Canonical Angular Momentum Growth in MICE 'Solenoid Mode' with Muon Ionization Cooling

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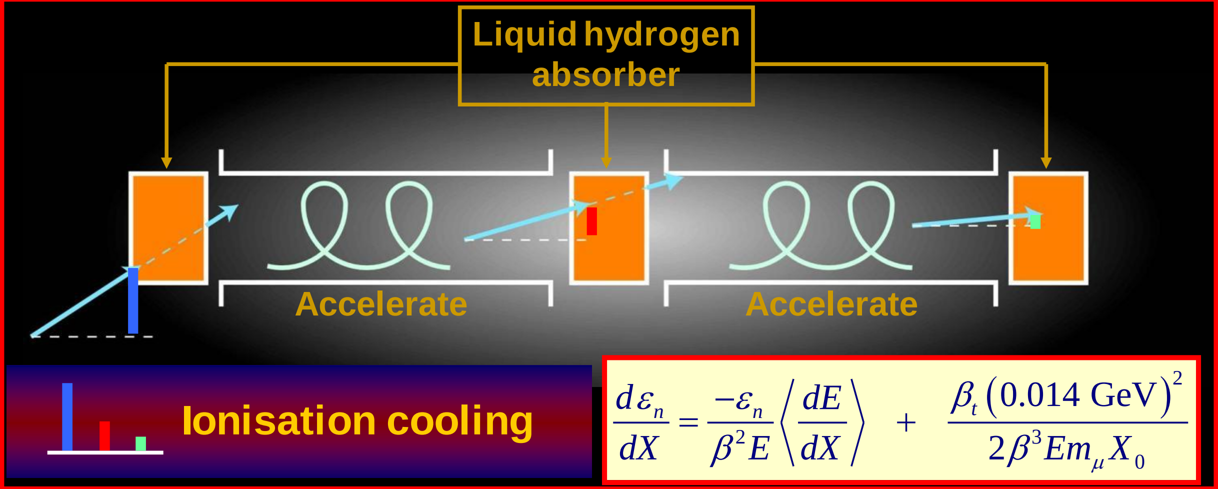
On behalf of the MICE collaboration

K. Long, 9 September, 2021

The principle of ionization cooling



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

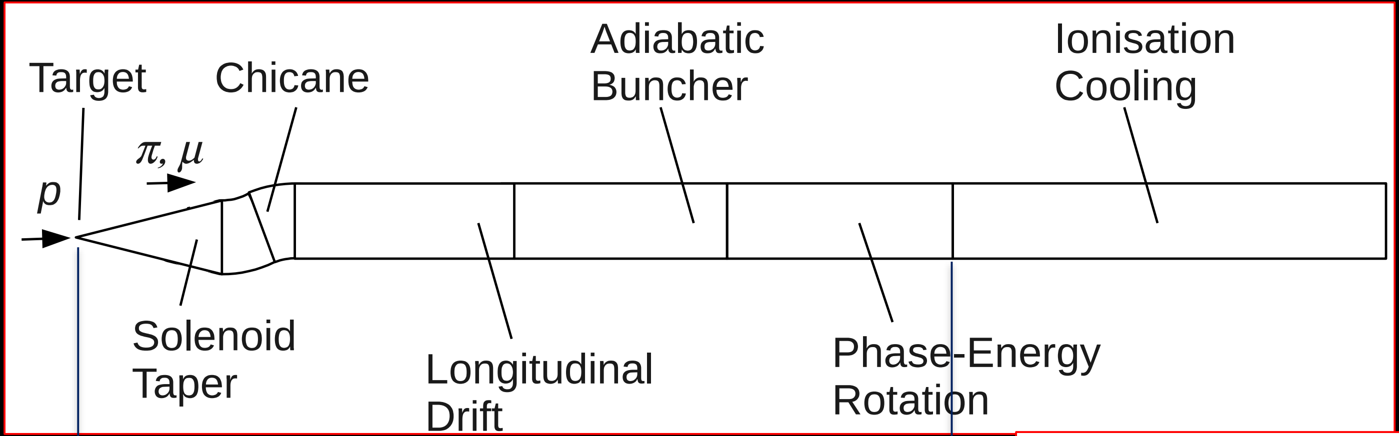
	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

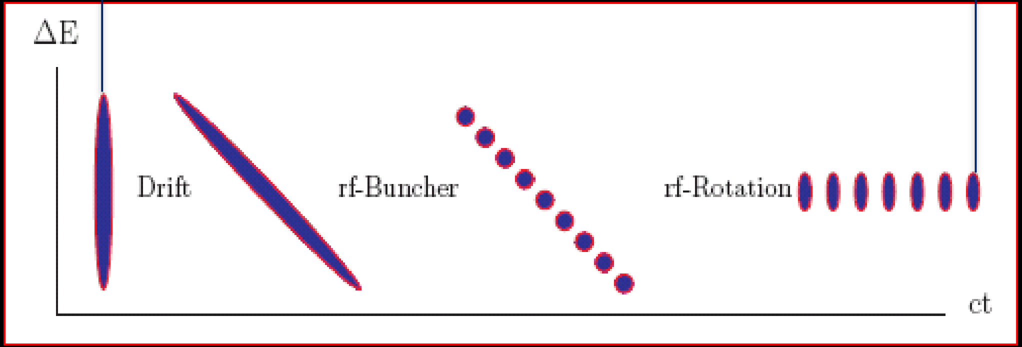
- **Competition between:**
  - dE/dx [cooling]
  - MCS [heating]

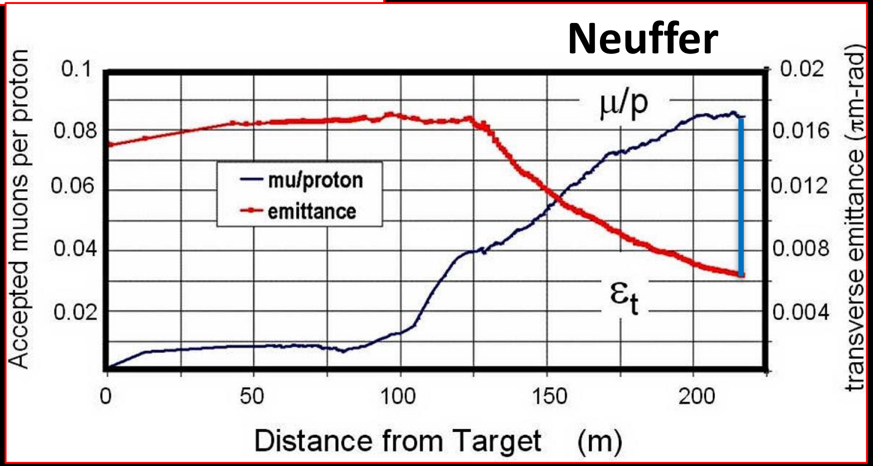
Requires compact magnetic lattice

- **Optimum:**
  - Low *Z*, large X_0
  - Tight focus / large acceptance
  - H_2 gives best performance

The ‘muon front end’





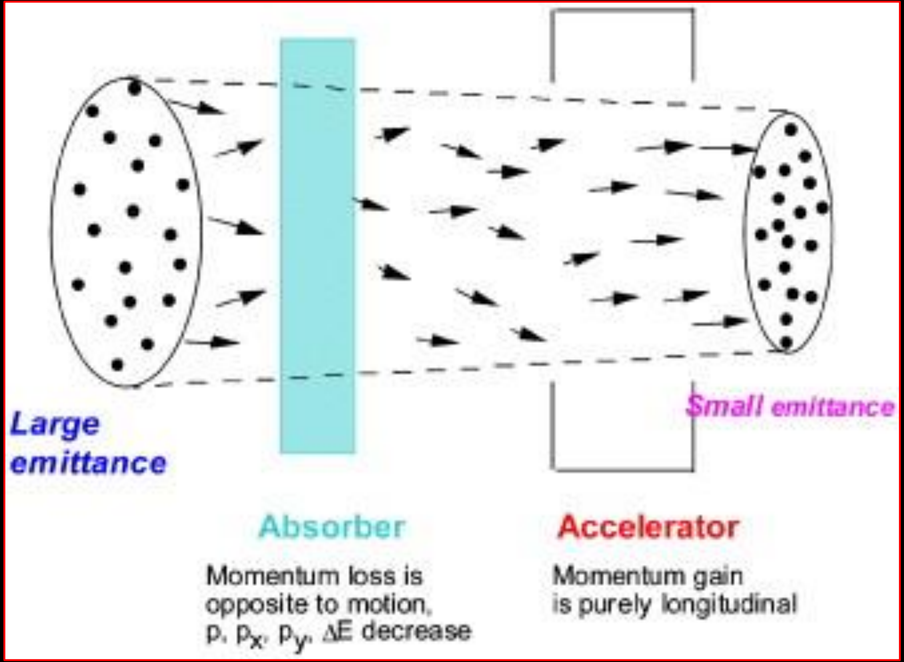


- **Ionization cooling essential:**
  - **Gives x2—3 in μ/proton**

Angular momentum

Entering solenoid, muons get a "*pt* kick" proportional to radial position:

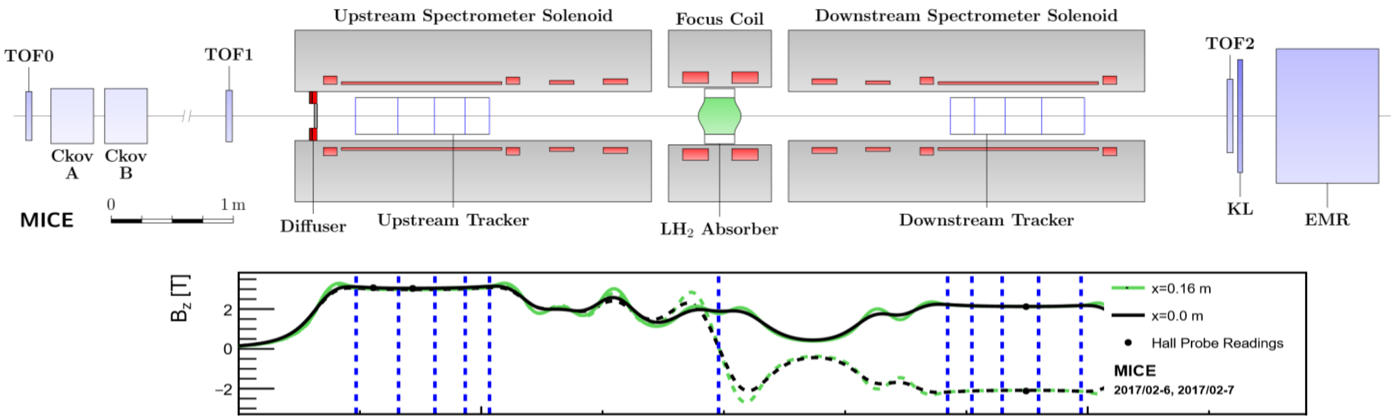
Angular momentum



Leaving solenoid, muons get a smaller kick …

1. Flip/solenoid mode lattice performance may differ
2. Need to study performance of solenoid mode

Cooling Channel Lattice



- Spectrometer solenoids upstream and downstream provide uniform 2-4 T field for SciFi trackers / detector systems
- Focus coil module provides tight focussing on absorber
- Can flip field polarity across absorber, prevents canonical angular momentum buildup
- MICE demonstrated cooling in flip mode - **Nature vol 578, pages 53-59 (2020)**

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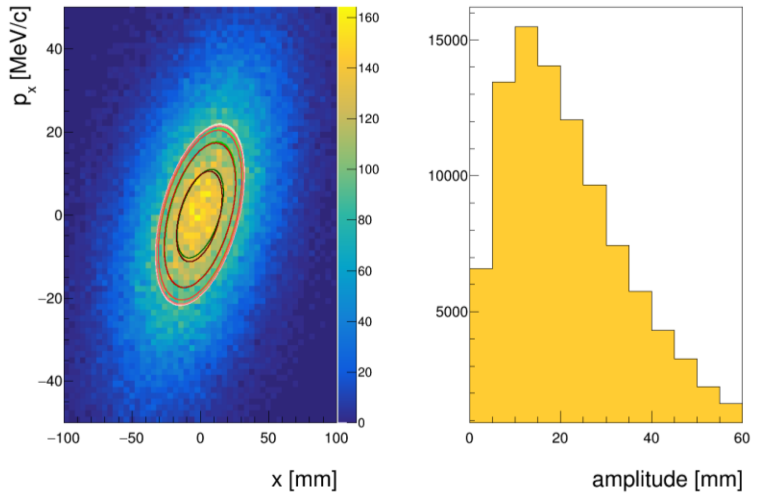
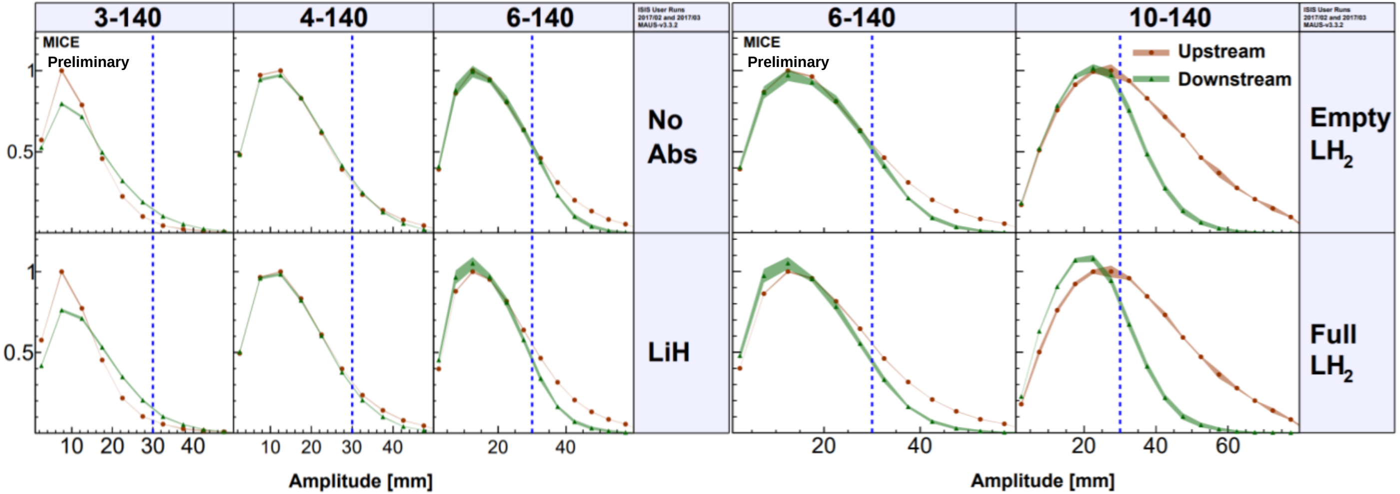
Amplitude

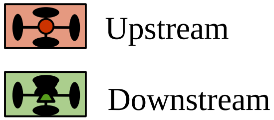


- Transverse amplitude is distance of muon at point $p = (x, p_x, y, p_y)$ from beam core in phase-space
  - Normalise phase space to RMS beam ellipse
- Related to transverse emittance by $A_\perp = \epsilon_\perp (p - \bar{p})^T \Sigma^{-1} (p - \bar{p})$, with Σ = 4D covariance matrix
- Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread, reducing amplitude
- Mean amplitude $\langle A_\perp \rangle$ ~ RMS emittance

Amplitude Change Across Absorber

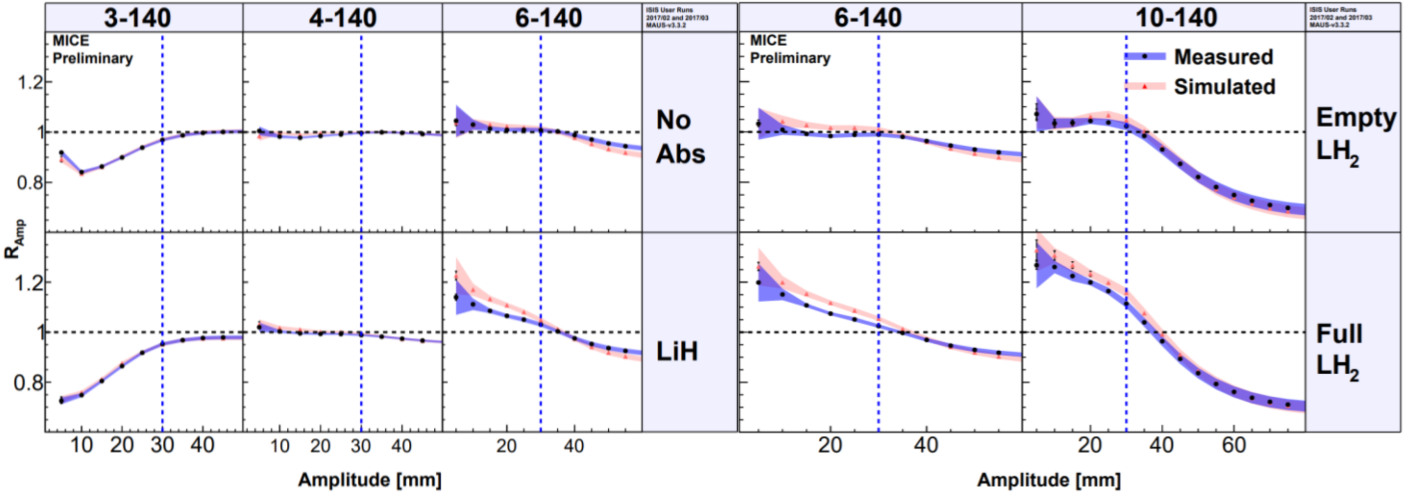


- No absorber → similar number of core muons
- With absorber → increase in number of core muons
  - Cooling signal
- Decrease in core muons for 3mm beam



140 MeV/c data

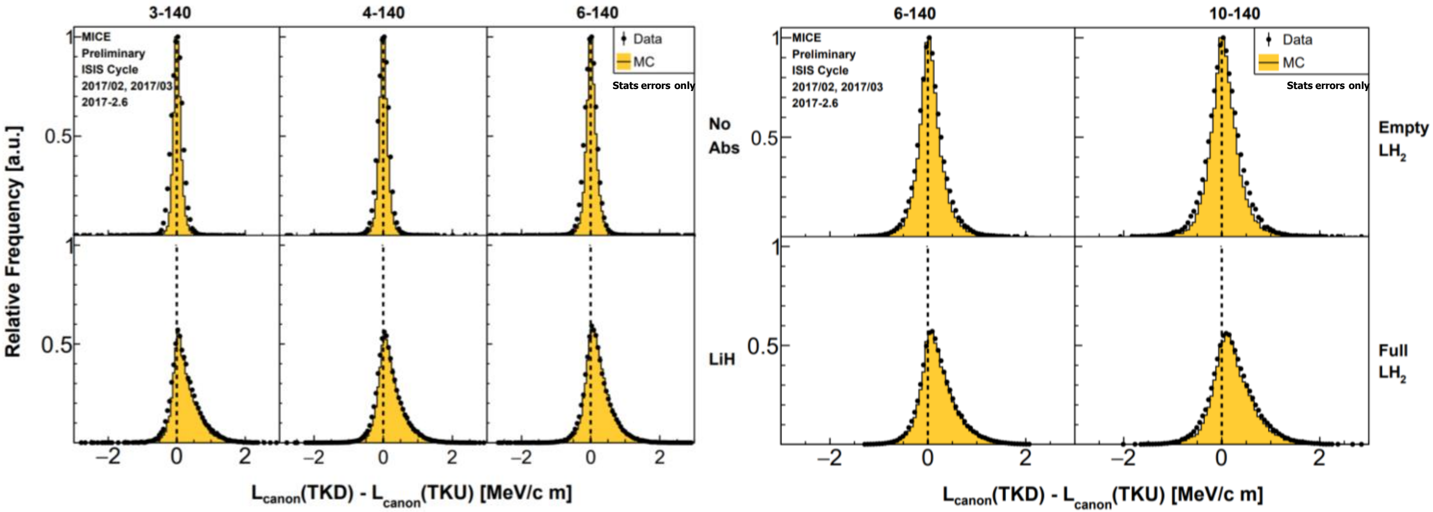
Ratio of core densities



- Ratio of downstream over upstream CDFs
- Core density increase for LH_2 & LiH absorbers → cooling
- More cooling at higher emittances
- Heating for 3mm beam

140 MeV/c data

Canonical Angular Momentum Growth



- $\mathrm{L_{canon}} \approx xP_y - yP_x + \frac{qr^2B_z}{2}$ (to first order)
- No absorber case shows little change
- Bias in canonical angular momentum distribution with LiH and LH_2

Conclusions

- Ionization cooling measured in solenoid mode
  - Simulation gives good description of data
- MICE cooling demonstration encompasses:
  - A variety of solenoid- and flip-mode optical set-ups
  - A range of beam momentum and emittance
  - Two absorber types (liquid hydrogen, lithium hydride)
- Solid demonstration of ionization cooling principle
- Foundations for development of 6D-cooling demo