Imperial College London

Science & Technology Facilities Council

Muon Ionization Cooling Experiment

K. Long, 2 July, 2018

Acknowledgements

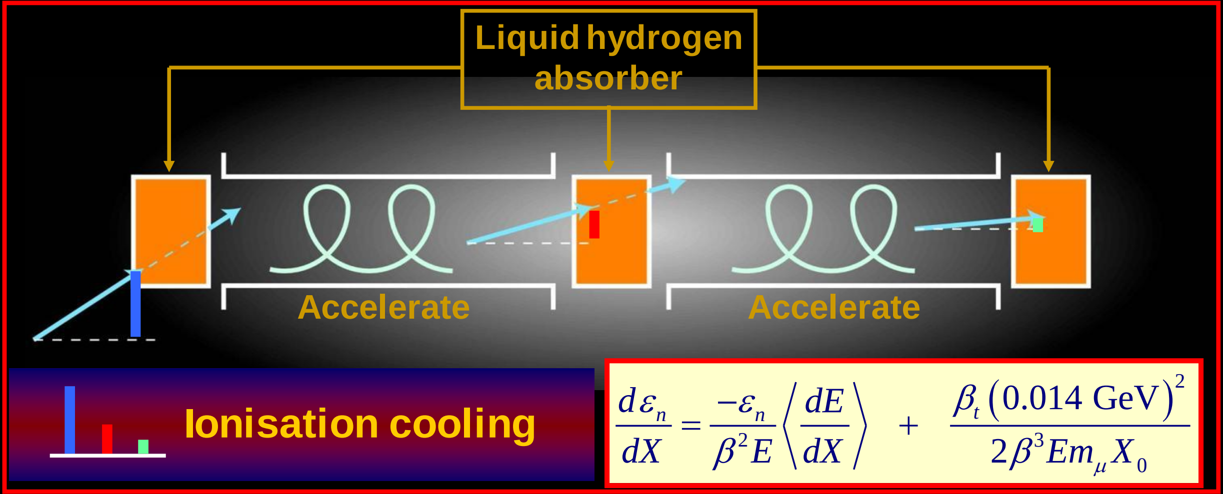
MICE collaboration …

and the many friends and colleagues who have provided material

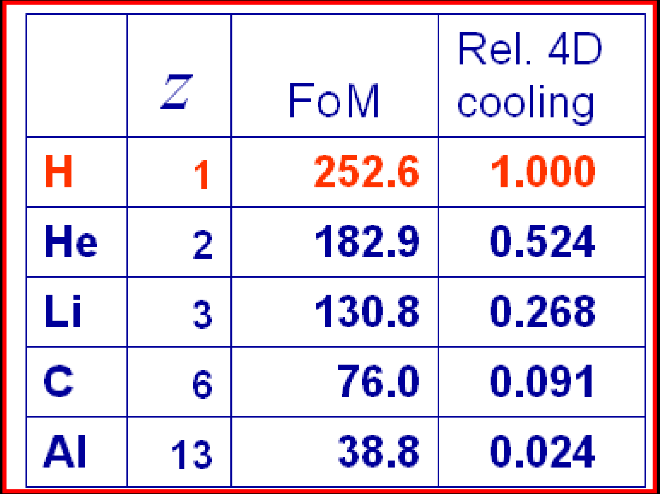
Contents

- Ionization cooling and MICE
- MICE study of ionization cooling
- Going forward
- Conclusions

The principle of ionization cooling



$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_t\left(0.014\ \text{GeV}\right)^2}{2\beta^3 E m_\mu X_0}$$



	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

- **Competition between:**
  - dE/dx [cooling]
  - MCS [heating]
- **Optimum:**
  - Low *Z*, large X_0
  - Tight focus

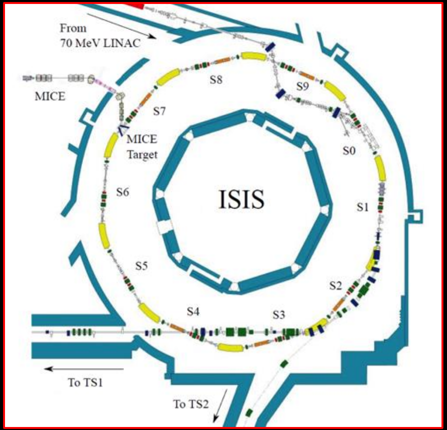
Challenge: lattice with tight focus at absorber *and* high transmistion

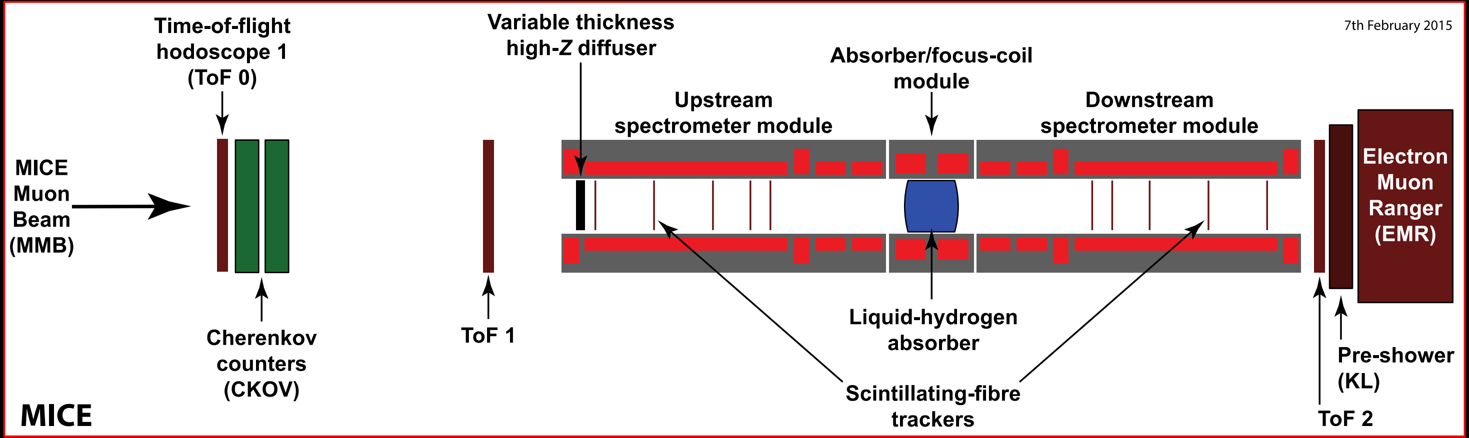
Muon Ionization Cooling Experiment

IONIZATION COOLING AND MICE

Muon Ionization Cooling Experiment

- **Proof of principle:**
  - Design, build commission tight-focusing, high-acceptance solenoid lattice;
  - Demonstrate integration and operation of liquid-hydrogen absorbers
  - Measure material properties that determine the ionization-cooling effect
  - Demonstrate the principal of ionization-cooling:
    - Study ionization cooling as a function of beam conditions and lattice settings





Time-of-flight hodoscope 1 (ToF 0)

Variable thickness high-*Z* diffuser

7th February 2015

Absorber/focus-coil module

Upstream spectrometer module

Downstream spectrometer module

MICE Muon Beam (MMB)

Electron Muon Ranger (EMR)

Cherenkov counters (CKOV)

ToF 1

Liquid-hydrogen absorber

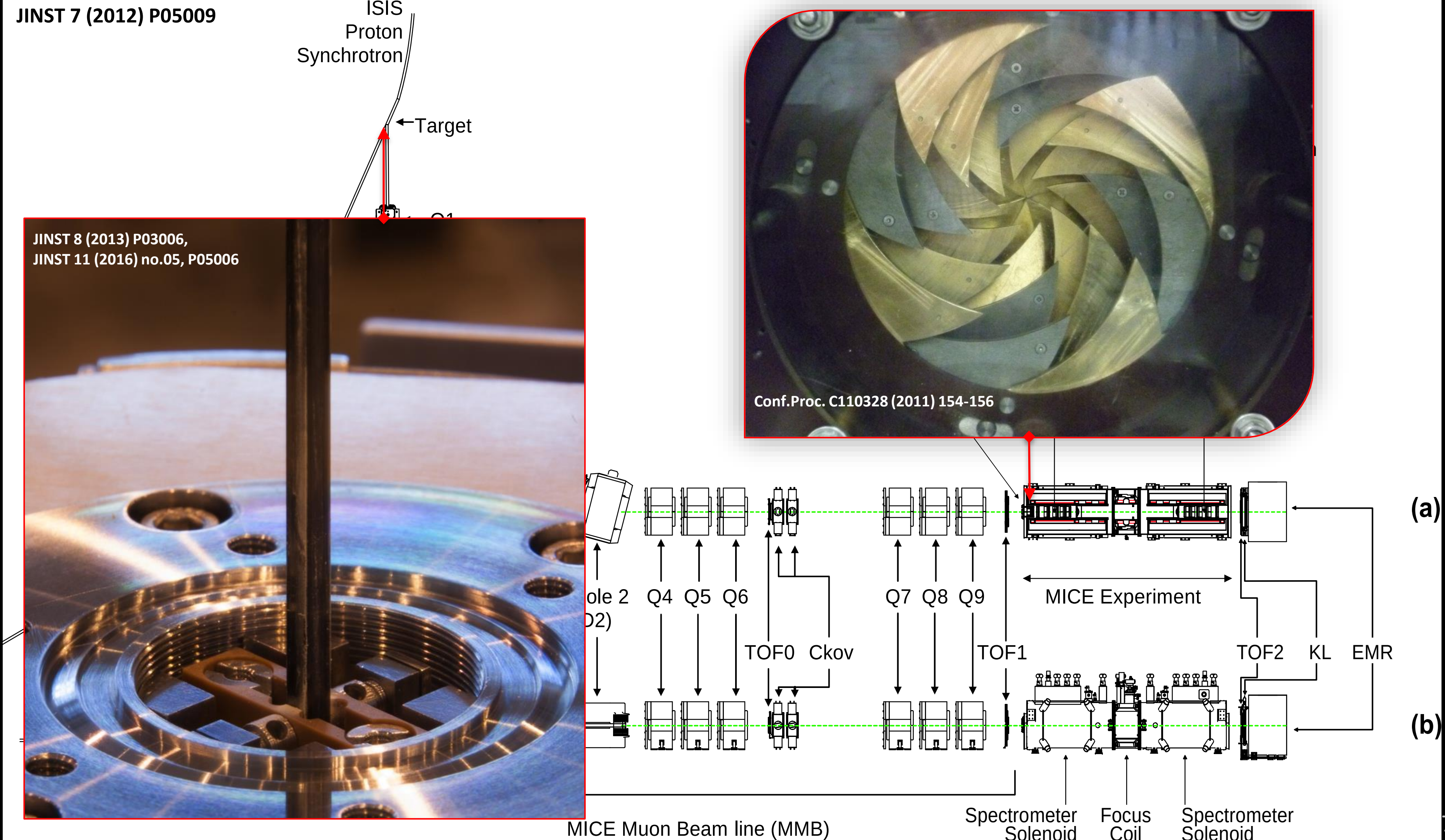
Pre-shower (KL)

Scintillating-fibre trackers

ToF 2

MICE

JINST 7 (2012) P05009



JINST 8 (2013) P03006,
JINST 11 (2016) no.05, P05006

Conf.Proc. C110328 (2011) 154-156

Embargoed!

But available online from Friday.

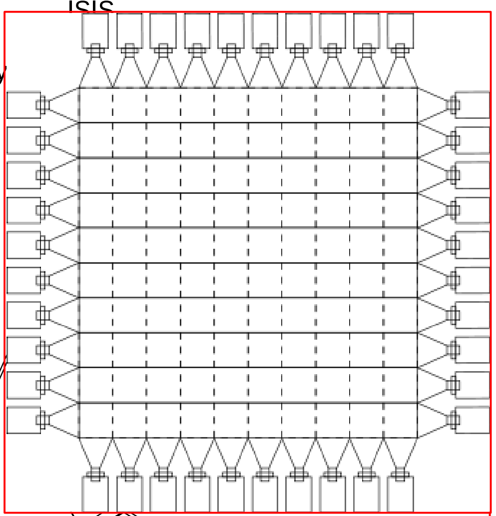
INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

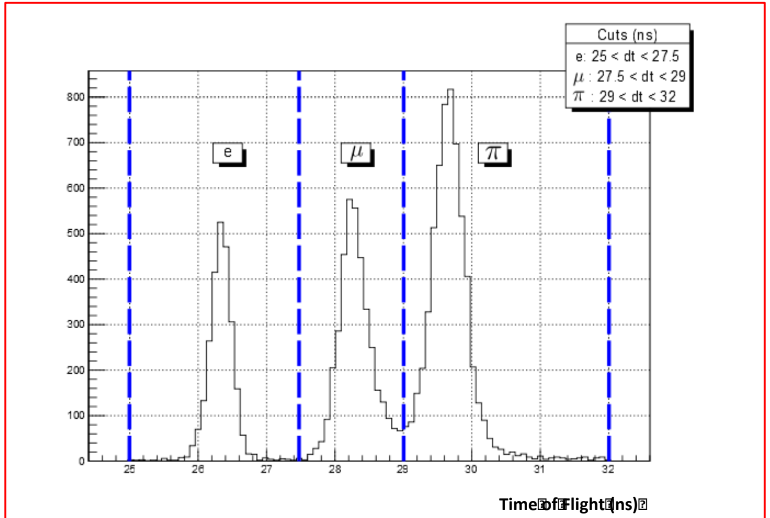
CERNCOURIER

VOLUME 58 NUMBER 6 JULY/AUGUST 2018

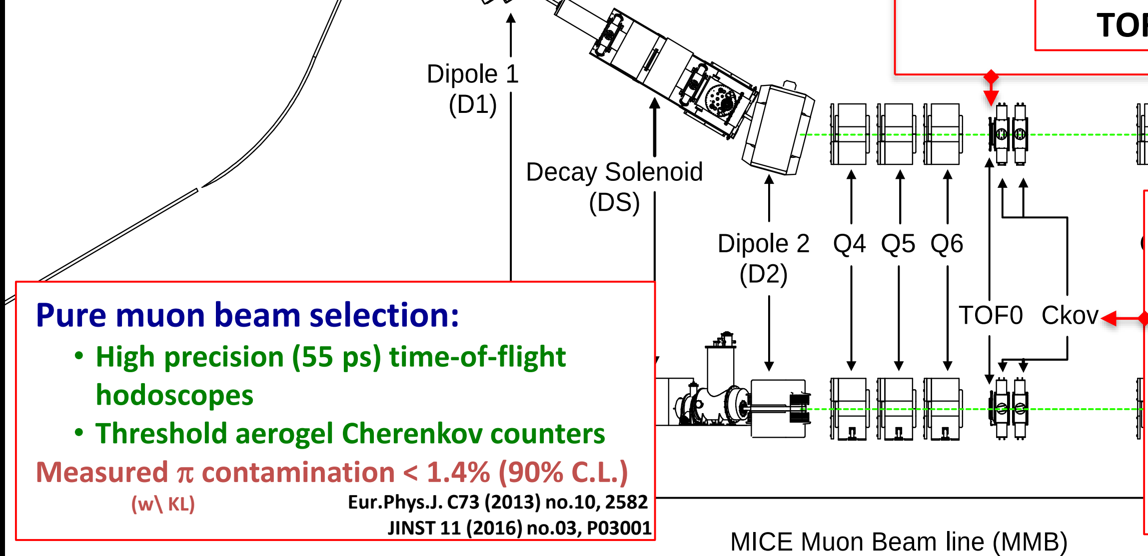
Targeting a muon collider

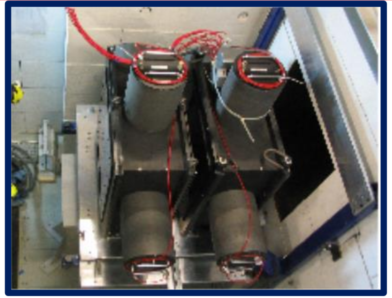
Art and science fuse at CERN
Neutrinos in their prime
Learning by machine





TOF distribution between TOF0 and TOF1





The Cherenkov Detectors

Pure muon beam selection:

- High precision (55 ps) time-of-flight hodoscopes
- Threshold aerogel Cherenkov counters

Measured π contamination < 1.4% (90% C.L.)

(w\ KL)

Eur.Phys.J. C73 (2013) no.10, 2582

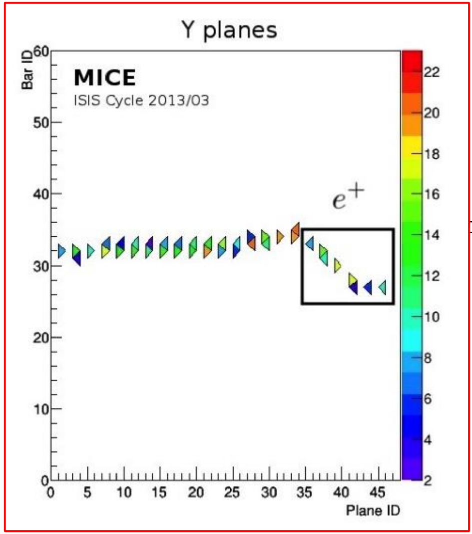
JINST 11 (2016) no.03, P03001

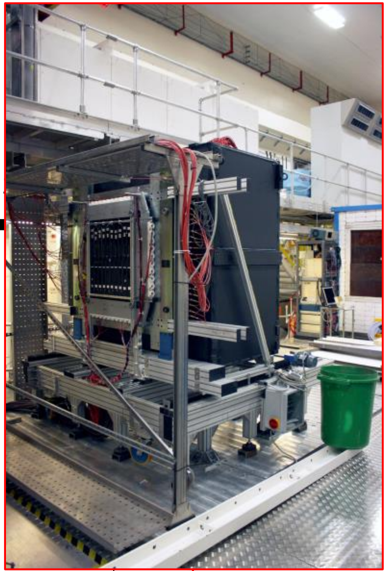
Rejection of decays:

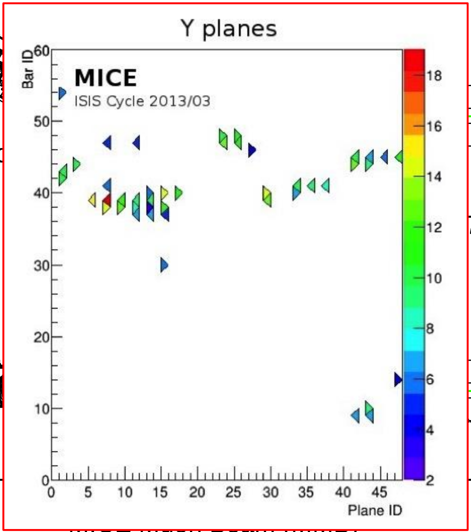
- **TOF2**
- **KLOE Light 'preshower' (KL)**
- **Electron Muon Ranger (EMR)**

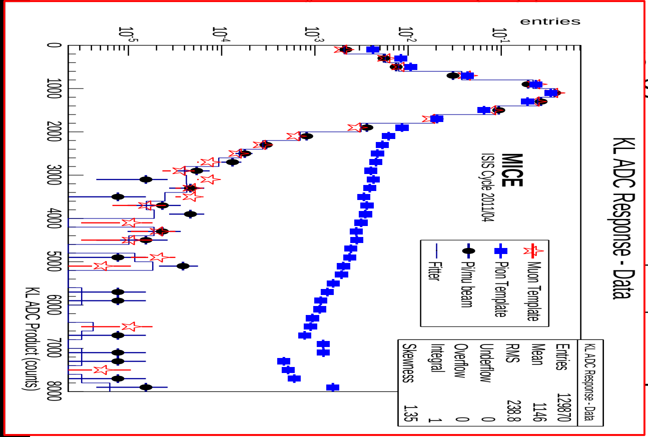
'*e*-tag' efficiency w\ EMR: > 98.6%

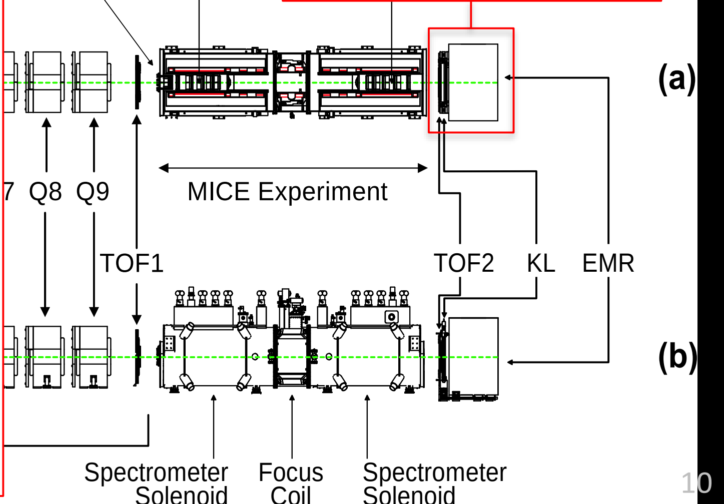
JINST 11 (2016) no.03, P03001
JINST 10 (2015) no.12, P12012







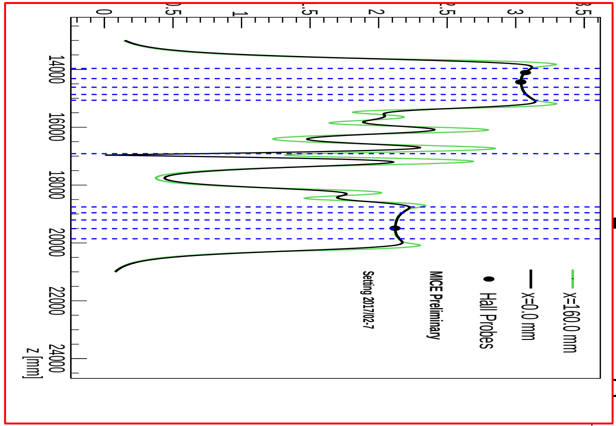


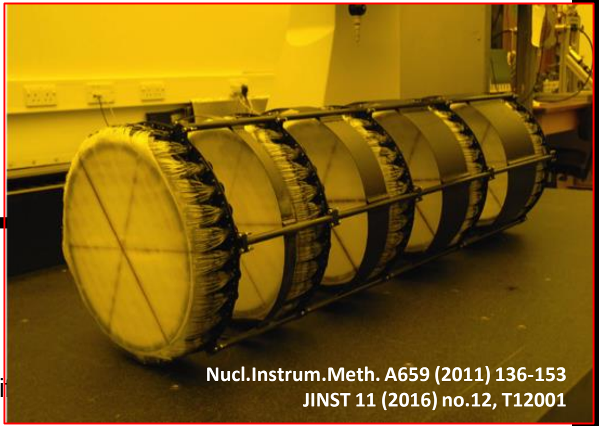


Transverse phase space measurment:

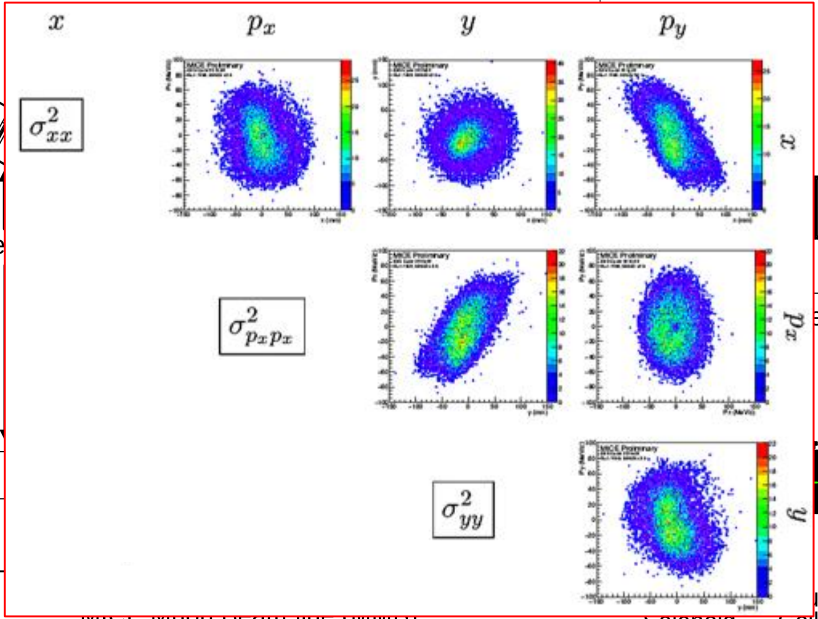
- Scintillating-fibre trackers
- Spectrometer solenoids

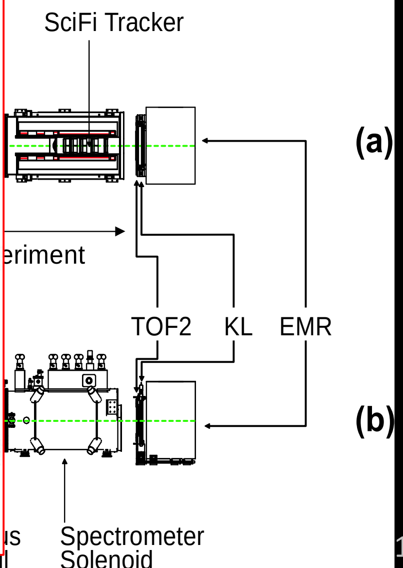
IEEE Trans.Appl.Supercond. 28 (2018) 4101304





Nucl.Instrum.Meth. A659 (2011) 136-153
JINST 11 (2016) no.12, T12001

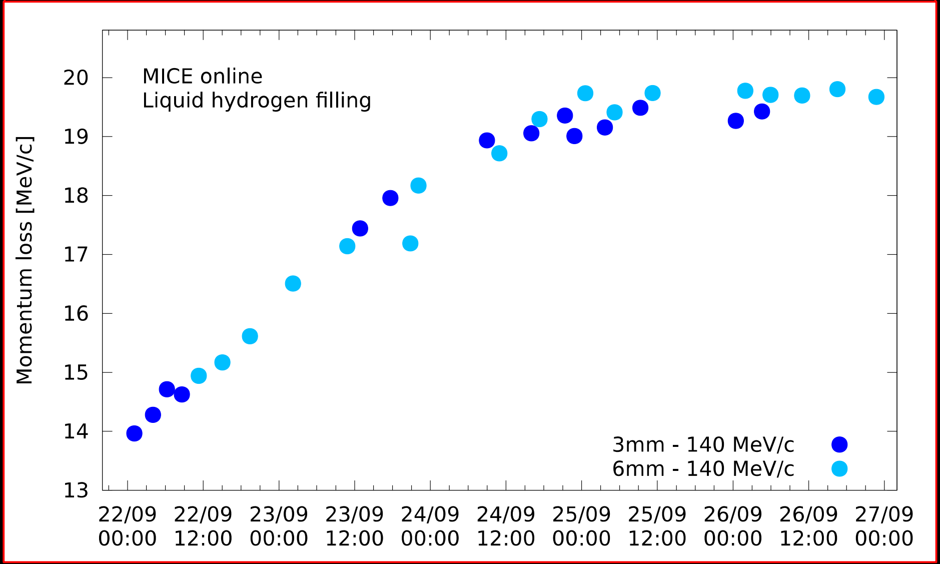




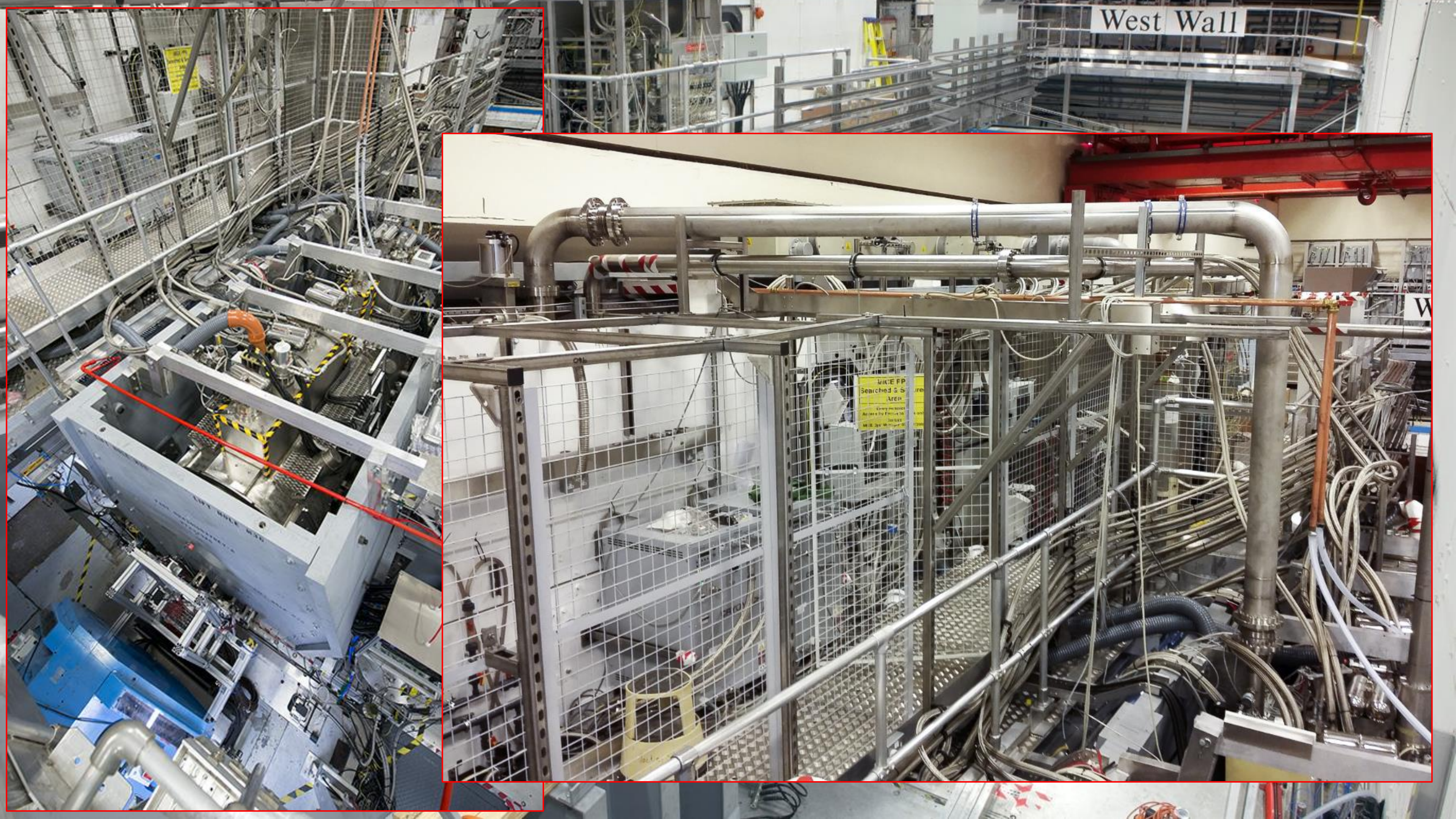
Liquid-hydrogen absorber

Online reconstruction:

- Mean momentum lost by muons as they pass through the liquid-hydrogen absorber.
- The data were recorded while the absorber was filling.



Conf.Proc. C100523 (2010) 421-423, Conf.Proc. C100523 (2010) MOPEB065,RAL-P-2018-003


West Wall
MICE FP
Searched & Secured
Area

Muon Ionization Cooling Experiment

MICE STUDY OF IONIZATION COOLING

Characterisation of the cooling equation

- **Evolution of normalized transverse emittance:**

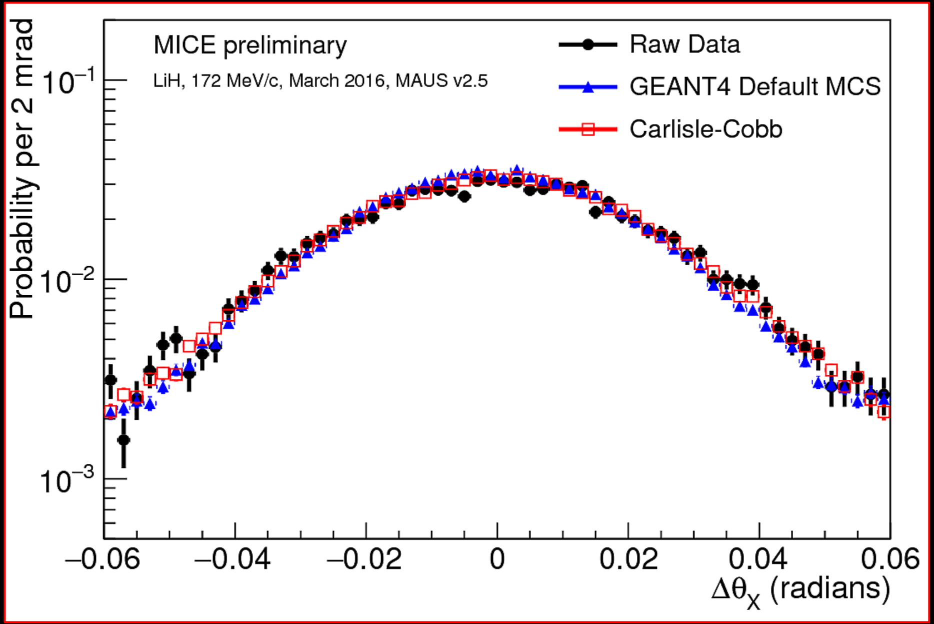
$$\frac{d\varepsilon_T}{ds} \approx -\frac{\varepsilon_T}{\beta_R^2 E}\left\langle \frac{dE}{ds} \right\rangle + \frac{\beta_T\,(13.6\mathrm{MeV})^2}{2\beta_R^3 E m_\mu X_0}$$

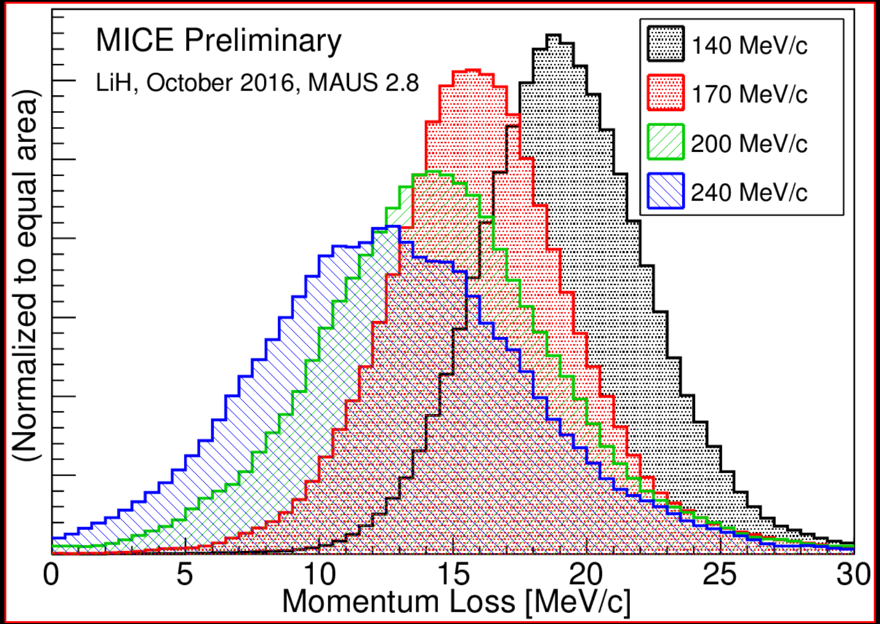
  - **Measured dependence on:**
    - **Input emittance:**
      - Vary beam optics/diffuser;
    - **Material:**
      - Absorber LH2; LiH
    - ***p*, *E* and β:**
      - Vary beam momentum, optics

Absorbers:

65 mm thick lithium hydride disk
350 mm thick liquid hydrogen vessel
45° polythene wedge absorber

Measurement of muon-LiH scattering

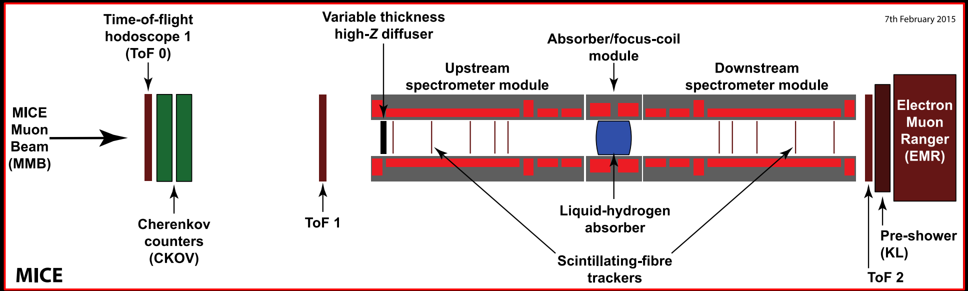


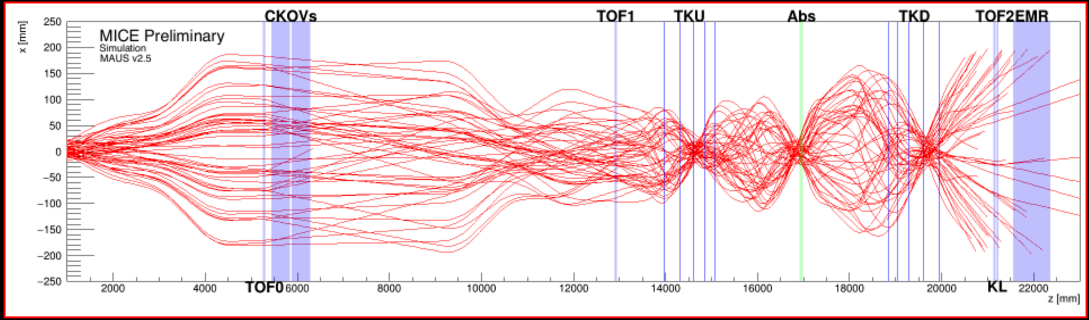


- Precision measurement of MCS
- Validate consistency of energy-loss model

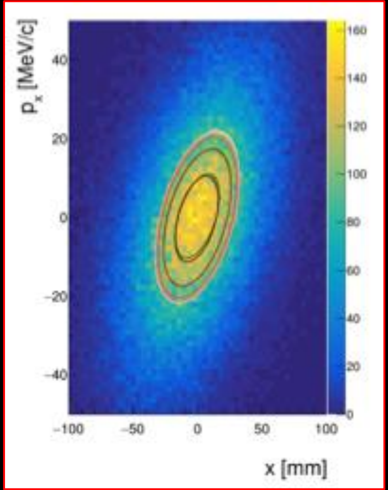
Single-particle technique

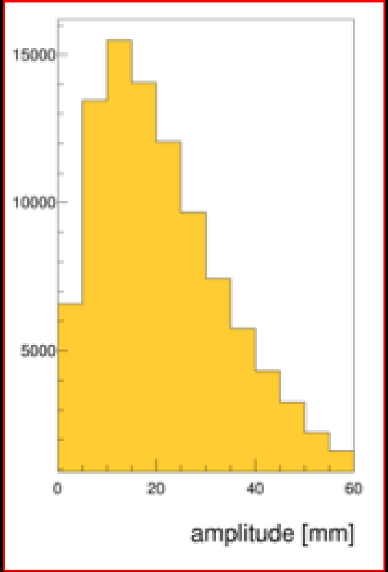
- Powerful! Fully measure one muon at a time:
  - Fast instrumentation, matched to beam intenstity:
    - Measure all 6D phase-space coordinates of each muon
  - Build muon ensemble offline:
    - Calculate ensemble properties
      - E.g. ε_T





Emittance and amplitude





Phase space, covariance, emittance and amplitude

Phase space: $\mathcal{P} = (x, p_x, y, p_y)^{\mathrm{T}}$

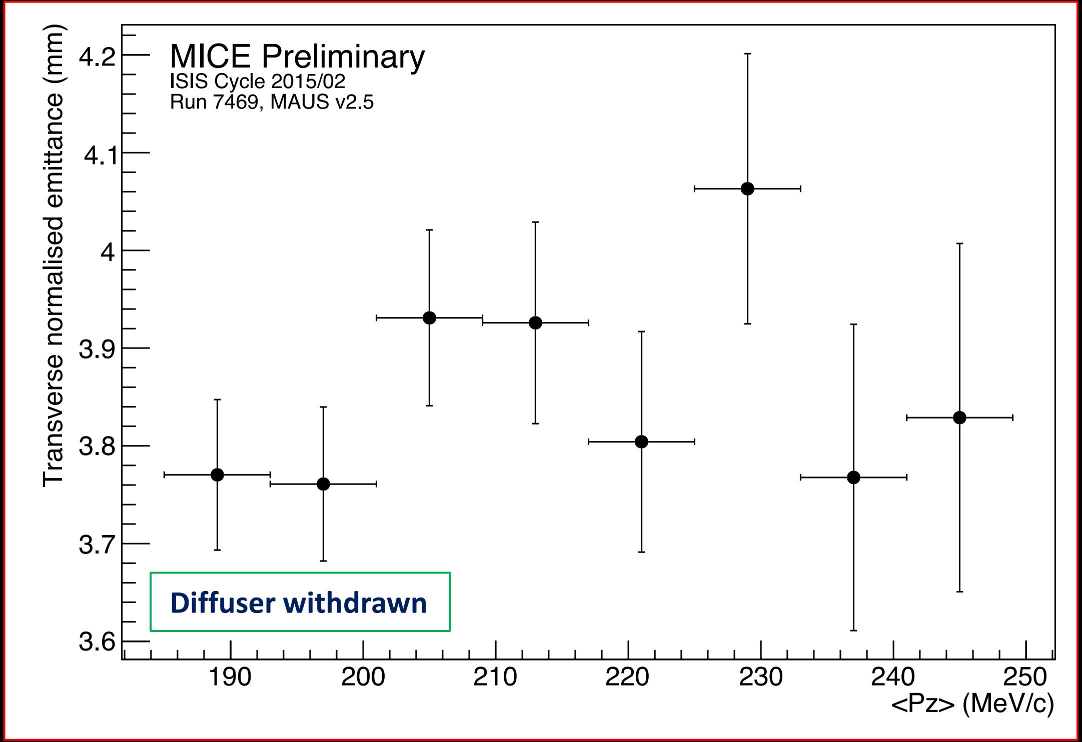
Covariance: $\mathcal{C} = \left\langle \Delta\mathcal{P}\Delta\mathcal{P}^{\mathrm{T}} \right\rangle$

Normalised transverse emittance: $\varepsilon_T = \dfrac{|\mathcal{C}|^{\frac{1}{4}}}{m_\mu}$

Transverse amplitude: $A_T = \varepsilon_T \mathcal{P}^{\mathrm{T}} \mathcal{C}^{-1} \mathcal{P}$

- Emittance:
  - Evaluated from RMS beam ellipse
- Amplitude:
  - Distance from core of beam
- Mean amplitude ~ RMS emittance

Measured input emittance



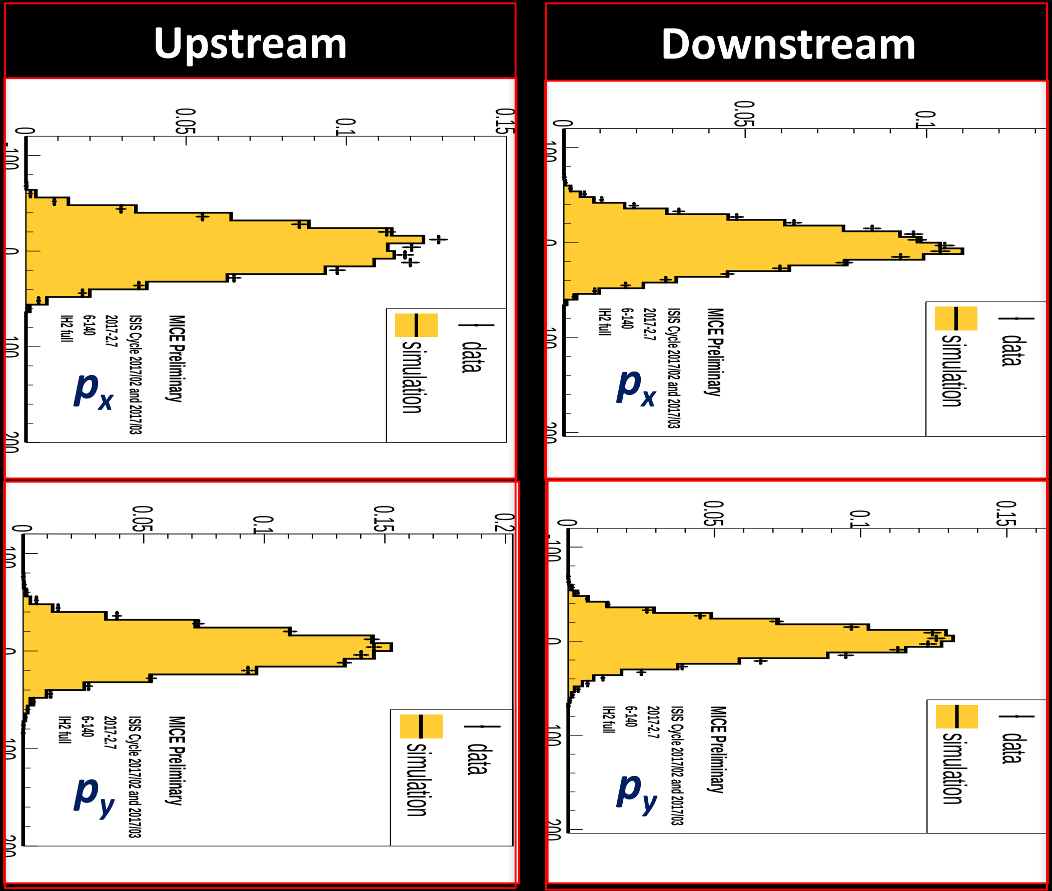
- **Precise measurement of emittance:**
  - **Full 4D covariance matrix, i.e. off-diagonal coupling terms included**
  - **Bin in P_Z to study dispersion**

Effect of lithium-hydride absorber

Simulation in good agreement with data

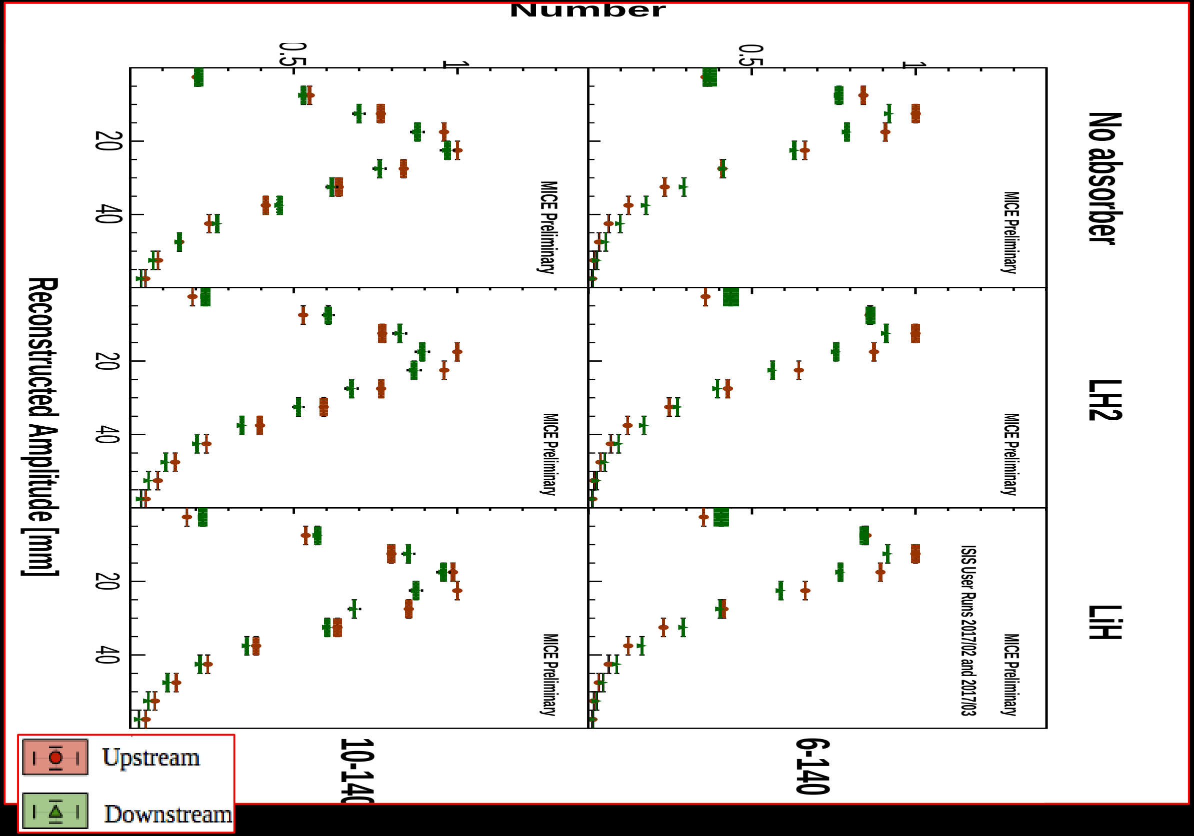
- Example:
  - ε_T = 6 mm
  - P = 140 MeV/c

Notation: P-ε_T = 6-140



arXiv:1806.01807; IPAC18 FRXGBE3

Change in amplitude across absorber



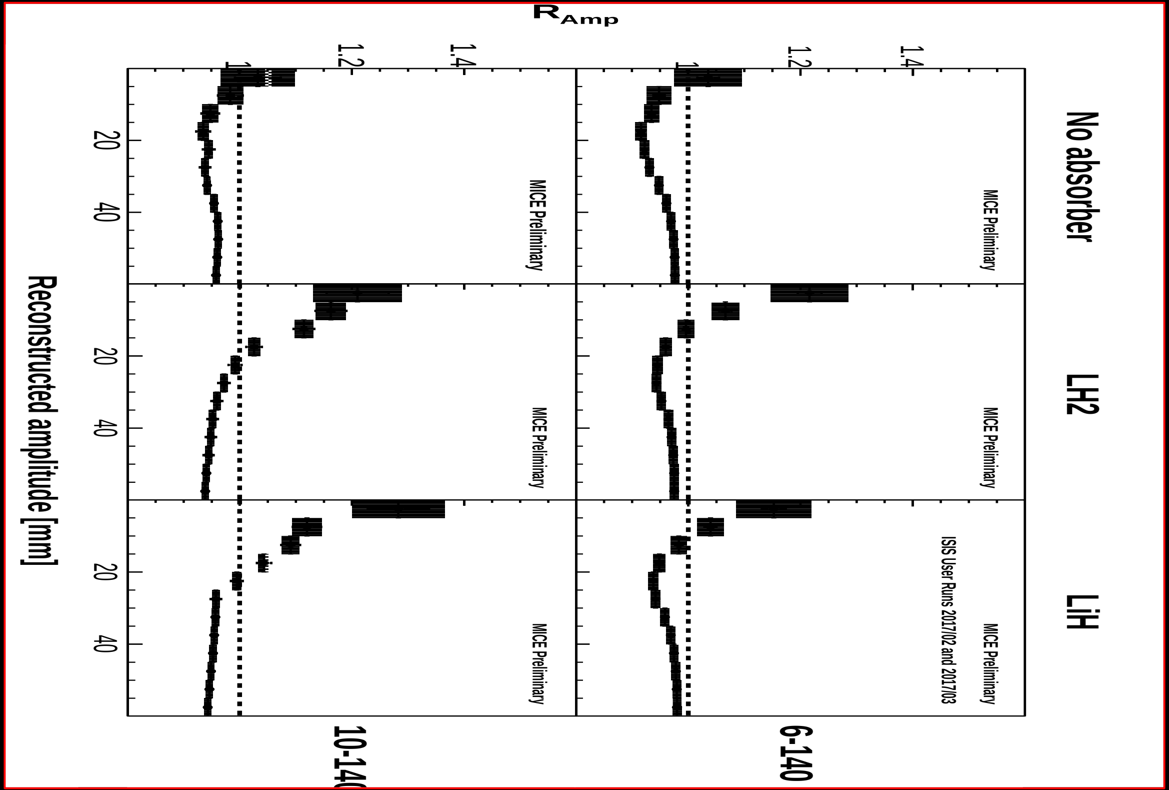
Muons in beam core:

- *Decrease with no absorber*
- *Increase* with LiH and LH2 absorbers

Ionization-cooling signal

arXiv:1806.01807; IPAC18 FRXGBE3

Core-density change across absorber



R_{amp} = ratio of cumulative density downstream to upstream

Core-density:

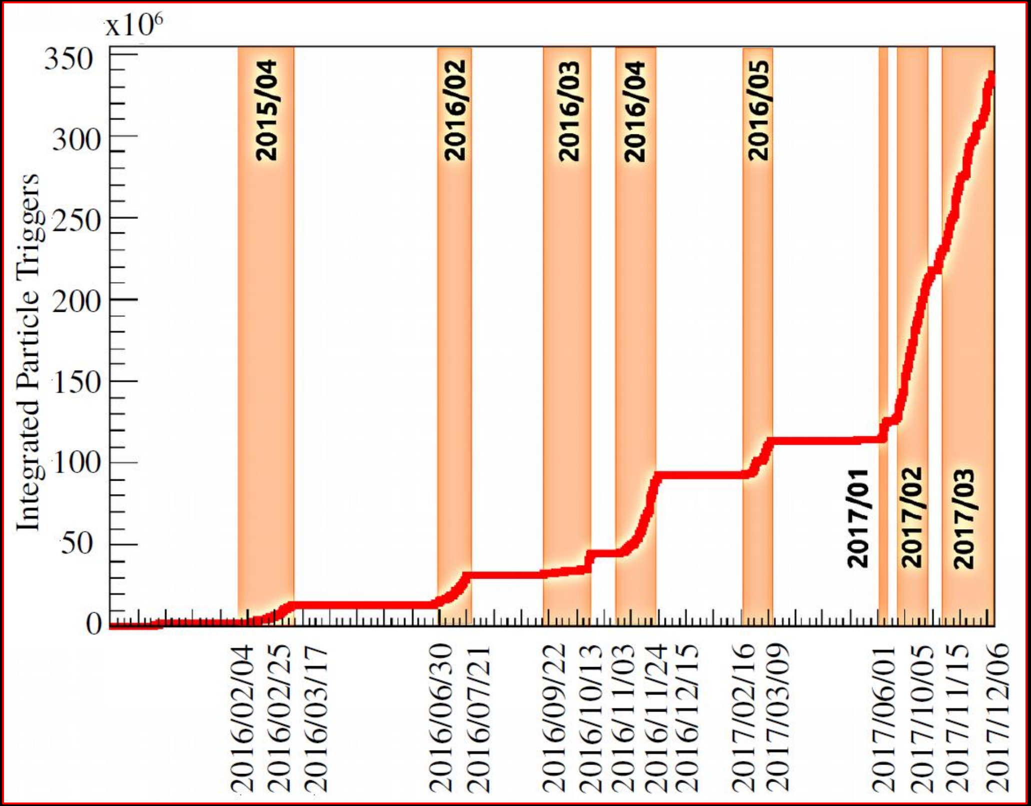
- *Increases* with LiH and LH2 absorbers
- *Consistent with 'no change'* for no absorber

Ionization-cooling signal

arXiv:1806.01807; IPAC18 FRXGBE3

The data set

- **Excellent data taking!**
- **'On tape':**
  - **Complete data sets:**
    - **LH2 full & empty**
    - **LiH full & empty**
    - **Polyethylene wedge**
- **Systematic study of ionization cooling now underway!**



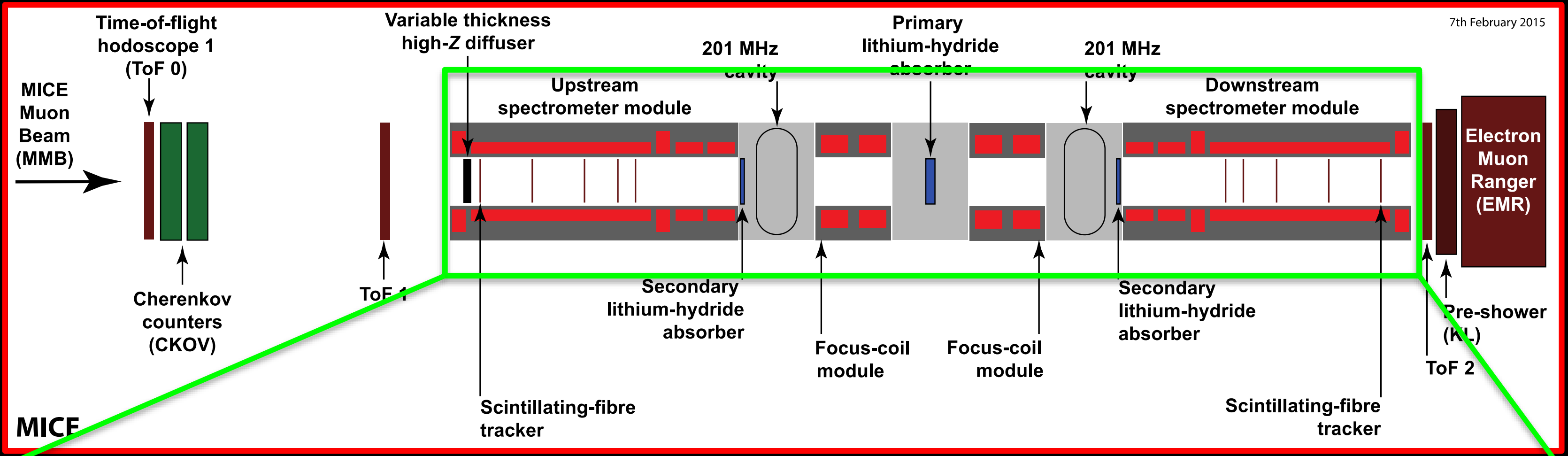
Muon Ionization Cooling Experiment

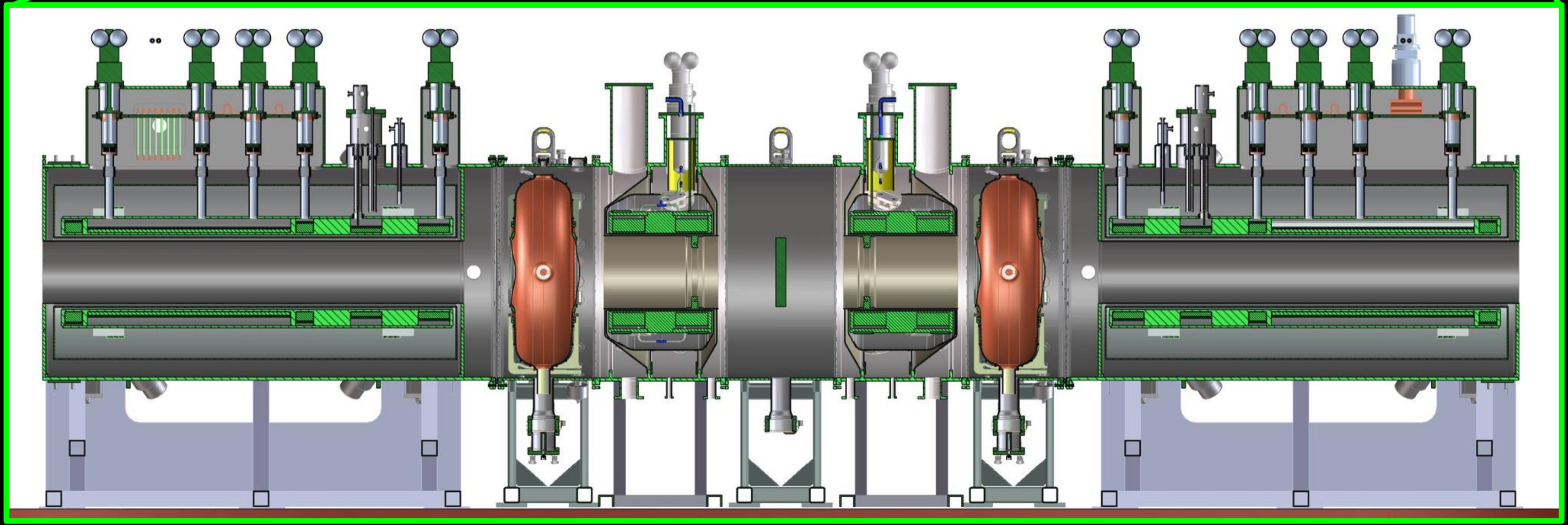
GOING FORWARD

Next steps in study of ionization cooling

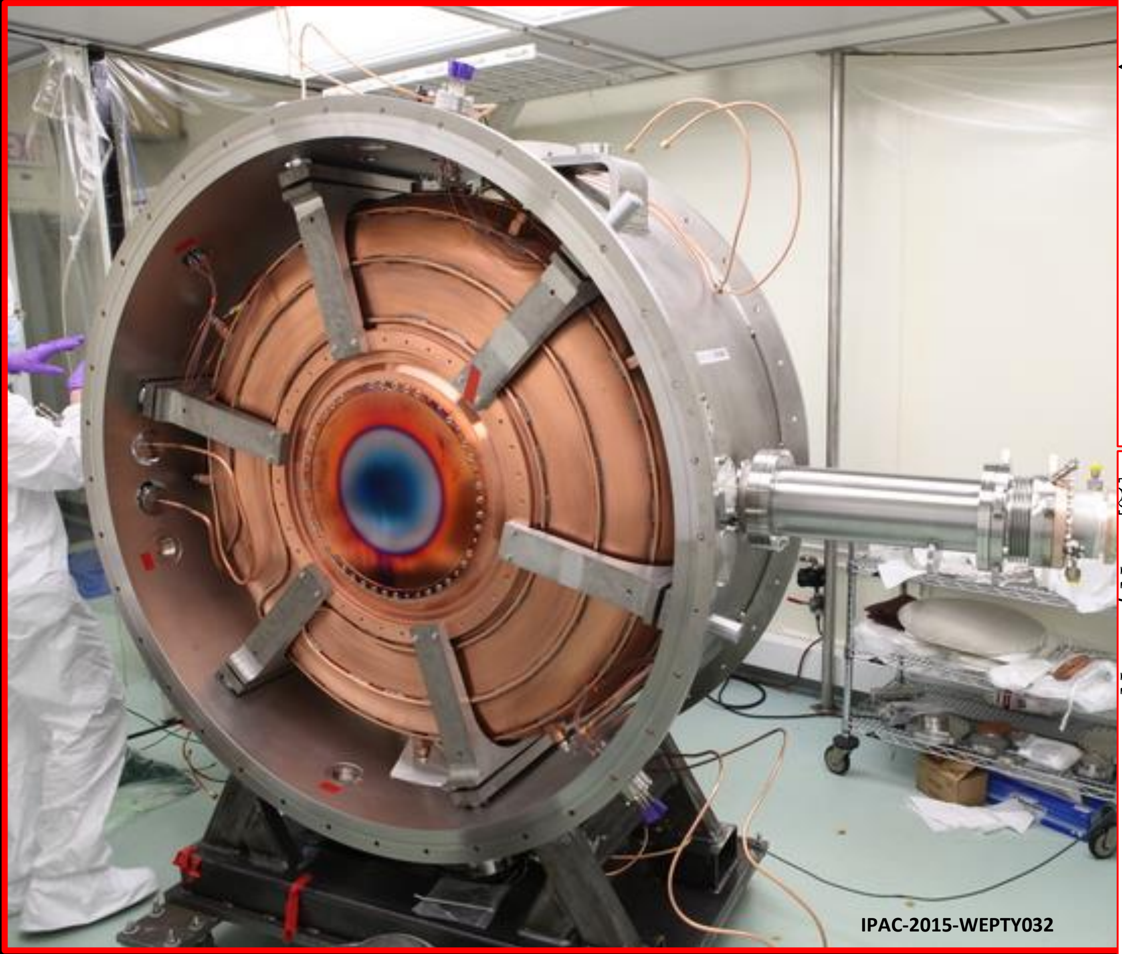
- MICE will:
  - Measure the factors that determine the ionization-cooling effect
  - Study ionization cooling as a function of:
    - Input beam emittance and momentum;
    - Lattice optics and absorber material (LiH and LH2);
  - Initial studies of emittance exchange with wedge absorber

- Possible next steps:
  - Add acceleration to MICE lattice, study 4D cooling with acceleration:
    - Design and components complete;





Phys.Rev.Accel.Beams 20 (2017) no.6, 063501



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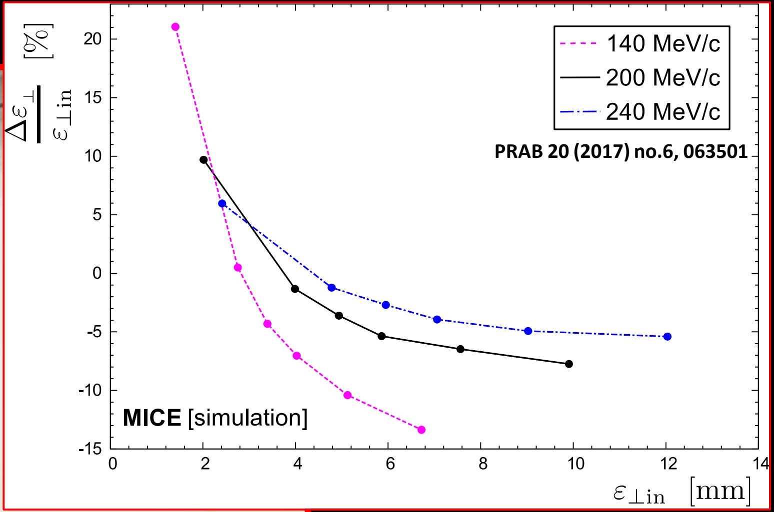
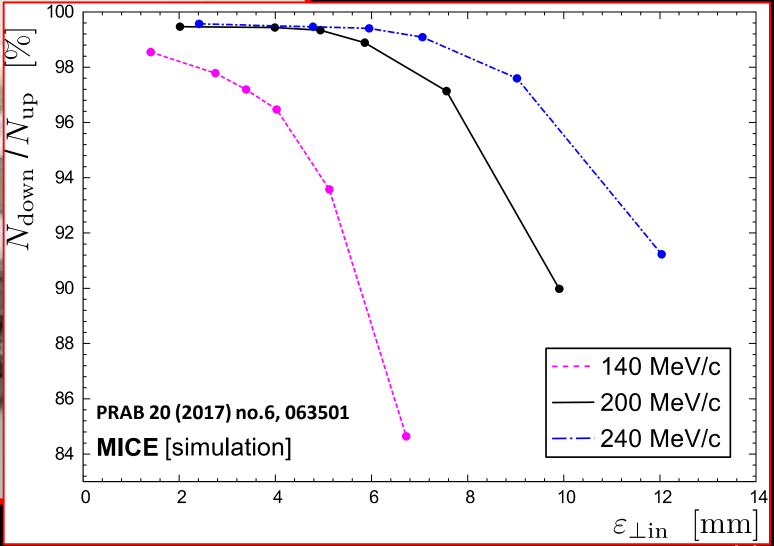


PRAB 20 (2017) no.6, 063501

MICE [simulation]



PRAB 20 (2017) no.6, 063501

MICE [simulation]

Next steps in study of ionization cooling

- MICE will:
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  - Study ionization cooling as a function of:
    - Input beam emittance and momentum;
    - Lattice optics and absorber material (LiH and LH2);
  - Initial studies of emittance exchange with wedge absorber

- Possible next steps:
  - Add acceleration to MICE lattice, study 4D cooling with acceleration:
    - Design and components complete;
  - Design and implement a 6D cooling experiment:
    - See concepts described in M.Palmer's contribution

Muon Ionization Cooling Experiment

CONCLUSIONS

- Ionization cooling observed:
  - Using LiH and LH_2 absorbers

A major milestone!

- Precise measurements using single-particle technique:
  - %-level measurement of emittance;
  - Detailed studies of multiple Coulomb scattering and energy loss
- A wealth of data being analysed:
  - Wide range of optics and initial p, ε settings
  - Scattering data
  - Polyethylene wedge absorber
- Build on successful execution of MICE programme to:
  - Design and implement a 6D cooling experiment;
  - Establish a particle-physics programme based on high-intensity, high-energy muon beam:
    - E.g. nuSTORM; see J. Pasternak's contribution