# MICE Experiment
# Status and Prospects

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on behalf of MICE Collaboration

29.09.2017, nufact'17, Uppsala

# Outline of the talk

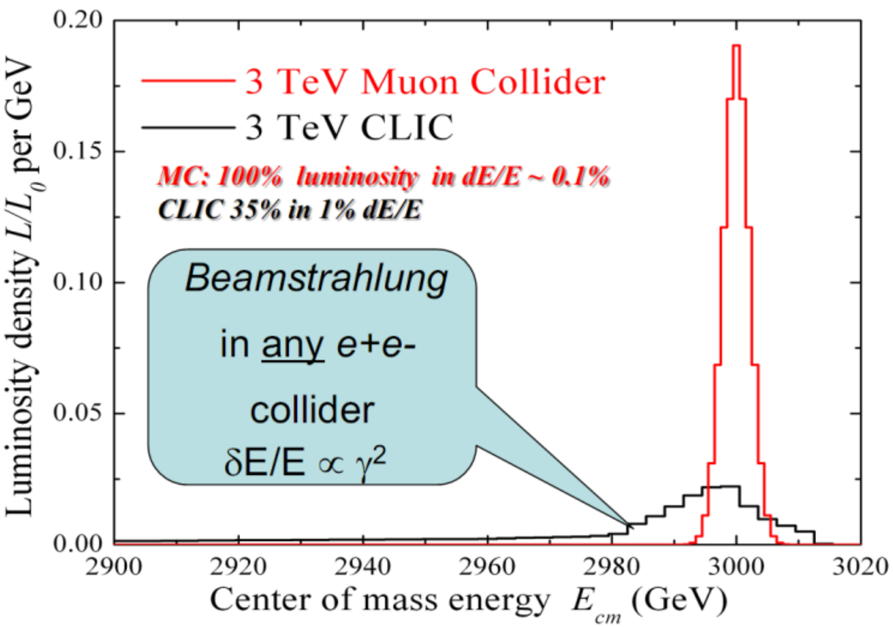
- Motivation
- Principles of ionization cooling
- MICE building blocks
- MICE Step IV
- Emittance measurement
- Data taking
- Possible upgrade plans
- Conclusion

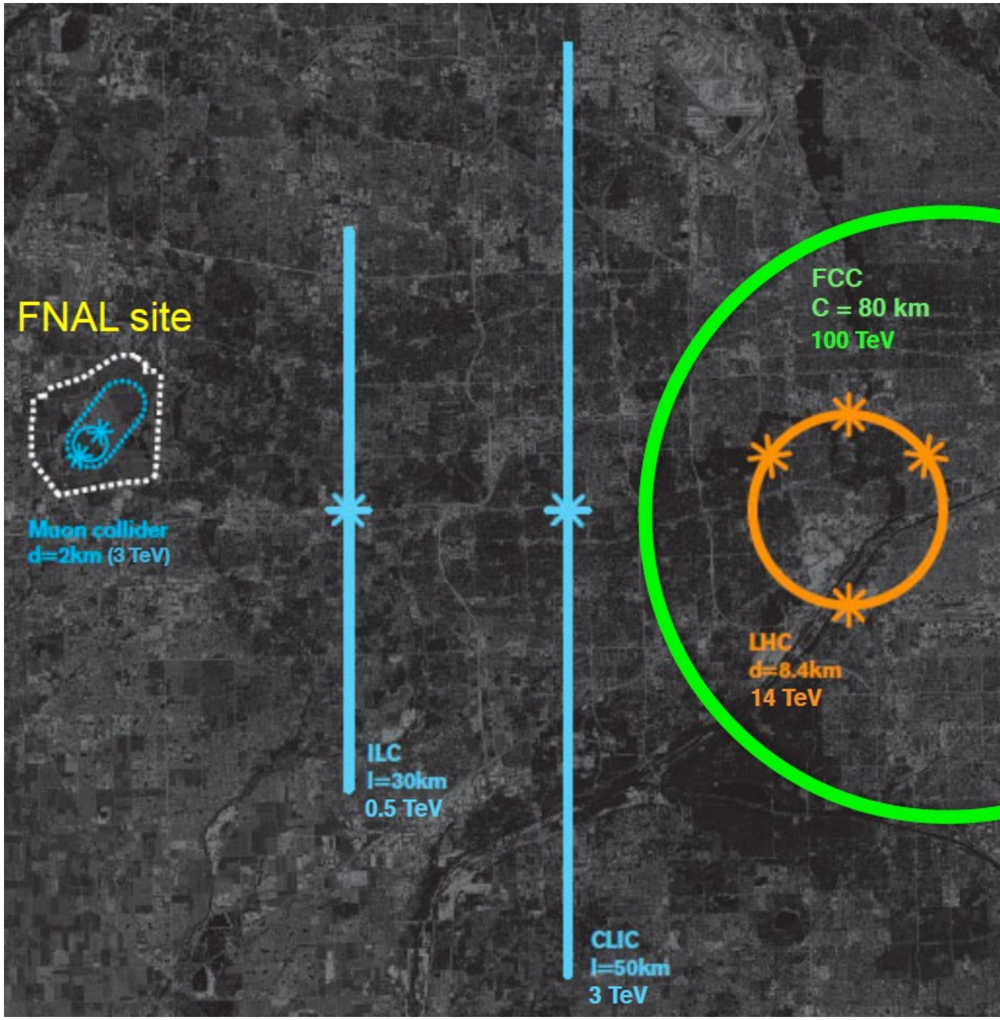
# Motivations for using muon beams (1)

- Muons as elementary leptons ~200 times heavier than electrons offer possibility to be used for colliding beam experiments
  - Allowing to avoid a large QCD background known in hadron colliders
  - Offering a full CM energy for creating new states (in contrary to hadron colliders)
  - Rate of emission of synchrotron radiation is highly suppressed -> allows to build compact collider facility
  - This also suppresses beamstrahlung -> allows to preserve the high quality beam
  - Large $m_{\mu}$ provides large coupling to the Higgs mechanism. The resonant Higgs production at the s-channel is possible.

# Sizes of various proposed colliders versus FNAL site

- Only Muon Collider would fit into Existing lab boundaries
- It will be able to use high quality beams



# Motivations for using muon beams (4)

- Muon beams are important for particle physics
  - Anomalous magnetic moment (g-2) – a possible sign of BSM physics
  - Searches for Lepton Flavour Violation -> complementary test of SM at a very high mass scale
  - Provide a high quality neutrino source -> the Neutrino Factory

# Challenges for using muon beams

- Muon beams are unstable (muon lifetime at rest ~2.2 $\mu$s)
  - All beam manipulations (capture, cooling, acceleration, collisions) have to be made very fast
- Muons are produced as tertiary beam (p$\longrightarrow\pi\longrightarrow\mu$)
  - Initial intensity and beam quality is rather weak

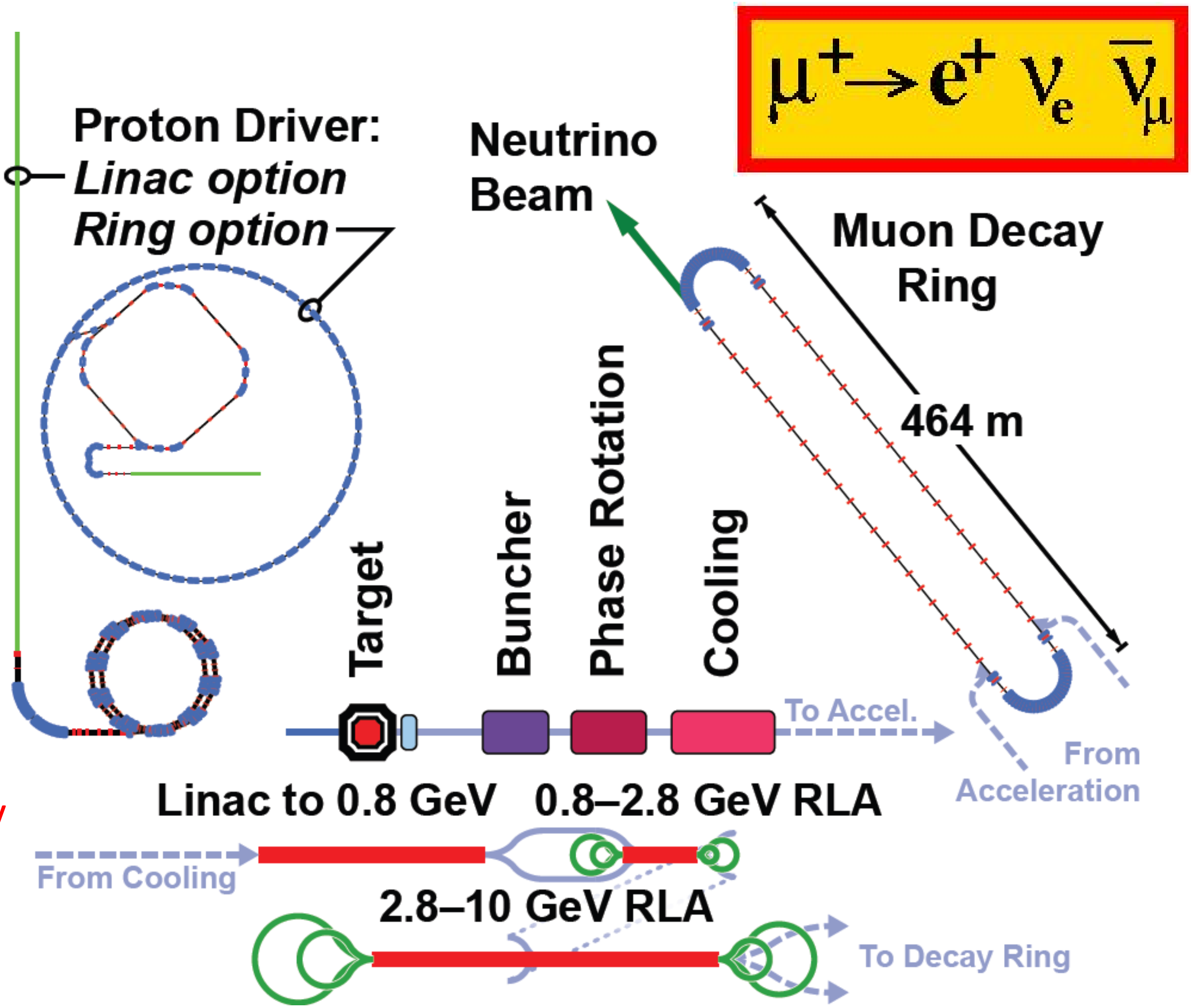
# Challenges for using muon beams (solution)

- Muon beams are unstable (muon lifetime at rest ~2.2 $\mu$s)
- Muons are produced as tertiary beam (p$\longrightarrow\pi\longrightarrow\mu$)

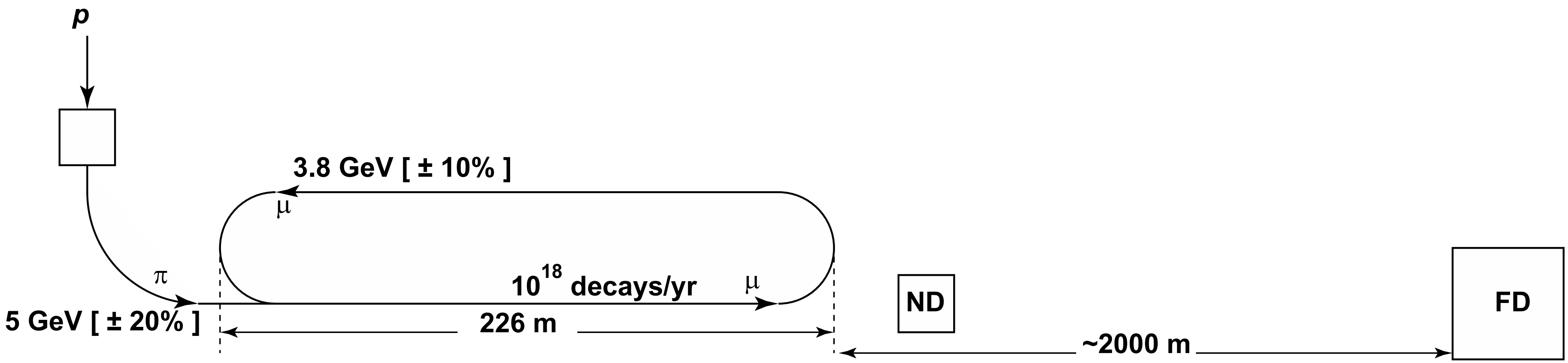
- Use ionization cooling, which is the only technique fast enough!
- Use high power proton driver (see C. Plostinar's talk)
- Develop rapid accelerators (see A. Bogacz's talk)

# Neutrino Factory, IDS-NF Design

- Provide $10^{21}$ muon decays per year toward a far detector
- Decays from 10 GeV muon beam (5 GeV – NuMax)
- Facility, which can provide precision measurements of neutrino oscillation parameters far beyond of conventional beams.
- Ionization cooling channel is an essential ingredient of the facility in order to obtain high intensity keeping the accelerator aperture reasonable in size.

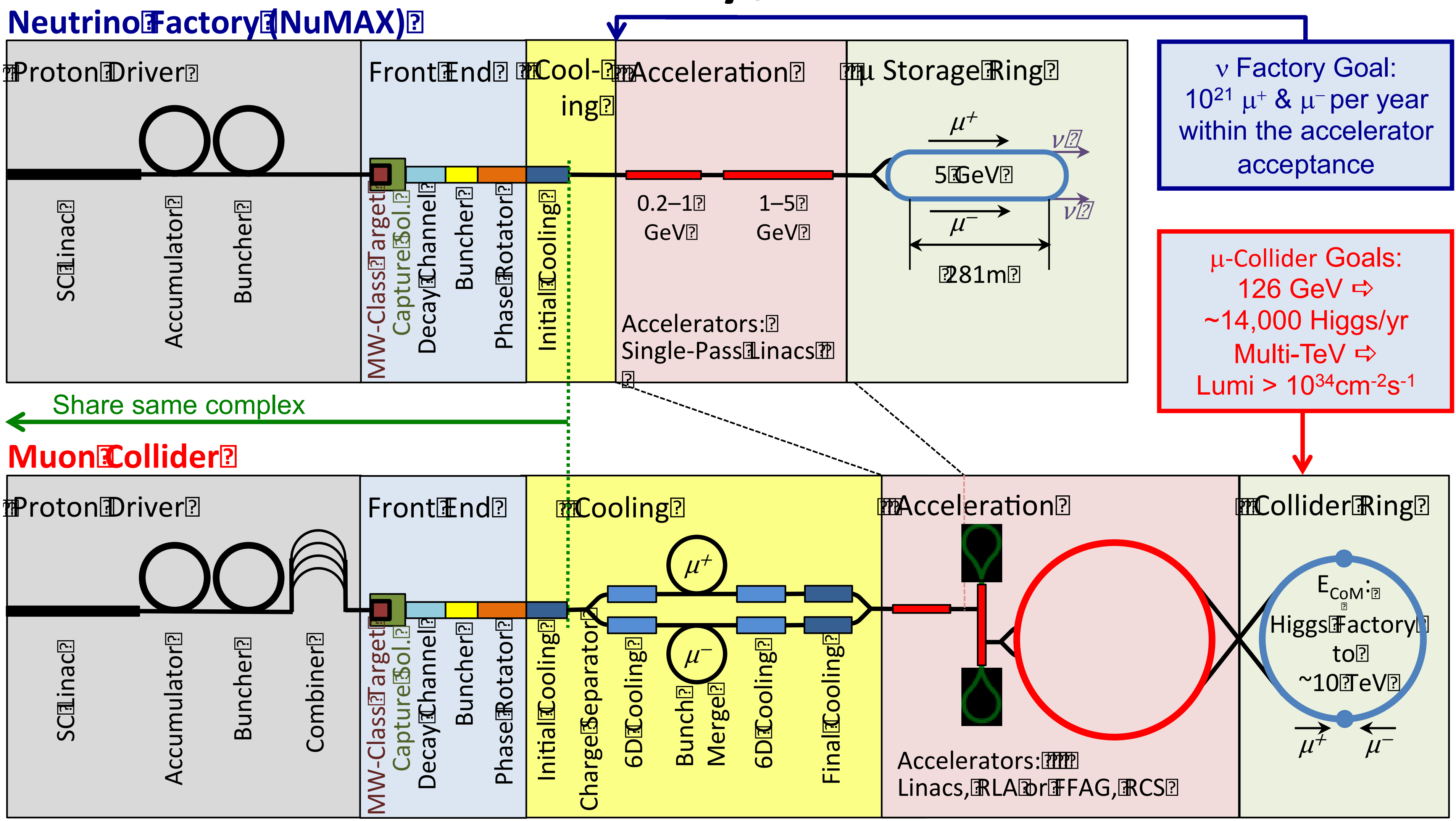


# First steps towards the Neutrino Factory - nuSTORM




- Novel source of neutrinos from both muon decay
  - ❑Neutrinos from pion decay also available
- Proof of principle for the Neutrino Factory concept
- Precision measurement of neutrino interactions
- May serve as R&D facility for a future Muon Collider
- Does not require muon cooling and can be based on existing technology  and has affordable price.

# Neutrino Factory/Muon Collider




For the Muon Collider cooling is absolutely essential

# What is Muon Ionization Cooling?


- Energy loss in the absorber reduces both $p_L$ and $p_T$
- Scattering heats the beam
- RF cavities restore $p_L$ only
- The net effect is the reduction of beam emittance – cooling (strong focusing, low-Z absorber material and high RF gradient are required)

Cooling Equation:

$$\frac{d\epsilon_n}{ds} \sim \underbrace{-\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu}}_{\text{Cooling}} + \underbrace{\frac{1}{\beta^3}\frac{\beta_\perp(0.014\text{GeV})^2}{2E_\mu m_\mu L_R}}_{\text{Heating}}$$

$d\epsilon_n/ds$ is the rate of change of normalised-emittance within the absorber; $\beta$, $E_\mu$ and $m_\mu$ the muon velocity, energy, and mass, respectively; $\beta_\perp$ is the lattice betatron function at the absorber; $L_R$ is the radiation length of the absorber material.

# Motivation

**MICE is the**

***Muon***

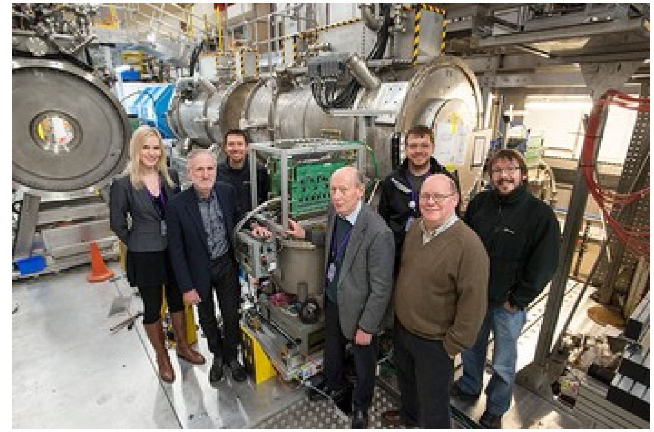
***Ionization***

***Cooling***

***Experiment***

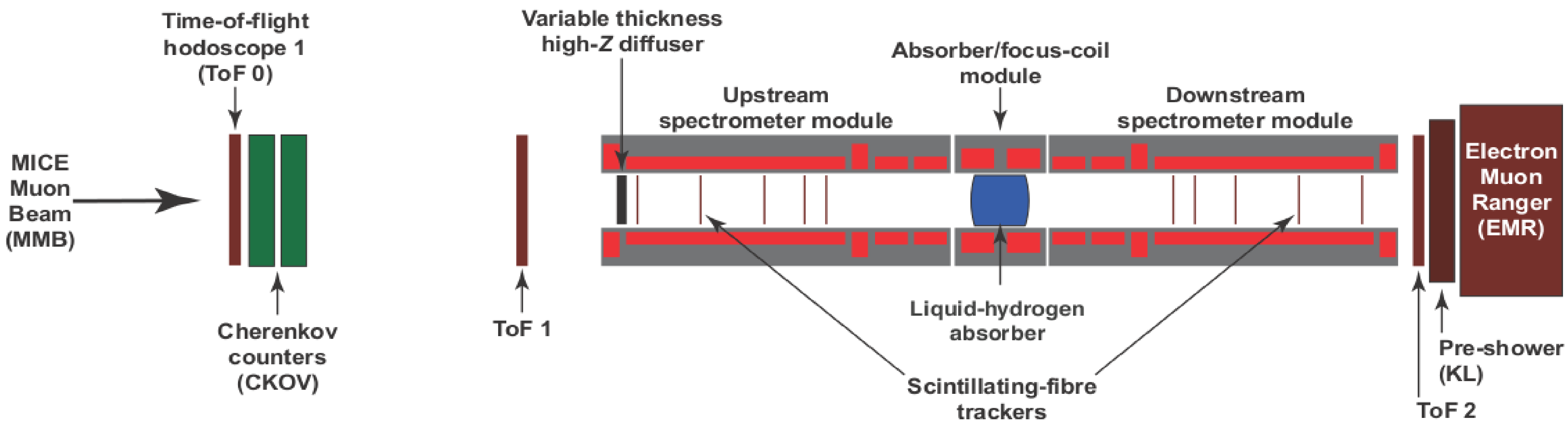
***MICE* is a proof of principle experiment to demonstrate that we can "cool" a beam of muons.**

# MICE: Collaboration



Over 100 collaborators from >10 countries and ~30 institutes.

# MICE:
# Muon Ionization Cooling Experiment



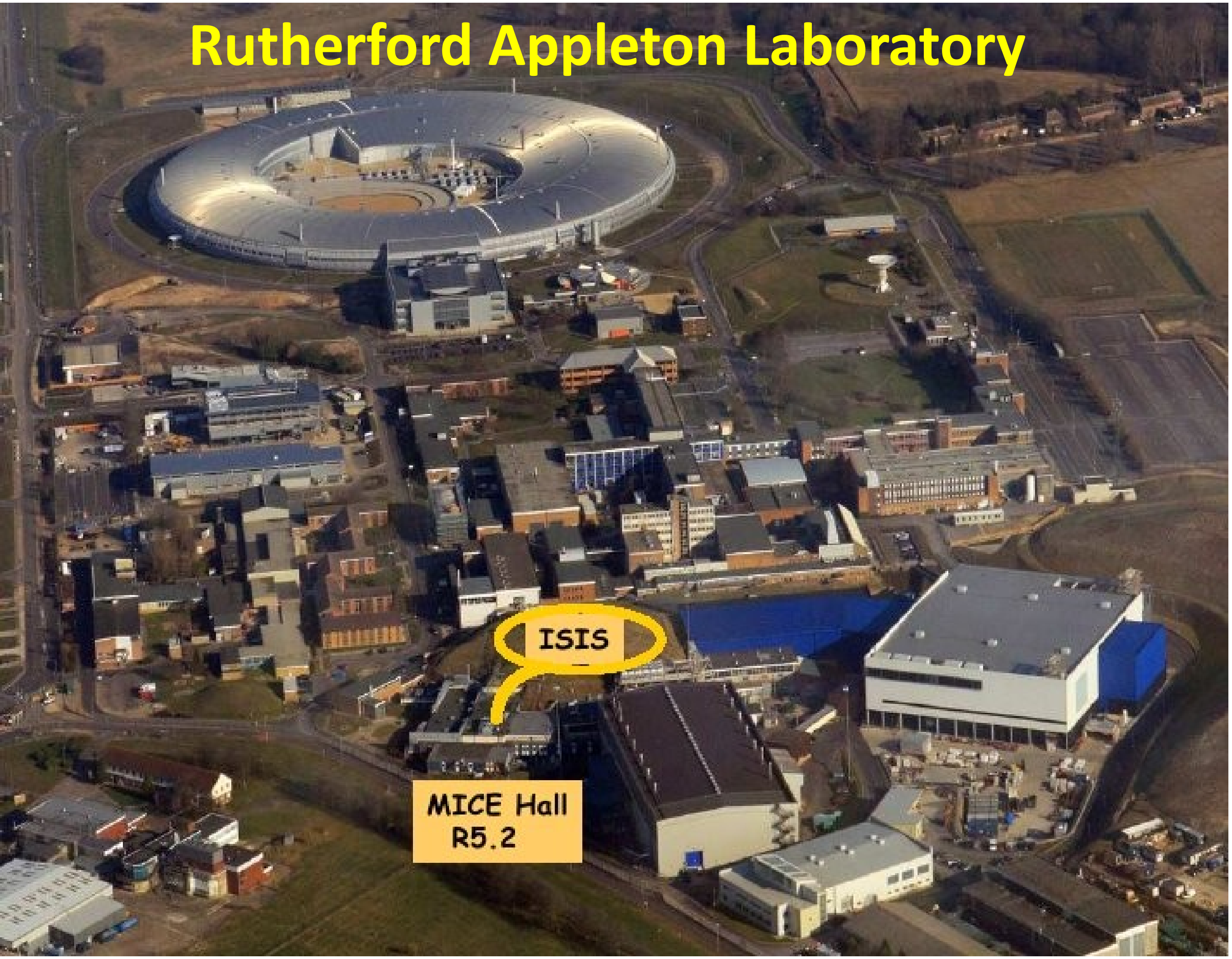

- **MICE Goals:**
  - **Design, build, commission, and operate a realistic section of cooling channel**
  - **Measure its performance in a variety of modes of operation and beam conditions**
  - **Measure material properties of potential absorbers (LiH and liquid hydrogen)**

**…results will be used to optimize Neutrino Factory, Muon Collider and future high brightness muon beam designs.**

# Principles of MICE Experiment

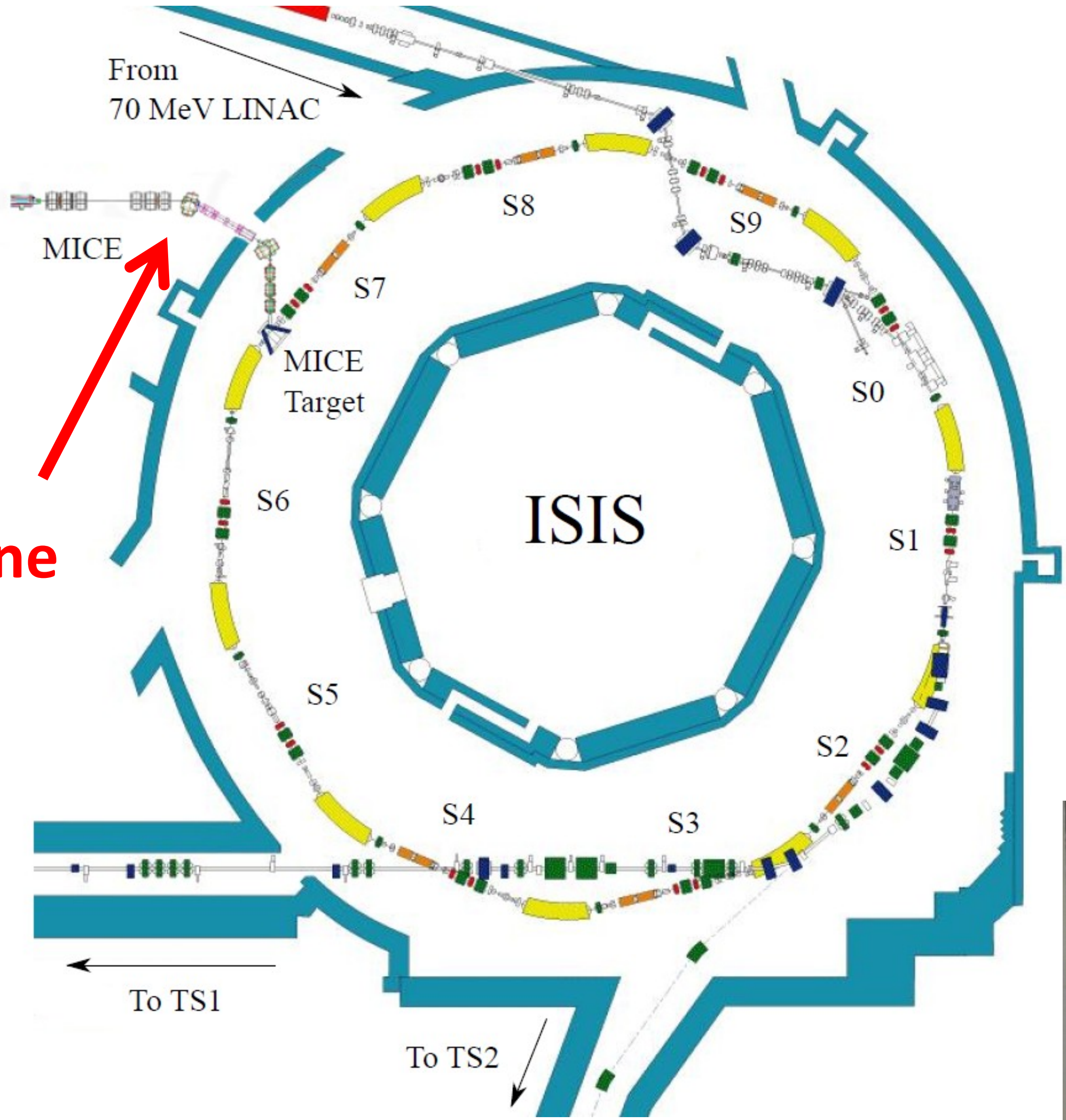
- ***Target – produce pions (using ISIS beam)***
- ***Beamline – create beam of muons***
- ***Particle ID – verify/tag muons (before/after)***
- ***Diffuser – create proper beam emittance***
- ***Trackers – measure emittance (before/after)***
- ***Absorber ($LH_2$ or LiH) – cooling***
- ***RF – re-establish longitudinal momentum (unfortunately not currently on our plan ☹)***
- ***Software and computing – use for MC simulations and data analysis***

# Where is MICE located?




**RAL,**
**Home of MICE**

# ISIS Accelerator at RAL

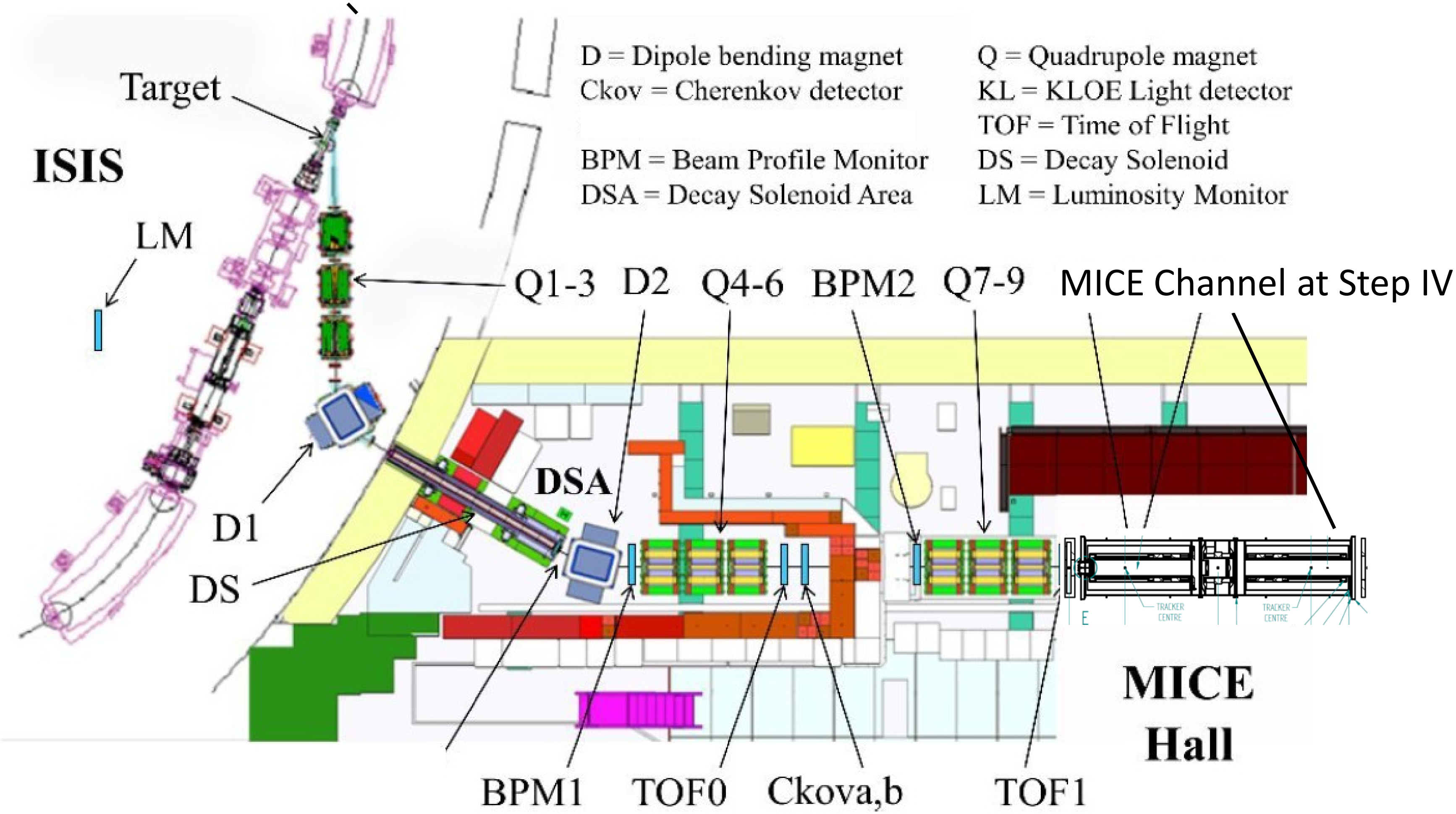



**MICE beamline**

**ISIS:**

- **One of the world's fastest synchrotrons (50 Hz)**
- **Produces 800 MeV proton beam with ~250 kW power**
- **Beam is used mainly for spallation neutron and muon production**
- **ISIS is equipped with internal target to feed MICE!**

# MICE Beamline

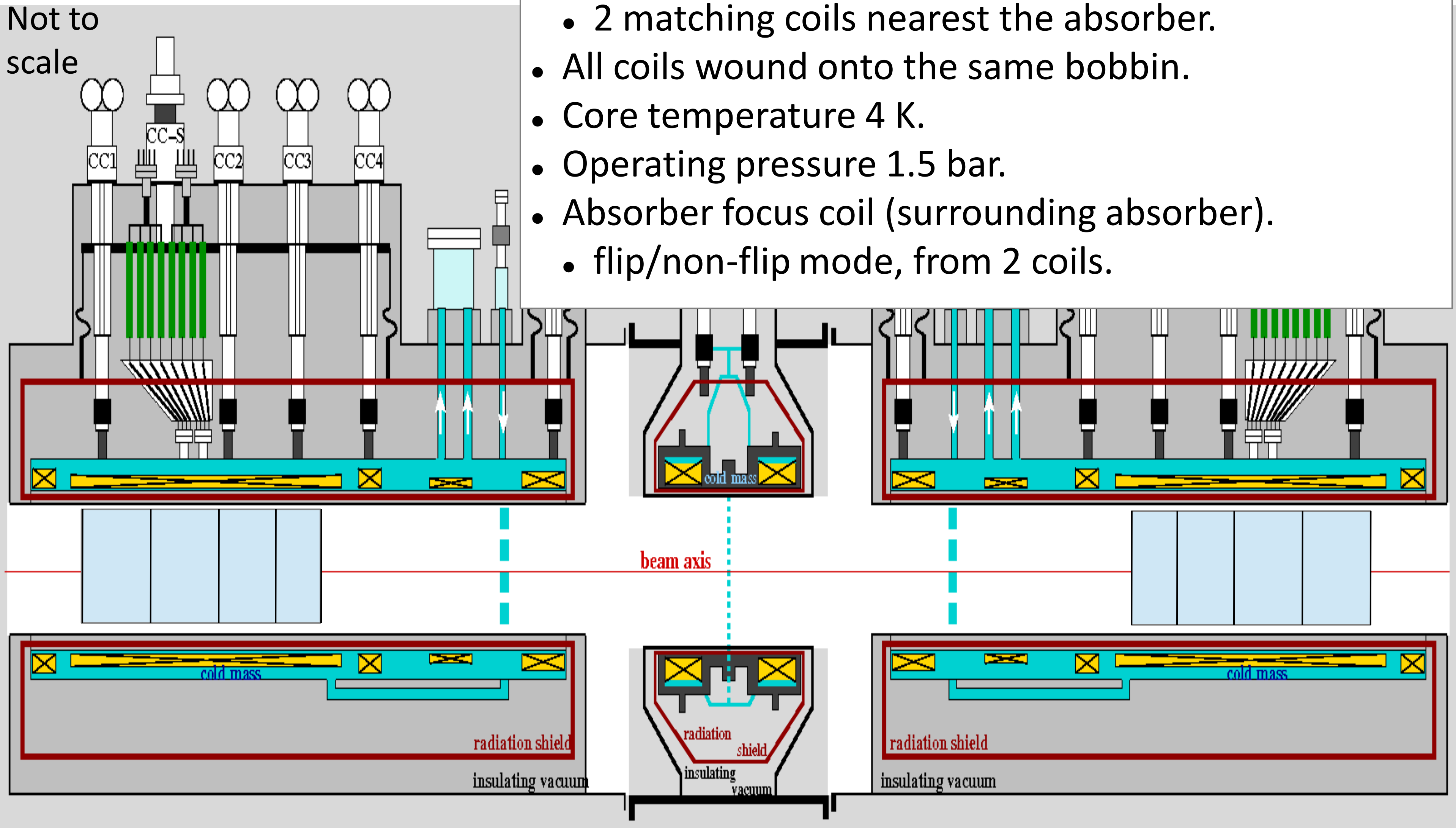



MICE Beamline
Conceptual Layout

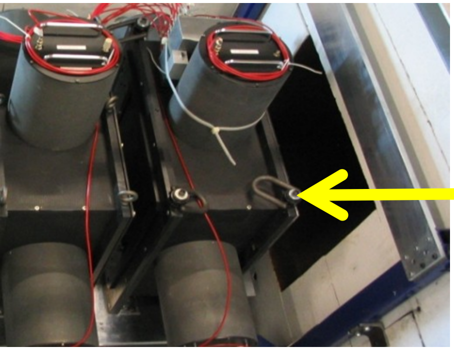
# The Magnets

- Two Spectrometer solenoids.
- Produce maximum of 4T magnetic field.
- 5 coils in each spectrometer solenoid:
  - Central coil which covers the Trackers.
  - 2 end coils either side of the central coil.
  - 2 matching coils nearest the absorber.
- All coils wound onto the same bobbin.
- Core temperature 4 K.
- Operating pressure 1.5 bar.
- Absorber focus coil (surrounding absorber).
  - flip/non-flip mode, from 2 coils.

Not to scale

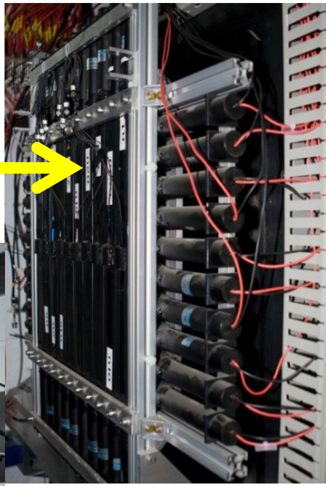


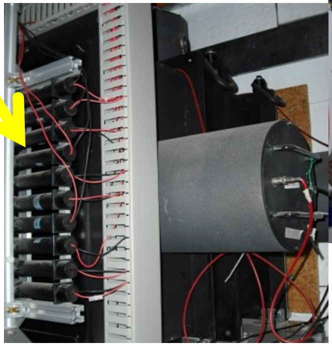
# MICE PID: Detectors

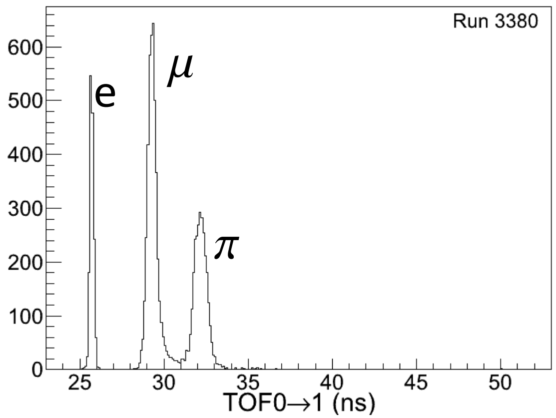


**Upstream PID:**
**discriminate p, •, •**

- *Time of Flight – ToF0 & ToF1*
- *Threshold Cerenkov*



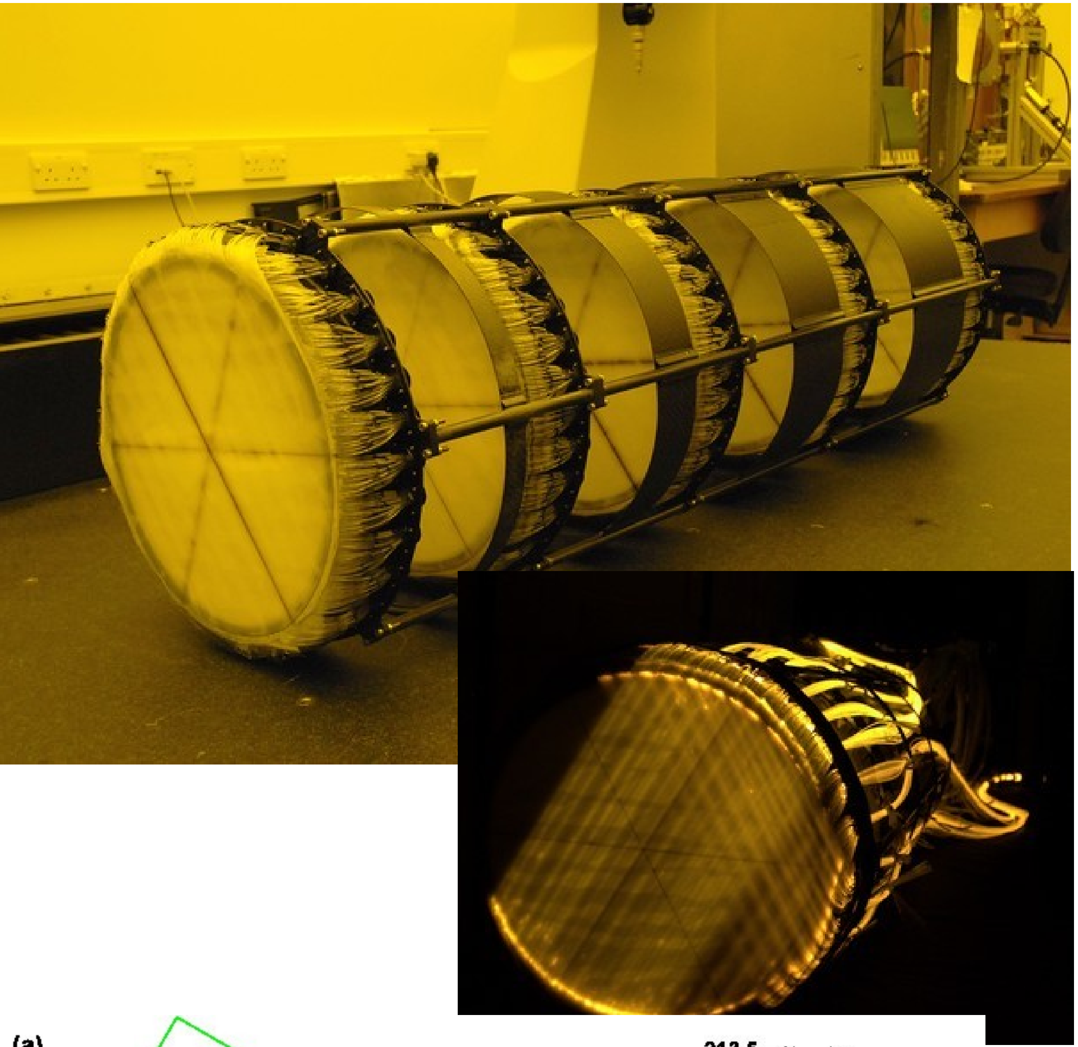




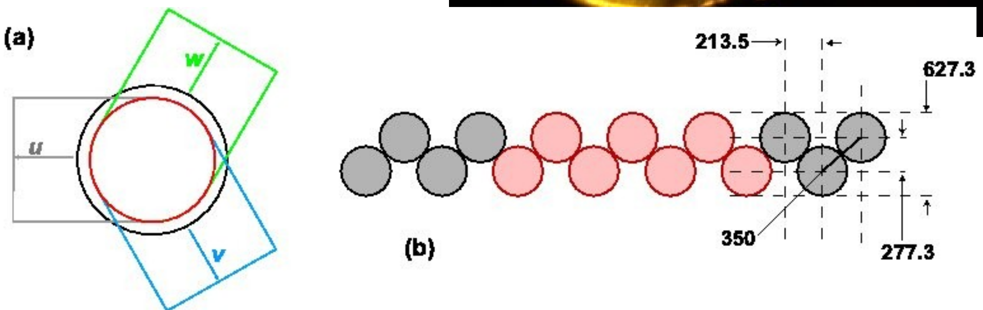

**Downstream PID:**
**reject decay electrons**

- *Time of Flight - ToF2*
- *Kloe-light Calorimeter - KL*
- *Electron-Muon Ranger -EMR*

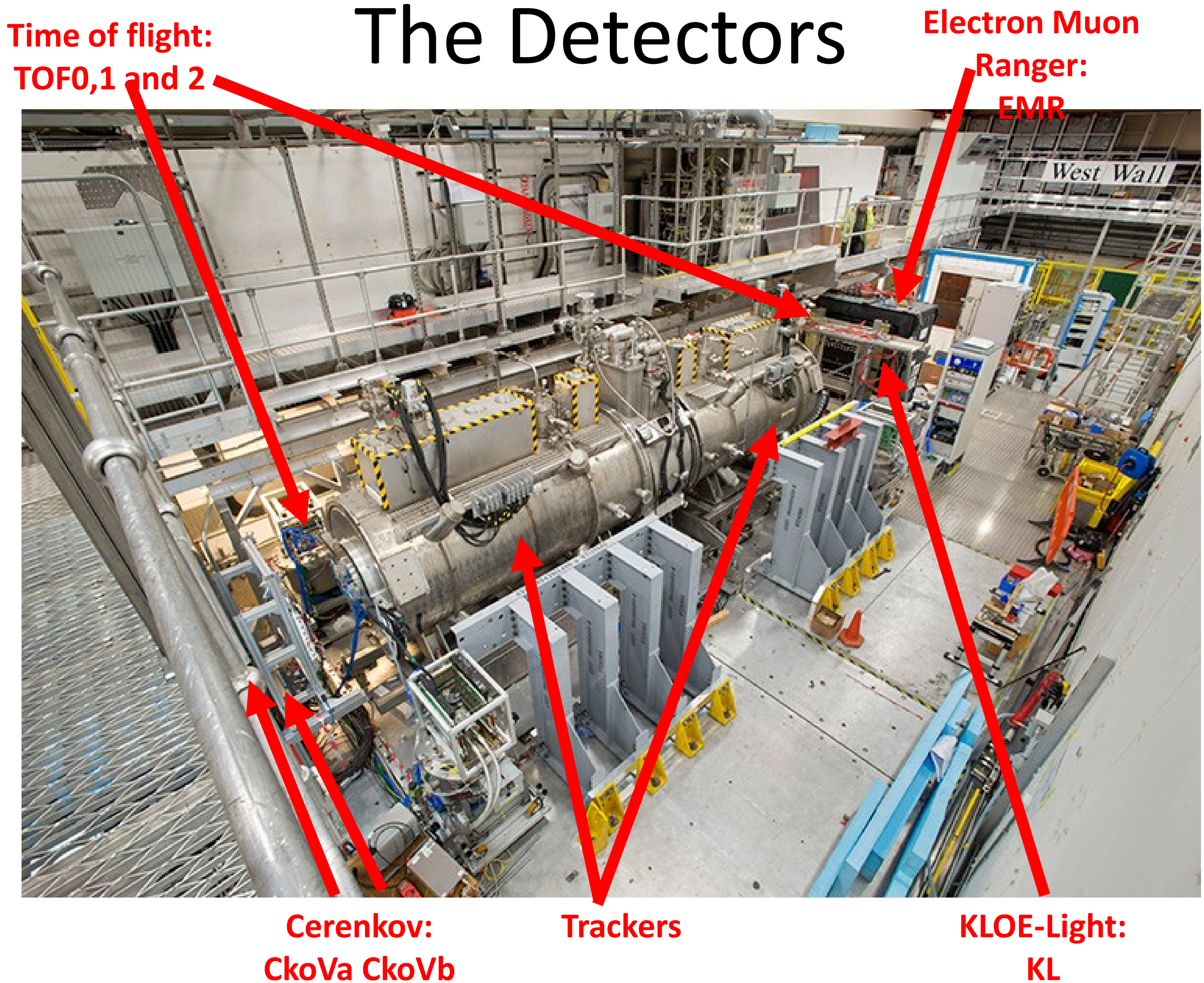
# The Trackers



- Two scintillating fibre trackers, one upstream, one downstream of the cooling channel.
- Each within a spectrometer solenoid producing a 4T field.
- Each tracker is 110 cm in length and 30 cm in diameter.
- 5 stations
  - varying separations 20-35 cm (to determine the muon $p_T$).
- 3 planes of fibres per station each at 120°.
- LED calibration system.
- Hall probes.
- Position resolution 470µm.

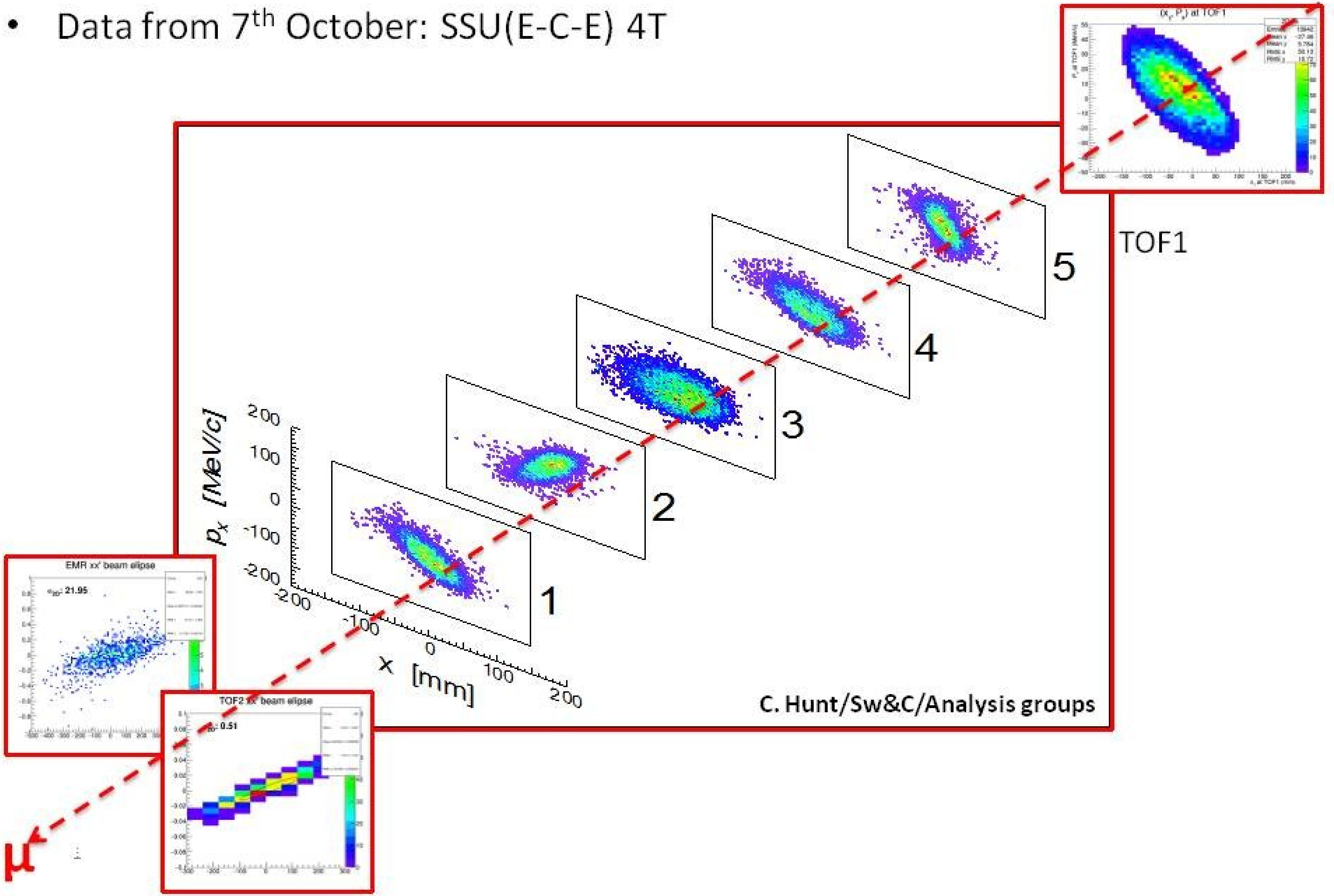


# The Detectors



# Principles of MICE phase space reconstruction

- Data from 7th October: SSU(E-C-E) 4T



# Emittance Calculation

The 4D normalised RMS transverse emittance is defined as $$\epsilon_n = \frac{1}{m_\mu}\sqrt[4]{\det\Sigma}$$

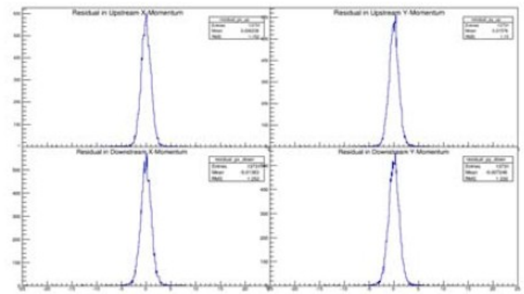
Where $m_\mu$ the muon mass and $\Sigma$ the covariance matrix:

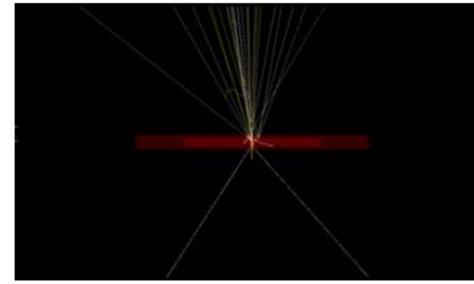
$$\Sigma = \begin{pmatrix} \sigma^2_{xx} & \sigma^2_{xp_x} & \sigma^2_{xy} & \sigma^2_{xp_y} \\ \sigma^2_{p_x x} & \sigma^2_{p_x p_x} & \sigma^2_{p_x y} & \sigma^2_{p_x p_y} \\ \sigma^2_{yx} & \sigma^2_{yp_x} & \sigma^2_{yy} & \sigma^2_{yp_y} \\ \sigma^2_{p_y x} & \sigma^2_{p_y p_x} & \sigma^2_{p_y y} & \sigma^2_{p_y p_y} \end{pmatrix}$$

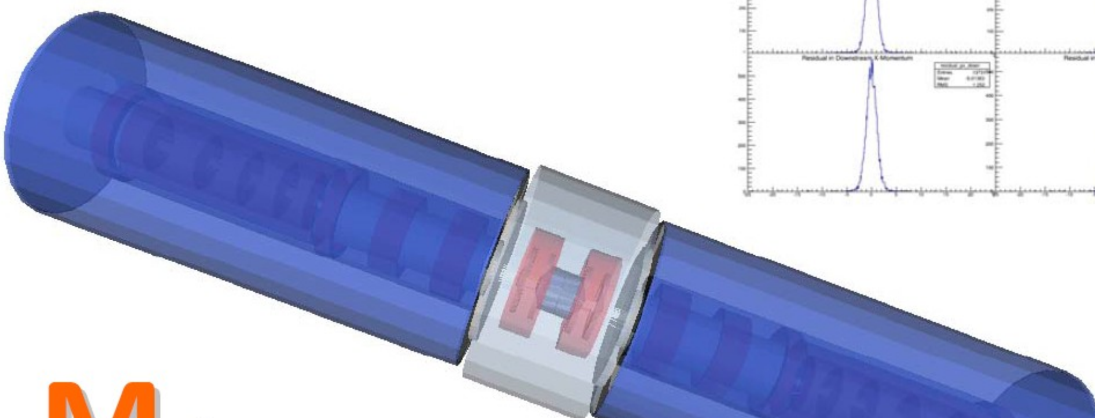
And $\sigma^2_{ij} = \langle ij\rangle - \langle i\rangle\langle j\rangle$ the covariance of i and j.

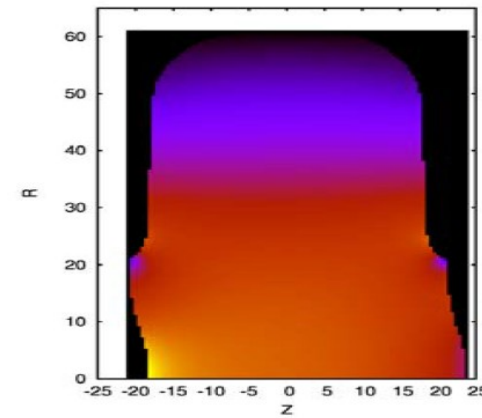
# Software and Computing

Home made simulation and analysis framework










**M**ICE

**A**NALYSIS

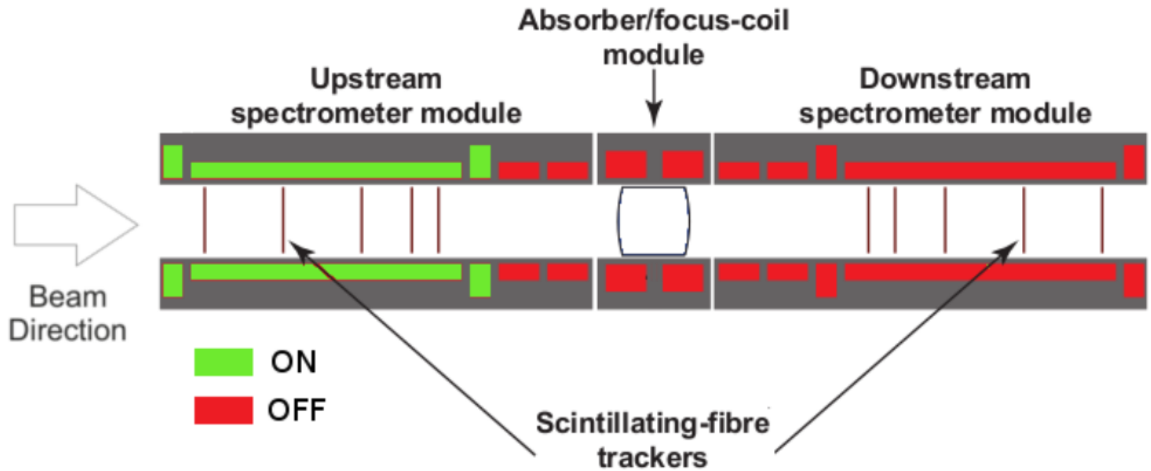
**U**SER

**S**OFTWARE

C++ framework wrapped in a python interface.

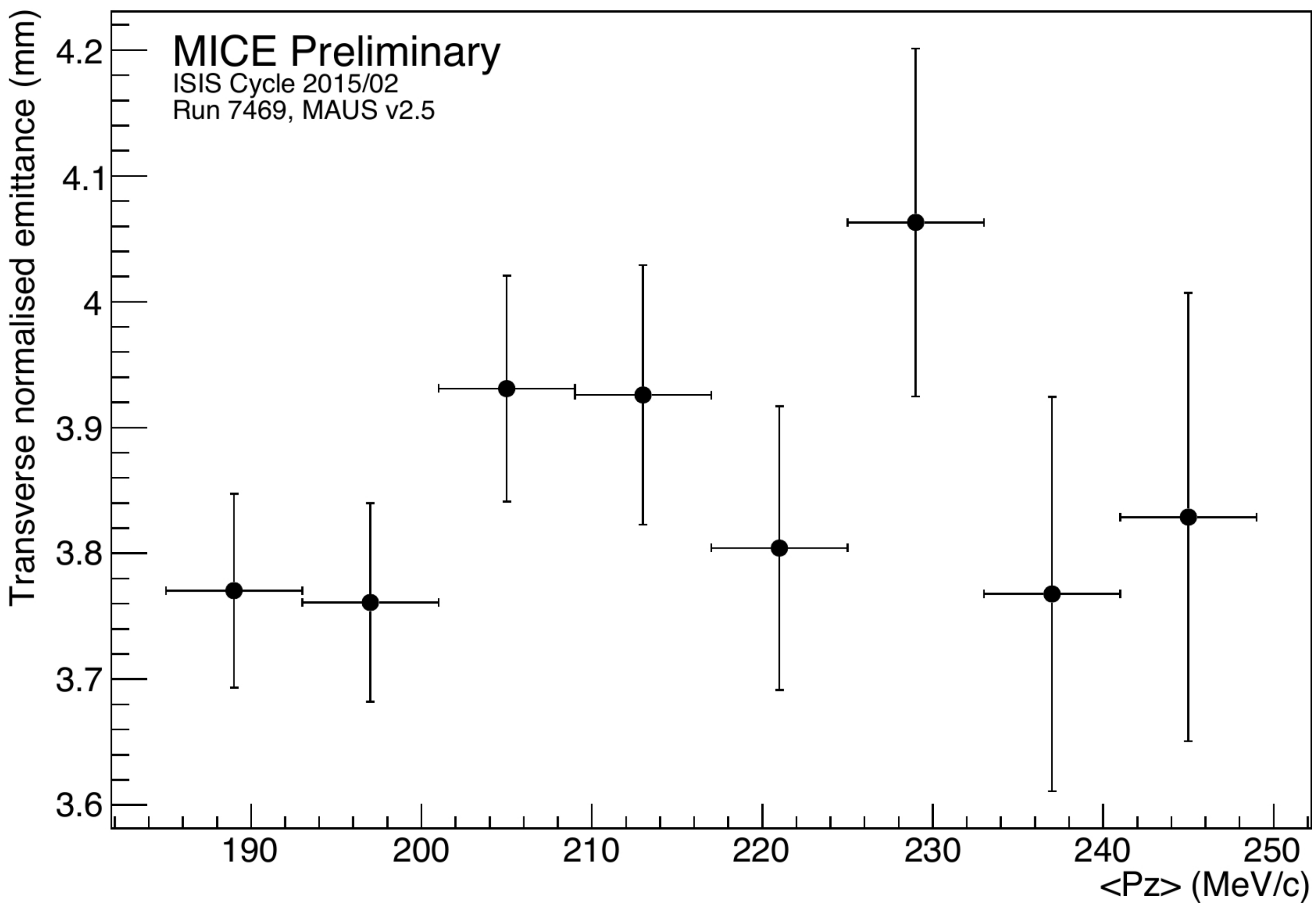
Developed by the collaboration for simulation and analysis of MICE.

# Emittance Measurement
# First Direct Measurement

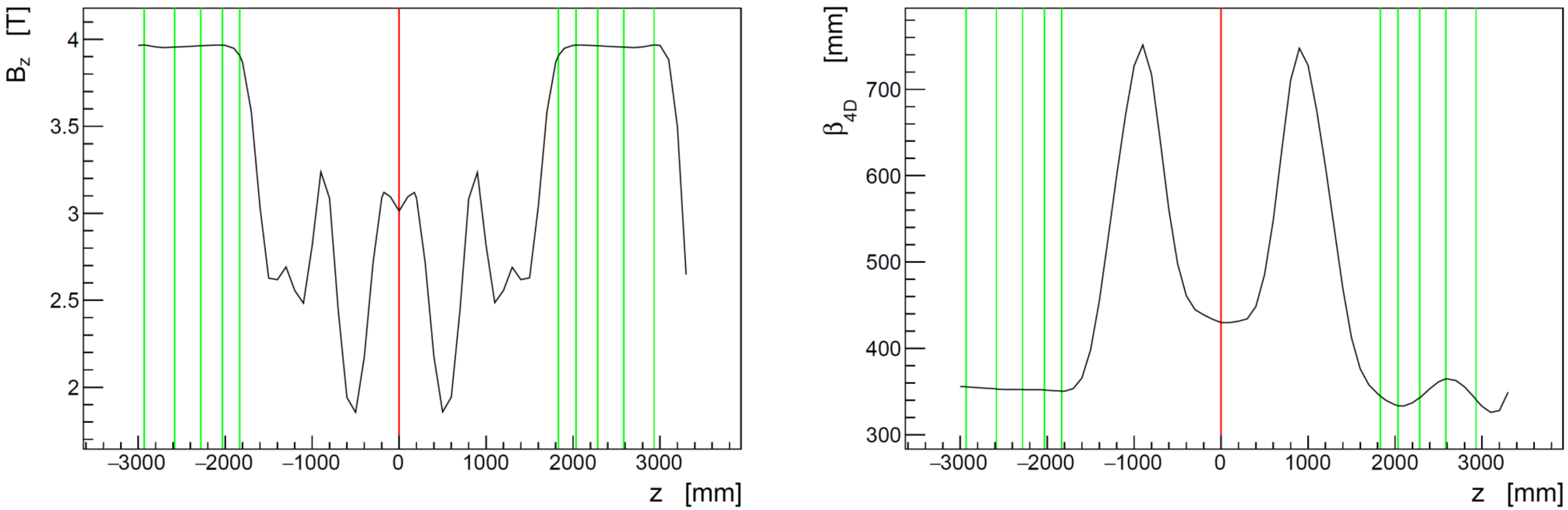



- Measurement only in Upstream Tracker: to measure the beam at the input to Step IV channel demonstrating the power of the technique.
- Data taken in October 2015
  - 200 MeV/c positive muon input beam
  - 19076 good muon tracks acquired
- This run was used to characterise the MICE muon beam and validate the tracker reconstruction.

# First Direct Measurement of Emittance



# Design Optics in Cooling Channel




Bz and Beta in solenoid mode at 4T

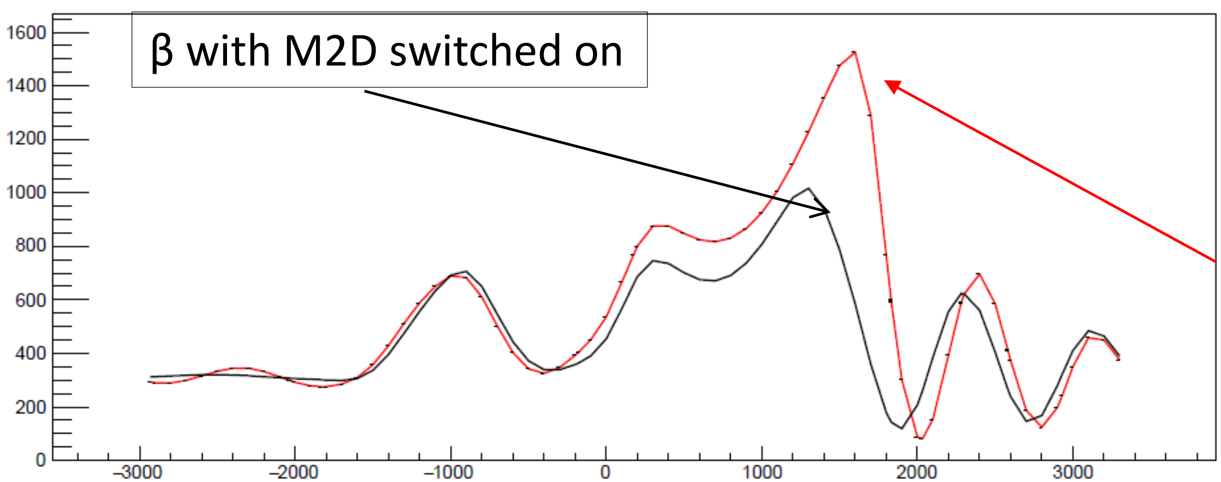
C. Hunt (IC) Thesis 2017

**Beam incoming from beam line, optimised for transmission, passes through variable thickness high-Z diffuser to increase emittance above the equilibrium value in a controlled way at the entrance to the Channel.**

- Optics of the channel assumes matched beam ($\alpha$=0) in both upstream and downstream solenoids.
    - To maximise transmission.
    - To minimise emittance growth due to mismatch.
    - In practice this condition is met only approximately, but a matched beam sample can be selected with sufficient statistics.
- Small beta waist is created with the help of Matched Coils and AFC at absorber (centre).
    - Solenoid and flip modes are proposed and used for data taking.
- Optics can only be approximately symmetric due to energy loss and large momentum spread.

# Beam Optics: Data Taking

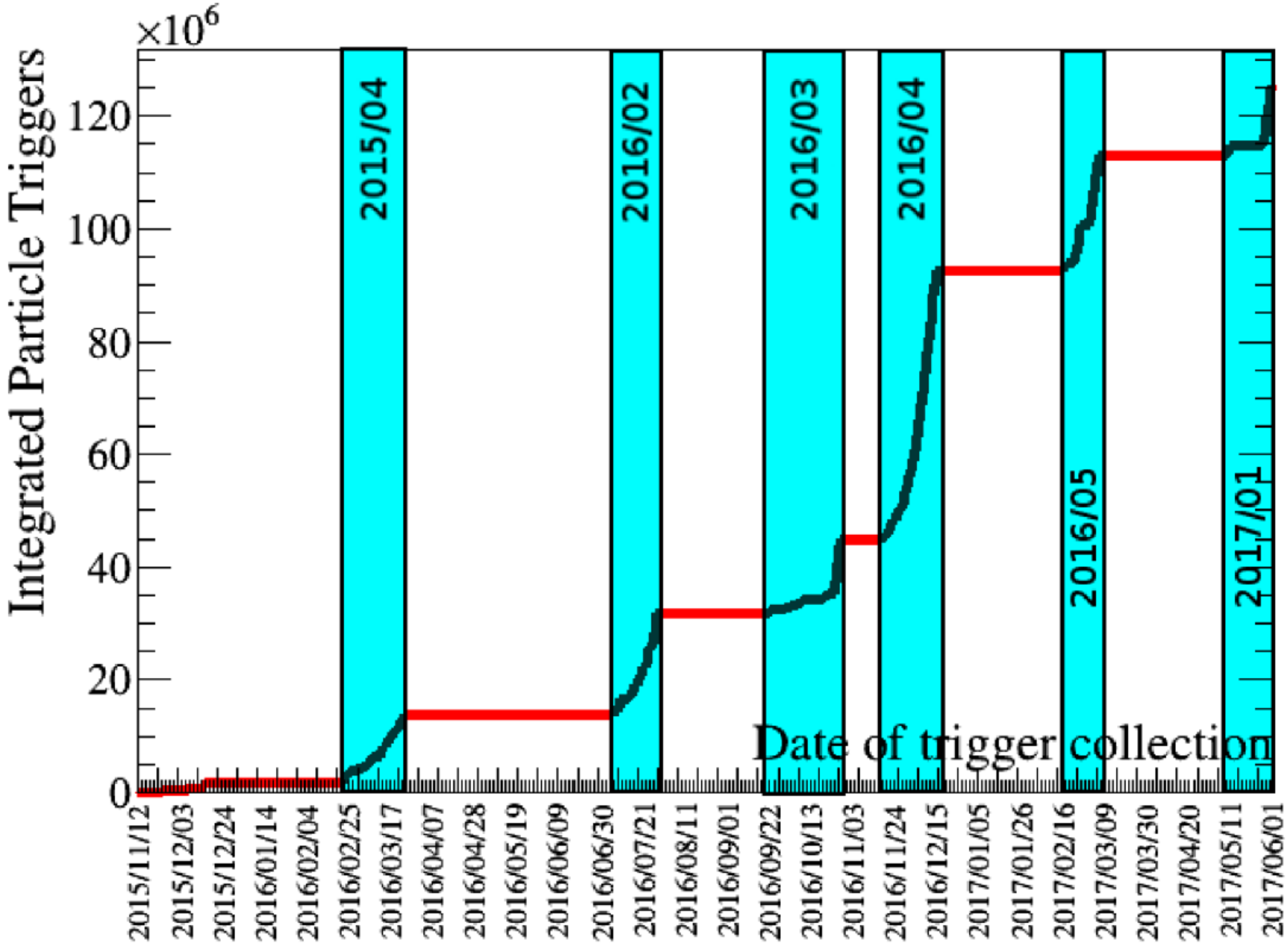
- Failure of QPS during training caused one of the Matching Coils in SSD to be inoperable.
- This caused beam mismatch and a decrease in transmission, which could be partially compensated.
  - Compensation required operation with reduced field in SSs (4T→3T)
  - As an effect the optics is non-symmetric
- In the downstream solenoid, the second match coil (M2D) was not operated as a precaution.
  - Operation with M2D on is foreseen in October.
- such that a cooling signal is




β without both downstream Matched Coils

Beta function in flip mode

# Particle Triggers Over Time



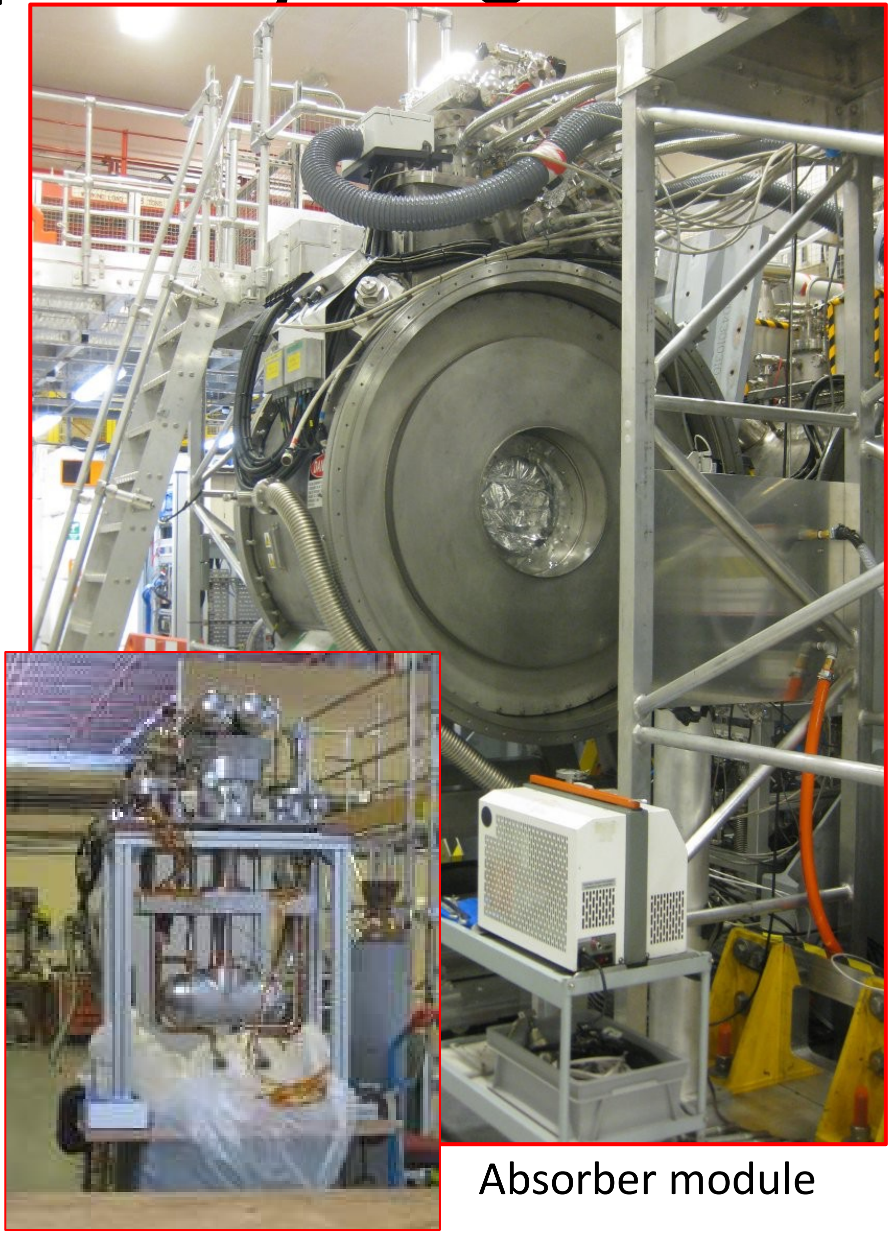

The integrated number of particle triggers collected by the MICE experiment.

The shaded bands highlight the ISIS user cycles during which the ISIS machine was operational.

MICE has collected just under $120\times10^6$ particle triggers so far.

# Cooling With Liquid Hydrogen

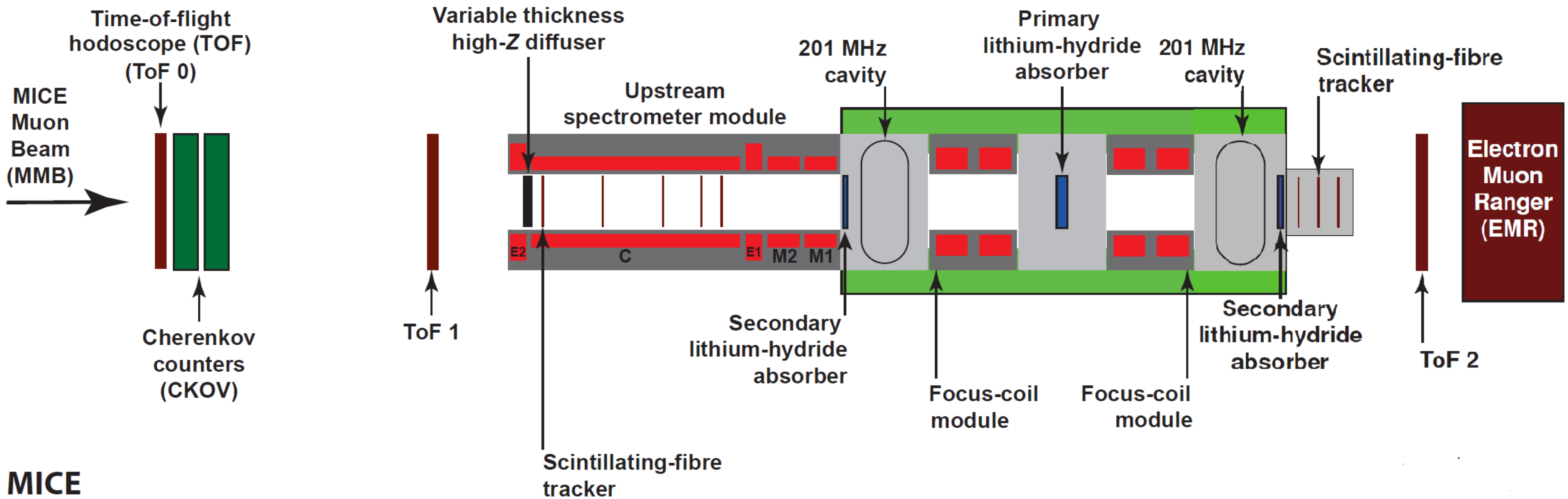
- $LH_2$ system installed and commissioned with Neon.
- Filling successfully accomplished this week!
- Data taking with $LH_2$ started!
- Exciting publications in preparation and to come!



Absorber module

Production condenser

# MICE Step IV Upgrade




MICE

- Upgrade to DEMO fully designed
  - Very good performance
  - RF cavities tested and constructed in the US
  - Power sources available and tested in the UK
  - Tracker support vessel, first build stage complete.
- IHEP Protvino, Russia is potentially interested as a host laboratory

# Scientific output of MICE

- Several papers is preparation
- A very important output is an unique inside into material properties of absorbers (mainly LiH and liquid hydrogen) – see J. Nugent's talk
- The main aim of MICE is muon beam cooling – see talks by C. Hunt and F. Drielsma
- Stay tuned for a rapid communication on our results very soon!

# Conclusions

- MICE is taking data in Step IV configuration
  - ❑ LiH absorber data are collected
  - ❑ Liquid hydrogen has been started this week!
- Important scientific outputs are expected
  - ❑ Testing Multiple Scattering and energy loss models in absorber materials (LiH and liquid hydrogen)
  - ❑ First results of normalised emittance evolution in a muon Cooling Channel
- MICE will measure factors that determine performance of ionisation cooling lattice, measure emittance evolution along the channel and seek to observe the reduction in normalised emittence.
- 6D/ultimate cooling demonstration is needed!