Muon Colliders, Neutrino Factories, and Results from the MICE Experiment

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Transforming Lives. Inventing the Future. www.iit.edu

25th Conference on Application of Accelerators in Research and Industry

Session TD-02: Emerging Accelerator Technologies

Grapevine, TX

14 Aug. 2018

Outline

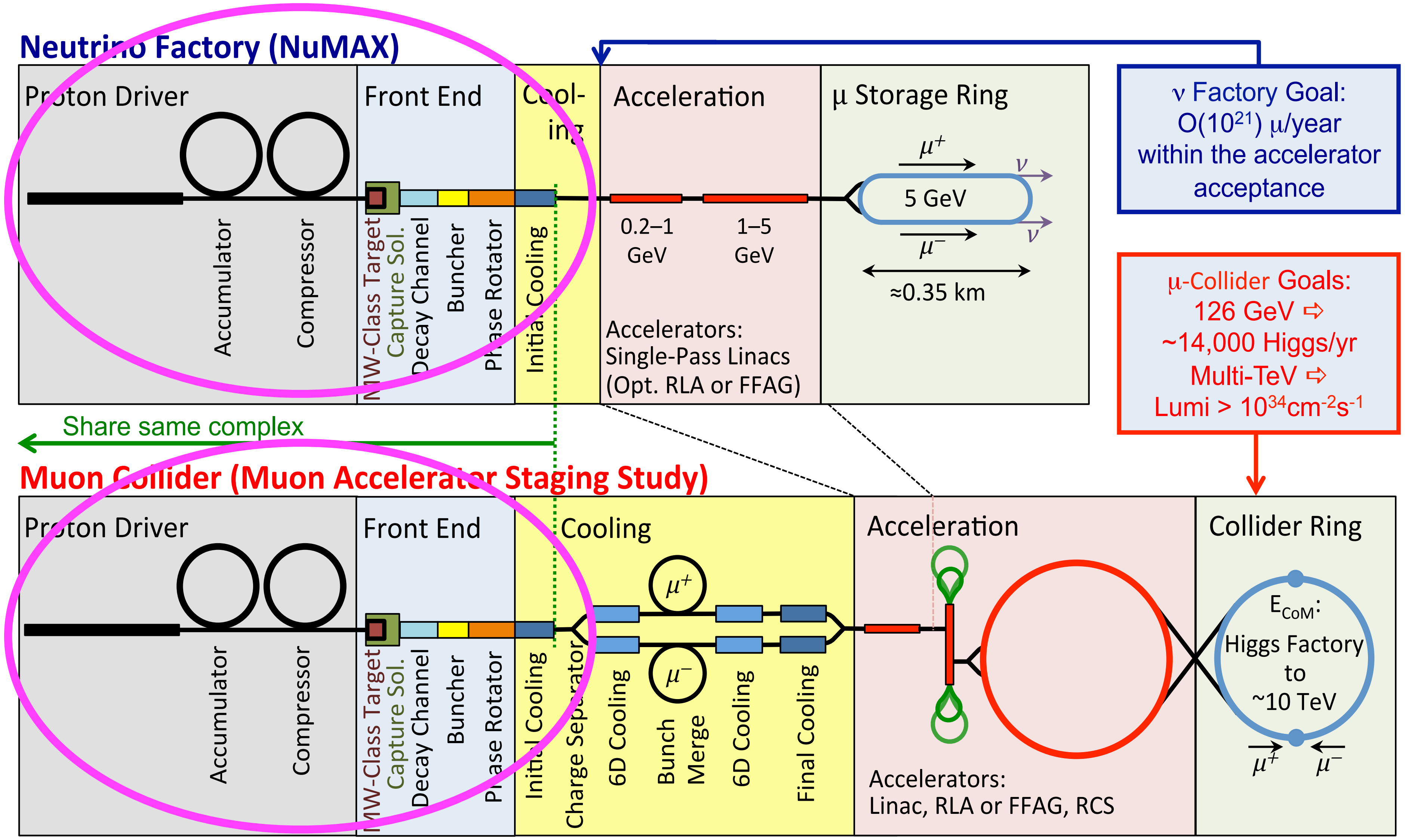
- Muon accelerators, neutrino factories, and muon colliders
- Muon cooling
- MICE
- Conclusions

Motivation for Muon Accelerators

- High-energy electron-positron colliders increasingly limited by unwanted radiative processes
- Heavier fundamental fermions — i.e., muons — offer an attractive way forward
  - *if* the muons can be efficiently cooled
- Muon storage rings could then serve as uniquely powerful $\ell^+\ell^-$ colliders
- *And* the world's best neutrino sources
  - to probe *beyond* the 3ν-mixing paradigm
- Cooled muon beams → L.E.-μ sensitivity upgrades:

  $g-2$, μ2e, muonium (M) gravity, M–$\overline{\text{M}}$ conversion…

NF and MC



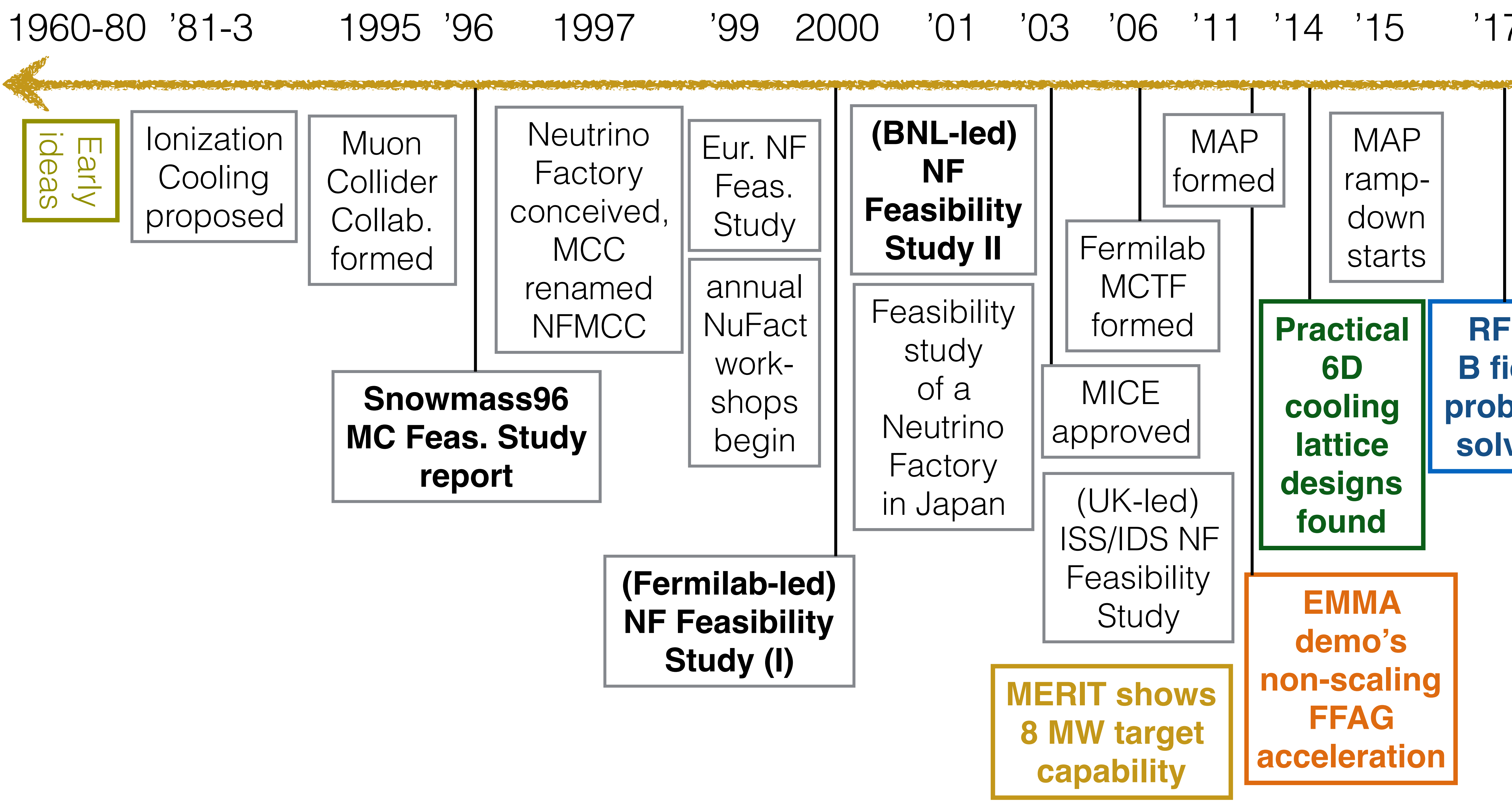
~ 10^{21} ν/year to remote detectors

$\mathcal{L} > 10^{34}$ cm^{-2} s^{-1}

E_{CM} up to 10 TeV and beyond

- Strong similarities! (1st 3 stages of NF reusable in MC)
  - both start with ~MW *p* beam on high-power tgt → π → μ, then cool, accelerate, & store

Muon Accelerator (partial) Timeline



Muon Accelerator (partial) Timeline

1995 '96 1997 '99 2000 '01 '03 '06 '11 '14 '15 '17 '18

- on g ed
- Muon Collider Collab. formed
- **Snowmass96 MC Feas. Study report**
- Neutrino Factory conceived, MCC renamed NFMCC
- Eur. NF Feas. Study
- annual NuFact work-shops begin
- **(Fermilab-led) NF Feasibility Study (I)**
- **(BNL-led) NF Feasibility Study II**
- Feasibility study of a Neutrino Factory in Japan
- MICE approved
- (UK-led) ISS/IDS NF Feasibility Study
- **MERIT shows 8 MW target capability**
- Fermilab MCTF formed
- MAP formed
- **EMMA demo's non-scaling FFAG acceleration**
- **Practical 6D cooling lattice designs found**
- MAP ramp-down starts
- **RF in B field problem solved**
- MICE completes data-taking
- 1st Eur. MC work-shop
- **MICE observes cooling**

Muon Accelerator Technical Challenges

1. High-power (up to 4 MW) *p* beam* and target
   - Hg jet feasible [MERIT@CERN, 2007]

e.g., SNS, ESS, PIP II SC Linac

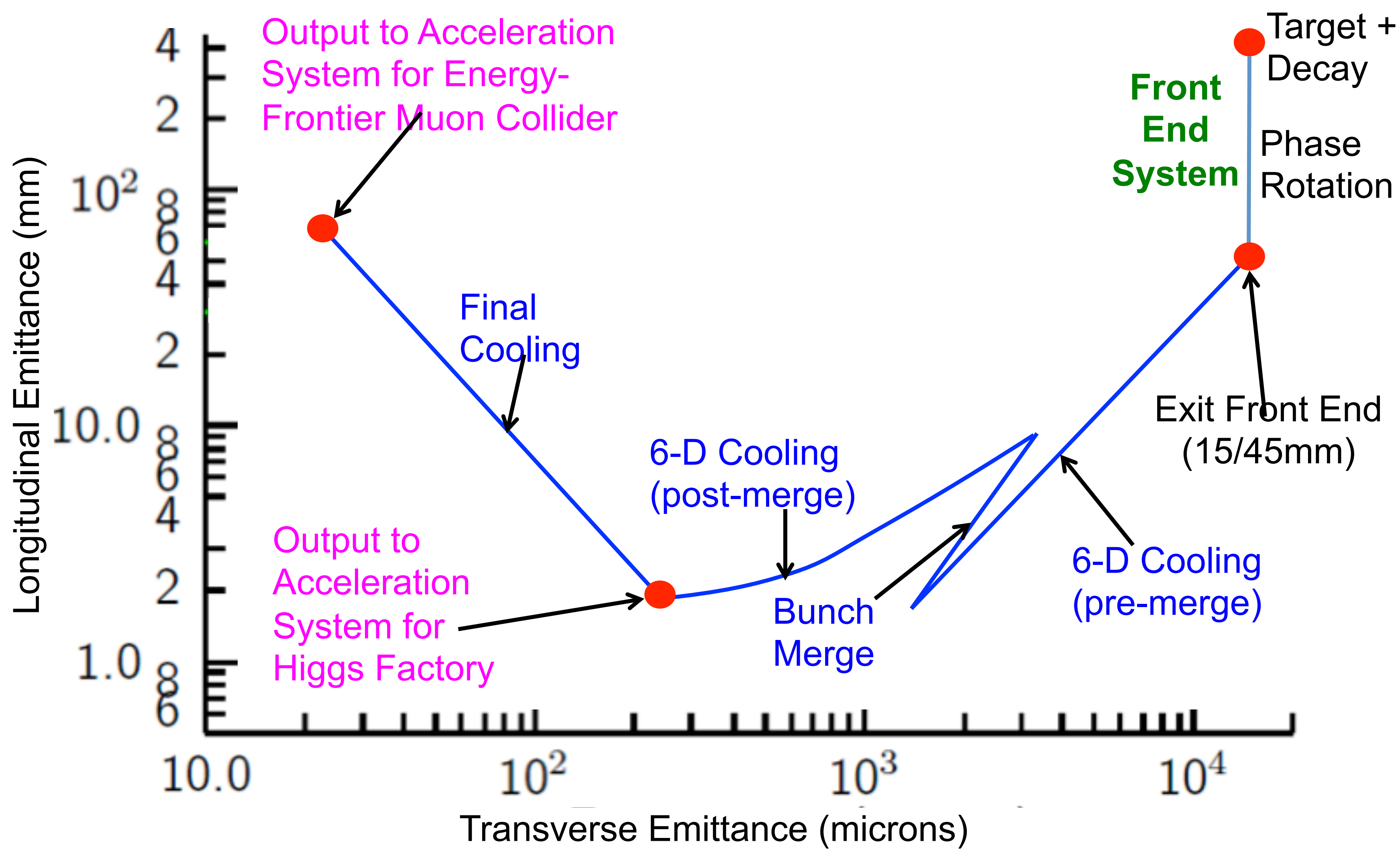
2. Muon beam cooling in all 6 dimensions
   - μ unstable, τ_μ = 2.2 μs ⇒ must cool *quickly*!...

* unless LEMMA shown to work

3. *Rapid* acceleration
   - Linac–RLAs–(FFAGs)–RCS [EMMA@DL, 2011]
4. High storage-ring bending field (to maximize # cycles before decay) and small $\beta_\perp$, for high $\mathcal{L}$
   - Solutions devised by MAP (FNAL), B ~ 10 T, $\beta_\perp$ ~ 1 cm

Muon Cooling

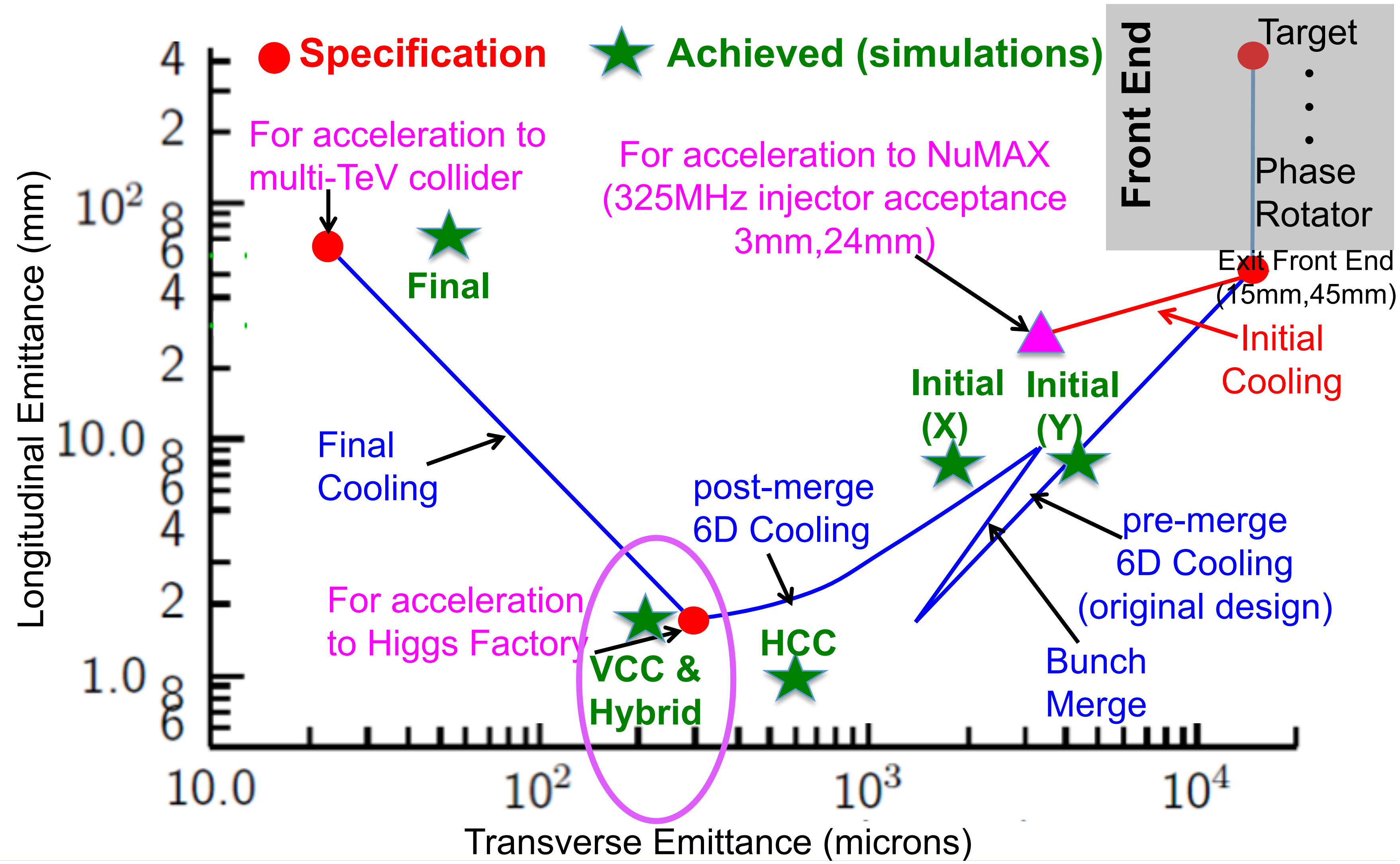
- Physics of multi-TeV lepton collisions calls for $\mathcal{L} \gtrsim 10^{34}$ cm^{-2} s^{-1}
- Higgs physics requires $\mathcal{L} \gtrsim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
- How to get there: (one scenario)
  - must cool both $\epsilon_\perp$ and $\epsilon_{||}$



  - need factor ≳10^6 total 6D emittance reduction

Muon Cooling

- Physics of multi-TeV lepton collisions calls for $\mathcal{L} \gtrsim 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
- Higgs physics requires $\mathcal{L} \gtrsim 10^{32}$ and $\Delta p/p \sim 10^{-5}$
- How to get there: (one scenario)
  - must cool both $\epsilon_{\perp}$ and $\epsilon_{||}$



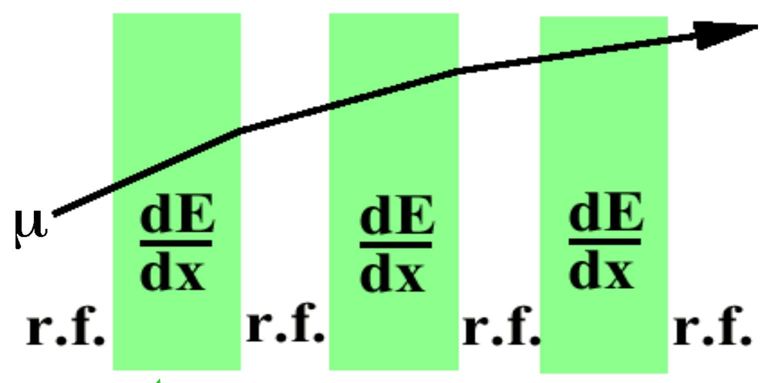
  - need factor $\gtrsim 10^6$ total 6D emittance reduction
    - simulation studies show most goals met or exceeded
      – ∃ ideas to go further

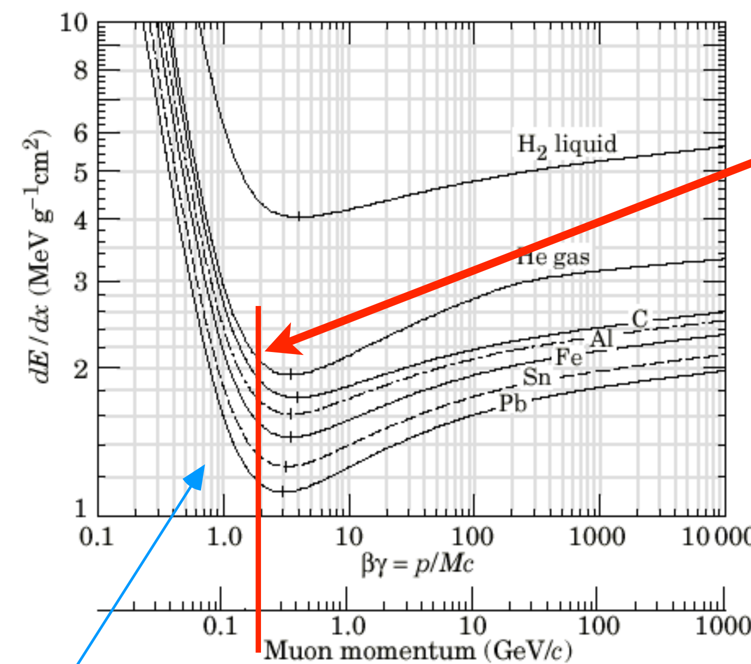
How cool muons?

- Problem: Average lifetime at rest = 2.2 μs
- But established cooling methods (stochastic, electron, laser) take seconds to hours!
- What cooling method can work in ≪ 2.2 μs?

Ionization Cooling

- Muons cool via *dE*/*dx* in low-Z medium:





- optimal working point is ≈ ionization minimum

– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- 2 competing effects ⇒ equilibrium emittance: $\varepsilon_0 \propto \beta_\perp \langle dE/dx \rangle X_0$

– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_\|$, i.e., transverse cooling:

$$\frac{d\varepsilon_n}{ds} \approx \frac{-1}{\beta^2}\left\langle \frac{dE_\mu}{dx} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{\beta_\perp (13.6\,\text{MeV})^2}{2\beta^3 E_\mu m_\mu c^2 X_0}$$

- Only* practical way to cool within μ lifetime

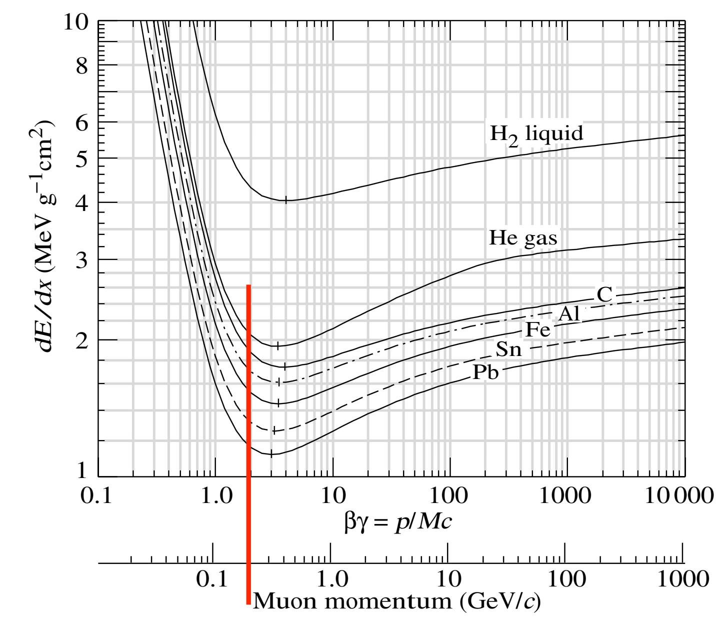
- Expt'l demo [MICE]

*unless optical stochastic cooling workable [IOTA]

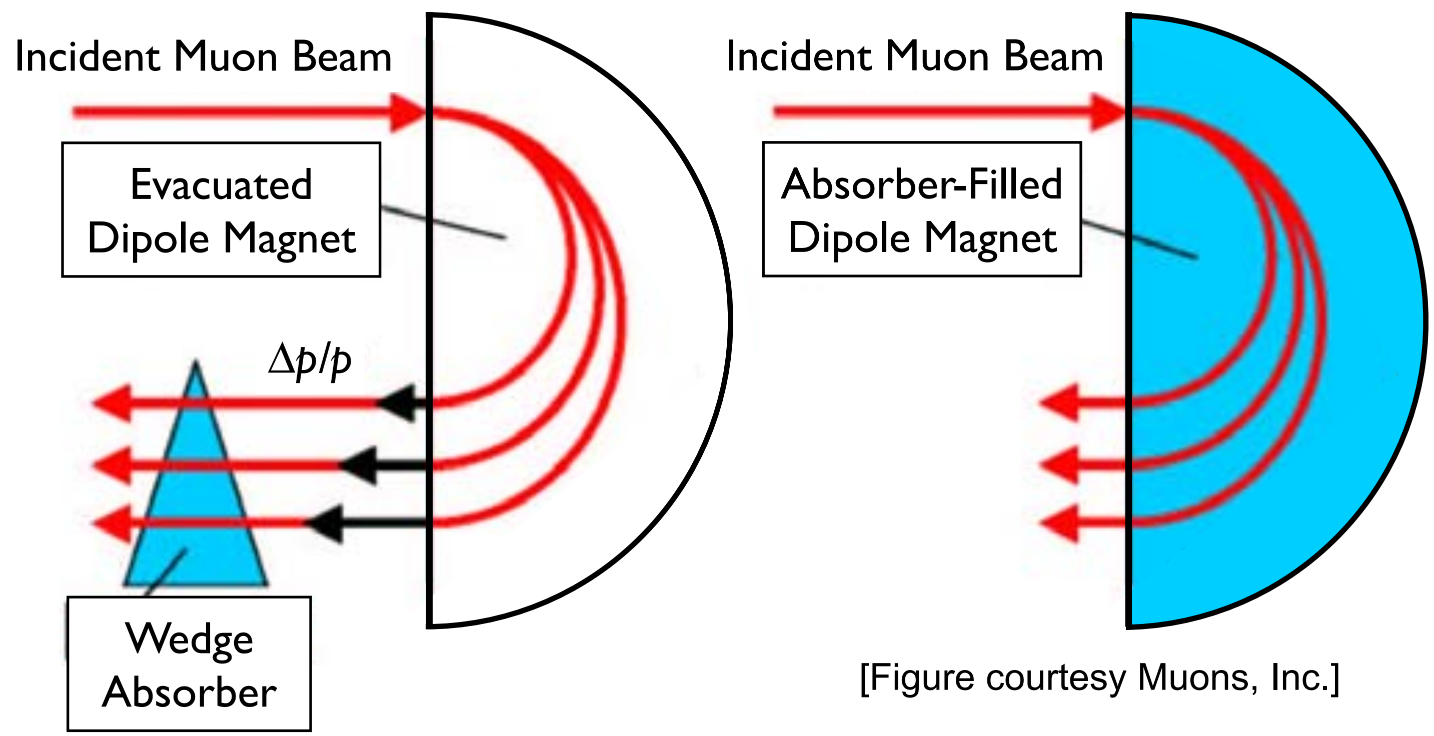
How to cool in 6D?

- Work above ionization minimum to get negative feedback in p_z?
- No – ineffective due to straggling

⇒cool longitudinally via *emittance exchange*:



- use dispersion to correlate momentum and position / path length



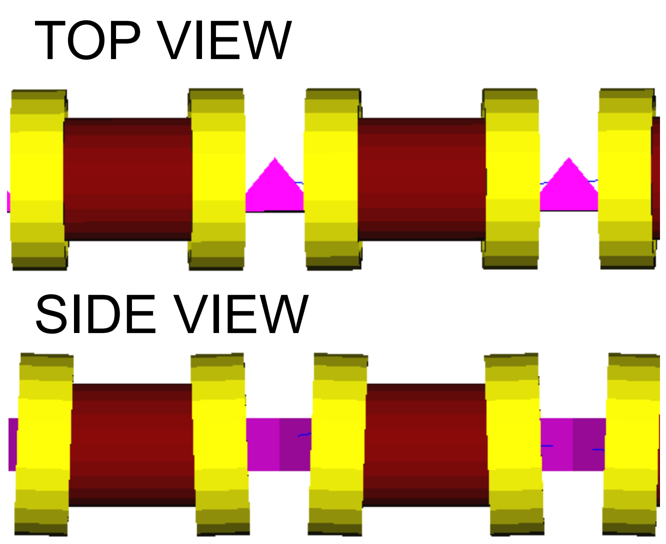
[Figure courtesy Muons, Inc.]

- Cool $\varepsilon_\perp$, exchange $\varepsilon_\perp$ & $\varepsilon_{||}$ → 6D cooling

How to cool in 6D?

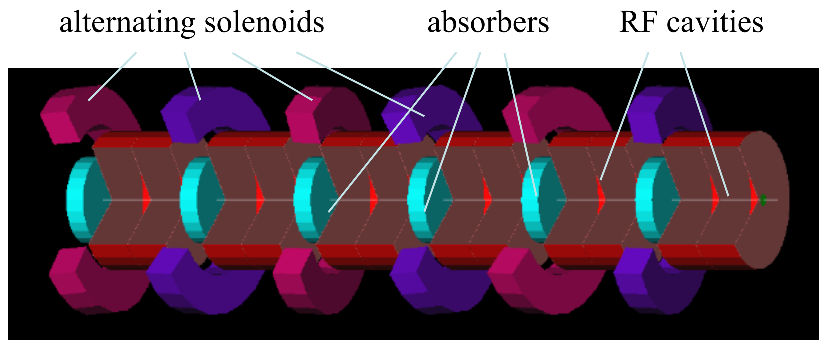
- Tricky beam dynamics: must handle dispersion, angular momentum, nonlinearity, chromaticity, & non-isochronous beam transport
- 3 types of solutions found viable in simulation:

Rectilinear FOFO



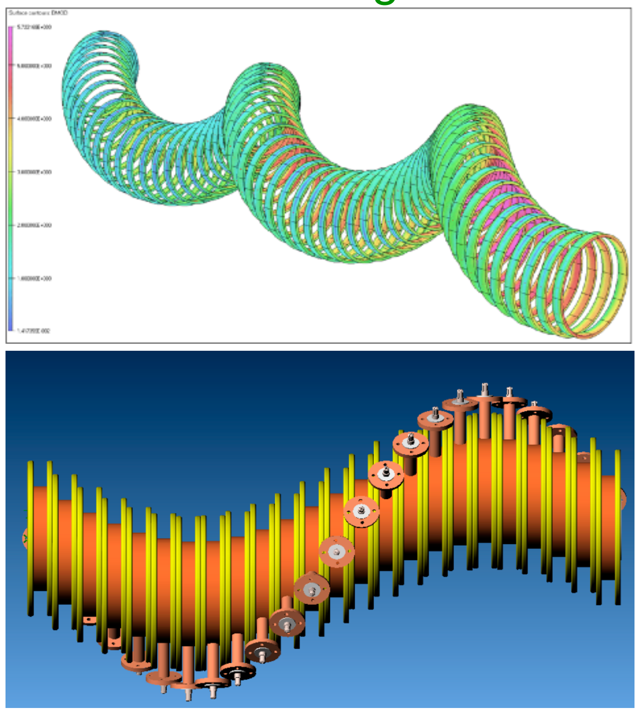
BNL & FNAL

FOFO Snake



Y. Alexahin, FNAL

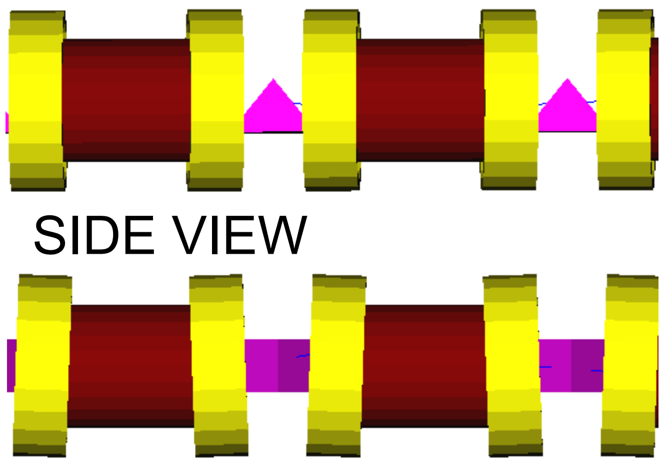
Helical Cooling Channel



Muons, Inc. & FNAL

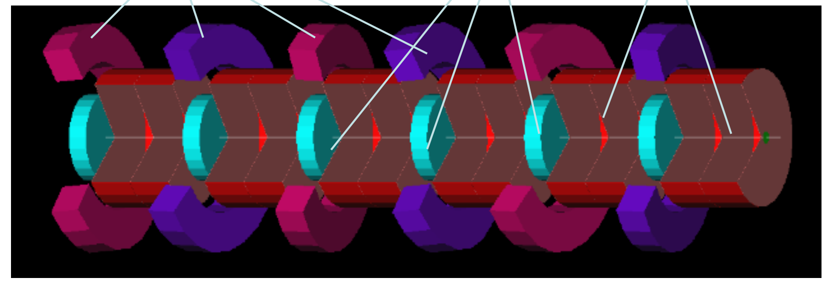
How to cool in 6D?

Rectilinear FOFO



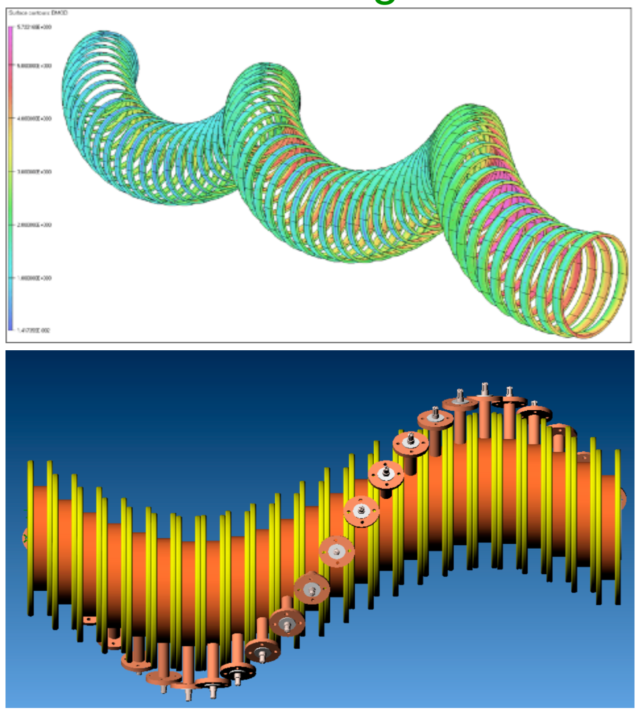
BNL & FNAL

FOFO Snake



Y. Alexahin, FNAL

Helical Cooling Channel



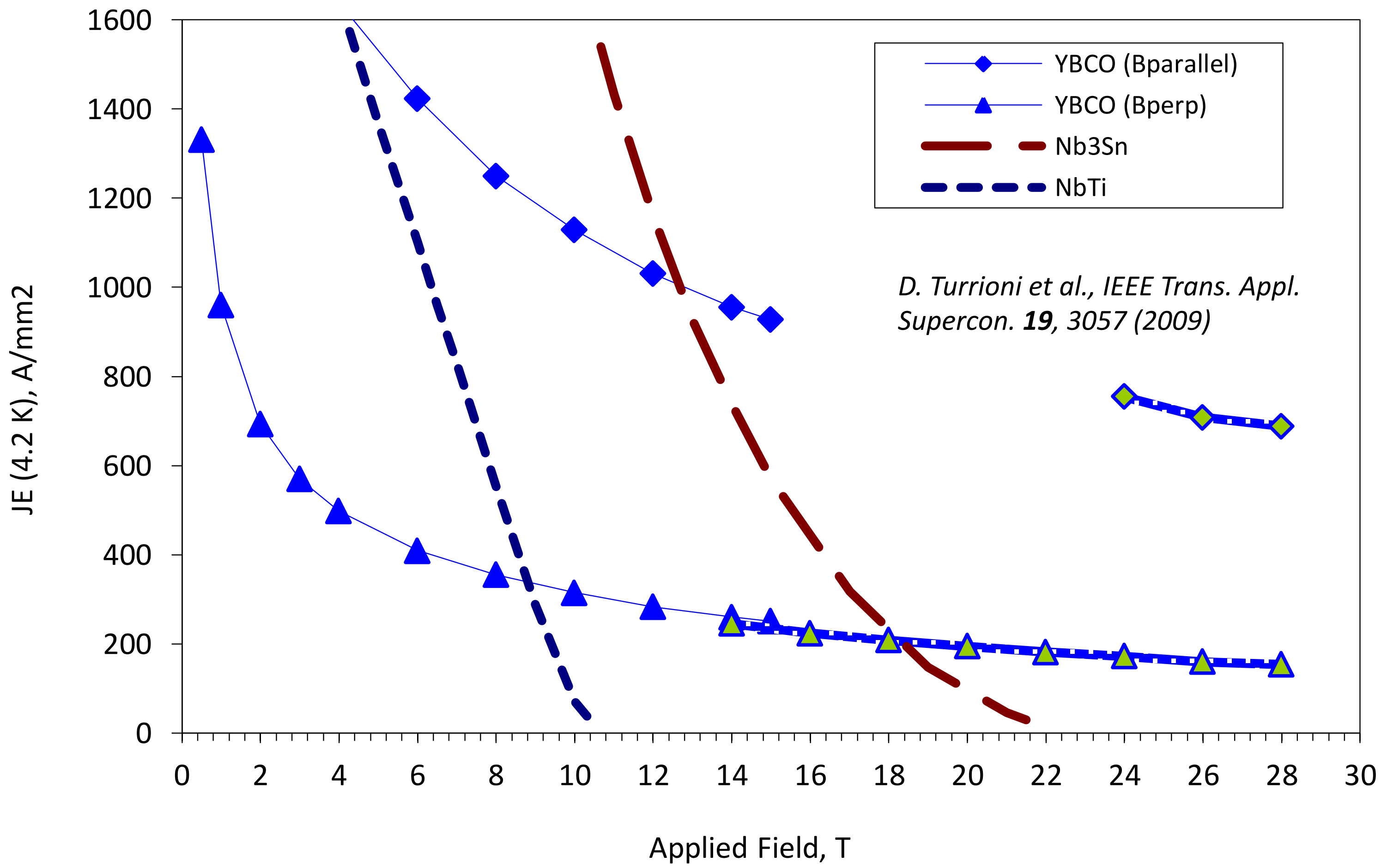
Muons, Inc. & FNAL

- FOFO Snake can cool both signs at once but limited in $\beta_{\perp,min}$ $\Rightarrow$ best for initial 6D cooling
- R_FOFO – both vacuum-RF & pressurized versions
- HCC may be most compact
- Performance limits of each not yet clear, nor which is most cost-effective

"Beyond" 6D Cooling

- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with *B* ~ 30 T at low momentum
  - gives lower β & higher *dE/dx*:

$$\beta_\perp \sim \frac{p}{B}$$

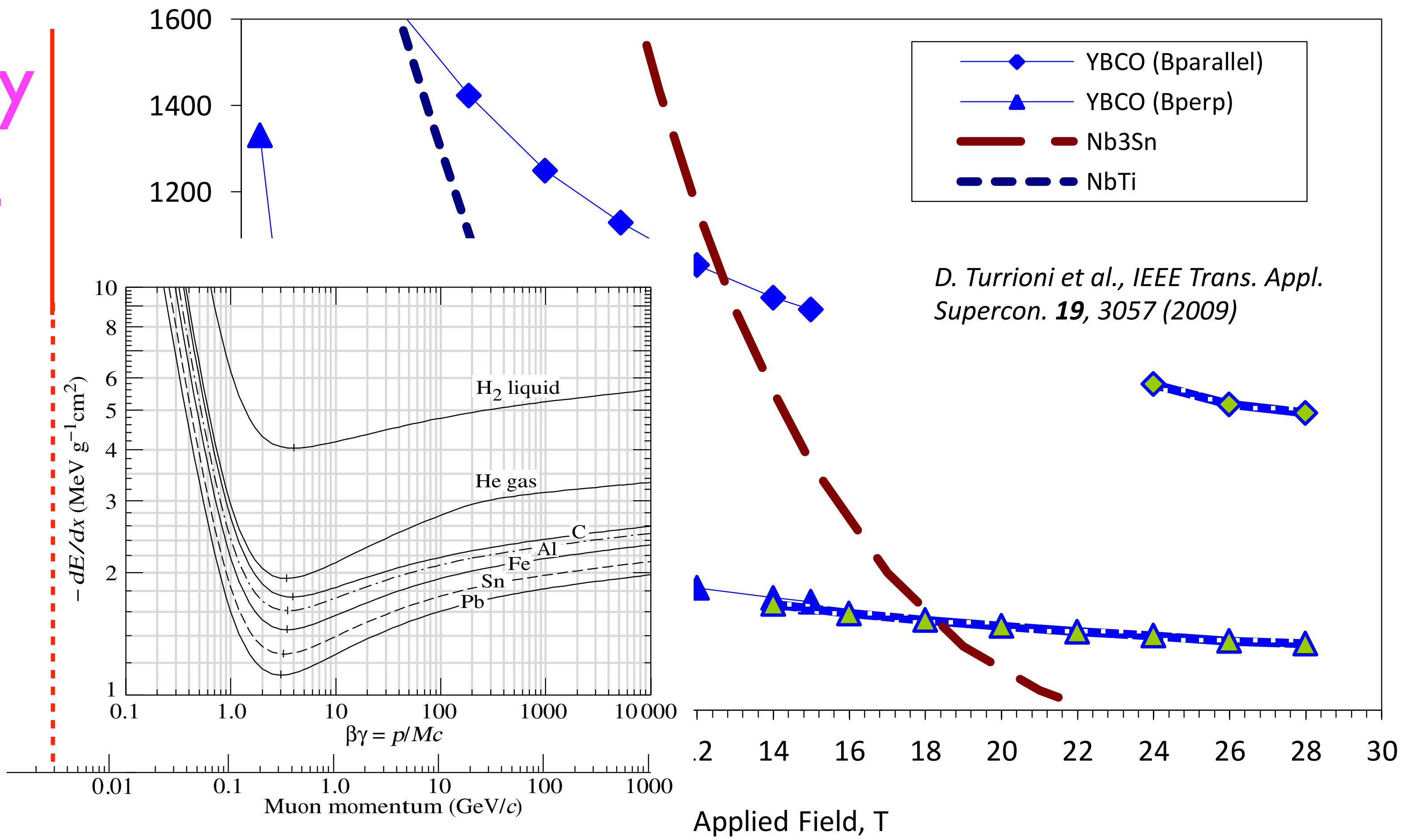


- Lower-*B* options under study as well (Derbenev PIC, REmEx, lithium lenses)

"Beyond" 6D Cooling

- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with B ~ 30 T at low momentum
  - gives lower β & higher dE/dx:

$$\beta_{\perp} \sim \frac{p}{B}$$

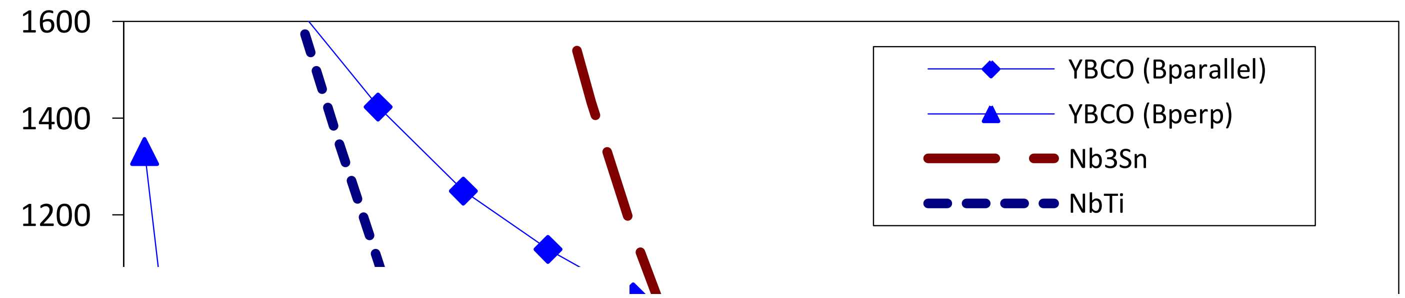


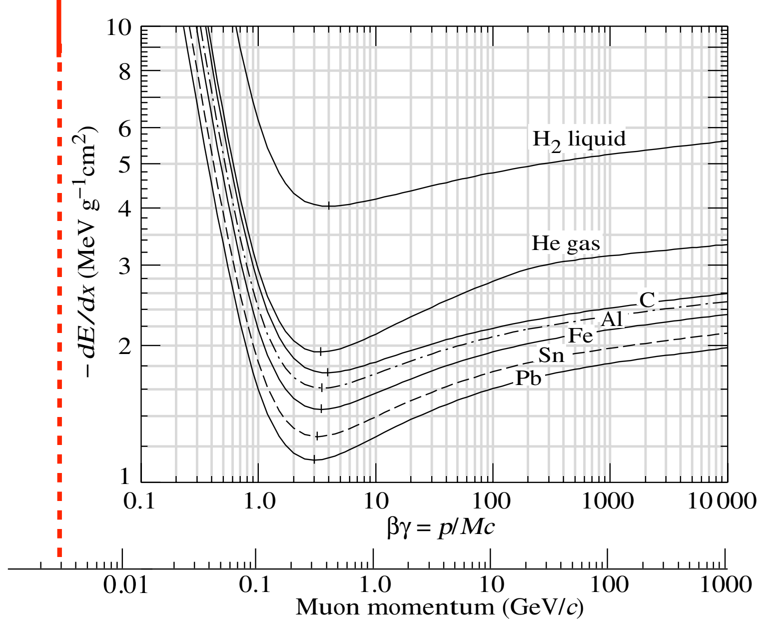
- Lower-B options under study as well (Derbenev PIC, REmEx, lithium lenses)

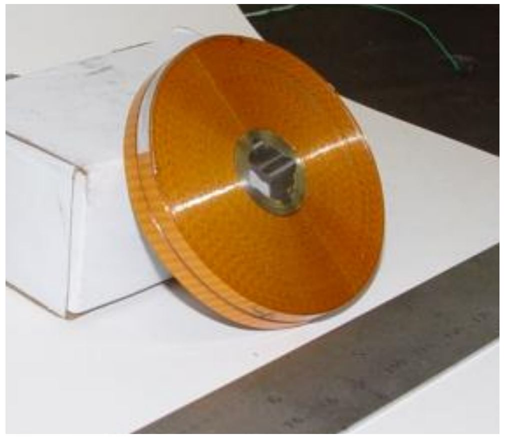
"Beyond" 6D Cooling

- To reach ≤25 μm transverse emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely with *B* ~ 30 T at low momentum
  - gives lower β & higher *dE/dx*:

$$\beta_\perp \sim \frac{p}{B}$$







High-field YBCO solenoid (BNL/Particle Beam Lasers, Inc.)

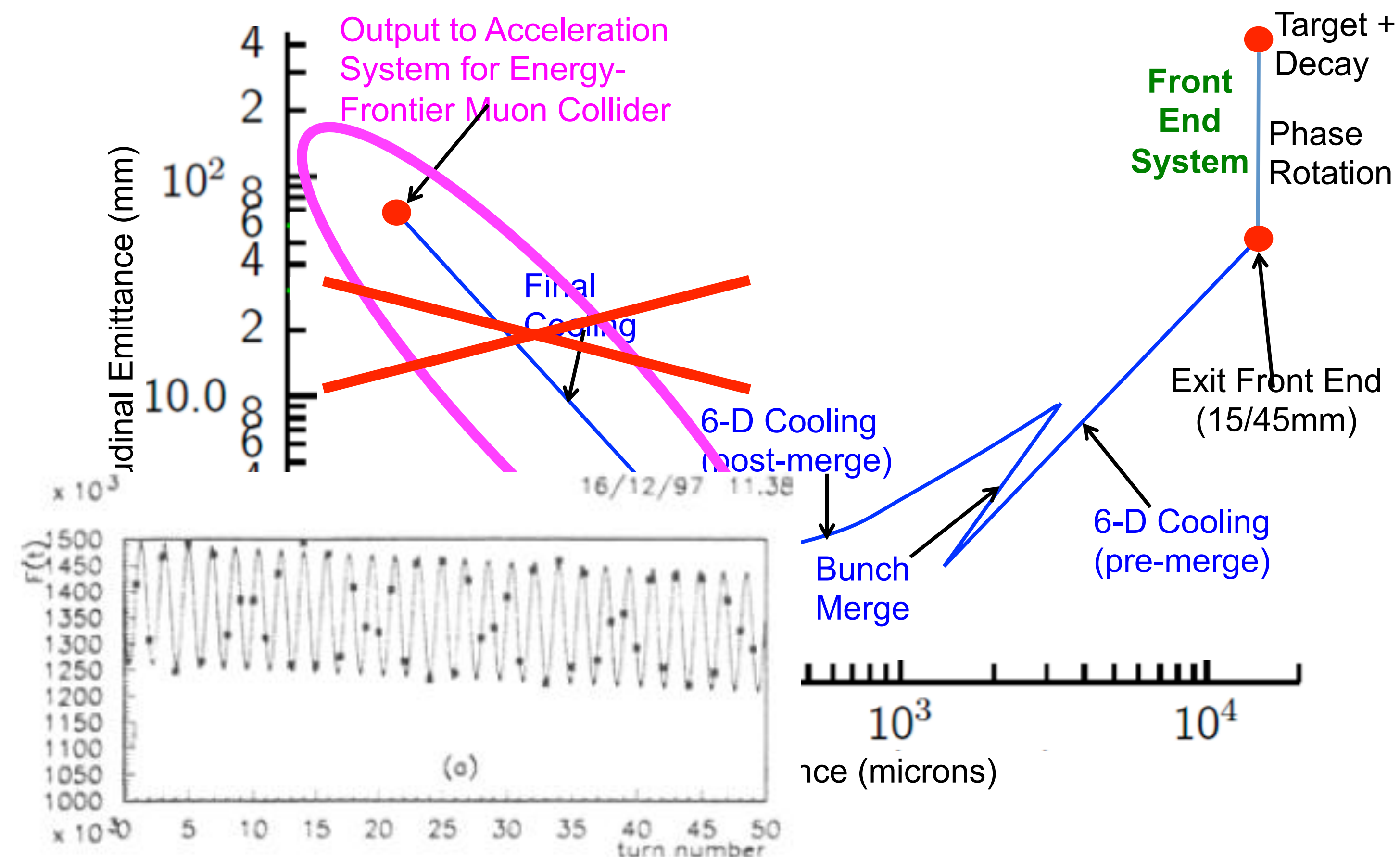
- Lower-*B* options under study as well (Derbenev PIC, REmEx, lithium lenses)

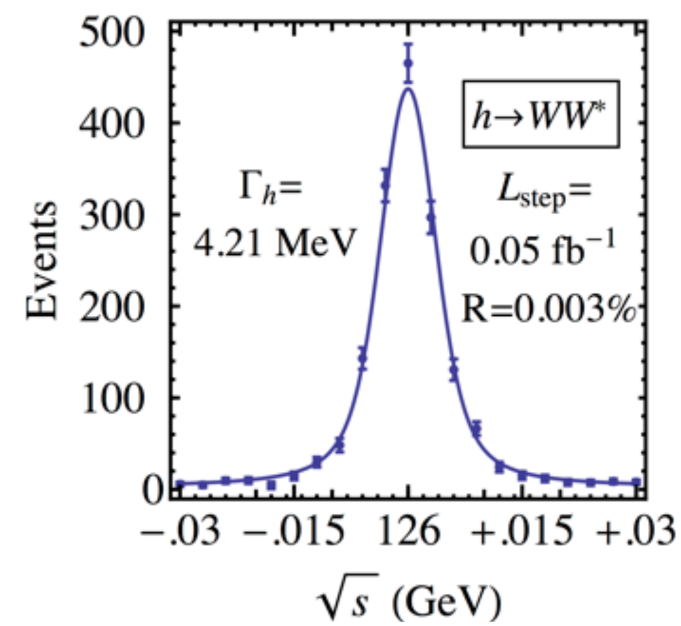
Higgs Factory Cooling

- $\mu^+\mu^-$ Higgs Factory requires exquisite energy precision:
  - use $\mu^+\mu^- \rightarrow h$ *s*-channel resonance, $dE/E \approx 0.003\% \approx \Gamma_h^{SM} = 4$ MeV

  $\Rightarrow$ omit final cooling

  - 10^{-6} energy calib. via $(g-2)_\mu$ spin precession!
  - measure Γ_h, lineshape (& m_h) via $\mu^+\mu^-$ resonance scan
    - the only way to do so!
    - and a key test of the SM



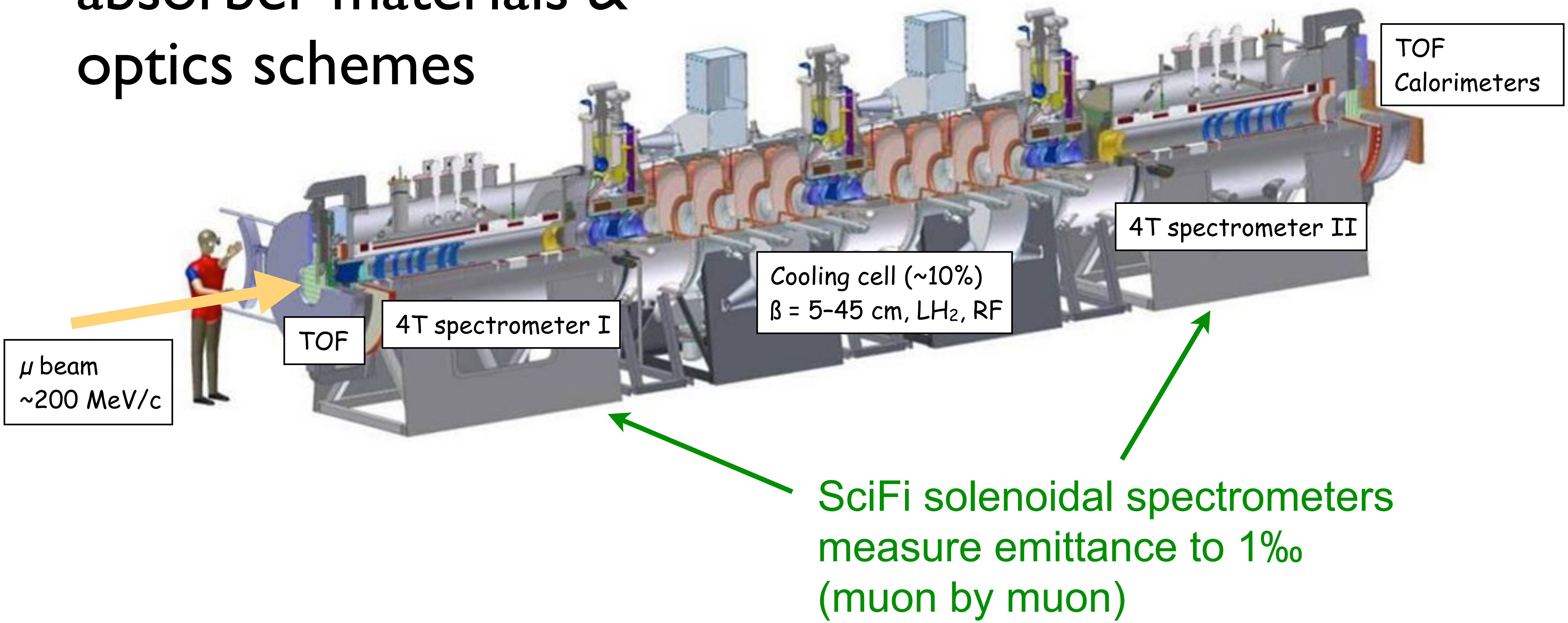


[P. Janot, HF2012]

MICE

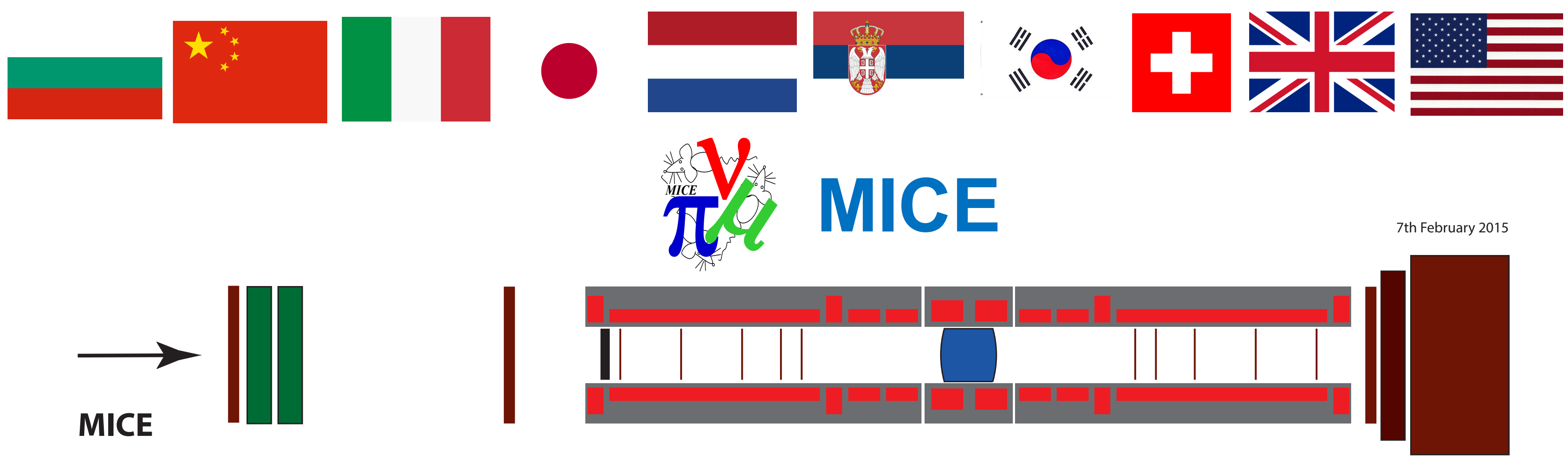
- International Muon Ionization Cooling Experiment at UK's Rutherford Appleton Laboratory (RAL)

- Flexibility to test several absorber materials & optics schemes



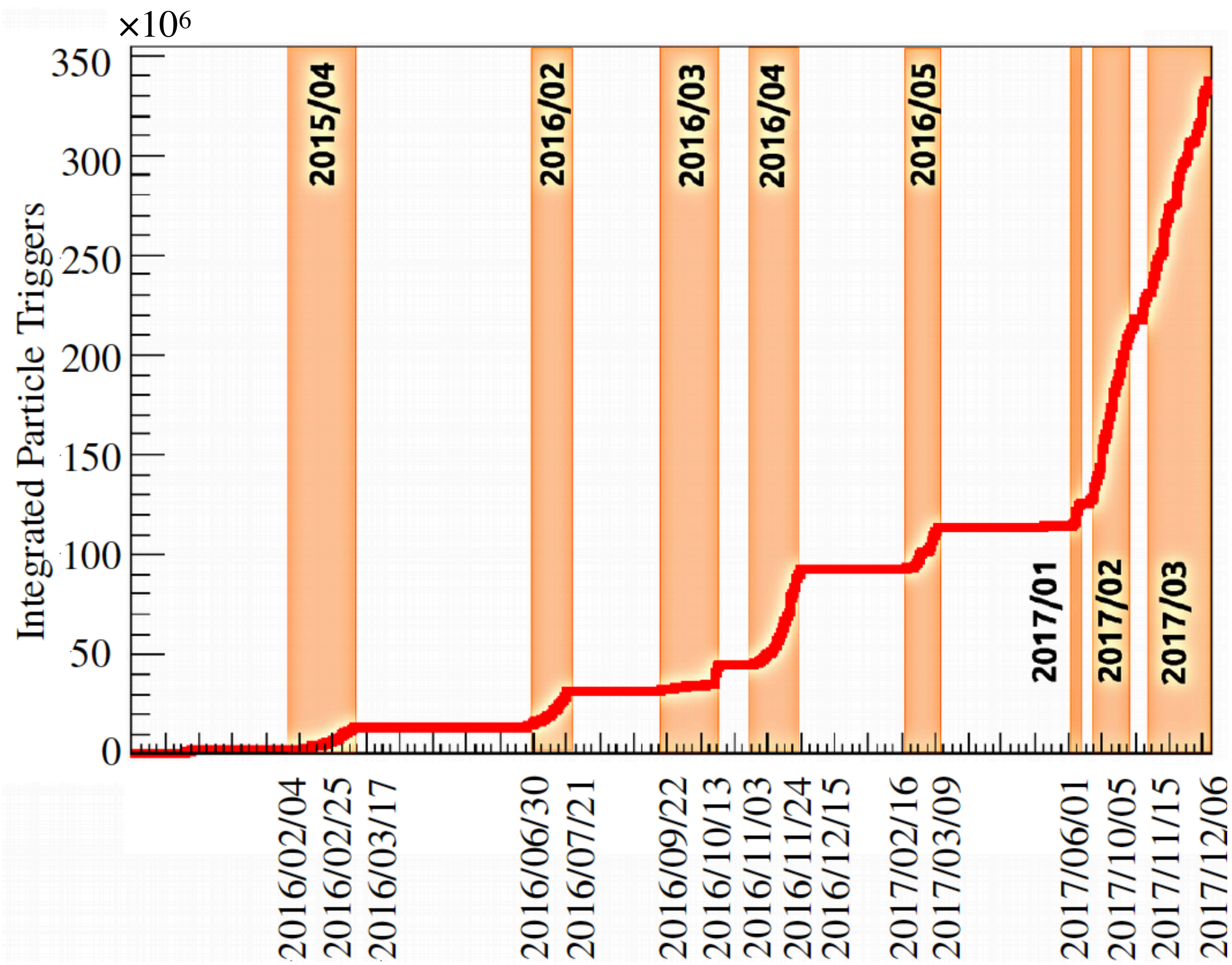
- **Status:** data-taking complete, analysis in progress

MICE



- International collaboration of >100 scientists and engineers, from >30 institutions in 10 countries

- Successful data-taking campaign finished in 2017



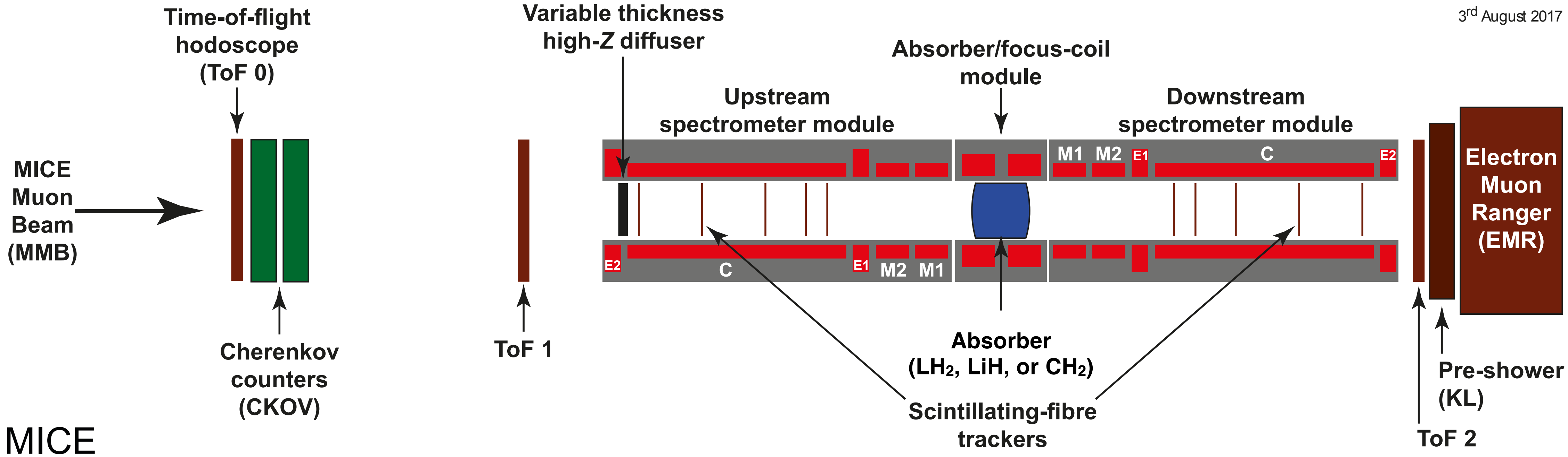
- 3.5×10^8 triggers recorded

Principles of MICE

- Cost-effective: use minimal cooling channel
  - one complete lattice cell → ~10% cooling effect
    - in the end we built only a single absorber–focus-coil module → ~5% cooling effect
- Measure emittance with 0.1% precision
  - allows even small cooling effects near equilibrium emittance to be well measured

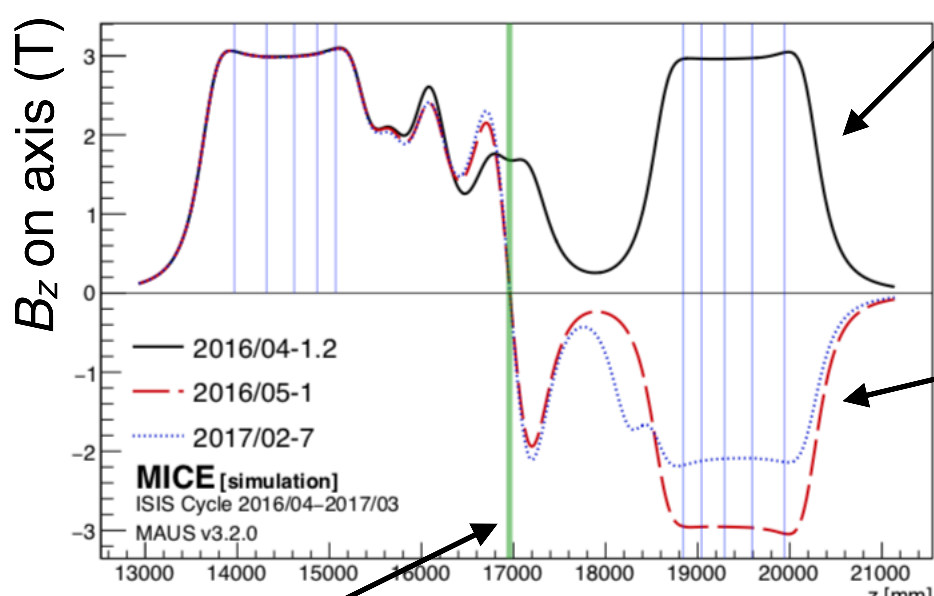
  ⇒ need to measure muon beam one muon at a time
- Vary all parameters to explore full performance range, validate simulation tools

Principles of MICE



MICE

- Typical optics vs. z:



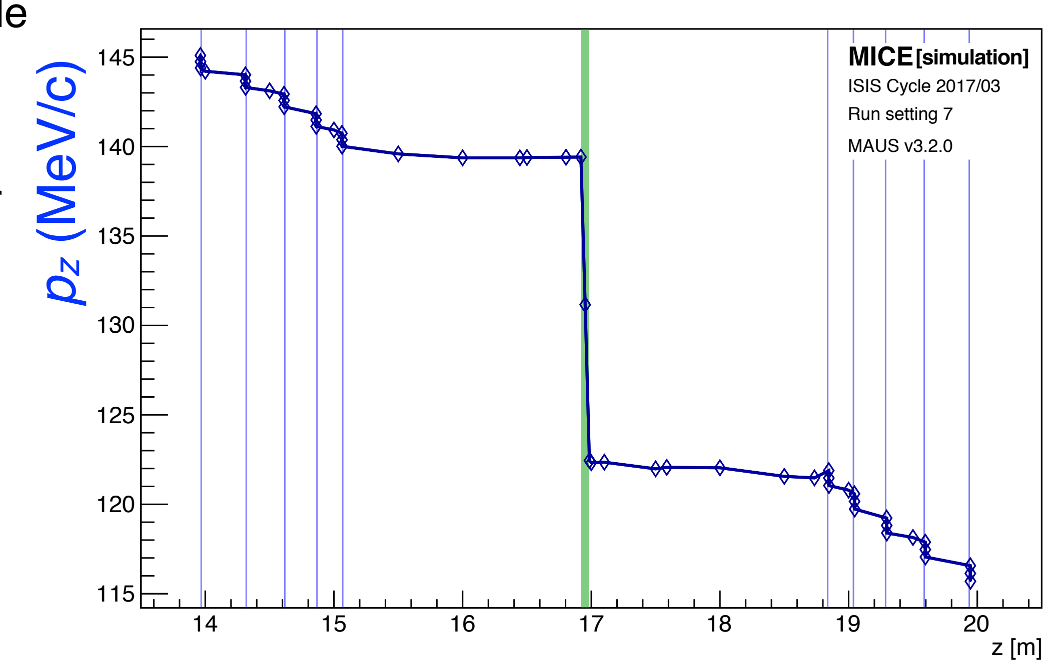
"Solenoid" mode

(Fields asymmetric about absorber when M1D & M2D off)

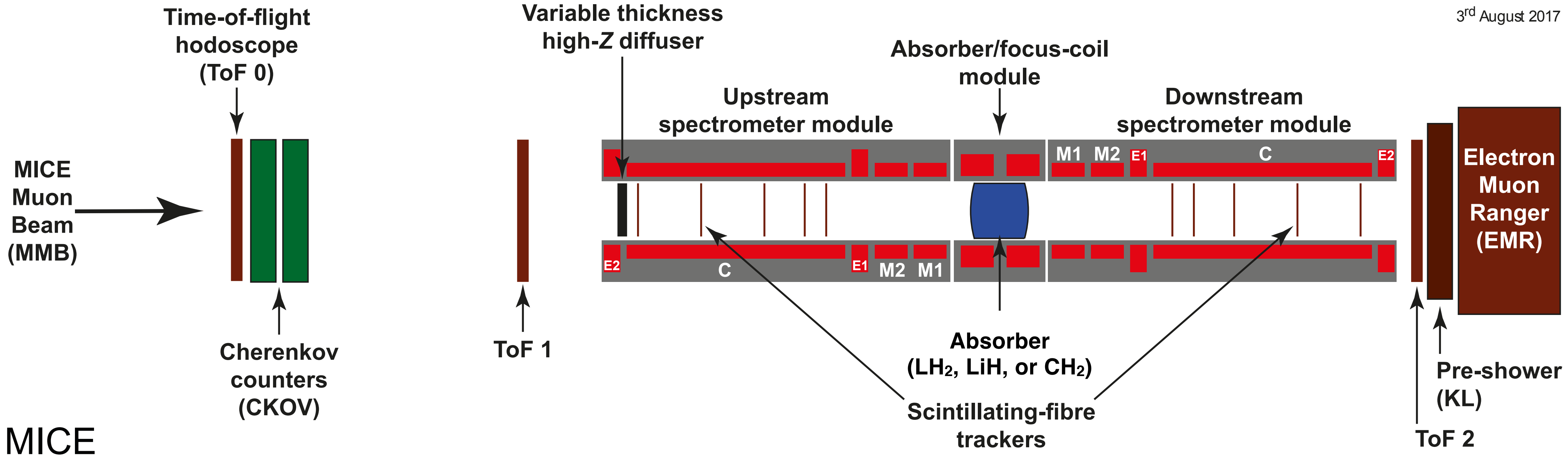
"Flip" mode

Absorber position

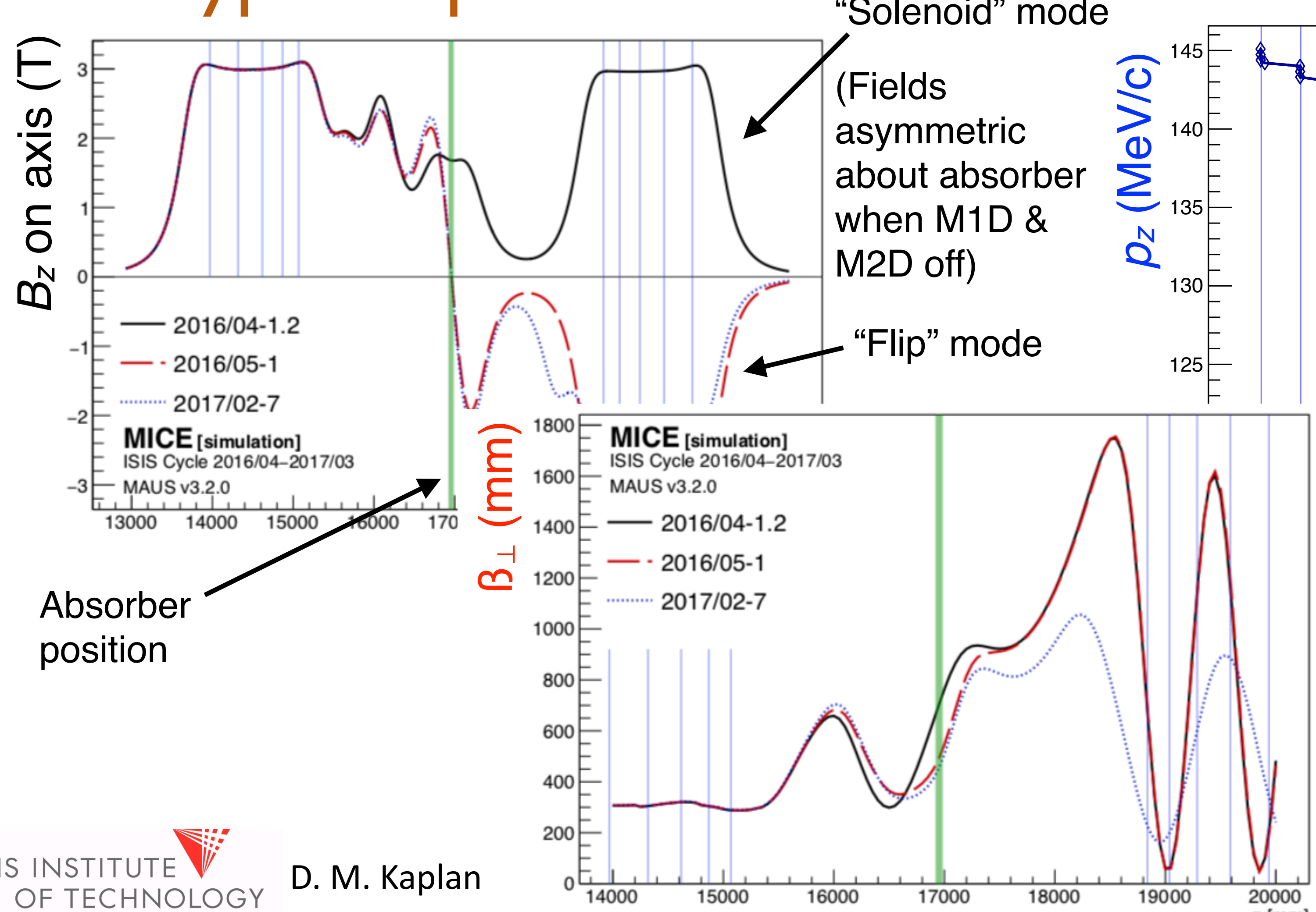
- Beam behavior vs. z:



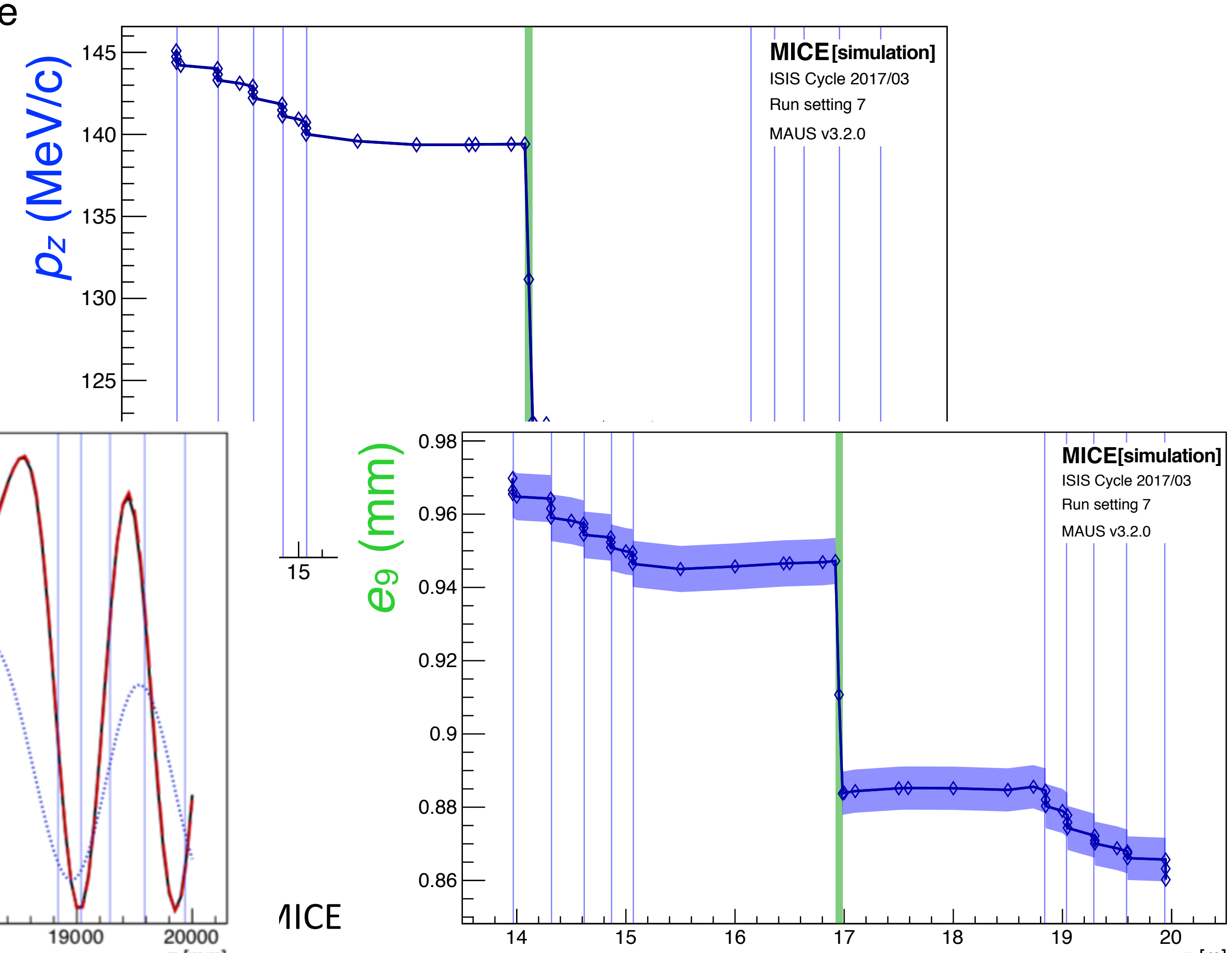
Principles of MICE



- Typical optics vs. z:

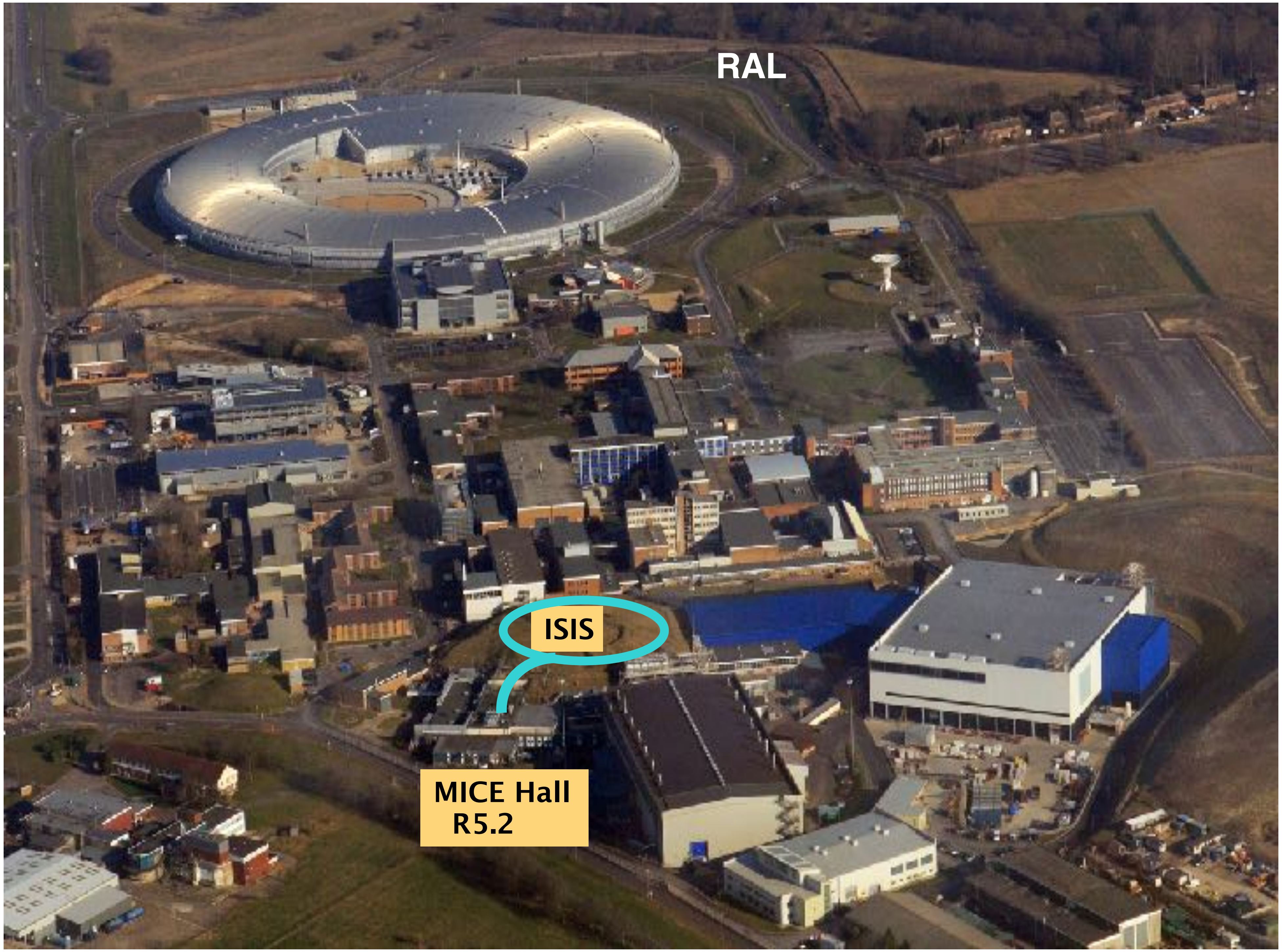


- Beam behavior vs. z:



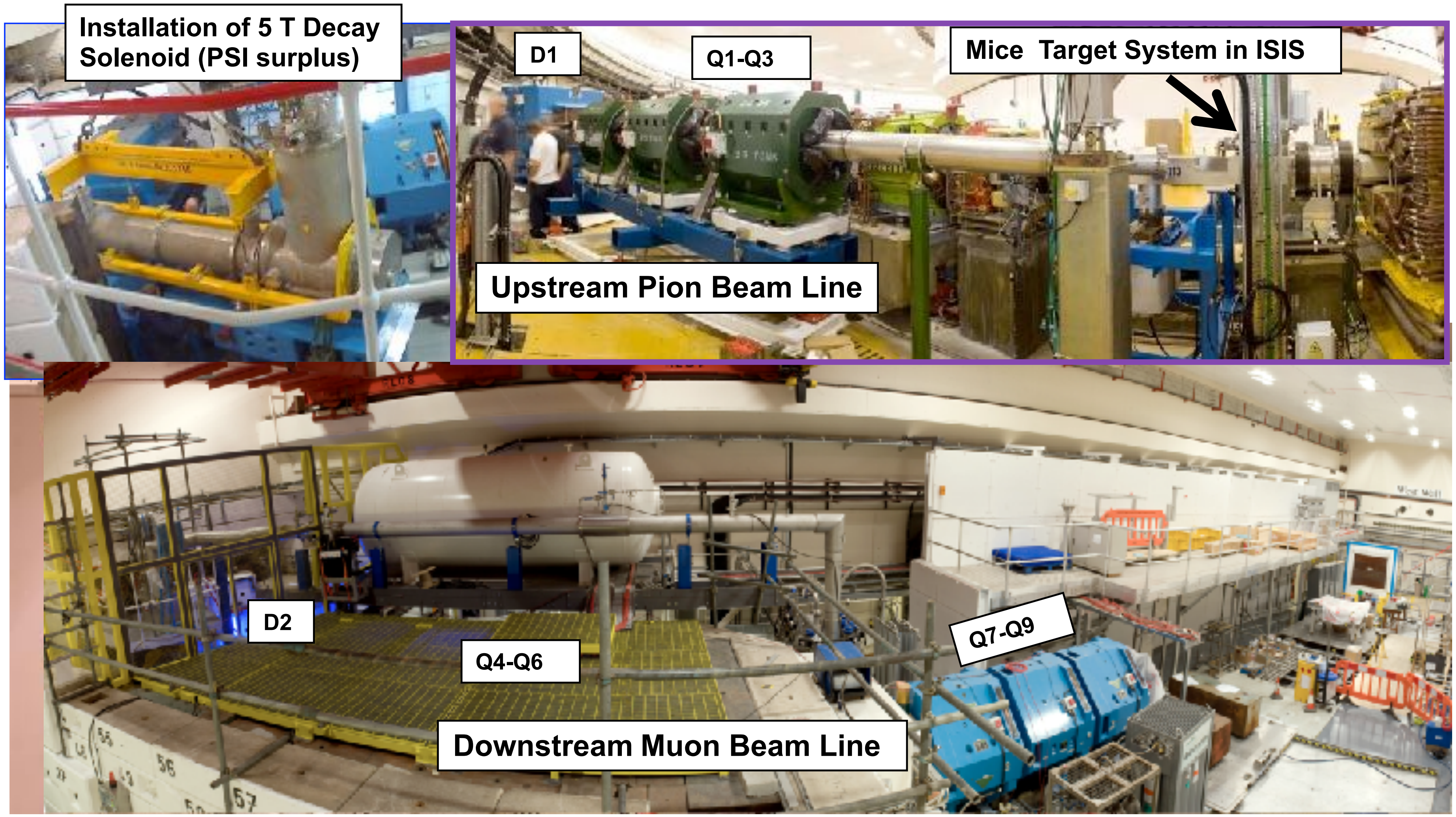
MICE Equipment

- Quick tour:



MICE Equipment

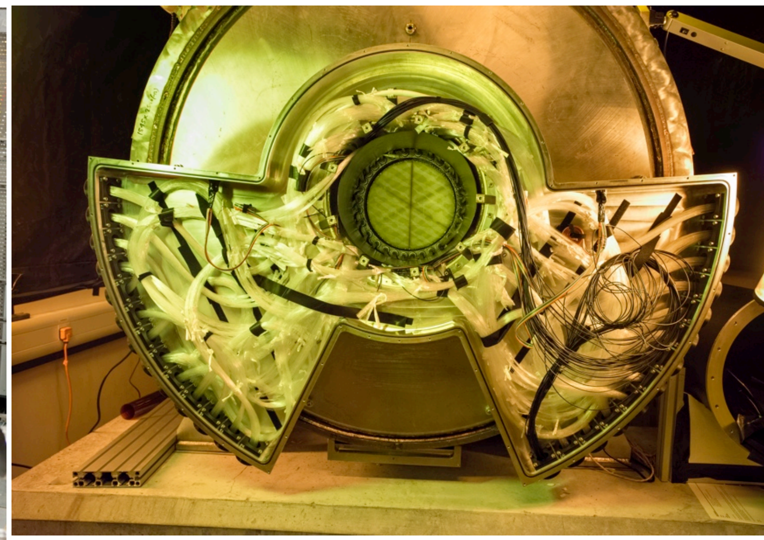
- Quick tour:



MICE Equipment

- Quick tour:

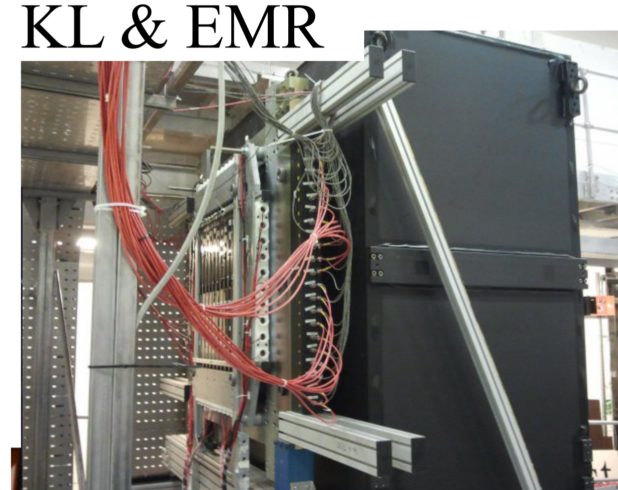
Spectrometer Solenoids



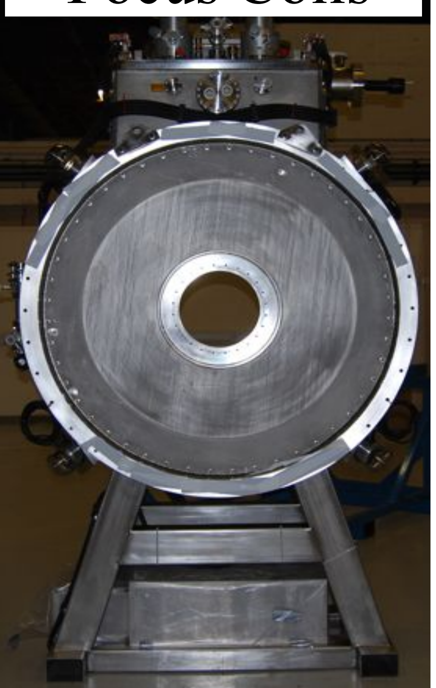
SciFi Trackers

Diffuser

KL & EMR

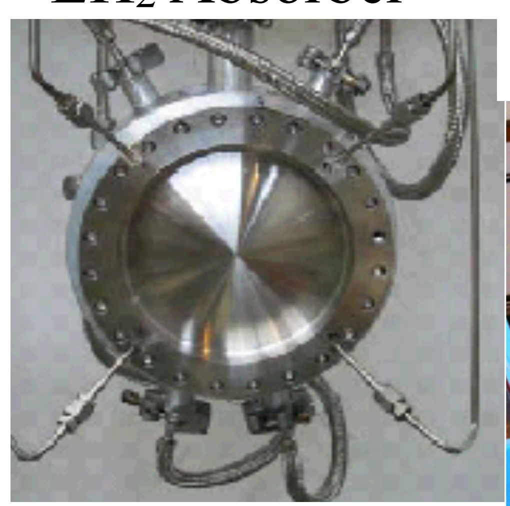


Focus Coils

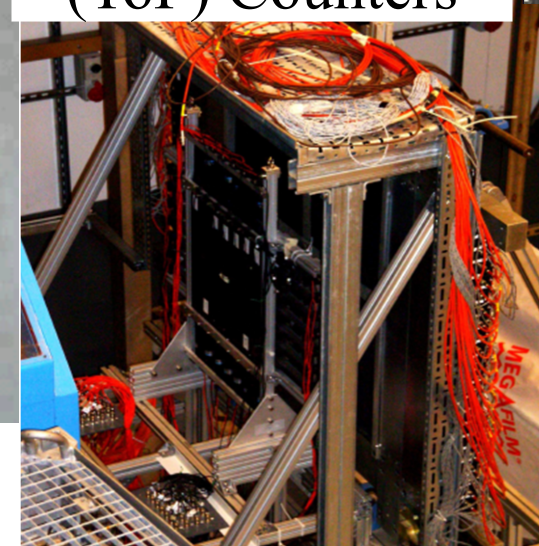


LiH Absorber

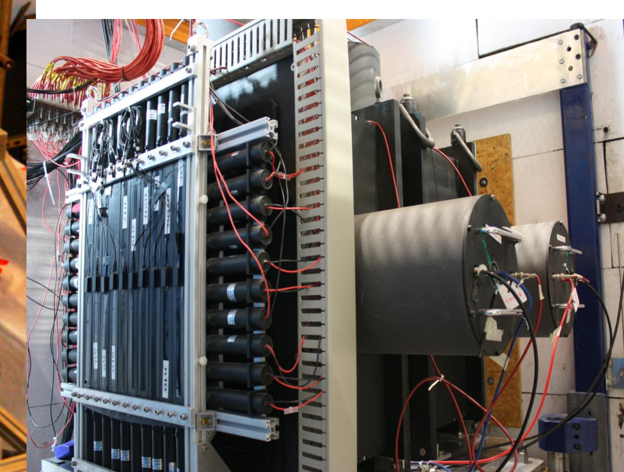
LH_2 Absorber



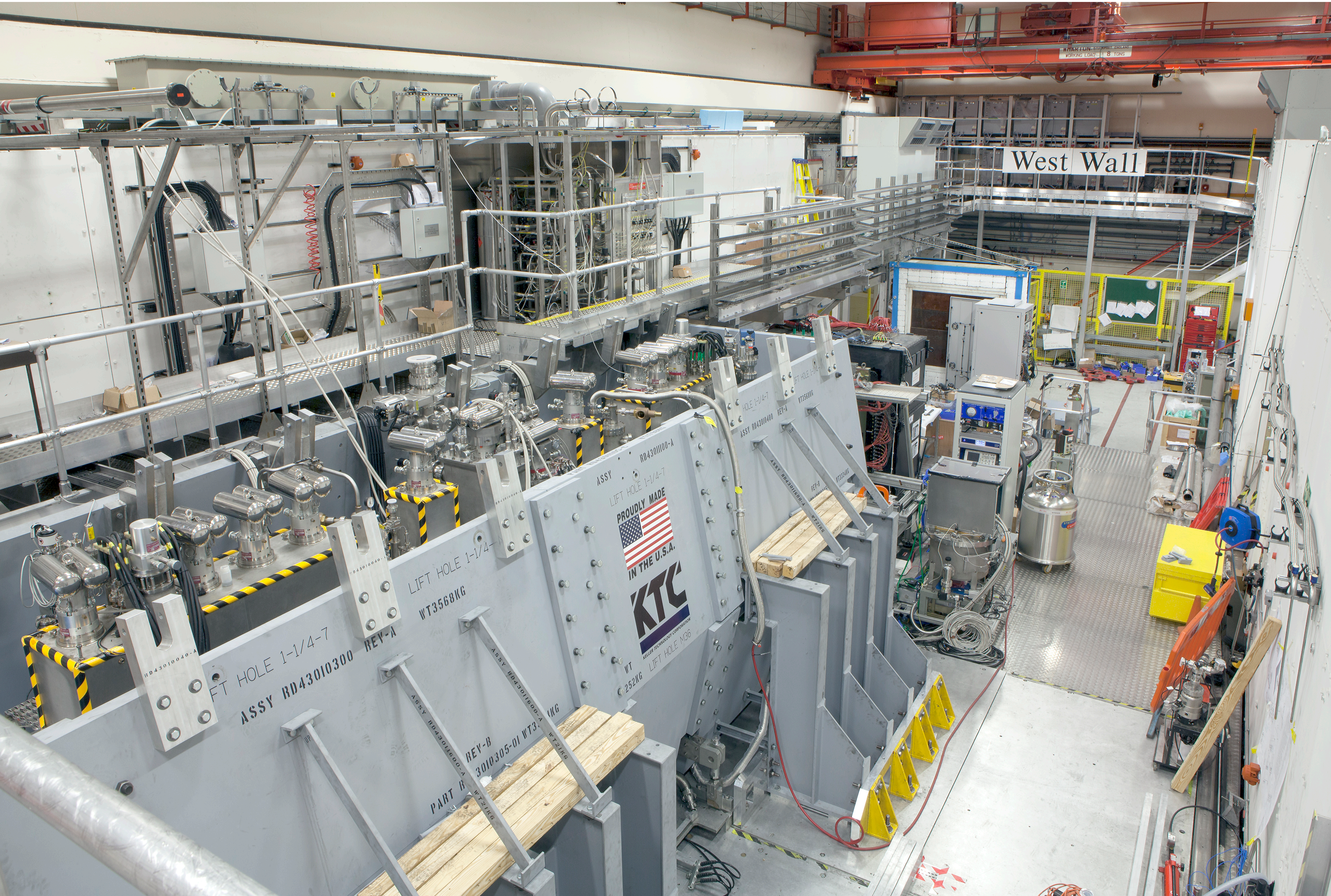
Time-of-Flight (ToF) Counters



ToF & Ckov Counters



MICE Equipment



Selected MICE Results…

Beam Characterization

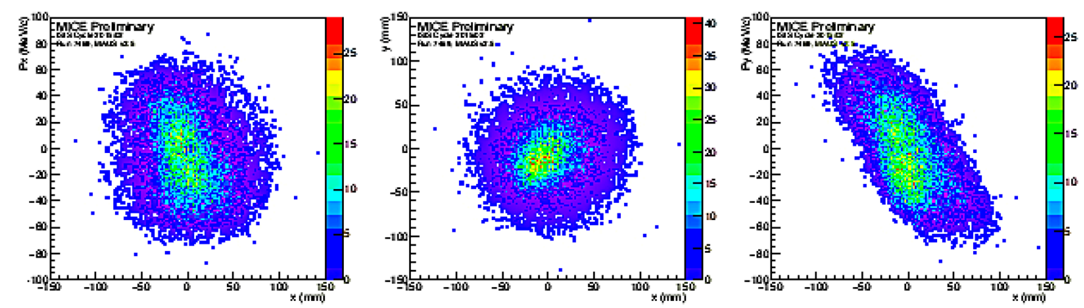
- Muon-beam emittance determined from measured individual-muon phase-space coordinates
  - 4D transverse phase-space of muons: (x, p_x, y, p_y)

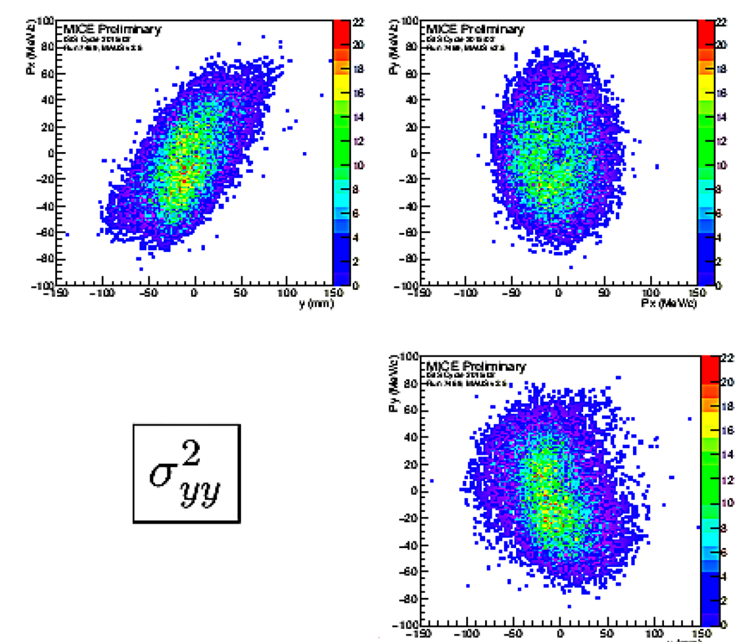
→ normalized RMS transverse emittance: $\varepsilon_n = \frac{\sqrt[4]{|\Sigma_4 D|}}{mc}$

Σ_4: 4D covariance matrix of coordinates

x p_x y p_y

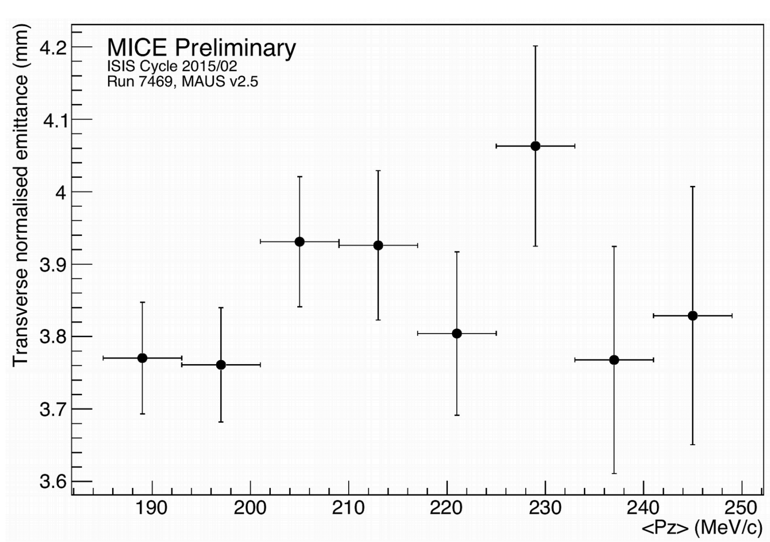
σ^2_{xx} $\sigma^2_{p_x p_x}$ σ^2_{yy}





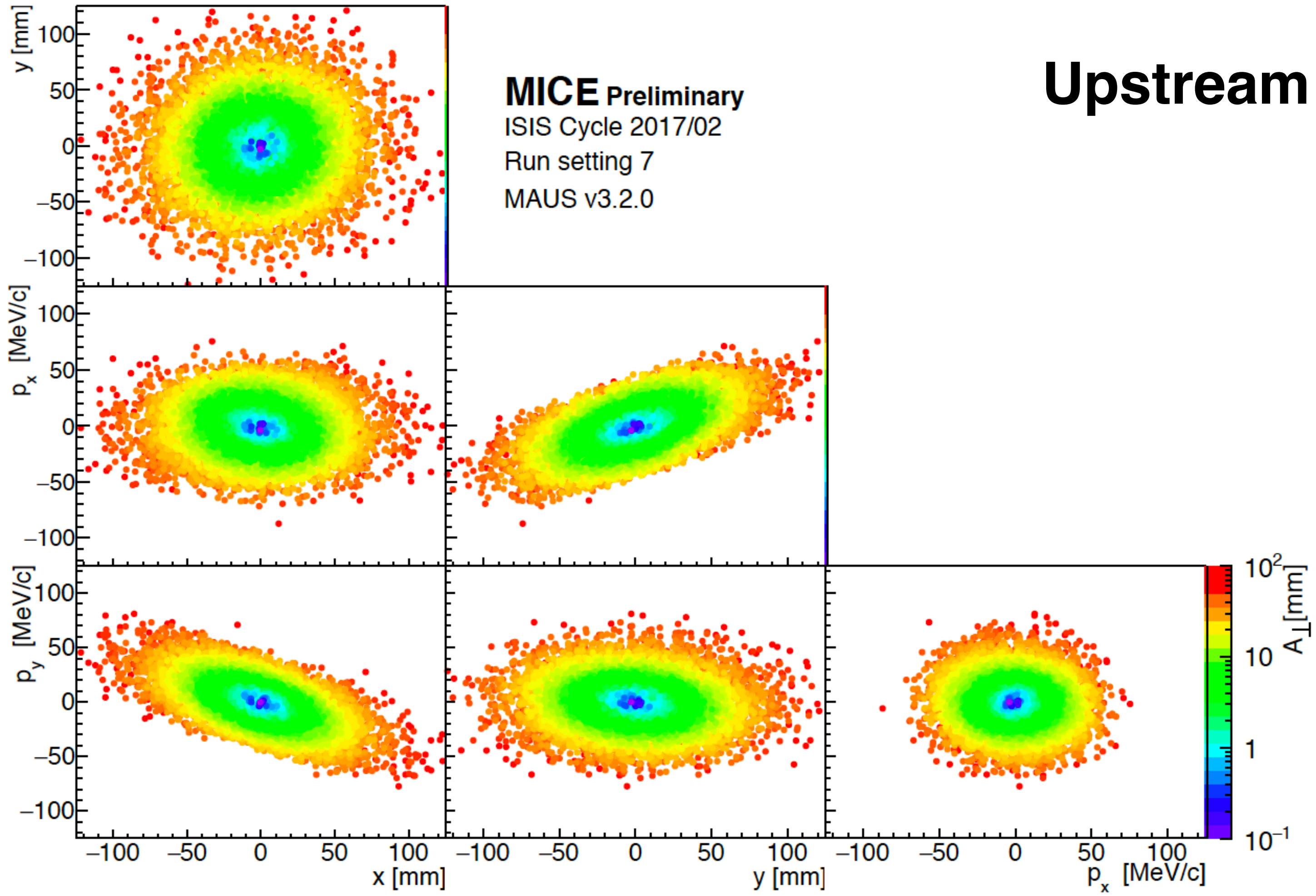
Poincaré sections (note x-p_y & y-p_x correlations due to solenoidal optics):

- give ε_n vs. p_z in typical ("3 mm") beam setting



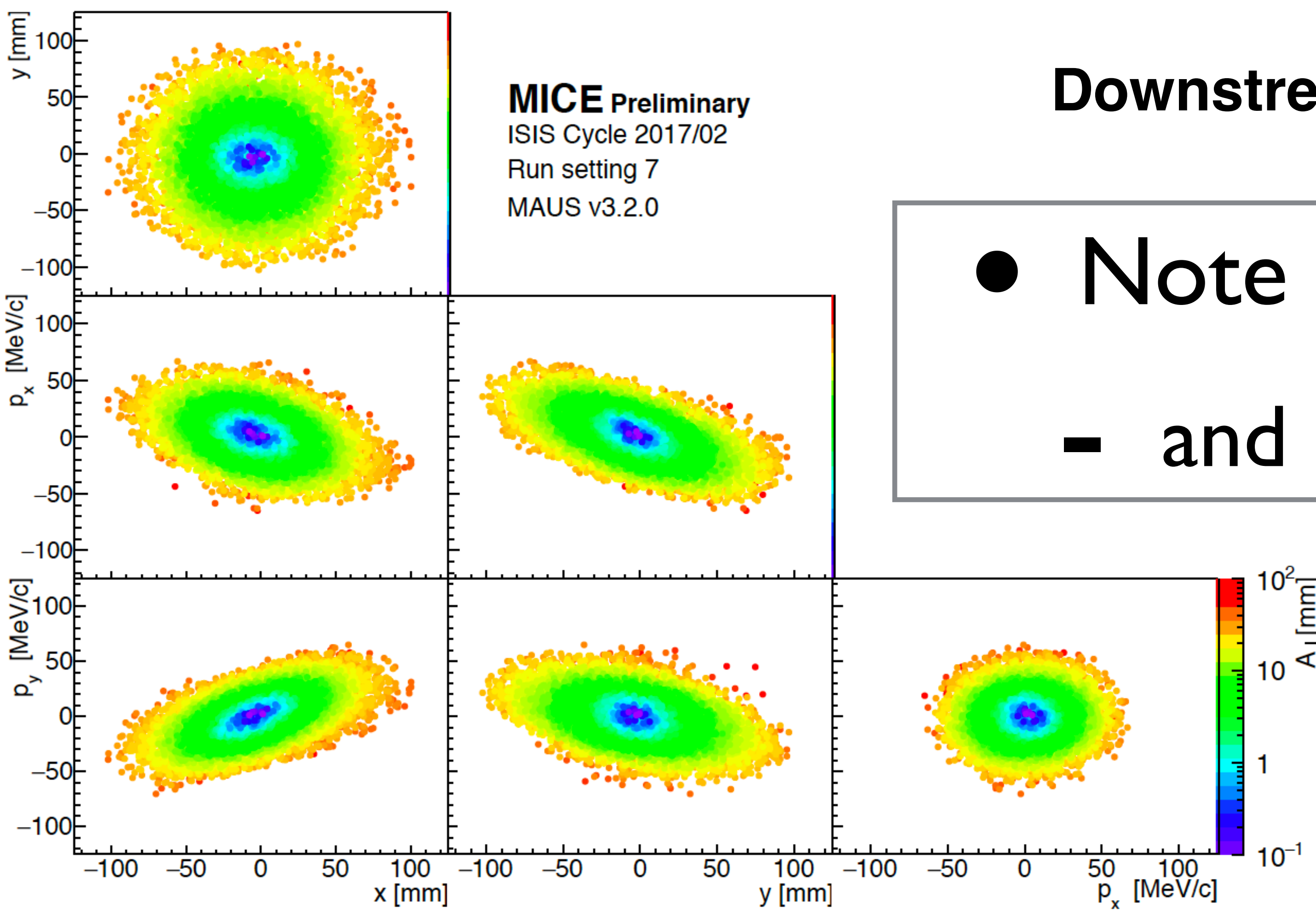
Cooling Measurements

- Since we know *each muon's* coordinates, can compute individual-muon *amplitudes*
  - 4D distance of each muon from beam centroid
  - more informative than emittance



Cooling Measurements

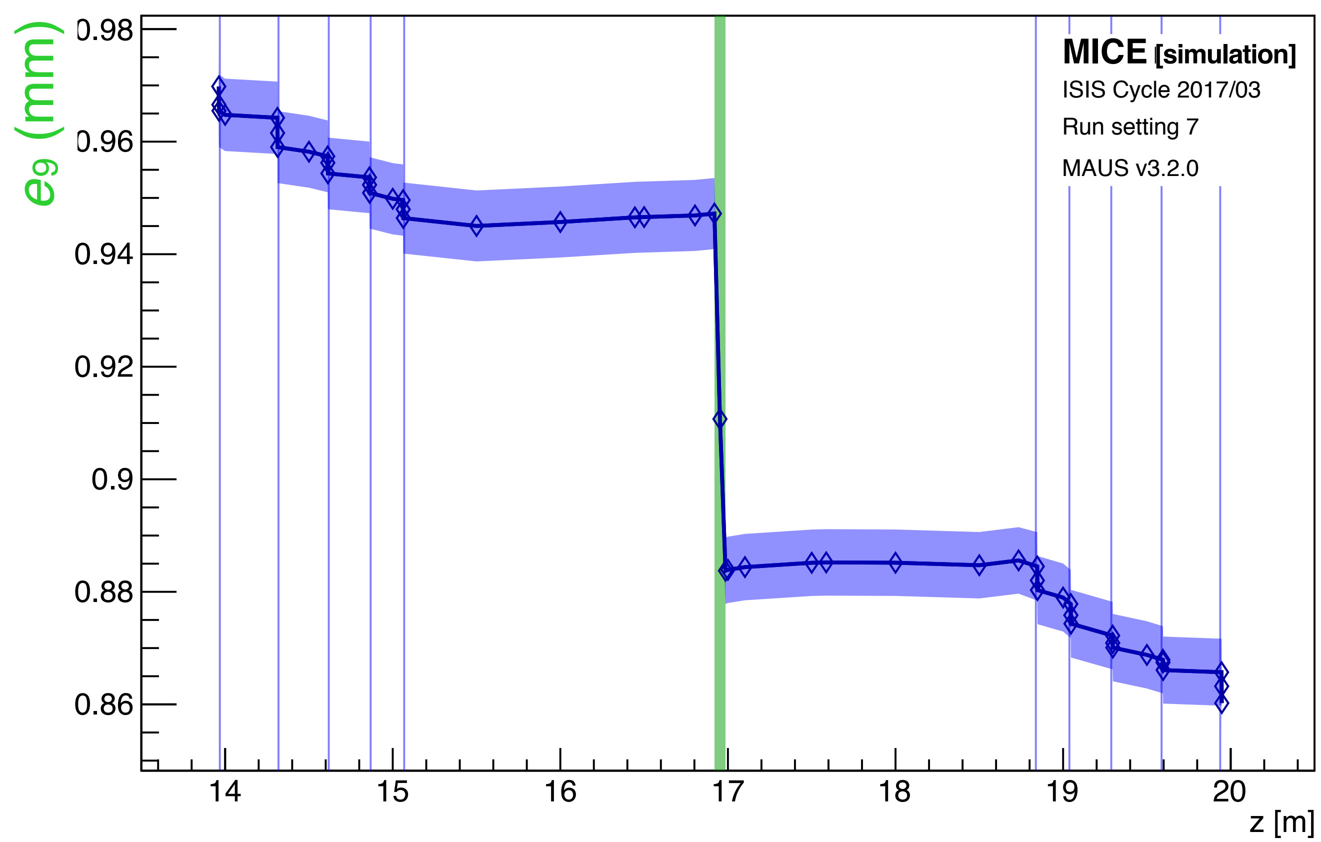
- Since we know *each muon's* coordinates, can compute individual-muon *amplitudes*
  - 4D distance of each muon from beam centroid
  - more informative than emittance



- Note cooling of beam core
  - and scraping of tails

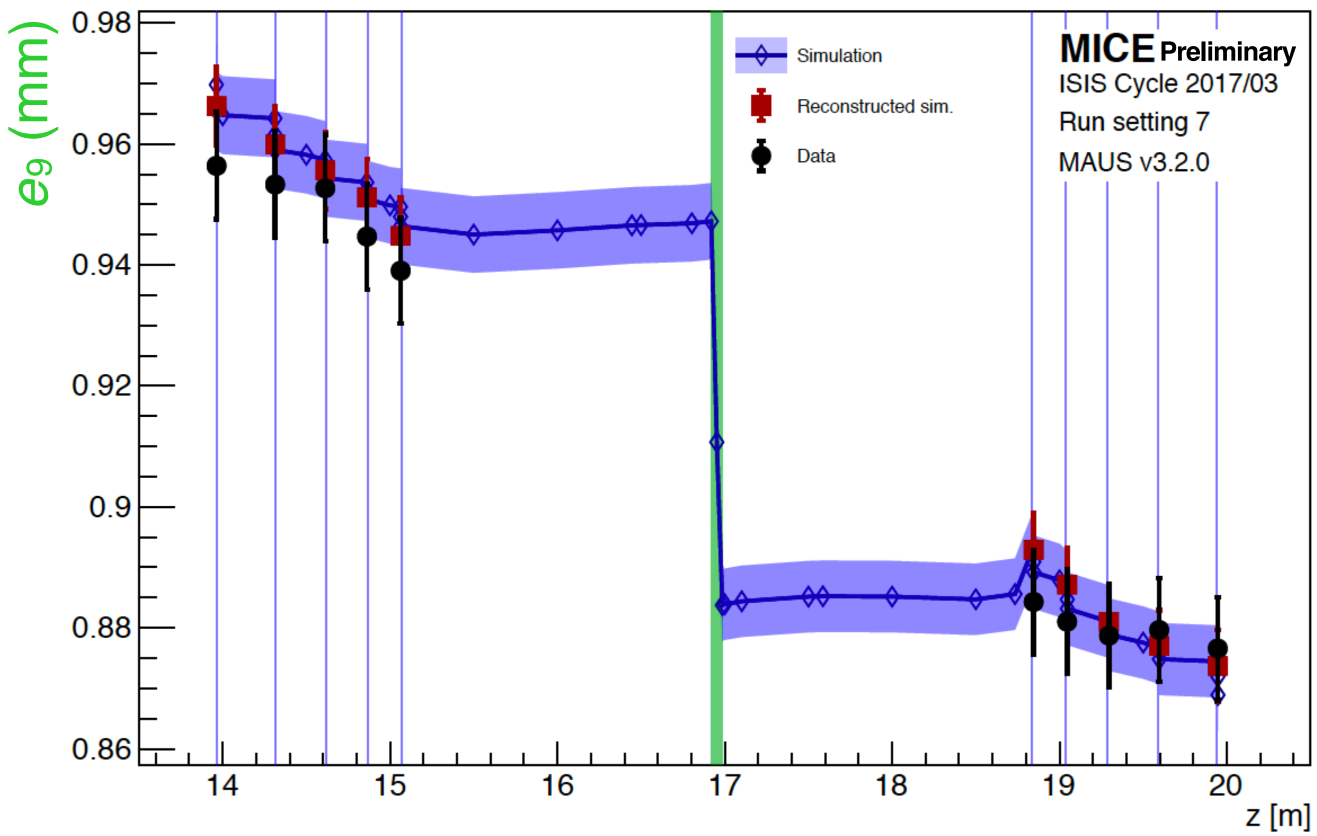
Cooling Measurements

- Other cooling indicators:
  - subemittance, fractional emittance, phase-space density, core volume
  - only time for one today: $e_9 \equiv$ emittance of central 9% of beam (1σ of 4D Gaussian beam)



Cooling Measurements

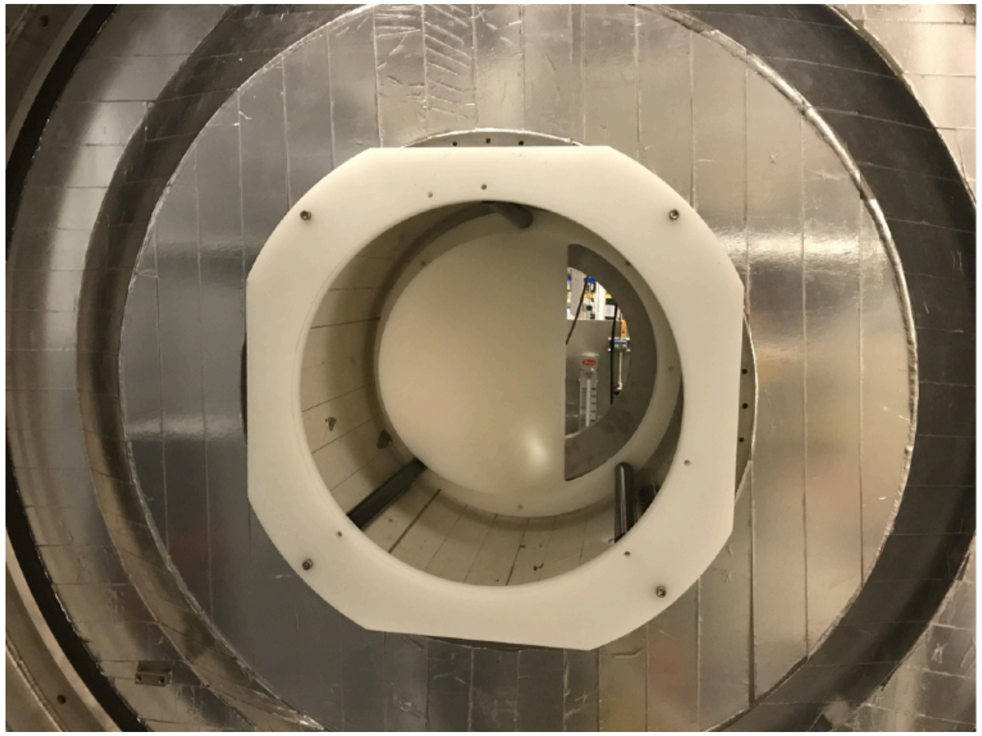
- Other cooling indicators:
  - subemittance, fractional emittance, phase-space density, core volume
  - only time for one today: $e_9 \equiv$ emittance of central 9% of beam (1σ of 4D Gaussian beam)

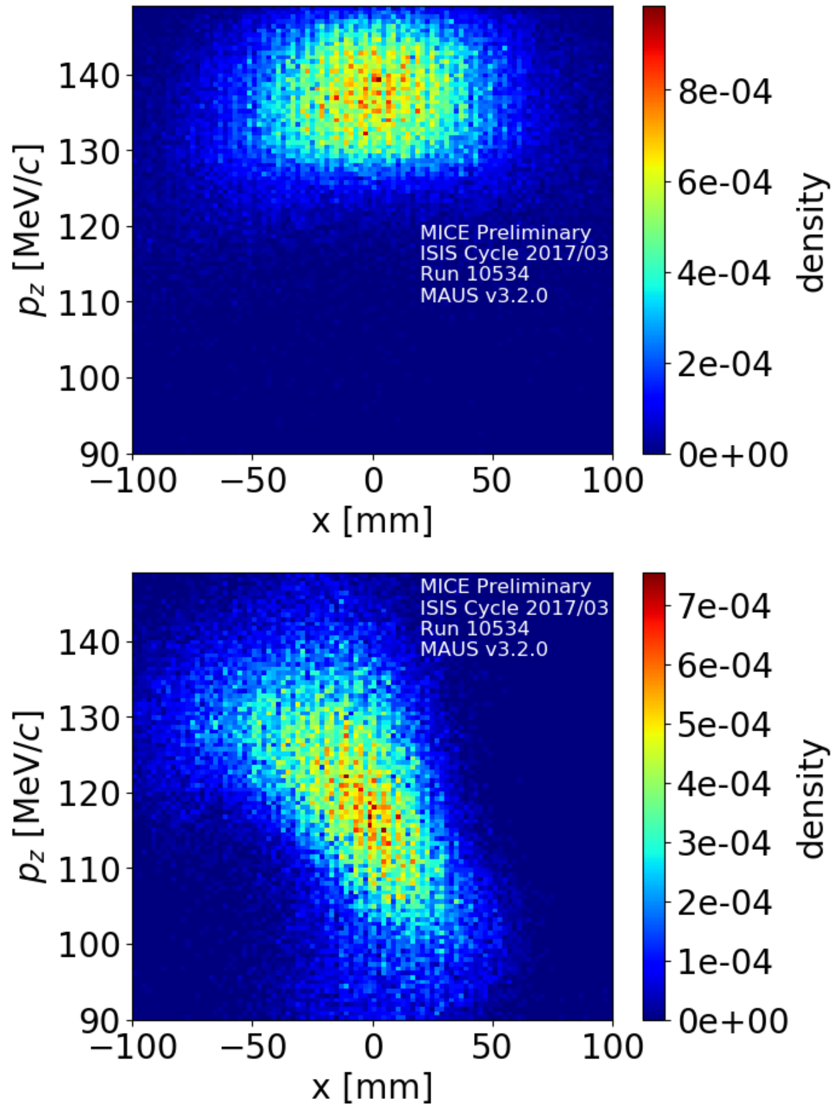


Also – 1st 6D cooling test:

- Aspects of 6D cooling / emittance exchange tested by inserting wedge absorbers in MICE

- MICE data with 45° polyethylene wedge:
  - test *reverse* emittance exchange





  - wedge increases momentum spread while reducing ε_n
  - can be used to increase MC $\mathcal{L}$

Conclusions

- 10^{21} ν/year Neutrino Factory feasible

  S. Choubey *et al.* [IDS-NF collaboration], Interim Design Report, Nova Science Publishers, Inc., 2011, arXiv:1112.2853 [hep-ex]

  → world's best measurements of neutrino mixing parameters!

- High-$\mathcal{L}$ Muon Collider looks feasible
  - buildable as Neutrino Factory upgrade
  - Higgs Factory could be important step on the way!

- First results from MICE validate efficacy of ionization cooling; more-complete results on the way
  - eliminate last in-principle obstacle to high-brightness muon accelerators

➡ such machines can be designed & built with confidence

Some MC/NF source material:

- **Neutrino Factory Feasibility Study II report** [S. Ozaki et al., eds, BNL-52623 (2001)]
- Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration [M. Alsharo'a et al., PRST Accel. Beams 6, 081001 (2003)]
- **Neutrino Factory and Beta Beam Experiments and Development** [C. Albright et al., arXiv:physics/0411123, www.aps.org/policy/reports/multidivisional/neutrino/upload/Neutrino_Factory_and_Beta_Beam_Experiments_and_Development_Working_Group.pdf (2004)]
- Recent innovations in muon beam cooling [R. P. Johnson et al., AIP Conf. Proc. 821, 405 (2006)]
- **International Design Study for the Neutrino Factory**, Interim Design Report [S. Choubey et al., arXiv:1112.2853]
- **Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S.**: A White Paper Submitted to the 2013 U.S. Community Summer Study of the Division of Particles and Fields of the American Physical Society [J.-P. Delahaye et al., eds., arXiv:1308.0494]
- Pressurized H_2 RF Cavities in Ionizing Beams and Magnetic Fields [M. Chung et al., PRL 111 (2013) 184802]
- Muon Colliders [R.B. Palmer, Rev. Accel. Sci. Tech. (RAST) 7 (2014) 137]
- Operation of normal-conducting RF cavities in multi-tesla magnetic fields for muon ionization cooling: a feasibility demonstration [D. Bowring et al., arXiv:1807.03473, submitted to PRL]
- The future prospects of muon colliders and neutrino factories [M. Boscolo, J.-P. Delahaye, M. Palmer, arXiv:1808.01858, submitted to RAST]
- map.fnal.gov; www.cap.bnl.gov/mumu/; mice.iit.edu
- **JINST Special Issue on Muon Accelerators** [iopscience.iop.org/journal/1748-0221/page/extraproc46]

Repository for final MAP and MICE papers