Recent results from MICE - implications for neutrino factory and muon collider schemes

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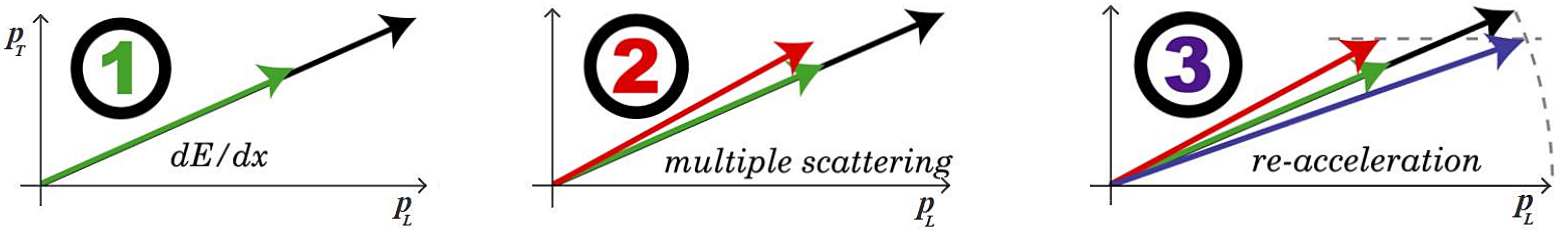
Overview

- Ionisation Cooling role in Neutrino Factory and Muon Collider
  - LEMMA
  - MAP-MC
  - MERIT
- Results from MICE
- Viewpoint from other experiments

Muon Ionization Cooling Principle



- Muons lose longitudinal and transverse momentum through ionization energy loss in an absorber
  - Non-conservative system
  - Normalised amplitude decrease
- Muons regain only longitudinal momentum in RF cavities
  - Overall, transverse momentum and amplitude is reduced
- Multiple scattering degrades the cooling effect
  - Mitigate by tight focussing
  - Mitigate by choice of low-Z absorber material
- Challenge to maintain tight focussing and high acceptance

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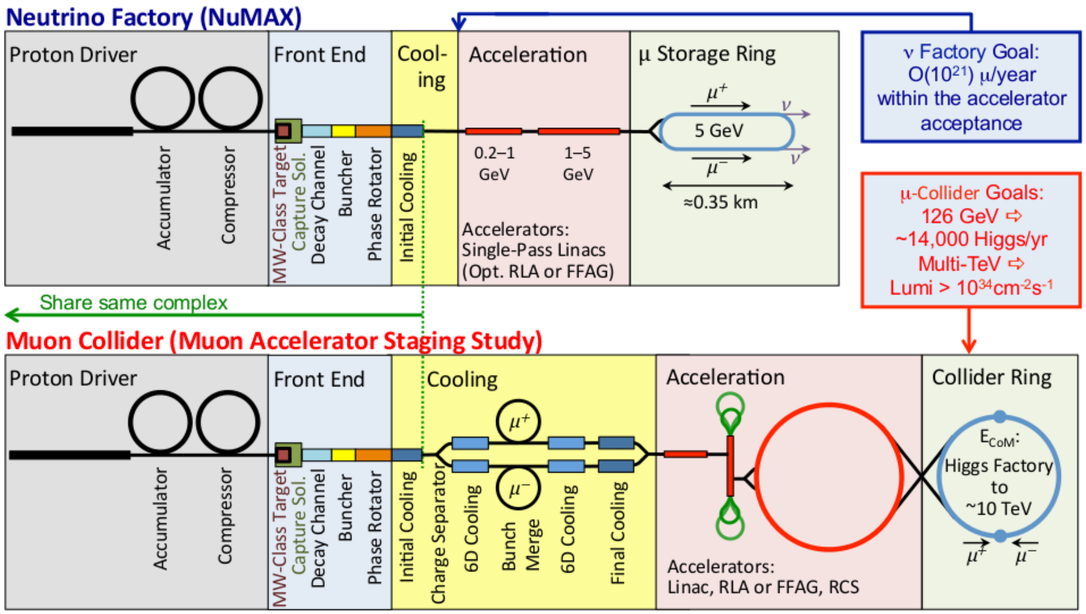
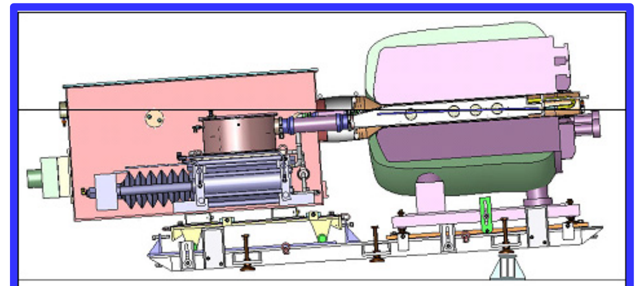
Muon Collider and Neutrino Factory

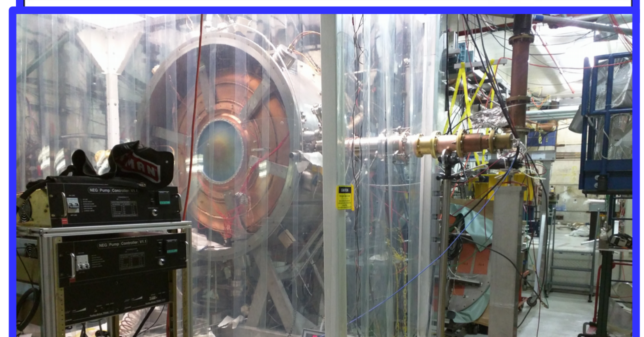


- Facility
  - High power protons
  - Target → pions
  - Capture → muons
  - Cooling
  - Rapid acceleration
  - Storage ring
- Rapid cooling → ionization cooling

R&D Programme

- MERIT
  - Demonstrated principle of liquid Mercury jet target
- MuCool Test Area
  - Demonstrated operation of RF cavities in strong B-fields
- EMMA
  - Showed rapid acceleration in non-scaling FFA
- MICE
  - Demonstrate ionization cooling principle
  - Increase inherent beam brightness → number of particles in the beam core
  - “Amplitude”





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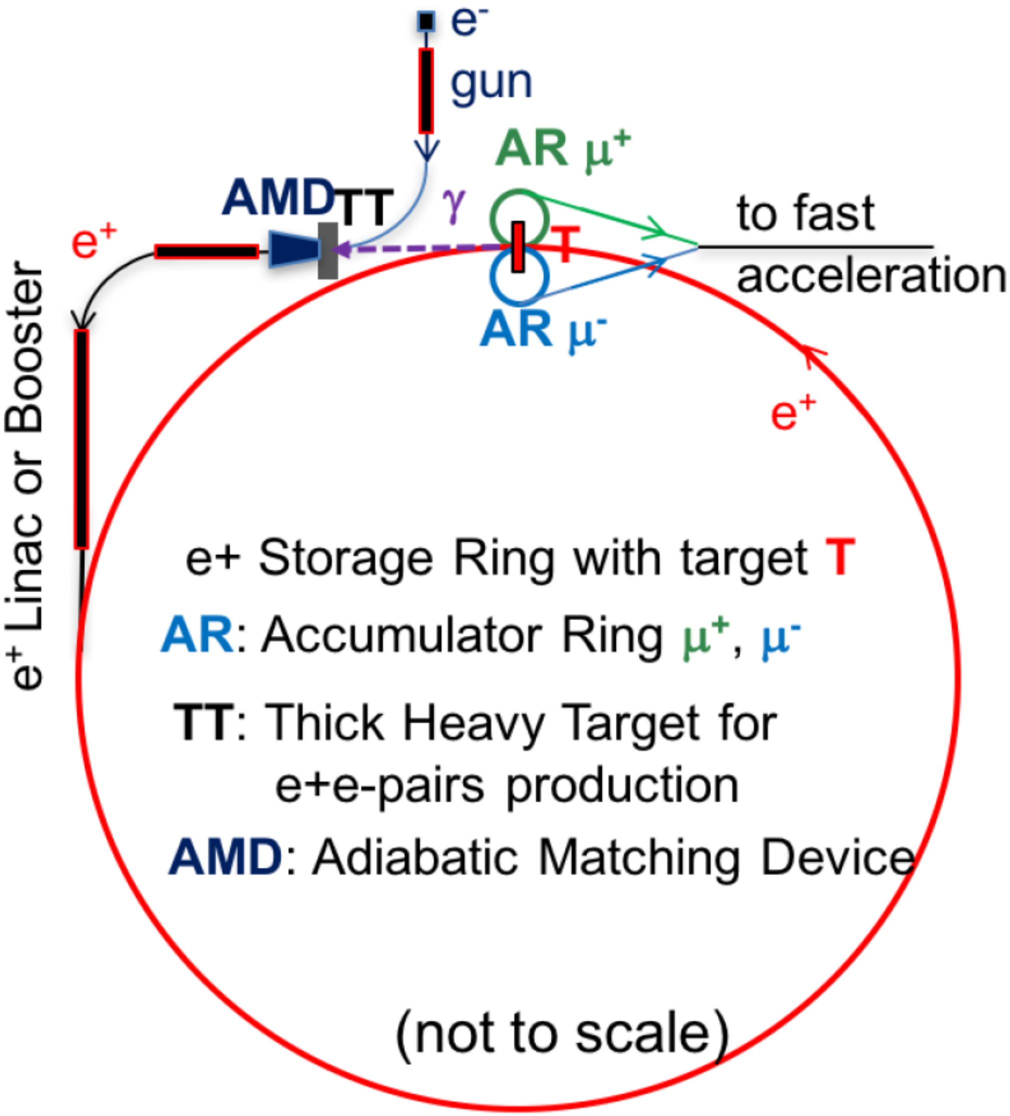
LEMMA



- Facility
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  - Rapid acceleration
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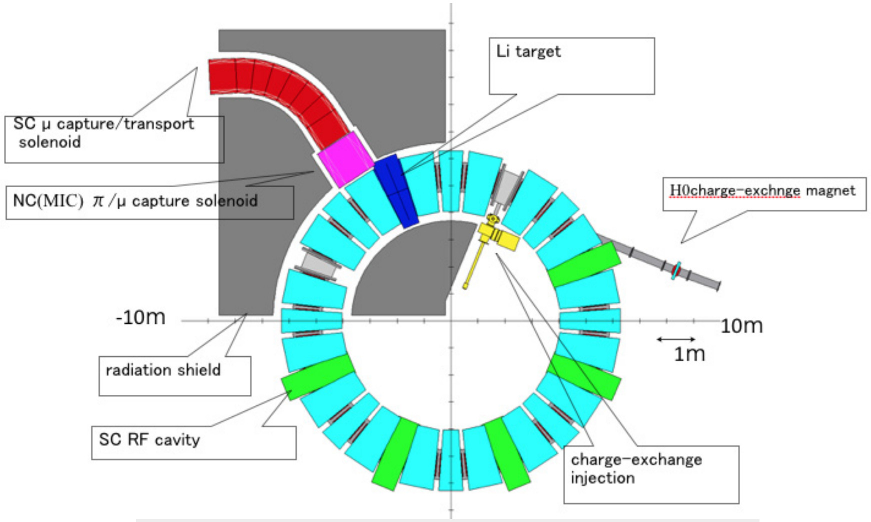
Multiplex Energy Recovery Internal Target (MERIT)

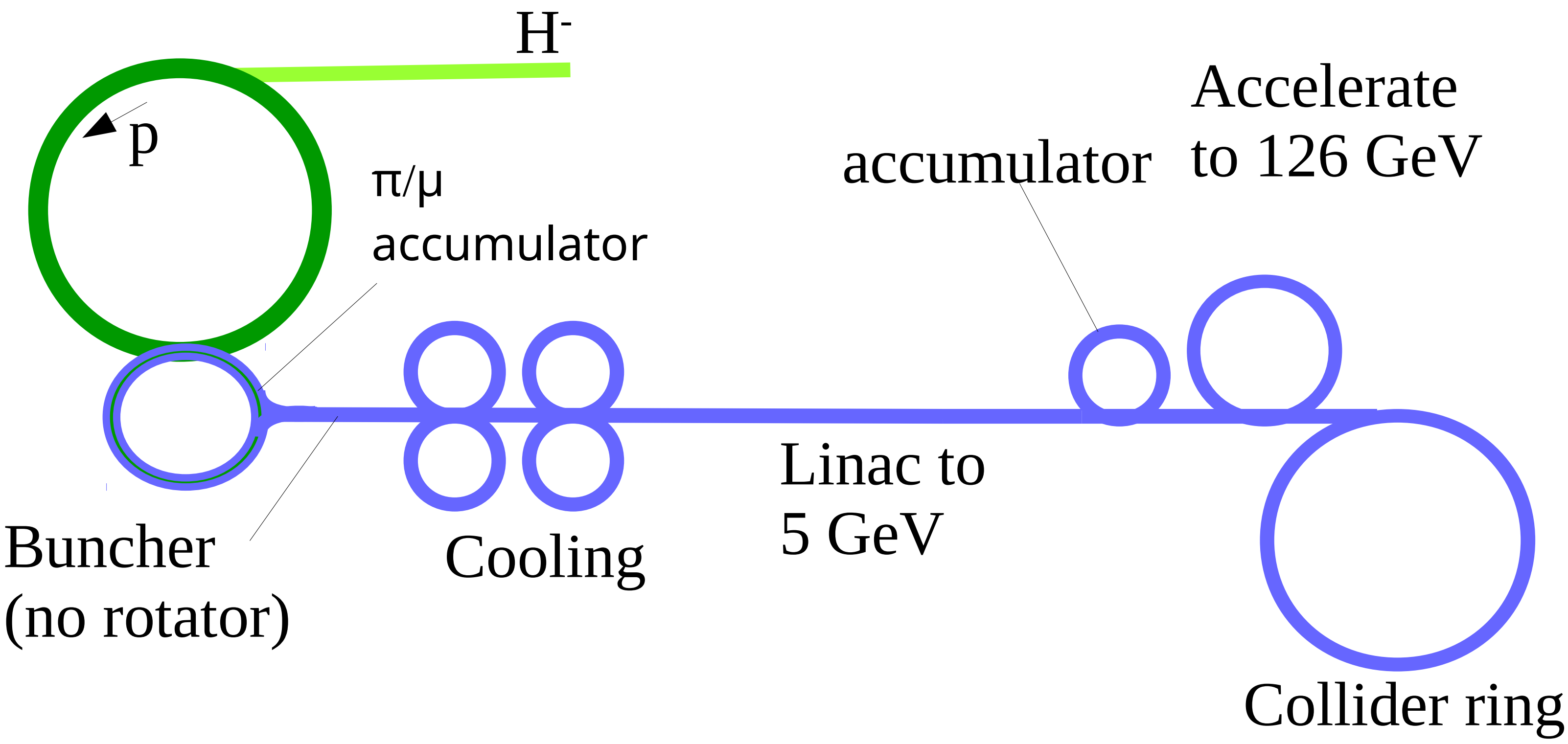
- MERIT muon production concept (Yoshi Mori, KURNS)
- Extend vertical aperture
  - Splitting coils further
  - Modify pole-tip profile
  - Very large DA
- Accelerate to top energy and hold
  - Wedge shaped liquid Li target
  - Serpentine (fixed frequency) acceleration
- Yields very long beam lifetime
- (CW) muon yield significantly higher than MAP MC



Ring configuration	H−FFAG
Energy Range [MeV]	500-800
Magnetic Rigidity [Tm]	3.633-4.877
Lattice	FDF
Average Radius [m]	5.044-5.5
Magnetic Field [T]: F	1.96-2.41
Magnetic Field [T]: D	1.71-2.11
Number of Cells	8
Field Index	2.43
Cell Tune: H	0.212
Cell Tune: V	0.18
Horiz. Beta Function [m]	2.5
Vert. Beta Function [m]	2.8
Dispersion function [m]	1.5

Using as a Muon Collider

- Scheme as follows



Summary of Cooling Requirements

- Energy loss goes with βγ
- Coulomb Scattering goes with 1/p
- Positrons behave quite differently to muons/protons

	Momentum [GeV/c]	βγ	Transverse?	Longitudinal?
MAP Muon Collider	0.24	~2	Yes	Yes
MAP Neutrino Factory	0.24	~2	Yes	Maybe
LEMMA e+	45	88000	Yes	Yes
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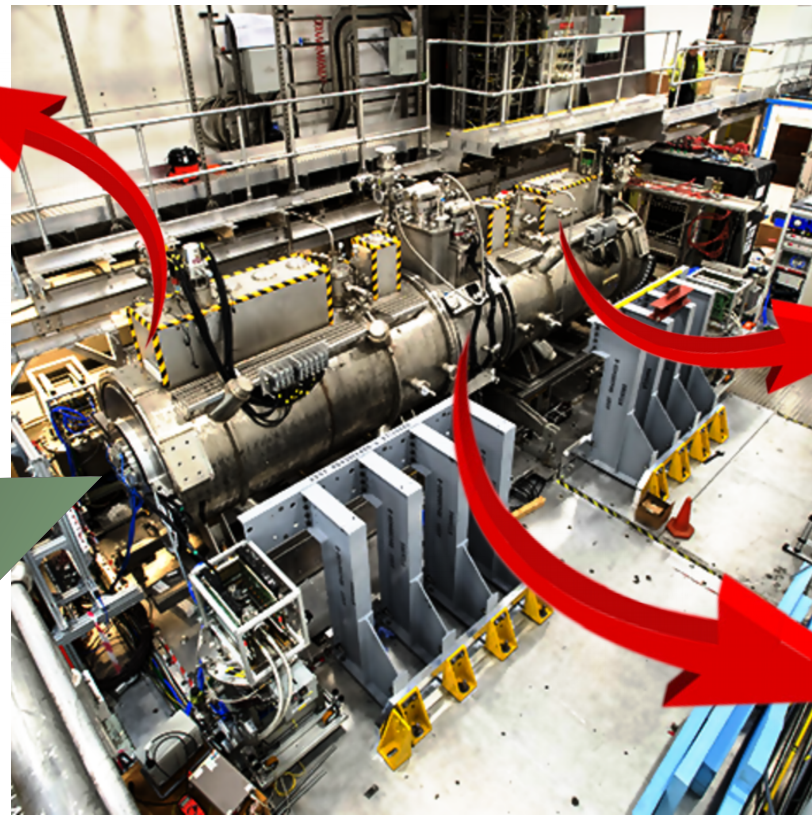
MERIT protons	1.5	1.5	Yes	Yes
MERIT μ	0.2-0.5	2-5	Yes	Yes

Muon Ionization Cooling Experiment

Measure muon position and momentum upstream



Beam

Measure muon position and momentum downstream

Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

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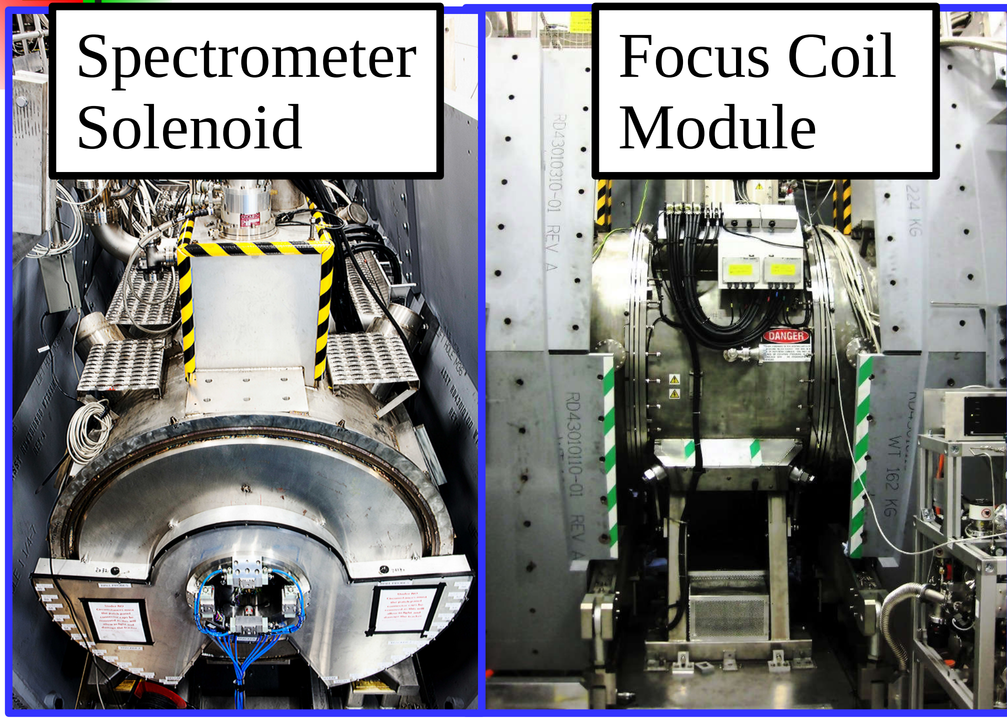
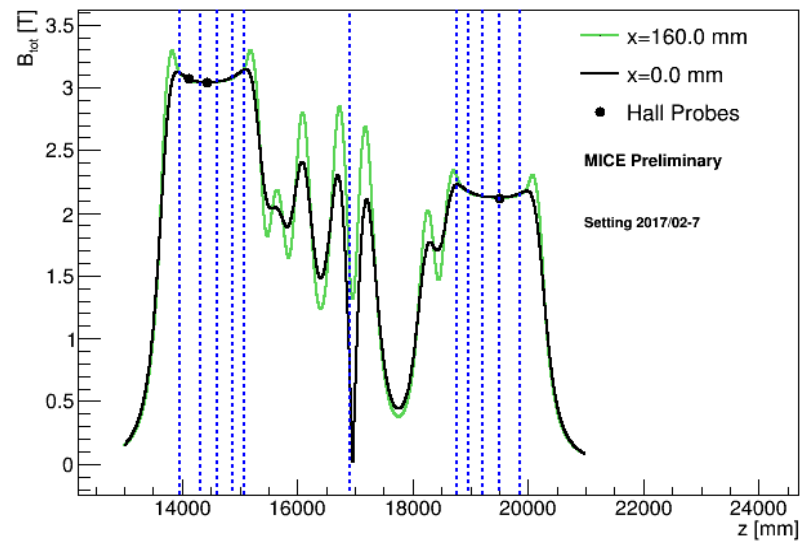
Magnets





- Spectrometer solenoids upstream and downstream
  - 400 mm diameter bore, 5 coil assembly
  - Provide uniform 2-4 T solenoid field for detector systems
  - Match coils enable choice of beam focus
- Focus coil module provides final focus on absorber
  - Dual coil assembly - possible to flip polarity

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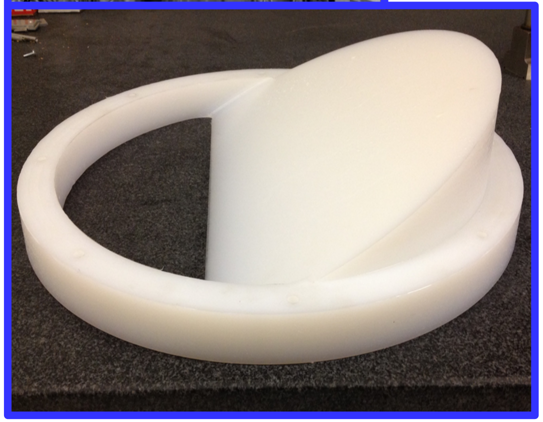
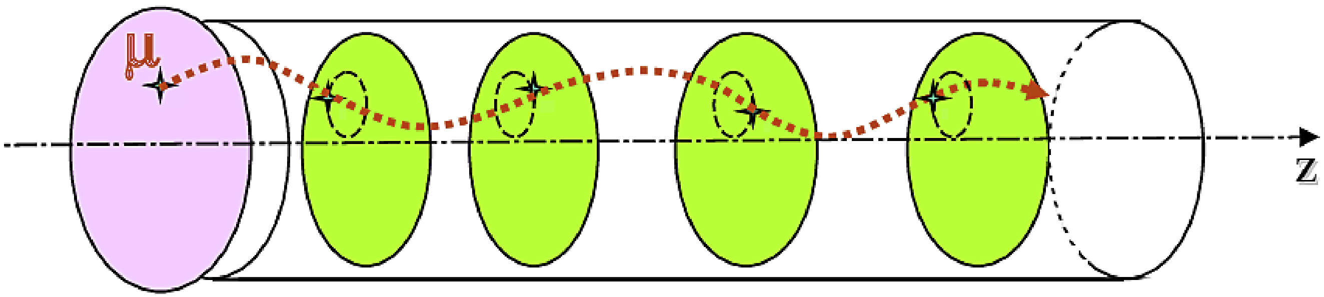
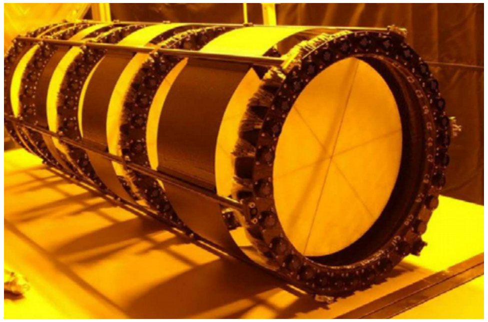
Absorbers

- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45º polythene wedge absorber for longitudinal emittance studies



Scintillating Fibre trackers

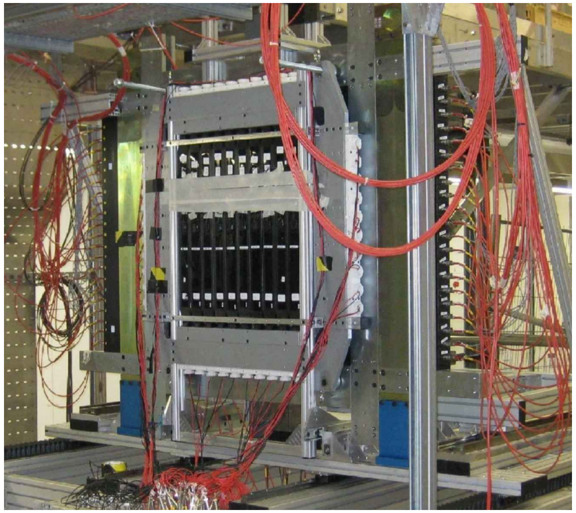


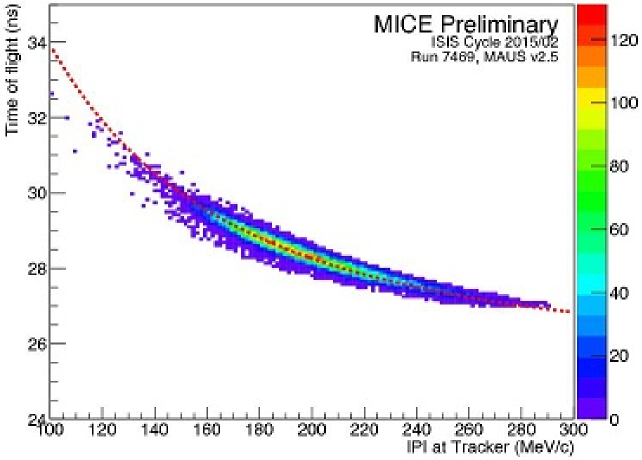


- Tracks form a helix in spectrometer solenoids
- Position of particles measured by 5 stations of scintillating fibres
- Reconstruct helix in two phases
  - Pattern recognition to reject noise
  - Kalman filter to get optimal trajectory
- Yields momentum and position of particles at reference plane
- **A scintillating fibre tracker for MICE**, NIM A 659, 2011
- **The reconstruction software for the MICE scintillating fibre trackers**, J.Inst.11, 2016

Time-of-Flight, Ckov and Calorimetry

- High precision Time-of-Flight detectors
  - Comparison of time-of-Flight with momentum enables rejection of impurities
- Threshold Cerenkov detectors provide rejection of impurities near the relativistic limit
- KLOE Light and Electron Muon Ranger provide calorimetry and rejection of decay electrons in downstream region
- **Electron-Muon Ranger (EMR) Performance in the MICE Muon Beam**, JINST 10 P12012 (2015)





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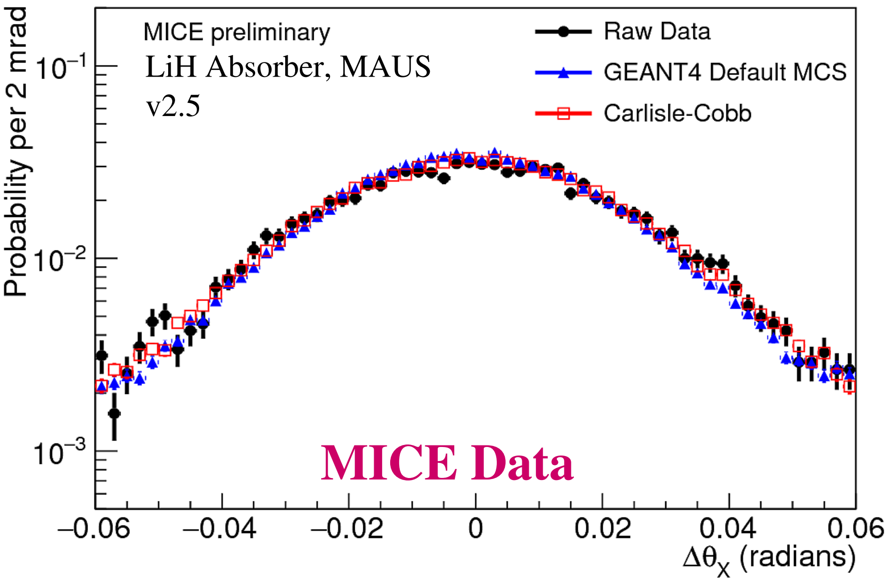
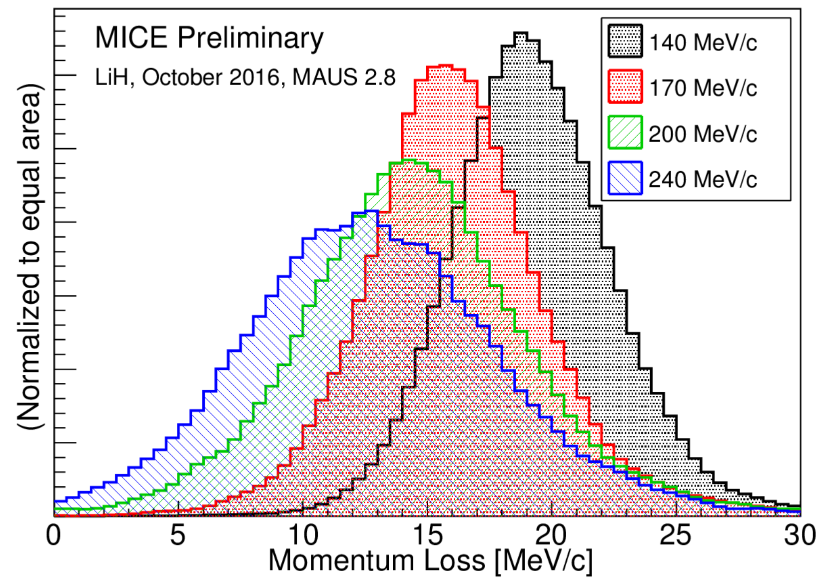
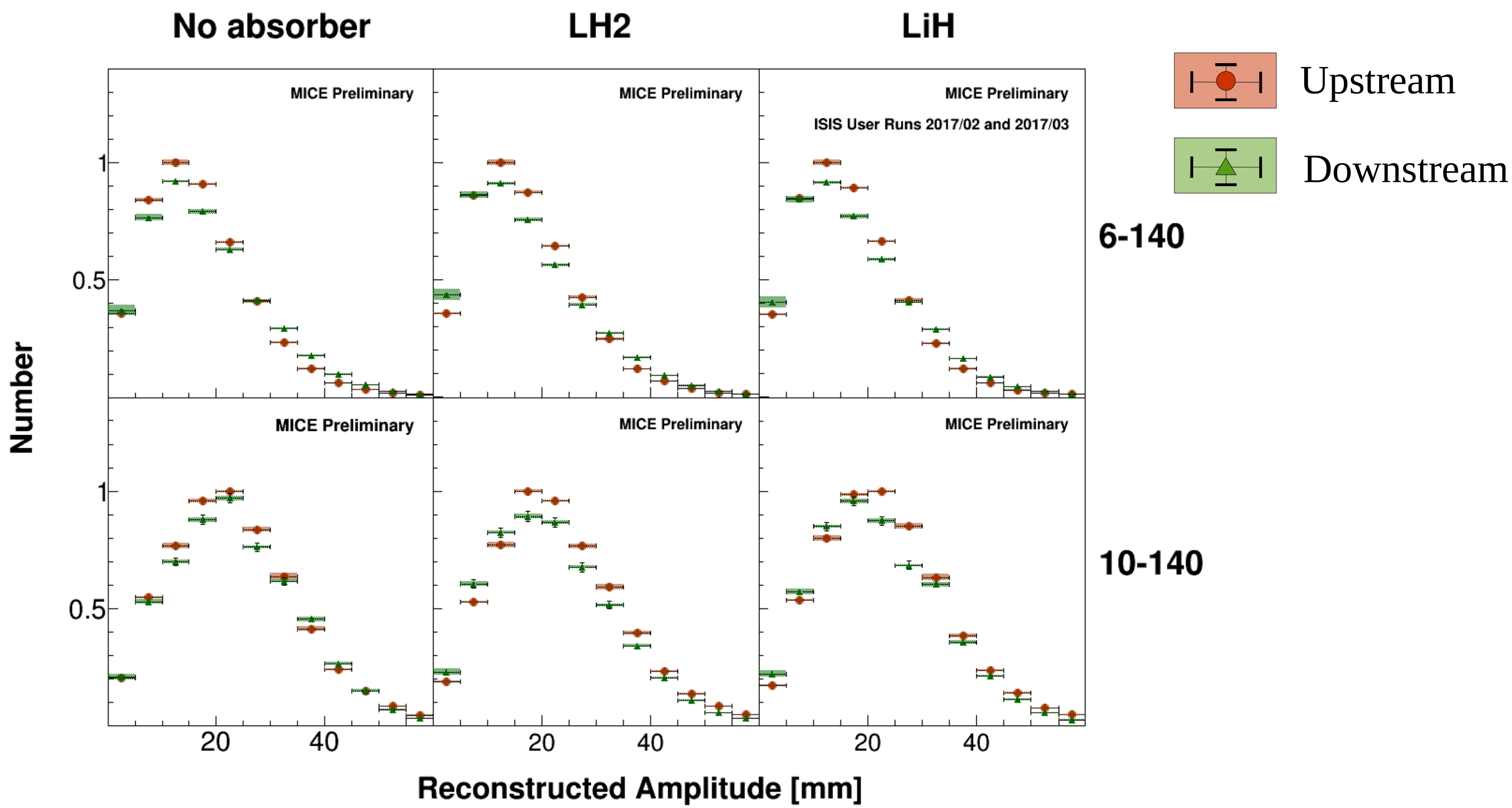
Material physics processes





- Energy loss and multiple Coulomb scattering underlie ionization cooling emittance decrease
- Precision measurement of multiple coulomb scattering
  - See next talk
- Validation of energy loss model

Change in Amplitude Across Absorber



- No absorber → decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

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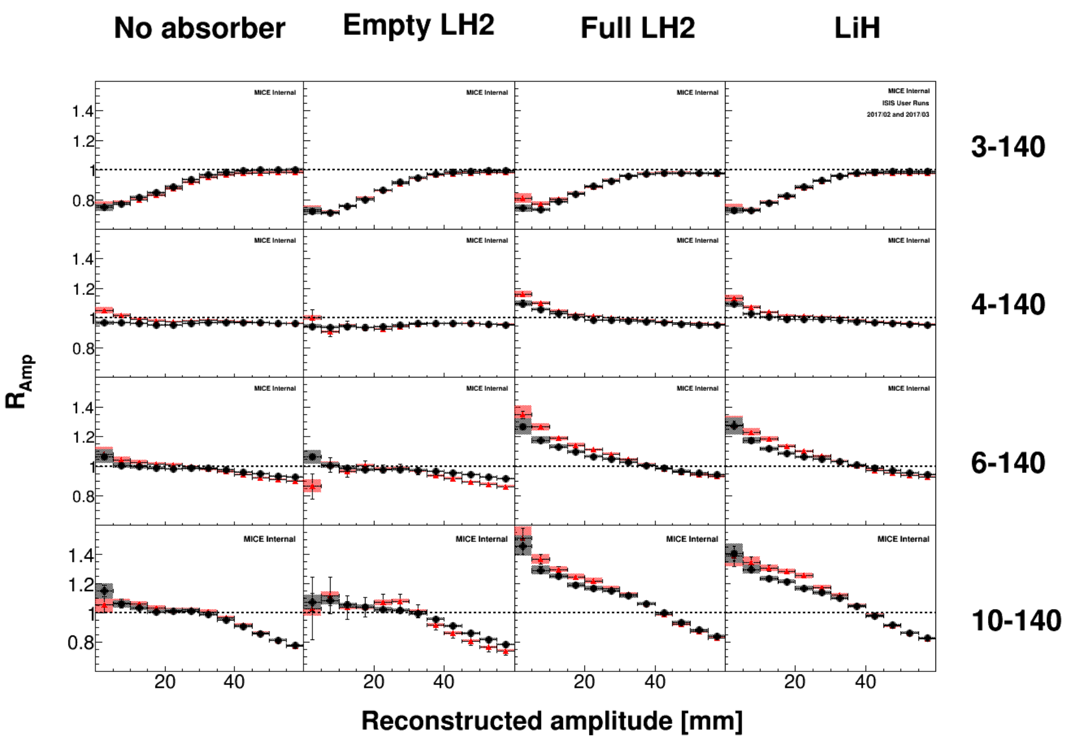
Ratio of core densities



- R_{amp} is ratio of CDF
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances

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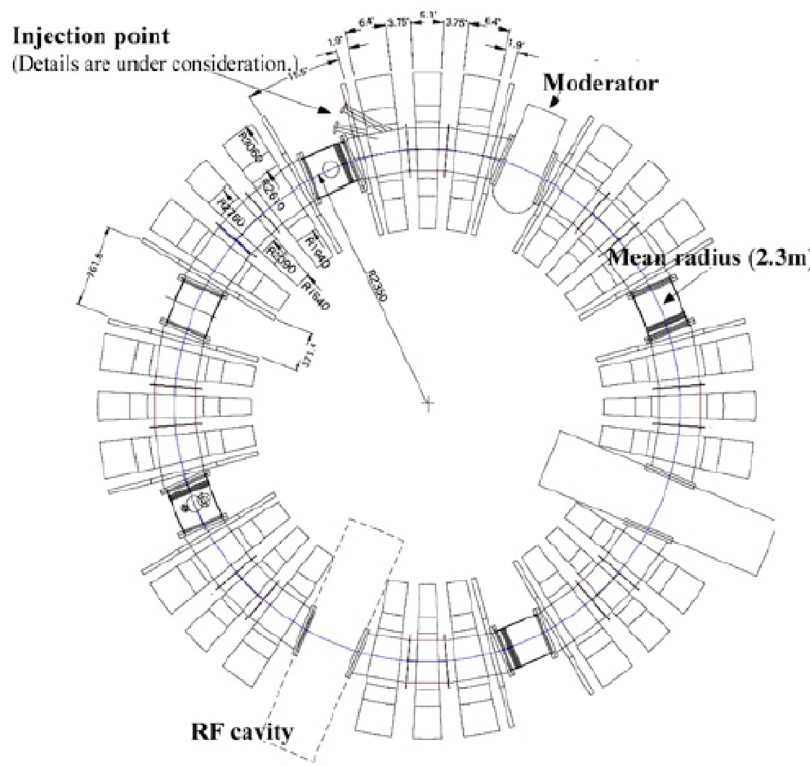
- What other cooling experiments exist/can be foreseen?

Energy Recovery Internal Target (ERIT)

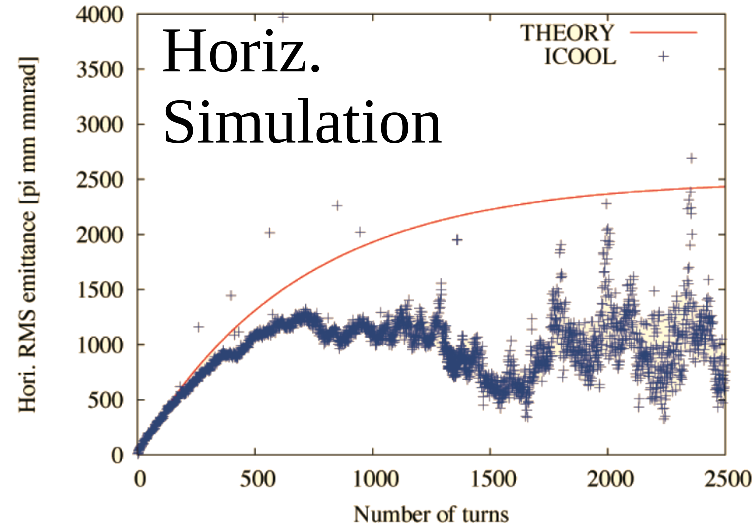
- KURNS ERIT ring (Mori et al)
- Study of neutron production for cancer therapy

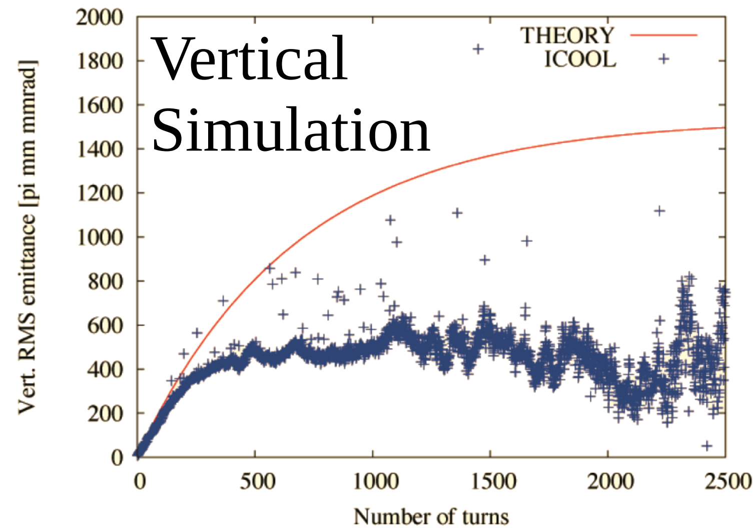
Mean Radius [m]	2.35
Number of Sectors	8
Max B Field [T]	0.9
Field Index	1.92
FD Ratio	3
Horizontal Tune	1.74
Vertical Tune	2.22
Horizontal Acceptance [microns]	7000
Vertical Acceptance [microns]	3000
RF Voltage [kV]	200
Harmonic Number	6
RF Frequency [MHz]	3.01



Energy Recovery Internal Target (ERIT)

- Excellent acceptance
- Beam survival ~ several 100 turns
- Limited in the end by vertical aperture
- Demonstrates that **amplification** using energy recovery is possible
- But does **not** demonstrate **stability**
- Does not demonstrate 6D cooling





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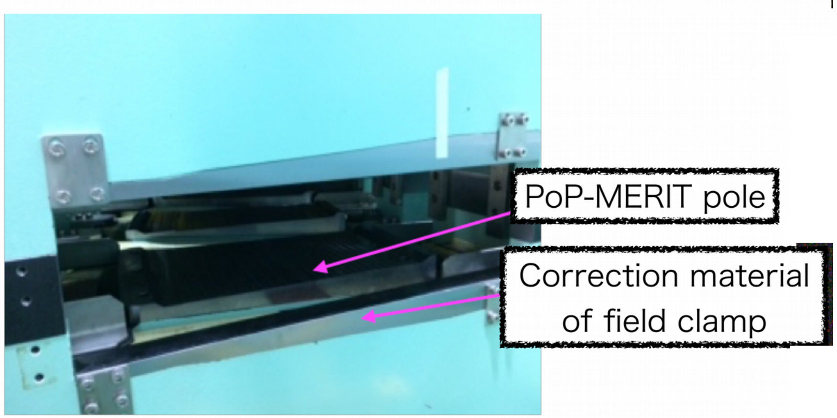
PoP-MERIT (Okita et al)

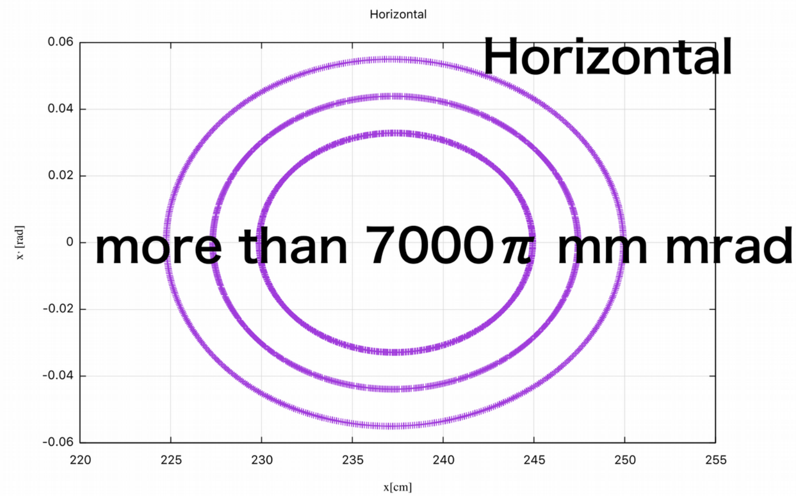
- Increased vertical acceptance in ERIT by modified pole tip

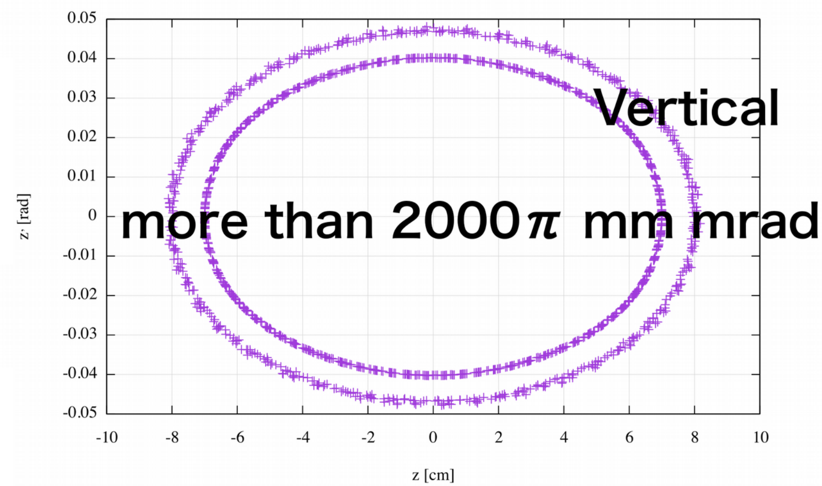
◉Status of Development of the ring
◇Construction work was finished last summer.
◇First beam injection was succeeded at last Sept.
◇Optimization of shape of field clamp for COD correction was carried out.

◉Beam study is carrying out.



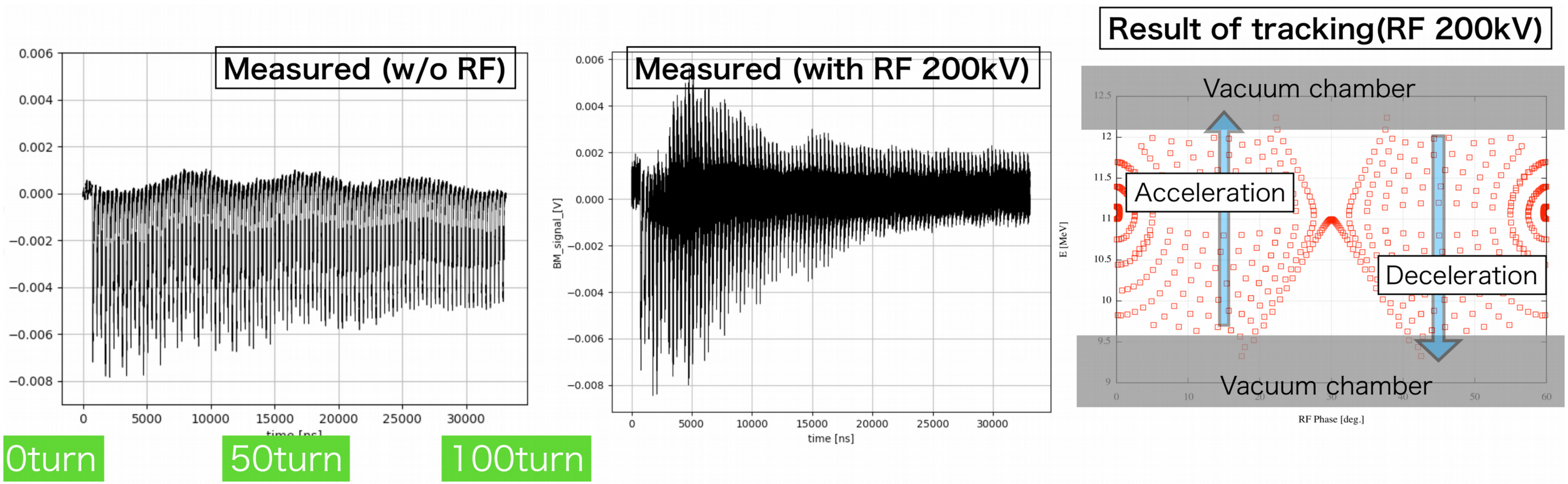
◇Acceptance @ E = 11.0 [MeV]





PoP-MERIT (Okita et al)

- Results from FFA



◉Result of experiment

◇Beam loss was happen by turning on the RF.

◇It is estimated that beam loss occurred at the horizontal aperture by acceleration and deceleration.

Missing Physics

- What is missing from the current state-of-the-art?
  1. Cooling in the intensity limit (MAP MC)
  2. Beam stability with internal target concept (MERIT, LEMMA)
  3. Higher energies (LEMMA)
  4. Electrons/positrons (LEMMA)
  5. High power internal target (MERIT, LEMMA)
- How can we address this?
  - Small test ring like PoP-MERIT (1, 2, ~5)
  - Test in existing electron beams (3, 4, 5)
  - Test in existing proton beams (5)
- Potential real world applications
  - Rare isotope production
  - Secondary particle production (e.g. soft neutrons)

To conclude

- Muon ionisation cooling is an essential part of the proton-based Neutrino Factory or Muon Collider
- Muon ionisation cooling is an essential part of LEMMA
- A small test ring would provide an ideal basis for investigating long-term behaviour of ionisation cooling
  - PoP-MERIT may help!
- References

  - Y.Mori et al., “Intense Negative Muon Facility with MERIT ring for Nuclear Transmutation”; Proc, 14th Conf. On Muon Spin Rotation,Relaxation and Resonanc(μSR2017), JPS Conf. Proc. 21, 011063(2018). https://journals.jps.jp/doi/book/10.7566/musr2017
  - Intense Muon Source with Energy Recovery Internal Target (ERIT) Ring Using Deuterium Gas Target, Yoshiharu MORI, Hidefumi OKITA,Yoshihiro ISHI, Yujiro YONEMURA and Hidehiko ARIMA pp.1-9, Vol.77, No.1, September 28, 2017 http://kenkyo.eng.kyushu-u.ac.jp/memoirs-eng/top.php