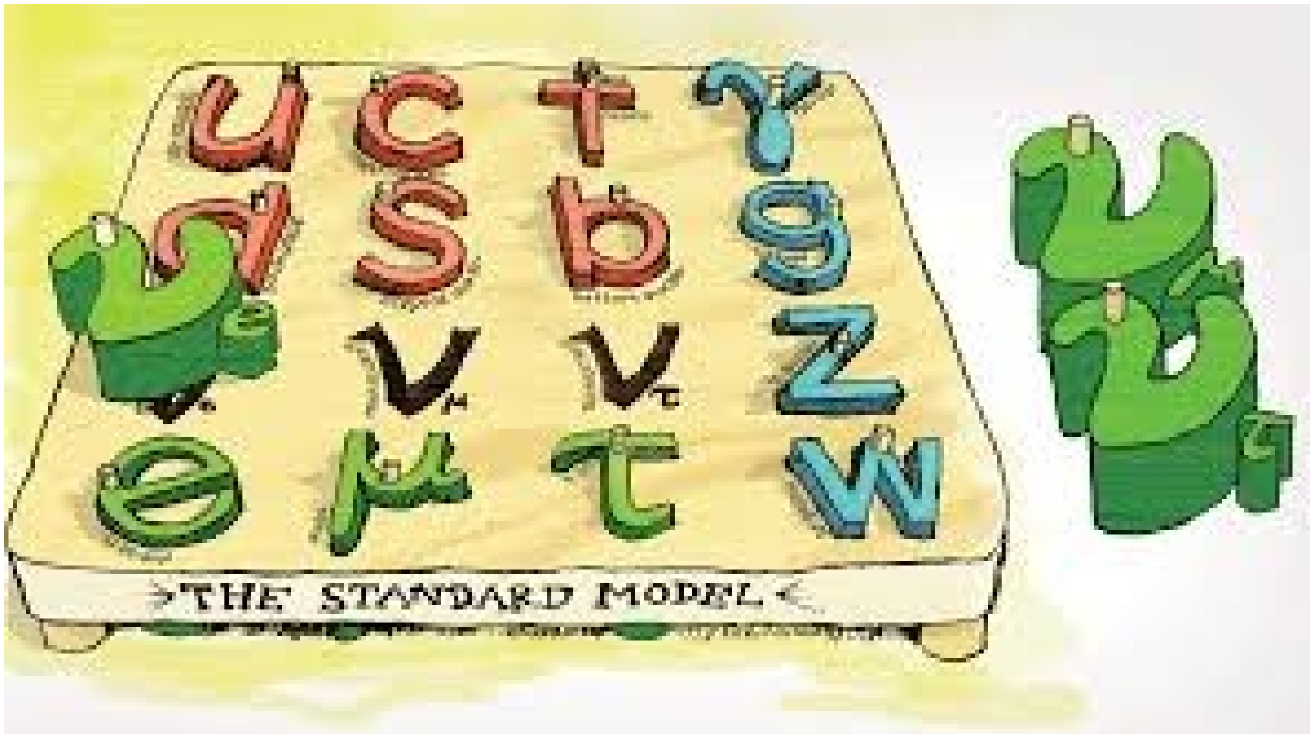
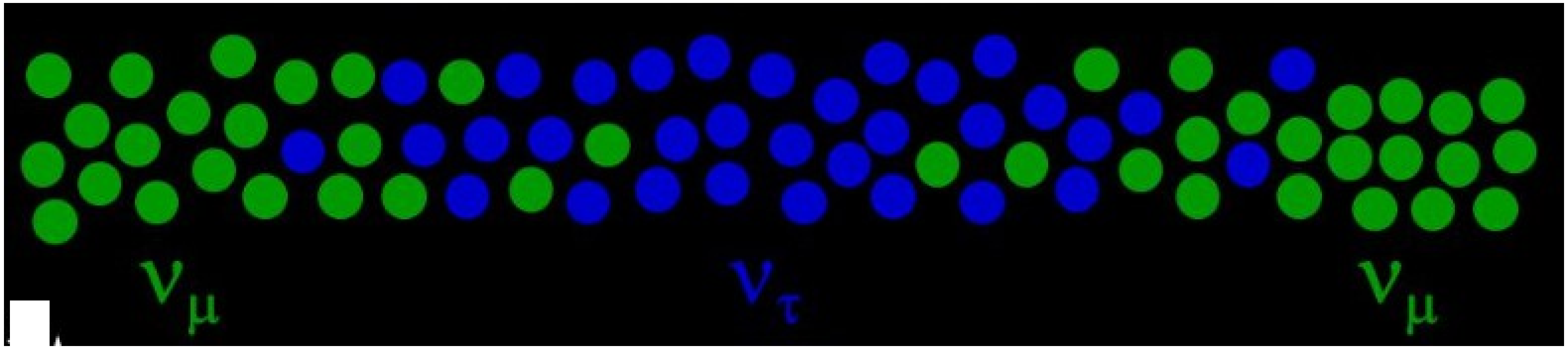
the muons are cool, man

Neutrinos



- Lightest fundamental fermions
- Do not fit easily into the Standard Model of Particle Physics
  - they have mass, but we don’t know how they get it
- are linked to some of the major questions in Particle Physics
  - e.g why is there more matter than antimatter in the Universe?

Neutrino Oscillations



Neutrinos can change flavour as they travel from point to point.

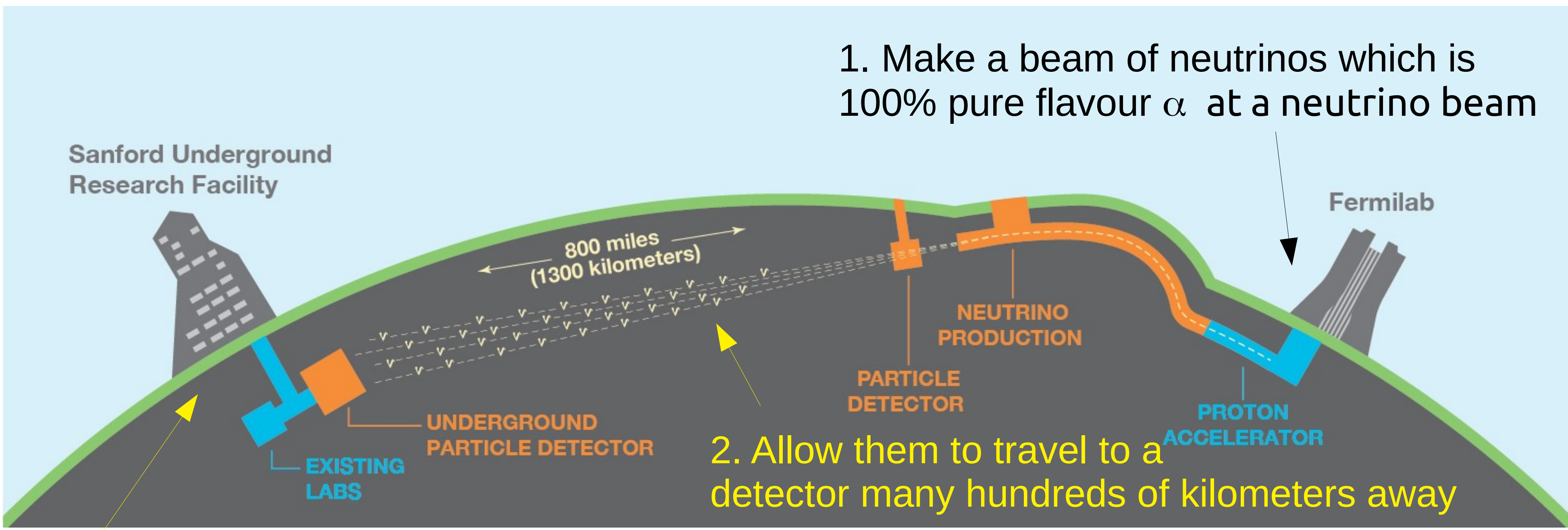
Neutrino Flavour Oscillations

The nature of these oscillations can give us information which will help elucidate these big questions

So we want to study these oscillations.

Neutrino Oscillation Experiments

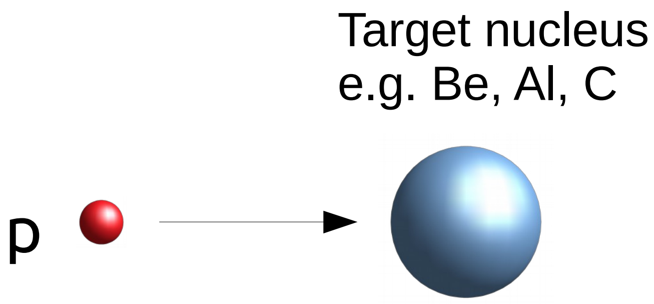
1. Make a beam of neutrinos which is 100% pure flavour α at a neutrino beam



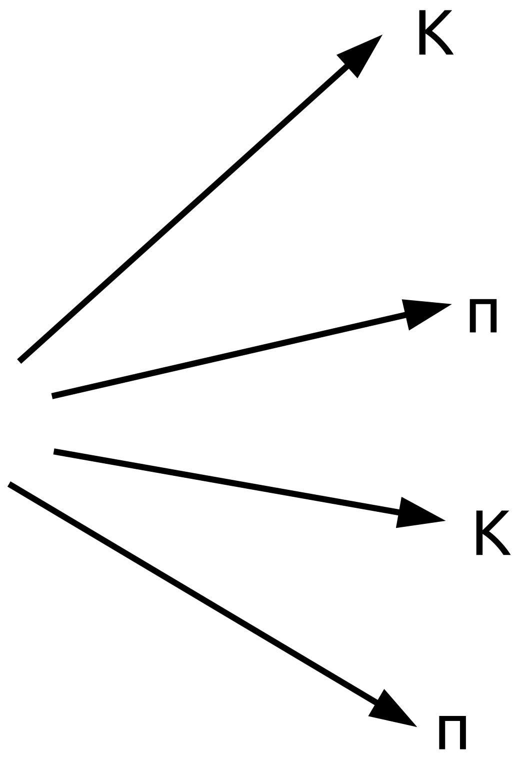
2. Allow them to travel to a detector many hundreds of kilometers away

3. Detect a fraction of these neutrinos as a different flavour β

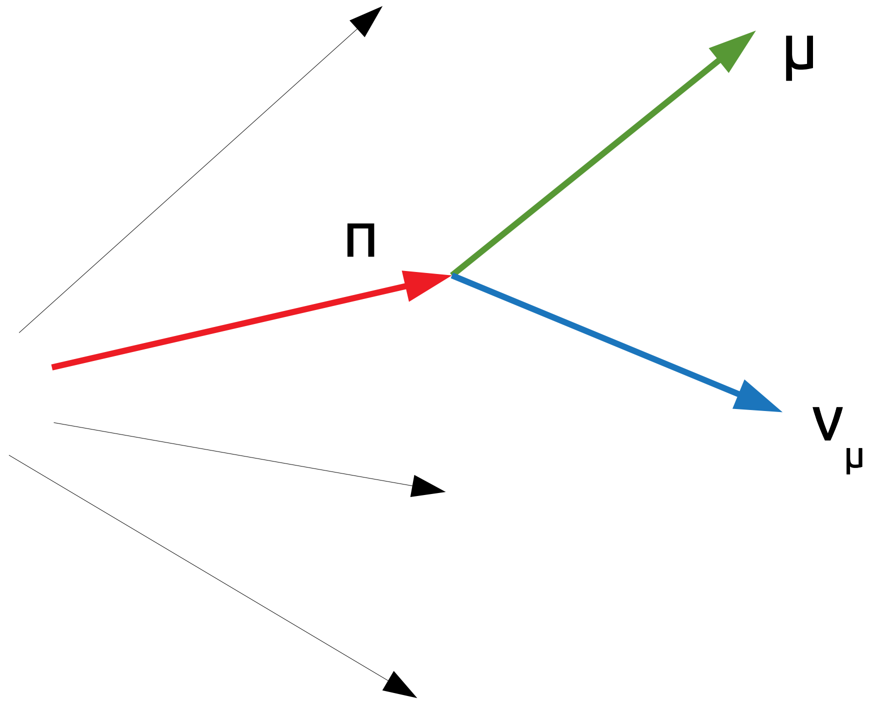
Making Neutrinos



Making Neutrinos

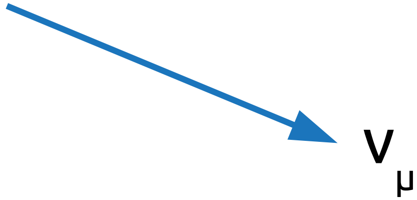


Making Neutrinos

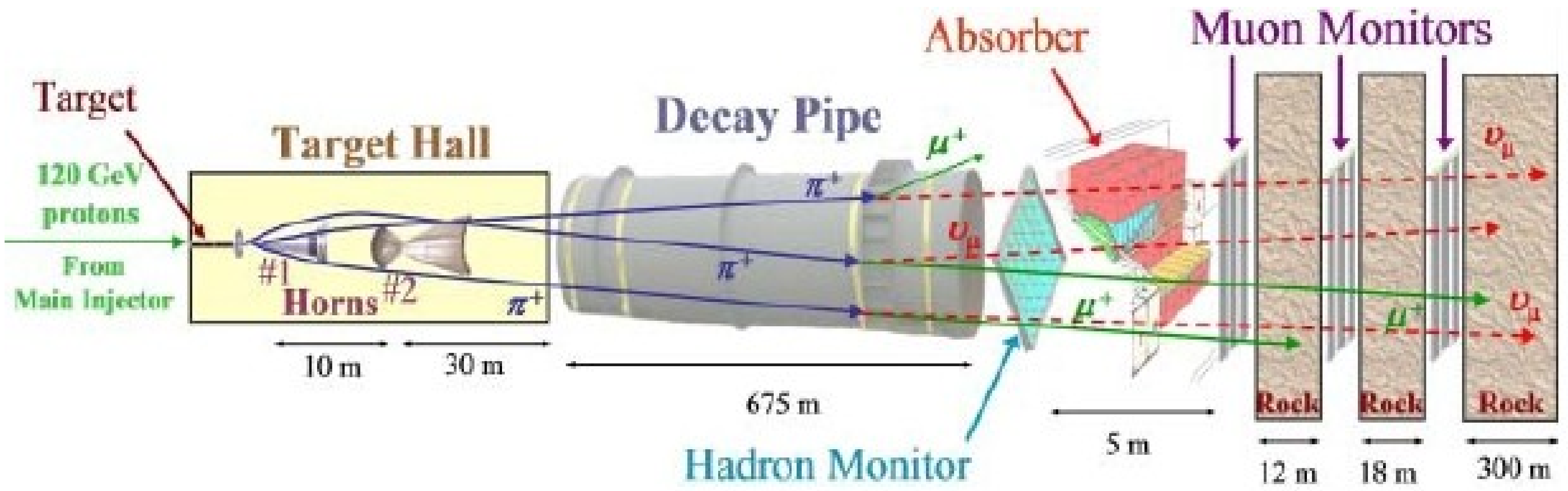


$$p + target \rightarrow \pi \rightarrow \mu + \nu_\mu$$

Making Neutrinos

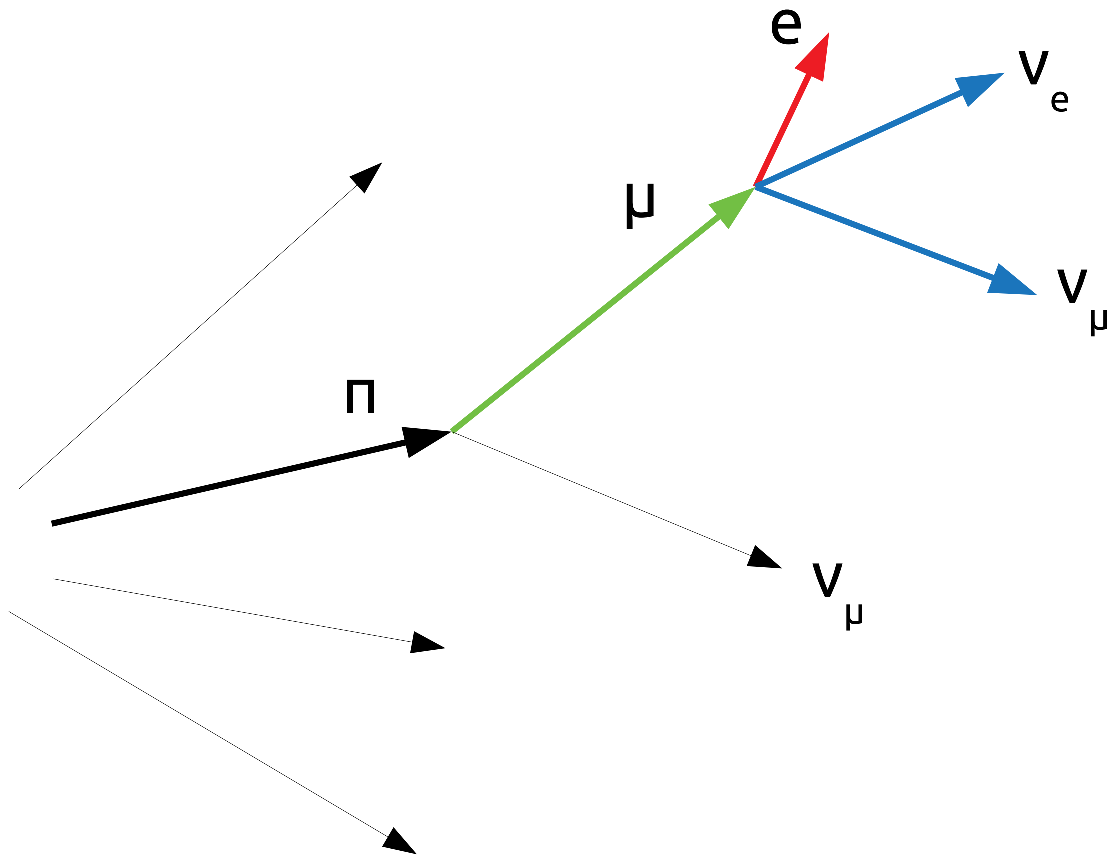


Engineering



- Can't count the number of neutrinos in the beam
- $N(\nu; E, \theta_\nu) \propto N(\pi; E_\pi, \theta_\pi)$
- Can't count the number of pions either so we need to simulate the flux
- Number and distribution of pions arises from hadronic fragmentation
- Strong interaction physics – very hard to model
- Uncertainty in the p-target interaction generates an uncertainty in the number and energy of neutrinos of around 5-10%

Making Neutrinos

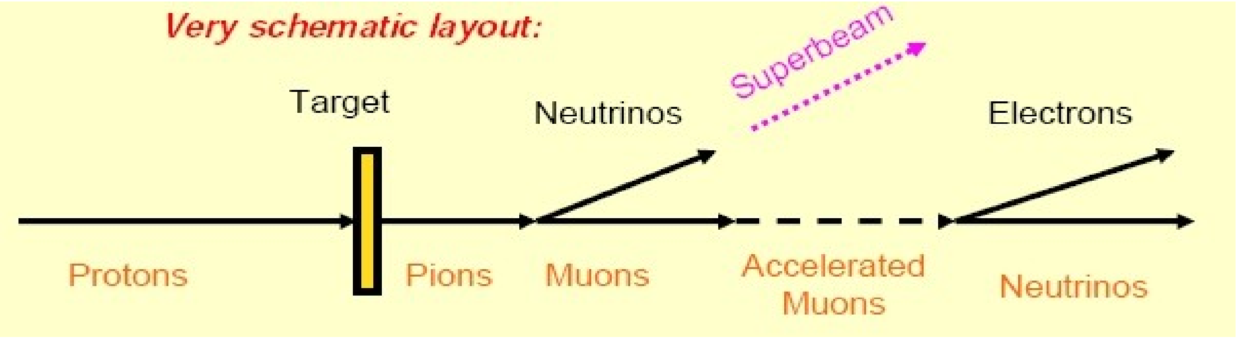


Neutrino Factory

- proton-nucleus interactions are hard to understand
- ...but muon decay is very precisely known

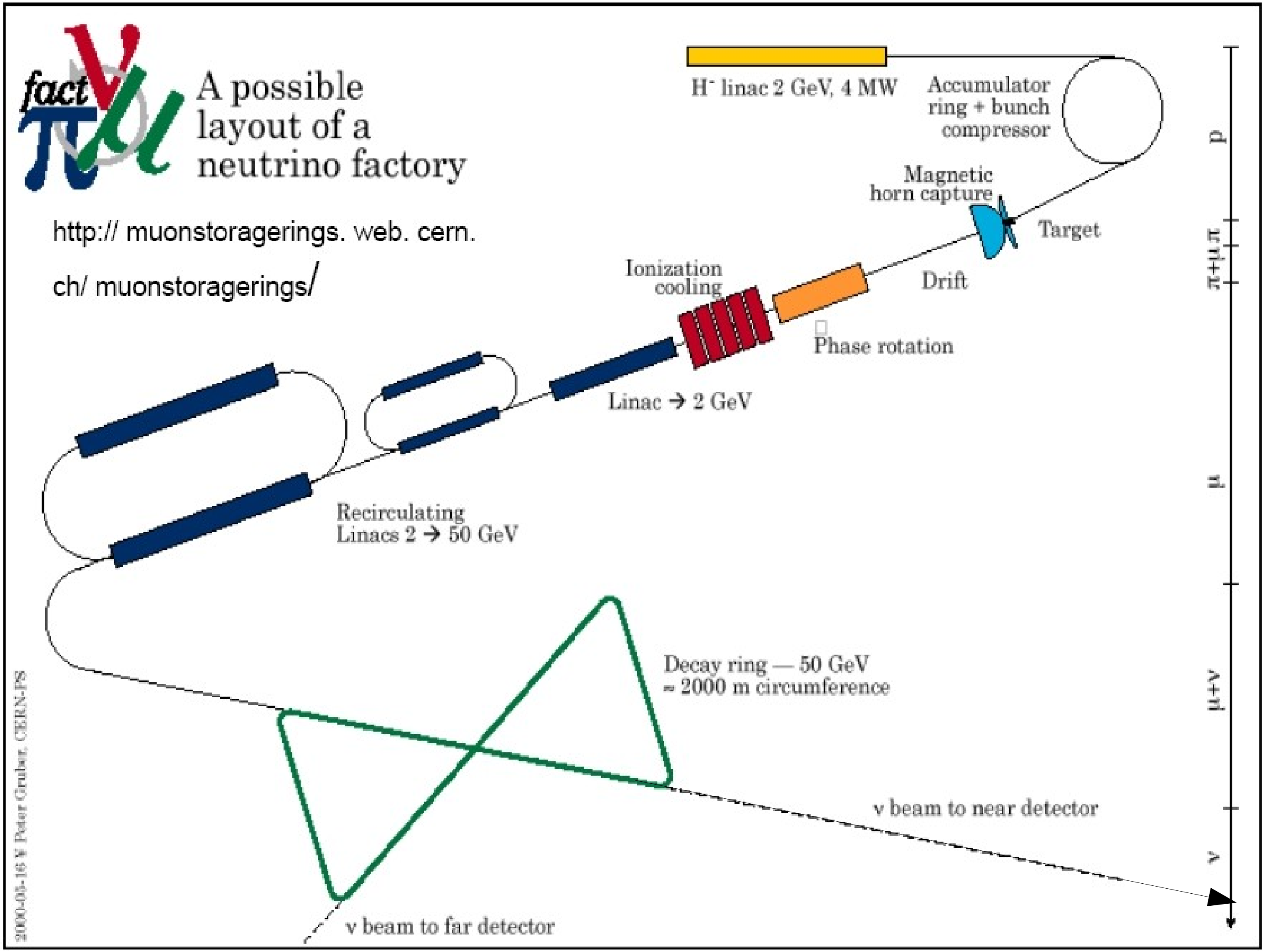
$$\mu^- \rightarrow e^- \overline{\nu_e} \, \nu_\mu$$

- Instead of taking the neutrinos from the pion decay, why not accelerate the muons to a single energy, let them decay and get the neutrino from the muon decay?



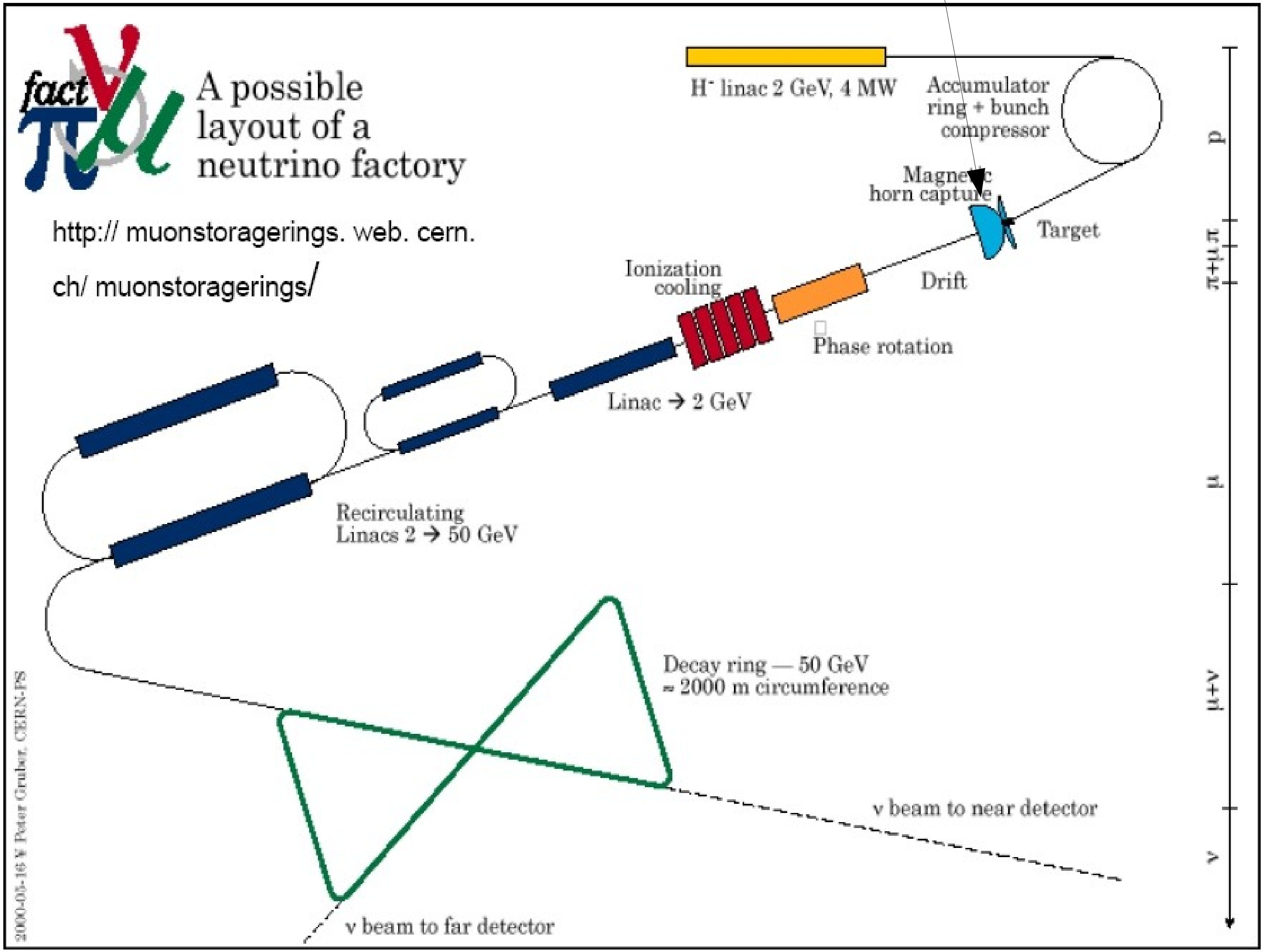
- Beam is very clean
- Extremely high neutrino flux
- Precise and predictable energy spectrum

Neutrino Factory



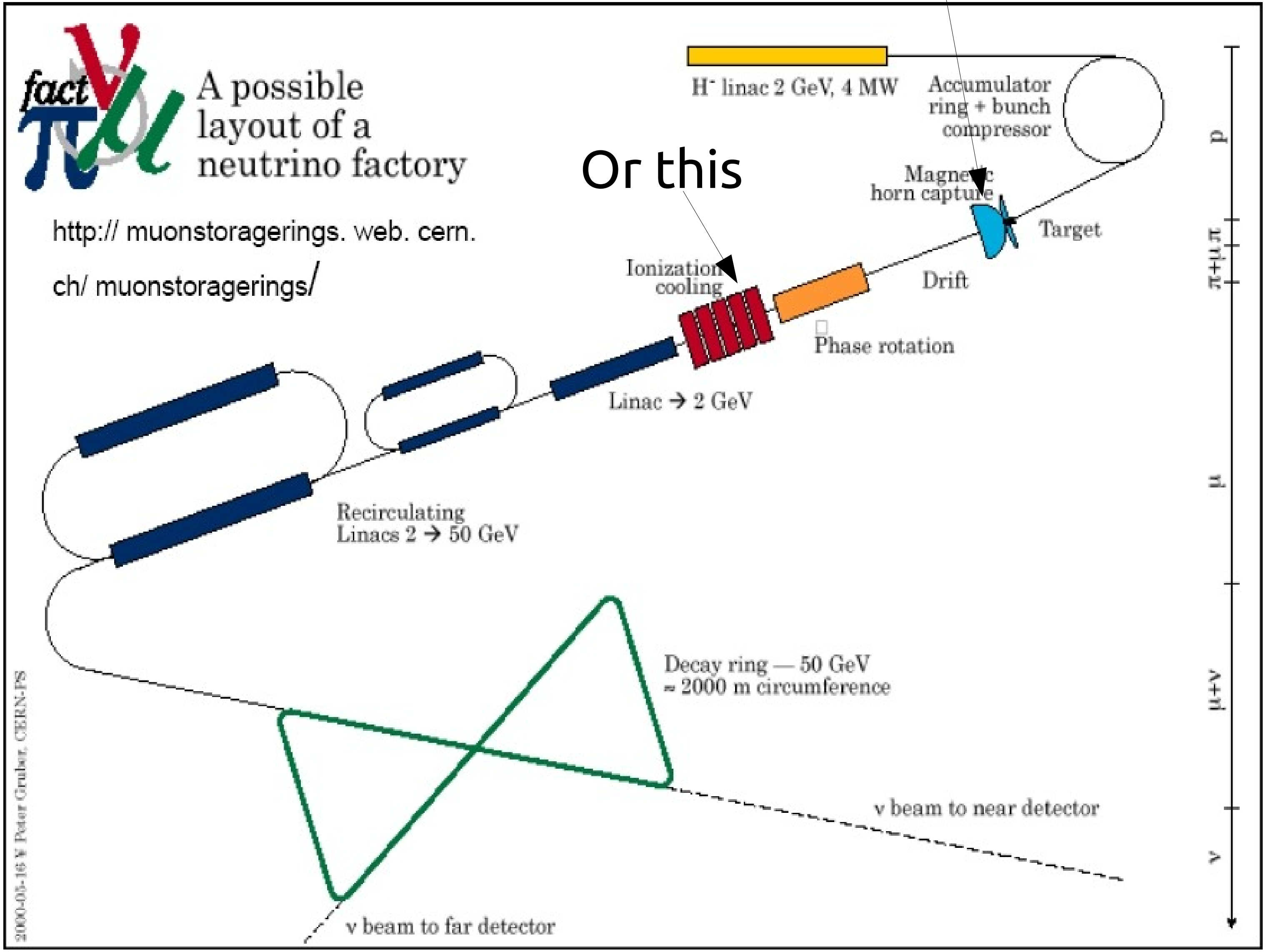
Umm….

Can't build this



Umm….

Can’t build this

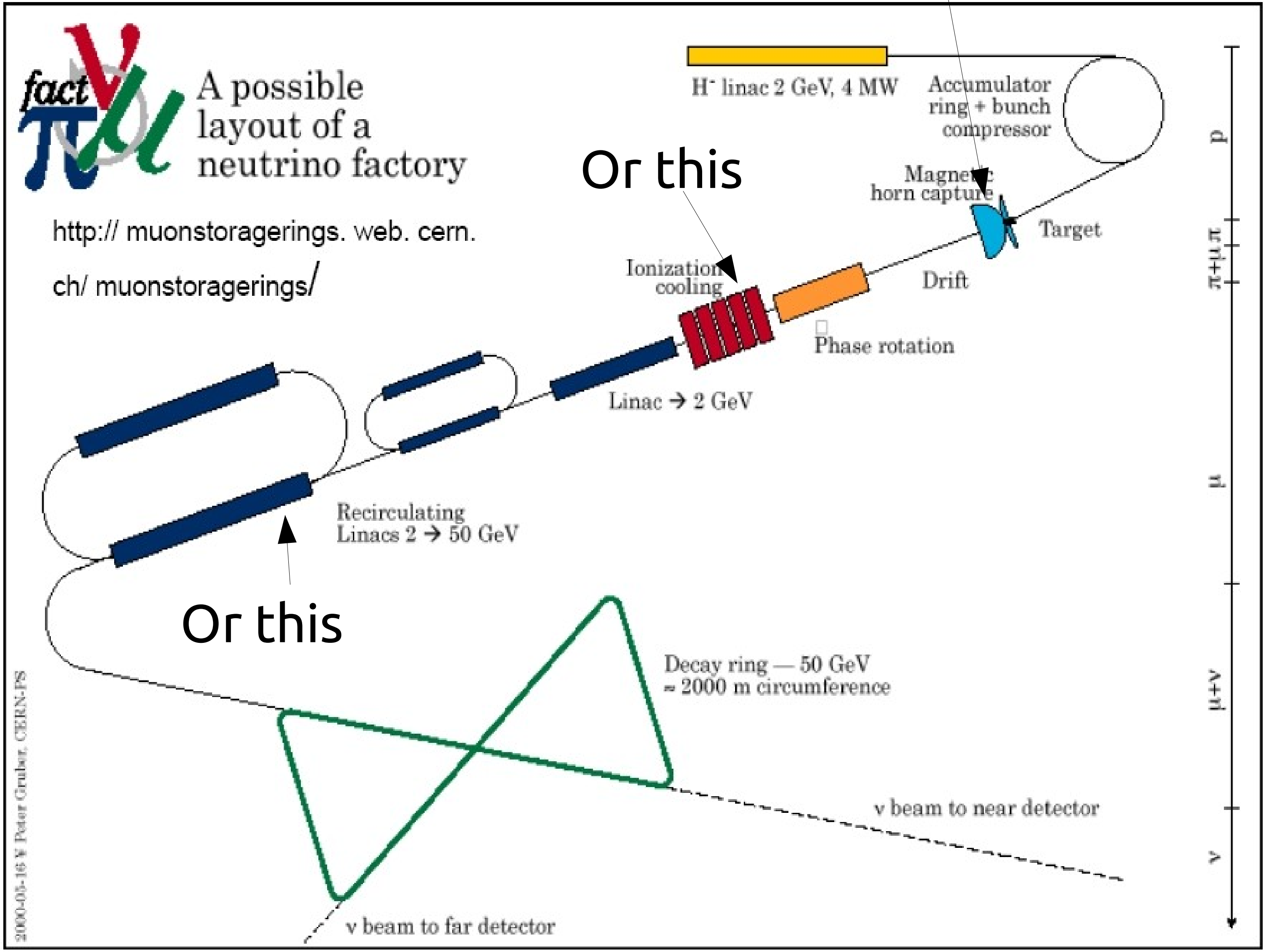


Umm....

Can't build this

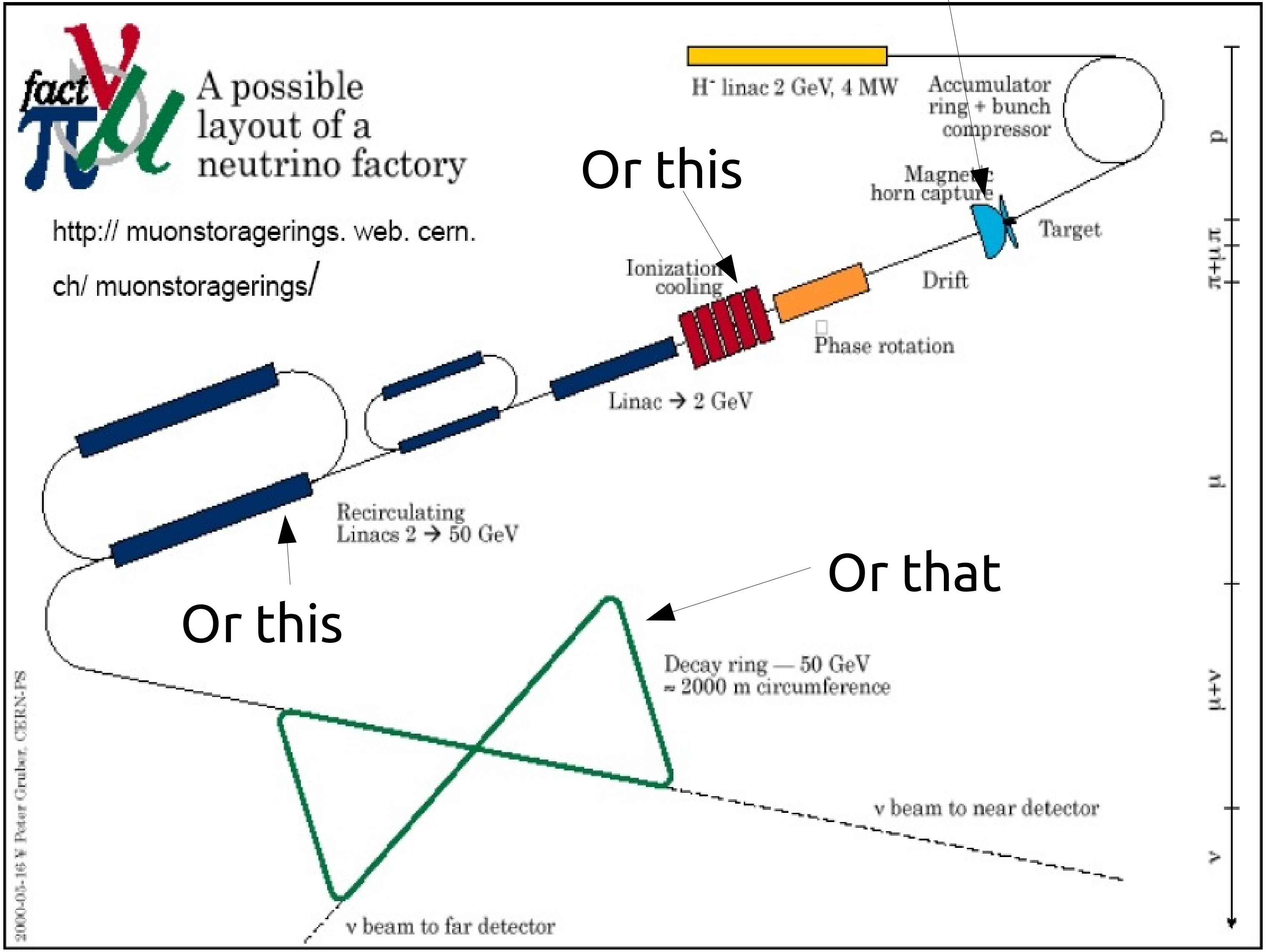
Or this

Or this



Umm….

Can't build this

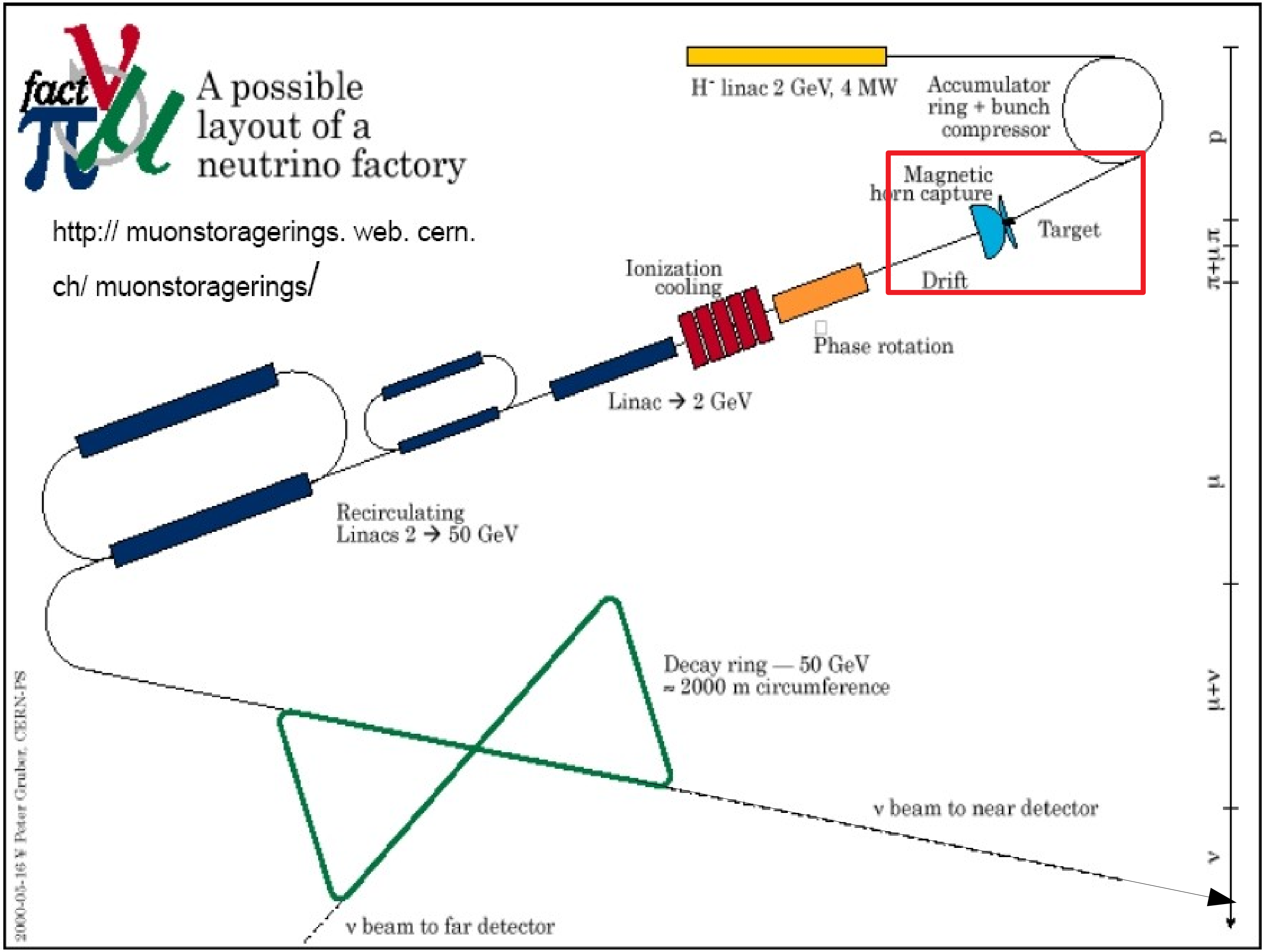


Or this

Or this

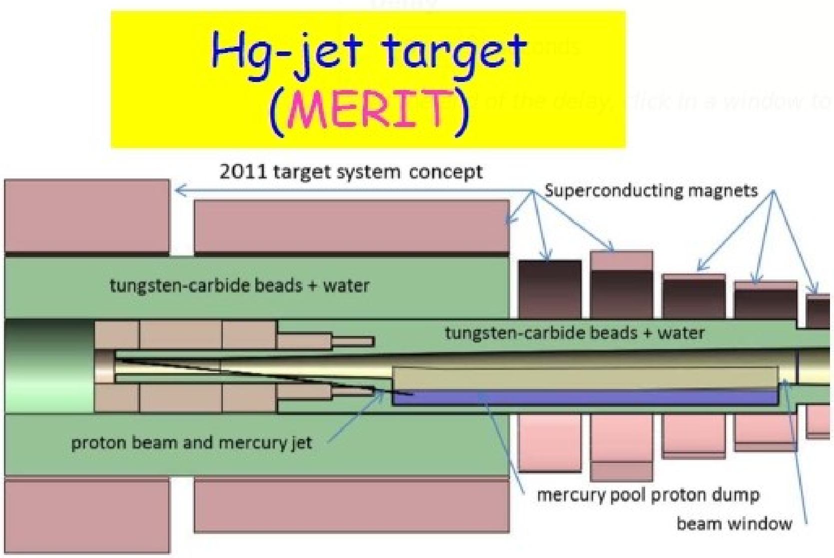
Or that

Neutrino Factory

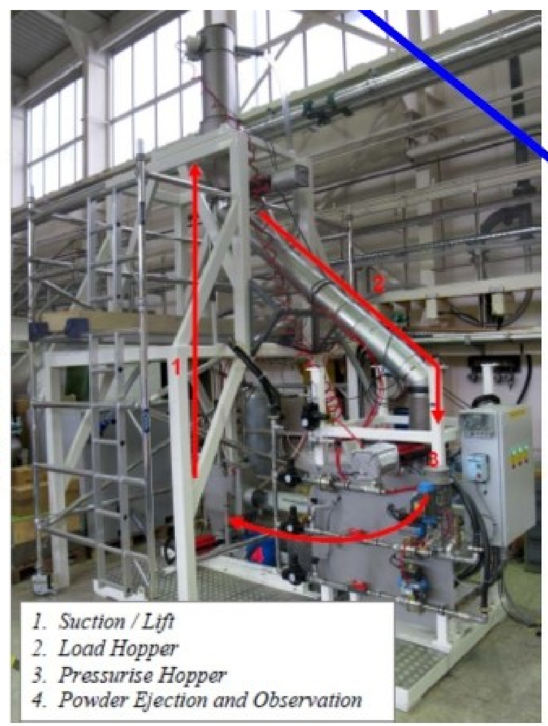


e.g. Targetry

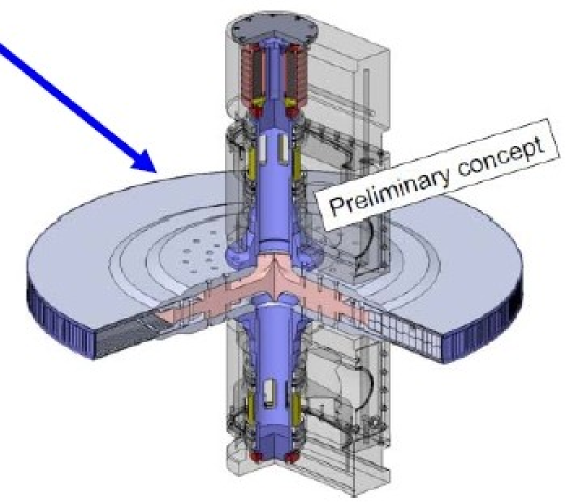
Energy per pulse on target is on the order of 2 MJ, delivered in an area of 0.1 cm^2 in less than 2 ns every 20 ms or so.
This leads to a temperature rise of more than 1000 degrees in the target per ms. Huge damage to target and surrounding material.



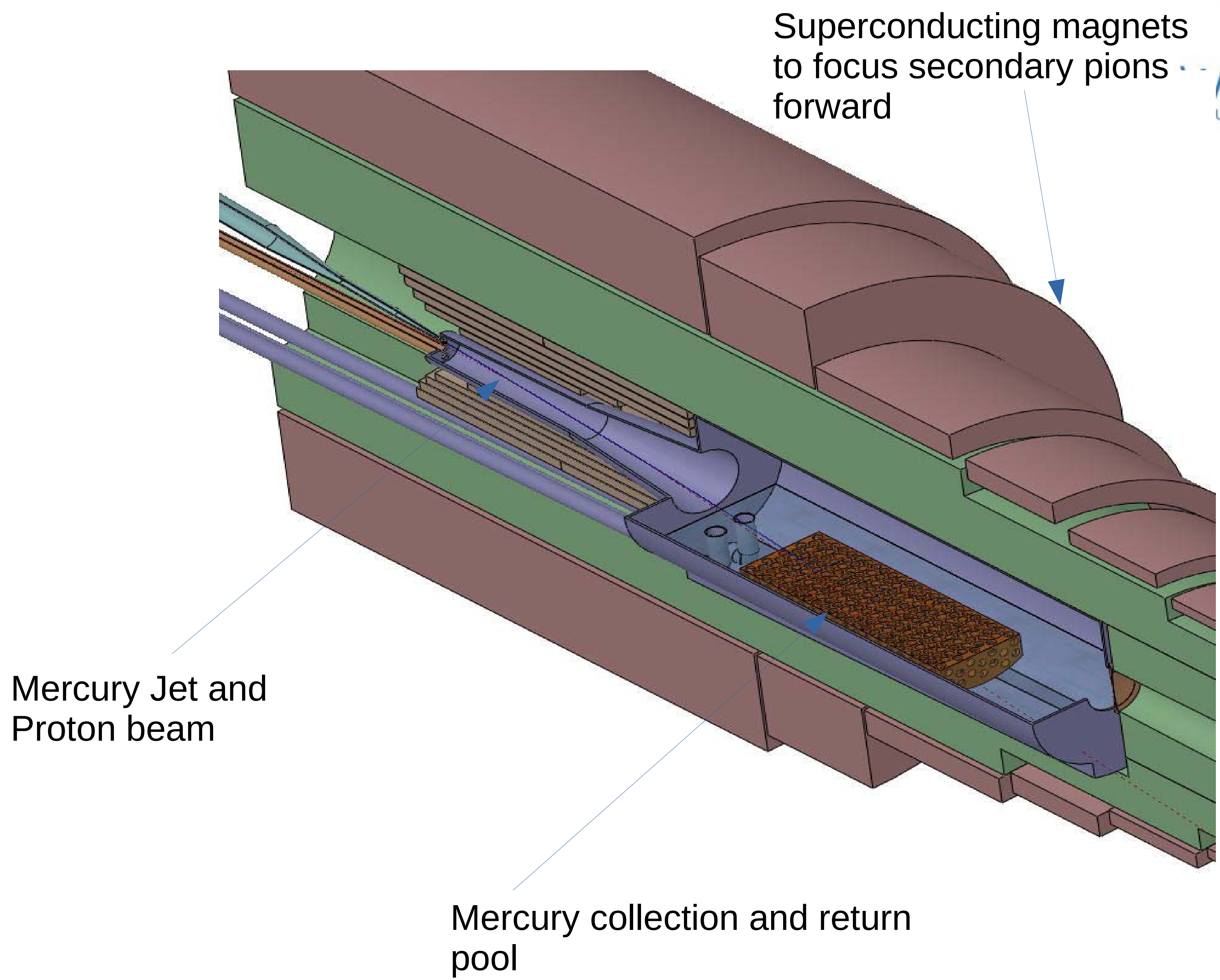
Mercury Jet



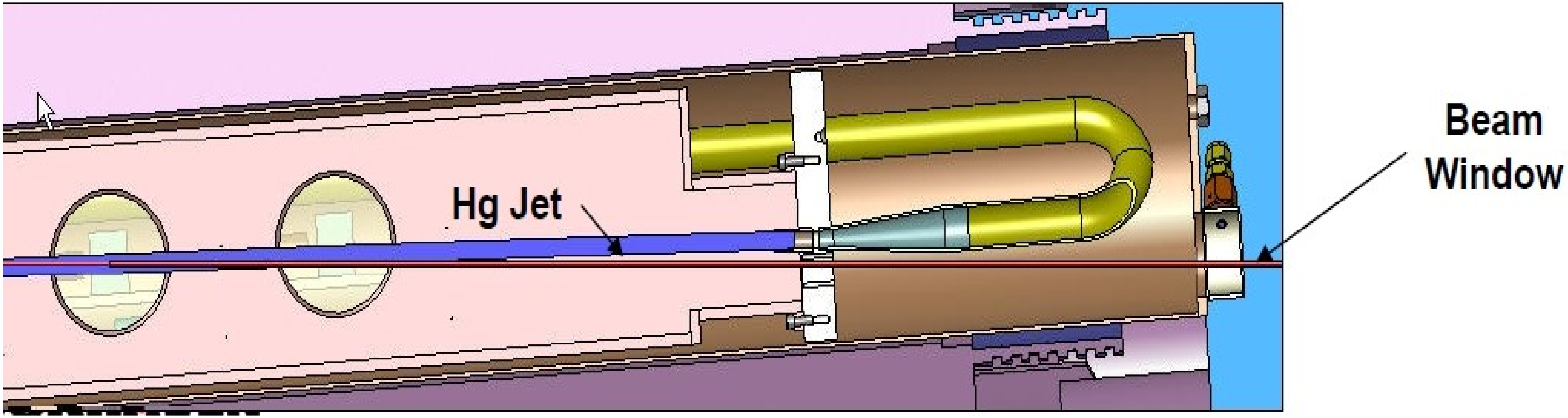
Powder Jet

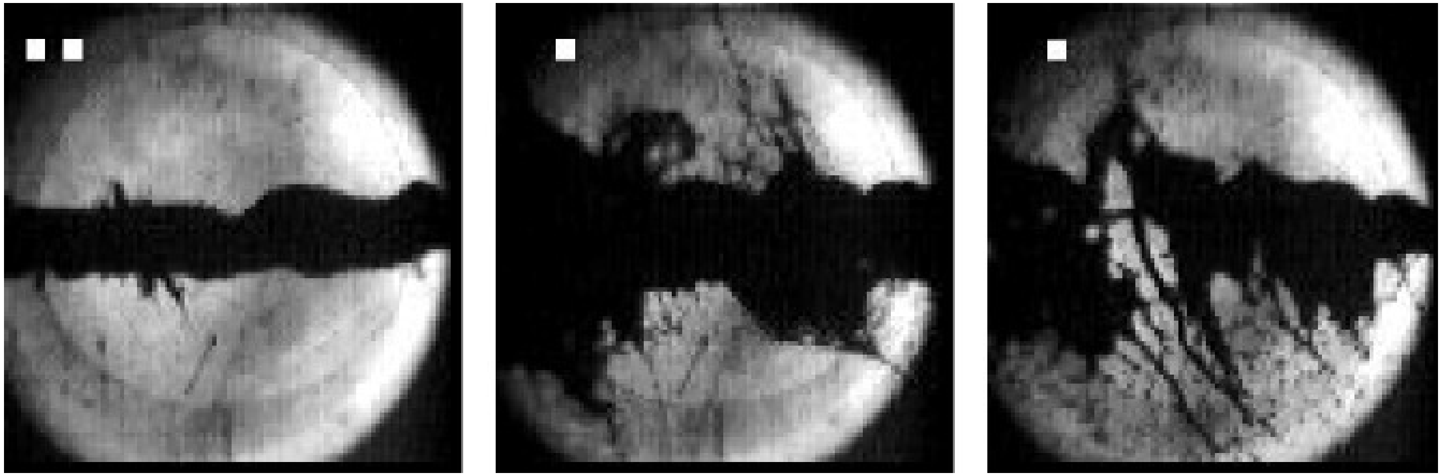


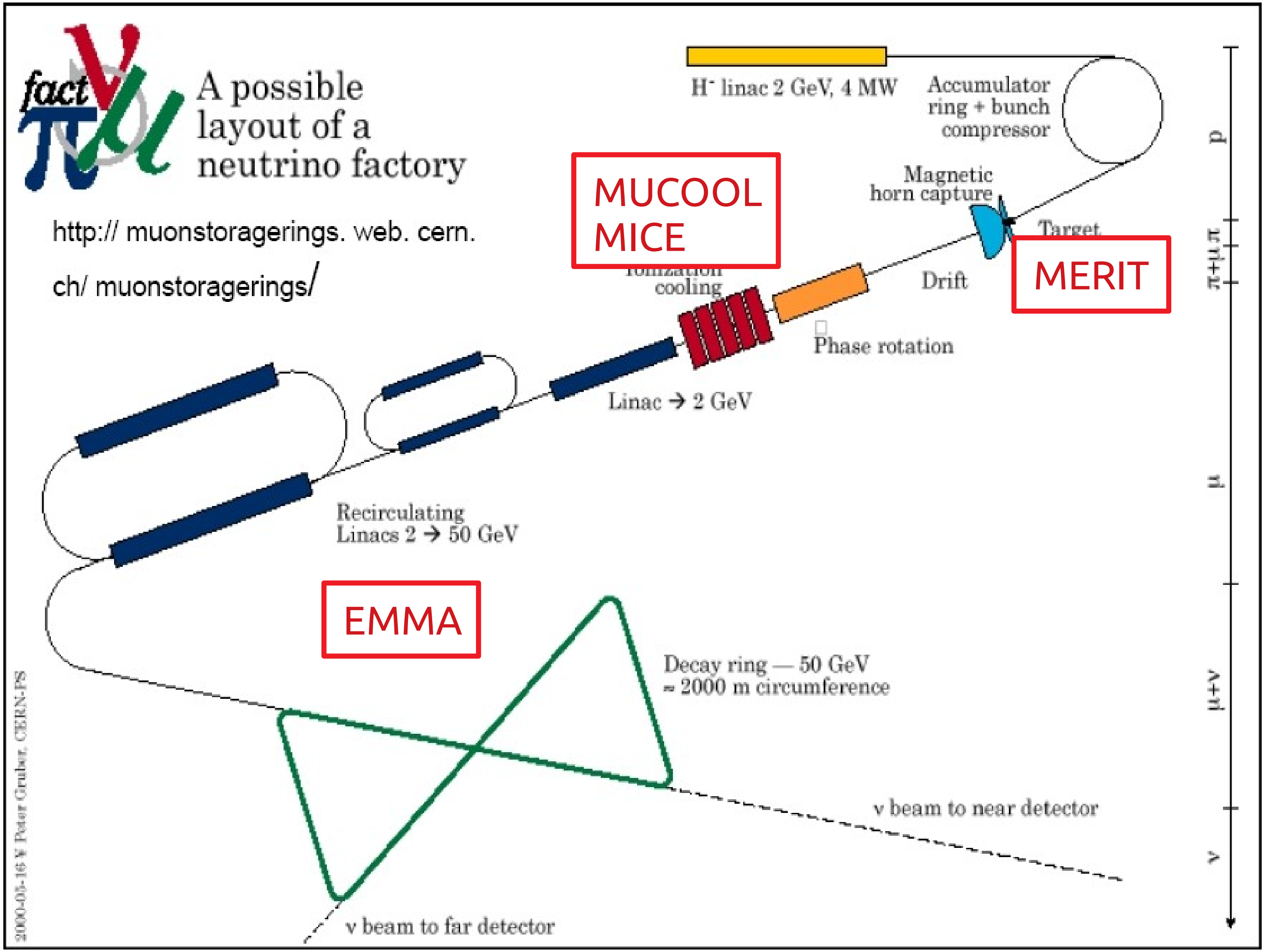
Rotating Disc


Superconducting magnets
to focus secondary pions
forward
Mercury Jet and
Proton beam
Mercury collection and return
pool

MERIT Experiment



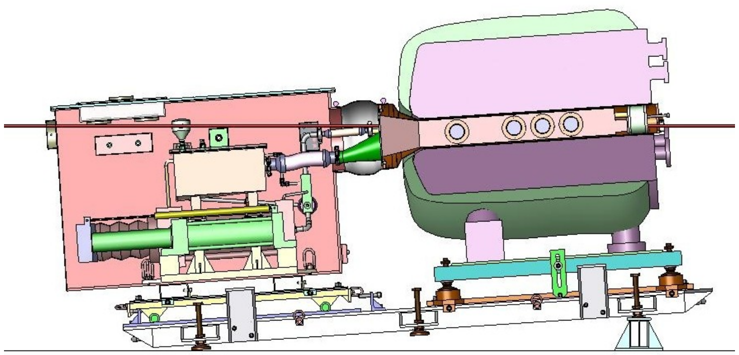


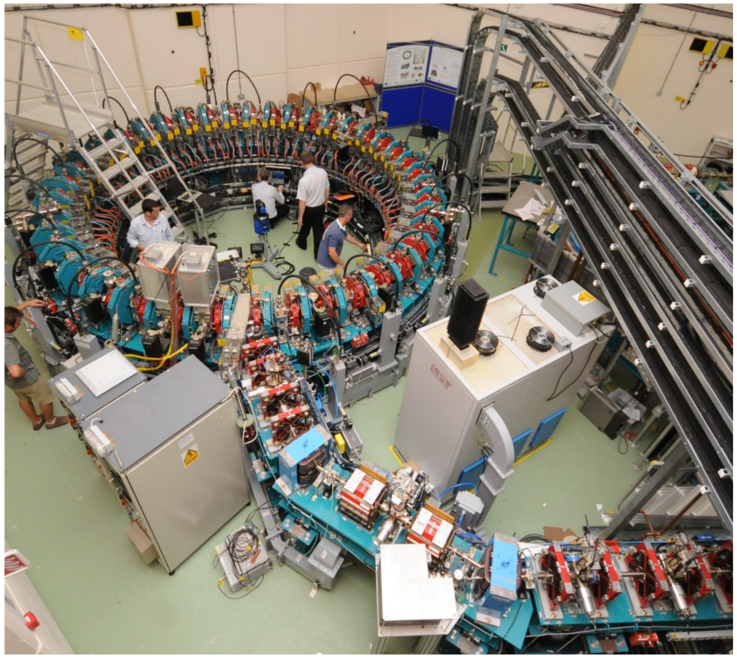


A possible layout of a neutrino factory
http:// muonstoragerings. web. cern. ch/ muonstoragerings/
H⁻ linac 2 GeV, 4 MW
Accumulator ring + bunch compressor
Magnetic horn capture
Target
MUCOOL
MICE
MERIT
cooling
Drift
Phase rotation
Linac → 2 GeV
Recirculating Linacs 2 → 50 GeV
EMMA
Decay ring — 50 GeV ≈ 2000 m circumference
ν beam to near detector
ν beam to far detector
p
π+μ,π
μ
μ+ν
ν
2000-03-16 ¥ Peter Gruber, CERN-PS

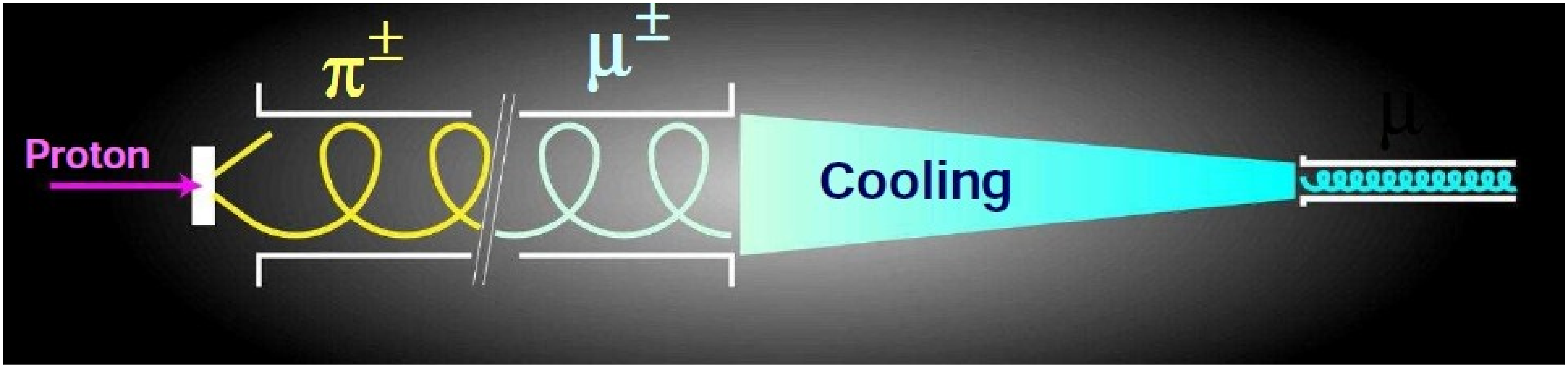
Accelerator R&D

- 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





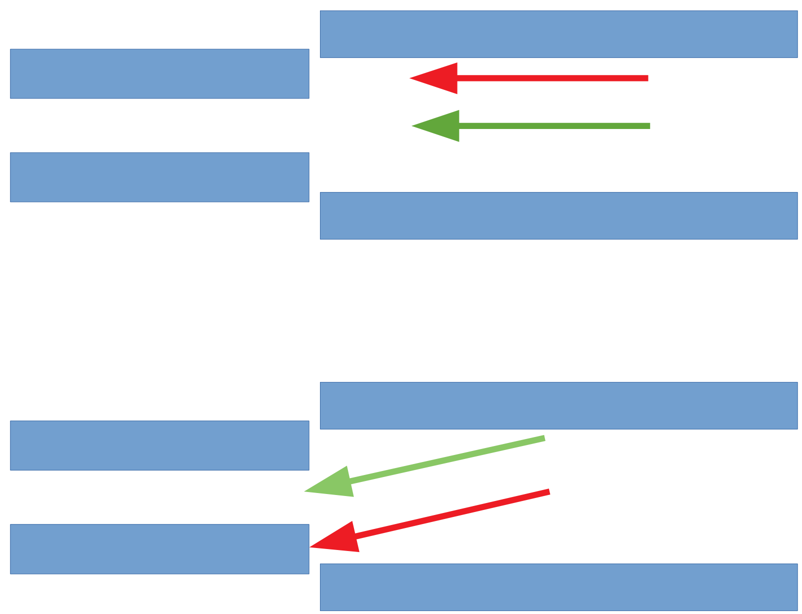
Beam Cooling



- Beam cooling is a process whereby the size of the beam is squeezed in order to make it fit into smaller, later section of an accelerator system
- There are a few different techniques to cool a beam
- They are all very slow
- Muons decay – for a neutrino factory we need to do the cooling quickly before all the muons vanish
- Only one method known : **ionisation cooling**

Beam Size

elements
in the
beamline

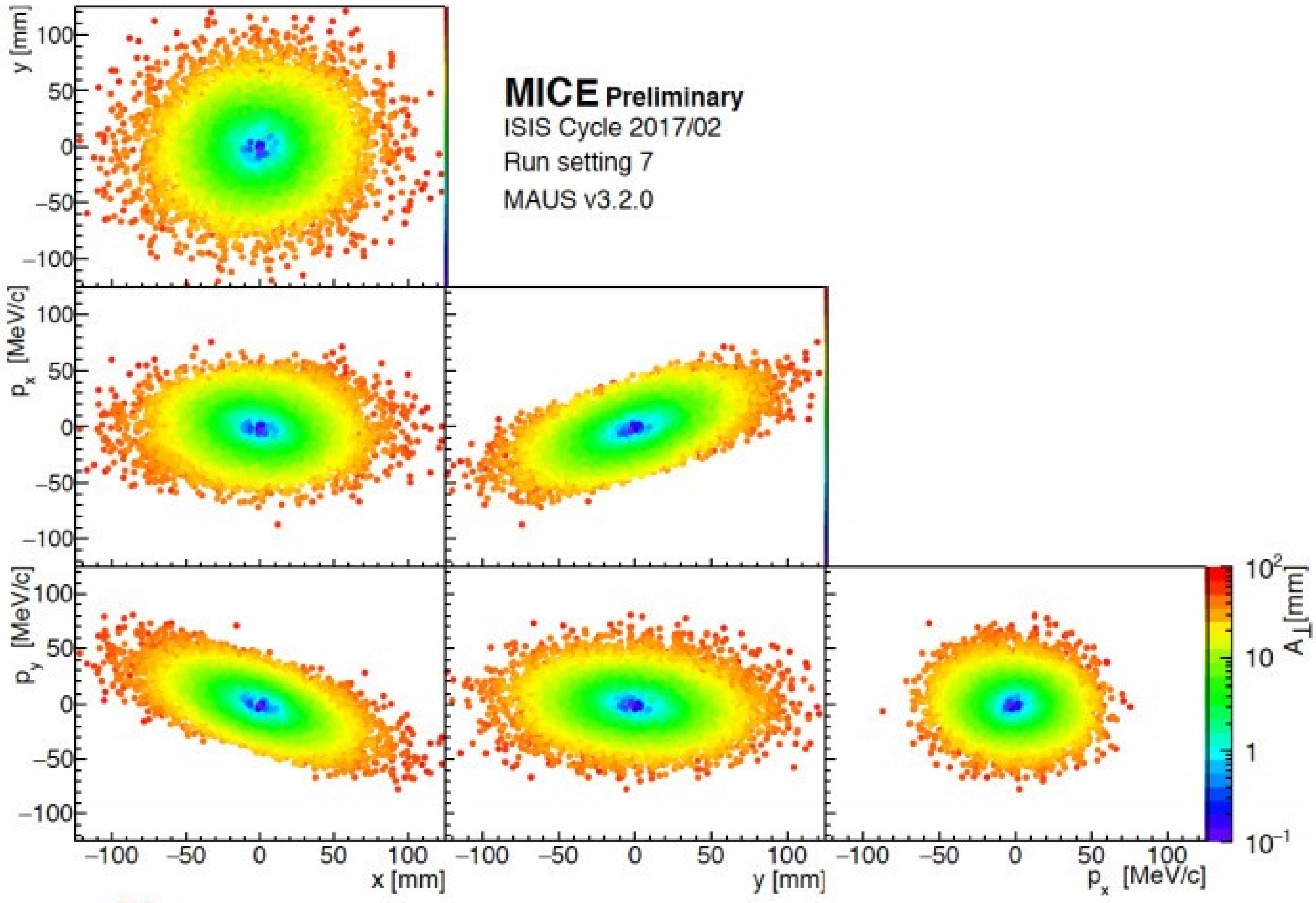


Particles on edge of aperture don't make it through

Particles with large transverse momentum don't make it through either

- Particles in a beam exist in a 4-D space (x, y, p_x, p_y)
- Beam size : volume of this space occupied by beam particles
- Known as **"emittance"** of the beam

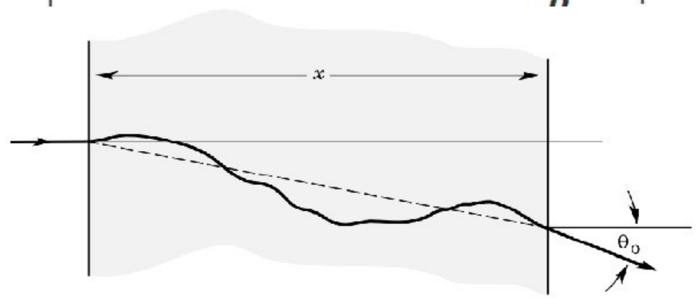
Beam Size



MICE Preliminary
ISIS Cycle 2017/02
Run setting 7
MAUS v3.2.0
y [mm]
p_x [MeV/c]
p_y [MeV/c]
x [mm]
y [mm]
p_x [MeV/c]
$A_\perp$[mm]
10^2
10
1
10^{-1}

Ionisation Cooling

- Lose energy and momentum going through *stuff*
- Tends to decrease the size of the beam 😄

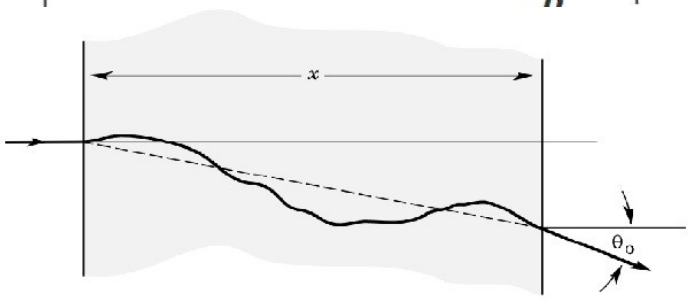


- Particle can undergo multiple scattering
- Tends to increase the size of the beam 😫

- Accelerate particle longitudinally to replace lost momentum

- As long as the effect of (1) is greater than that of (2) we can cool the beam
- If (2) is greater than (1) then we blow the beam up, heating it.

Ionisation Cooling



- Lose energy and momentum going through *stuff*
- Tends to decrease the size of the beam 😄

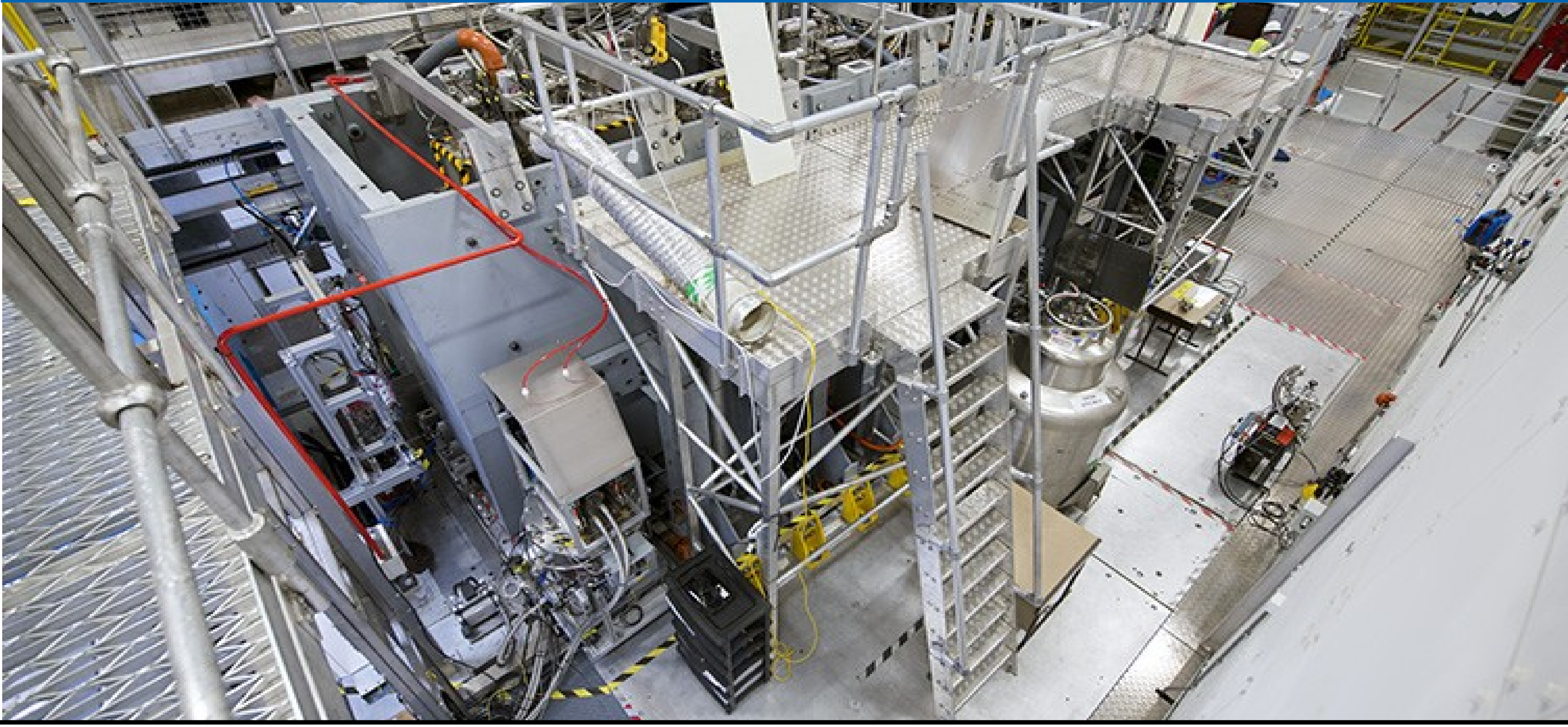
- Particle can undergo multiple scattering
- Tends to increase the size of the beam 😫

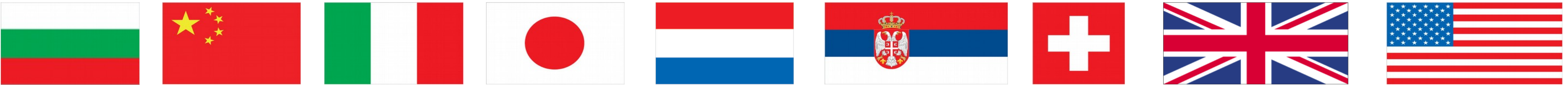
- Accelerate particle longitudinally to replace lost momentum

Best choice of *stuff* : liquid hydrogen

MICE

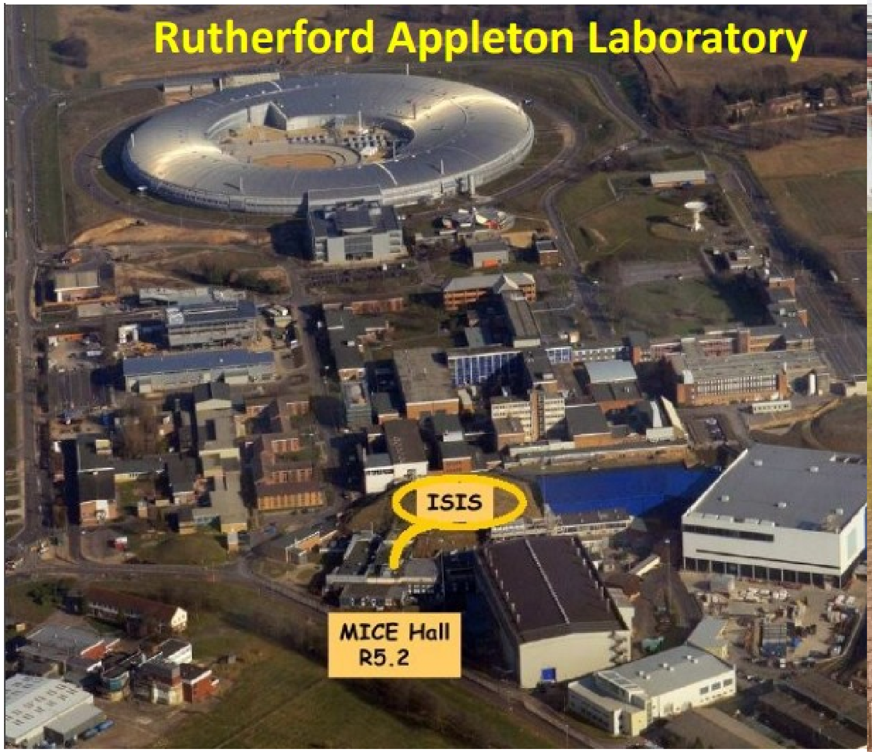
Muon Ionization Cooling Experiment





MICE was designed to demonstrate ionisation cooling

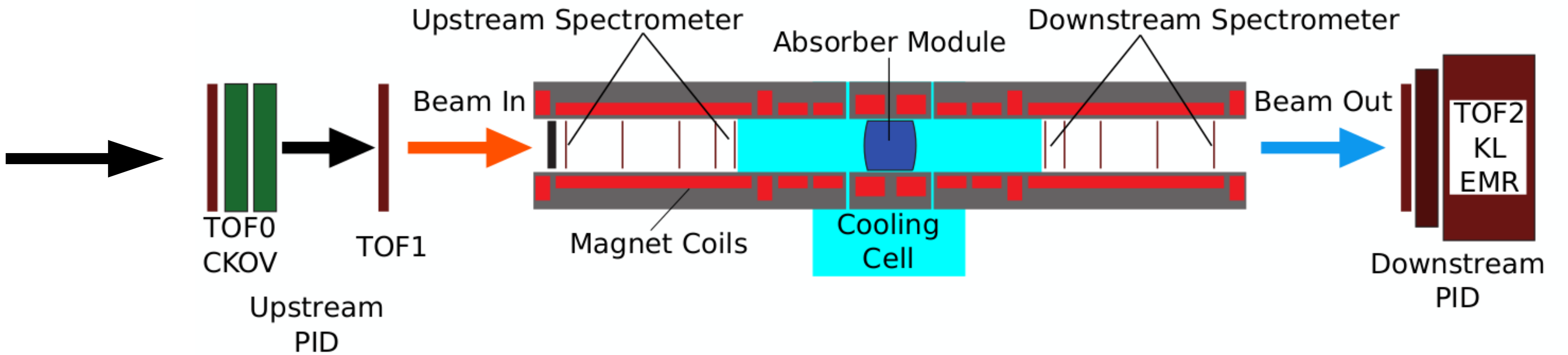
MICE



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

MICE

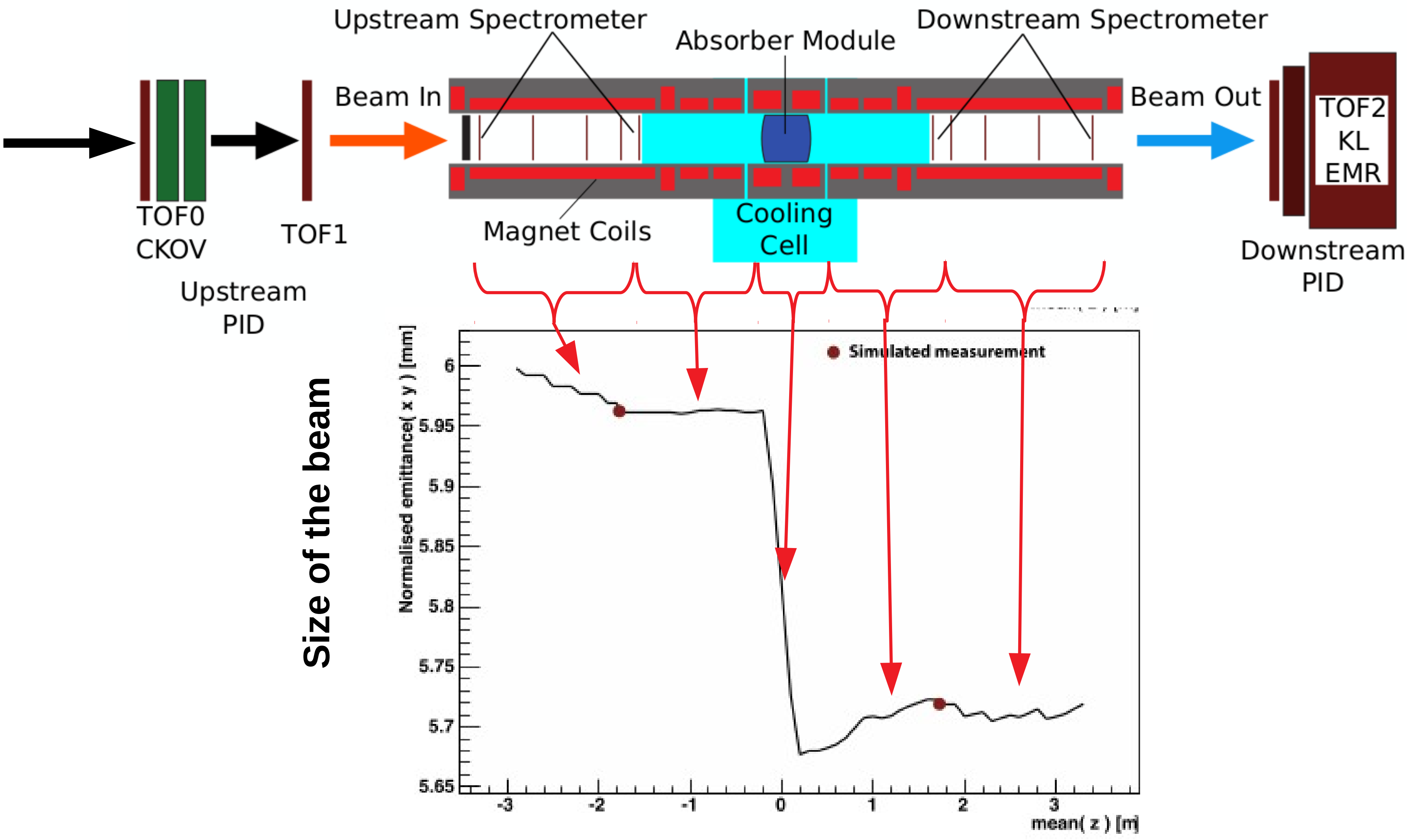
- MICE goal is to verify emittance reduction from ionization cooling



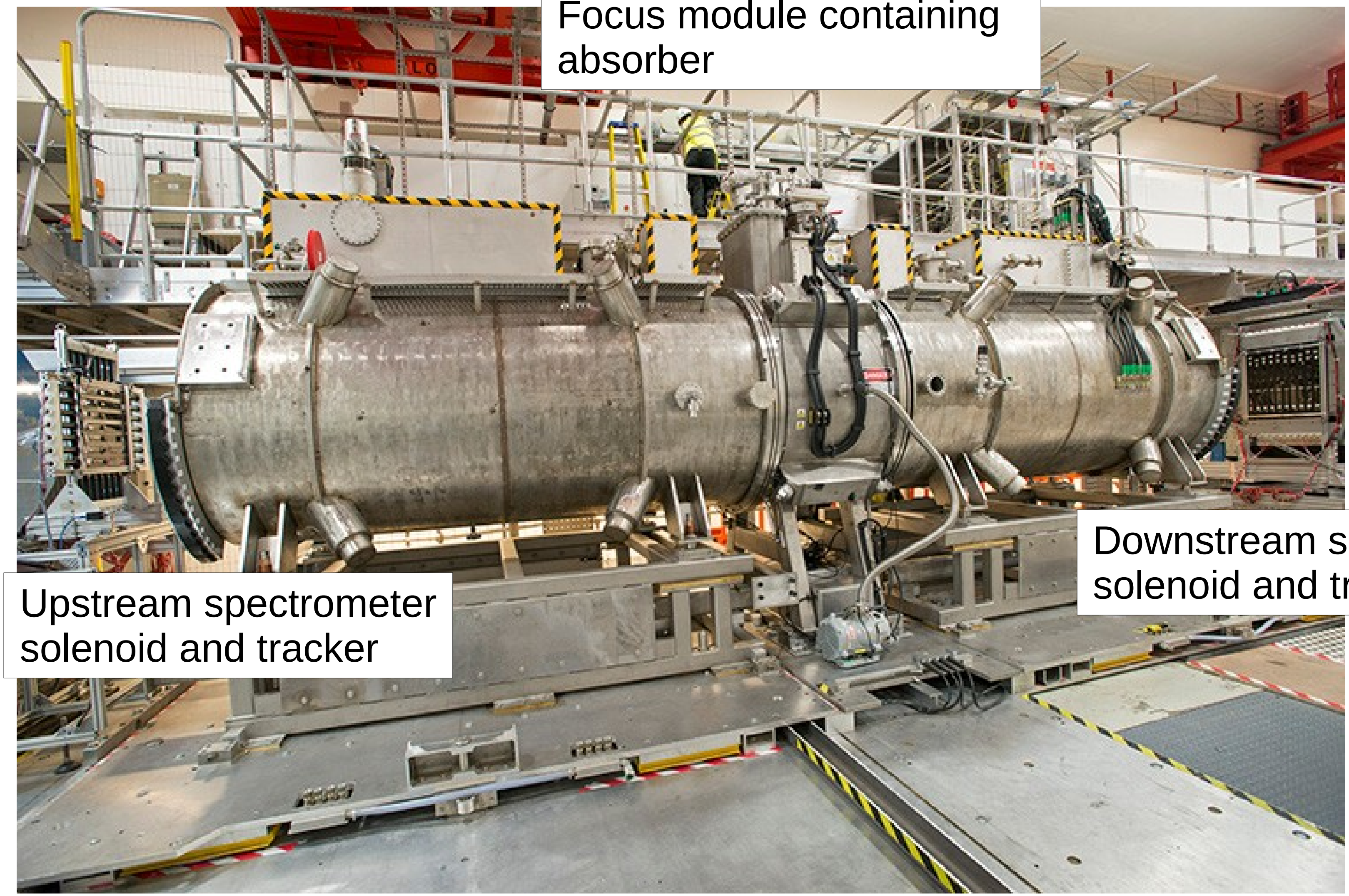
- Generate muons from proton-Ti interactions in the ISIS accelerator at RAL
- Pass single muons through the channel
- Particle ID detectors (CKOV/TOF/EMR) make sure that the particle is a muon
- Construct a beam later on in software
- Measure the size of the muon beam upstream and downstream of the absorber
- *Change in size of beam is indicative of ionisation cooling*

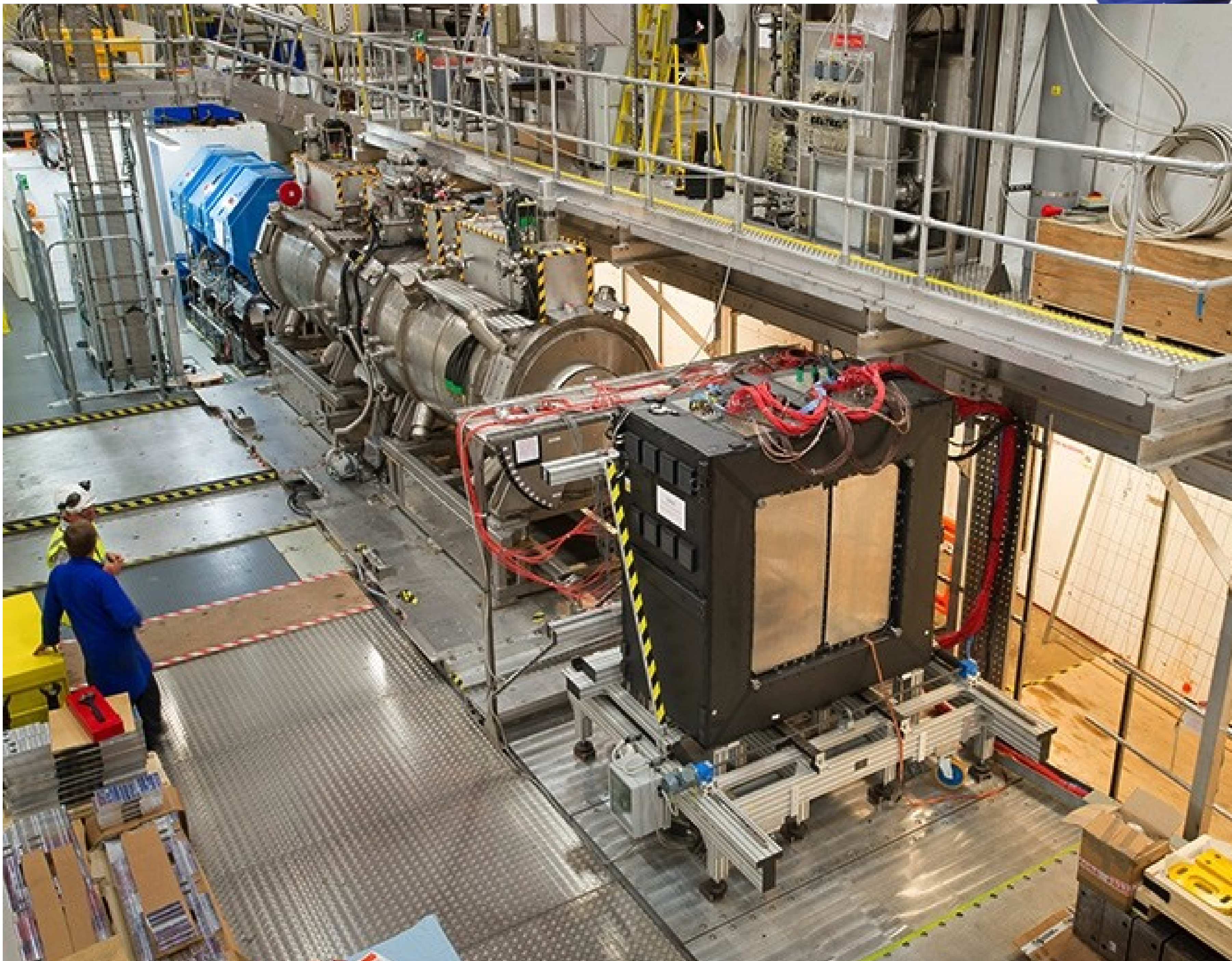
MICE

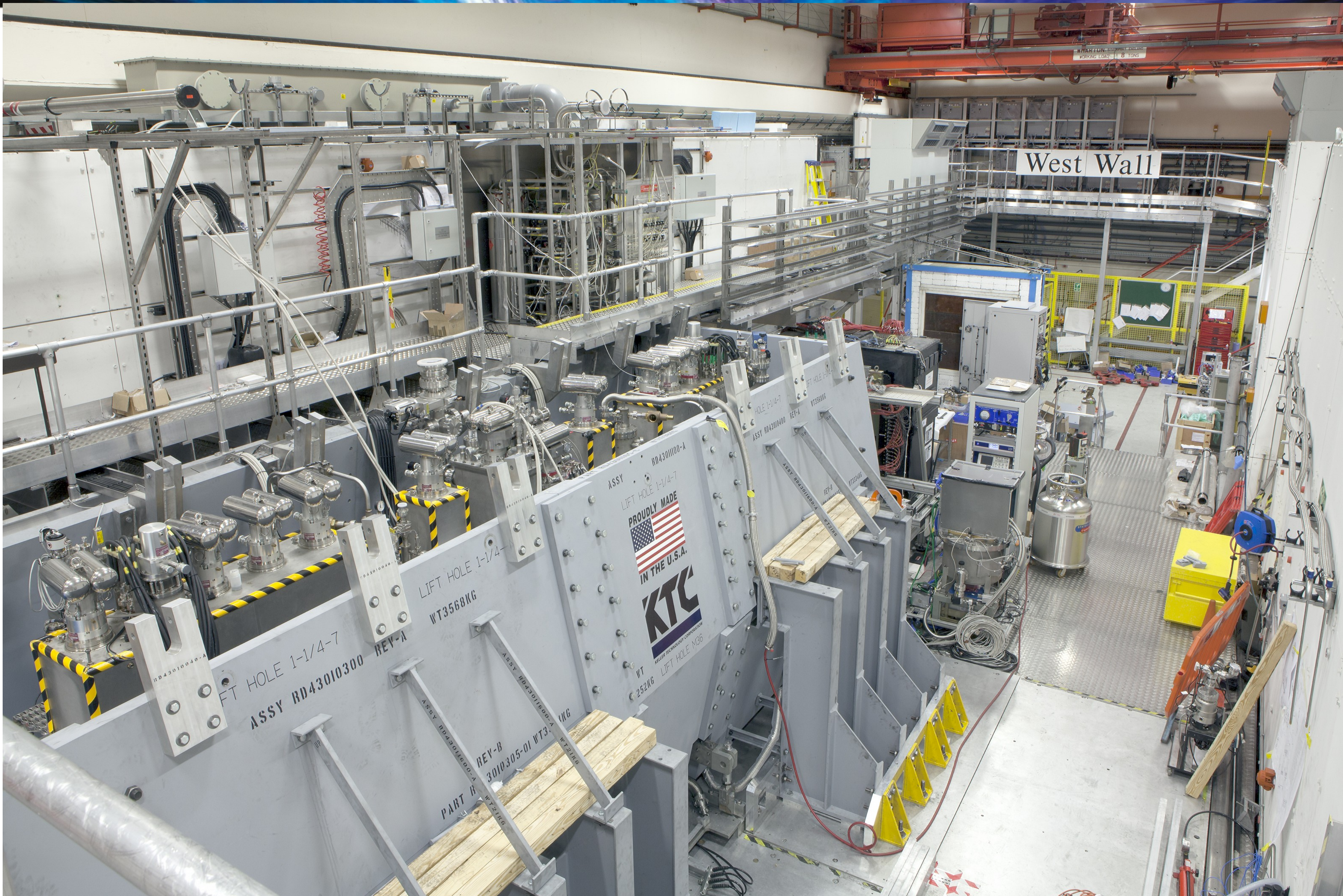
- MICE goal is to verify emittance reduction from ionization cooling



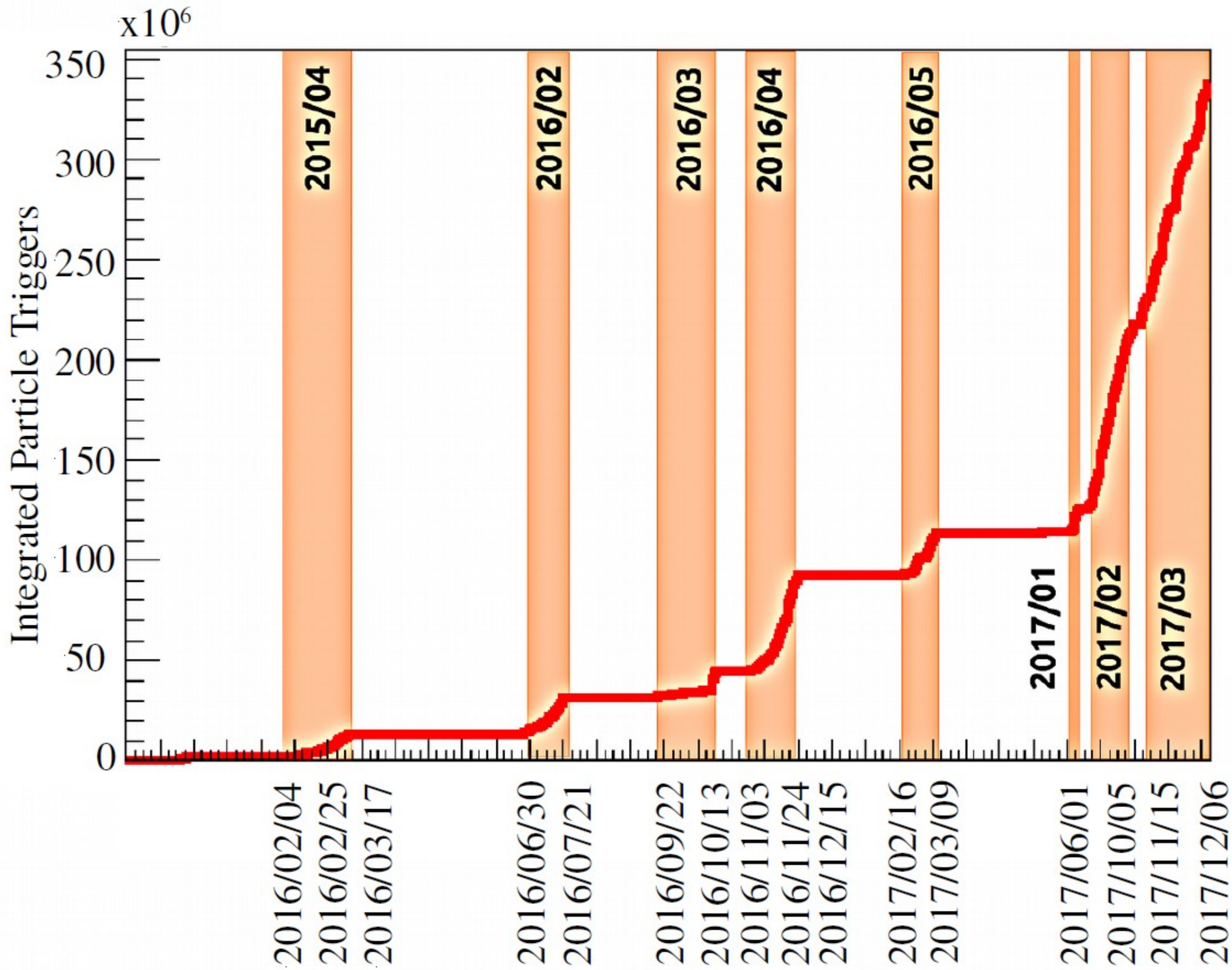
MICE


Focus module containing absorber
Upstream spectrometer solenoid and tracker
Downstream spectrometer solenoid and tracker



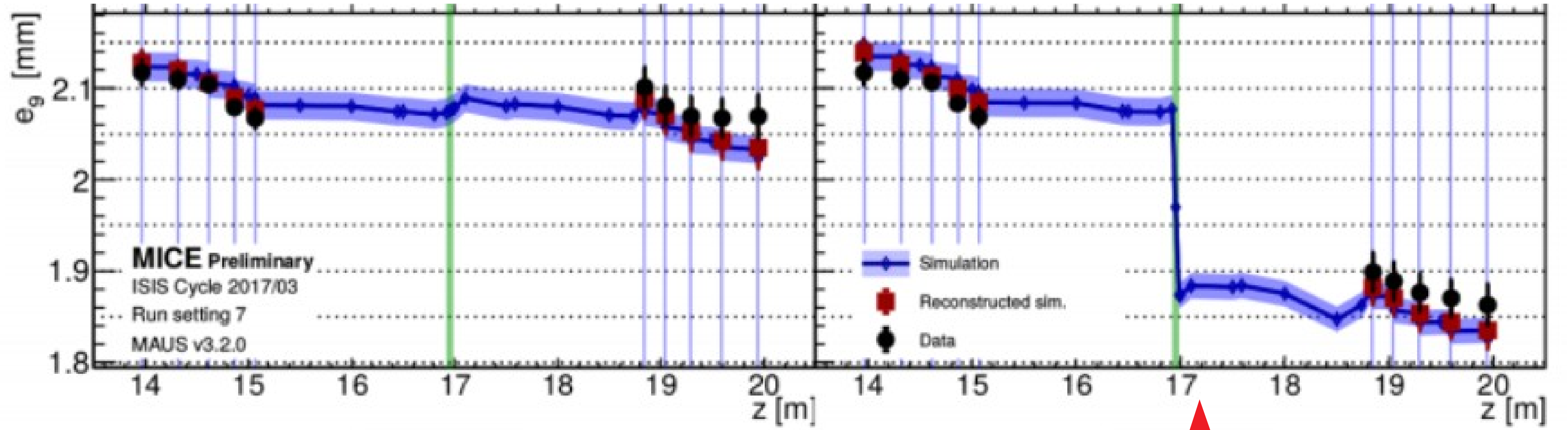

West Wall
PROUDLY MADE IN THE U.S.A.
KTC
LIFT HOLE 1-1/4-7
ASSY RD43010300 REV-A
WT3568KG
ASSY RD43011100-A
LIFT HOLE M36

MICE Data-taking



Results

No LH_2 in beamline — LH_2 introduced



Distance along the channel

The muons are cool !

Accelerator R&D

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- 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
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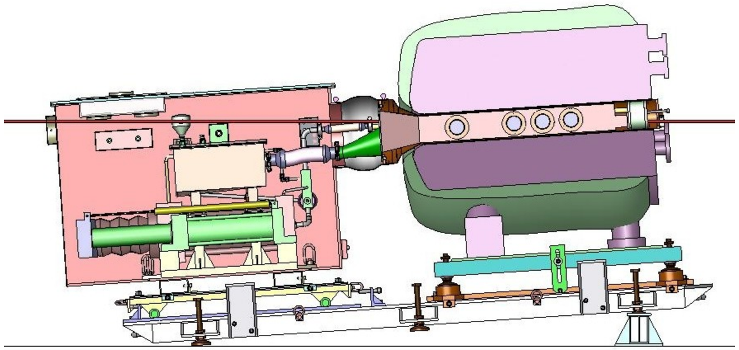
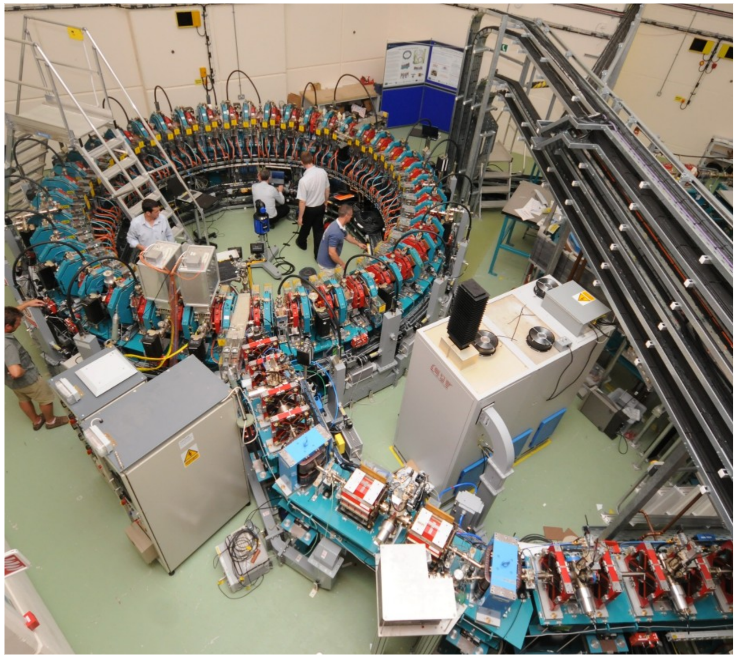
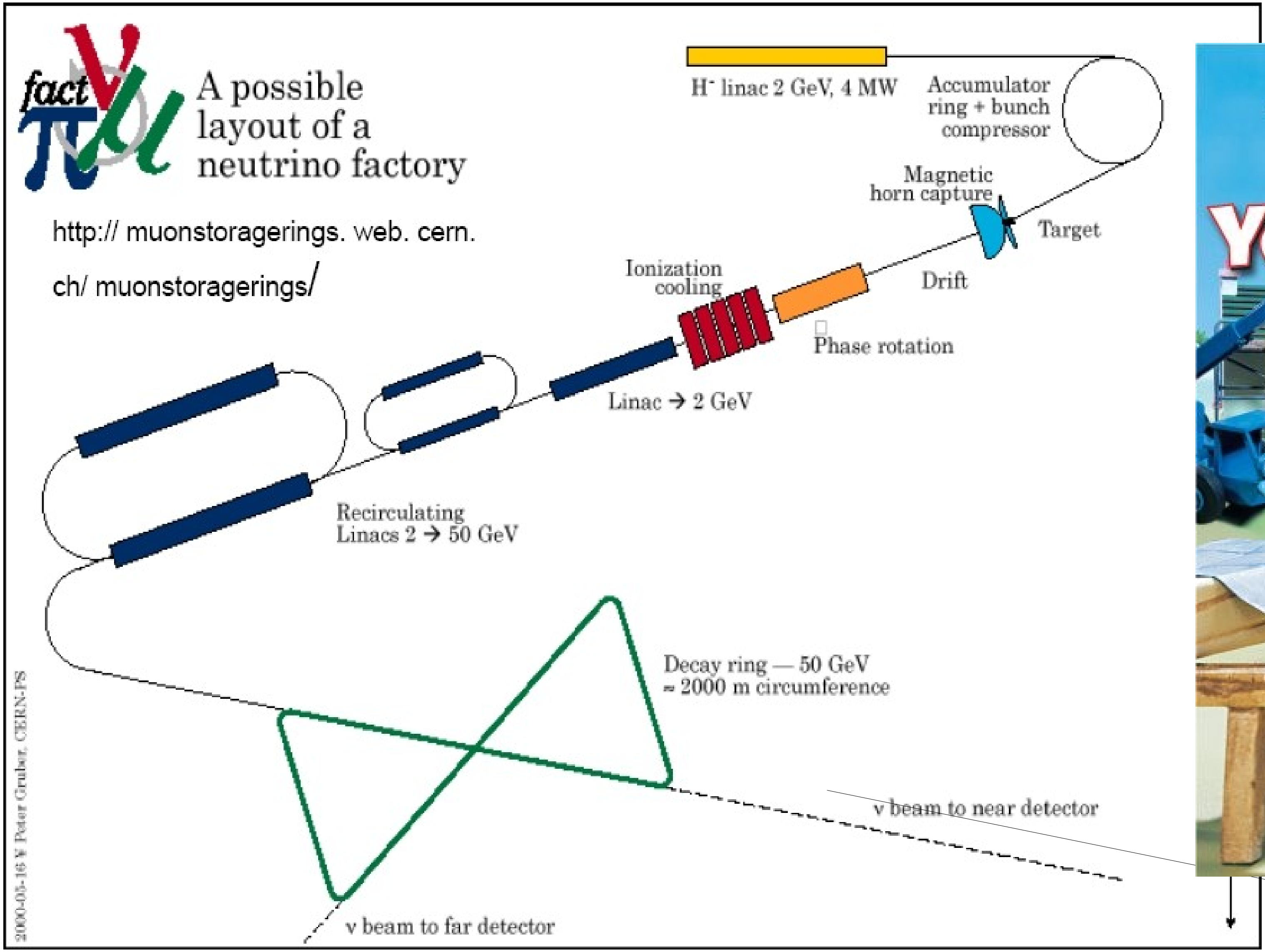
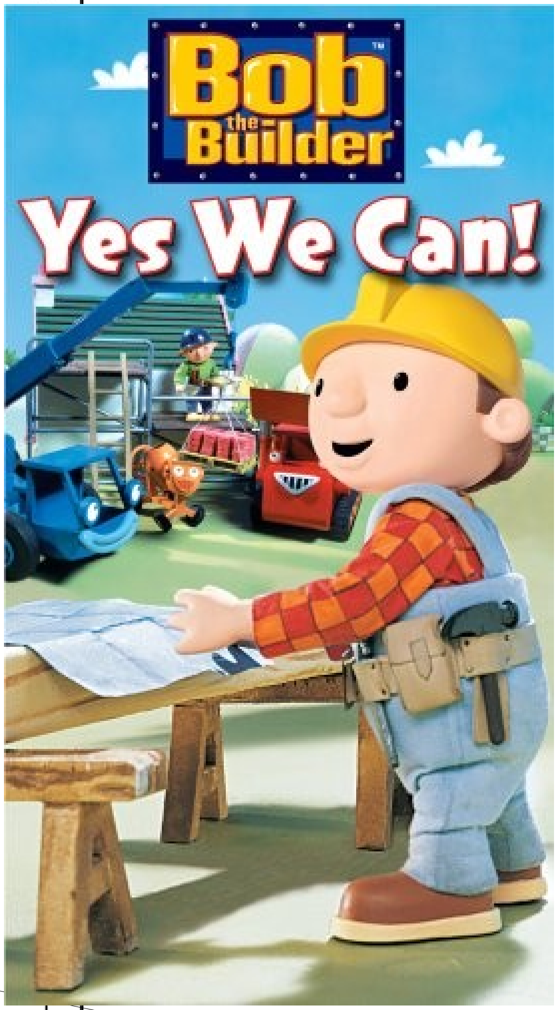




Can we build it?





Summary

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- High precision neutrino experiments may require different methods of making the neutrinos
- The neutrino factory is the ultimate neutrino machine
    - precisely understood neutrino flux
    - lots and lots of neutrinos
- Needed R&D to validate ideas for cutting-edge engineering
- The MICE experiment tested the last step of the design – beam cooling
- It looks like it works, and can be built!
- ...but will we…?

Backups

- Accelerators were first built in the 1920’s/30’s to accelerate protons/ions and electrons for fundamental research
- Now accelerators have many uses
- **Hadron accelerators**
  - Discovery machines e.g. LHC
    - Messy hadronic environment
  - Medical isotope production
  - Hadron beam therapy etc etc
- **Lepton accelerators**
  - Precision machines e.g. LEP
  - Possible “Higgs factories”
- **Secondary particle accelerators**
  - pions, kaons, neutrinos e.g. NUMI

Circular Machines

- ✓ Accelerate beam in many turns
- ✓ Can use a single injection many times
- ✗ are limited by synchrotron radiation losses particularly for lepton machines

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

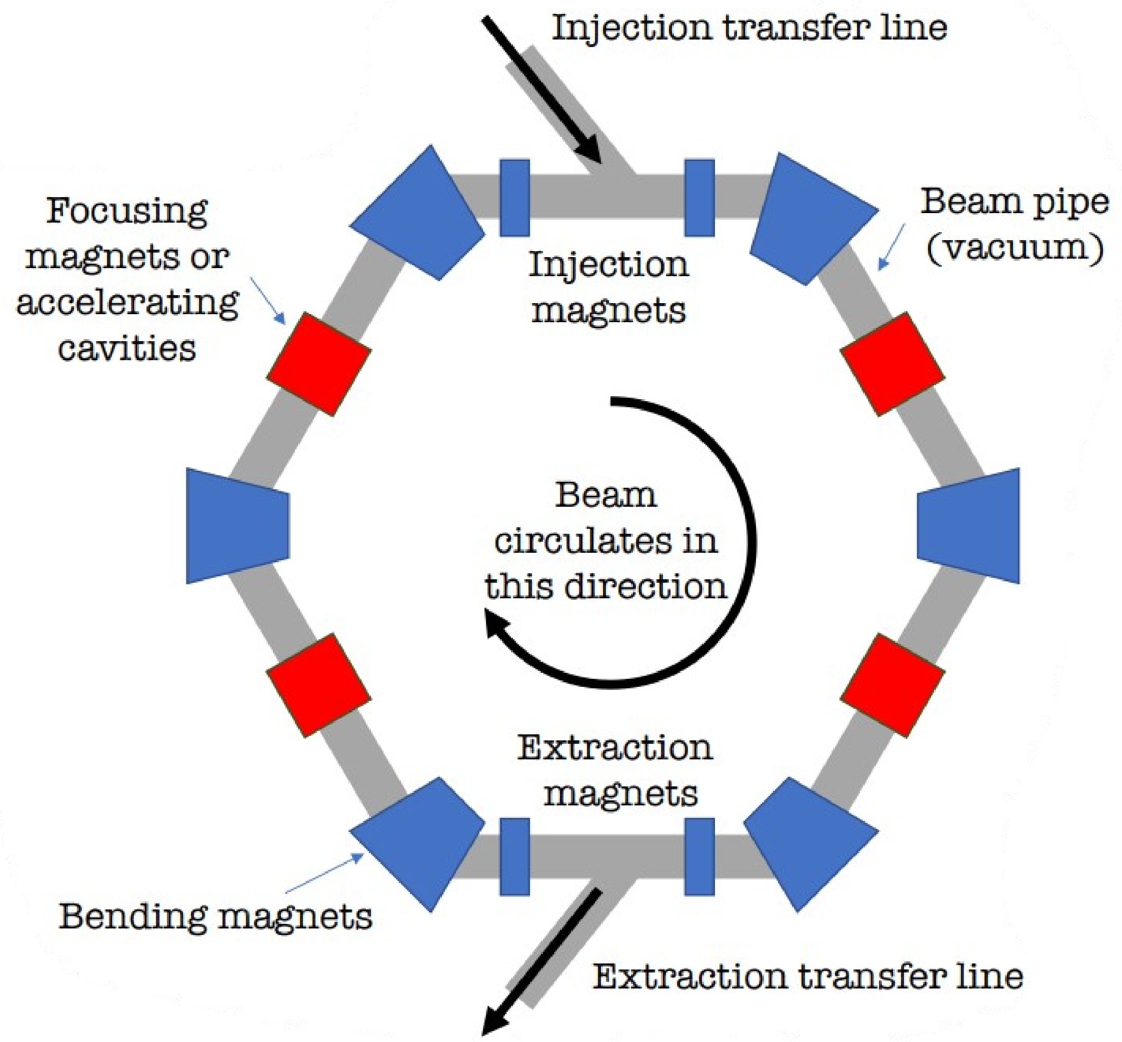
Linear Machines

- ✓ Almost no radiation loss
- ✗ Have to achieve energy/ luminosity in a single pass
- ✗ Limited by available power

Anatomy of an accelerator

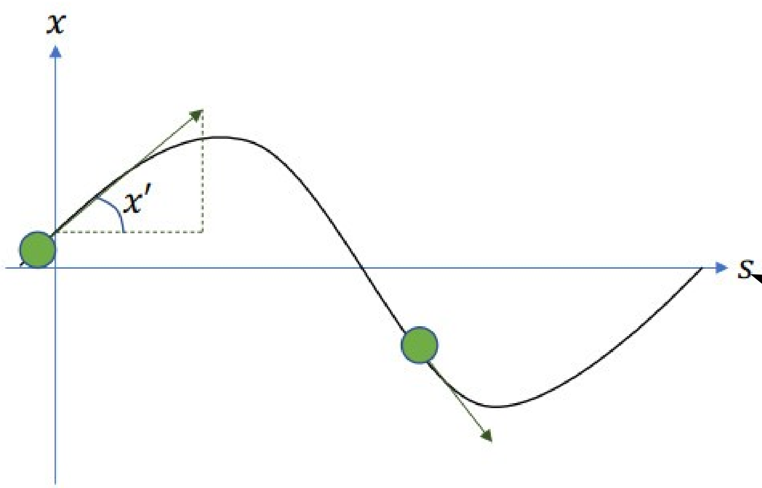
- Beam arrives through a transfer line and is injected into the main ring via "kicker" magnets
- Beam is accelerated over many turns
- Beam is extracted (more kicker magnets) and sent to experiment or later acceleration stage

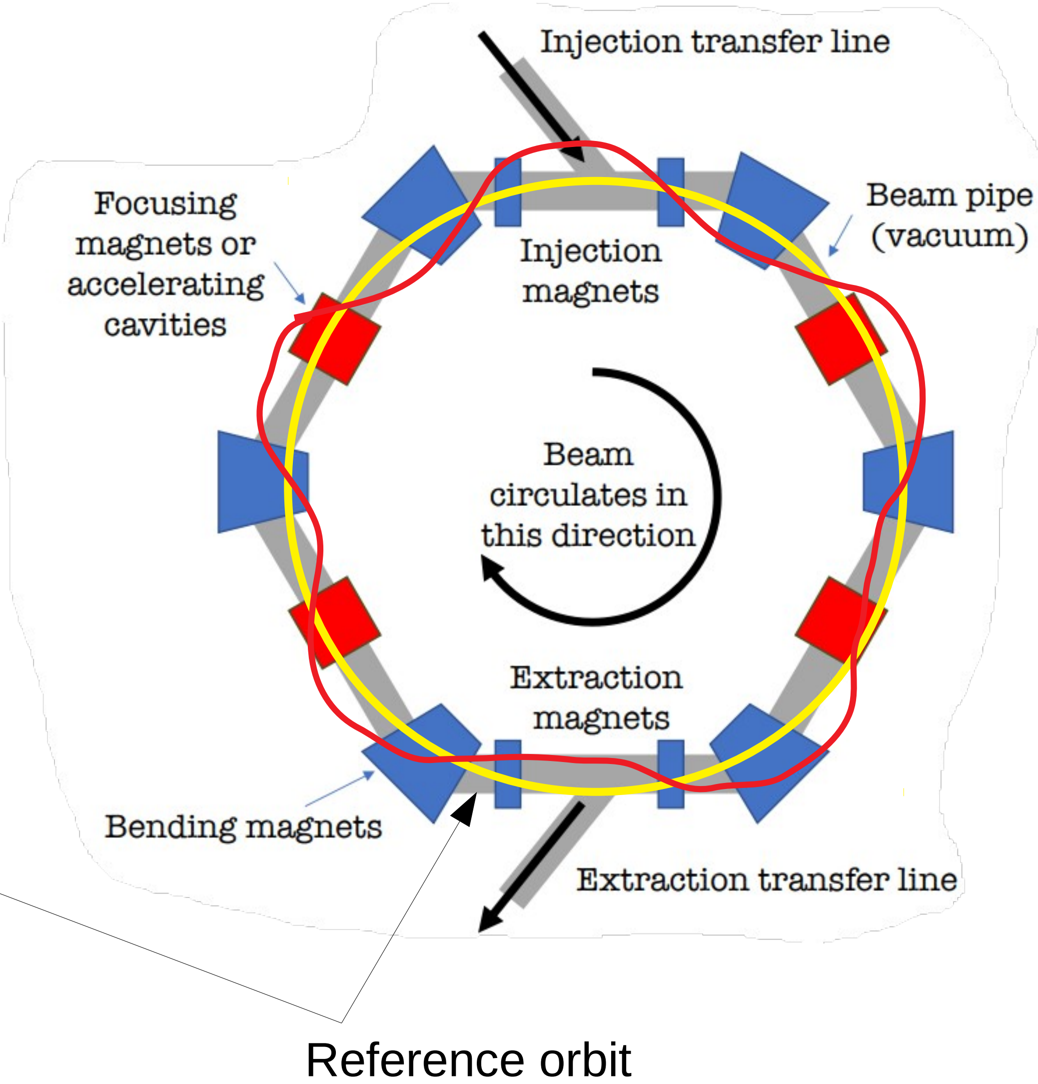
- Beams are usually made of bunches of particles, rather than continuous beams



Beam Concepts

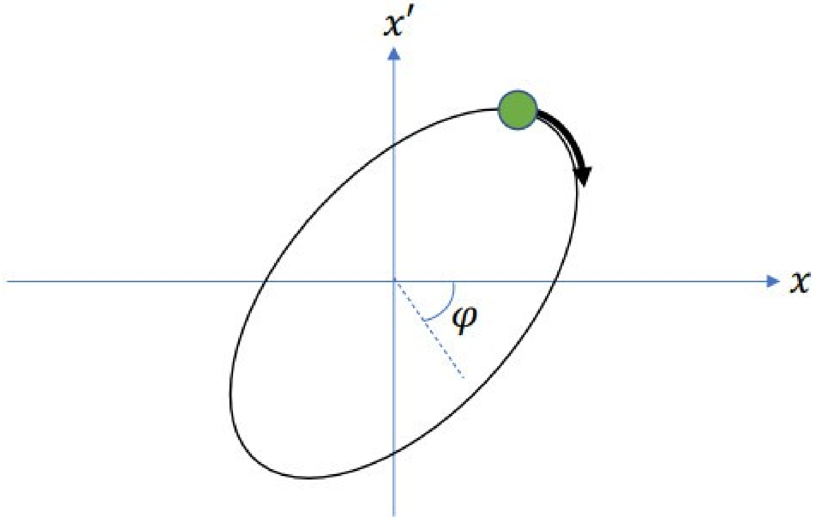
- Particle motion is controlled by magnetic fields
- A single particle will typically oscillate around an idealised reference orbit

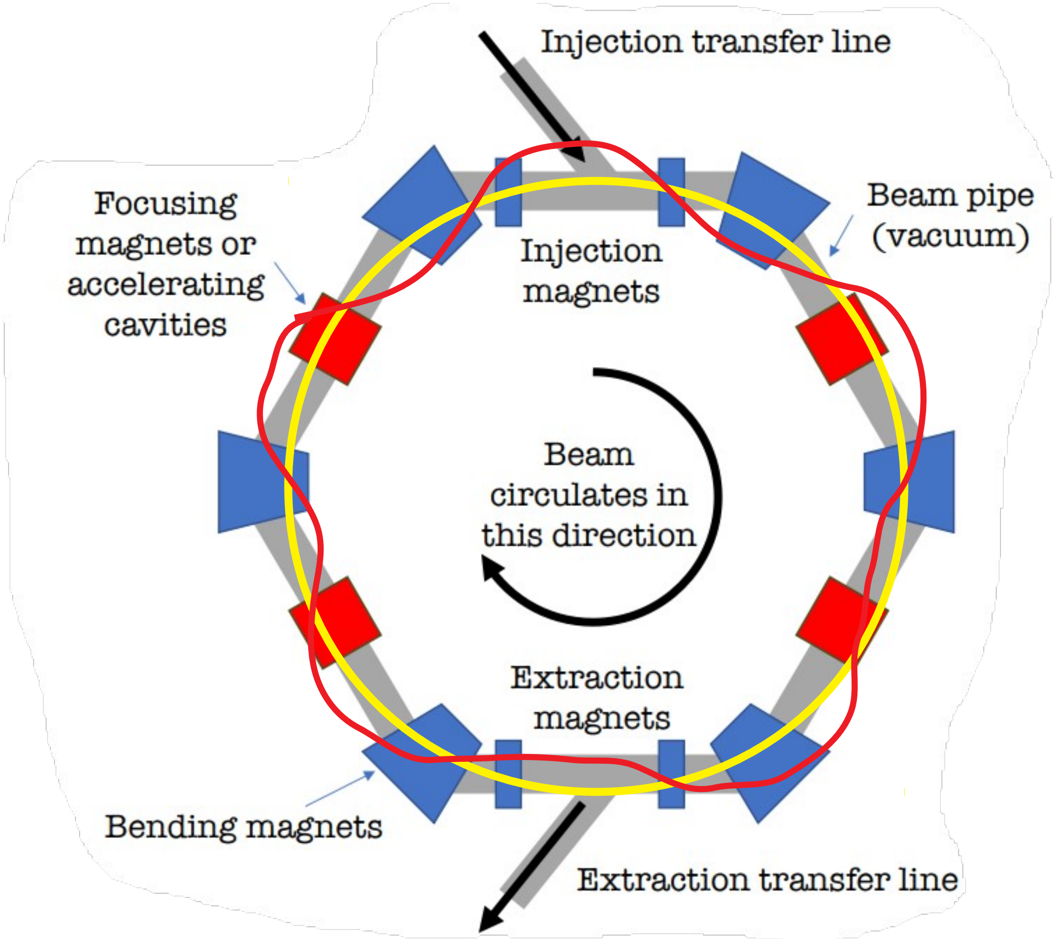




Beam Concepts

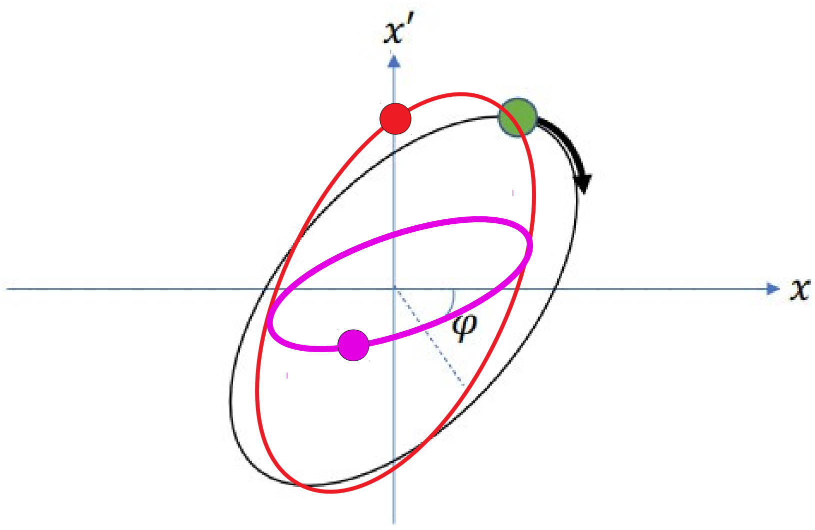
- Particle traces out an ellipse in phase space (x,dx/ds) or (x, p_x)
- In stable beams the particle traces the same ellipse over and over again

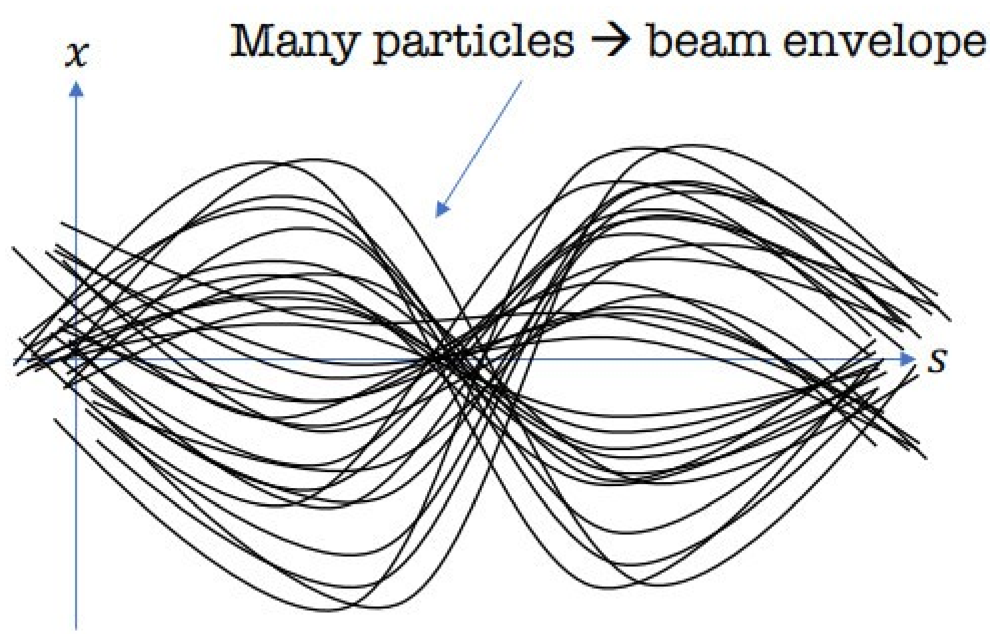




Beam Concepts

- Different particles will trace out different oscillations around the reference orbit





Beam concepts

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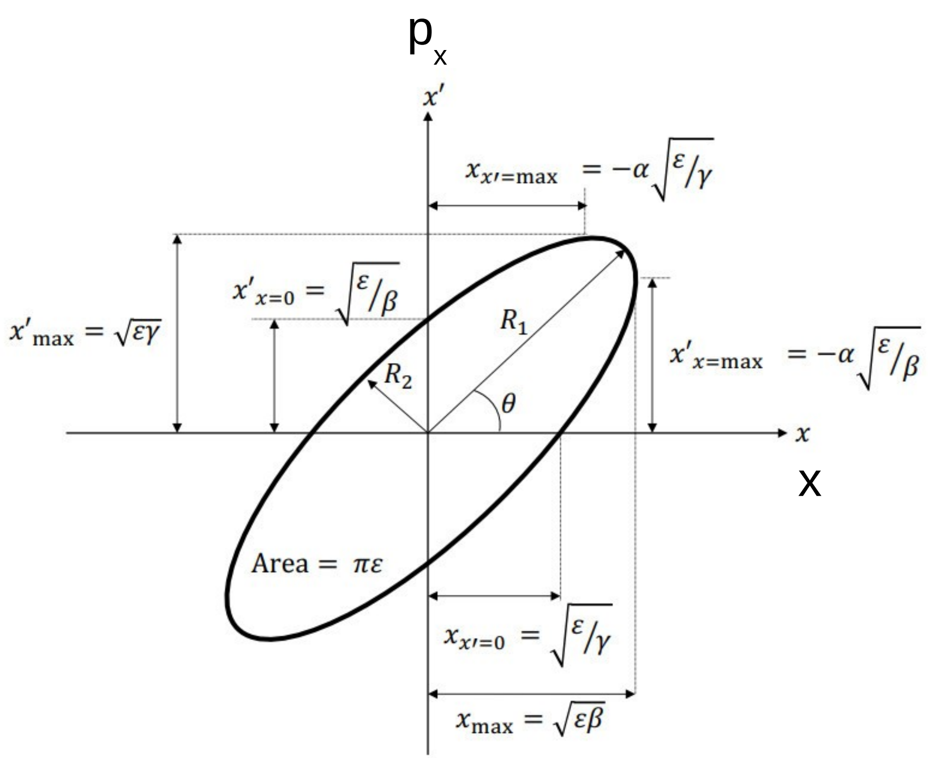
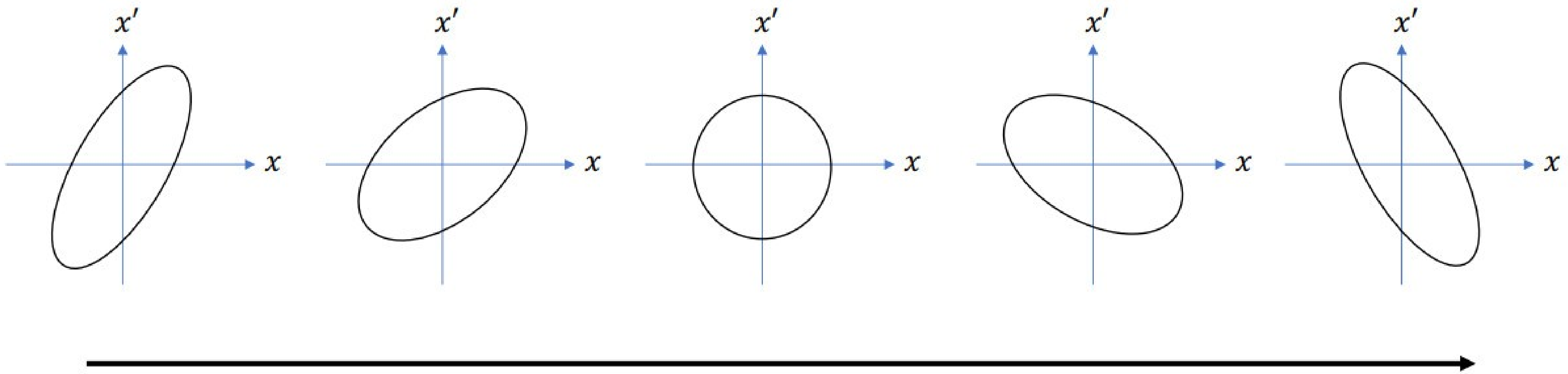


- RMS ellipse of all particles is the *machine ellipse*
- Defined by the *Twiss parameters*
  - α → related to beam tilt
  - β → related to beam shape and size
  - ε → *emittance* of the beam

$$\epsilon = \pi R_1 R_2$$

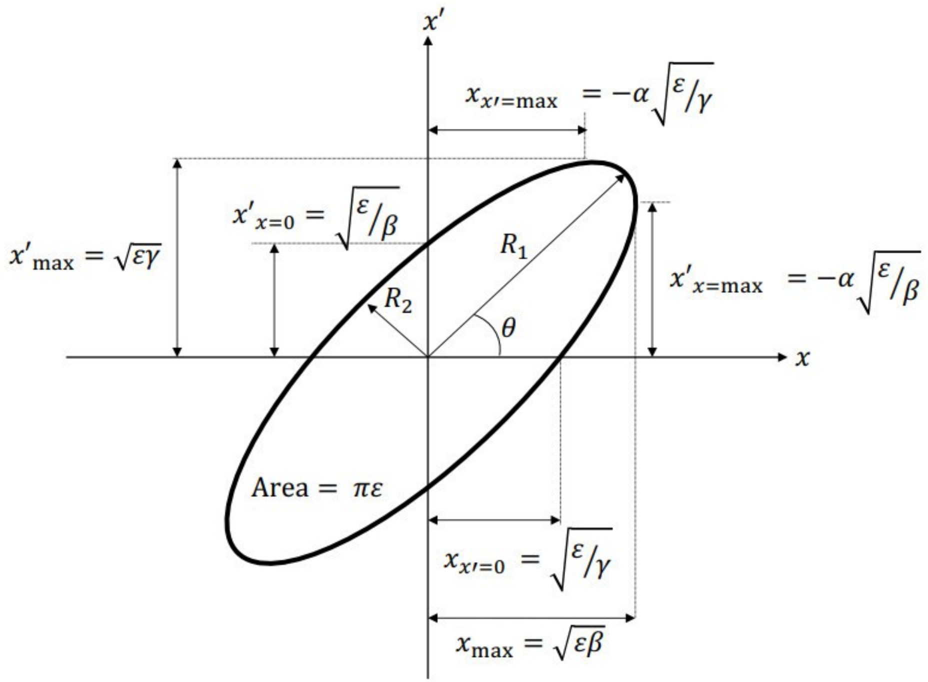
  - volume of the beam in phase space
  - conserved quantity
  - variously defined as we are measuring an ensemble of particles

Beam ellipse



- The machine ellipse rotates and changes shape as the beam moves through different accelerating structures
- However the area of the ellipse – the emittance – is constant if the beam is only acted upon by conservative forces
- This is a consequence of something called Liouville's theorem

Beam concepts



- ε → *emittance* of the beam
- $\varepsilon_\perp$ → transverse emittance → area of beam in transverse space: (x,y,p_x,p_y)
- transverse emittance changes with momentum so we generally talk about the *normalised transverse emittance*
  - $\varepsilon_{\perp,N} = \varepsilon_\perp \beta\gamma$
  - independent of beam momentum for conservative forces

Beam concepts

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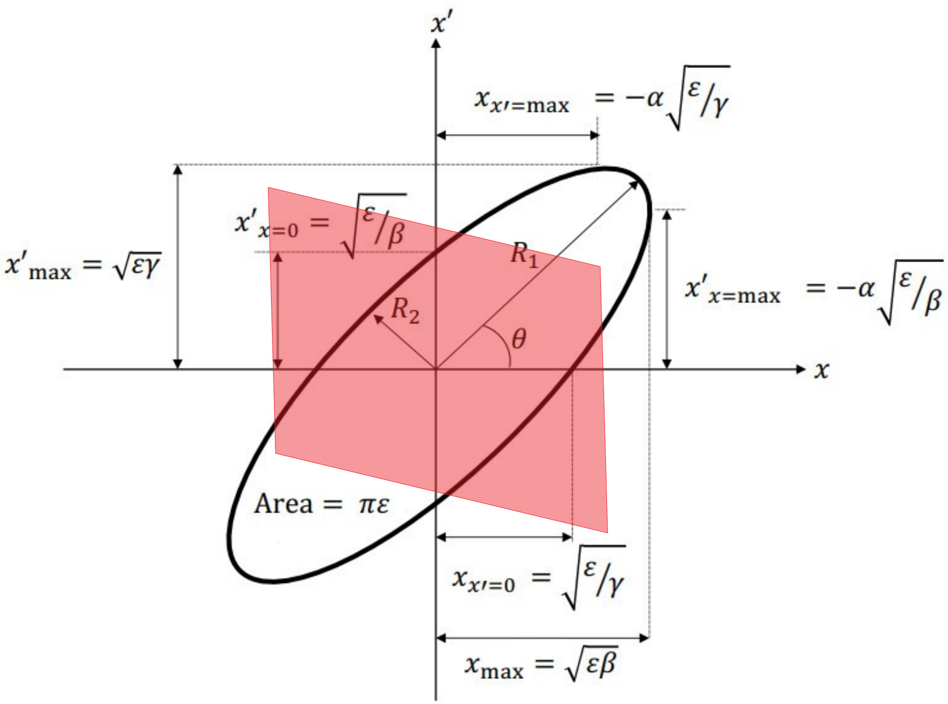
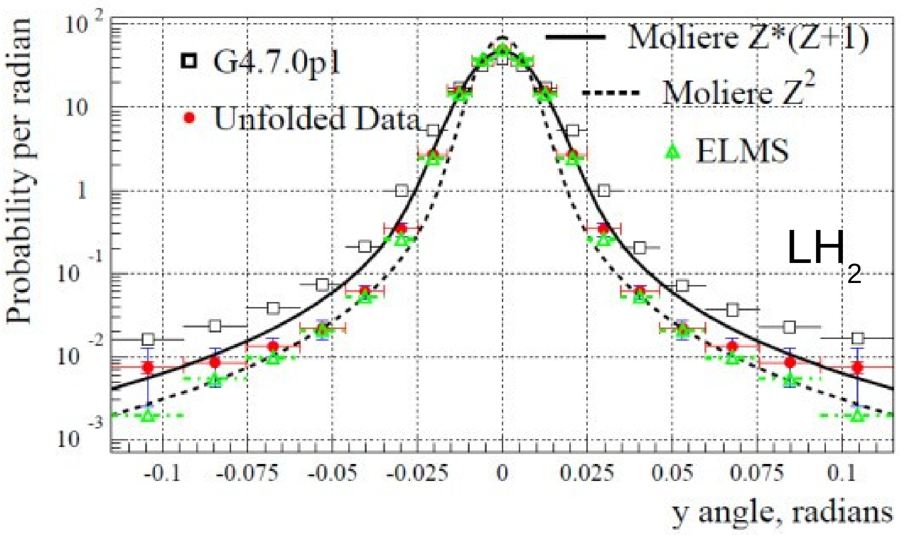
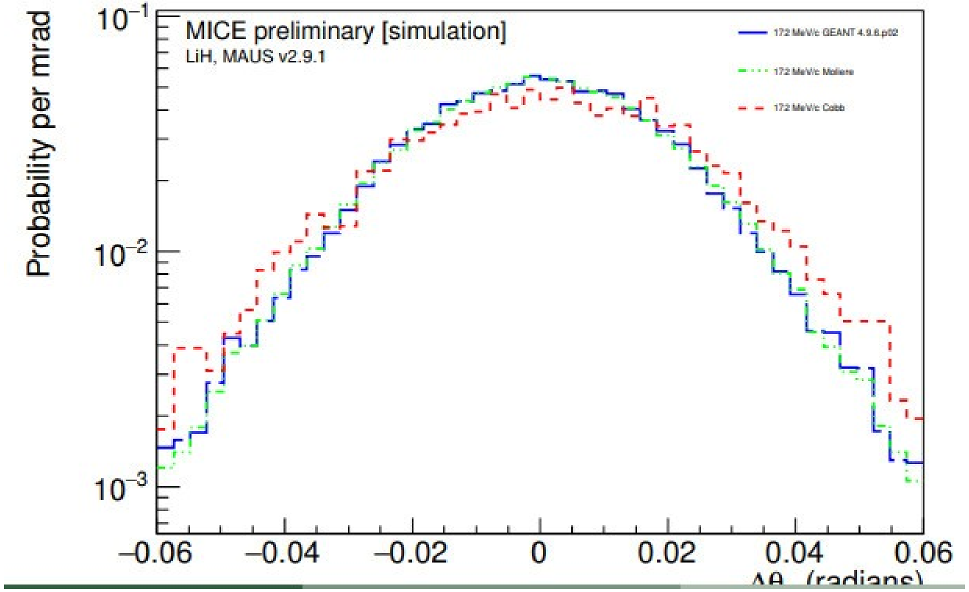


- Different parts of an accelerator have different apertures which only particles within a certain volume in phase space will enter
- If emittance is larger than the aperture volume then particle are lost from the beam
- Act of squeezing the beam emittance to maximise transmission through the beam channel is called *beam cooling*
- A number of different cooling techniques are available, but they are too slow for muons which decay quickly
- MICE was designed to test the concept of *ionisation cooling* for muons

Multiple Scattering

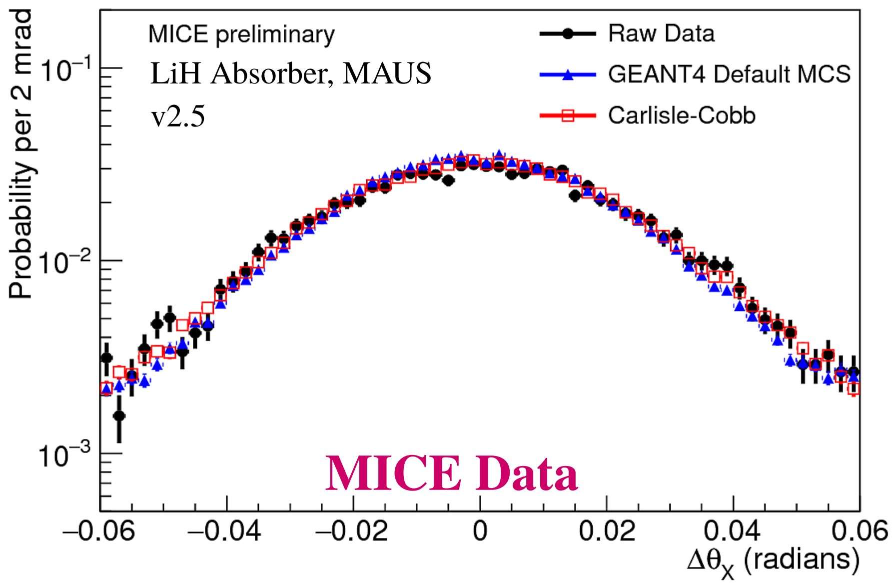
MuScat Nucl. Phys. Proc. Suppl. 149 (2005) 99-103

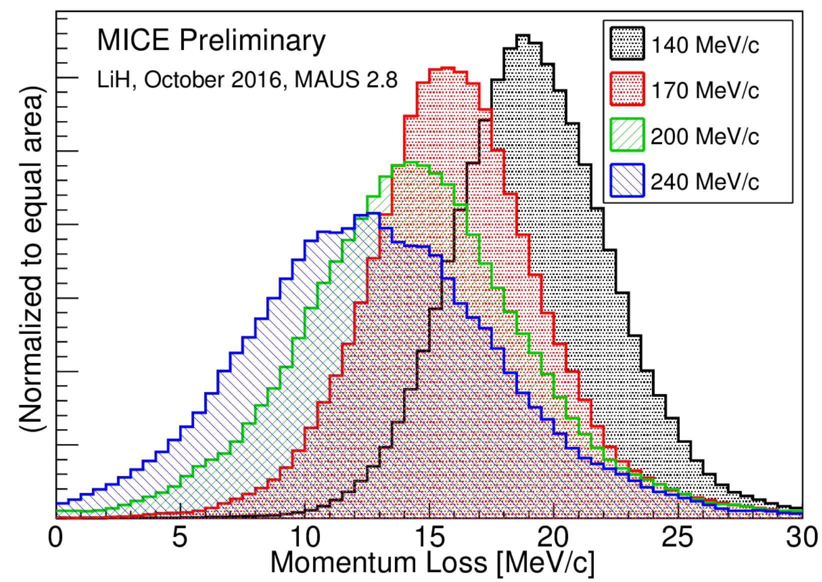




- Energy loss and Multiple Coulomb Scattering underlie emittance reduction
- Critical to know whether our models reproduce these processes
- MuScat showed that, in 2005, GEANT 3 modelled MCS in high-Z materials well, but failed to model MCS for low-Z materials
- MICE is validating the models included in GEANT 4 for LH_2 and LiH materials

Multiple Scattering





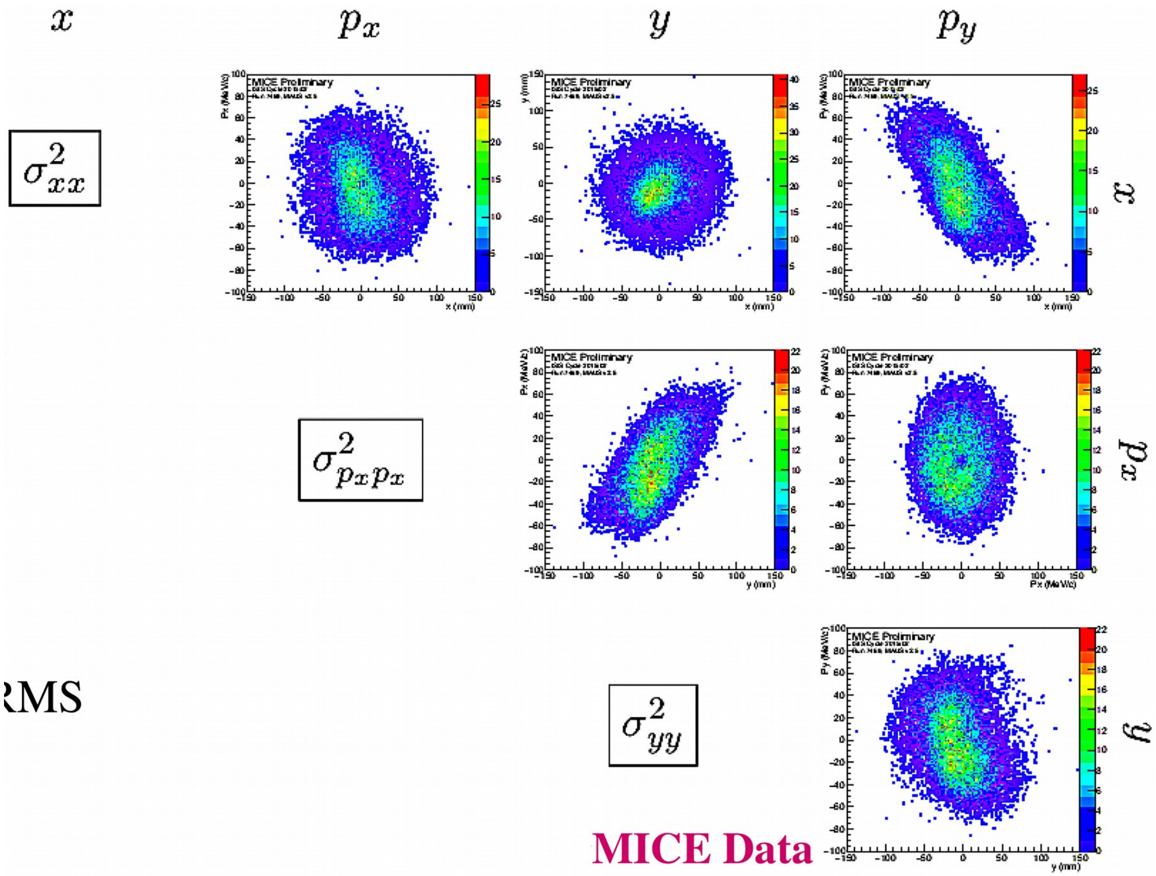
- Preliminary and on-going work; systematics are still being evaluated
- Plan to measure scattering distributions for LH2 / LiH absorber at different momentum settings
- Studies to validate energy loss models are also underway (but less developed)

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
- Beam dispersion introduced by momentum selection in upstream magnets

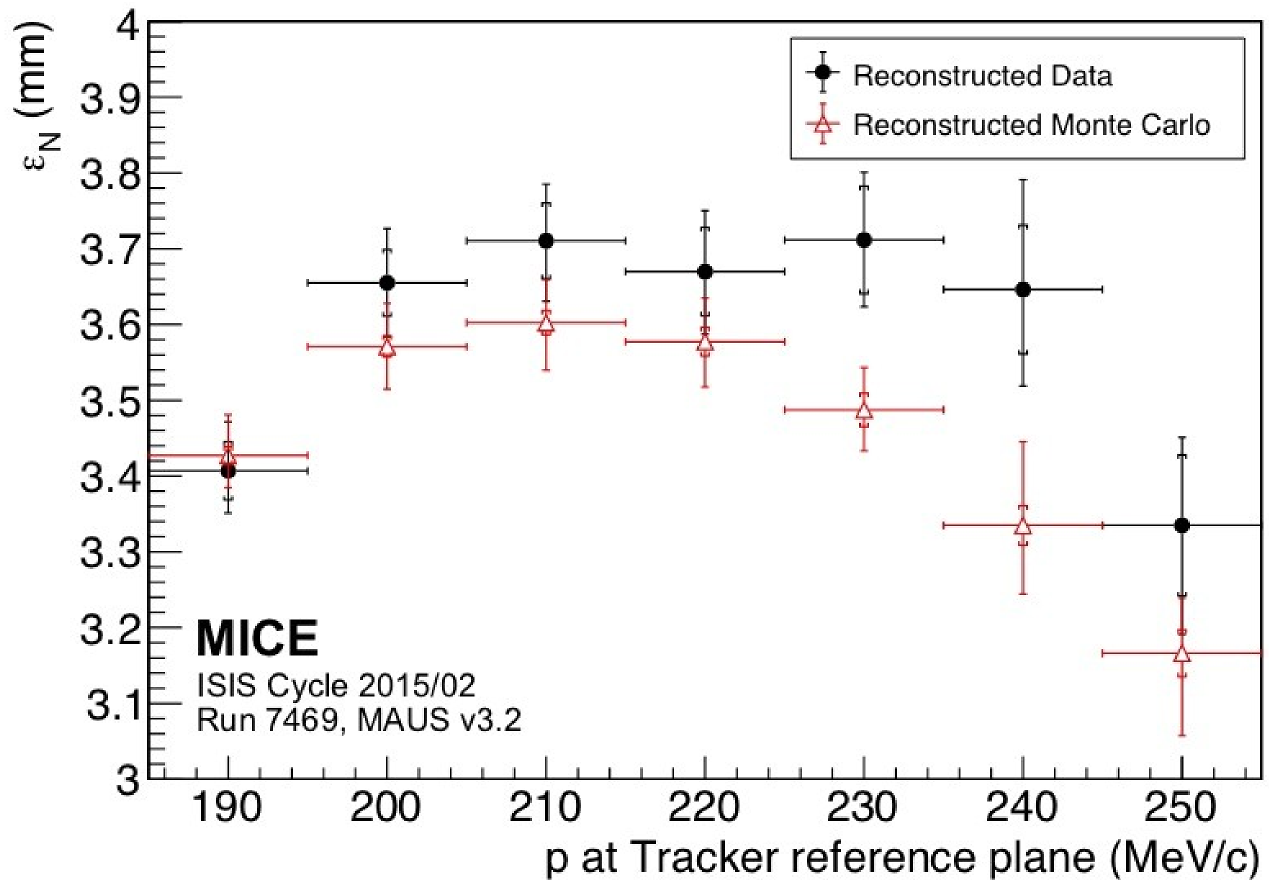
$$\epsilon_{\perp,N}=\frac{1}{m_\mu}\sqrt[4]{det\,\Sigma_{4D}}$$



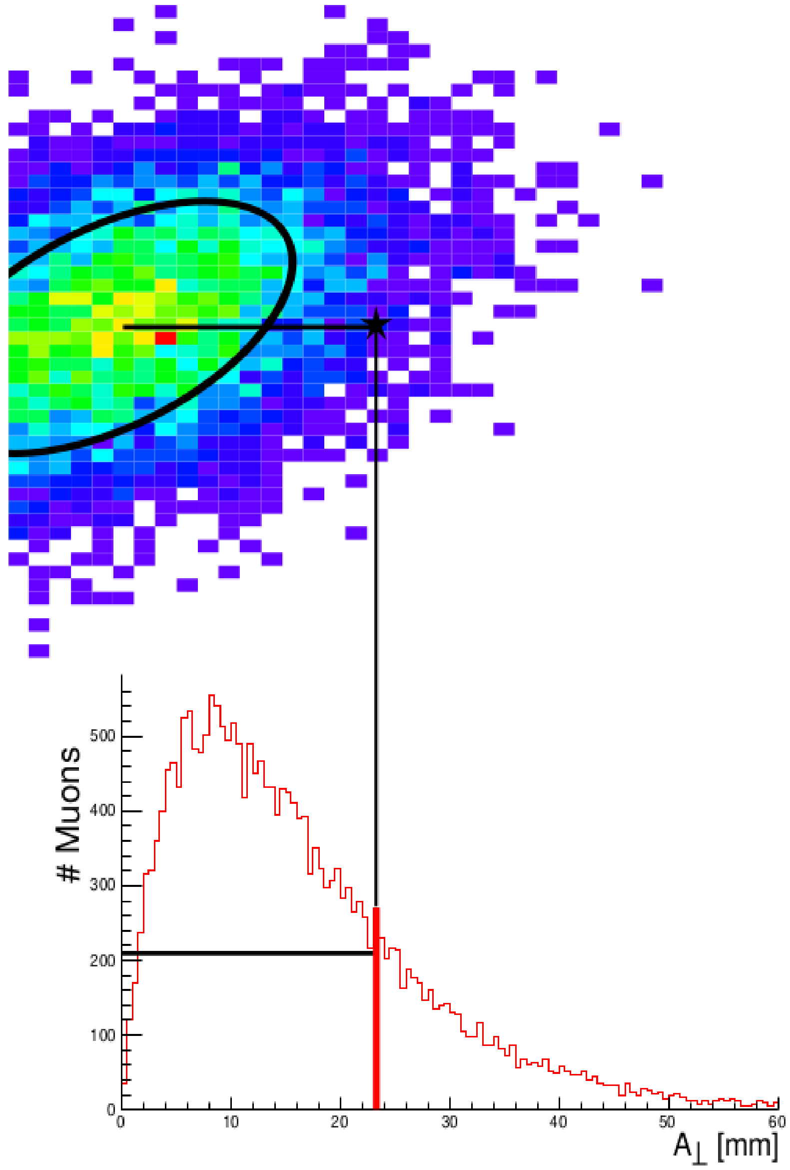
Beam Emittance

- 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



Emittance Reduction



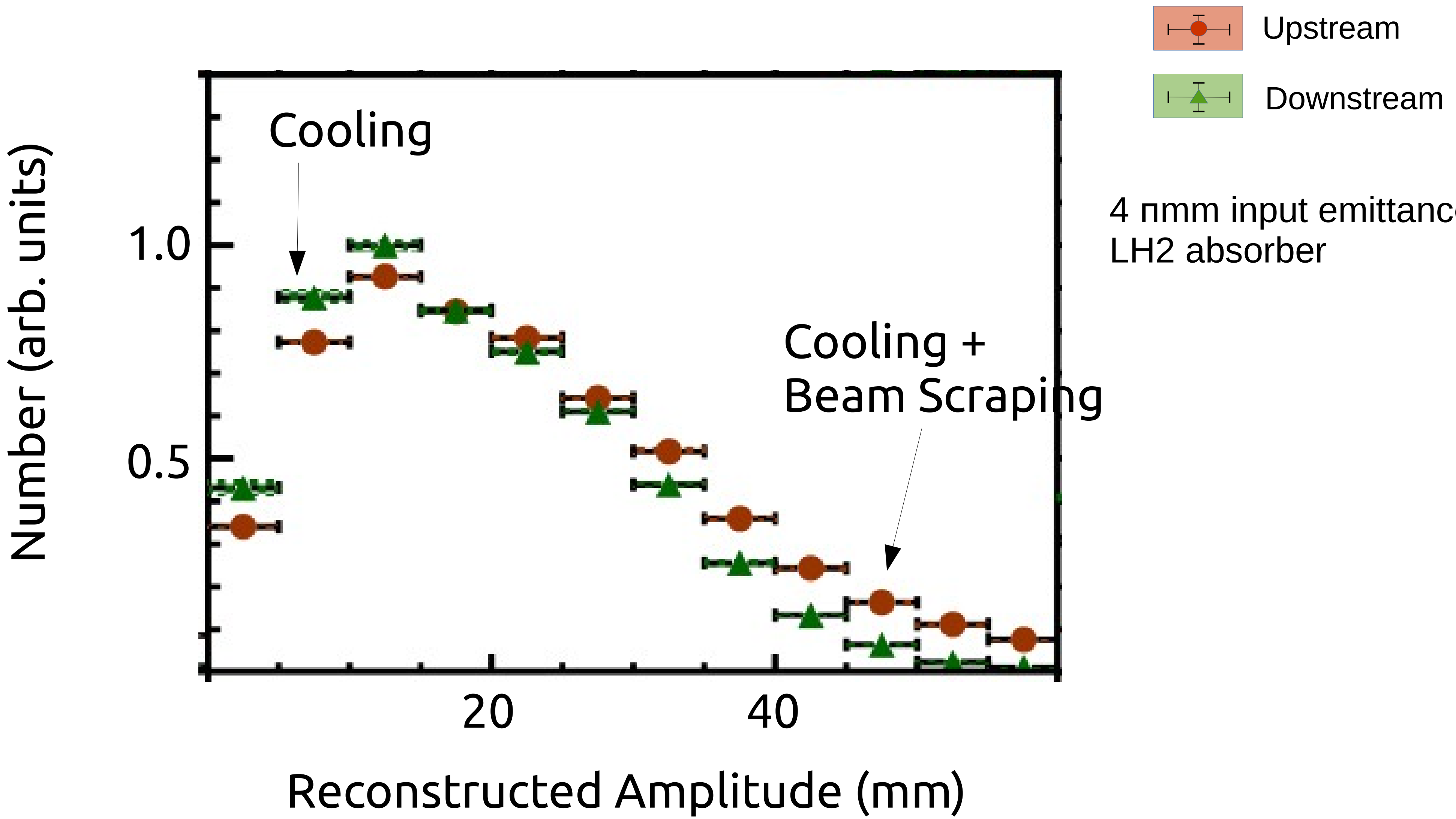
- Transverse single-particle amplitude
  - Distance of a muon from the beam core in phase space at closest tracking plane to absorber

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

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

- Mean amplitude is proportional to RMS emittance
- Ionization cooling reduces amplitude in the core of the beam → migration of particles to low amplitudes

Transverse Amplitude



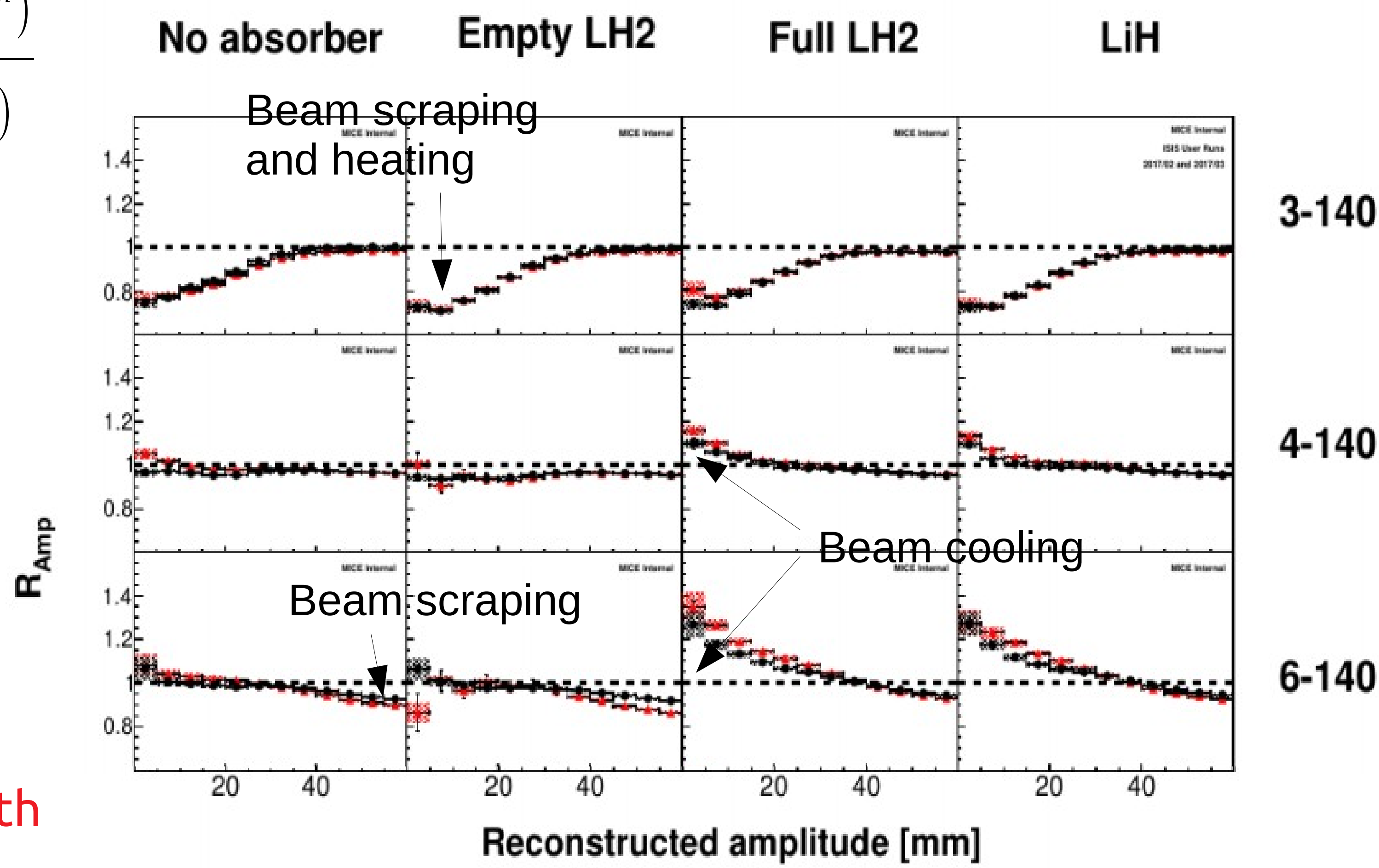
4 πmm input emittance
LH2 absorber

Cumulative Amplitude

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

- Cooling : increase in the number of muons in the core at low amplitude
- Cooling : $R_{amp} > 1$

- Ionisation cooling observed
- Agrees broadly with expectation



Fractional Emittance Evolution

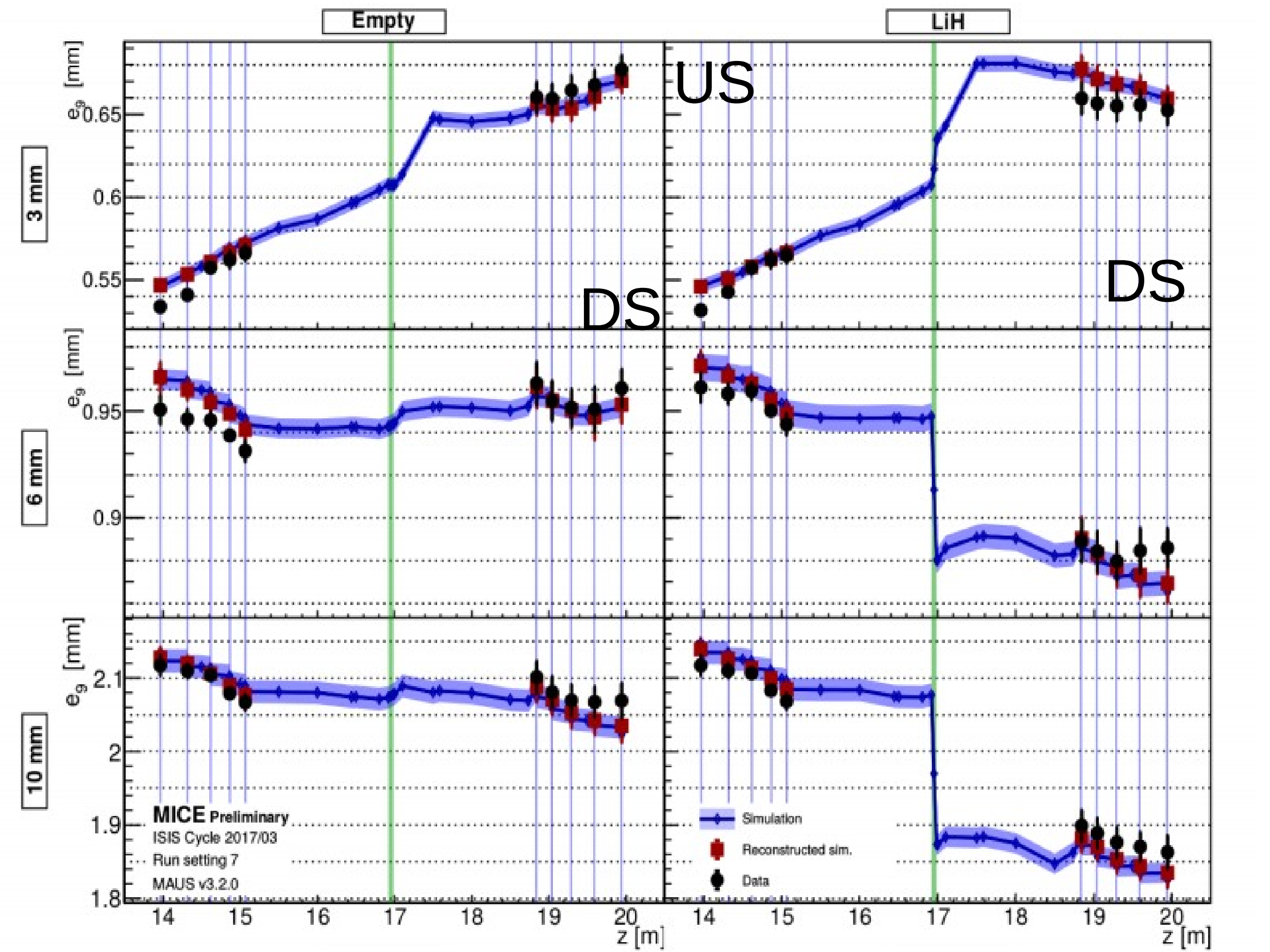
Fractional emittance:

US

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

~~MICE~~ Hall in November 2018

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MICE Goals

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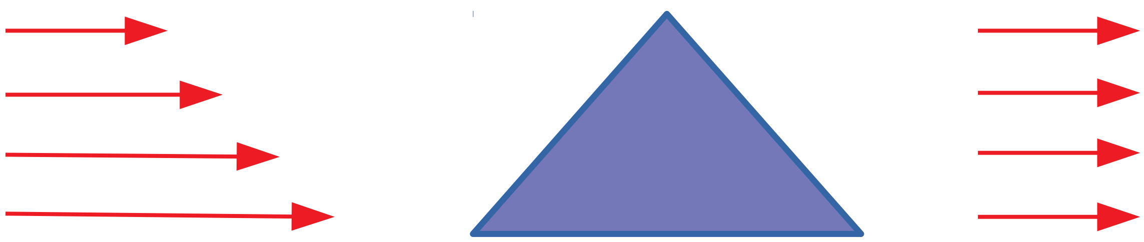
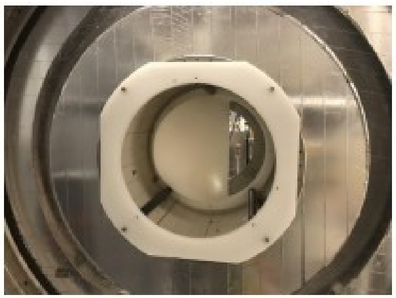
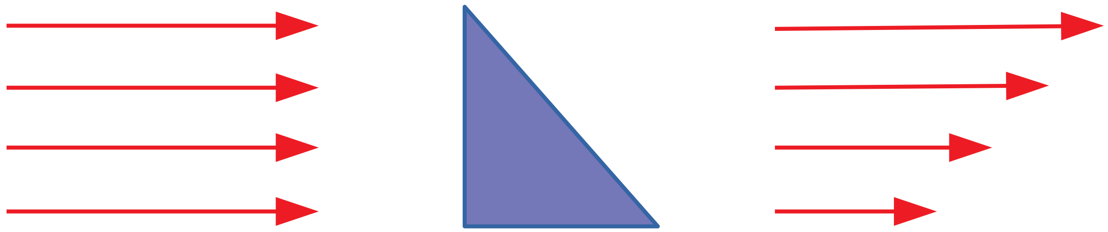
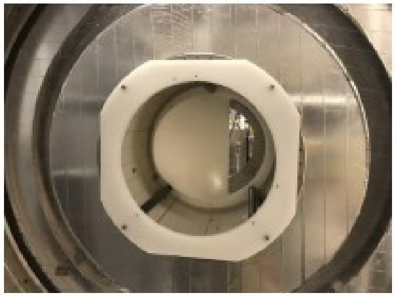
- Essentially a technology demonstrator
    - Can we safely operate liquid hydrogen absorbers? ✓
    - Can we operate a tightly packed lattice?
        - With high field magnets + liquid hydrogen? ✓
        - With high field magnets + liquid hydrogen + RF? ✗
    - Do we see the expected emittance change?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

Reverse emittance exchange

- Longitudinal cooling requires momentum dependent path length through an absorber

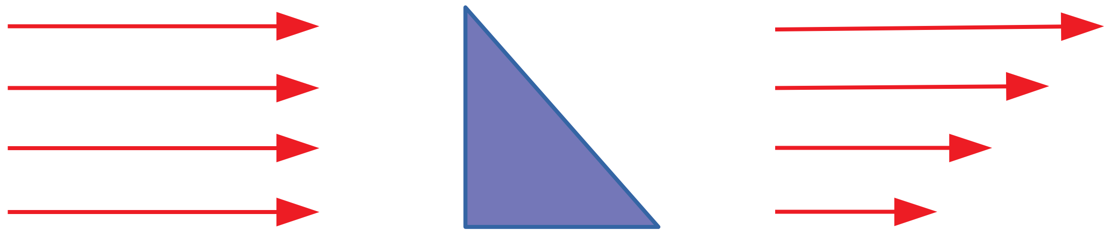



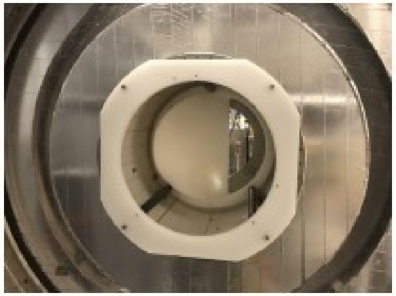
- MICE can’t study longitudinal cooling, but it can demonstrate longitudinal heating

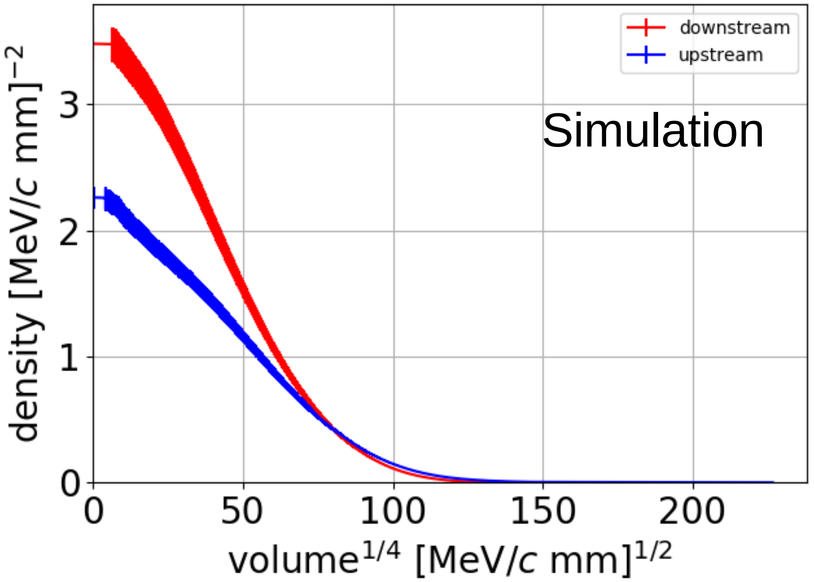
Reverse emittance exchange

- Longitudinal cooling requires momentum dependent path length through an absorber



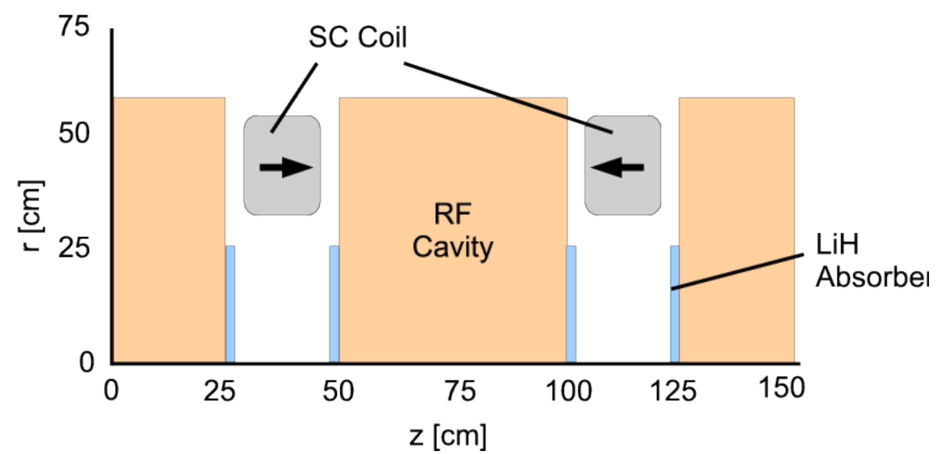


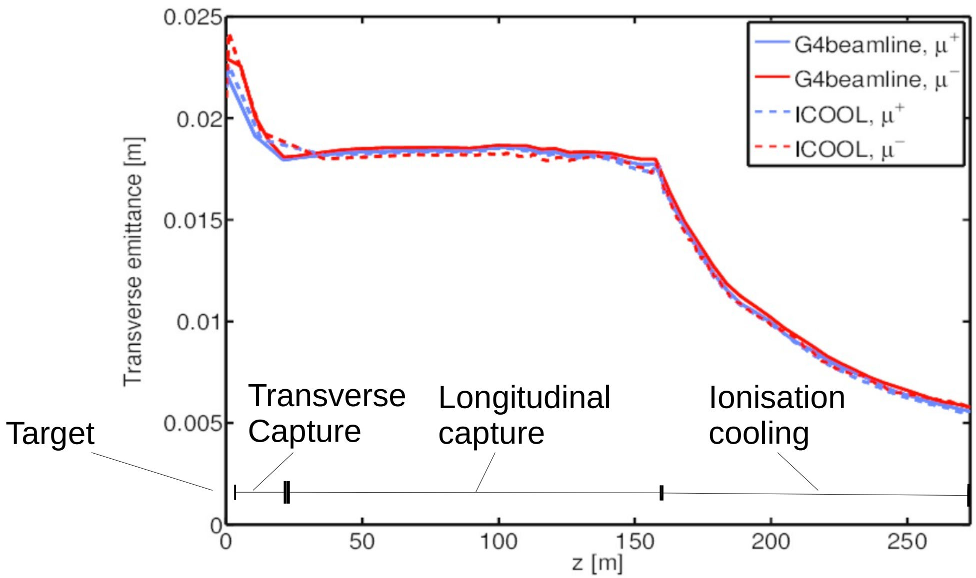
- MICE can't study longitudinal cooling, but it can demonstrate longitudinal heating
- wedge absorber introduces a correlation between momentum and transverse position whichcan couple to transverse emittance
- longitudinal heating leads to transverse cooling through reverse emittance exchange



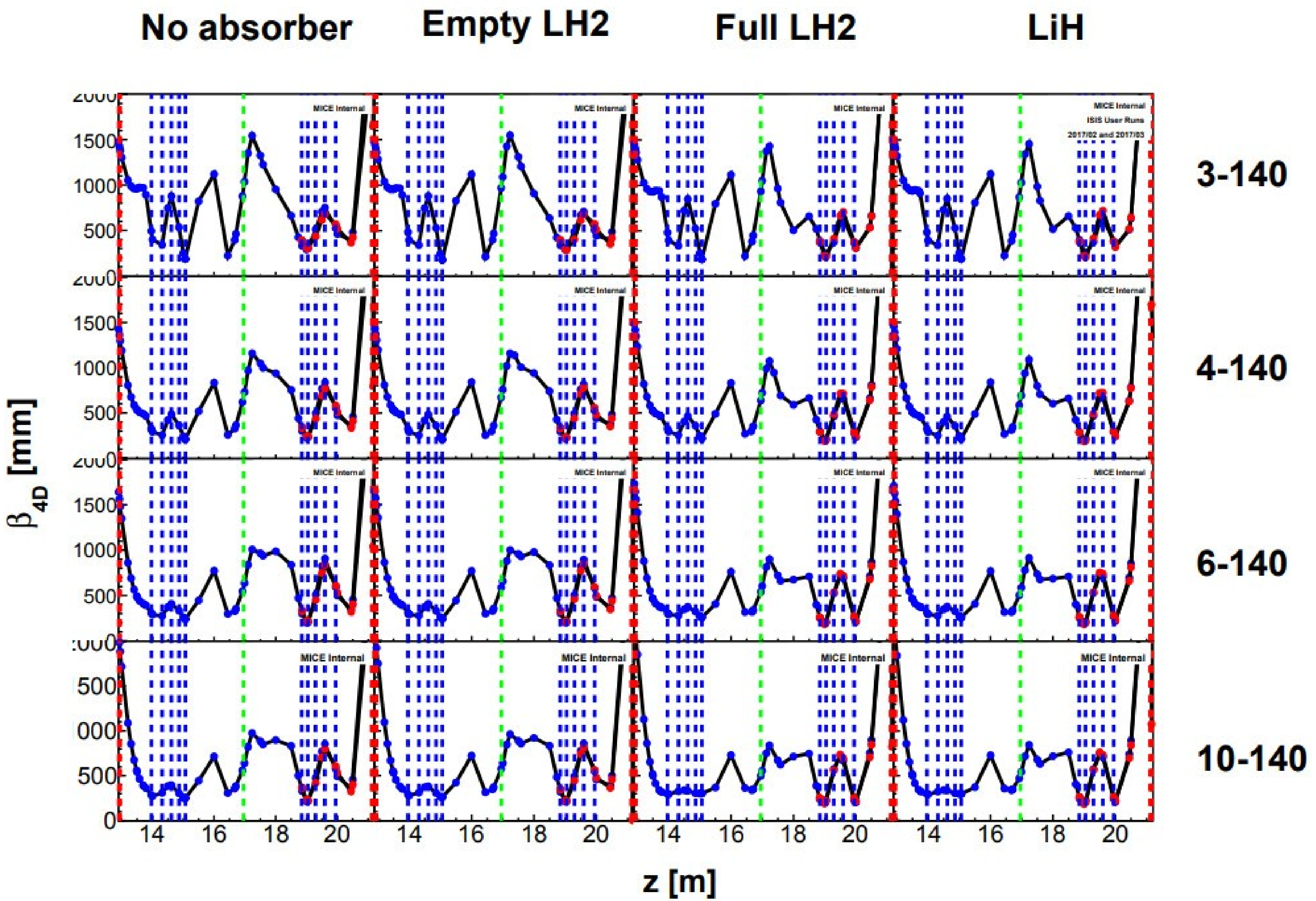
4D Cooling lattice

- 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





Transverse β_{4D}



Ionisation Cooling

Emittance change as a function of distance along the beam

The Emittance Equation:

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

Ionisation Cooling

Emittance change as a function of distance along the beam

The Emittance Equation:

Energy loss in material

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

Cooling

Ionisation Cooling

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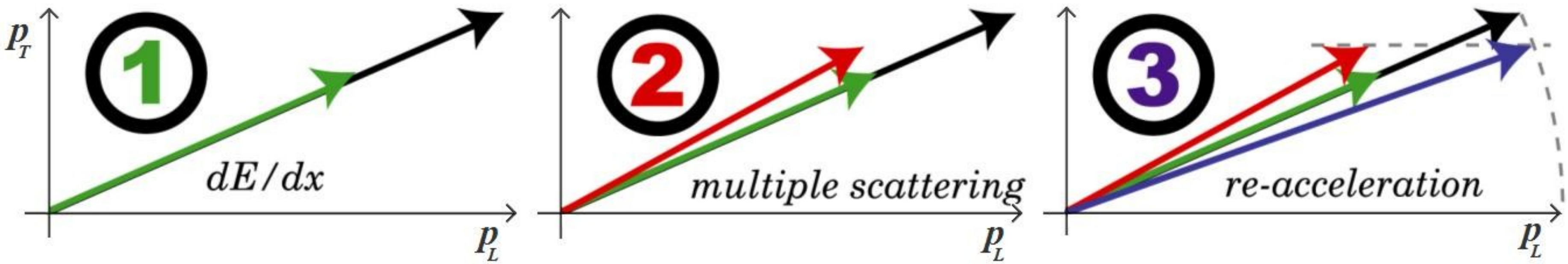


Emittance change as a function of distance along the beam

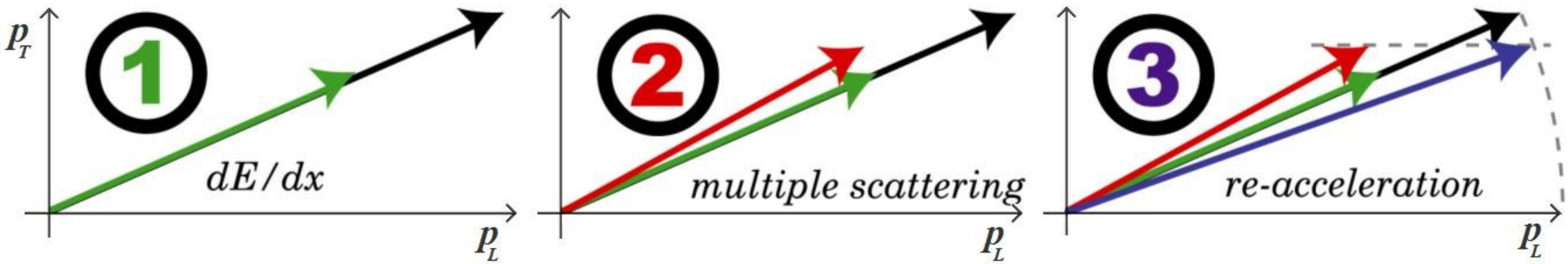
The Emittance Equation:

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

Transverse width of beam

Heating
(Multiple Scattering)

Ionisation Cooling



Emittance change as a function of distance along the beam

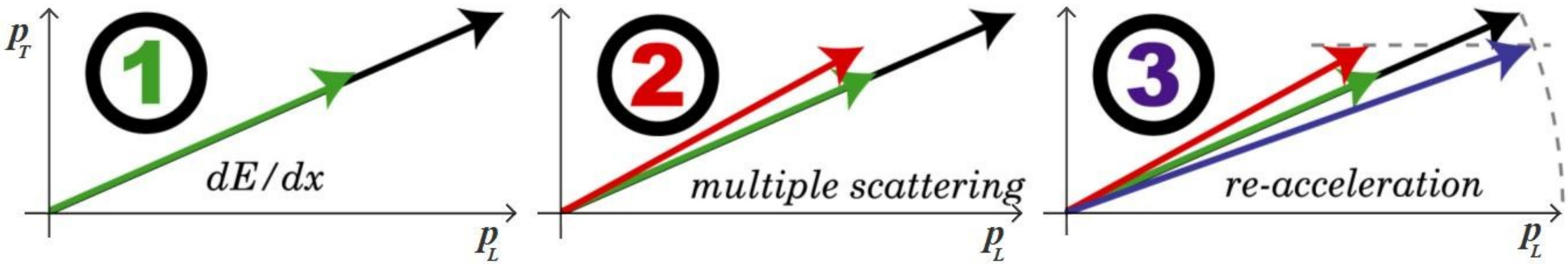
The Emittance Equation:

Radiation length in the material

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

Heating
(Multiple Scattering)

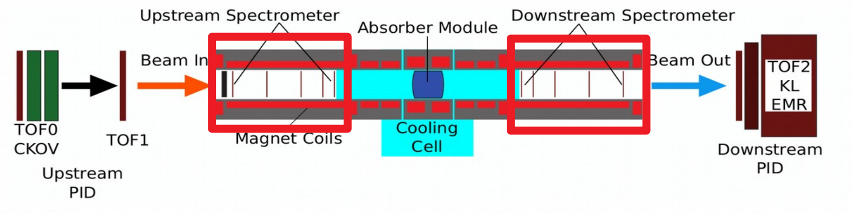
Ionisation Cooling



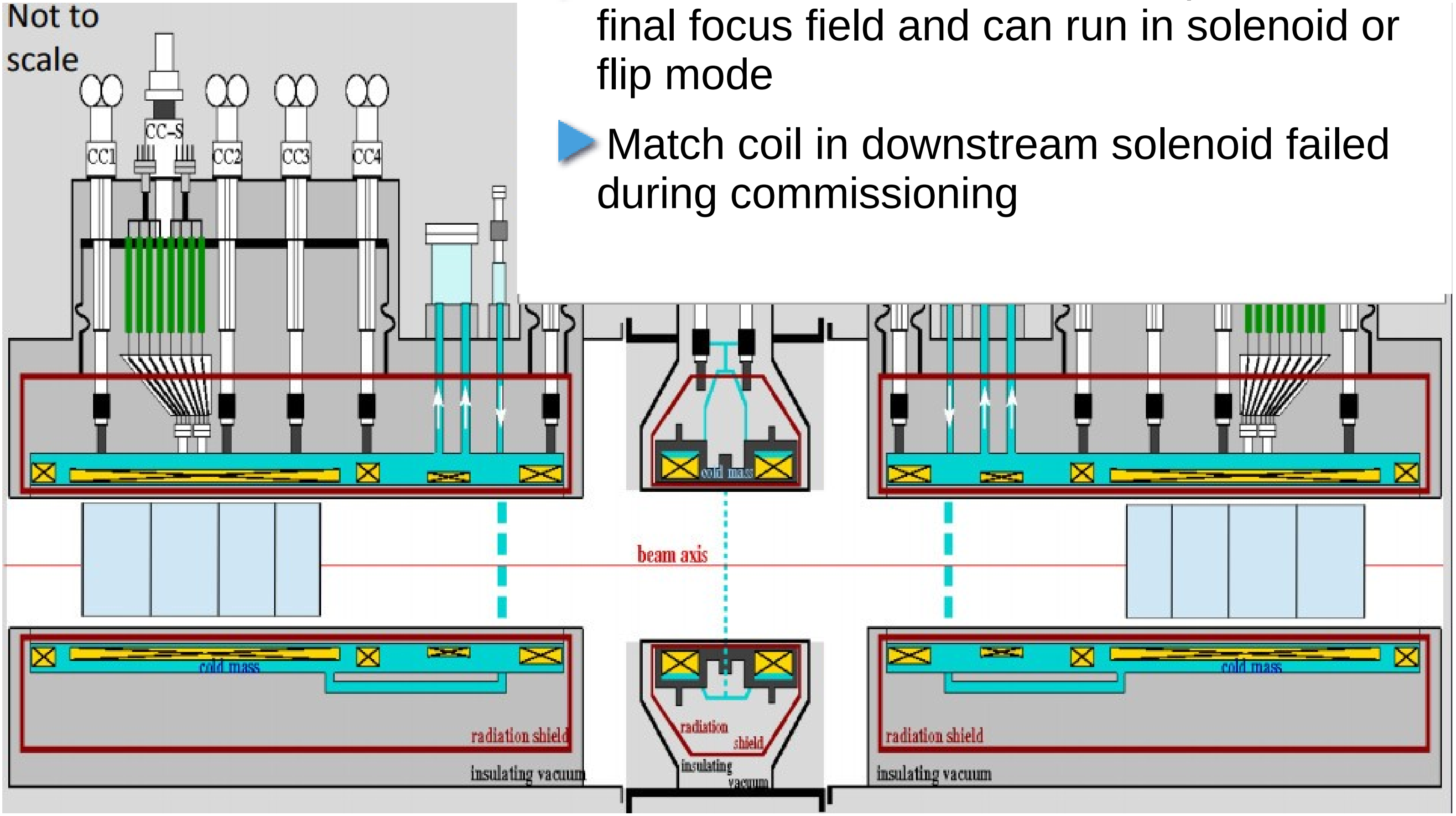
$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\,MeV)^2}{2\beta^3 E m_\mu X_0}$$

- for cooling we require muons to go through a material with
  - high dE/dx
  - low densities
  - large absorber X_0
  - minimal other material in the beam
- low $\beta_t \rightarrow$ tight beam focus

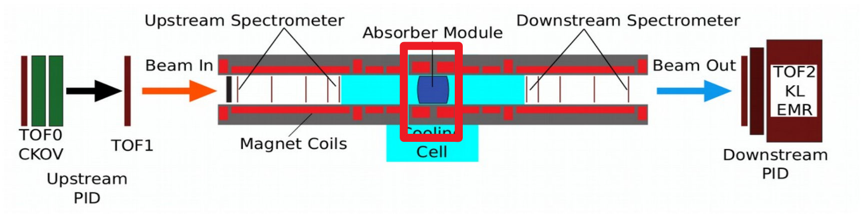
Analysing magnets

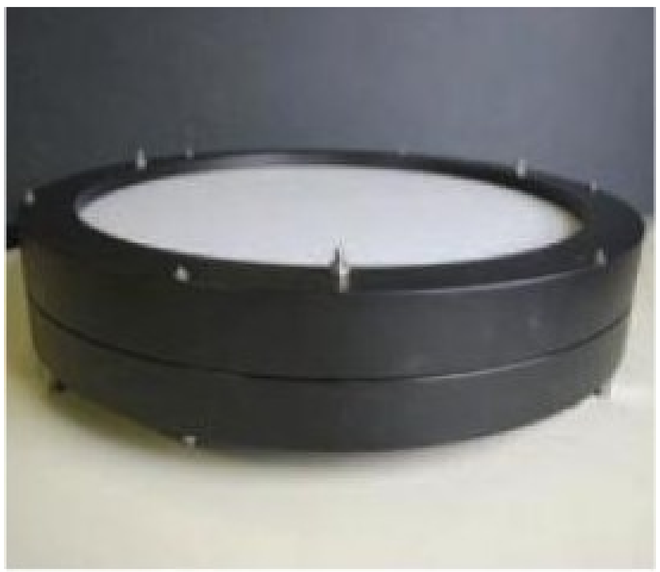


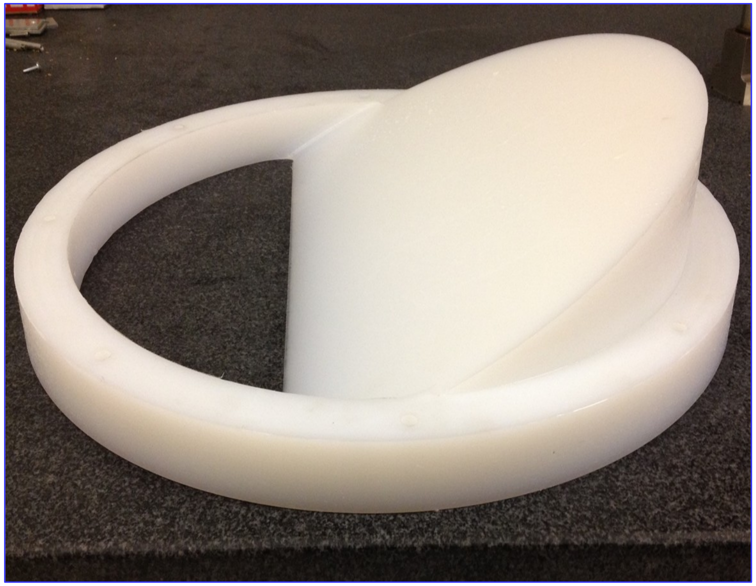
- 400 mm bore, 5 coil assembly
- Nominal 4T (run at 3T for data-taking)
- 4K core temperature
- Focus coil contains absorber, provides final focus field and can run in solenoid or flip mode
- Match coil in downstream solenoid failed during commissioning



Absorbers

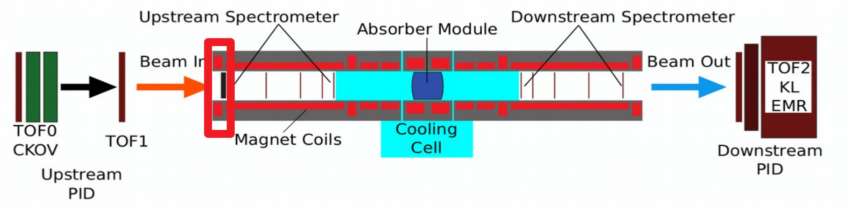


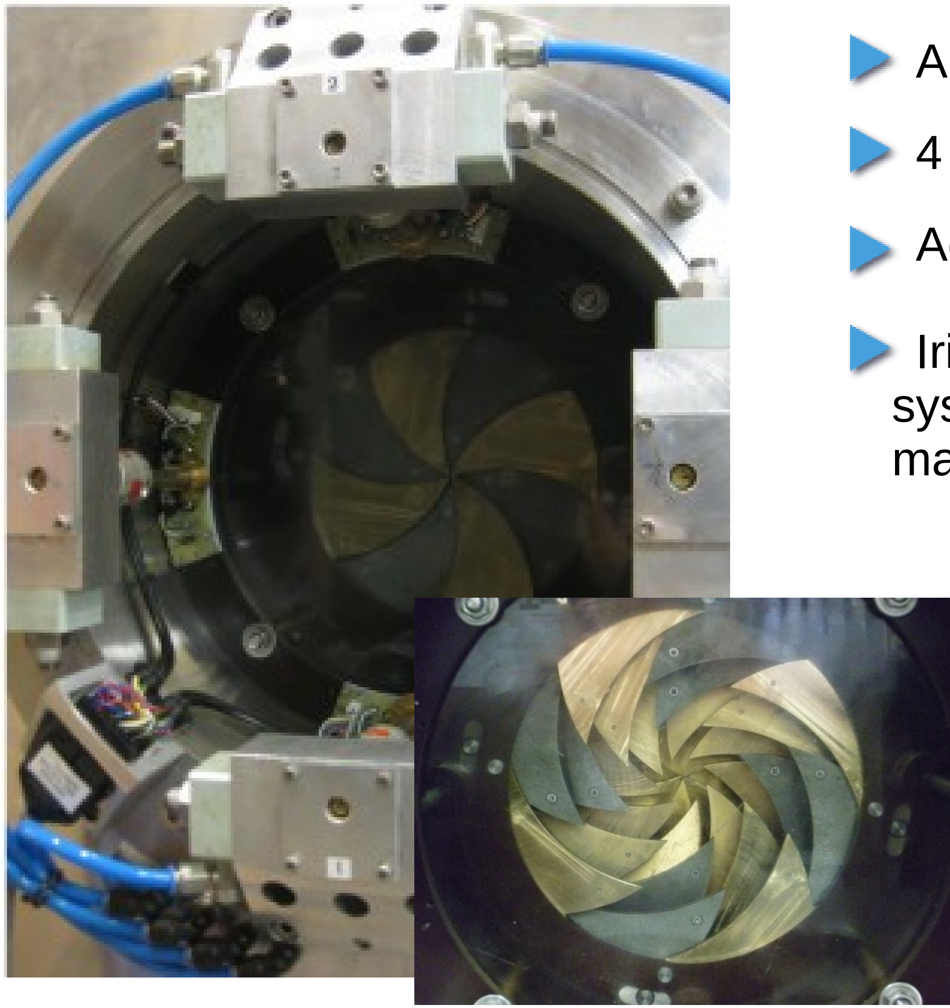




- 65 mm thick LiH absorber disc
- 350 mm thick LH_2 absorber
    - LH_2 vessel terminated by two 180 micron Al windows
- Polyethylene wedge absorber designed for longitudinal emittance studies

Diffuser



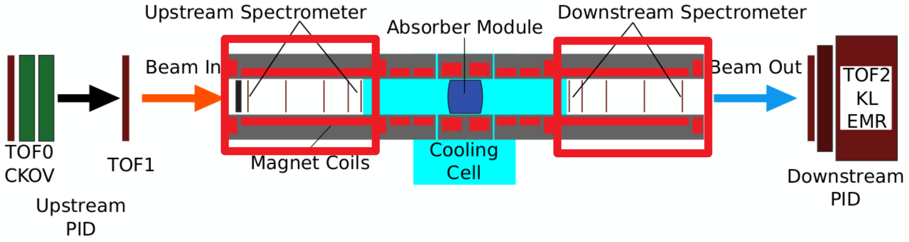


- Positioned at the upstream entrance of the upstream solenoid
- Artifically inflates the emittance of the input beam
- 4 irises made of brass and tungsten
- Add up to 3 X_0 into the beam, in 0.2 X_0 steps
- Irises opened and closed using a pneumatic system, as motors would not work in the solenoidal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

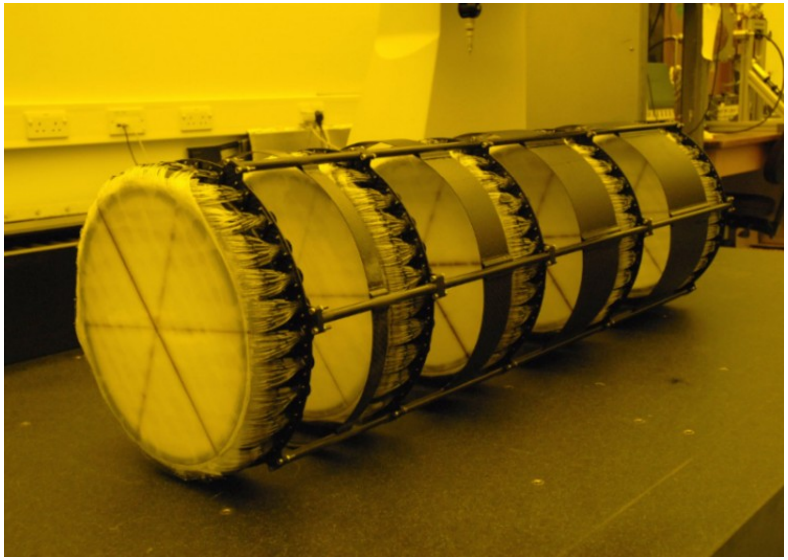
$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (13.6\,MeV)^2}{2\beta^3 E m_\mu X_0}$$

Trackers

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

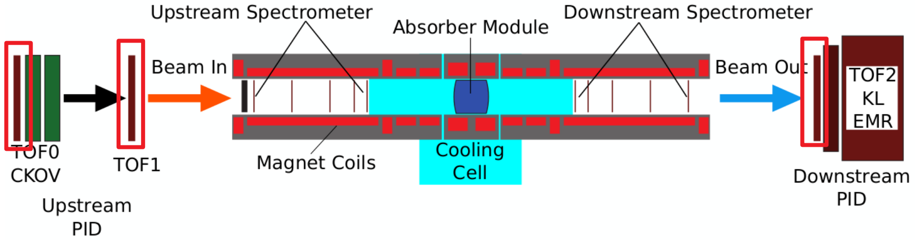


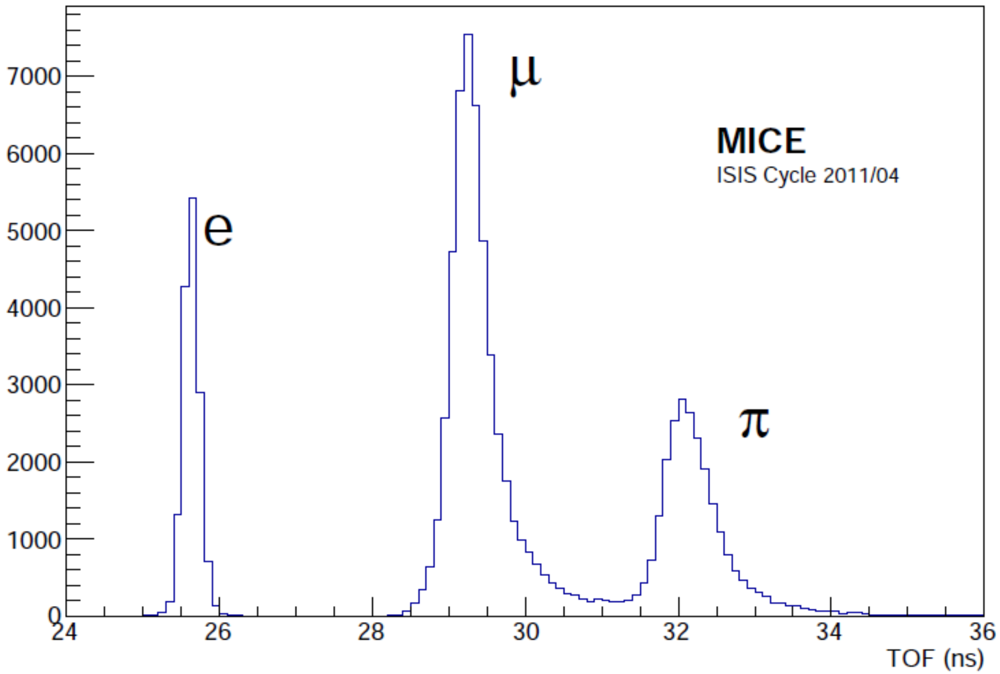
Track position resolution	470 micron
$\sigma(p_T)$	1 – 2 MeV/c
$\sigma(p_z)$	3 – 4 MeV/c



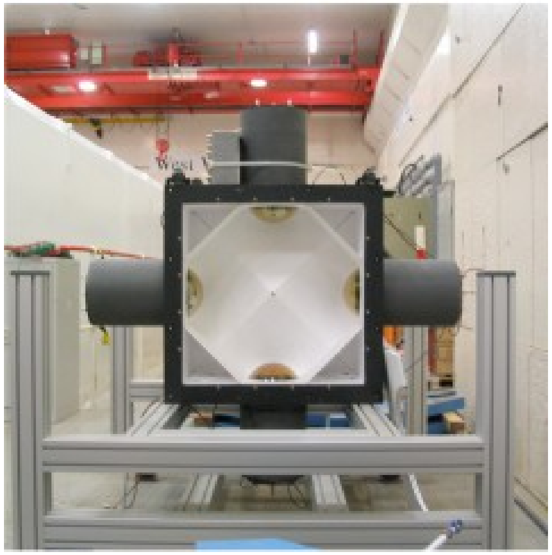
TOF Detectors

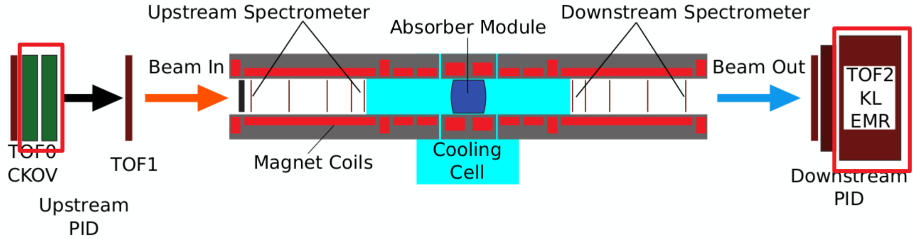
- 3 Time-of-flight stations
  - 2 planes of fast scintillator
  - Double ended readout
- 50-60 ps hit time resolution
- provides PID and p_z check

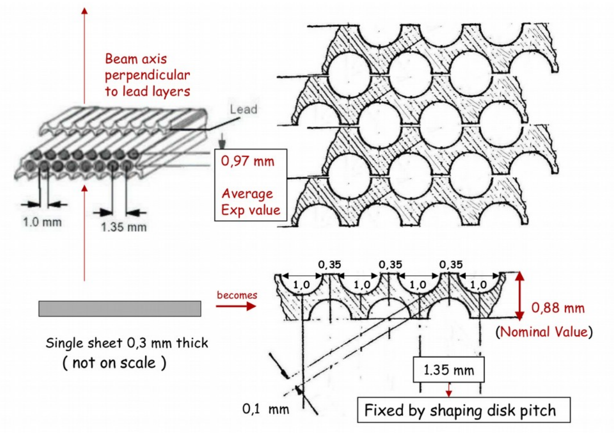




Cerenkov / KL







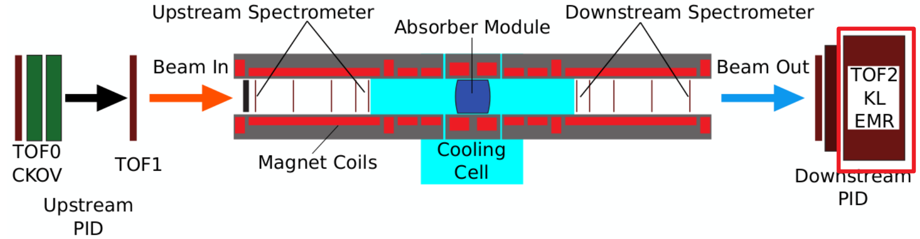
- Upstream threshold Cerenkov counters
- Twin aerogel slabs with n = 1.07 and 1.12

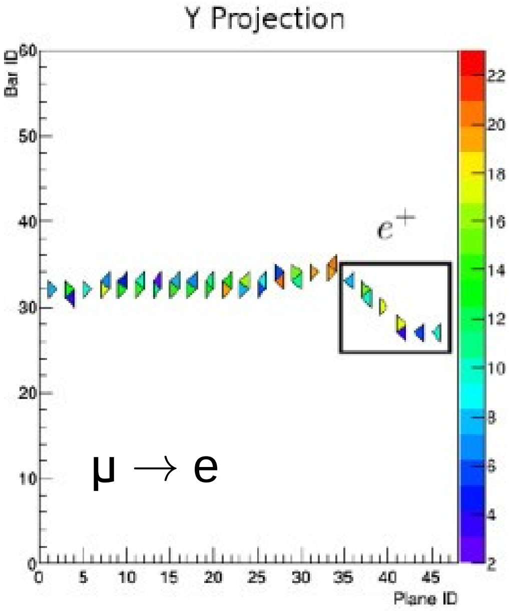
	CKOV – A n = 1.07	CKOV - B n = 1.12
p < 200 MeV/c		
200 < p < 240		Muons
p > 240 MeV/c	Pions	Muons Pions

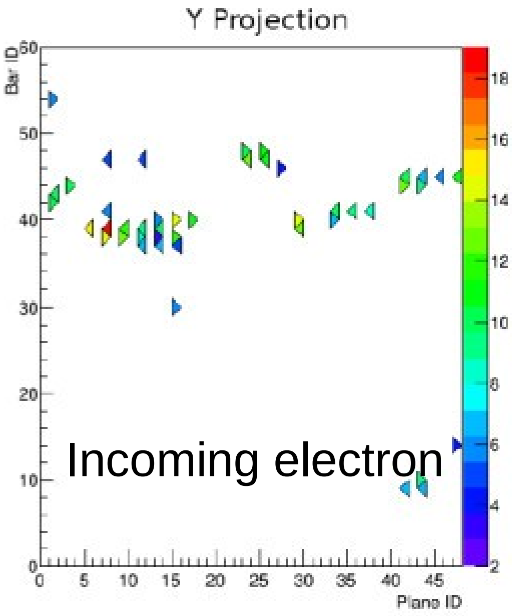
- Sampling calorimeter made from interspersed lead foils and scintillating fibres
- preshower for the EMR
- Enables rejection of electrons from downstream measurement

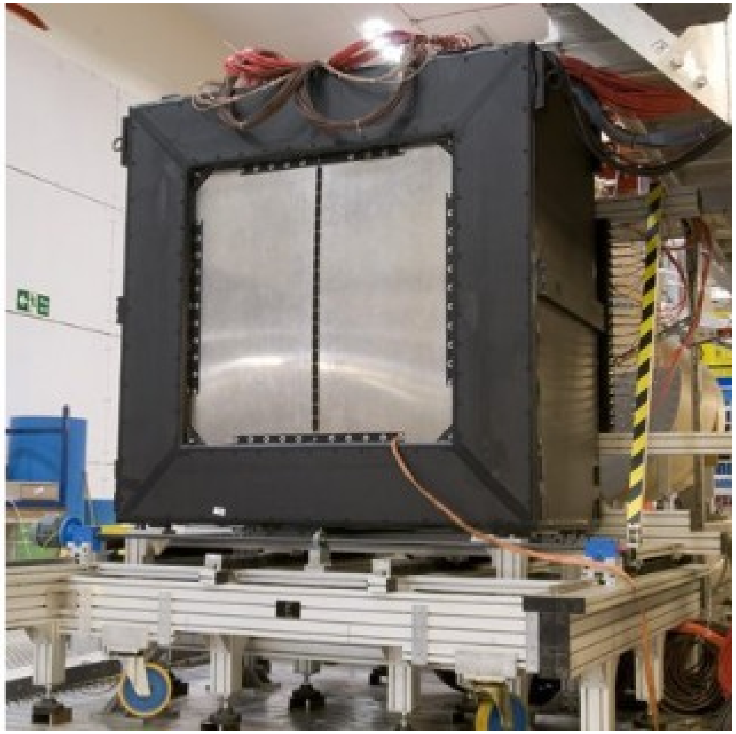
EMR

- 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

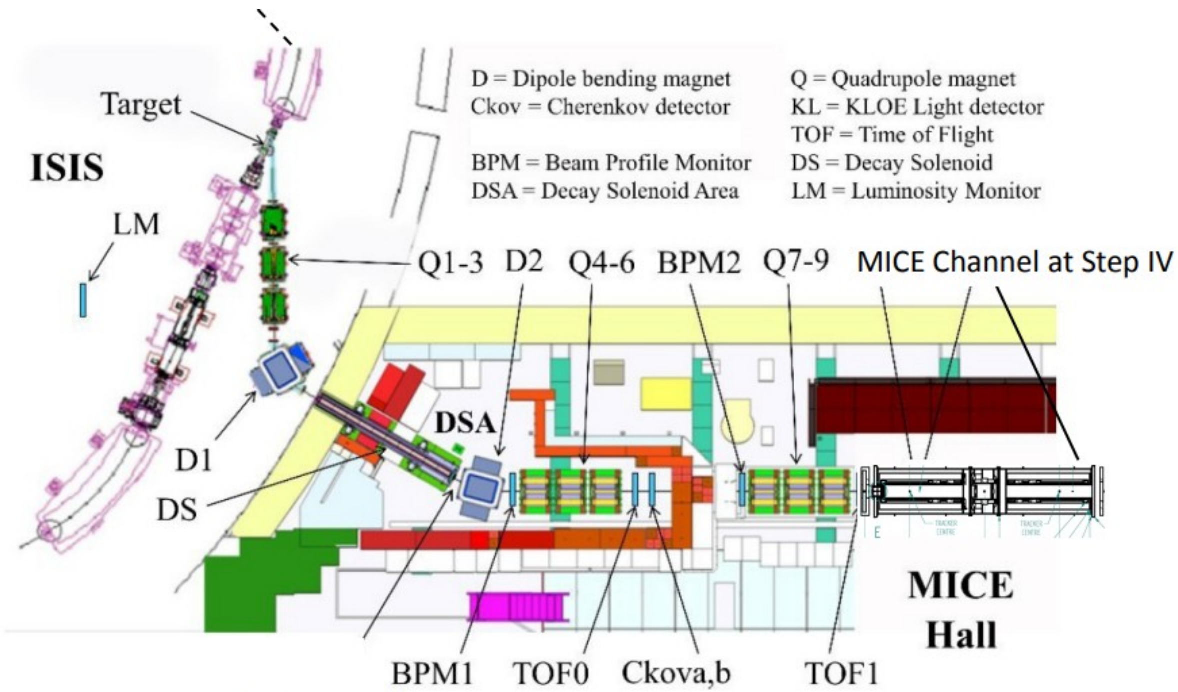






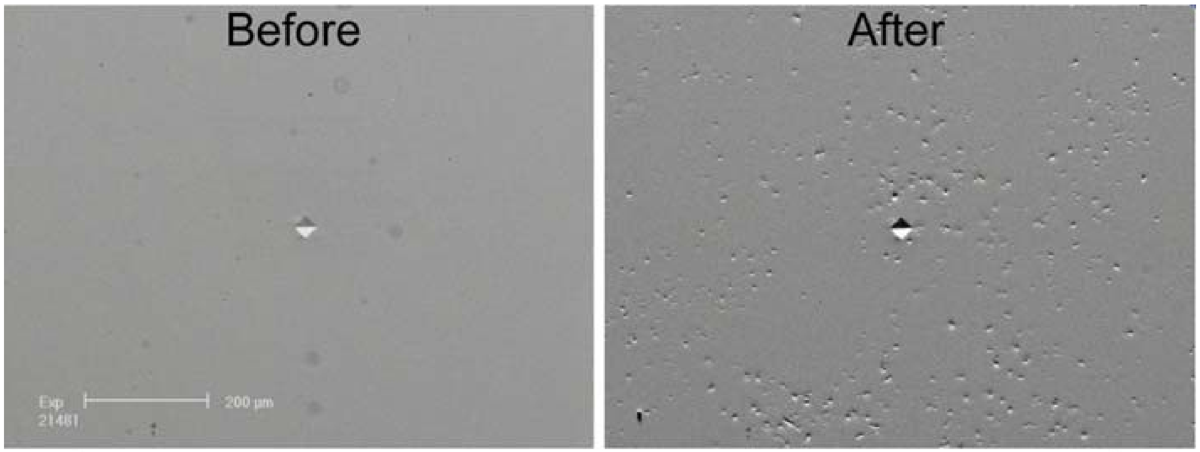


MICE Muon Beamline



- 800 MeV protons hit custom-made Ti target in the ISIS beamline
- Pions from these interactions are siphoned into extraction line
- pions decay to muons in the line
- 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%

Issues



TL - High Power Target
Specimen # 29754
Equivalent SNS Power Level = 2.5

Cavitation of Target wall by flying mercury droplets.

This could erode the entire thing over period of use

Radiation damage of surrounding shielding due to neutrons could make the superconducting magnets that surround the target region quench - i.e. become normally conducting.

Same thing happened to LHC magnets after first switch-on