MeV)^2}{2\beta^3 E m_\mu X_0}$$

Cooling

Ionisation Cooling



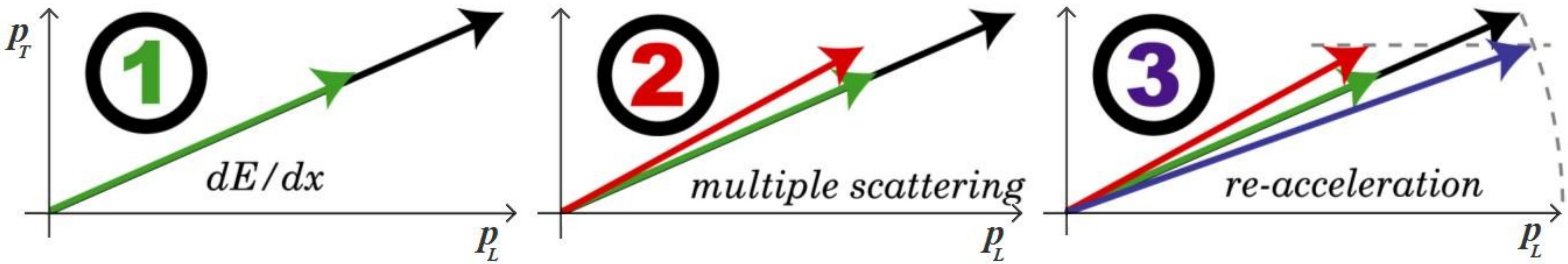
- Fast cooling achieved through ionisation energy loss in an absorber
- Followed by re-acceleration to replace lost momentum
- Stochastic effects limit emittance loss
- Multiple scattering increases beam emittance
- Tight focus and low-Z absorber material limits relative effect of scattering

$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX}\right\rangle + \frac{\beta_t (13.6\, MeV)^2}{2\beta^3 E m_\mu X_0}$$

Transverse width of beam

Heating

Ionisation Cooling



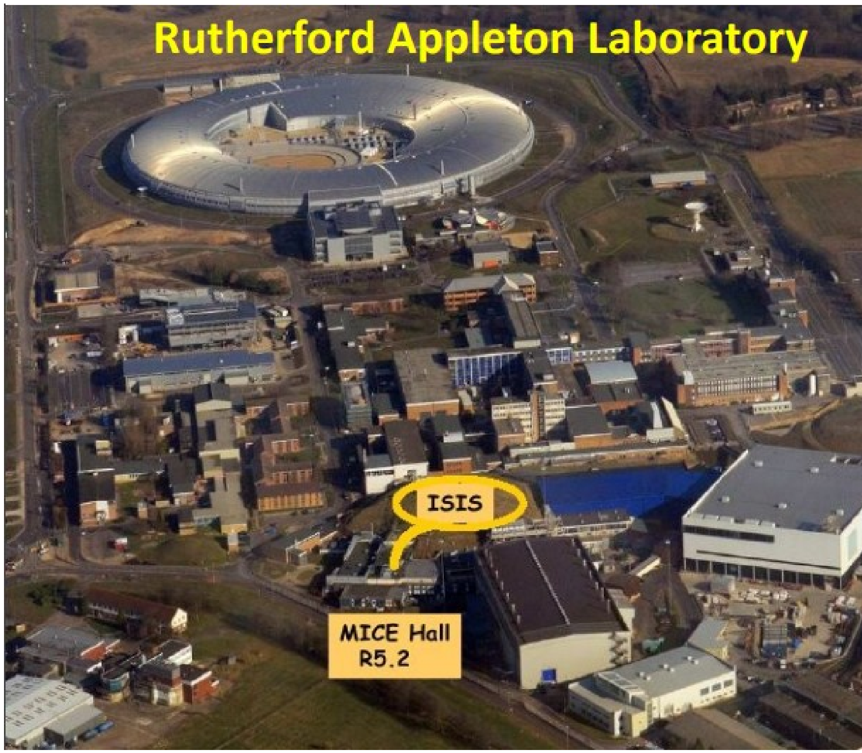
$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\,MeV)^2}{2\beta^3 E m_\mu X_0}$$

$$\epsilon_{eq,n} = \frac{\beta_t (13.6\,MeV)^2}{2\beta m_\mu X_0 \langle \frac{dE}{dx} \rangle}$$

- For efficient cooling we require
  - absorber material with
    - high dE/dx
    - low densities
    - large X_0

    } LH_2
  - minimal other material in the beam
  - low $\beta_t \rightarrow$ tight beam focus
- cooling cannot take place below an *equilibrium emittance*

MICE



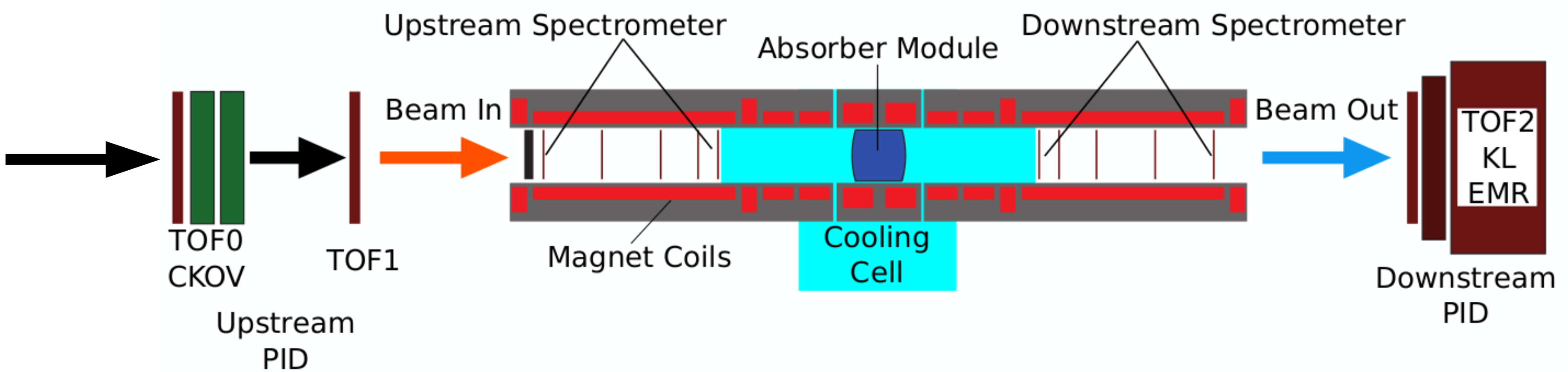
- Over 100 collaborators in 30 institutes in 10 countries
- Used the ISIS proton synchrotron at the Rutherford Appleton Laboratory

MICE

- A technology demonstrator:
  - Can we safely operate liquid hydrogen absorbers?
  - Can we operate a tightly packed lattice?
    - With high field magnets + liquid hydrogen?
    - With high field magnets + liquid hydrogen + RF?
  - Do we see the expected emittance change?
  - Do we see the expected transmission?

MICE

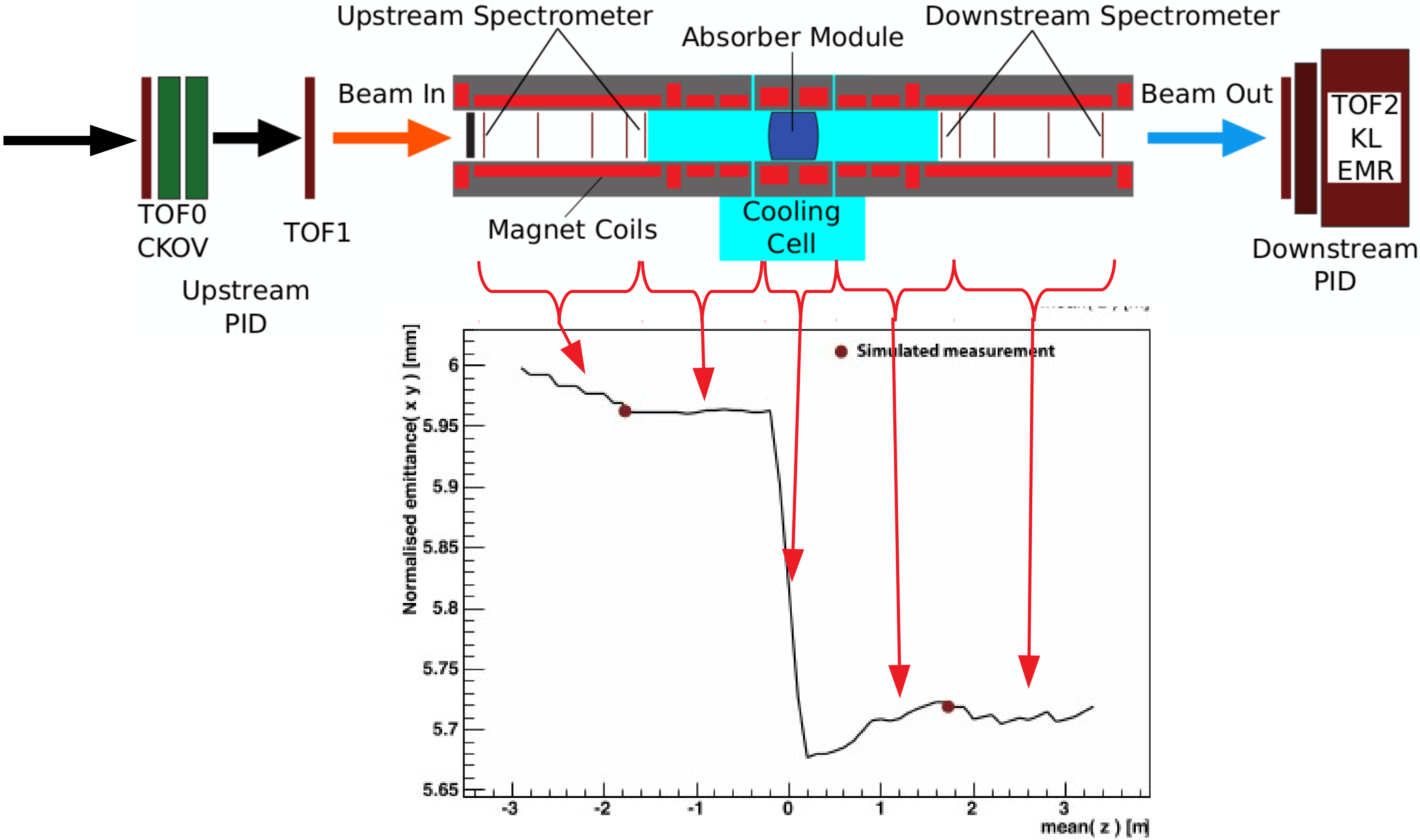
- MICE goal is to verify emittance reduction from ionization cooling



- Generate muons from proton-Ti interactions in the ISIS accelerator at RAL
- Pass single muons through the channel and measure their properties upstream and downstream of the absorber
- Assemble a virtual beam in software by cutting on the upstream beam distributions
- Construct the emittance of the beam ensemble upstream and downstream of the absorber
- *Change in normalised transverse emittance indicative of ionisation cooling*

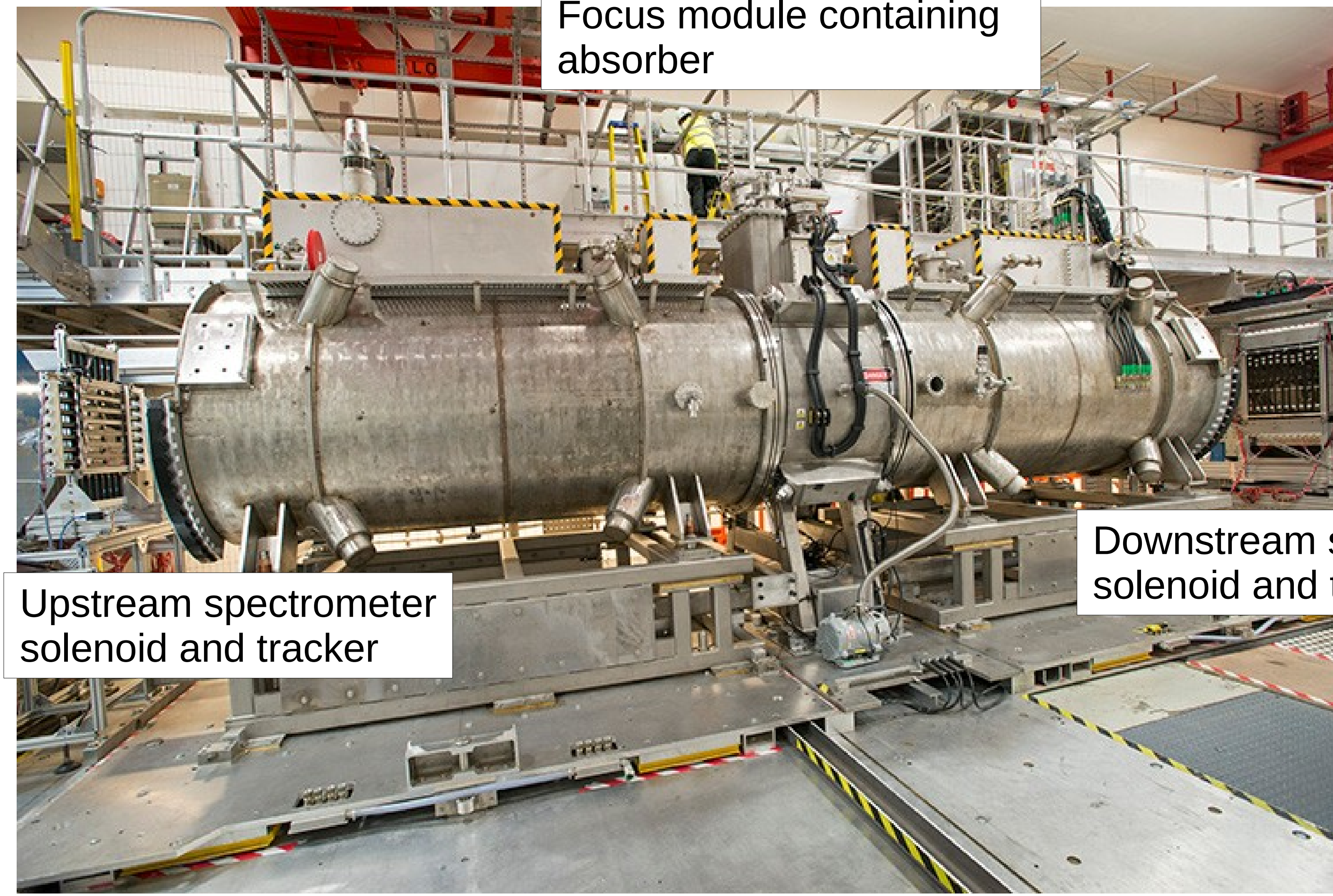
MICE

- MICE goal is to verify emittance reduction from ionization cooling

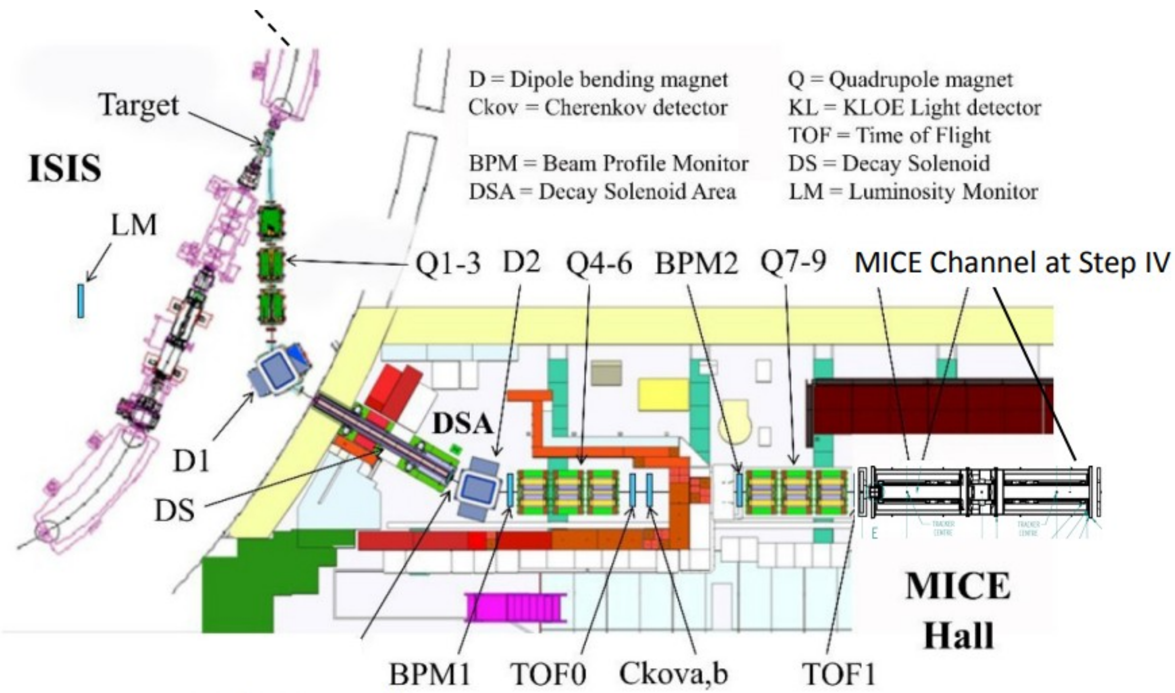


MICE

WARWICK
THE UNIVERSITY OF WARWICK

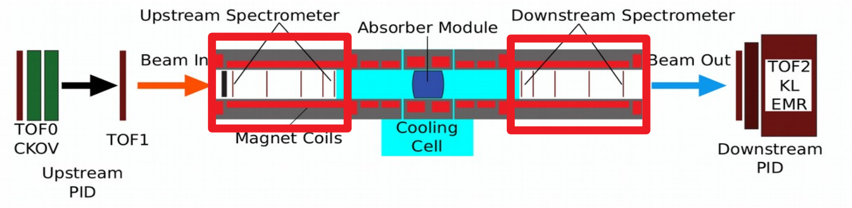


MICE Muon Beamline

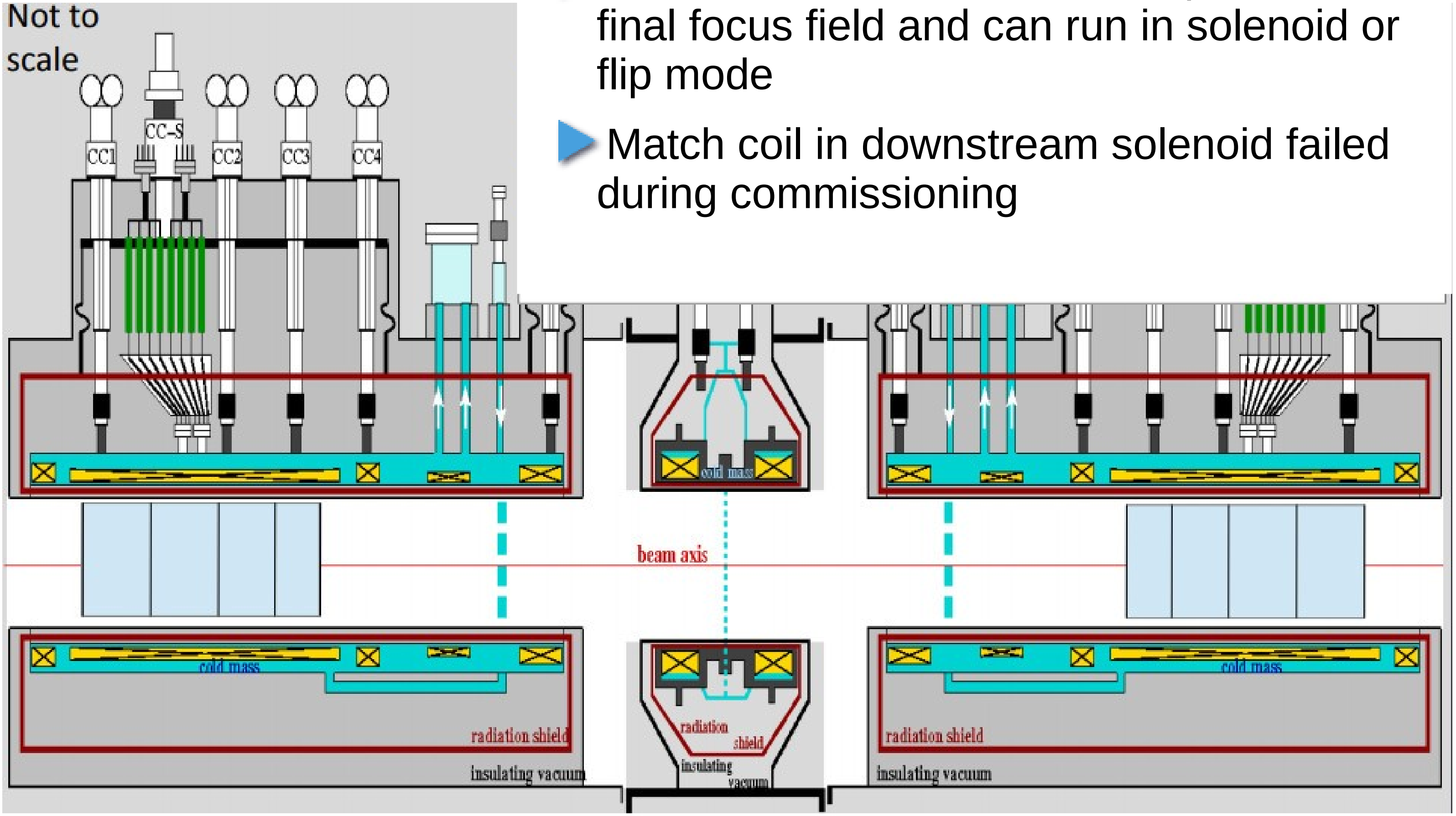


- 800 MeV protons hit custom-made Ti target in the ISIS beamline
- Pions from these interactions are siphoned into extraction line
- pions decay inside a decay solenoid to muons
- 3 ms spill in two 100 ns bursts every 324 ns
- 120 MeV/c < p_{μ} < 260 MeV/c
- Muon emittance between 2 π mm.rad and 10 π mm.rad
- Pion contamination in muon beam is less than 1%

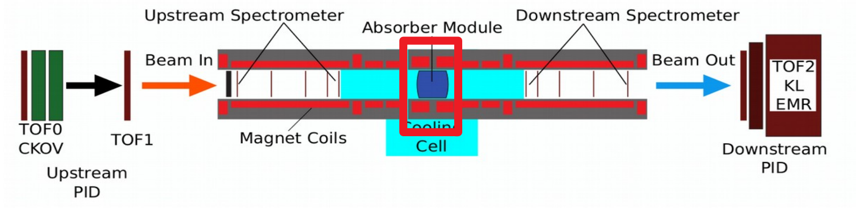
Analysing magnets

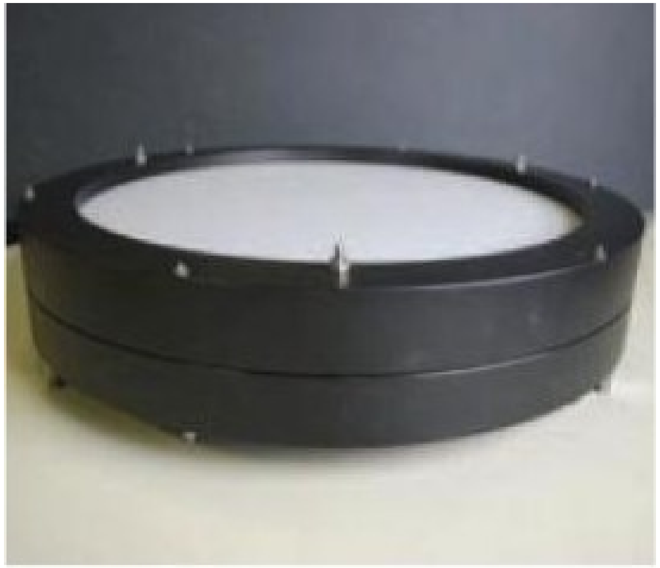


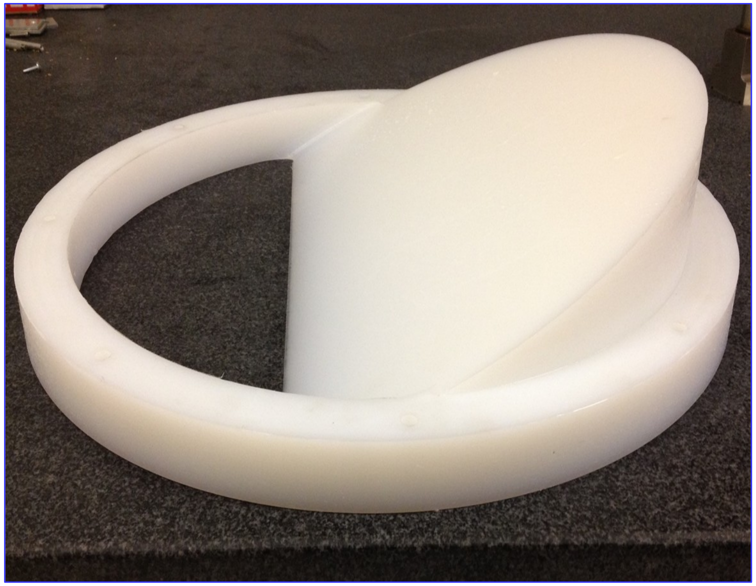
- 400 mm bore, 5 coil assembly
- Nominal 4T (run at 3T for data-taking)
- 4K core temperature
- Focus coil contains absorber, provides final focus field and can run in solenoid or flip mode
- Match coil in downstream solenoid failed during commissioning



Absorbers

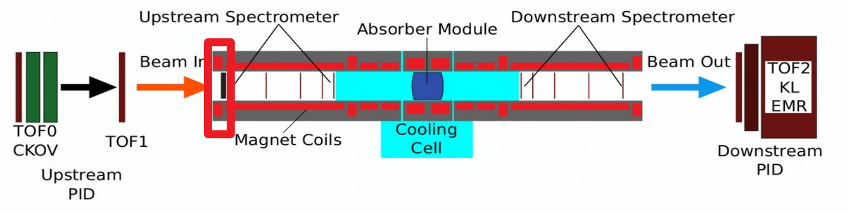


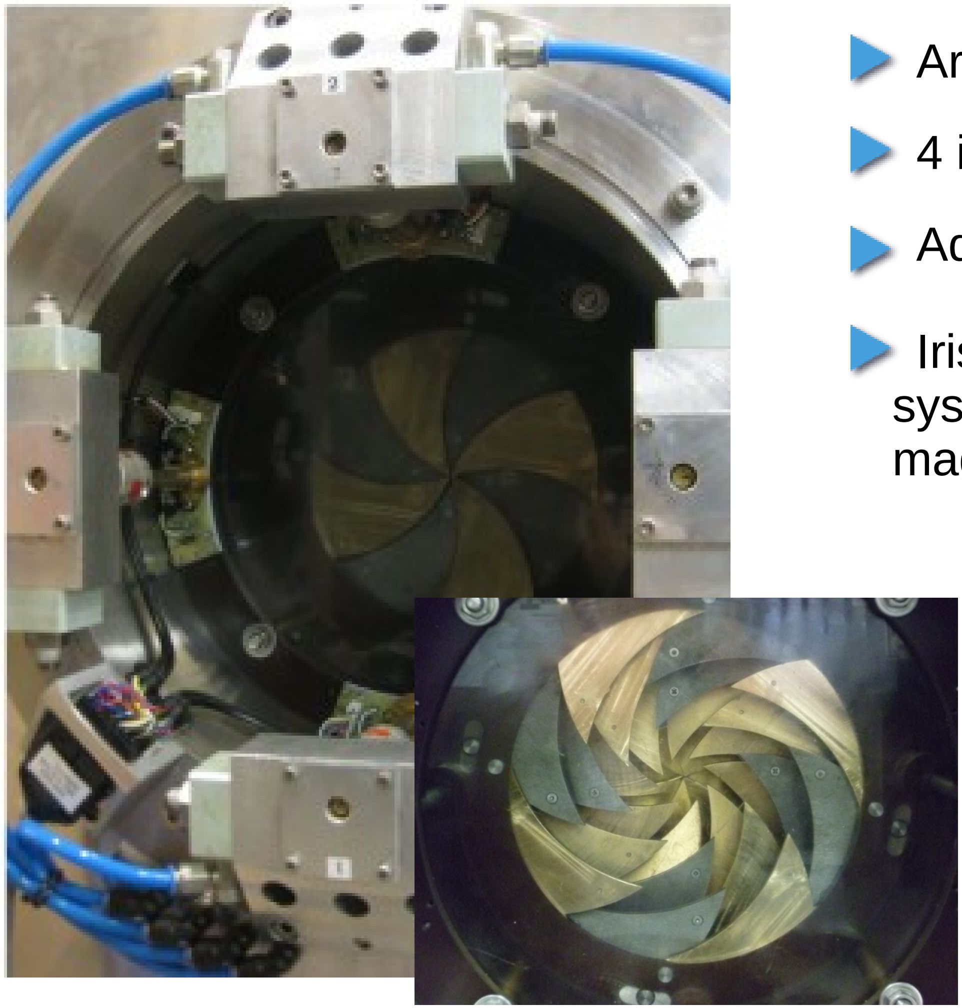




- 65 mm thick LiH absorber disc
- 350 mm thick LH_2 absorber
    - LH_2 vessel terminated by two 180 micron Al windows
- Polyethylene wedge absorber designed for longitudinal emittance exchange studies

Diffuser



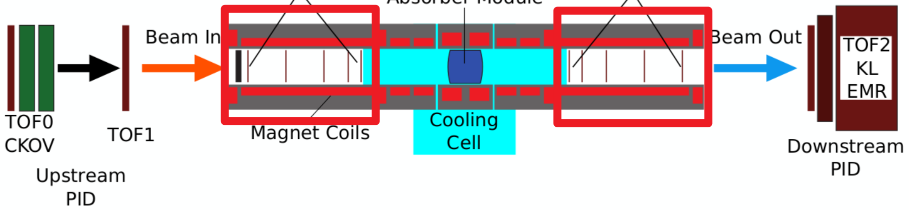


- Positioned at the upstream entrance of the upstream solenoid
- Artifically inflates the emittance of the input beam
- 4 irises made of brass and tungsten
- Add up to 3 X_0 into the beam, in 0.2 X_0 steps
- Irises opened and closed using a pneumatic system, as motors would not work in the solenoidal magnetic field

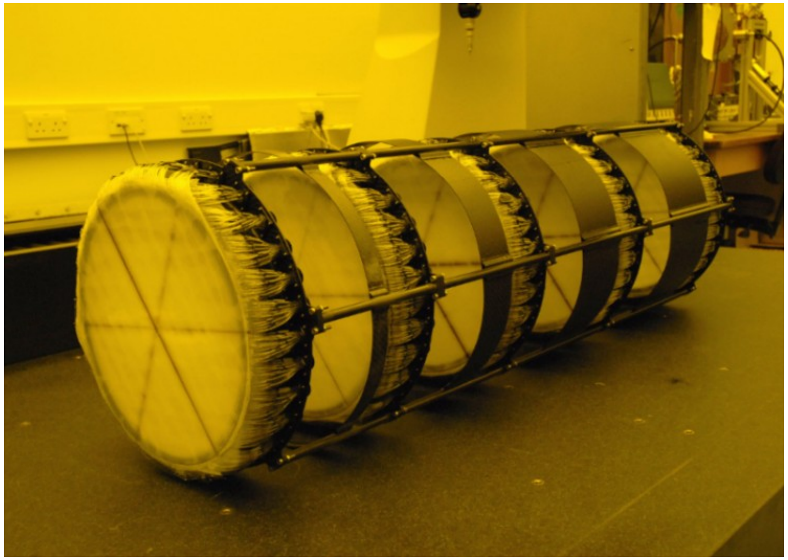
$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\, MeV)^2}{2\beta^3 E m_\mu X_0}$$

Trackers

- Scintillating fibre planes positioned upstream and downstream of the absorber
- 5 stations per tracker
- 3 planes per station at relative 120^{o} rotation
- Contained within the 4T fields of the spectrometer solenoids

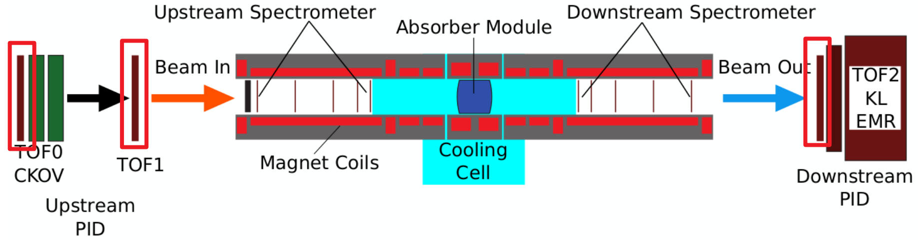


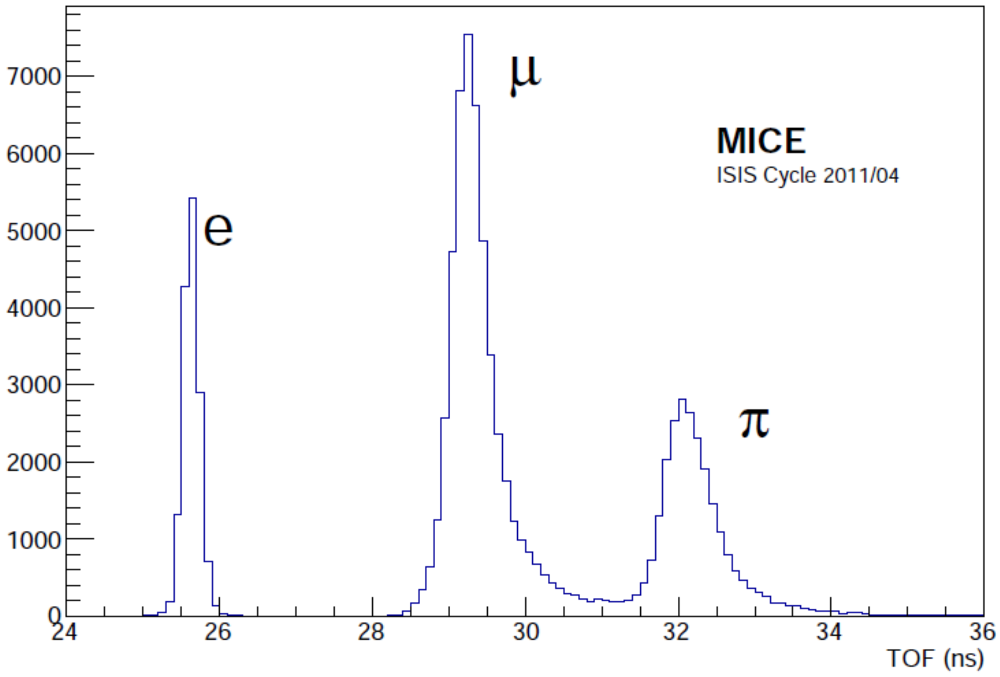
Track position resolution	470 micron
σ(p_T)	1 – 2 MeV/c
σ(p_z)	3 – 4 MeV/c



TOF Detectors

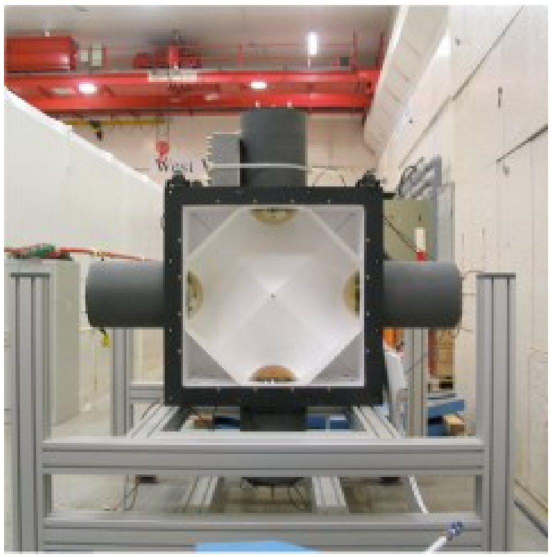
- 3 Time-of-flight stations
  - 2 planes of fast scintillator
  - Double ended readout
- 50-60 ps hit time resolution
- provides PID and p_z check

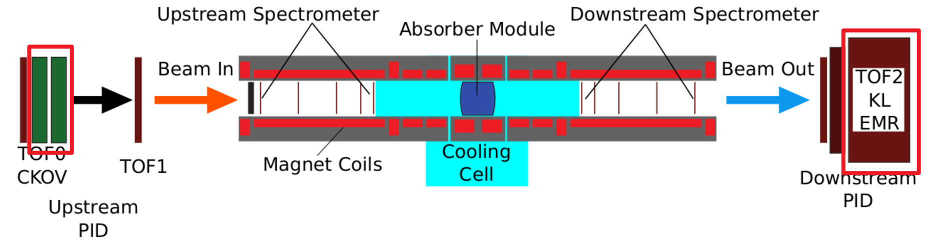


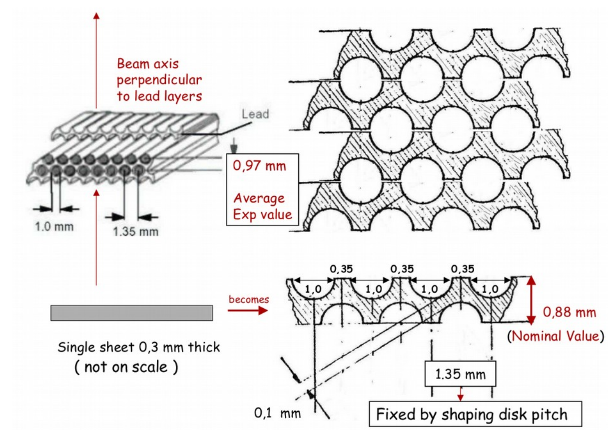


Cerenkov / KL

WARWICK
THE UNIVERSITY OF WARWICK







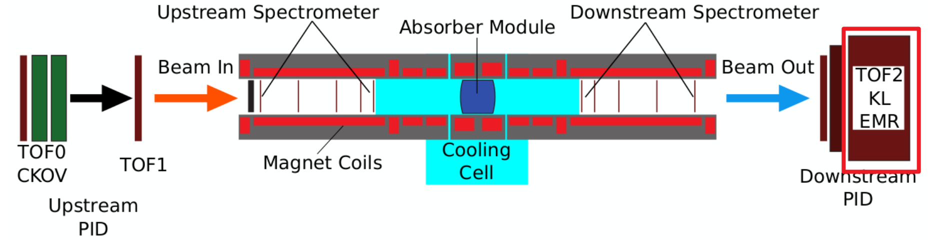
- Upstream threshold Cerenkov counters
- Twin aerogel slabs with n = 1.07 and 1.12

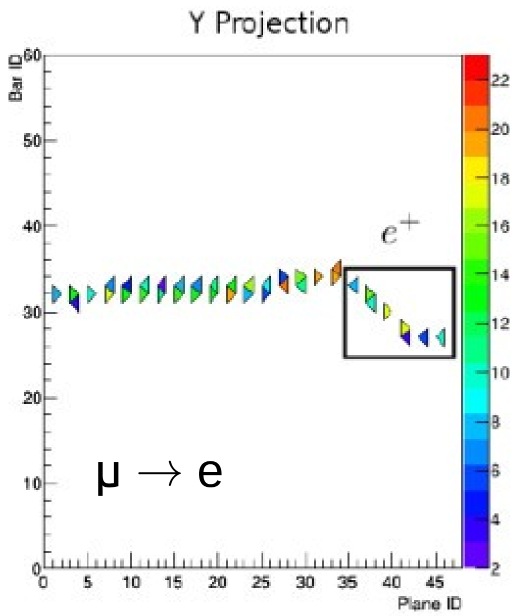
	CKOV – A n = 1.07	CKOV - B n = 1.12
p < 200 MeV/c		
200 < p < 240		Muons
p > 240 MeV/c	Pions	Muons Pions

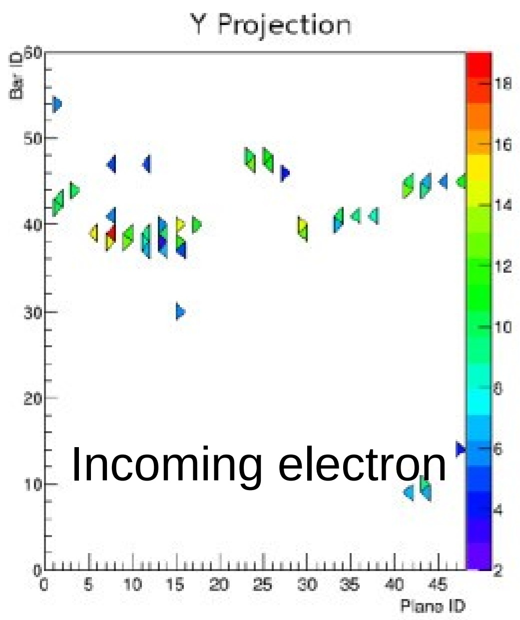
- Sampling calorimeter made from interspersed lead foils and scintillating fibres
- preshower for the EMR
- Enables rejection of electrons from downstream measurement

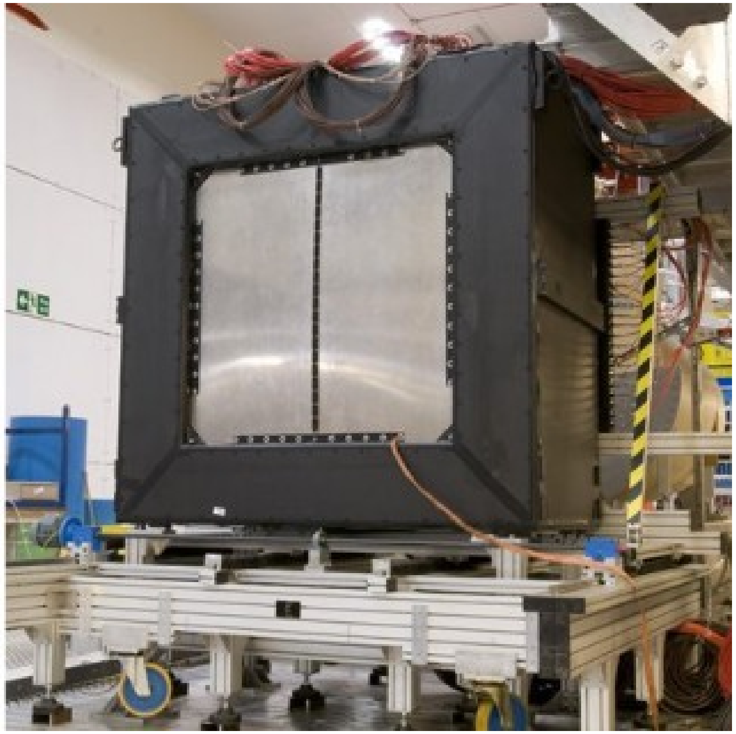
EMR

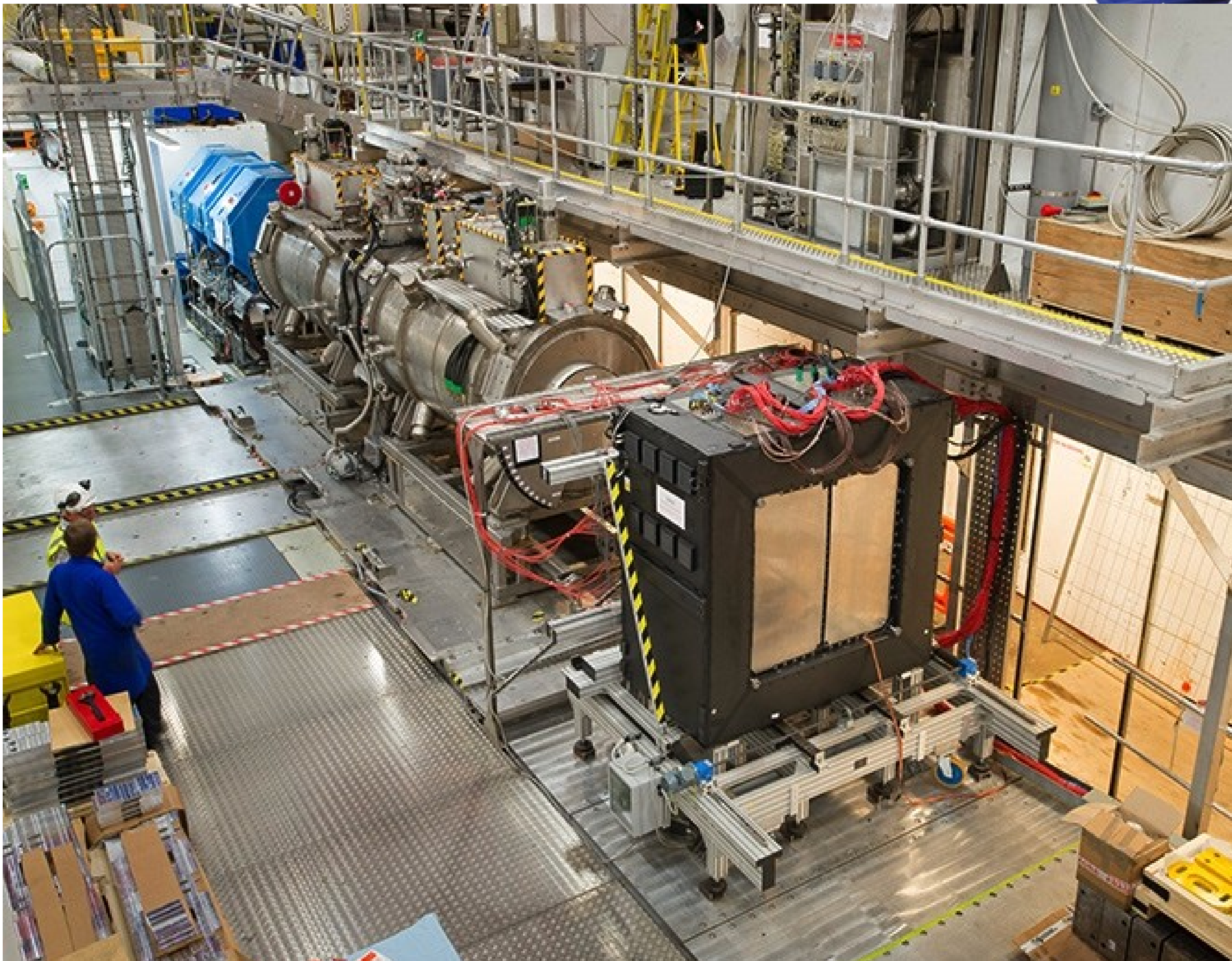
- Electron-Muon Ranger
- Totally active scintillator detector
- 48 plans of 60 MINERvA-style triangular scintillator bars readout by MAPMTs
- Electron tag efficiency : 98.6% only using EMR

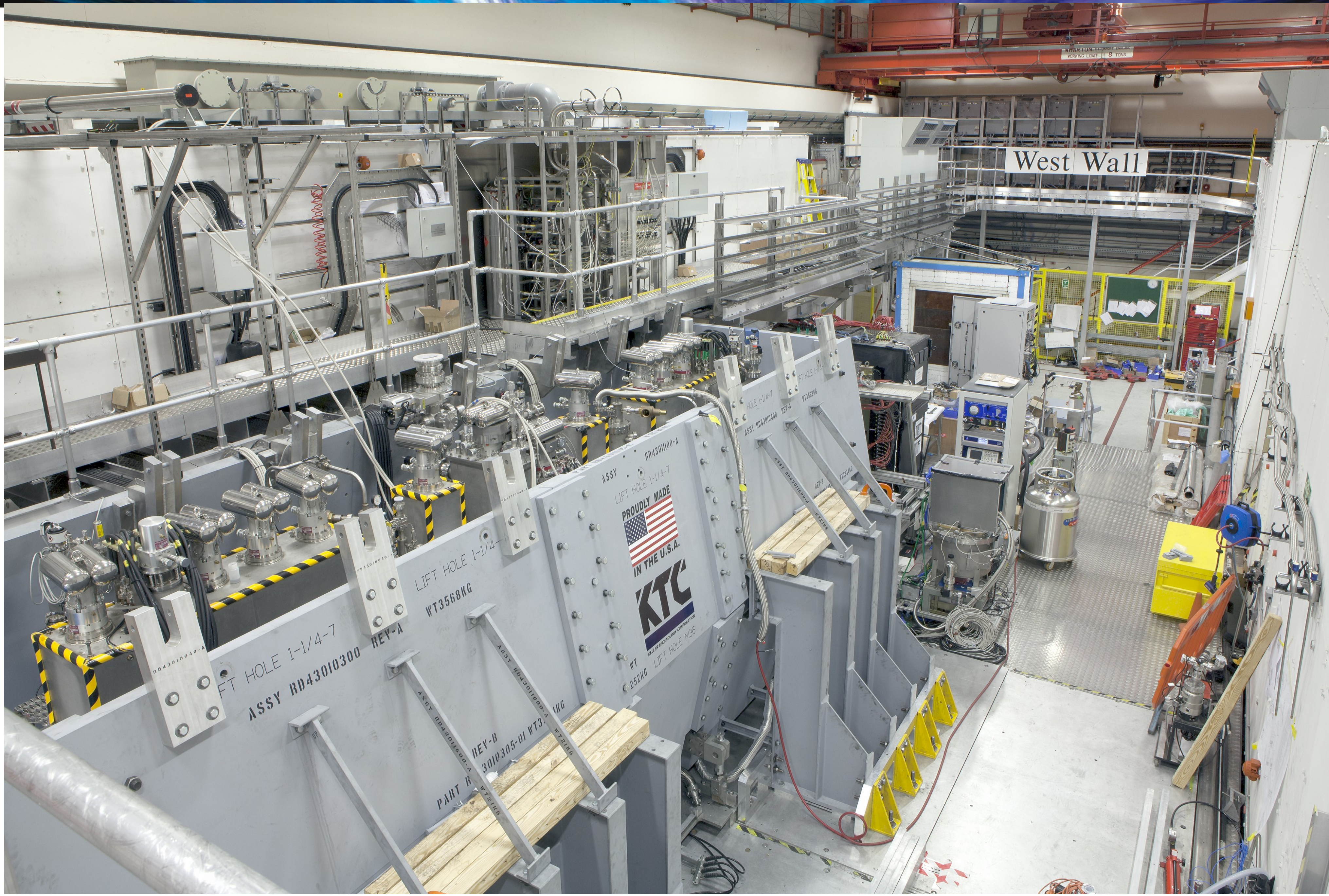




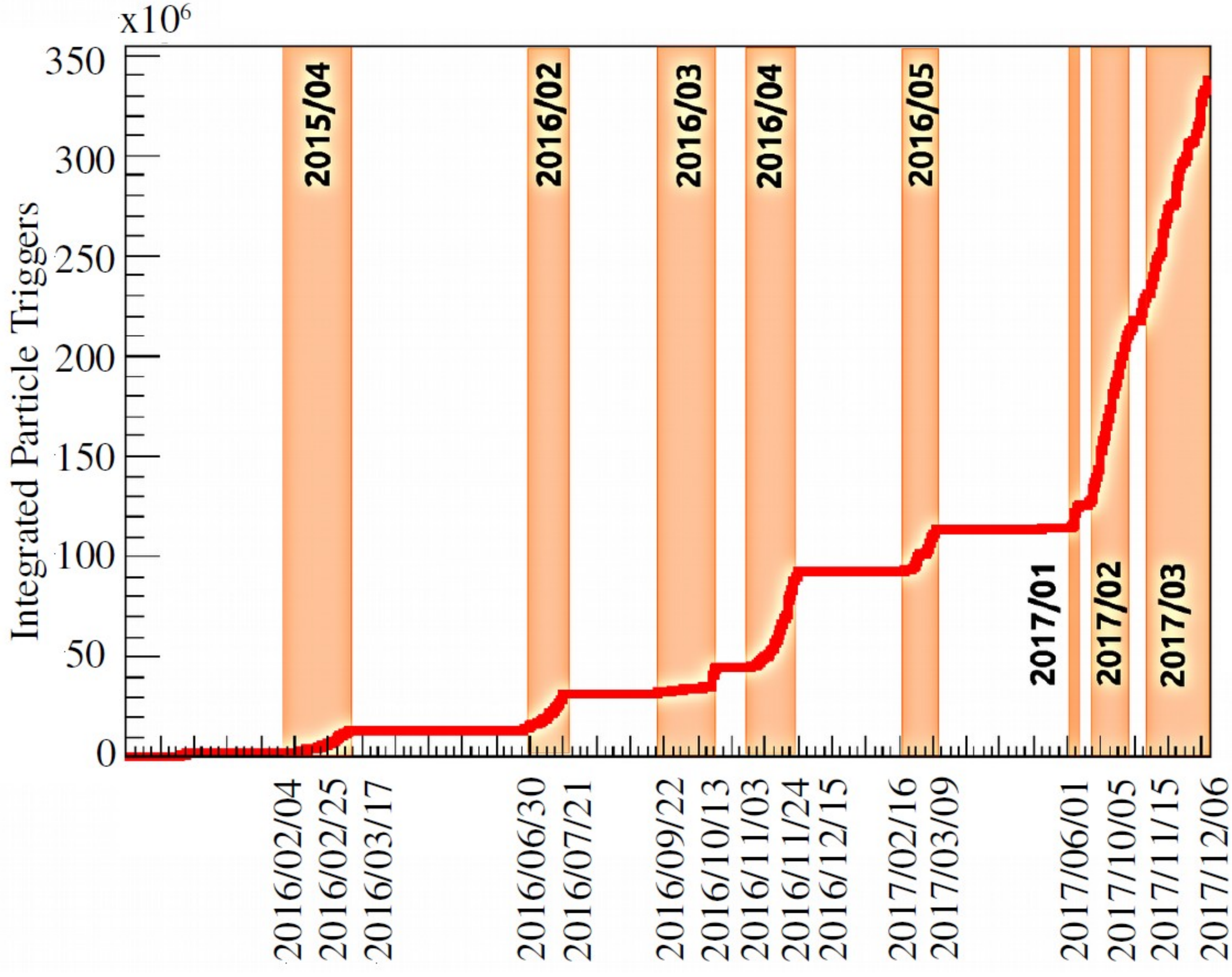







West Wall
PROUDLY MADE IN THE U.S.A.
KTC
LIFT HOLE 1-1/4-7
ASSY RD43010300 REV-A
WT3568KG
LIFT HOLE M36

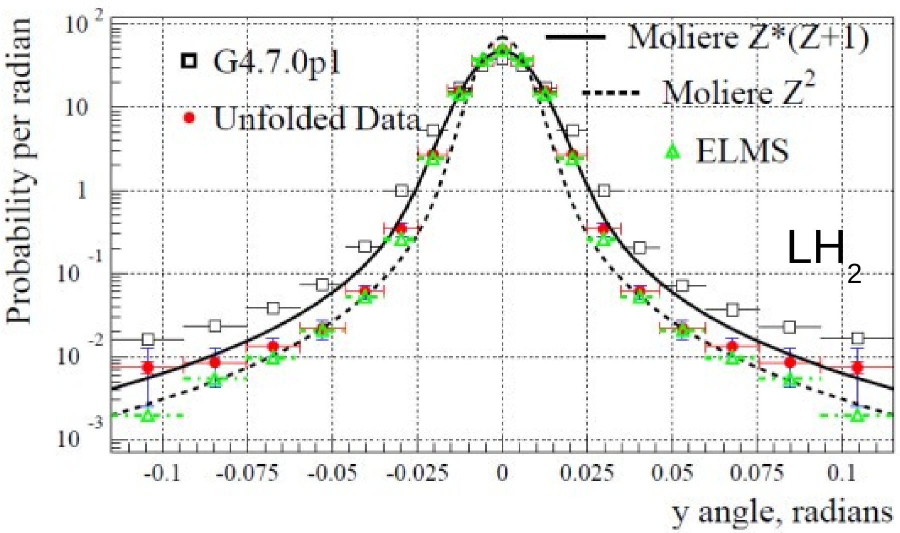
MICE Data-taking

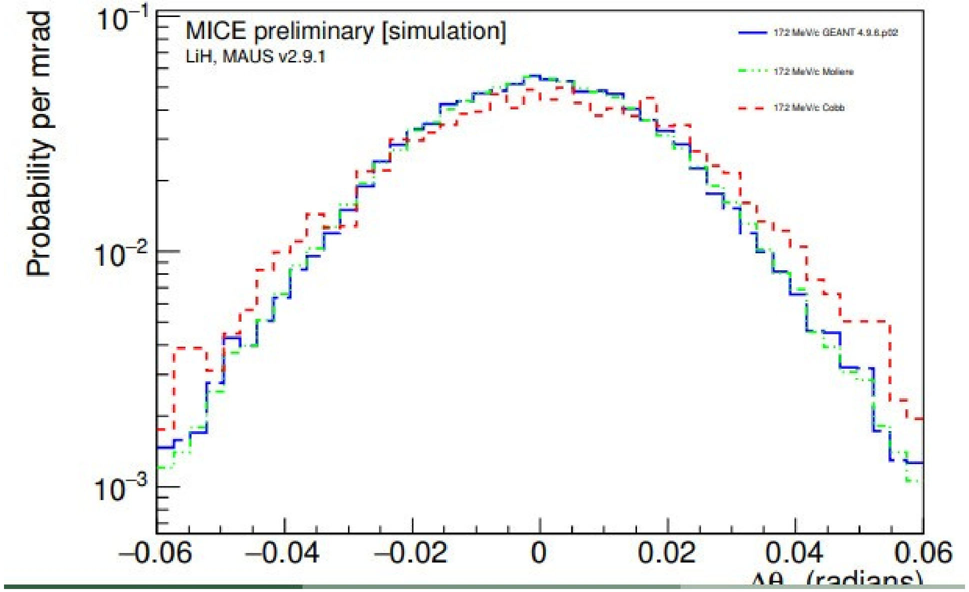


MICE Analysis

1. Multiple Scattering

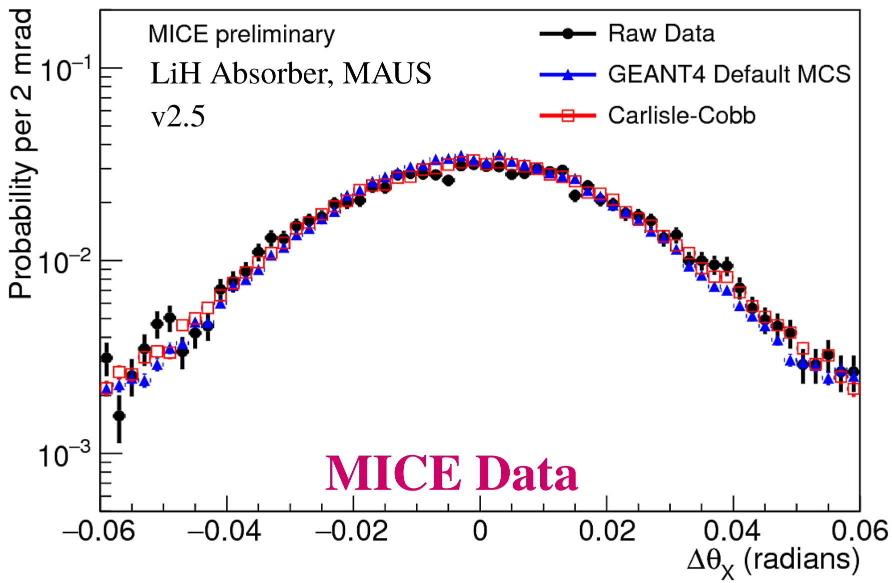
MuScat Nucl. Phys. Proc. Suppl. 149 (2005) 99-103

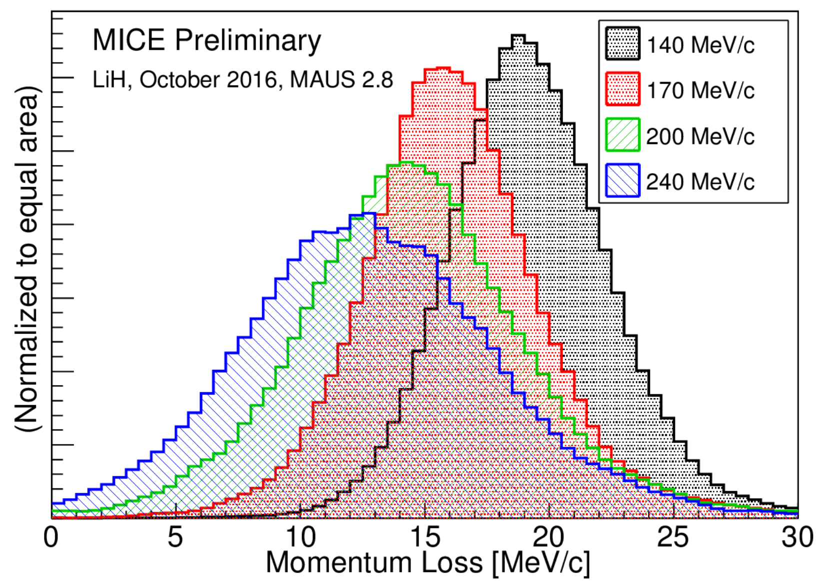




- Physics of energy loss and Multiple Coulomb Scattering underlie emittance reduction
- Critical to know whether our models reproduce these processes
- In 2005 MuScat showed that GEANT modelled MCS in high-Z materials well, but failed to model MCS for low-Z materials
- MICE is validating the models included in GEANT 4.9 for LH_2 and LiH materials

MCS and Energy Loss





- Preliminary and on-going work; systematics are still being evaluated
- Measured for LH2 & LiH absorbers over a range of momentum
- Studies to validate energy loss models are also underway
- Data validates Geant 4 MCS and energy loss model

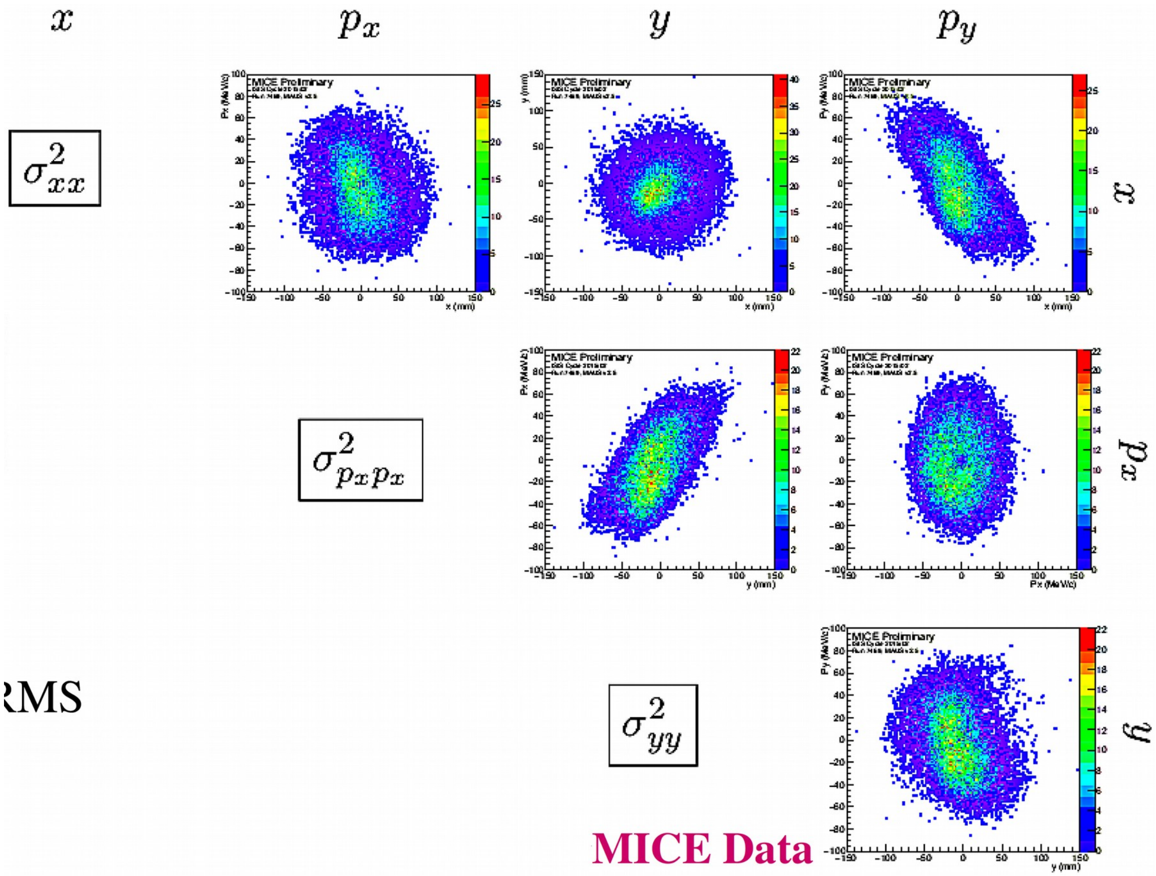
2. Beam Emittance

- Single particle emittance determination : create virtual beams by forming ensembles of single particles
- Recreate the (x,p_x,y,p_y) phase space

- Time of flight used for event selection
- Single track events with TOF consistent with muon

$$\epsilon_{\perp,N} = \frac{1}{m_\mu} \sqrt[4]{\det \Sigma_{4D}}$$

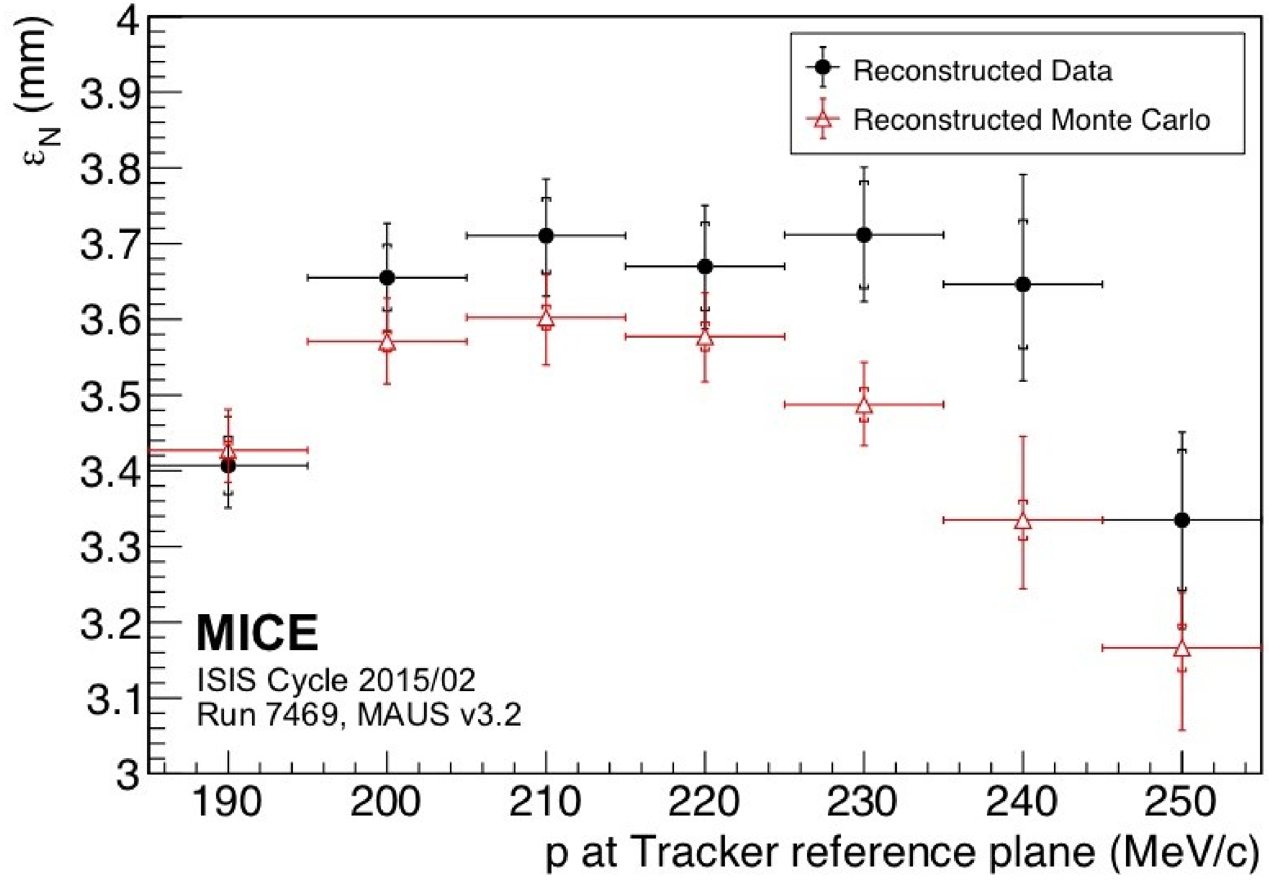
4D transverse covariance matrix in (x,y,p_x,p_y)



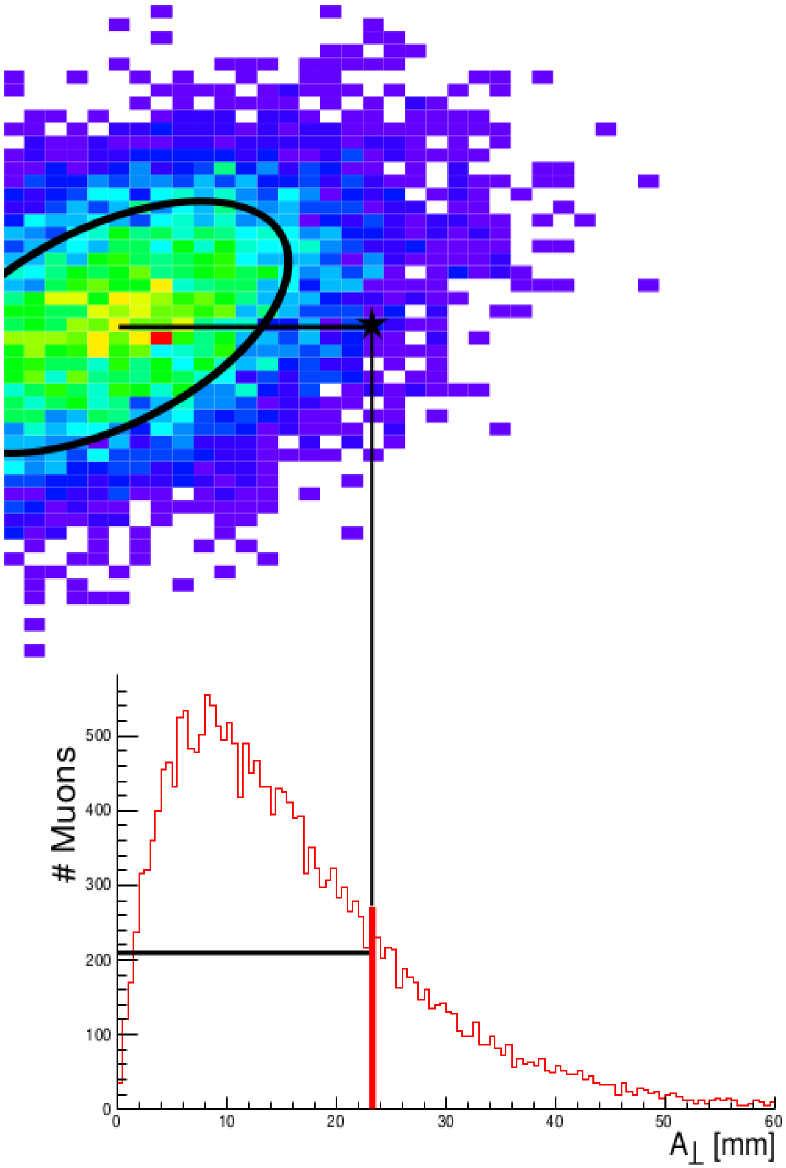
Beam Emittance

- Single particle emittance determination : create virtual beams by forming ensembles of single particles

- Input beam emittance measured in upstream spectrometer only
- Normalised transverse emittance should be flat with momentum
- Beam scraping on the aperture of the diffuser decreases emittance at low momentum
- MC does not describe beam perfectly



3. Emittance Reduction



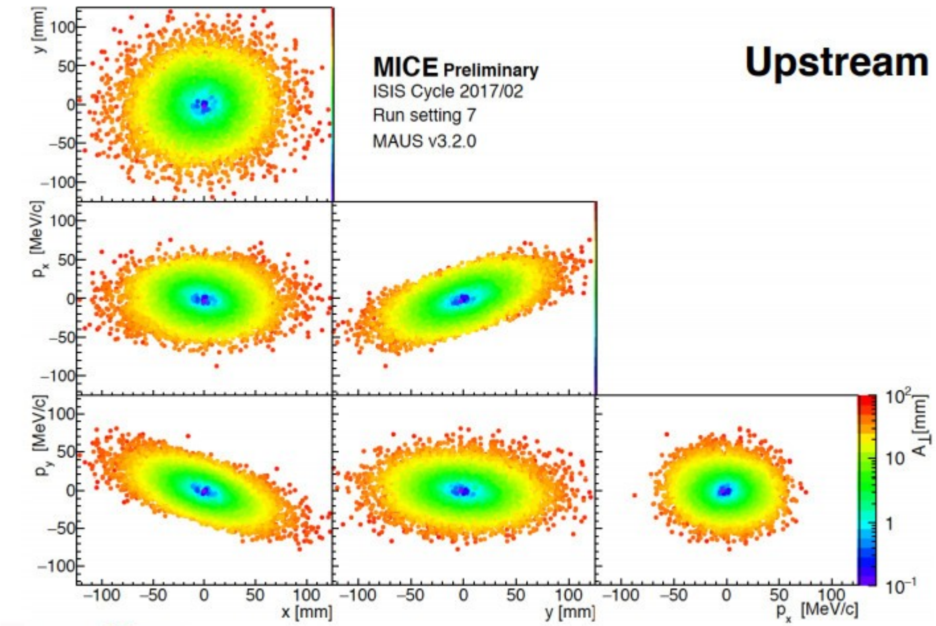
- Transverse single-particle amplitude
  - 4D distance of a muon from the beam core in phase space at closest tracking plane to absorber

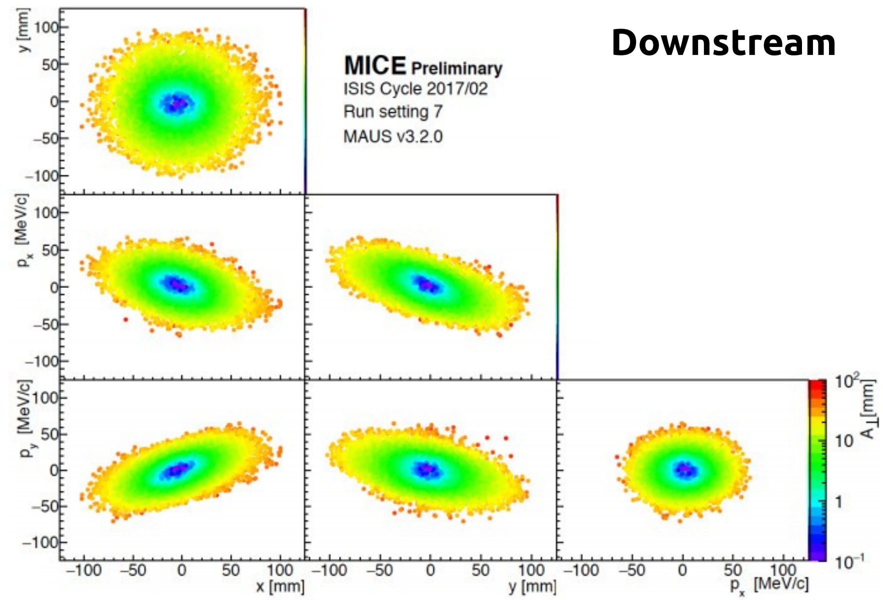
$$A_{\perp} = \epsilon_{\perp,N} \boldsymbol{u}^T \Sigma_{4D}^{-1} \boldsymbol{u}$$

$$\boldsymbol{v} = (x, p_x, y, p_y) \qquad \boldsymbol{u} = \boldsymbol{v} - \langle \boldsymbol{v} \rangle$$

- Amplitude distributed as a χ^2 distribution with 4 dof and with mean equal to 4 $\varepsilon_{\perp,N}$
- Ionization cooling reduces amplitude in the core of the beam

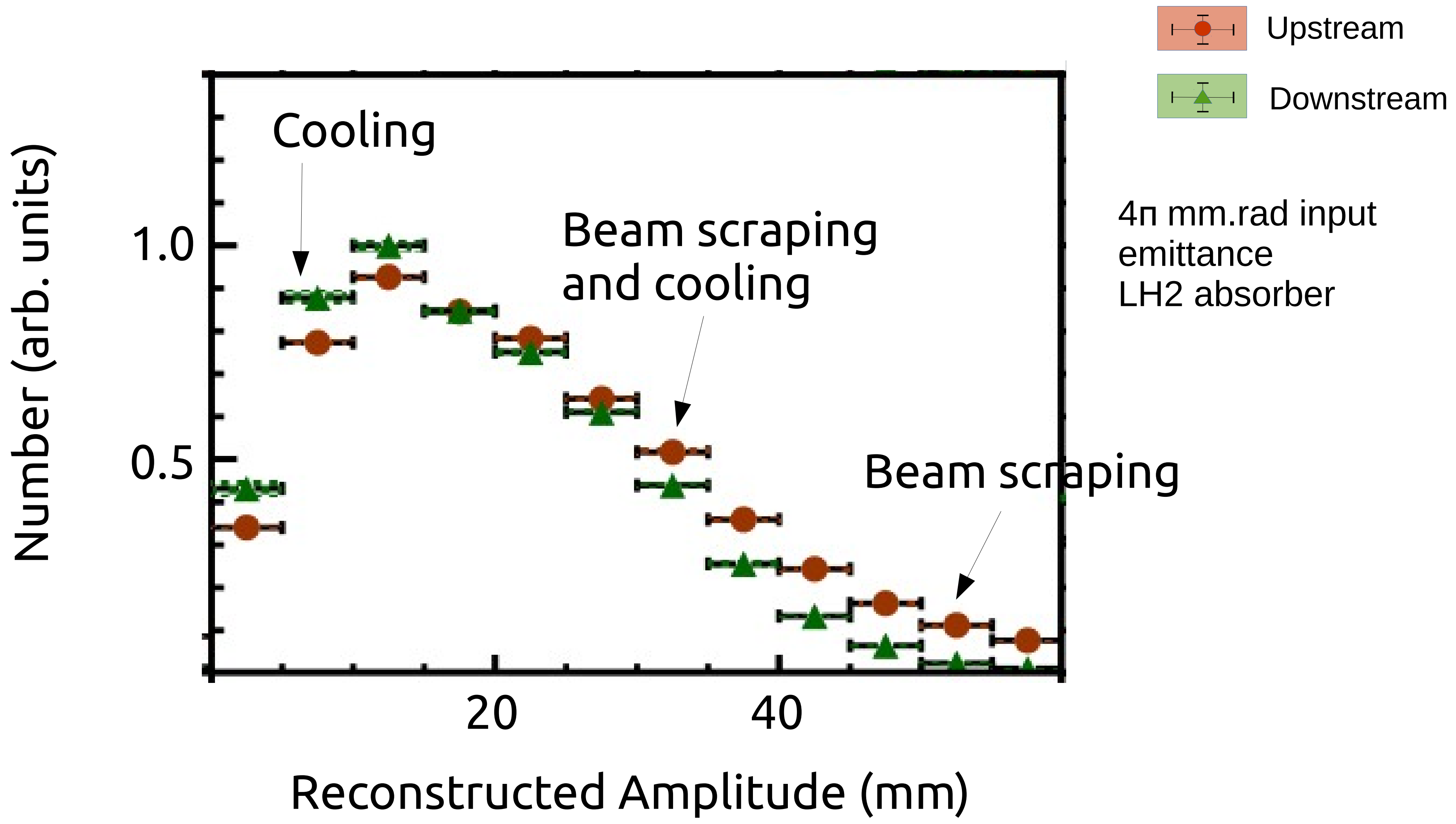
Transverse Amplitude





- Increase in core density indicative of cooling
- scraping of tails on apertures
- Straight forward RMS emittance measurement is biased by beam scraping
- Core of the beam is linear and transmitted unlike the tails
- Need a statistic to isolate effects in the core

Transverse Amplitude



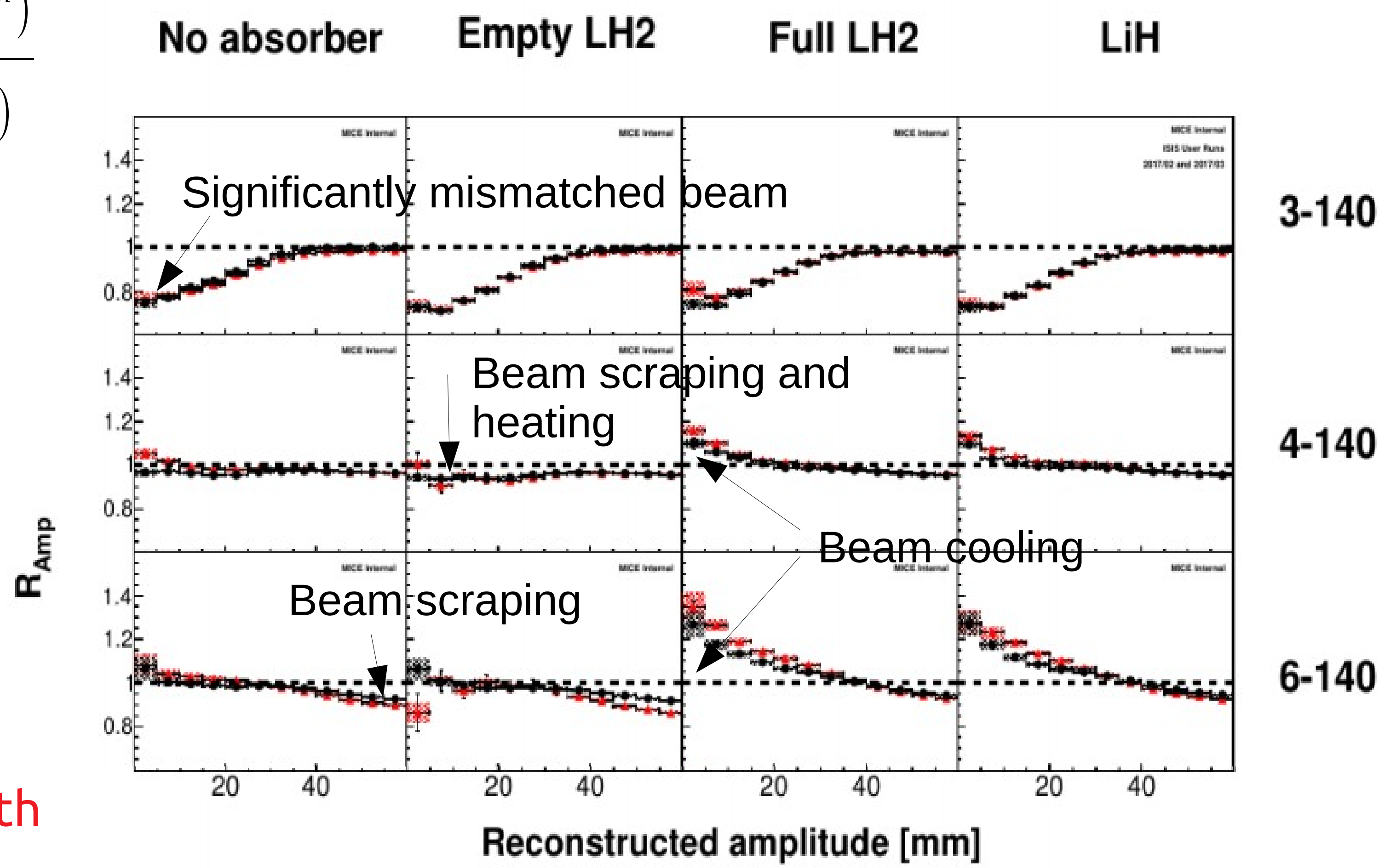
4π mm.rad input emittance
LH2 absorber

Cumulative Amplitude

$$R_{amp}(N) = \frac{\sum_{i=1}^{N} \left(Amp_i^{Down} \right)}{\sum_{i=1}^{N} \left(Amp_i^{Up} \right)}$$

- Cooling : increase in the number of muons in the core at low amplitude
- Cooling : $R_{amp} > 1$
- Ionisation cooling observed
- Agrees broadly with expectation

Preliminary



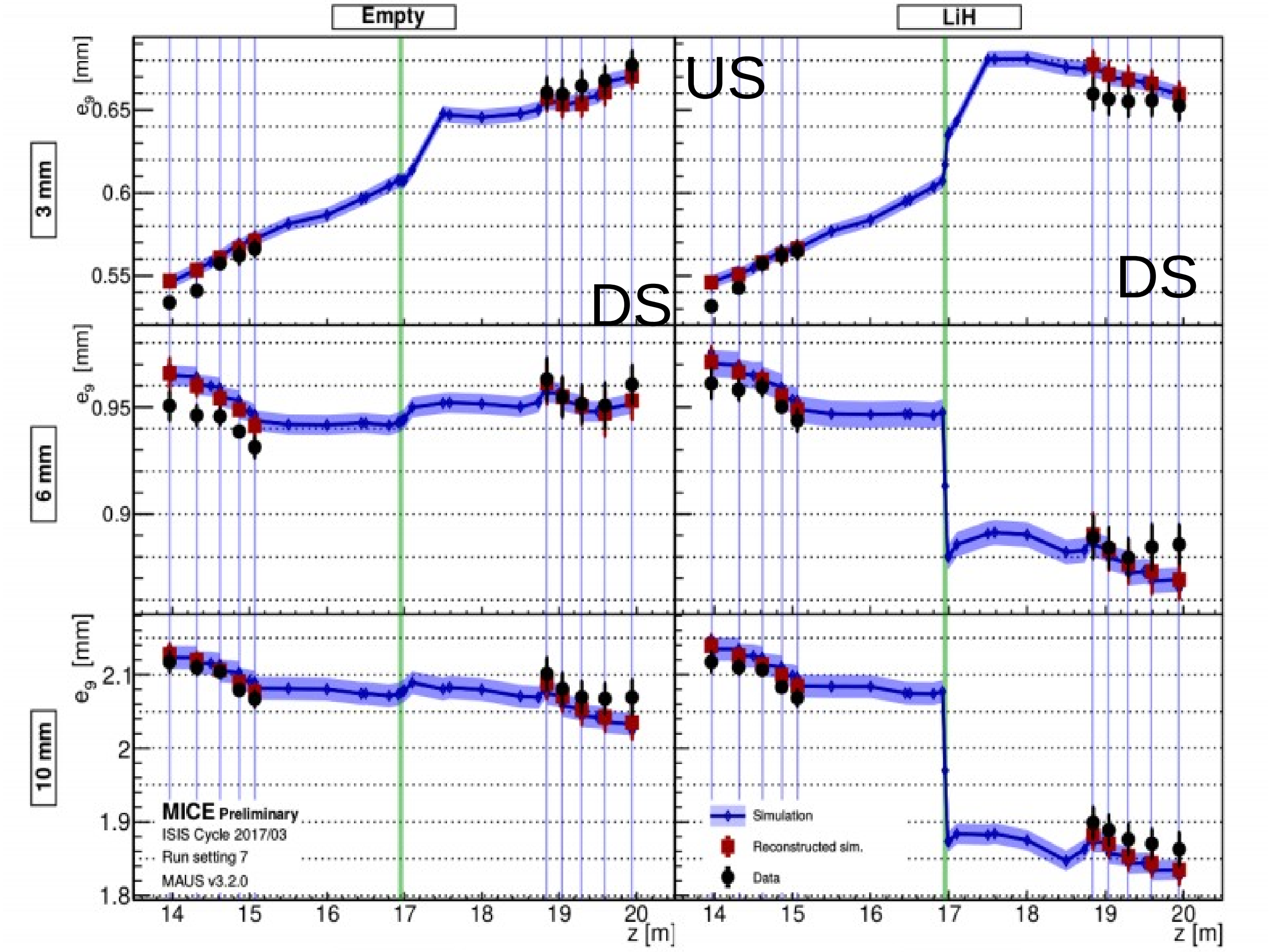
Fractional Emittance Evolution

Fractional emittance:

Emittance occupied the central α% of particles in the core of the beam.

α = 9% is 1σ of 4D transverse phase space

Also shows expected ionisation cooling effect



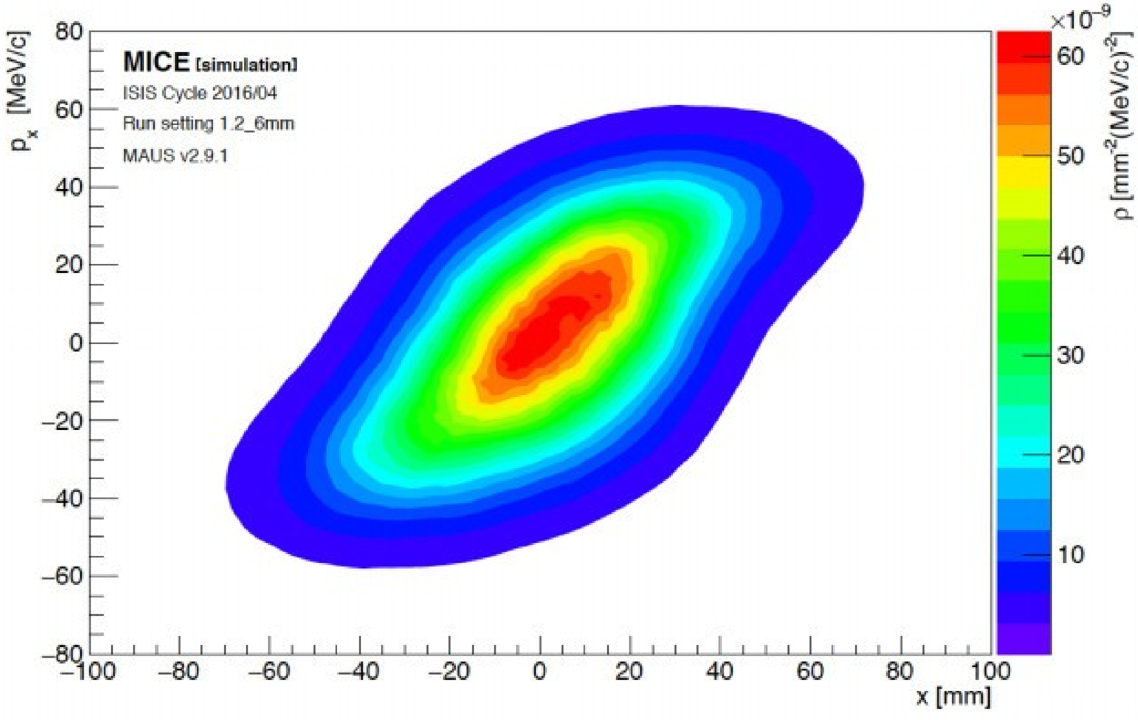
The Future of MICE

The Future of MICE

MICE Hall in November 2018

The analysis continues

- Precision studies of emittance evolution
- Studies of multiple scattering and energy loss in LiH and LH2
- Studies of reverse emittance evolution
- Non-parametric phase space evolution



- reconstruction of local beam density using kNN algorithm

Summary

- Muon colliders and neutrino factories require muon beam ionisation cooling
- Significant hardware R&D effort over the last decade to validate each step of the beam production
- MICE designed to validate ionisation cooling
    - Ionisation Cooling has been observed
- MICE is gone but the analysis continues
    - The first emittance analyses are being published now with other analyses on the way:
        - Precision studies of emittance evolution
        - Studies of multiple scattering on LiH and LH2
        - Studies of reverse emittance exchange
        - Non-parametric phase space evolution

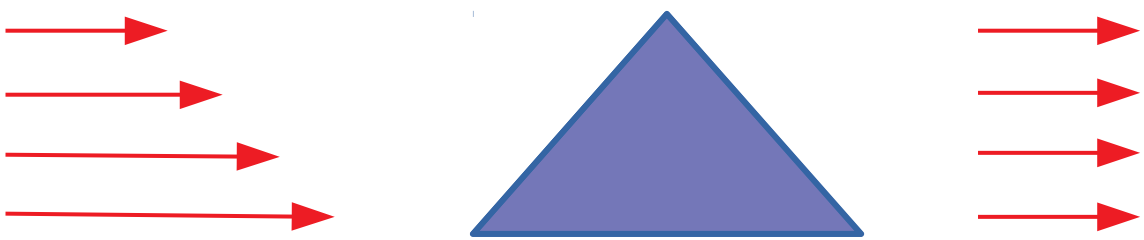
Backups

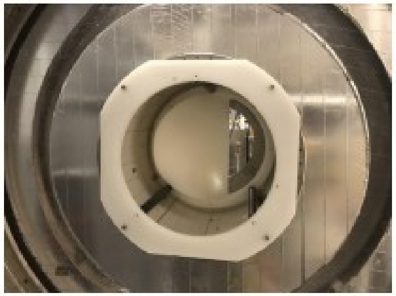
MICE Goals

- Essentially a technology demonstrator
  - Can we safely operate liquid hydrogen absorbers? ✓
  - Can we operate a tightly packed lattice?
    - With high field magnets + liquid hydrogen? ✓
    - With high field magnets + liquid hydrogen + RF? ✗
  - Do we see the expected emittance change? ✓
  - Do we see the expected transmission? ✓

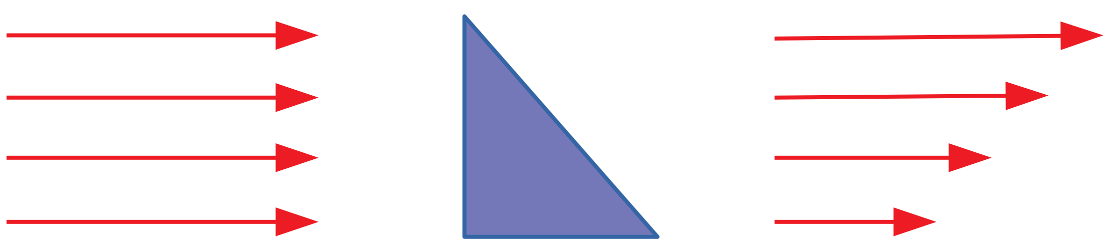
Reverse emittance exchange

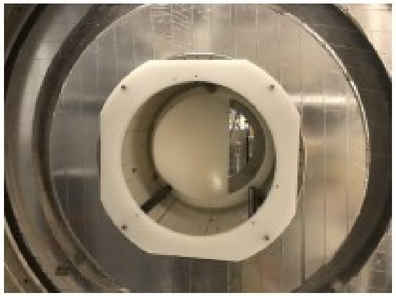
- Longitudinal cooling requires momentum dependent path length through an absorber





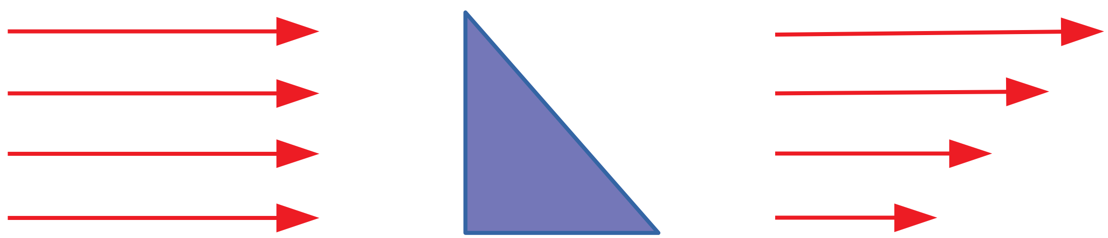
- MICE can’t study longitudinal cooling, but it can demonstrate longitudinal heating

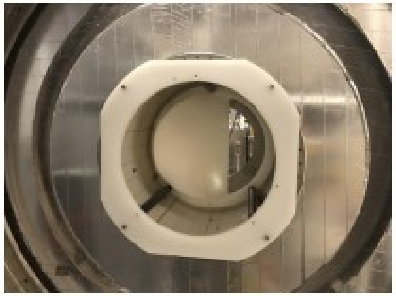




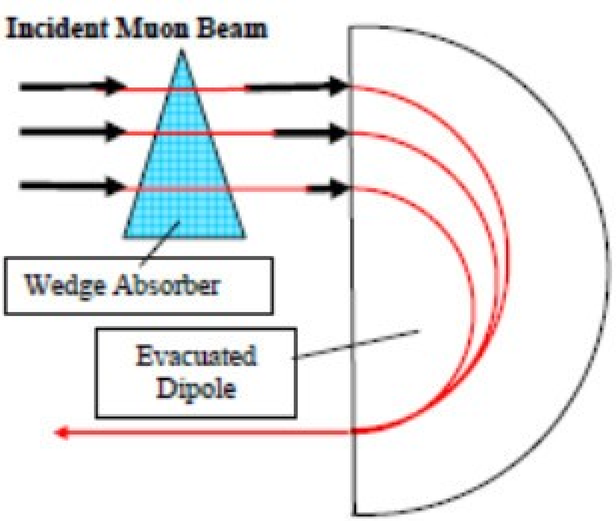
Reverse emittance exchange

- Longitudinal cooling requires momentum dependent path length through an absorber



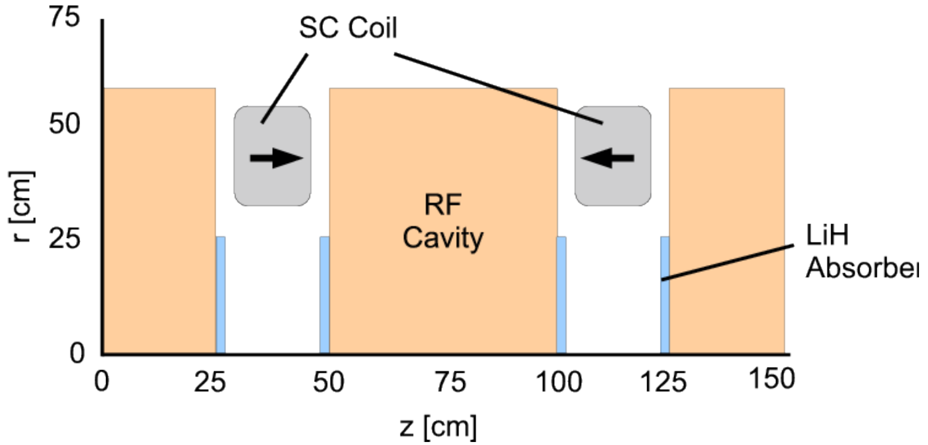


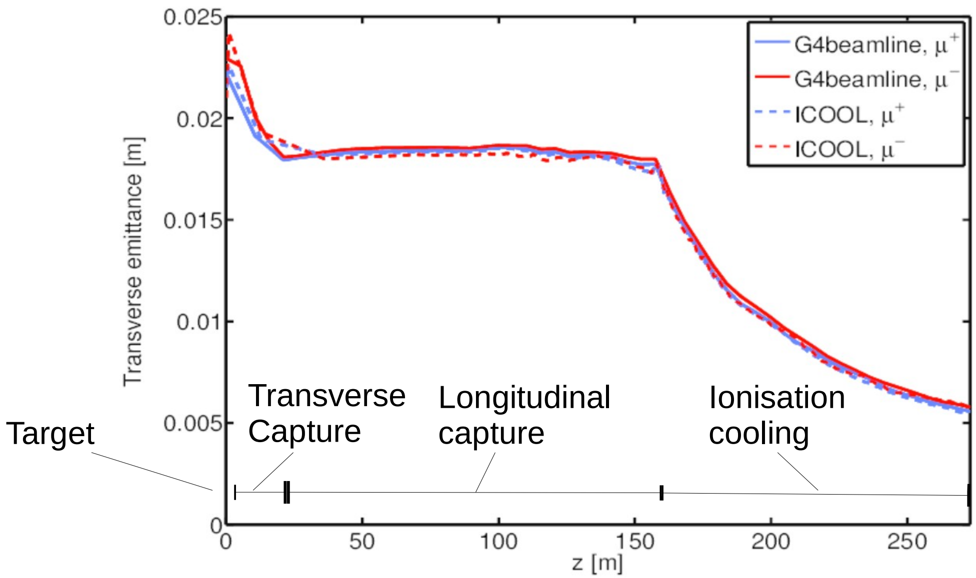
- MICE can't study longitudinal cooling, but it can demonstrate longitudinal heating
- wedge absorber introduces a correlation between momentum and transverse position which can couple to transverse emittance
- longitudinal heating leads to transverse cooling through reverse emittance exchange



4D Cooling lattice

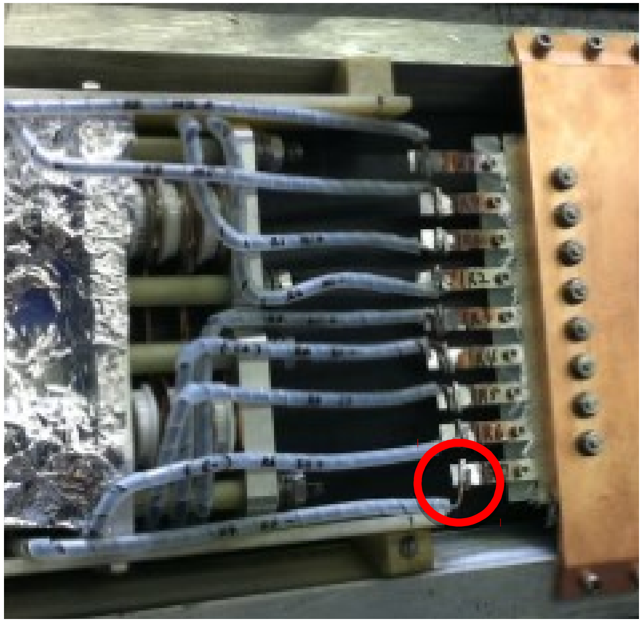
- Cooling for a neutrino factory
- Compact lattice
  - RF adjacent to magnets
  - LiH/LH2 absorber adjacent to RF
- Intermediate field magnets
  - 2.8 T
  - 350 mm radius aperture
- High gradient RF
  - 15-20 MV/m @ 201 MHz





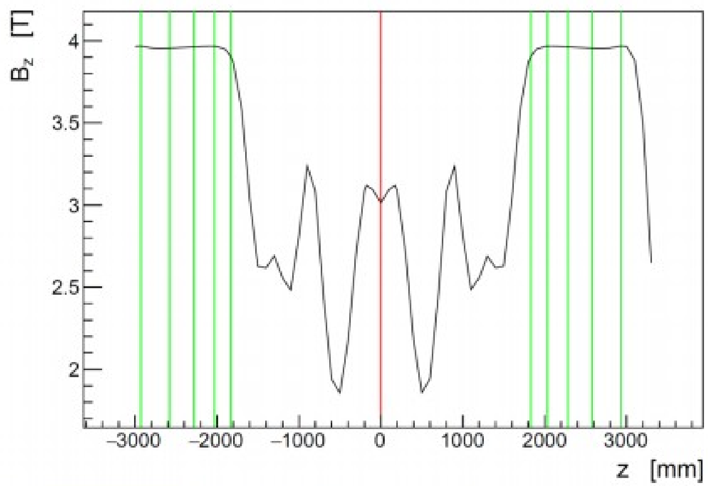
SSD Failure

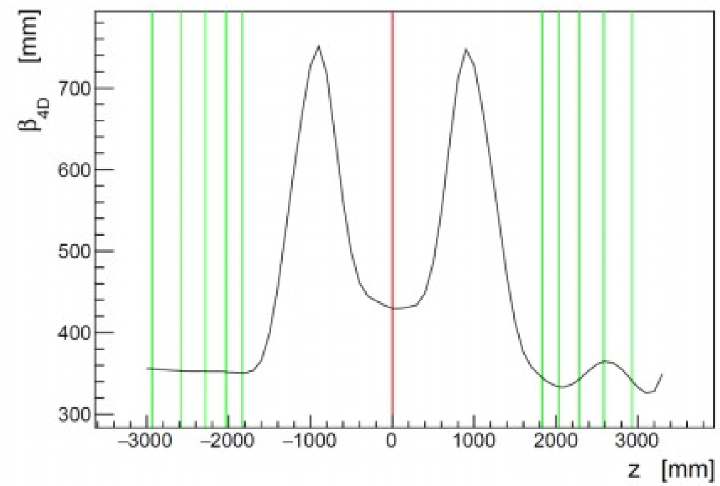
- In September 2015 one of the match coils in the downstream spectrometer failed during a training quench
- Traced to a poor connection inside the cold mass
- Review of options :
  - construct entirely new magnet
  - construct new cold mass
  - add a new correcting solenoid to the channel
  - run as is for Step IV
- All options involved significant cost and project delay
- Decided to run as is for Step IV whilst constructing a new cold mass for operation in Step V (cooling with RF)



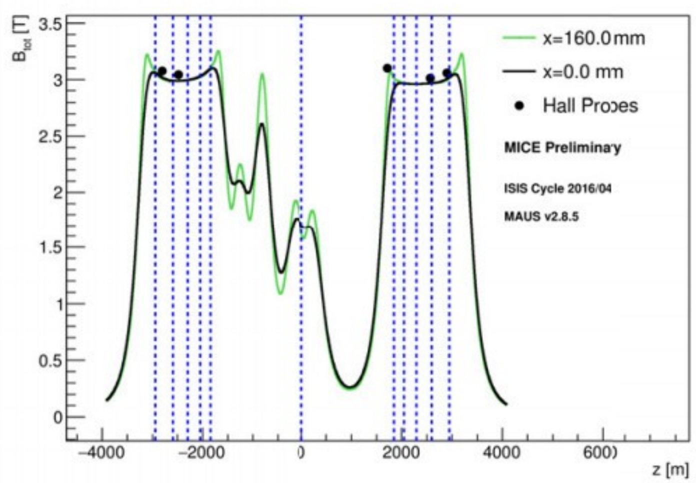
Beam optics

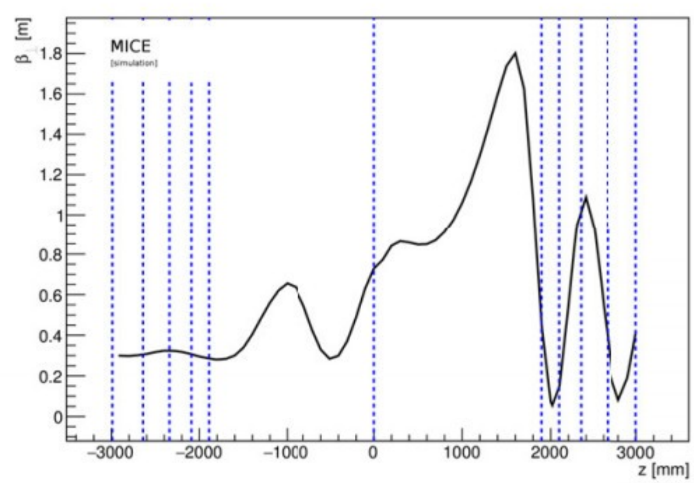
- Planned B_z and β_{4D} function in solenoid mode at 4T



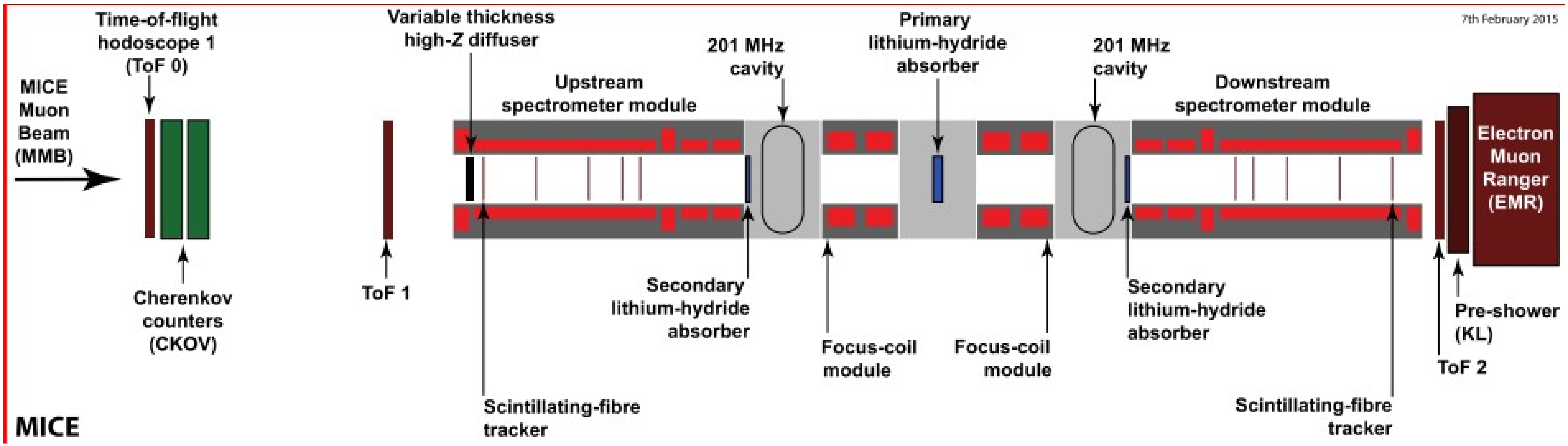


- optics after M1D failed; running at 3T

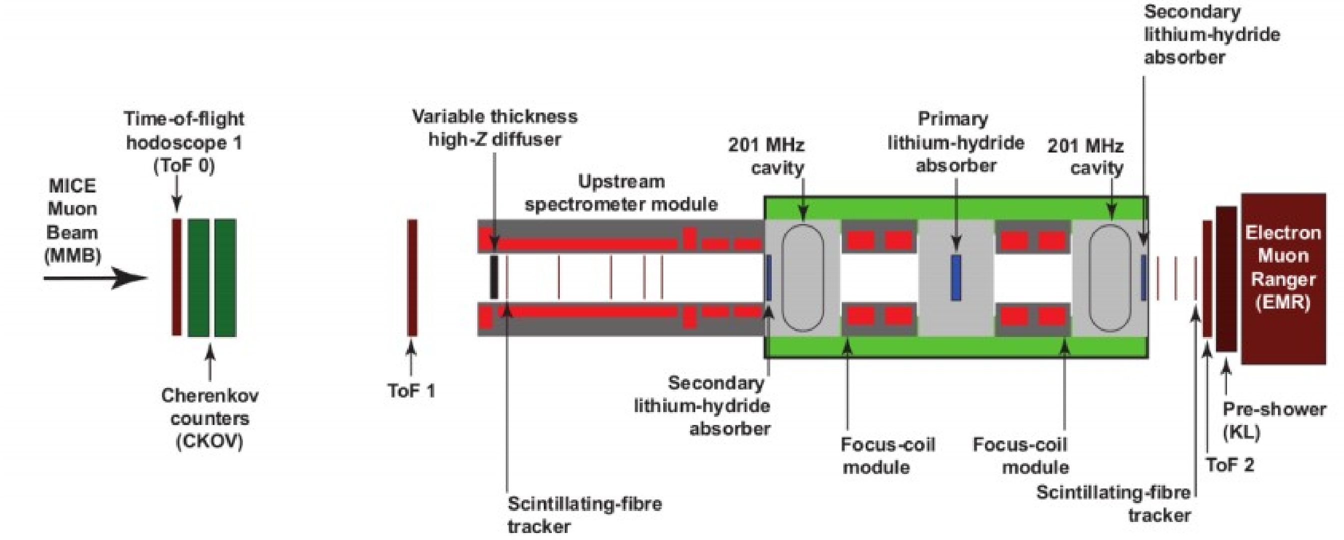


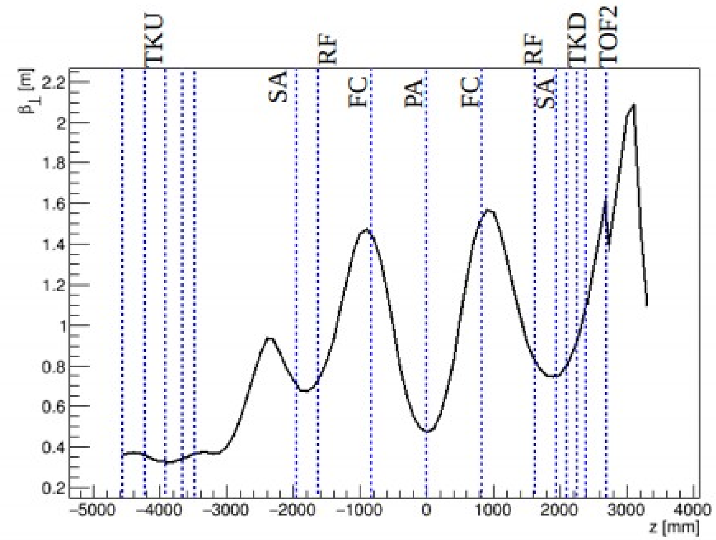


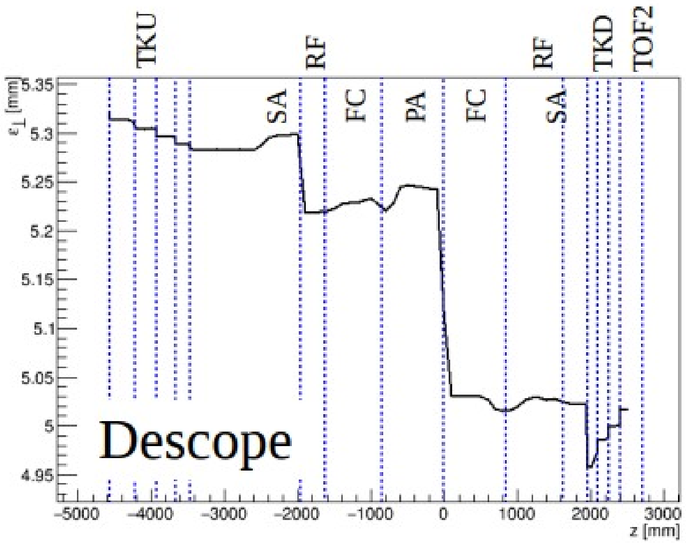
Cooling with RF



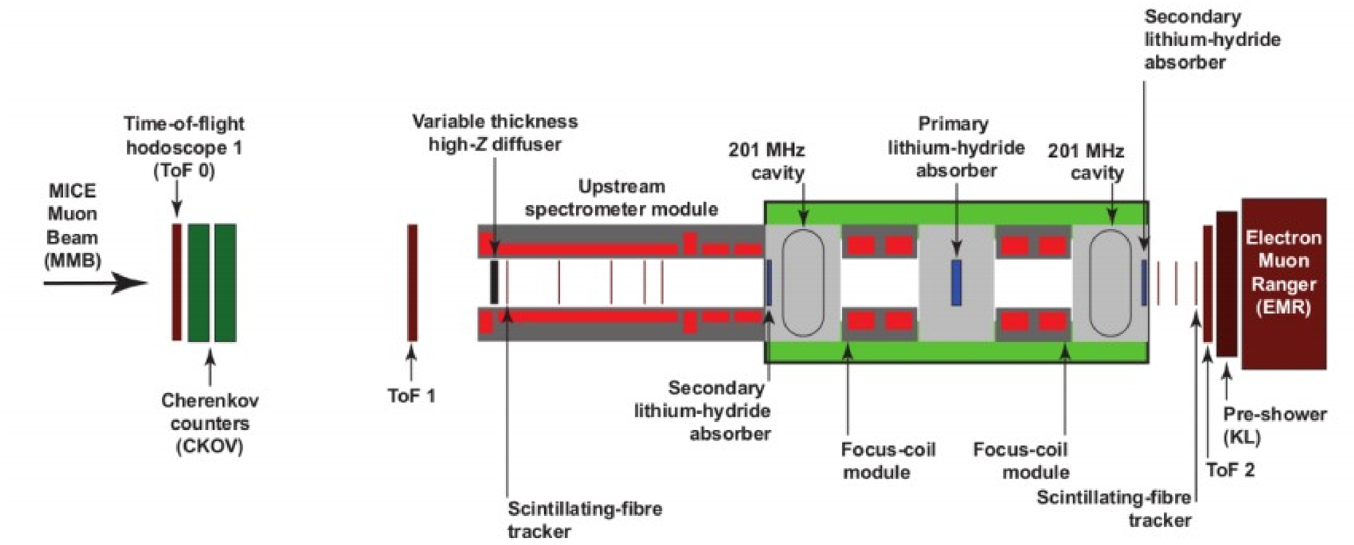
Descope


MICE Muon Beam (MMB)
Time-of-flight hodoscope 1 (ToF 0)
Cherenkov counters (CKOV)
ToF 1
Variable thickness high-Z diffuser
Upstream spectrometer module
Scintillating-fibre tracker
Secondary lithium-hydride absorber
201 MHz cavity
Primary lithium-hydride absorber
201 MHz cavity
Secondary lithium-hydride absorber
Focus-coil module
Focus-coil module
Scintillating-fibre tracker
ToF 2
Pre-shower (KL)
Electron Muon Ranger (EMR)


TKU
SA
RF
FC
PA
FC
RF
SA
TKD
TOF2
z [mm]

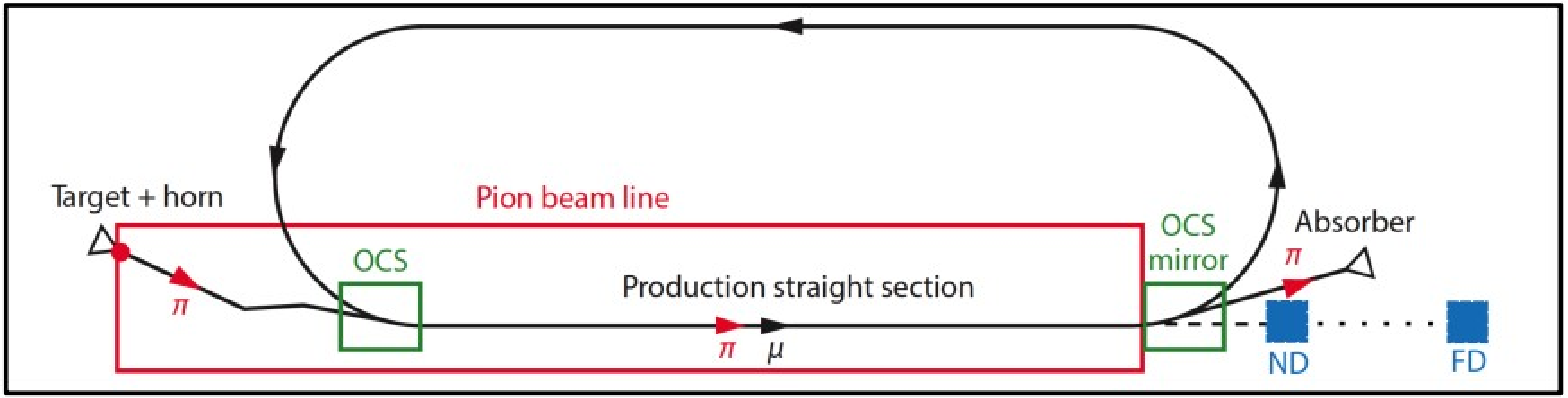

TKU
SA
RF
FC
PA
FC
RF
SA
TKD
TOF2
Descope
z [mm]

Descope

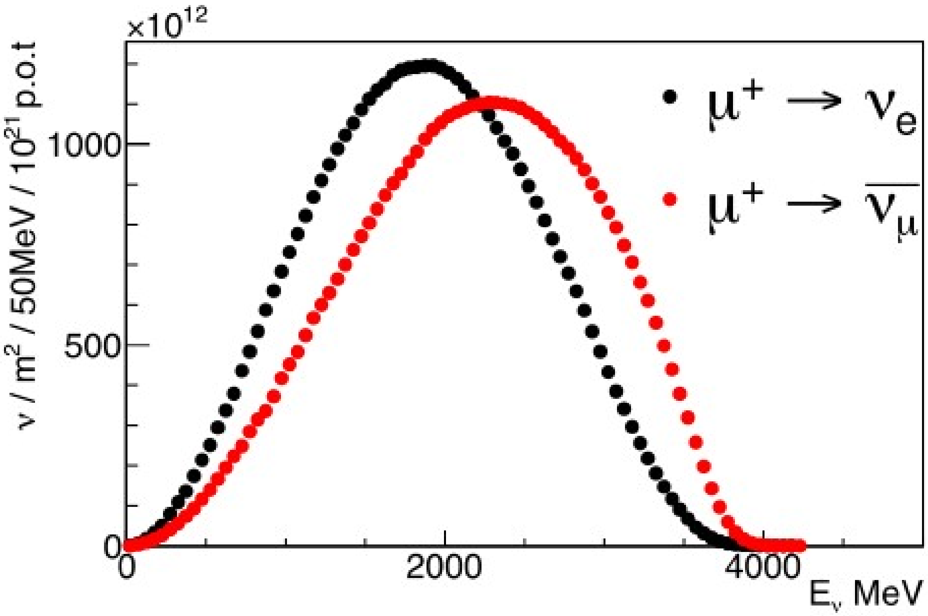


- Modified channel proposed as an upgrade after the 2016/17 data-taking run
- International MICE Project Board approved the design
- STFC decided not to go forward with the upgrade due to (I) lack of resources in the UK accelerator program and (ii) the cancellation of the US DOE muon program. This would have led to the withdrawal of the US groups from MICE and the transfer of some risk to the UK.

nuSTORM



- Facility based on a low energy muon storage ring
- Uses existing proton drivers and conventional pion production and capture
- Direct injection of pions in the storage ring



nuSTORM

- A solid design which is capable of being built now is available
- Significant work with CERN on siting, engineering and services
- Would permit high statistics cross section measurements with 1% flux error
- R&D detector testbed integrated with Neutrino Platform
- Submitted to European Particle Physics Strategy process