First Ever Ionization Cooling Demonstration in MICE

Paul Soler (U.Glasgow), Jingyu Tang (IHEP)
on behalf of the MICE Collaboration

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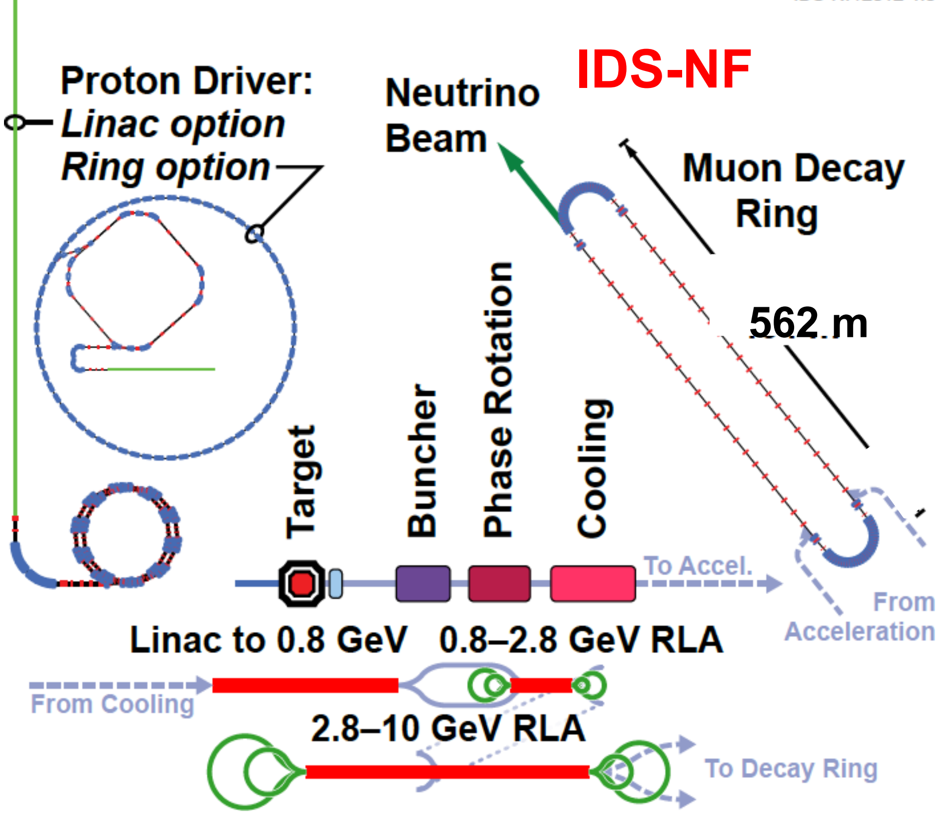
Outline

- From Neutrino Factory to Muon Collider
- Introduction to MICE experiment
- Emittance cooling demonstration at MICE
- Conclusions

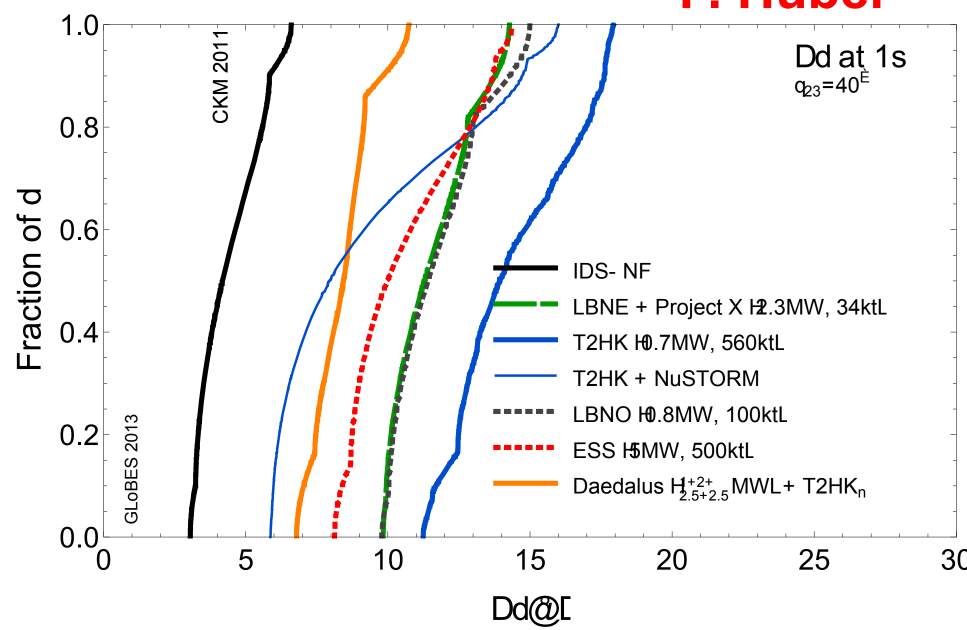
Neutrino Factory

- International Design Study for a Neutrino Factory (IDS-NF):
  - Most sensitive facility for the study of CP violation in neutrinos

IDS-NF/2012 4.0



P. Huber

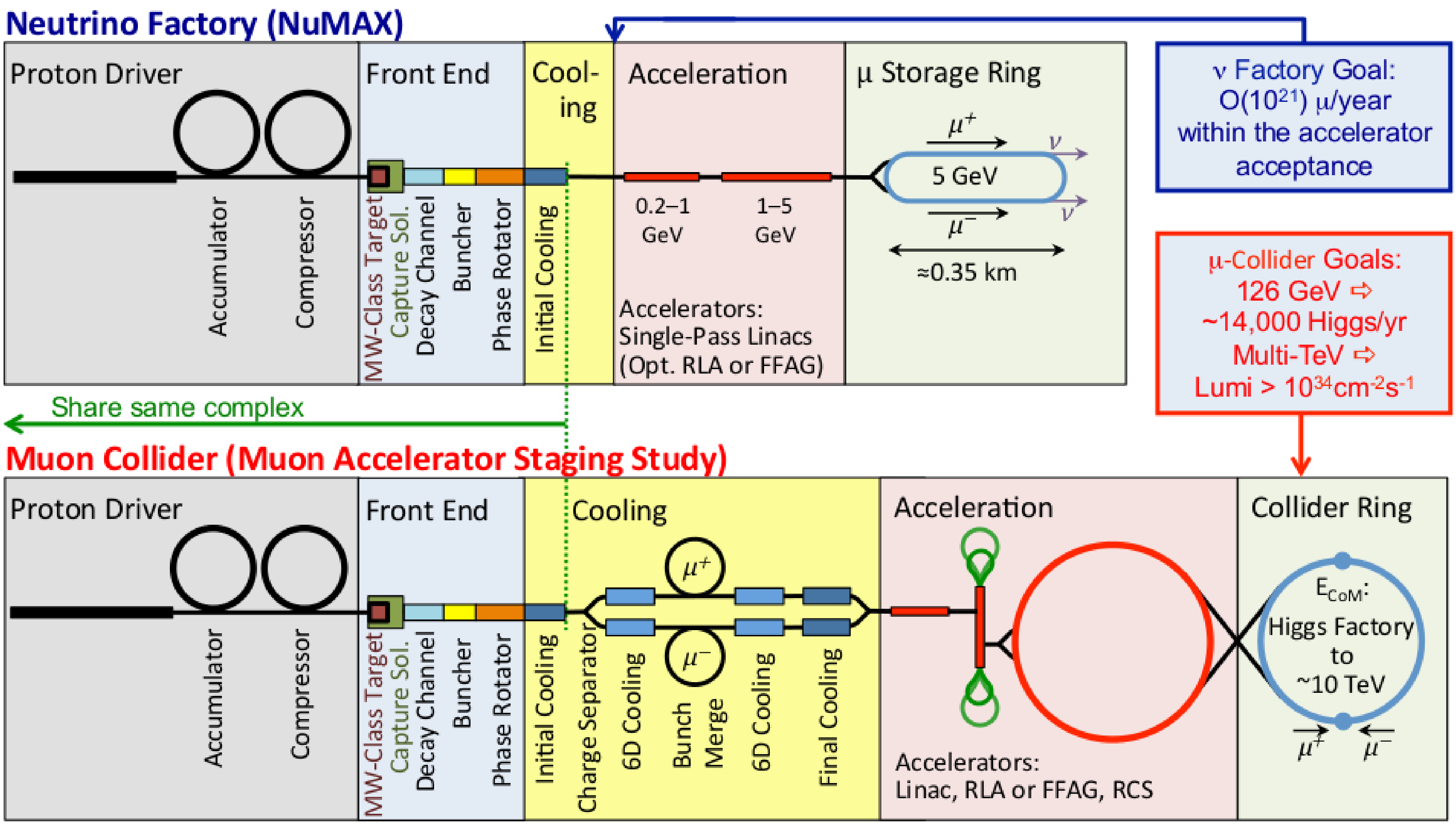


Can reach uncertainty in δ_{CP} of 5°

Test three-neutrino mixing paradigm

From Neutrino Factory to Muon Collider

- Staging of Neutrino Factory, leading to a Muon Collider, carried out within the US Muon Accelerator Programme (MAP)

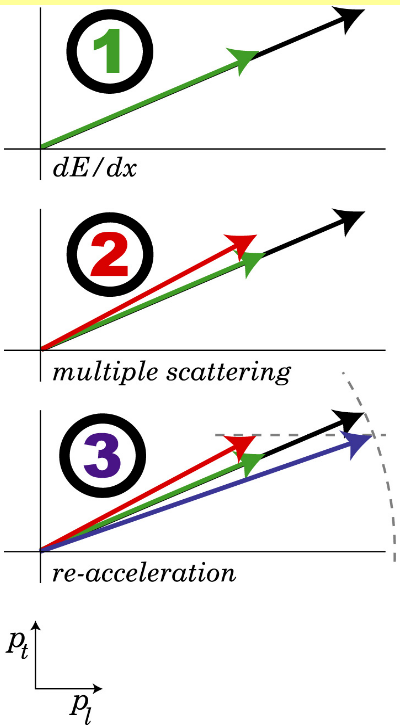


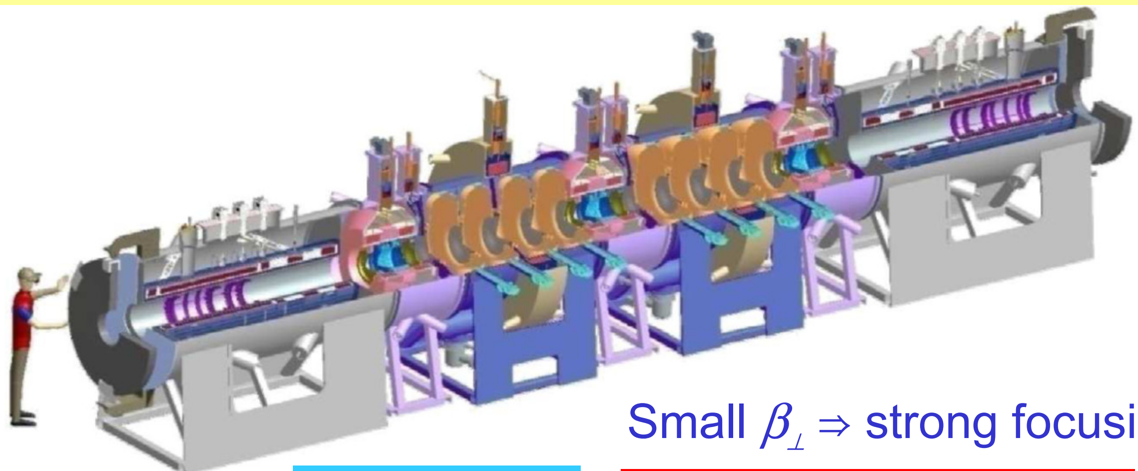
Only high energy lepton collider that can reach 10 TeV and beyond

Muon Cooling

- Muon Ionization Cooling:
  - Muon Ionization Cooling is the key technology required to be able to realise a Neutrino Factory and a Muon Collider (akin to stochastic cooling that enabled proton-antiproton collider in 1980s)

Principle	**Practice**





Small $\beta_\perp \Rightarrow$ strong focusing

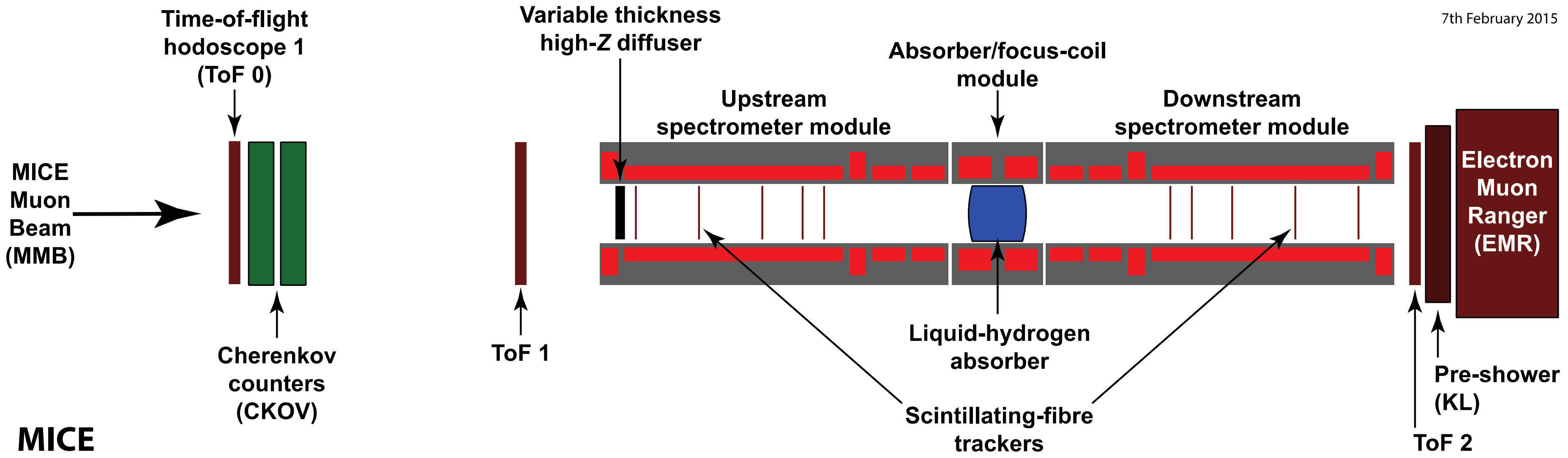
$$\frac{d\varepsilon_T}{dz} \approx \quad + \quad$$

Ionization:

Multiple scattering:

Muon Ionization Cooling Experiment

- Muon Ionization Cooling Experiment:
  - Letter of Intent: **November 2001**
  - Proposal at Rutherford Appleton Laboratory (RAL): **January 2003**
  - International collaboration built muon ionization cooling experiment at RAL

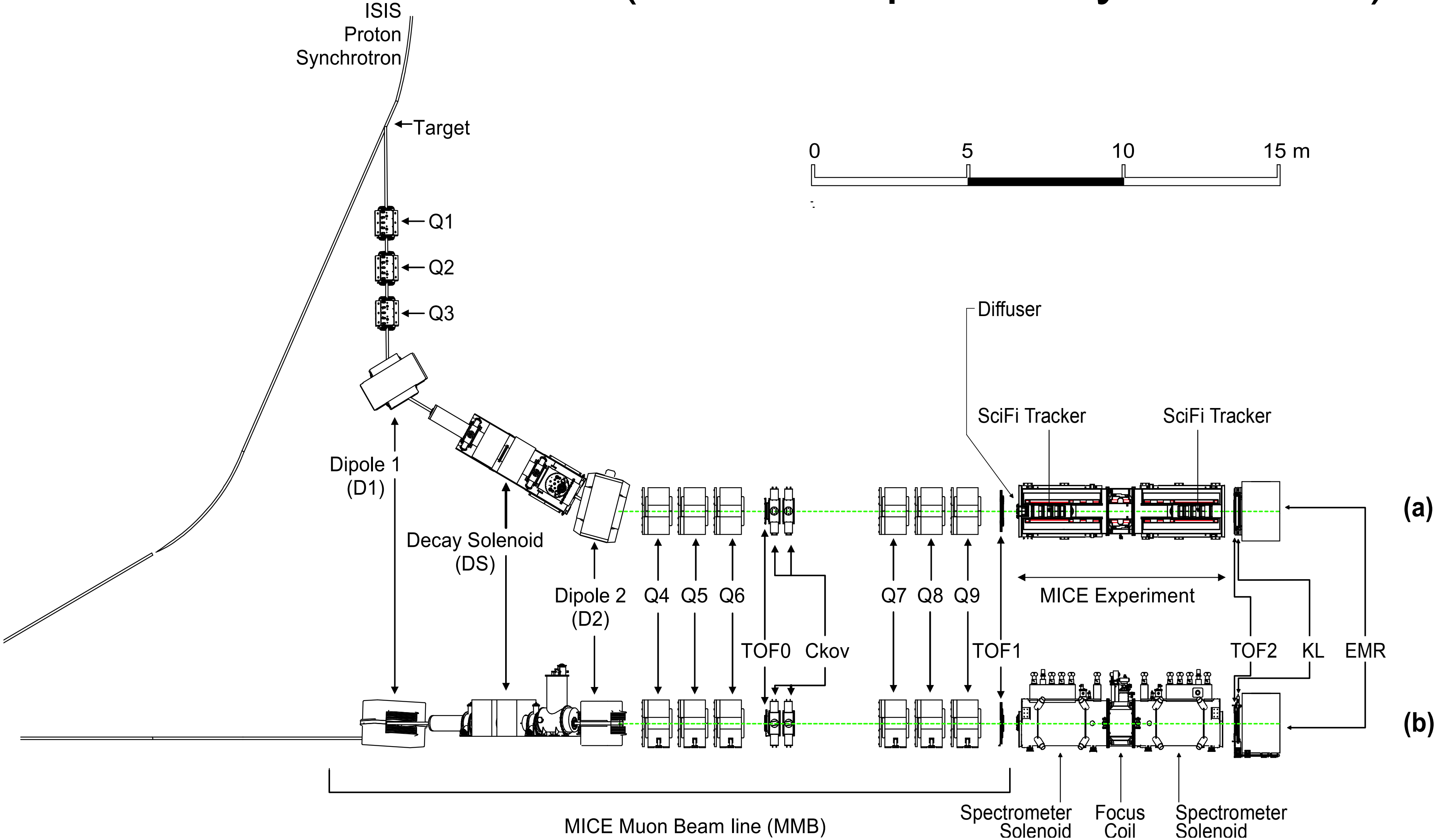


- We are extremely grateful to all the funding agencies that are contributing and have contributed to MICE
  - STFC from UK
  - NSF and DoE from USA
  - INFN in Italy, Swiss National Science Foundation, European Community, Institutional Funding in Bulgaria, Netherlands, Serbia
  - Japan Society for the Promotion of Science, Chinese Academy of Sciences, institutional funding South Korea

MICE

MICE Beam

- Muon beam from ISIS (800 MeV proton synchrotron)



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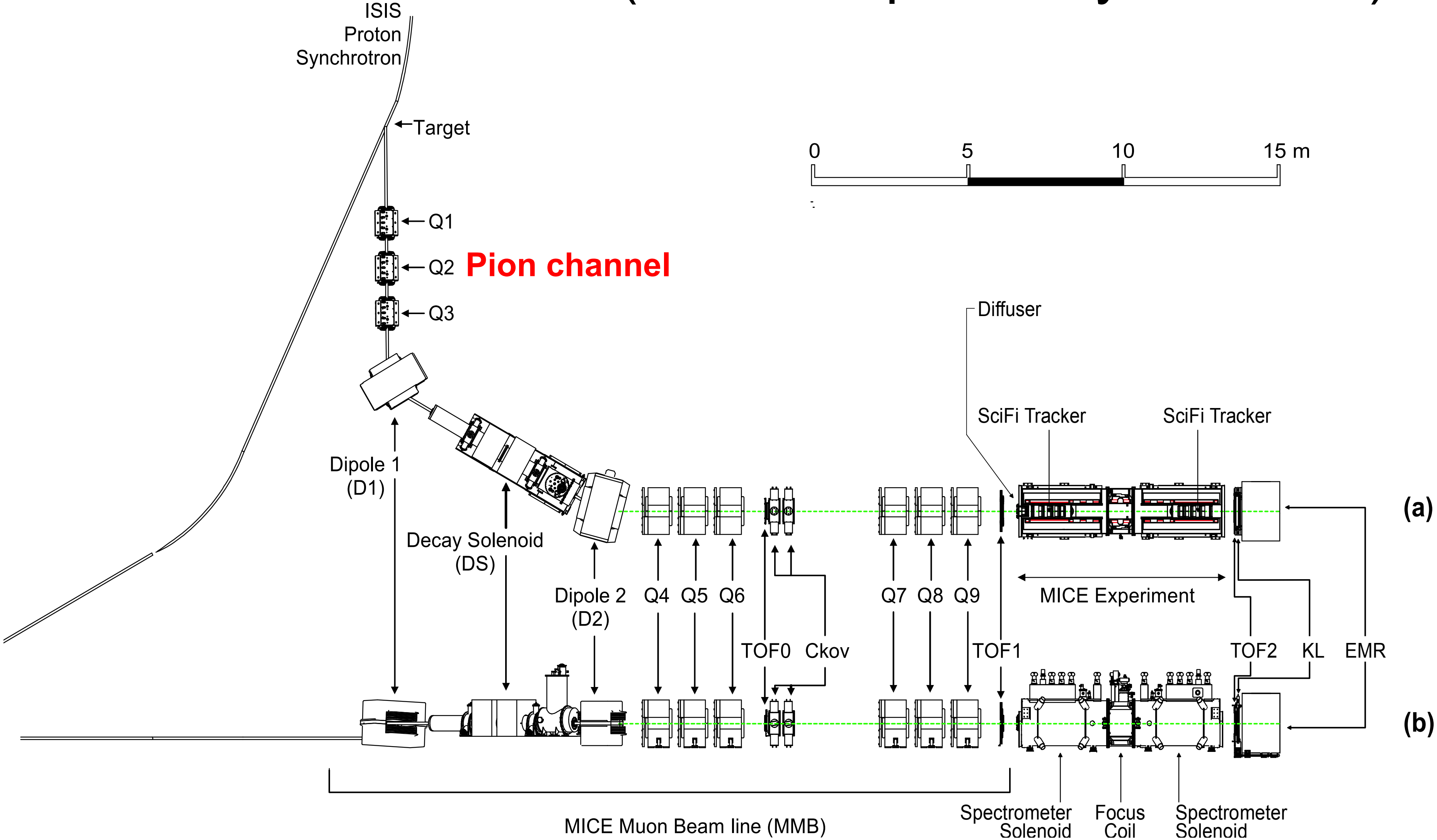

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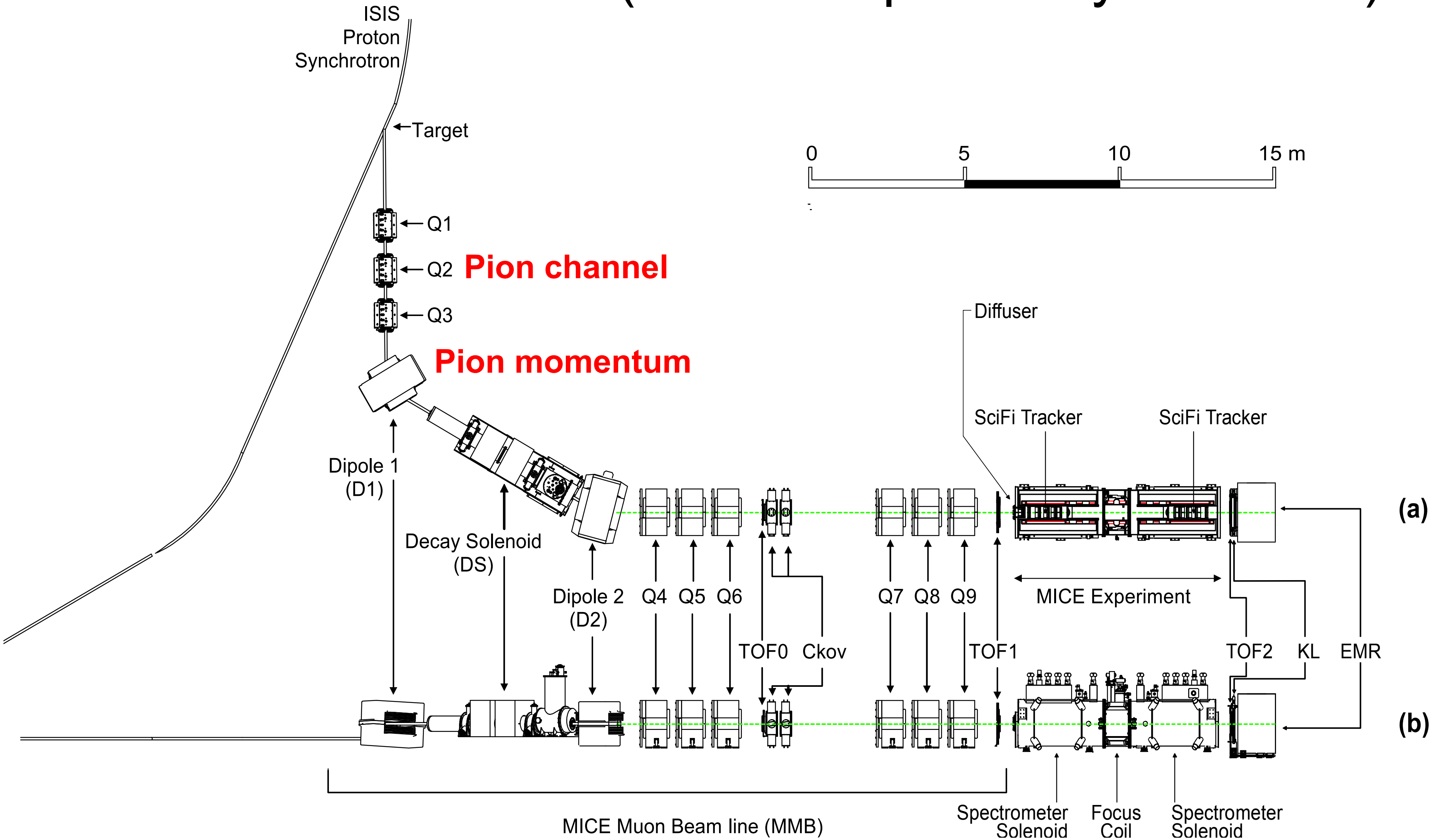

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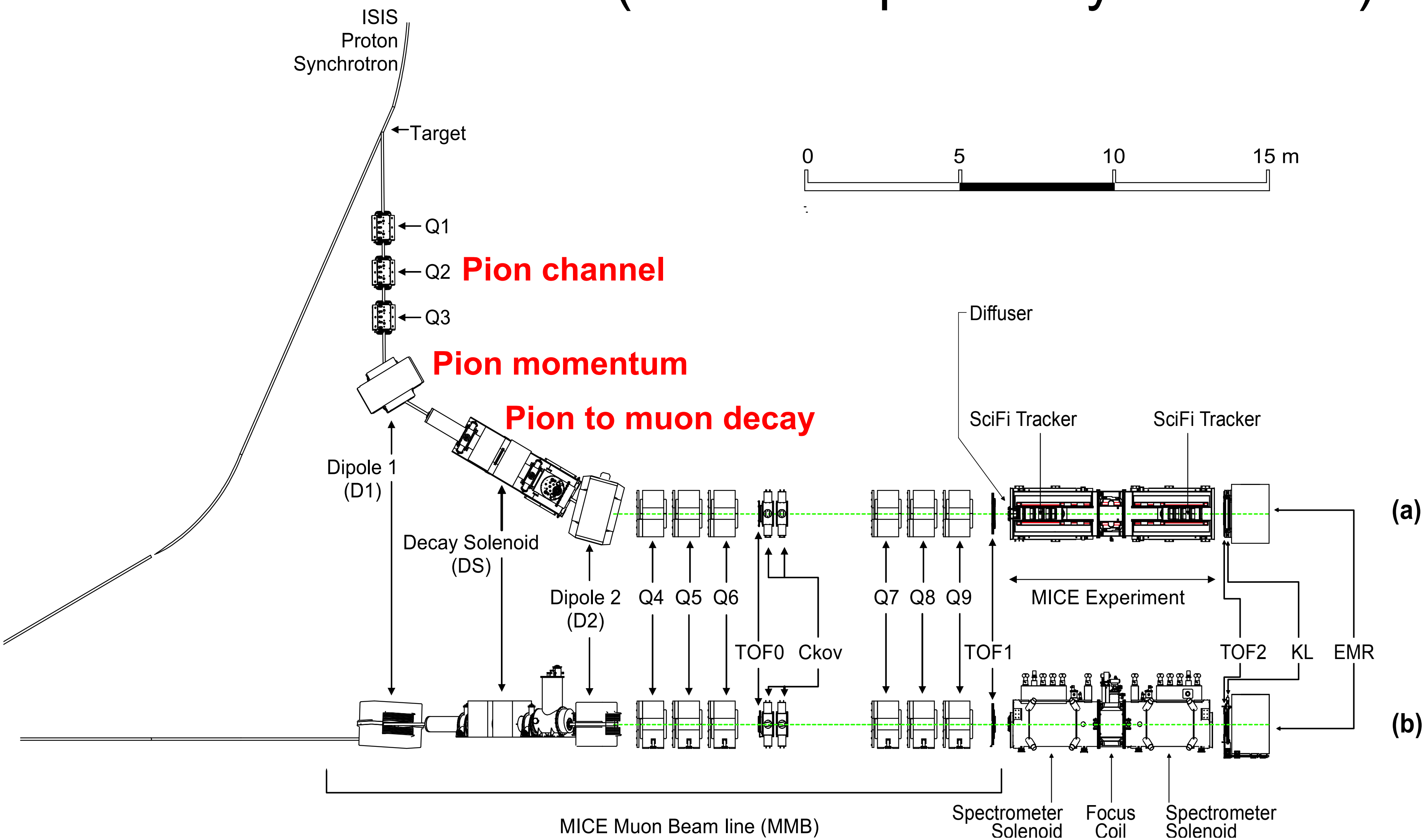

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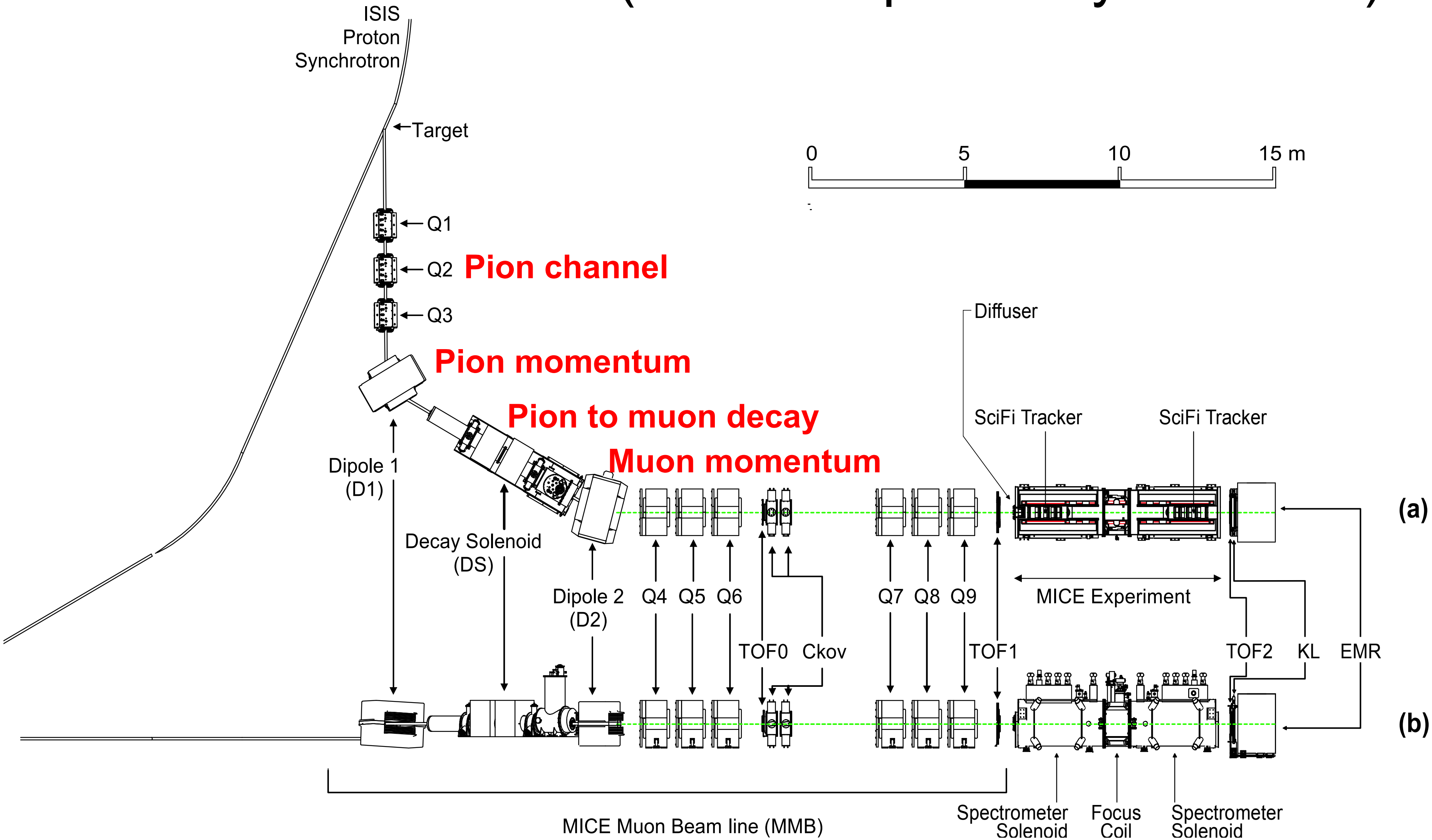

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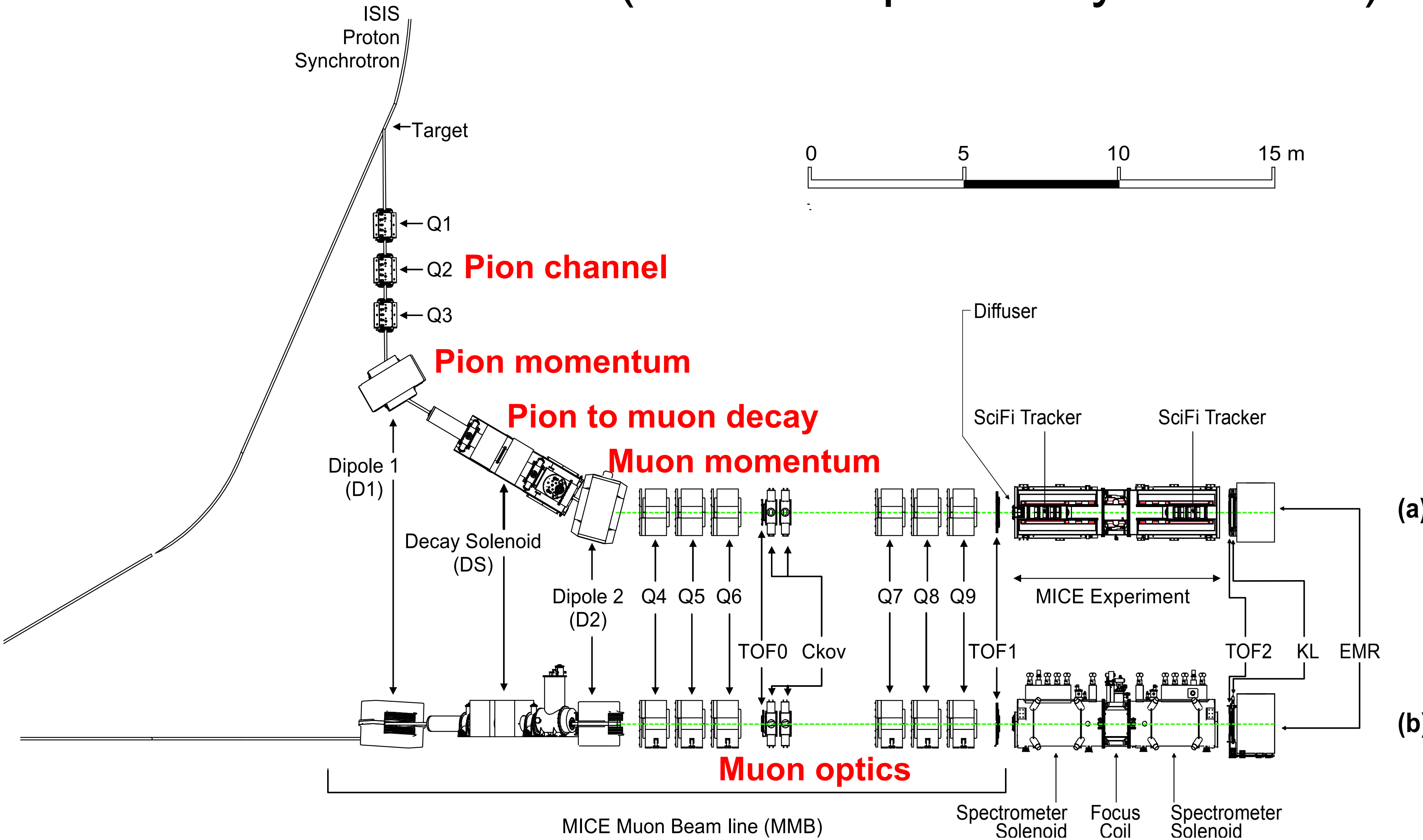

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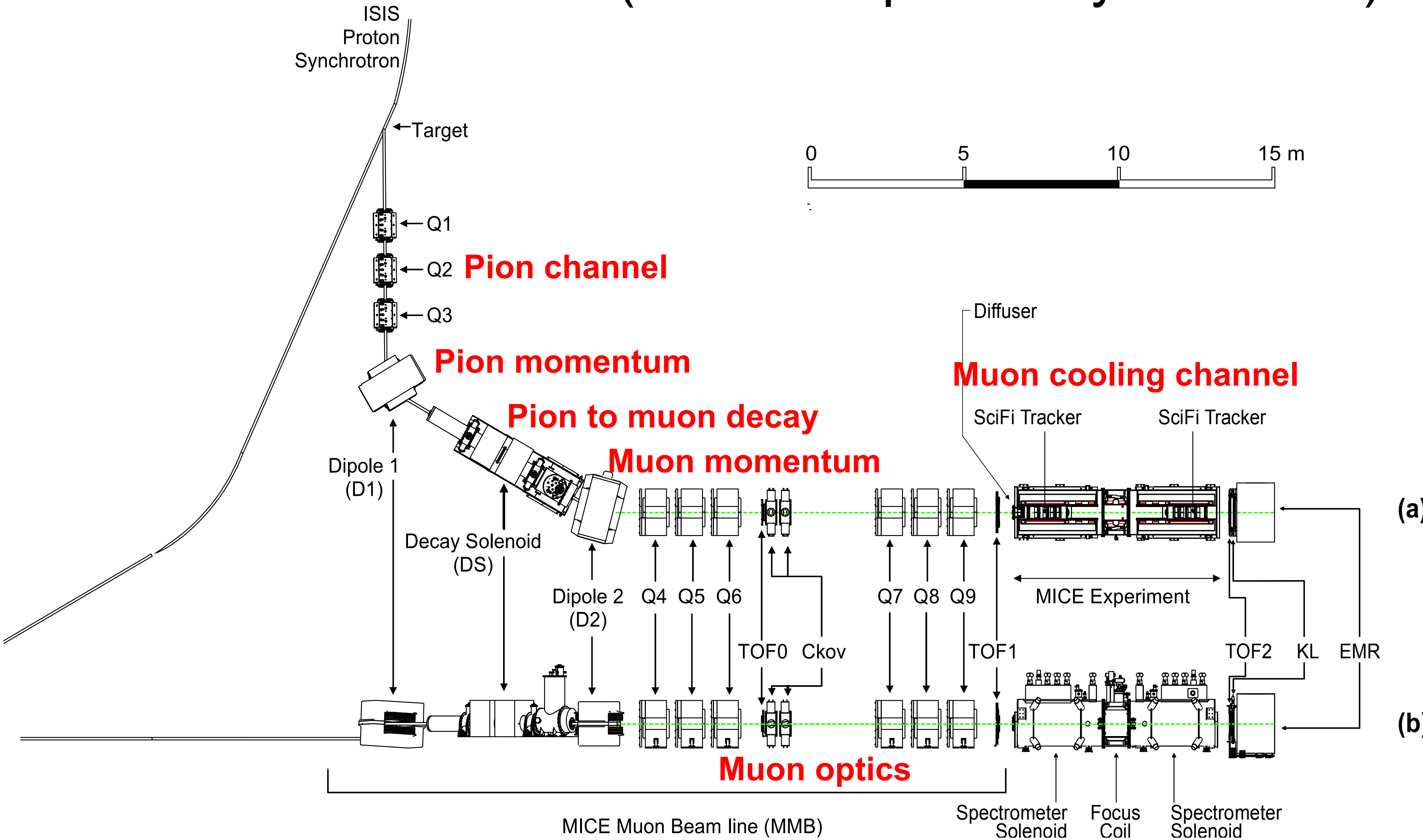
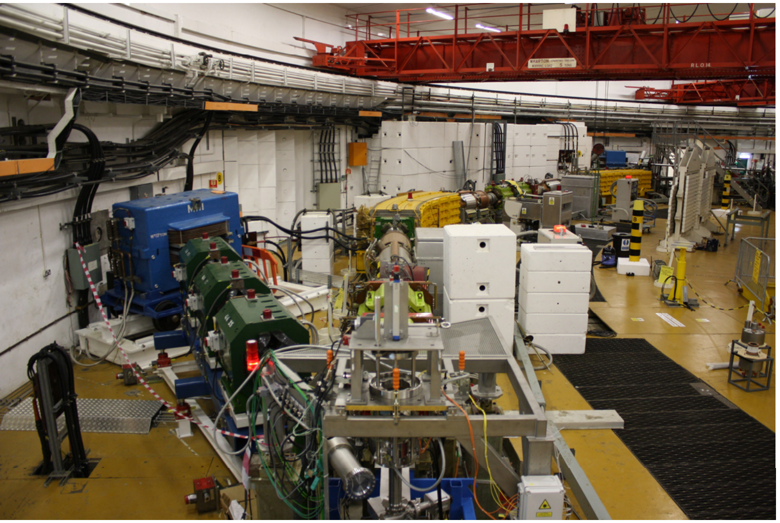


MICE Beam and detectors

- Muon beam, target, detectors and diffuser:



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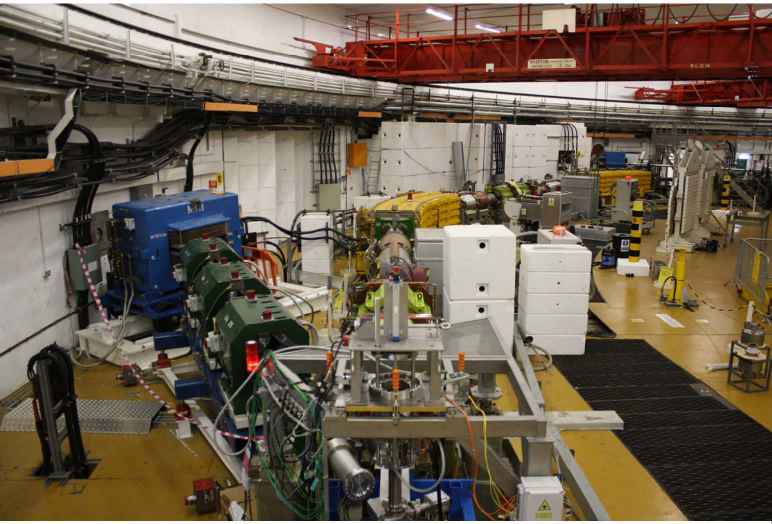

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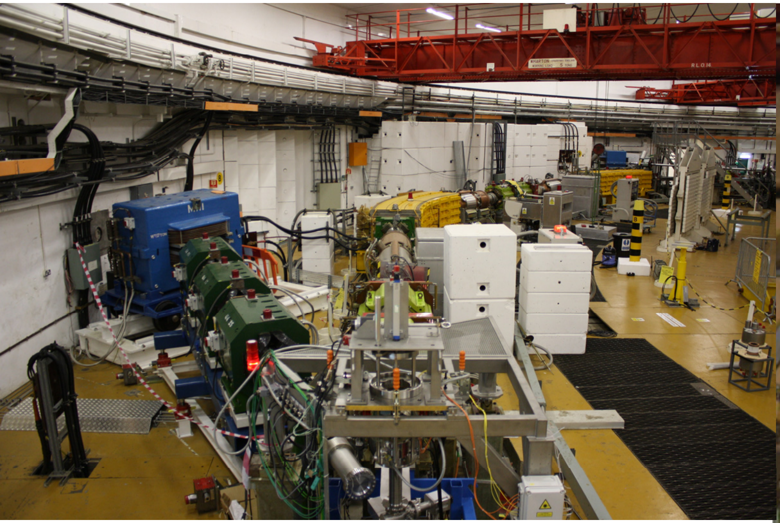

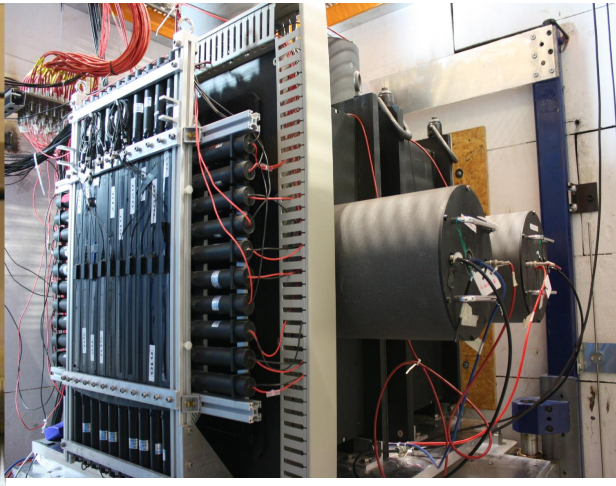

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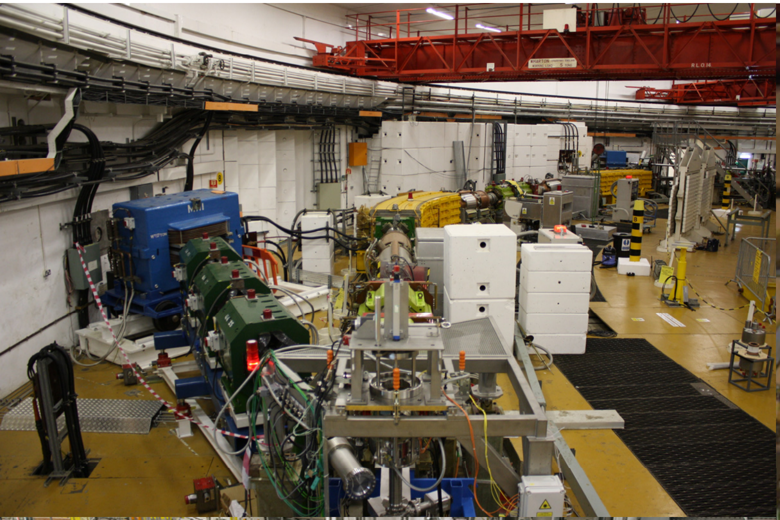

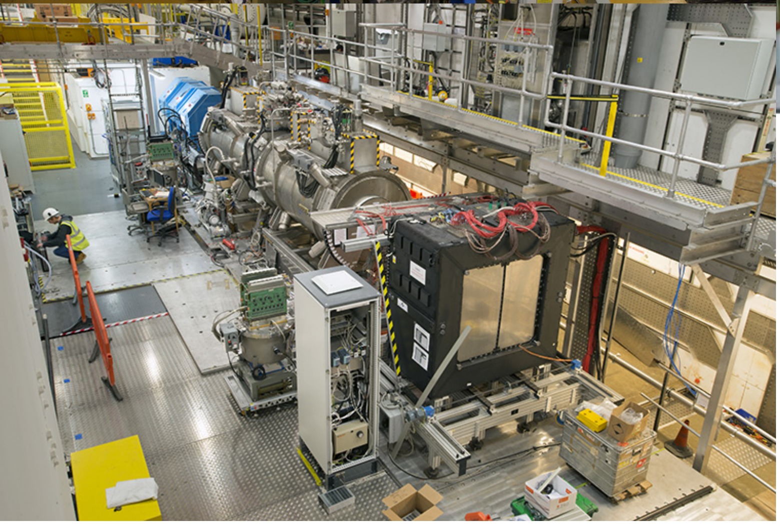

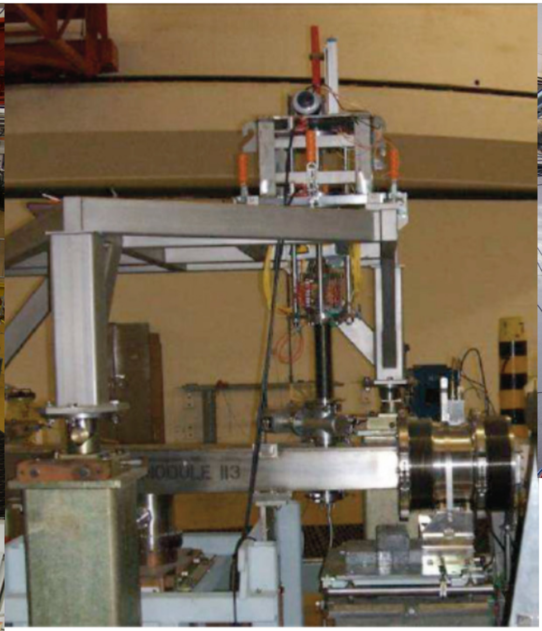

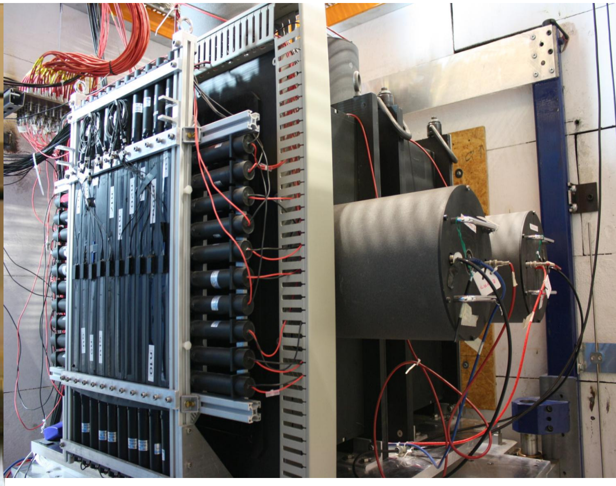

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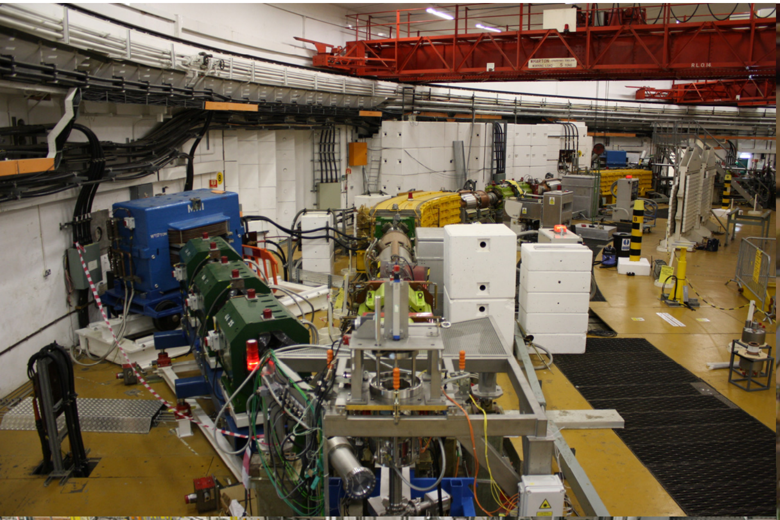

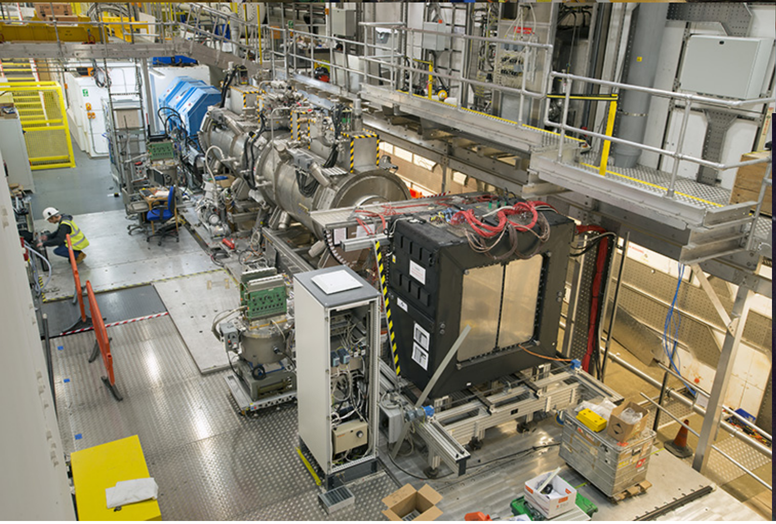

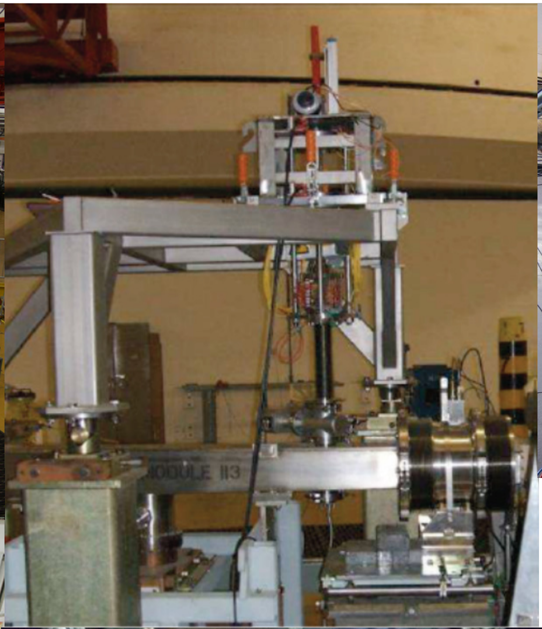

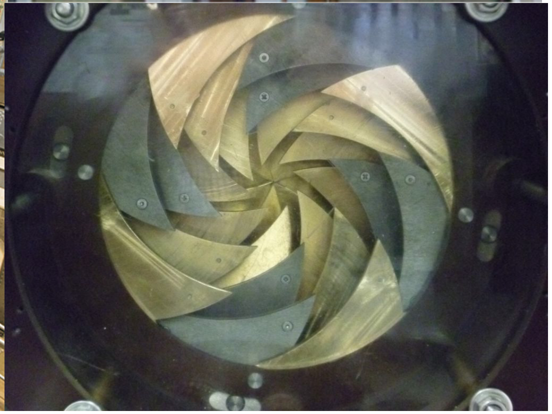

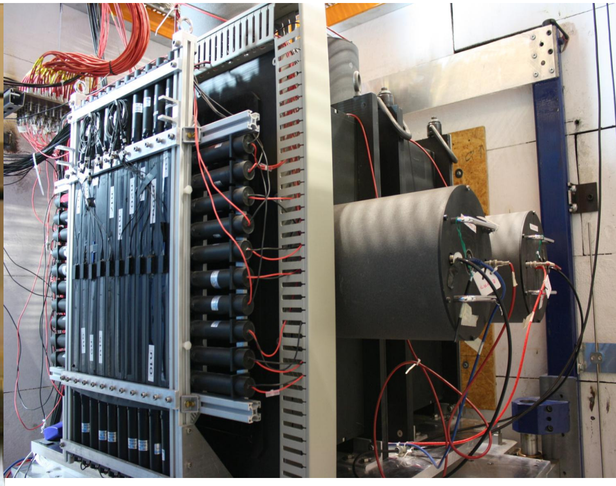

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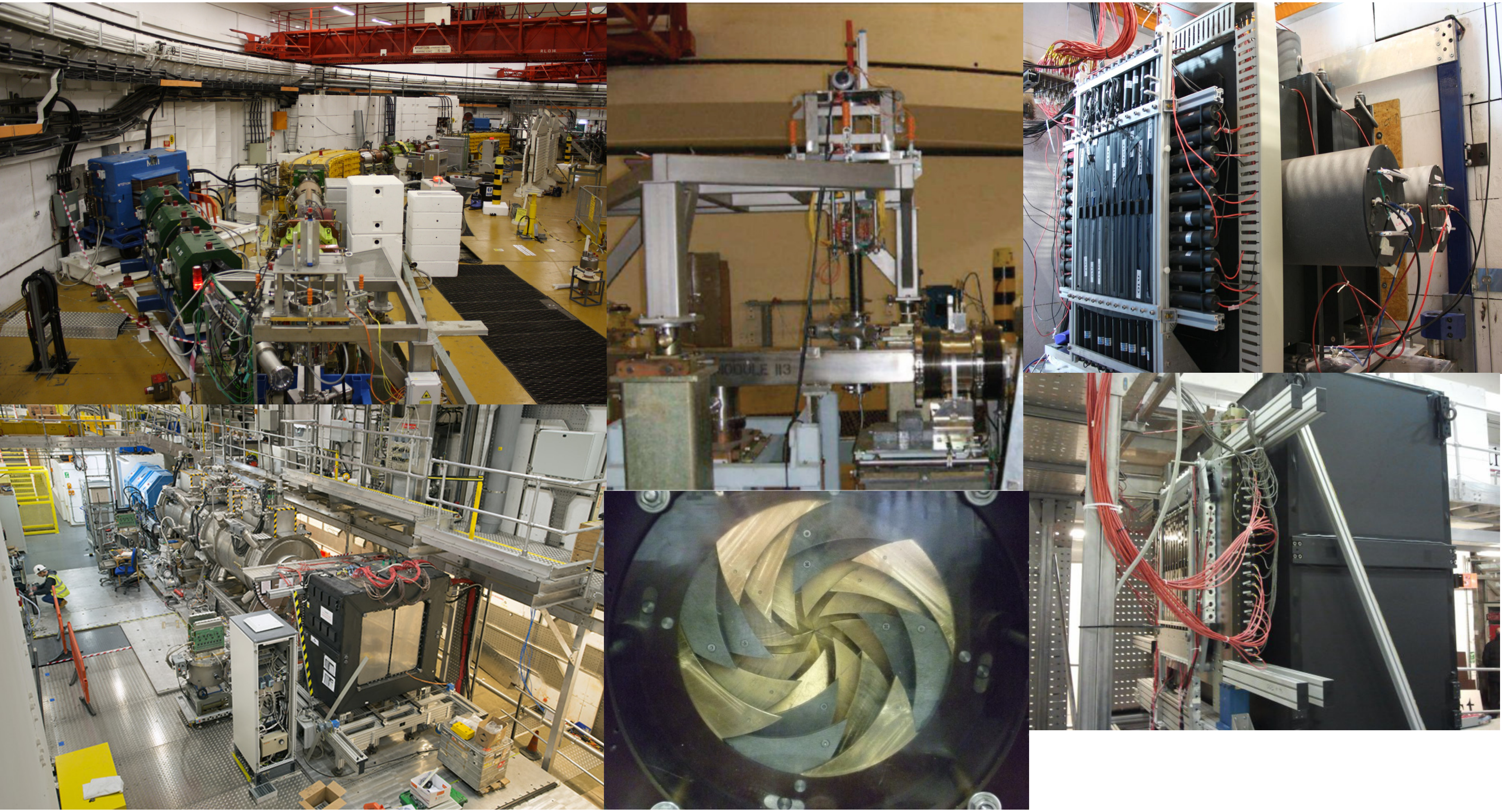
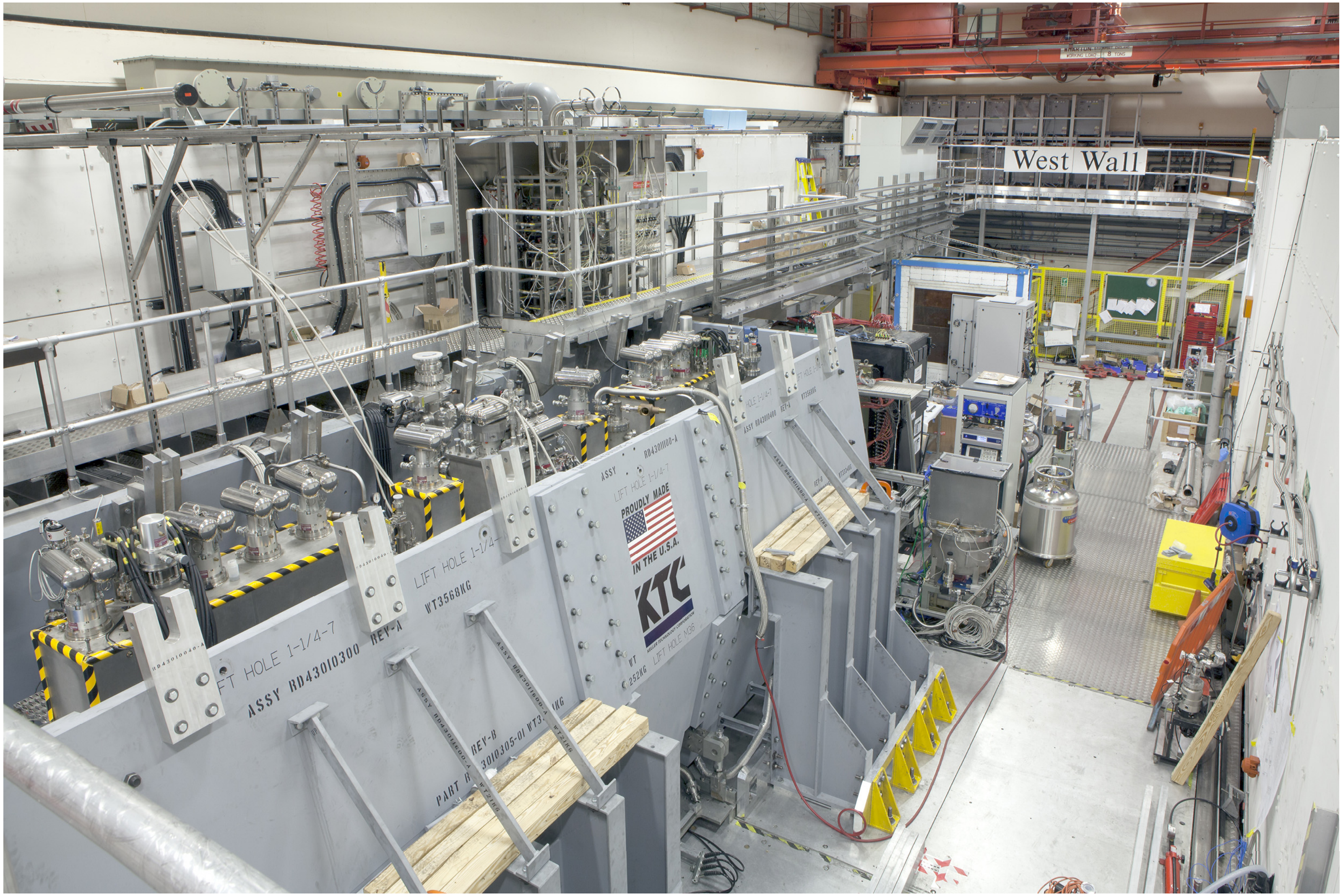


Muon Ionization Cooling Experiment

- Cooling Channel with Partial Return Yoke



MICE Science Goals

- MICE goals: make first measurement of ionization cooling and explore change of emittance as a function of:
  - Input emittance: vary beam optics and diffuser thickness
  - Absorber material: liquid hydrogen (350mm), lithium hydride (65 mm) and 45^o polyethylene wedge absorber
  - Momentum and optical beta function
- Change parameters of cooling formula to explore potential cooling performance of future facilities in detail

$$\frac{d\varepsilon_T}{dz} \approx -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2mc^2\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

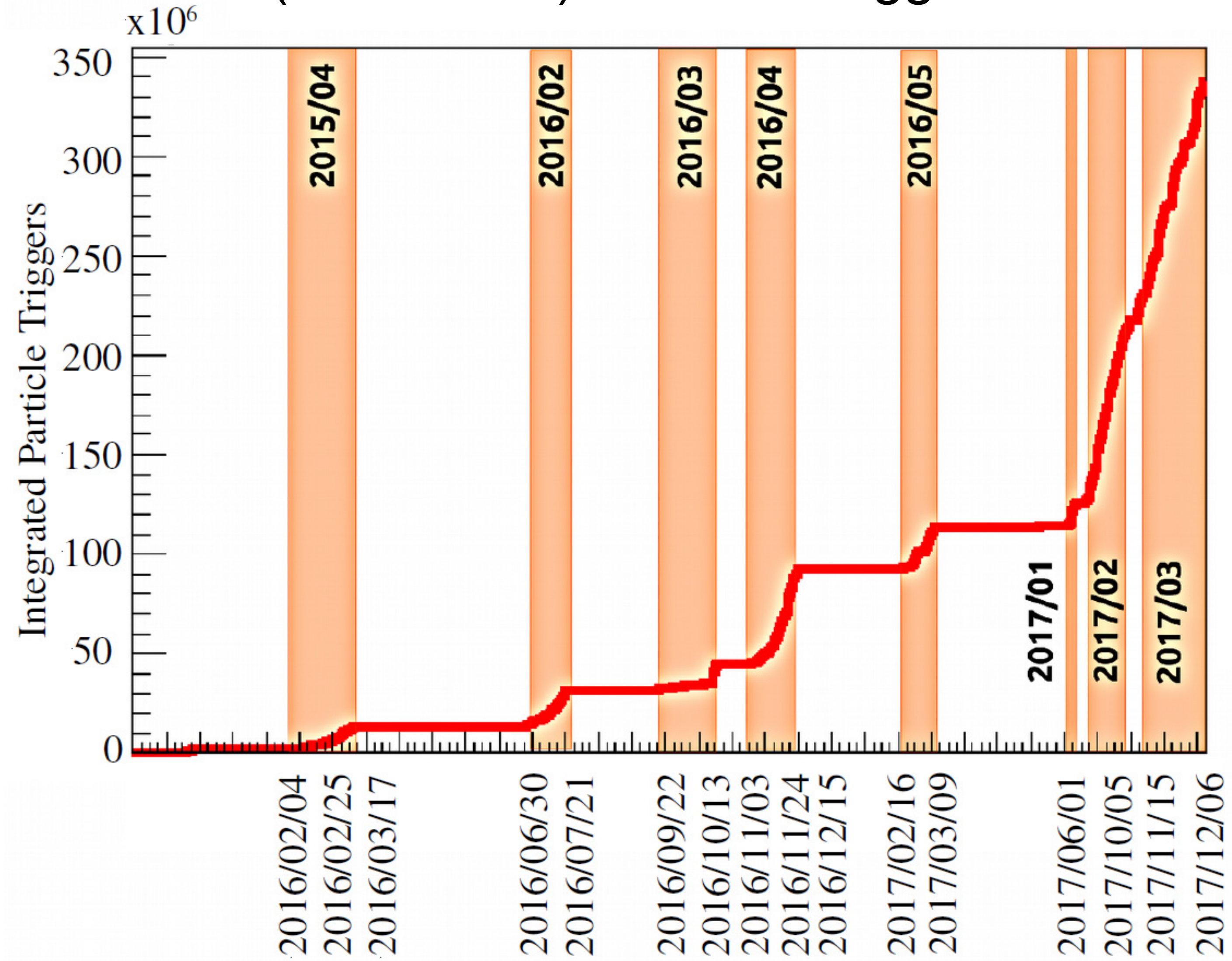
ε_T = 3 mm, 6 mm, 10 mm

$X_0(LH_2)$ = 890 cm, $X_0(LiH)$ = 102 cm, $X_0(CH)$ = 47.9 cm

p_μ= 140 – 240 MeV/c

MICE Data

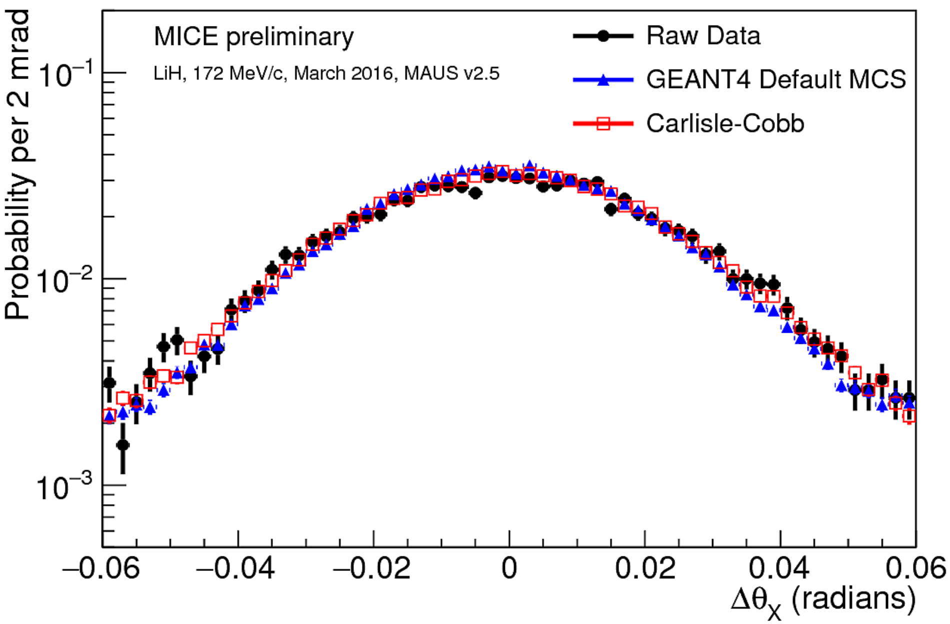
- MICE data set (2015-2017): 350x10^6 triggers

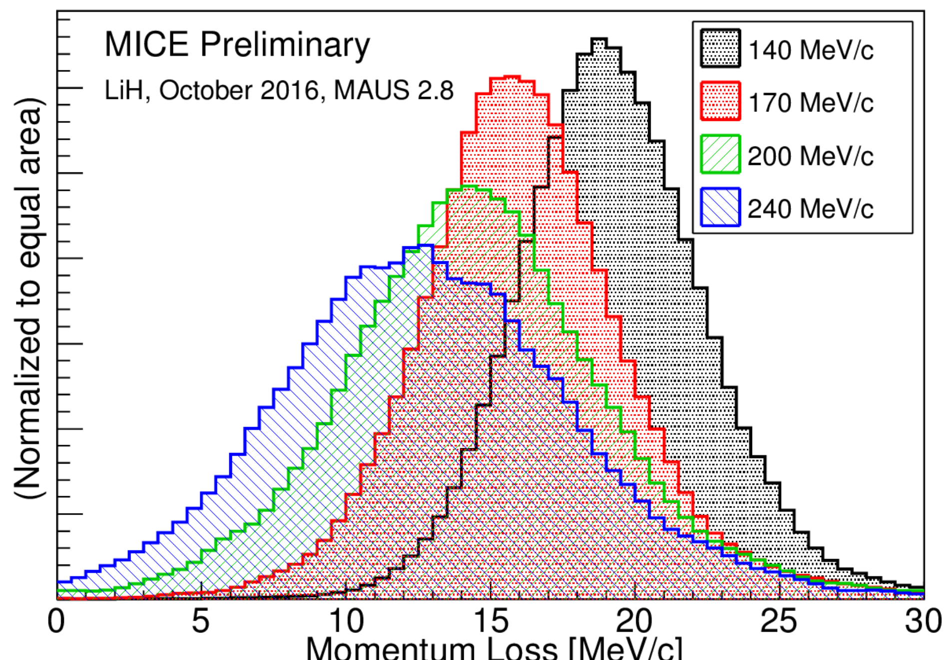


Multiple Coulomb Scattering

- First measurement of muon Multiple Coulomb Scattering in lithium hydride at 140-240 MeV/c:
  – Validation of Molière scattering model and Geant4

Details: poster by Tang





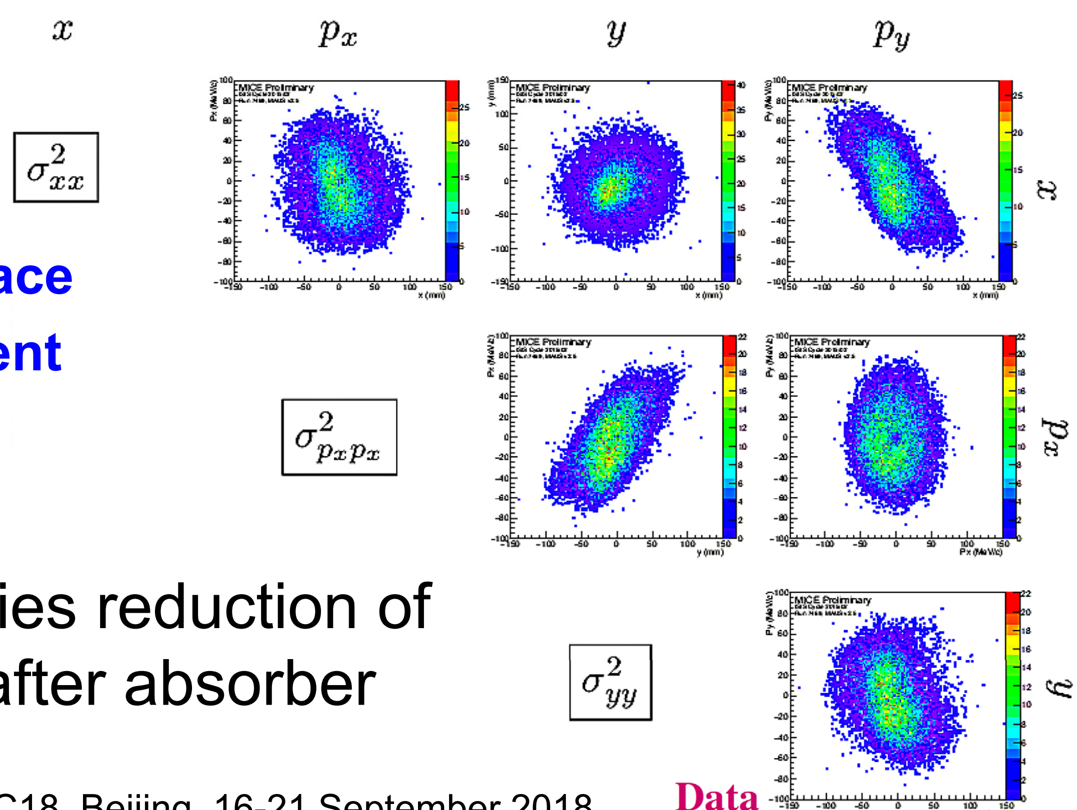
- Validation of energy loss model

Measurement of beam emittance

- Single particle reconstruction: creates virtual beams by performing ensemble of all particles
- 4D-phase space of particles: (x, p_x, y, p_y)
- Normalised RMS transverse emittance: $\varepsilon_T = \frac{\sqrt[4]{|\Sigma_{4D}|}}{mc}$ 4D covariance matrix: Σ_{4D}

Ellipsoid containing 4D phase-space RMS volume

Reconstructed phase space shows coupling of different variables for emittance calculation

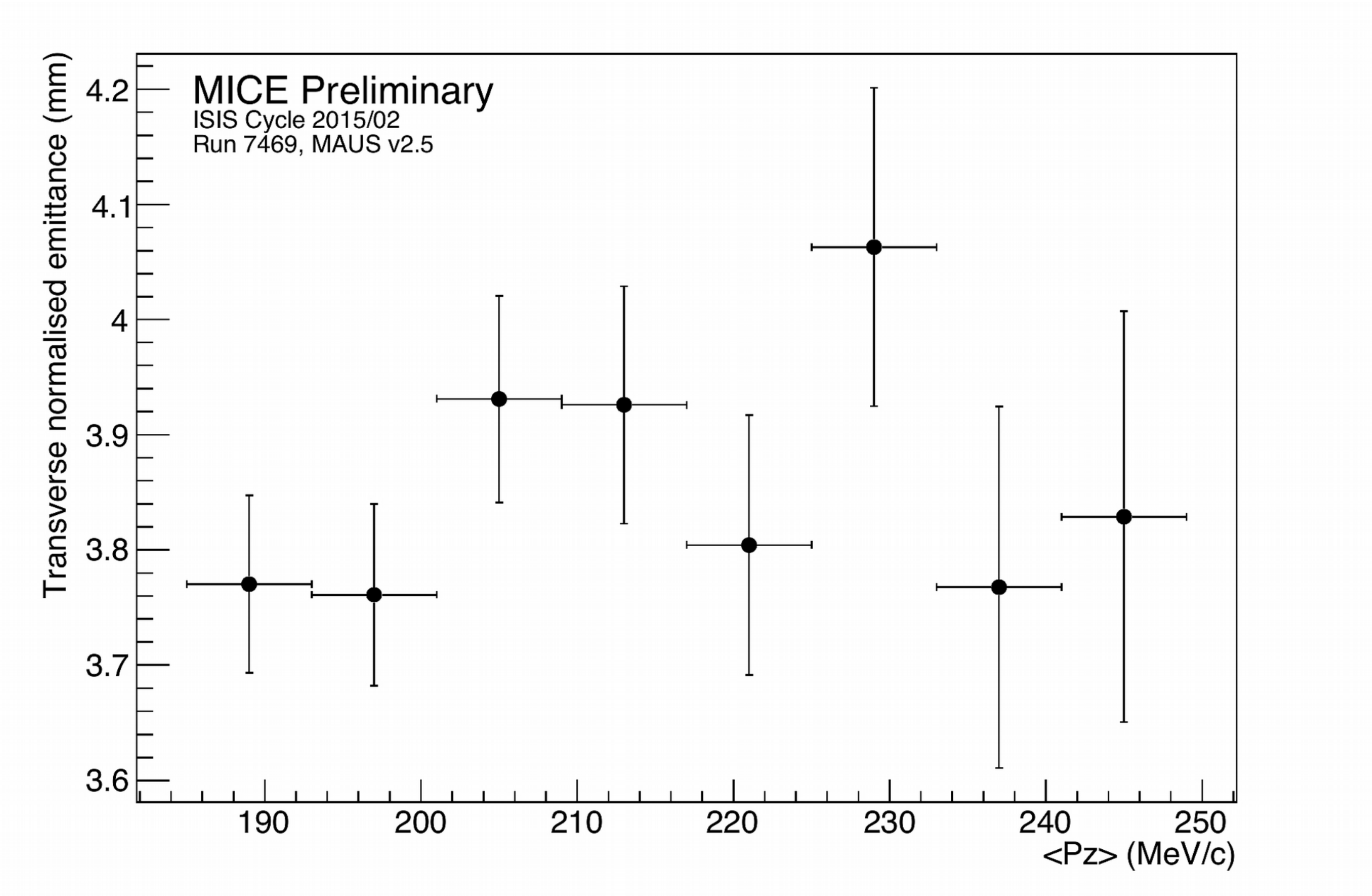


- Ionization cooling implies reduction of transverse emittance after absorber

Details: poster by Z.H.Li

Emittance evolution

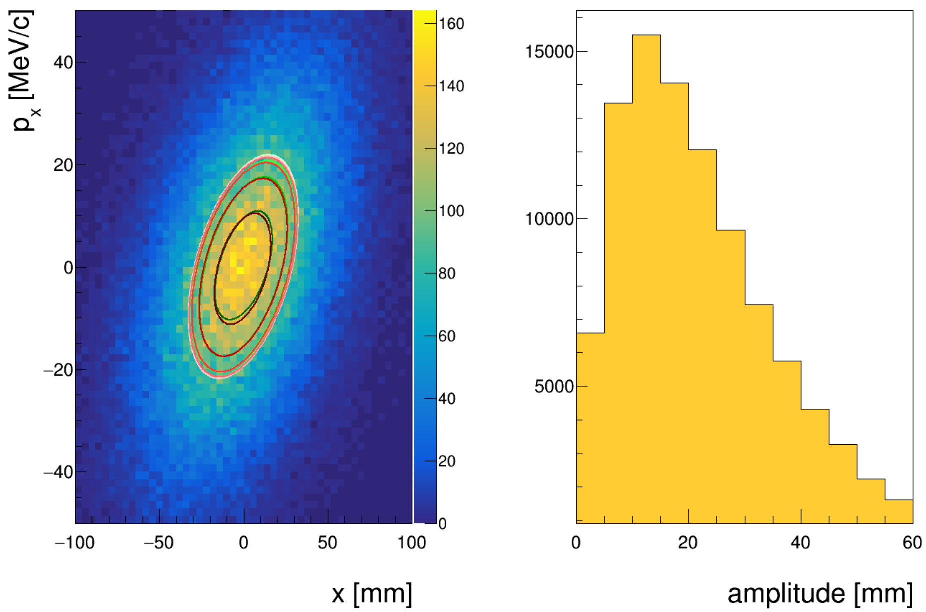
- Measurement of emittance using single-particle method:
  - MICE data shows flat emittance as function of momentum



Transverse single-particle amplitude

- Transverse single-particle amplitude:
  - Phase-space distance of muon from beam core

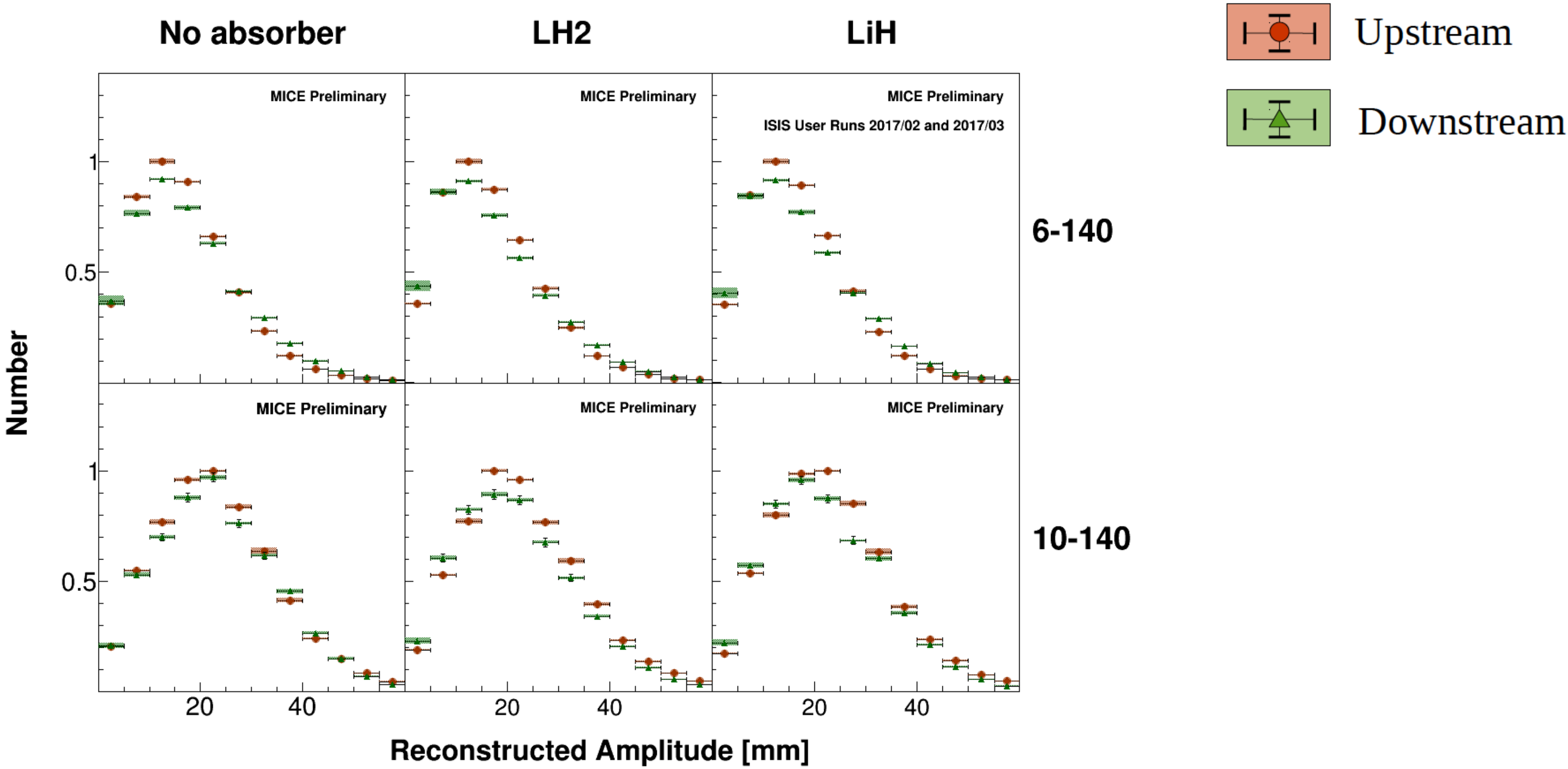
$$A_\perp = \varepsilon_T \mathbf{u}^T \Sigma^{-1} \mathbf{u} \quad \text{with} \quad \mathbf{v} = (x, p_x, y, p_y) \quad \text{and} \quad \mathbf{u} = \mathbf{v} - \langle \mathbf{v} \rangle$$



- Mean amplitude is proportional to RMS emittance
- Ionization cooling reduces amplitude in the core of the beam (higher amplitude density at low amplitudes)

Change in amplitude across absorber

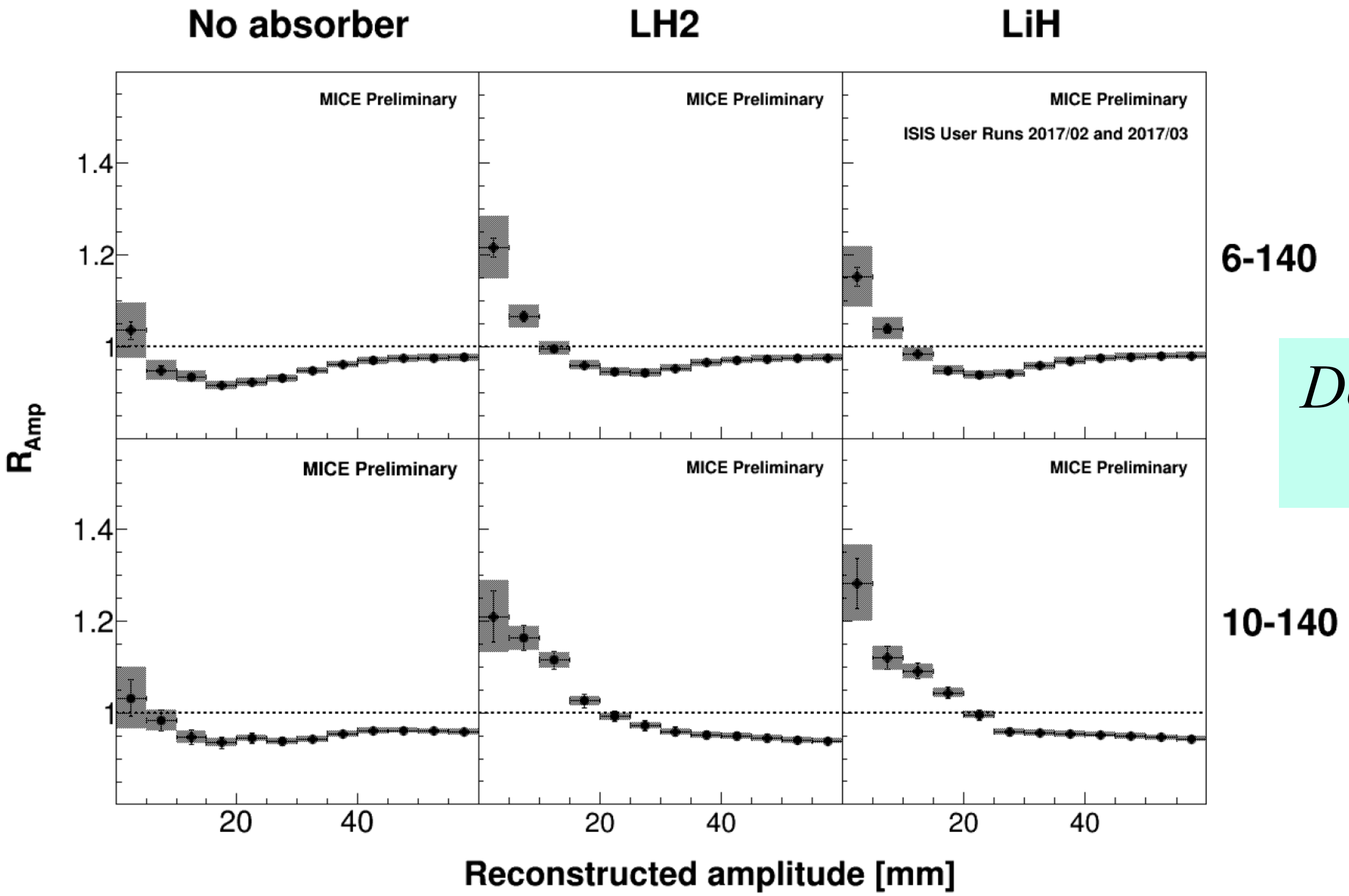
- No absorber: decrease in number of core muons
- Absorber: increase in number of core muons (cooling signal)



Ratio of cumulative core densities

- Cumulative core density increase for LH2 and LiH absorbers
- More cooling (R_{Amp}>1) at higher input emittances

$$R^N_{Amp} \equiv \frac{\sum_{n=1}^{N} A_n^{down}}{\sum_{n=1}^{N} A_n^{up}}$$



Details: poster by W.B. Liu

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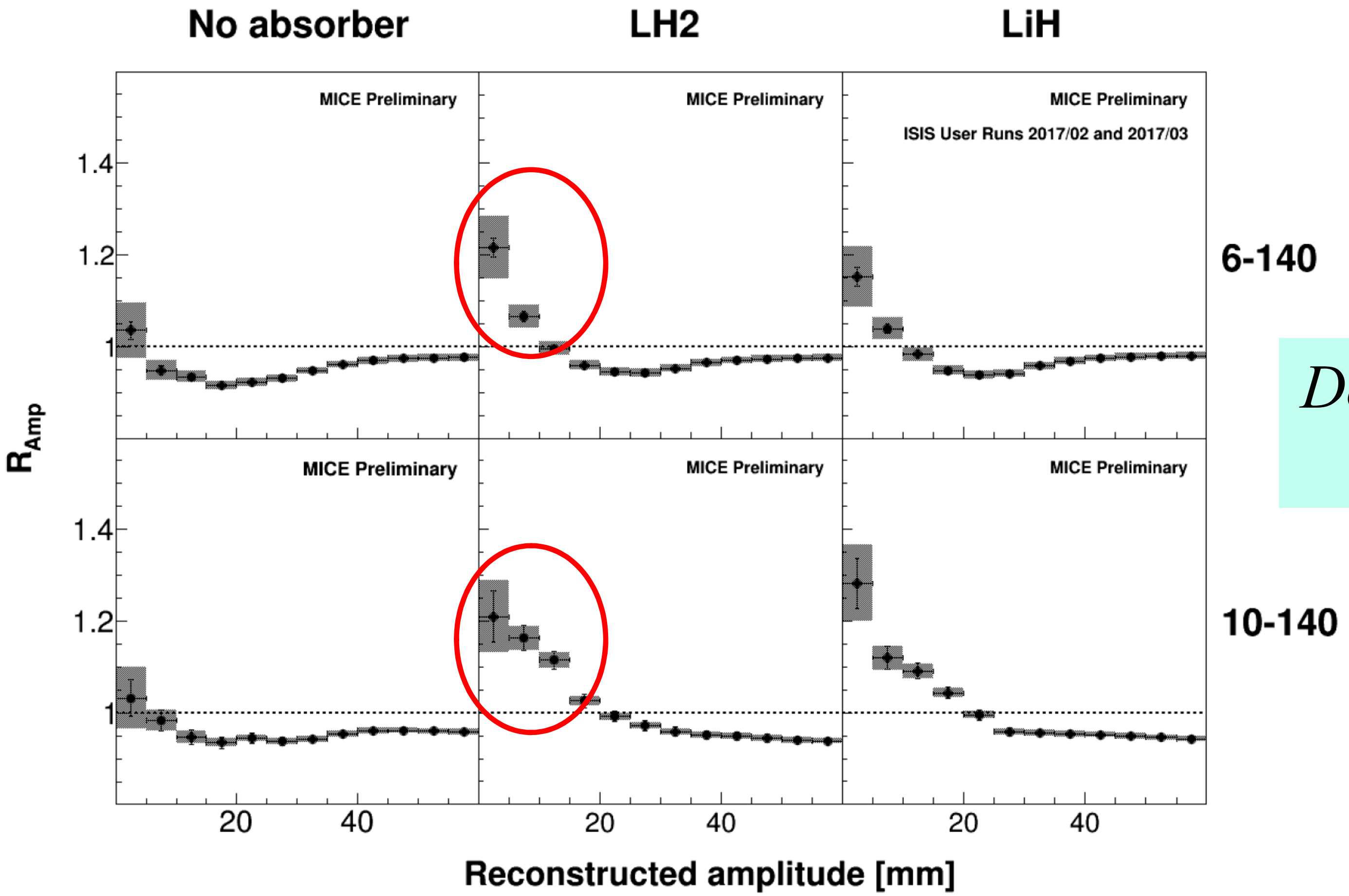

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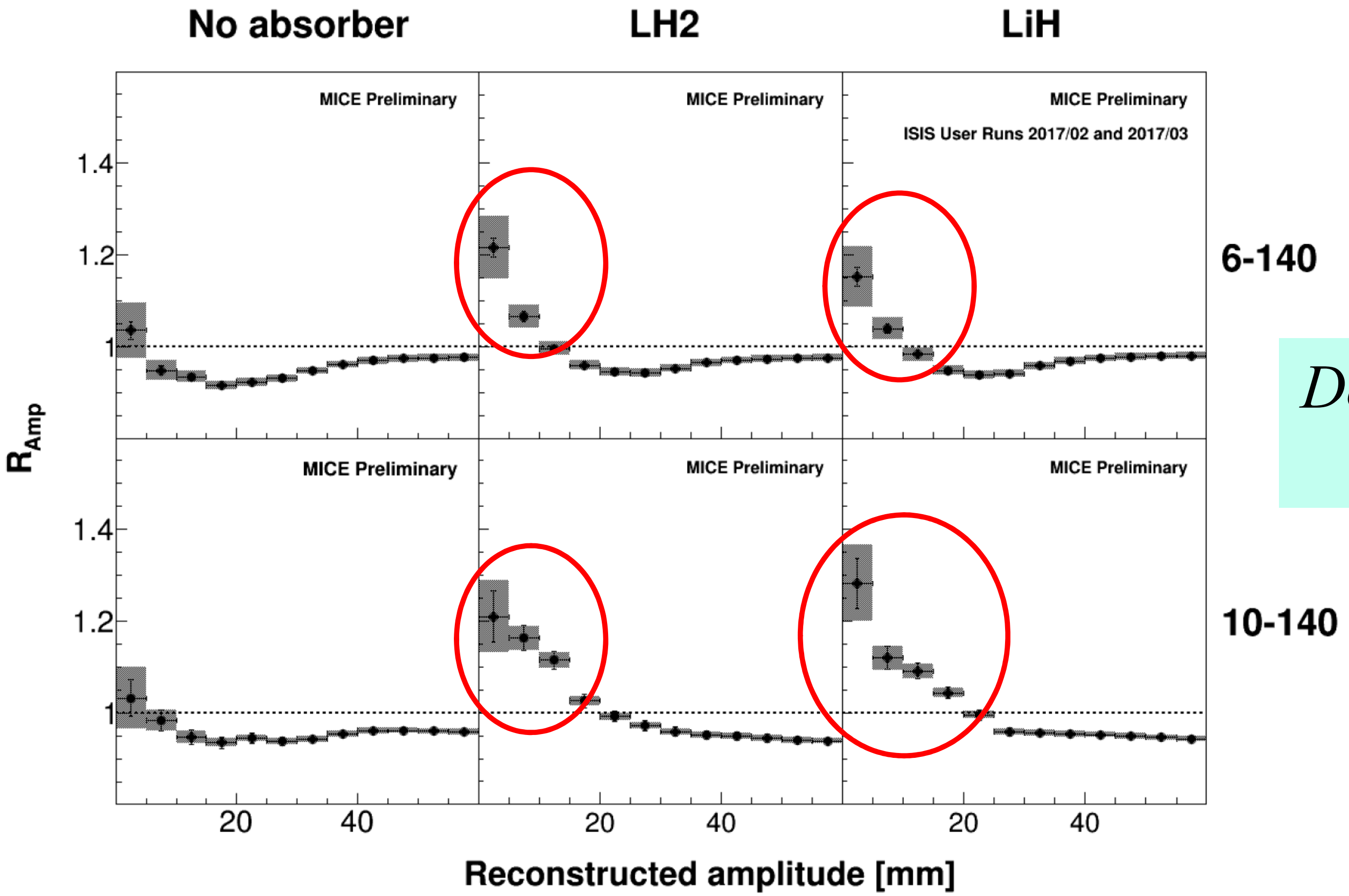

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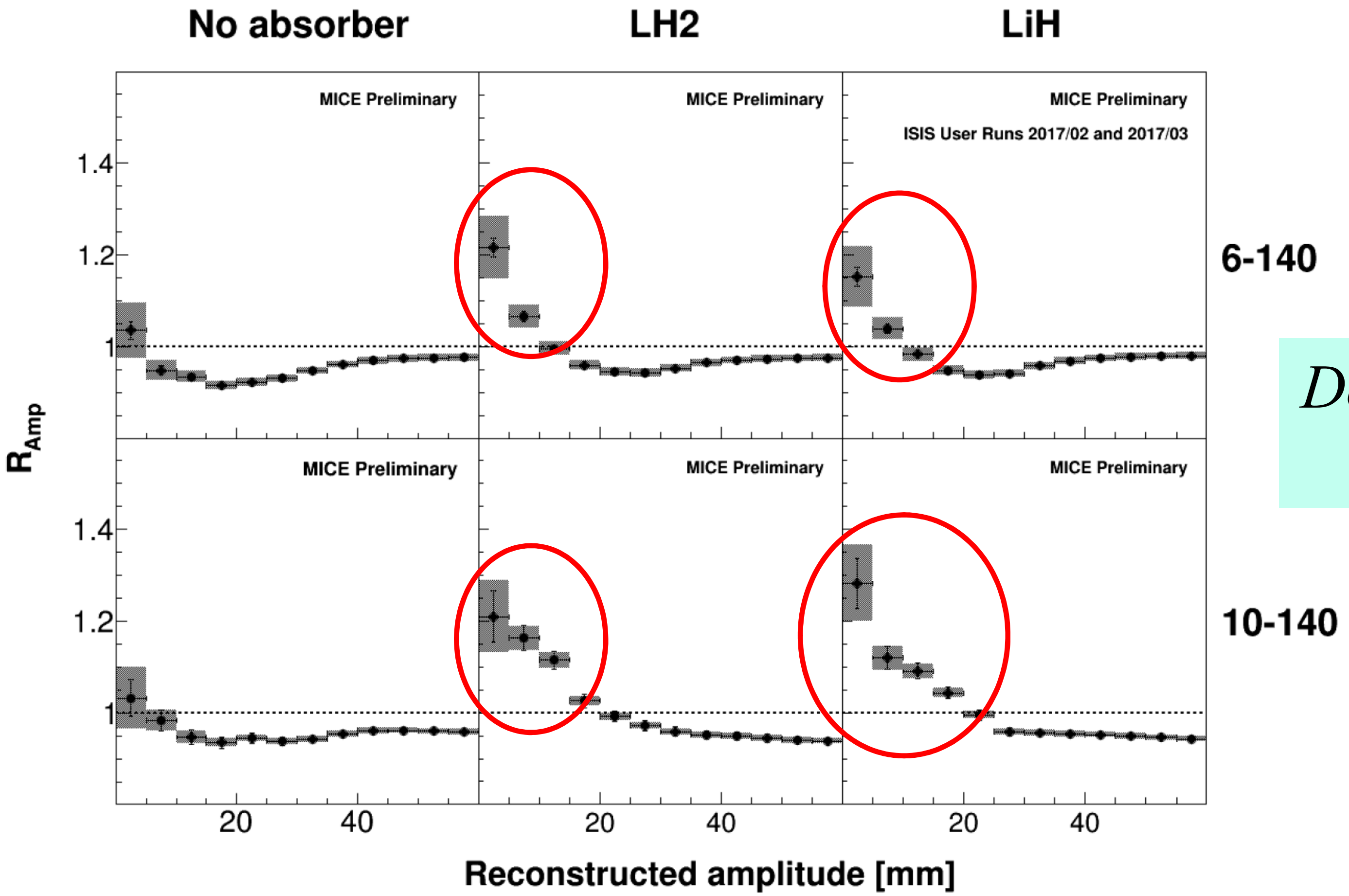

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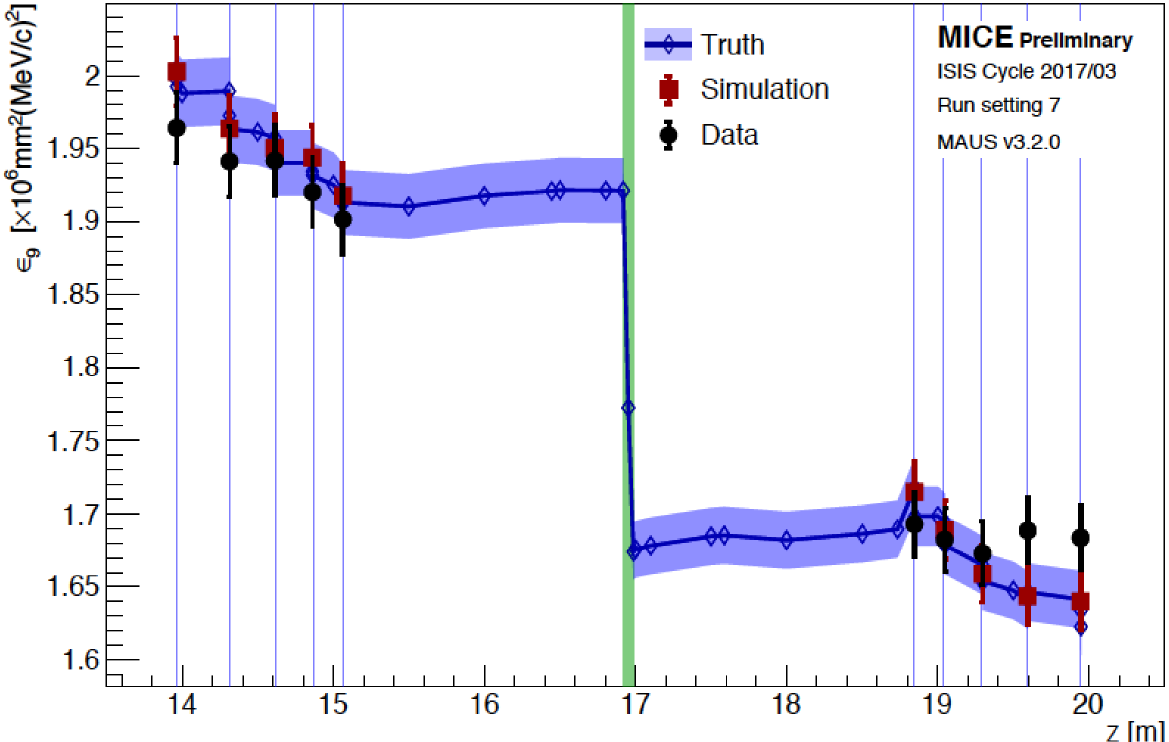
First demonstration and characterisation of ionization cooling!

Fractional emittance evolution

- Fractional emittance is phase-space volume occupied by fraction α of beam (α=9% is 1σ of 4D phase space)

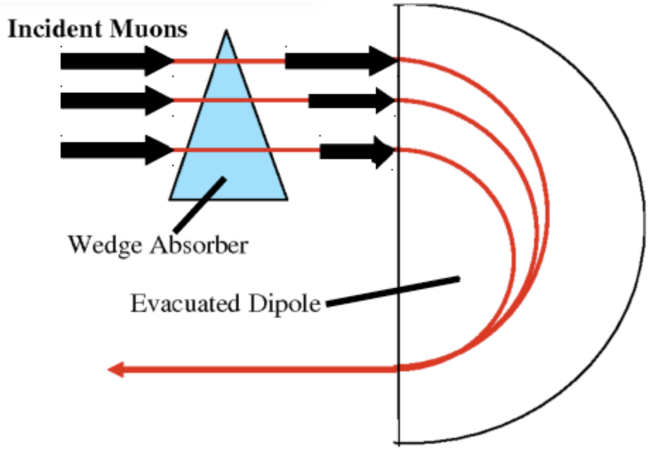
$$\varepsilon_\alpha = \frac{1}{2}\left(\pi m c \varepsilon_T\right)^2 \Rightarrow \frac{\Delta\varepsilon_\alpha}{\varepsilon_\alpha} \approx \frac{2\Delta\varepsilon_T}{\varepsilon_T}$$

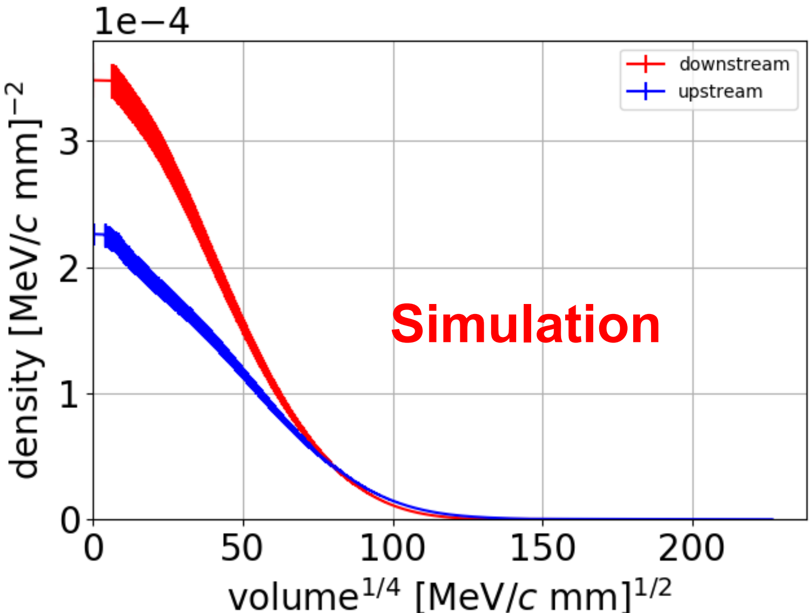
- Fractional (9%) emittance evolution 6 mm, 140 MeV/c, LiH, flip

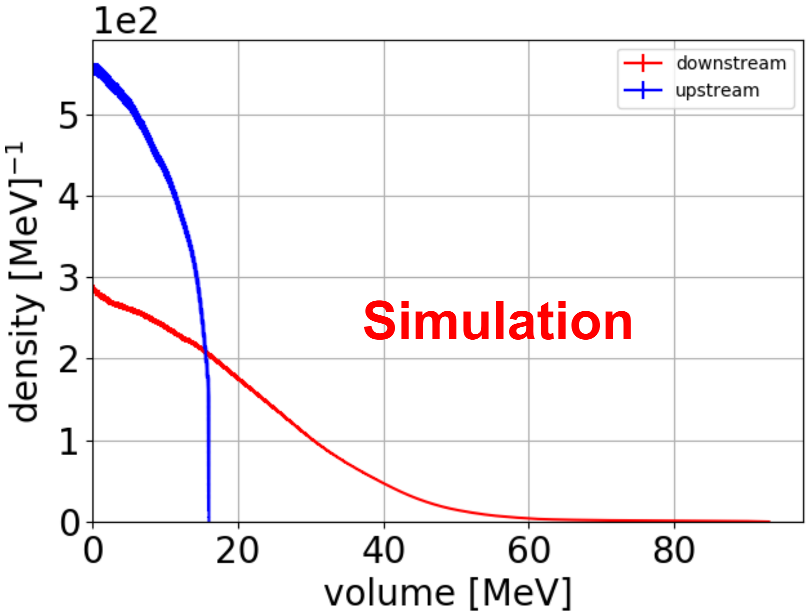


Reverse emittance exchange

- Emittance exchange: muon collider 6D cooling and g-2
- Reverse emittance exchange lengthens bunch and increases luminosity in MC
- Polyethylene wedge absorber







Reverse emittance exchange: transverse cooling and longitudinal heating

Conclusions

- The Muon Ionization Cooling Experiment (MICE) was constructed at RAL and collected 350 million triggers to fully characterise ionization cooling
- MICE is studying ionization cooling in detail: evolution transverse emittance beam amplitudes, multiple Coulomb scattering, energy loss, reverse emittance exchange

July 2018

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MICE has demonstrated ionization cooling for the first time

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- All main technologies required for neutrino factory and muon collider have now been demonstrated: ionization cooling (MICE), liquid mercury target (MERIT), Fixed Field Alternating Gradient accelerators (EMMA)