ILLINOIS INSTITUTE OF TECHNOLOGY

Progress Towards the Completion of the MICE Demonstration of Sustainable Muon Ionization Cooling

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25 August 2014

NuFact'14

Outline

I Motivation

II Procedure for Cooling Muons

III MICE Description

IV Step V Status

- I Hardware status
- II Phasing muons

V Future

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Motivation

MICE is the

Muon

Ionization

Cooling

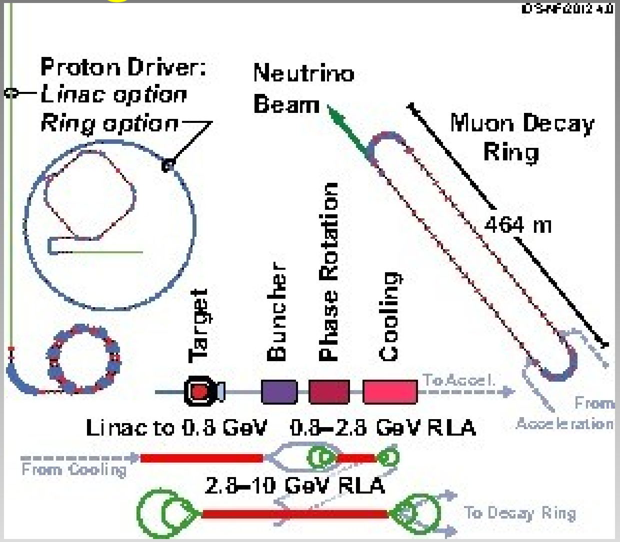
Experiment

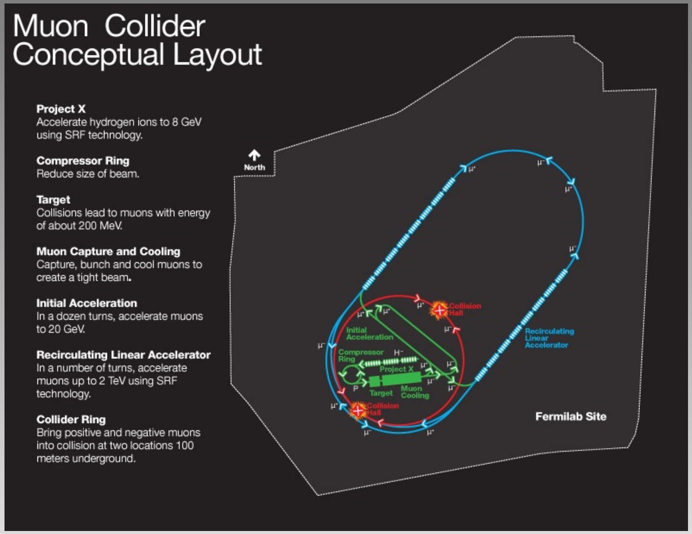
MICE **is a proof of principle experiment to demonstrate that we can "cool" a beam of muons.**

Motivation

The goal of MICE is:

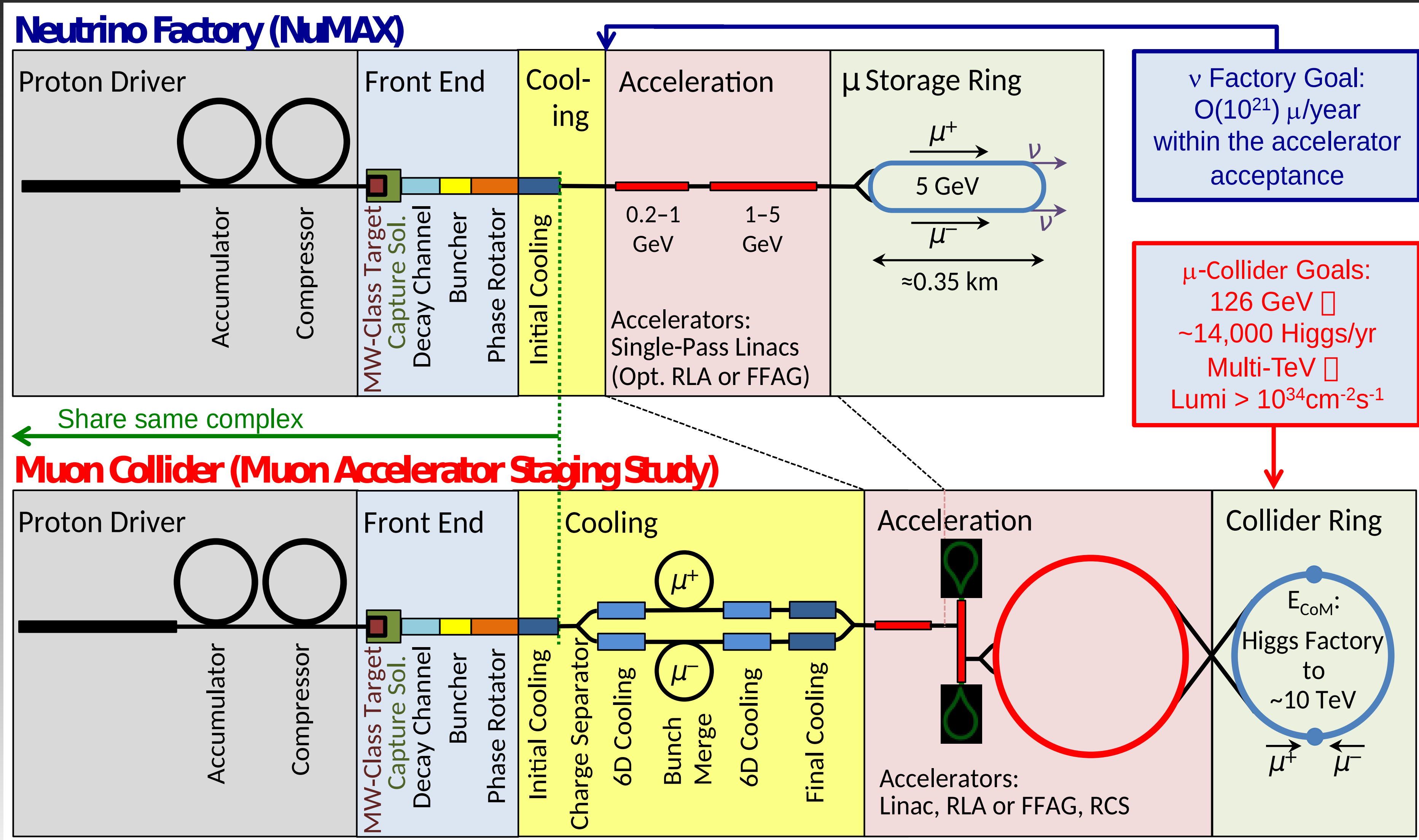
- ***Design, build, commission and operate a realistic section of muon cooling channel***
- ***Measure its performance for several momenta and emittance settings***





Results to be used to optimize Neutrino Factory and Muon Collider designs.

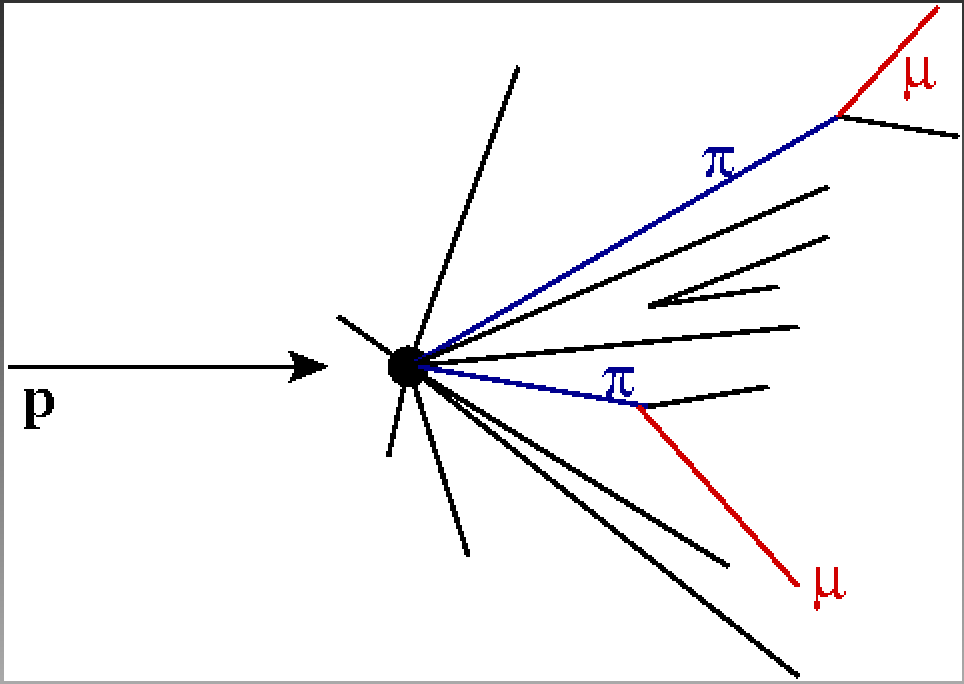
Motivation:
Synergies



Motivation

Why cool muons?

- muons are created as tertiary particles
- created with large inherent emittance – beam spread in 6D phase space:
  - x, y, z
  - p_x, p_y, p_z



- accelerators require particles in tight bunches
- must "cool" muons – reduce emittance of beam
  - "smaller beam" reduces cost of accelerator
  - "smaller beam" increases luminosity

See talk by Ryan Bayes

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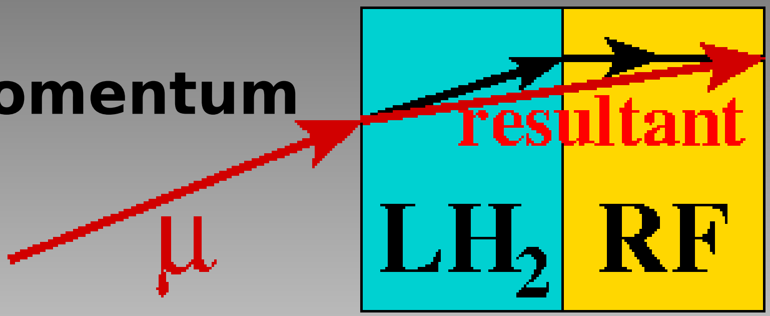
Procedure:
Ionization Cooling

- "Cooling" muons refers to reducing the emittance of the muon beam.
- Conventional techniques won't work (too slow)
- Due to short muon lifetime, the only viable option is ionization cooling. Must cool ***AND*** accelerate muons rapidly:
  - diagram vectors represent momentum
  - lose momentum in p_T and p_L
  - restore p_L



- Magnetic fields increase x' & y', thus reducing the impact of multiple scattering

Procedure:
Ionization Cooling

Cooling is:
- Momentum loss in all dimensions via dE/dx

Sustainable cooling is:
- "Cooling" & reestablishment of longitudinal momentum w/RF

Strong focusing at absorber yields small $\beta_\perp$

cooling | **heating**

$$\frac{d\,\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle \frac{d\,E_\mu}{ds} \right\rangle \frac{\varepsilon_N}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014\,GeV)^2}{2\,E_\mu m_\mu X_0}$$

Low Z absorbers means large X_0

MICE Procedure

MICE will measure a 10% cooling effect with 1% accuracy => a 0.1% relative emittance measurement

1. *create beam of muons*
2. *identify muons and reject background*
3. *measure muon emittance–ensemble of single μ measurements*
4. *"cool" muons in low-Z absorber*
5. *replenish longitudinal momentum*
6. *re-measure muon emittance*
7. *identify muons to reject electrons from μ decay*

Emittance change is difference of measurements

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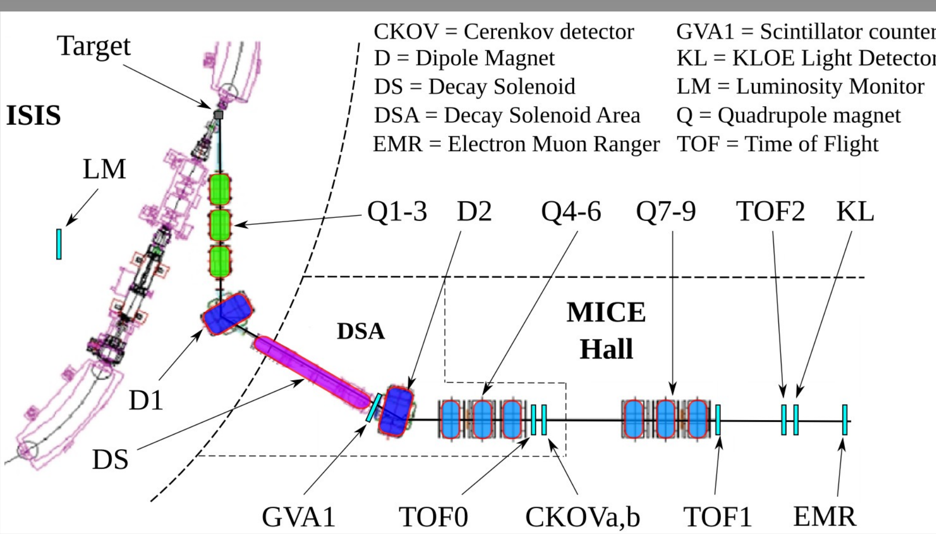
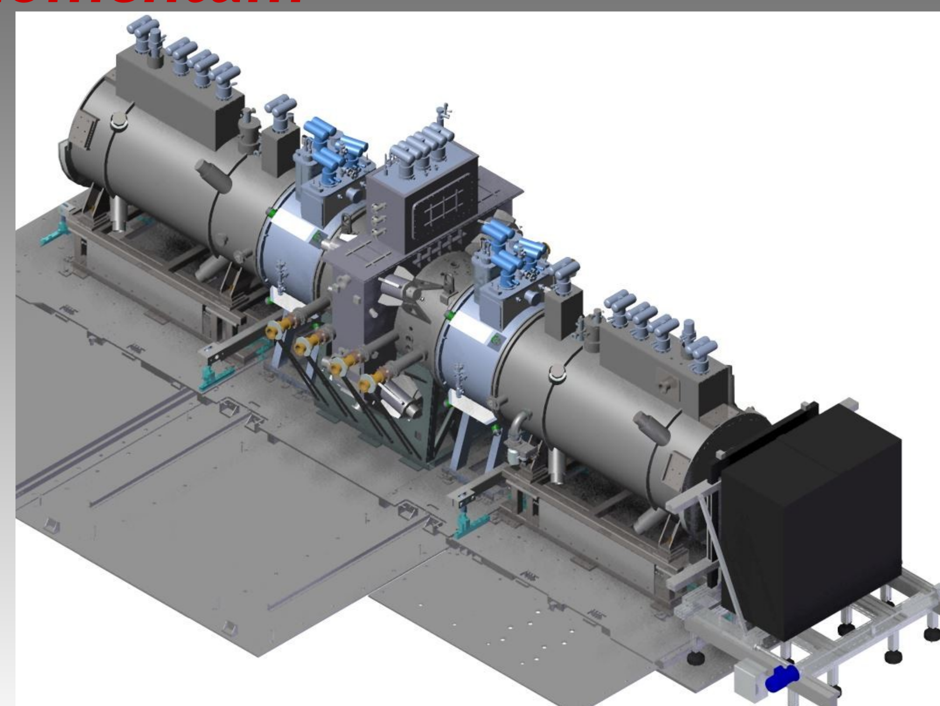
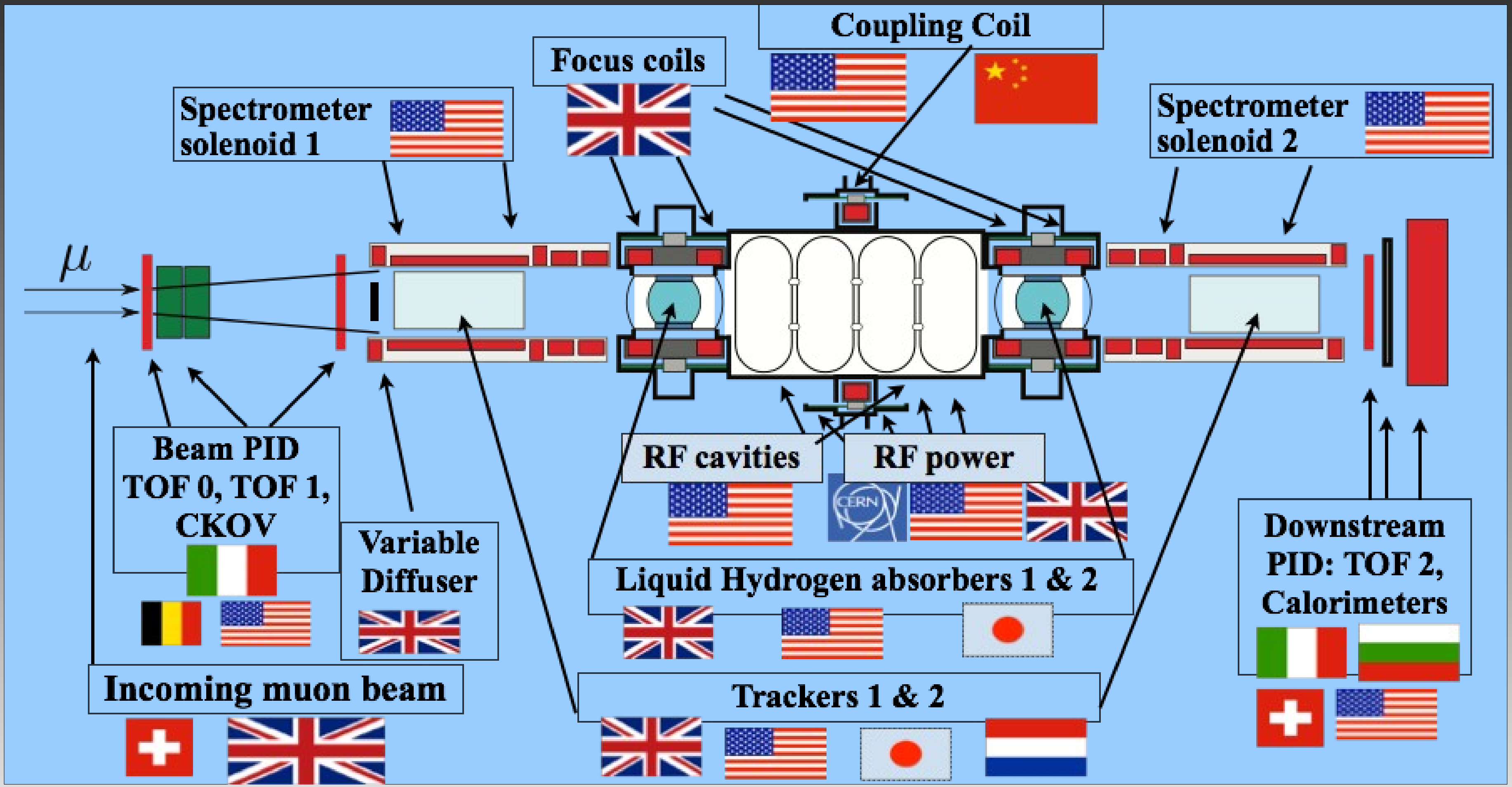
Description

- *Beamline – create beam of muons*
- *Particle ID – verify/tag muons (before/after)*
- *Trackers – measure emittance (before/after)*
- *Absorber (LH_2 or LiH) – cooling*
- *RF – replenish longitudinal momentum*

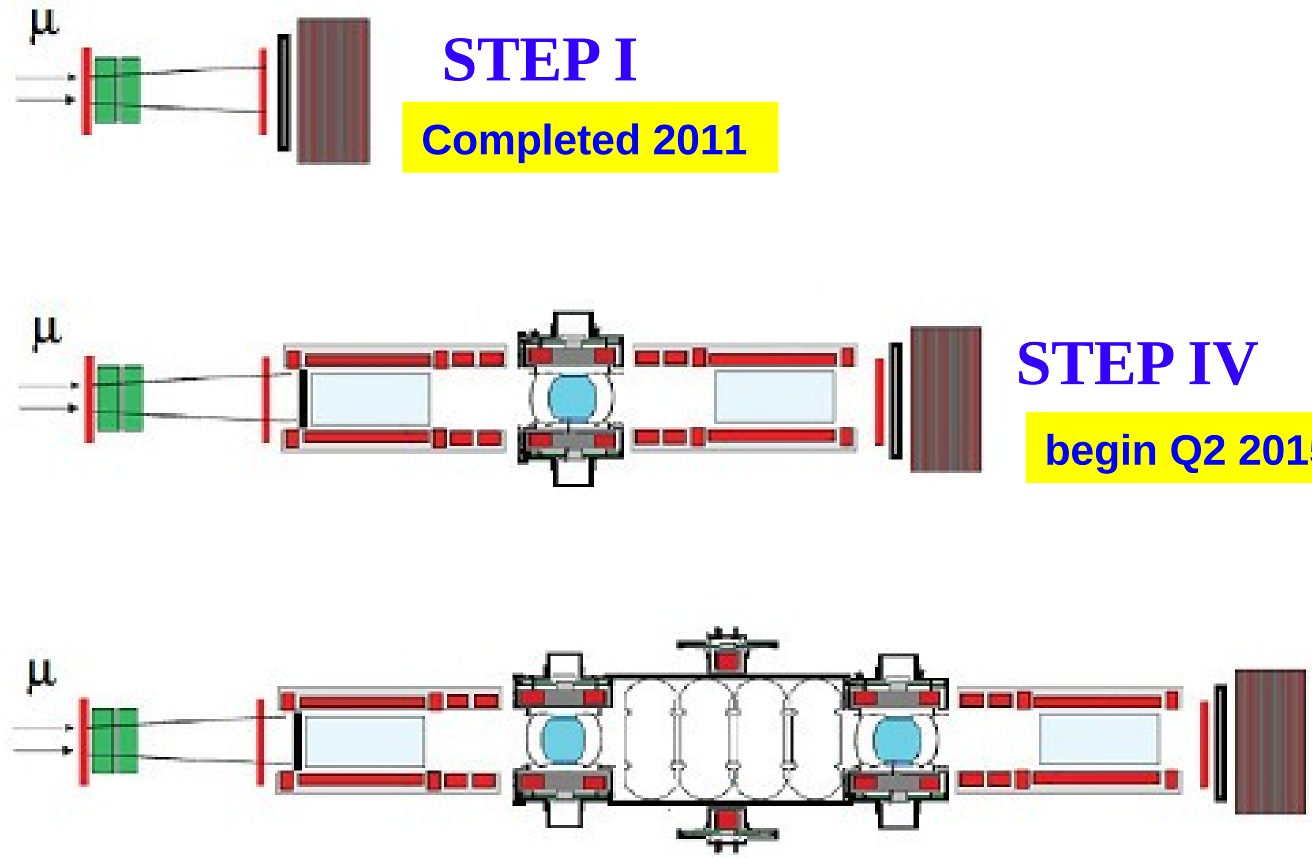




Description: *Who are MICE?*



MICE Schedule



STEP I

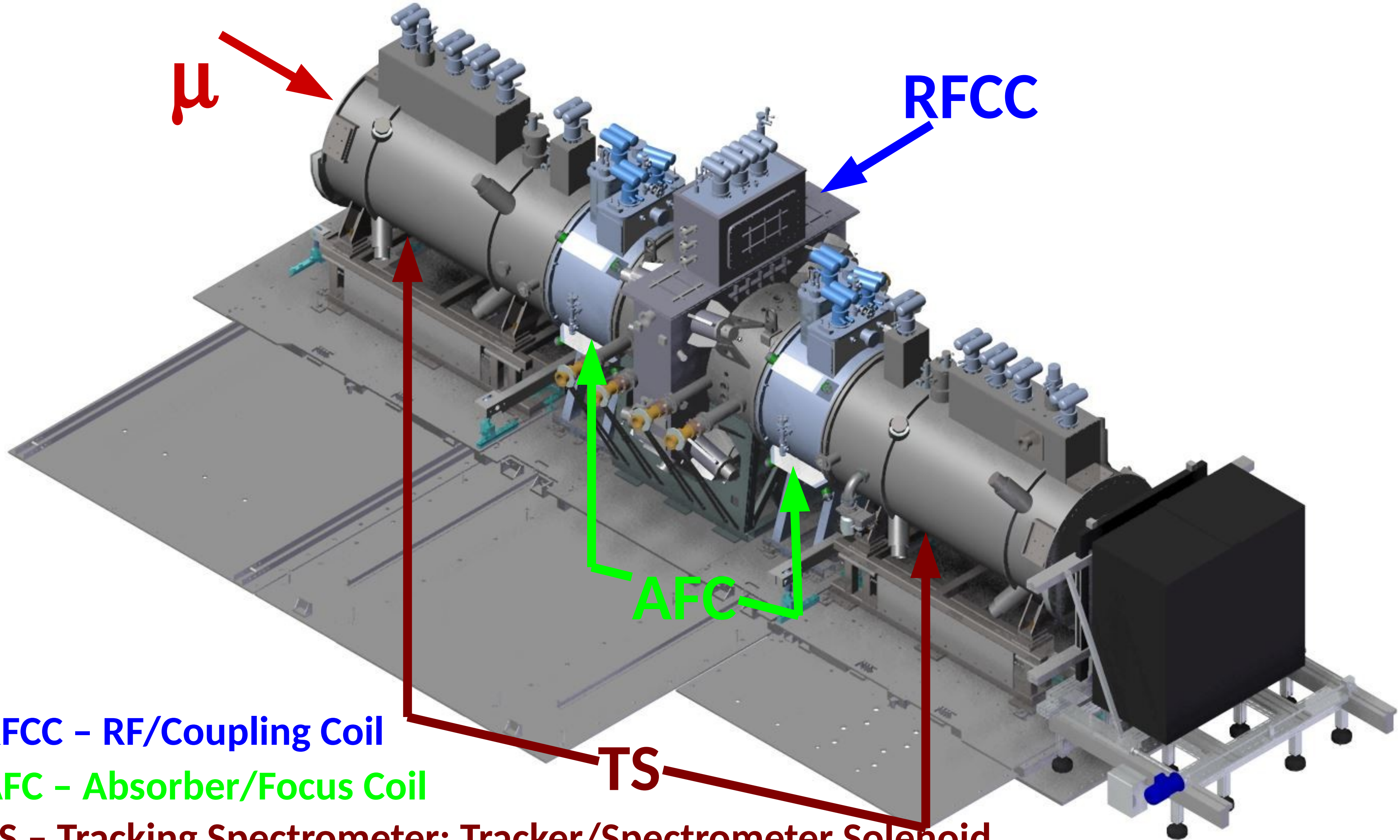
Completed 2011

STEP IV

begin Q2 2015

STEP V

Step V Cooling Channel



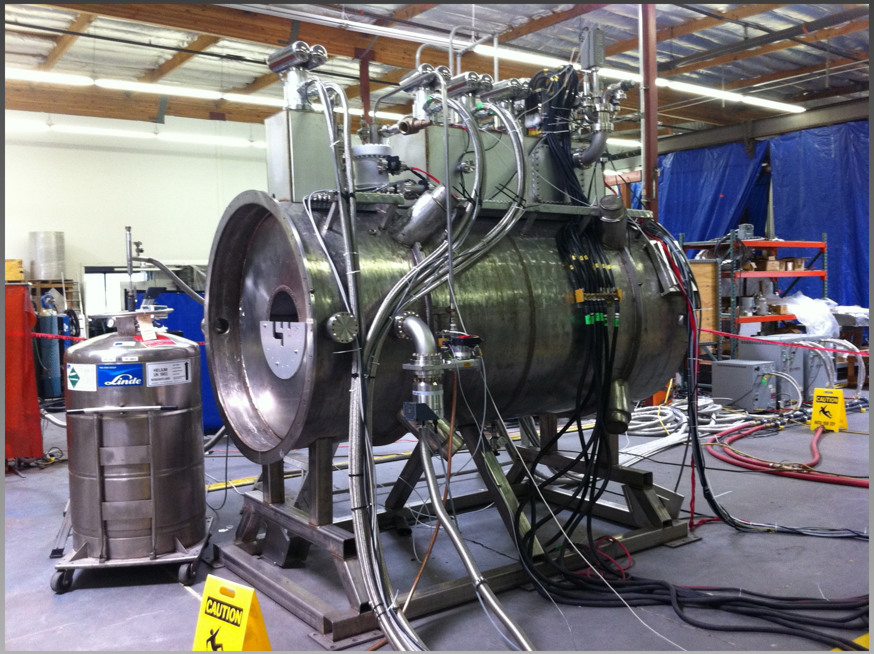
RFCC – RF/Coupling Coil

AFC – Absorber/Focus Coil

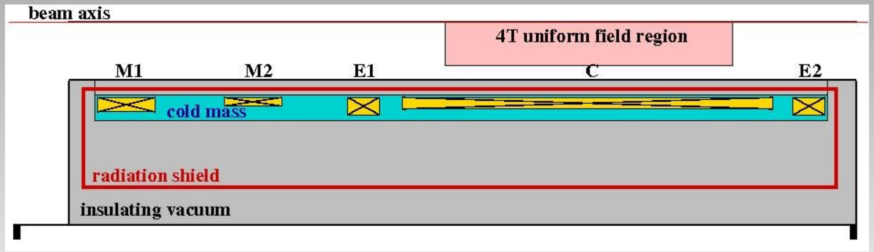
TS – Tracking Spectrometer: Tracker/Spectrometer Solenoid

Spectrometer Solenoids

- 4 T superconducting solenoids
- 20 cm warm bore
- 2.9 m long

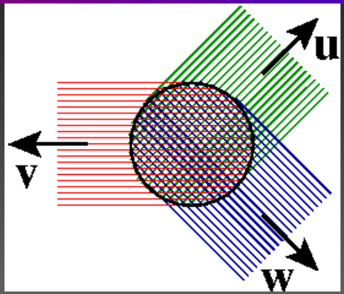


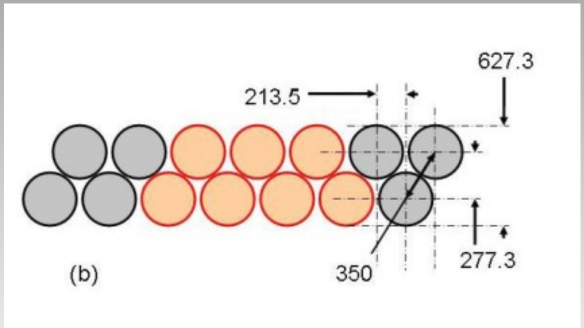
- 5 coils:
  - 1 tracker coil
  - 2 end coils
  - 2 matching coils



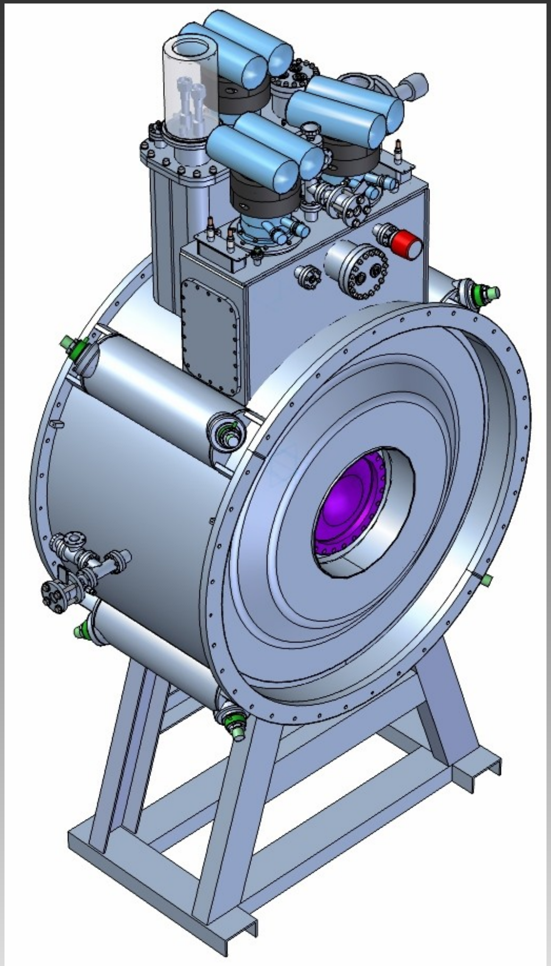
MICE Tracking

- Two trackers – before/after
- Measures x, y, x', y', z
- 5 stations/tracker
- 3 stereo planes/station – U/V/W
- 1400 350 µm fibers/plane
- double layer, 7 fibers/group
- <0.2% dead channels
- >10.5 photoelectrons/MIP
- 470 µm RMS position resolution

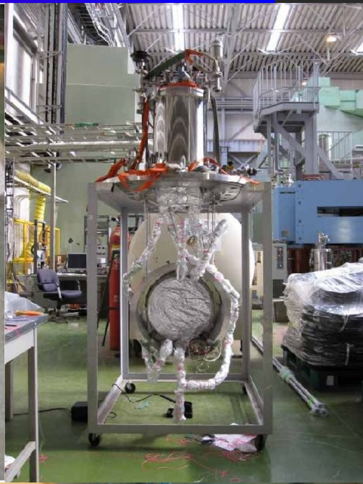




Absorber/Focus Coils

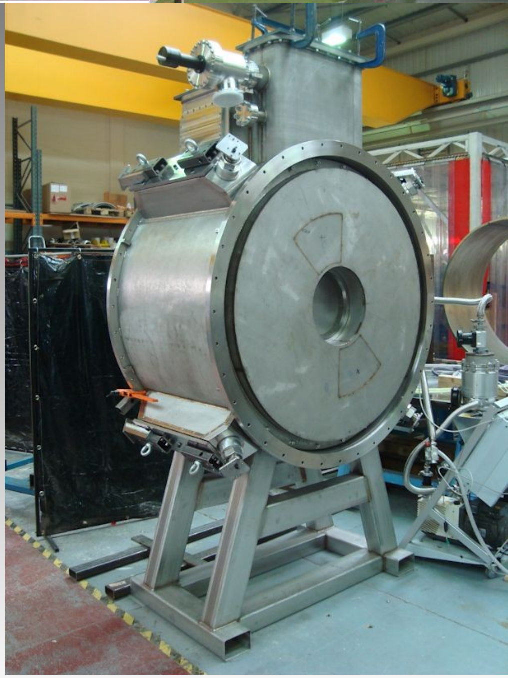


LH_2 Absorbers



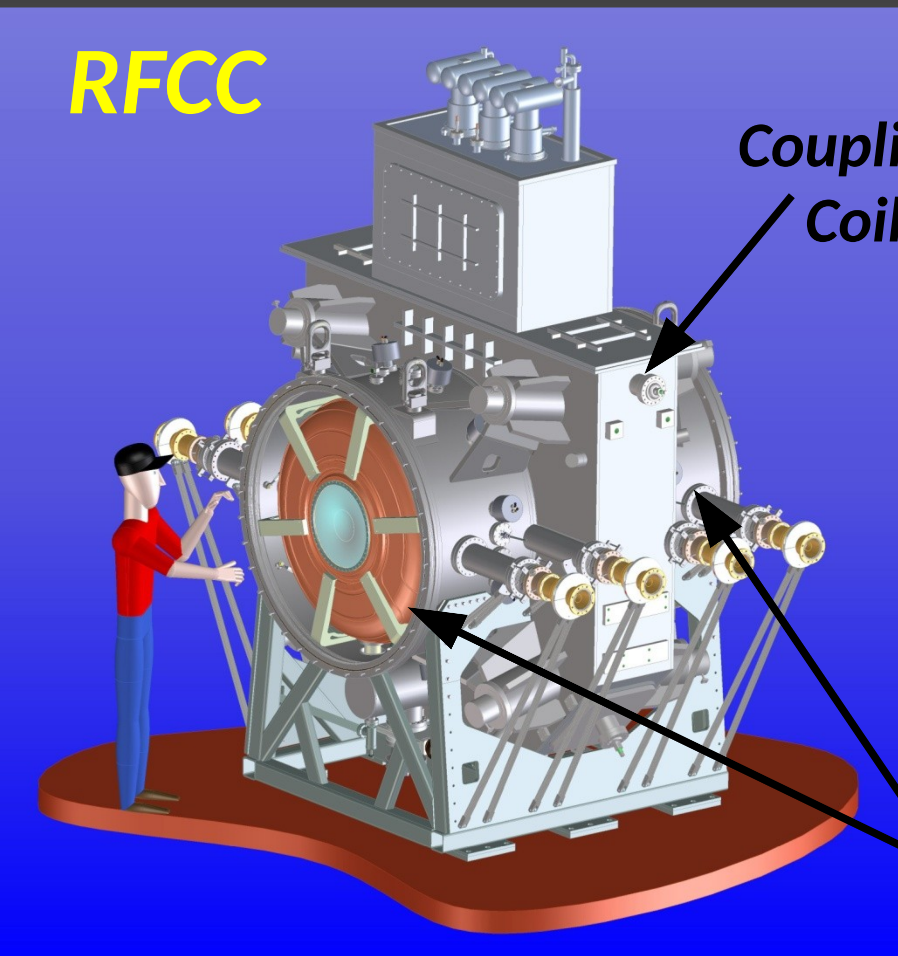
Focus Coil

2 coils operated:
- solenoid mode
- flip mode



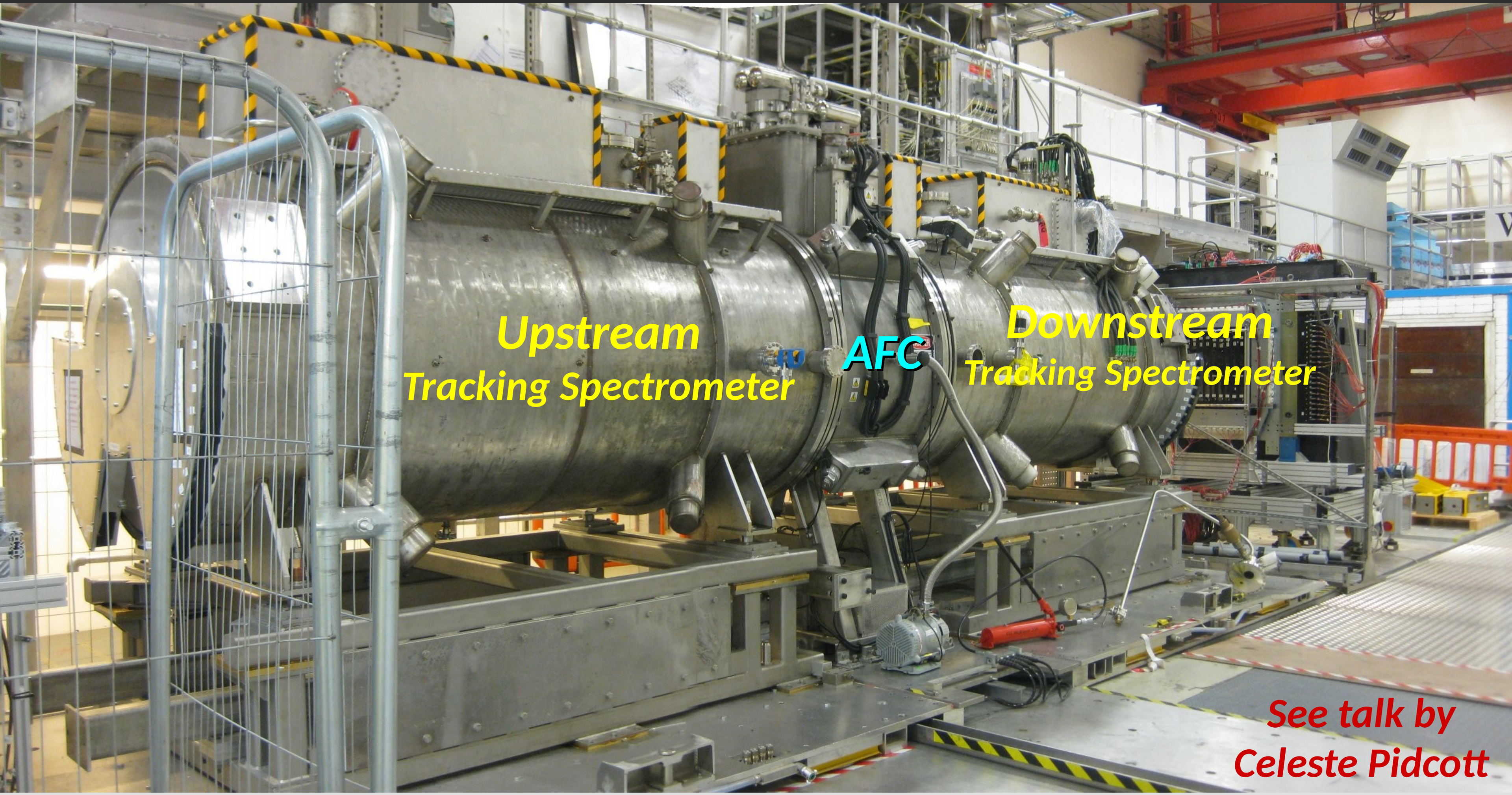
RF/Coupling Coils

Re-acceleration with RFCC



Coupling Coil

Step IV Status



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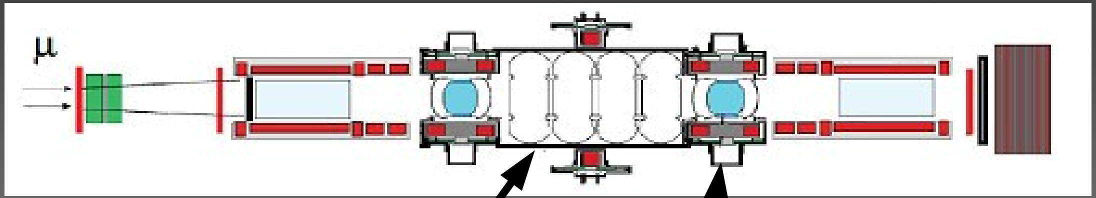
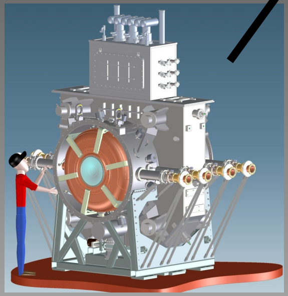
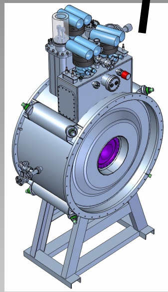
Step IV to Step V Transition

The transition from Step IV to Step V requires:







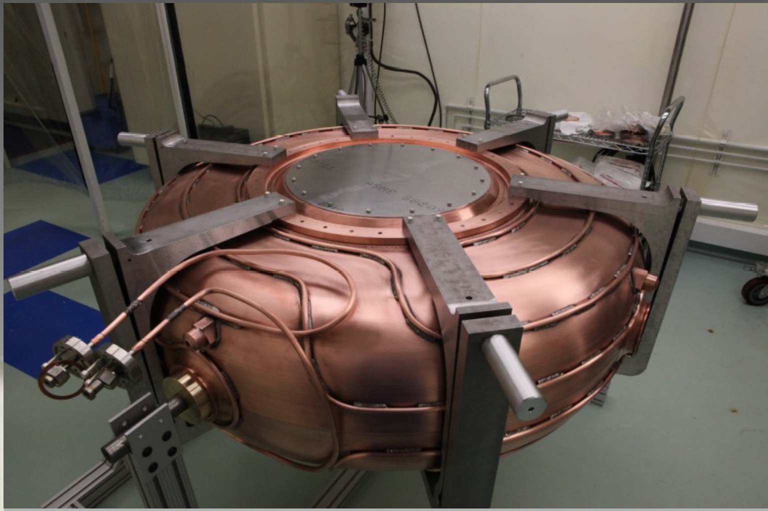
- ***Addition of RFCC module***
- ***Addition of a second AFC module***
  - already built and under test
- ***Extension the Partial Return Yolk (PRY)***

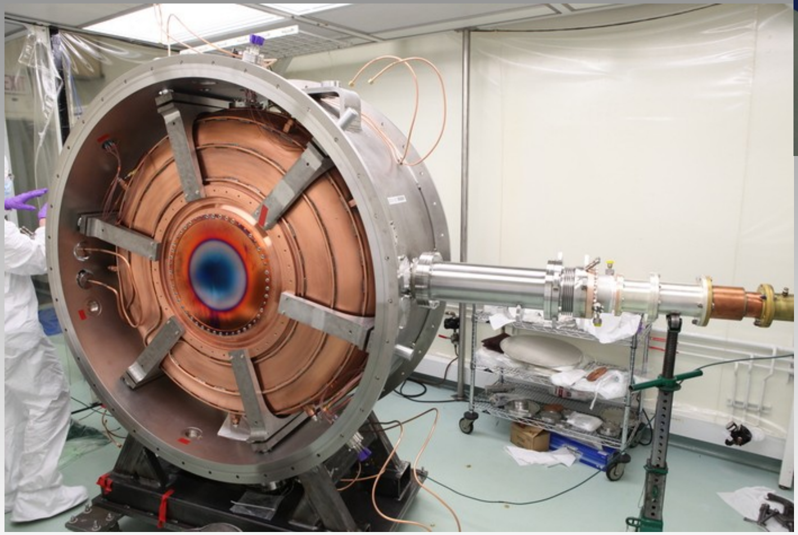
RF Requirements

- Demonstration of sustained cooling (MICE Step V) requires 4 RF cavities – total of 8 MV/m
  - Each cavity is 430 mm long with a Q of 44,000 and is resonant at 201.25 MHz
  - The cavities must operate in a strong magnetic field
- Driver system must provide 1 MW to each cavity (500 kW/coupler)
  - Provide required energy with four 2 MW amplifier chains
  - Distribution network must not impede service access to cooling channel
  - LLRF phase control of 0.5^{o} and 1% in amplitude regulation
- Require a system to determine the RF phase in each cavity during the transit of each individual muon
  - allows the experiment to compare the impact of the cooling channel on each individual particle
  - comparison of tracker measurements of phase space with predictions will test our understanding of the cooling process

RFCC Hardware Status:
RF Cavities

- 10 Cavities made, 1 electropolished
- New couplers designed and in operation
- Single cavity under test at Fermilab's MTA
- Early results:
  - 1MW, 8 MV/m at 5 Hz rate
  - no breakdown observed
  - low radiation levels

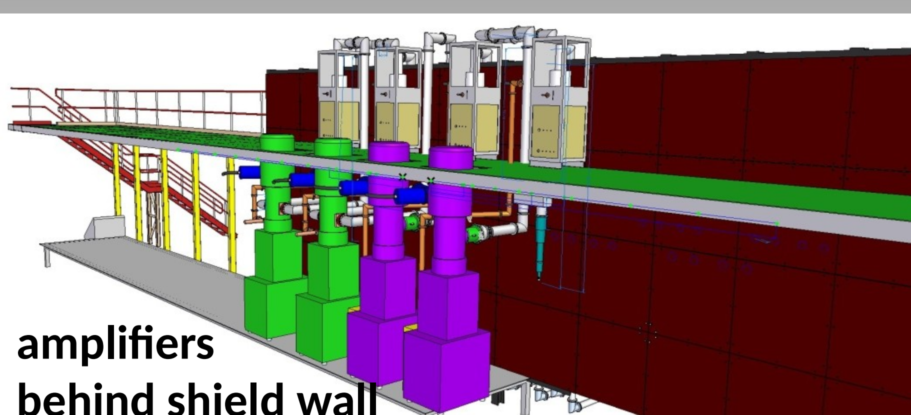




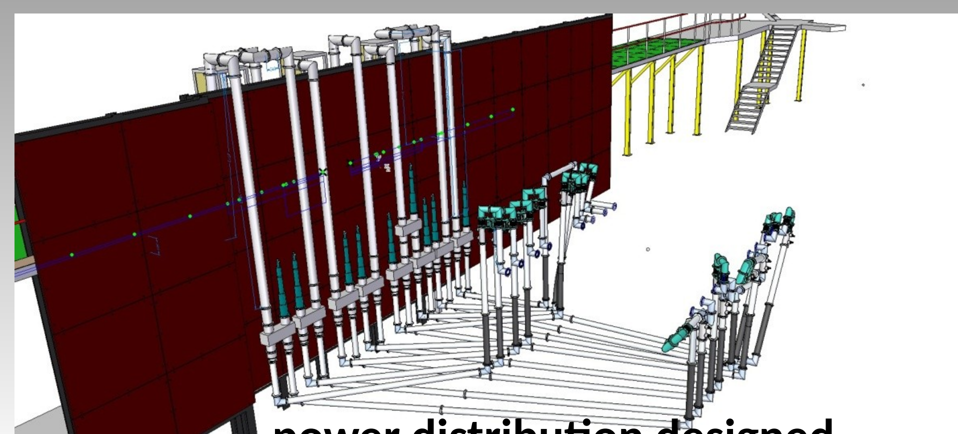
RFCC Hardware Status:
RF Power Train

- ~4 kW SSPA driving ~250 kW tetrode driving 2 MW triode
- Operation: 1 Hz, 1 ms pulse, 2 MW power, 201.25 MHz
- One amplifier chain complete
- 2nd chain: refurbished and tetrode commissioned

- successful EU-TIARA test of full chain in MICE hall December 2013



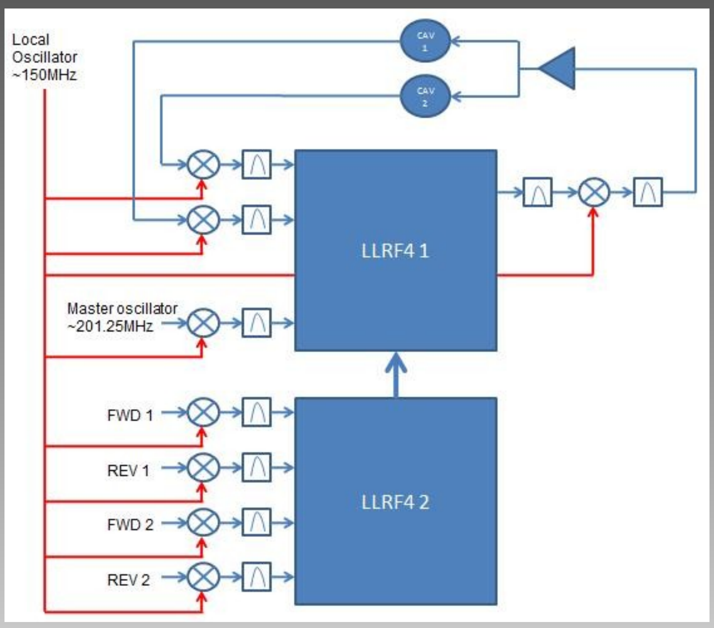
amplifiers behind shield wall

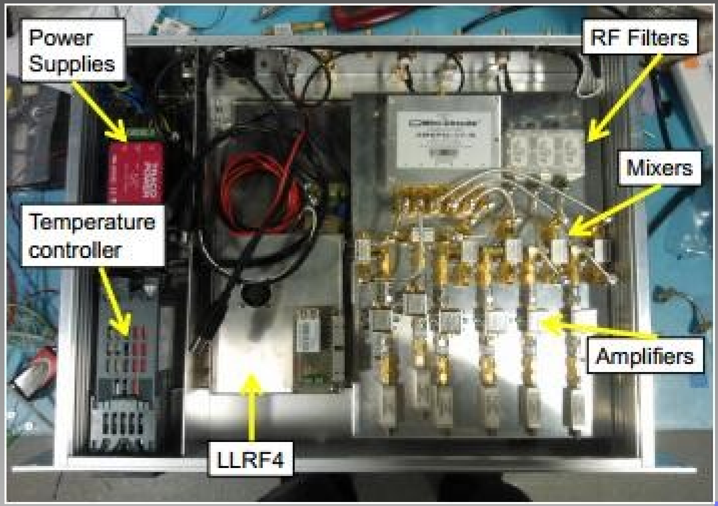


power distribution designed

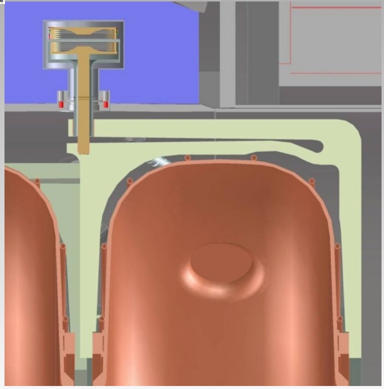
RFCC Hardware Status:
RF Controls

- *One amplifier/pair of cavities, pairs at fixed relative phase*
- *LLRF uses LLRF4 boards from LBNL—hardware and software designed*
- *Require phase control of 0.5^o and 1% amplitude regulation*





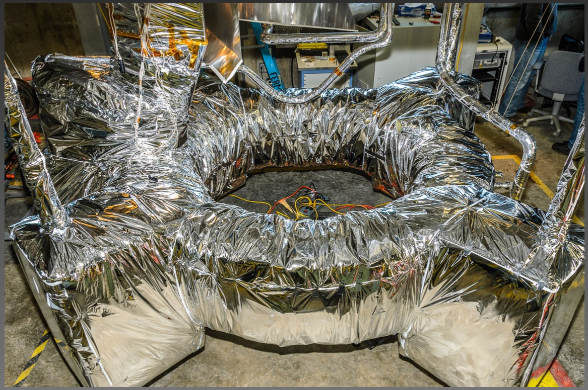
- **Cavities mechanically deformed by 6 pneumatically controlled tuner forks to maintain resonance**
- **Tuning range +/-350 kHz**

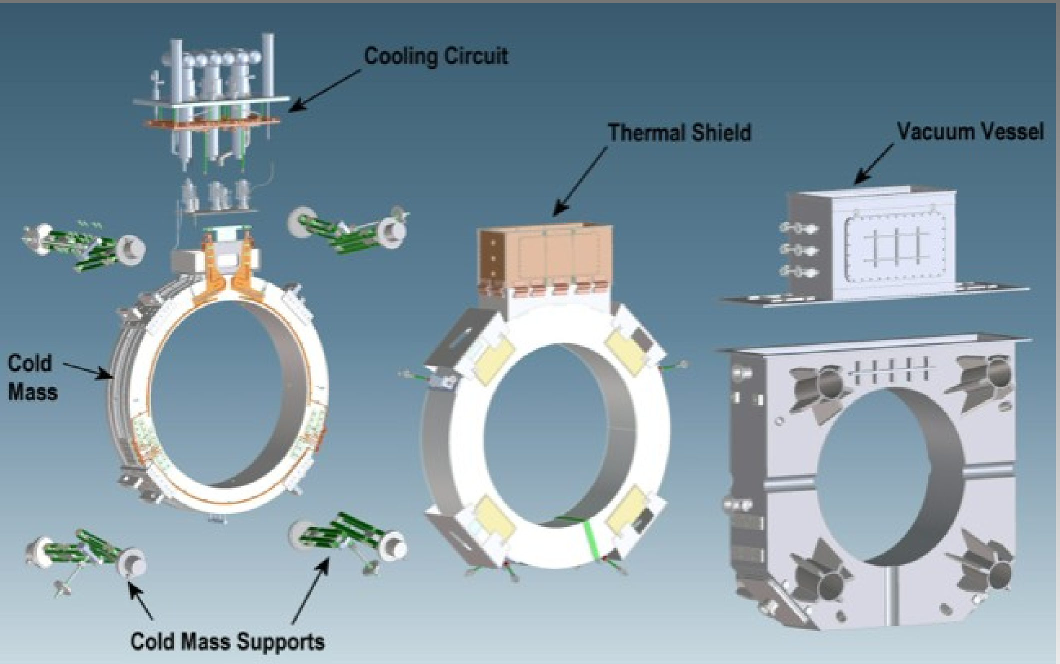


RFCC Hardware Status:
Coupling Coil

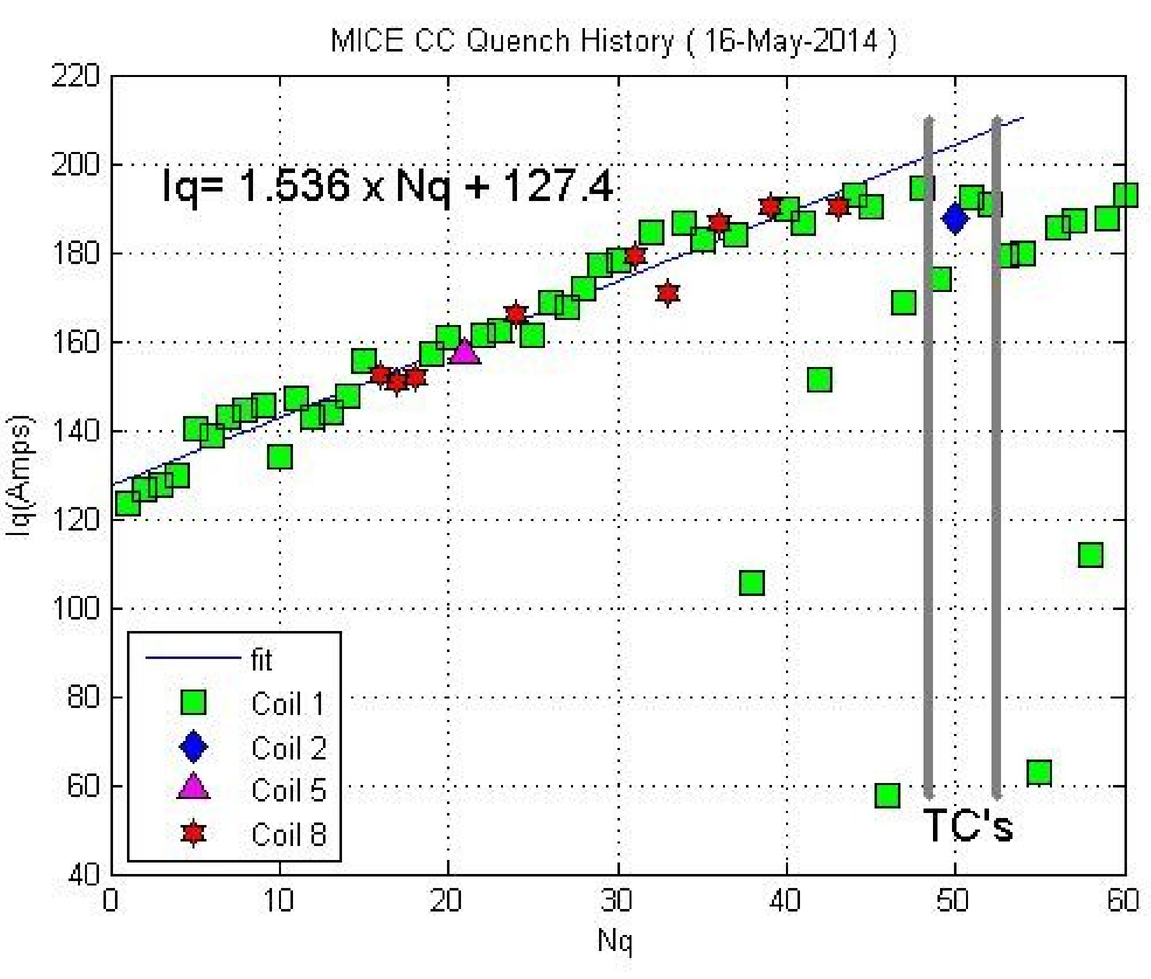
MICE Coupling Coil:

- 2.6 T
- 750 mm ID, 102 mm thick, 285 mm length
- Coil complete and tested





RFCC Hardware Status:
Coupling Coil



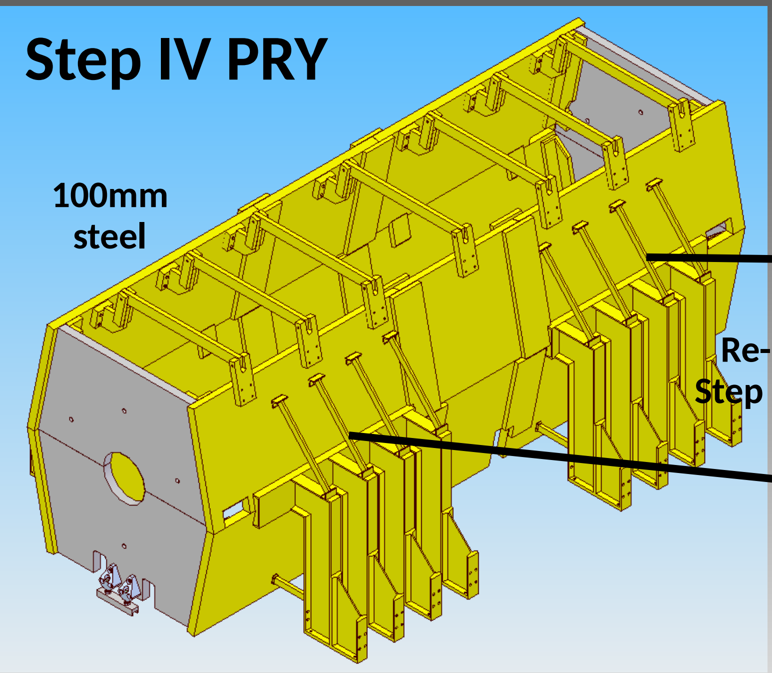
- Slow training progression (~60 quenches)
- Good memory after thermal cycles

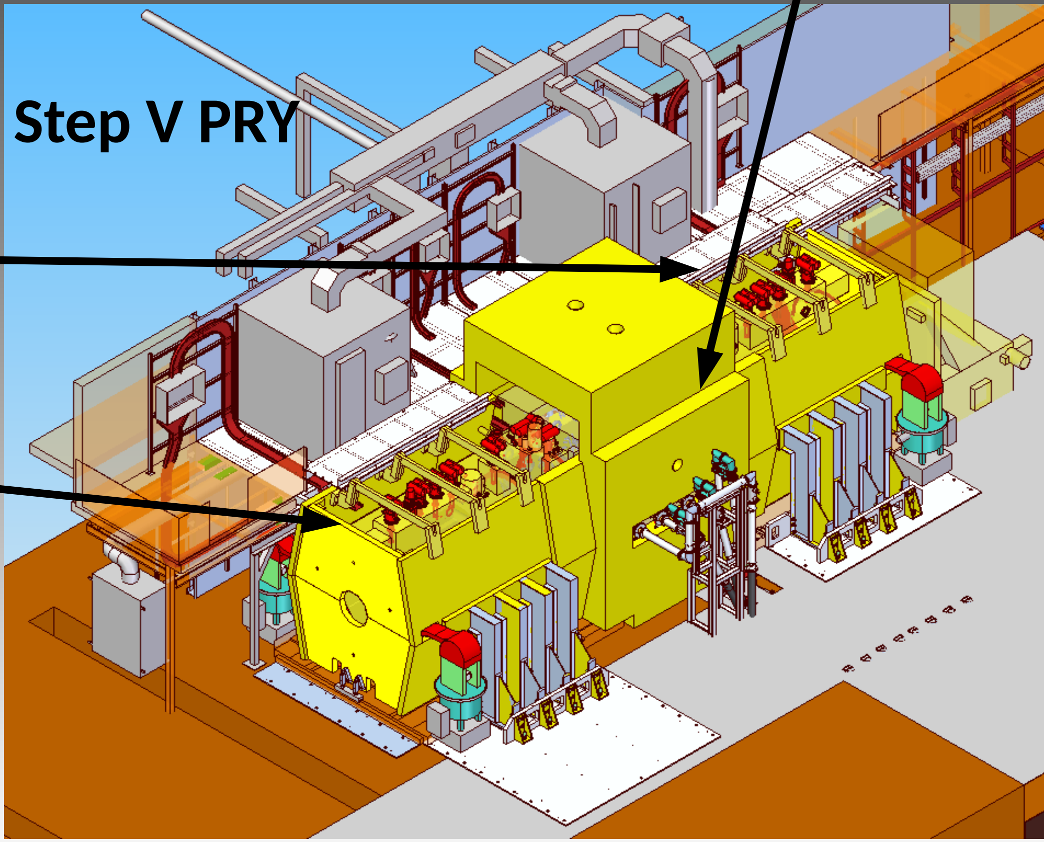
Peak current appears to be limited by cooling circuit limitations

Step V Hardware Status:
Partial Return Yolk

MICE magnets built w/out return yoke:

- stray flux mitigated by "Partial Return Yoke" or PRY
- coupling coil generates significantly more flux than with the Step IV configuration





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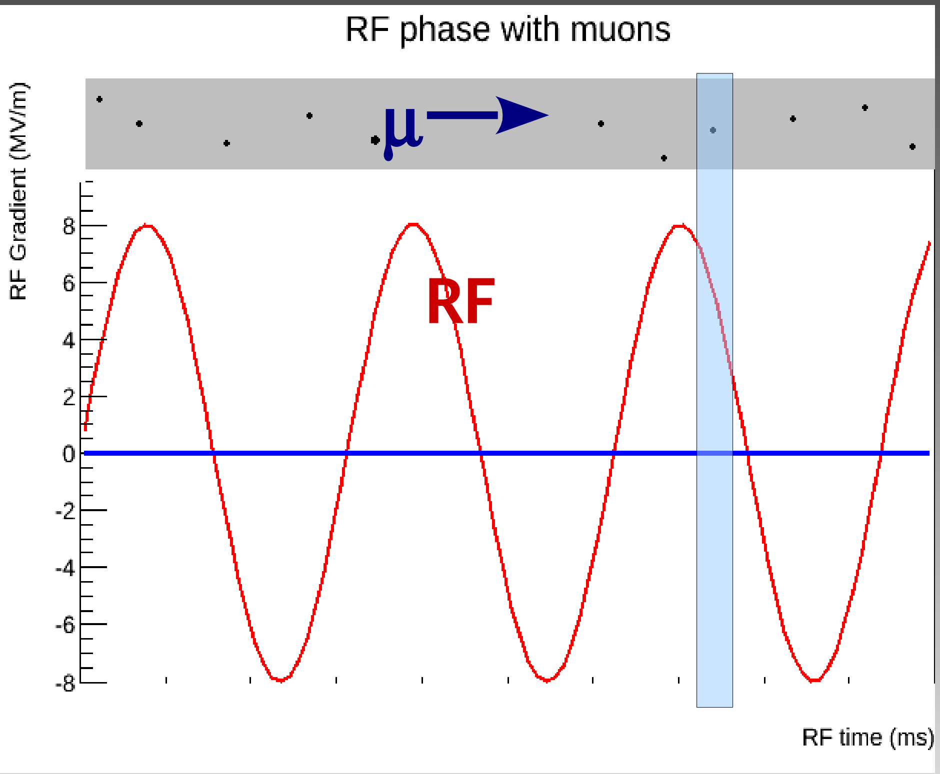
RF Phasing with Muons

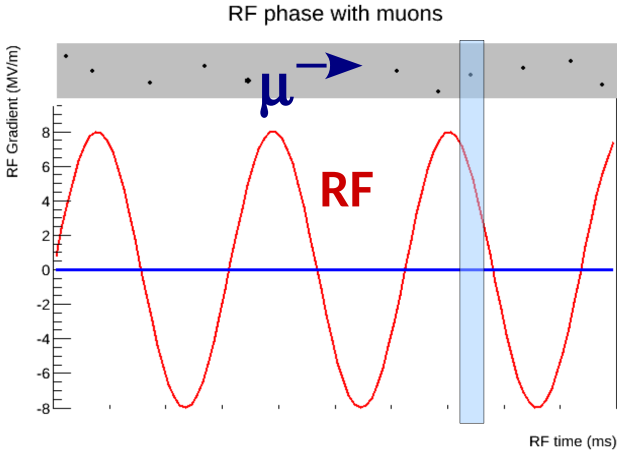
Must measure RF amplitude & phase for each μ



- No particle bunching in MICE
- Must select μ in phase w/RF
- ToF gives μ w/~50 ps resolution
- Offline use ToF & tracker to project μ to first RF cavity
- Require measuring RF phase wrt μ
- Desire 50 ps/3=16.7 ps => 1° phase
- Cavity linewidth is ~5 kHz in 201.25 MHz, or 2 parts in 10^5
- Max phase shift in 1 cycle is ~0.01°
- Can project ~100 cycles from measurement point, adding 1° error
- Need accurate baseline to project
- May be substantially eased by the LLRF feedback loop gain bandwidth

RF Phasing with Muons

- **Require:**
  - 1% amplitude measurement
  - 5° phase measurement
- **201.25 MHz => 4.97 ns period**
- **5° of 4.97 ns is 69 ps**
- **2 solutions for phase measurement:**
  - Copy LLRF signal and send on precision cable to ToF1, then return signal on identical detector cables to detector TDCs and compare ToF and LLRF TDC values
  - Split cavity diagnostic RF signal from cavity. Using synchronized trigger from LLRF for ToF TDCs to time-stamp, digitize signal and correlate offline with ToF TDC time-stamped information
- **RF digitization is required for amplitude measurement**
- **Undersampling being explored for digitization**



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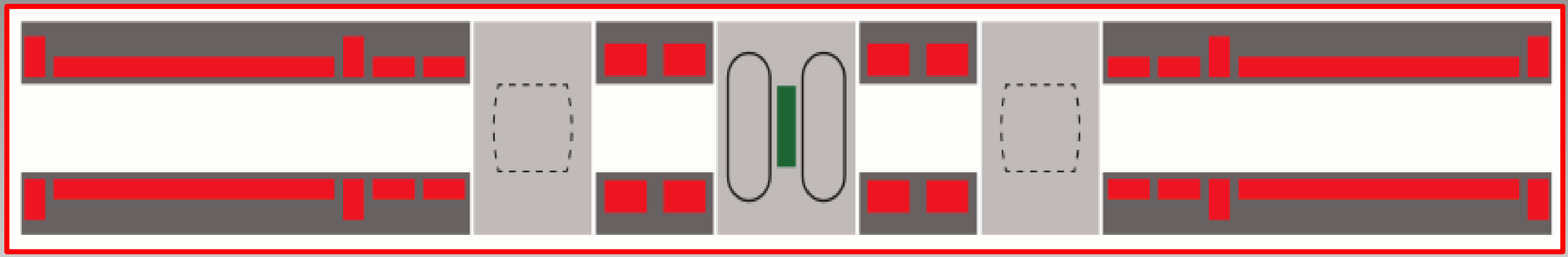
Future

The previous slides described the canonical MICE Step V.

However in light of the recent US P5 recommendations, the US MAP (Muon Accelerator Program) has been directed to ramp down its activities. MAP was reviewed by US DOE in mid-August and the US contributions to the MICE project (a part of the MAP) received favorable support. However, we have been asked to complete the project by end September 2017, and this will impact the scope of Step V.

Future

- DOE review of MAP/MICE recommends:
  - Demonstration of ionization cooling with re-acceleration
  - Equipment required to make this demonstration must be operational and taking data during 2017
- The collaboration is evaluating the options by which it can achieve this, including:
  - A simplified "Step 3pi/2" configuration (might look like)



Future

	Step IV	Step $\frac{3\pi}{2}$
Study of properties that determine cooling performance		
Material properties of LH_2 and LiH	**Yes**	LH_2 and/or LiH
Observation of $\epsilon_\perp^{\mathrm{n}}$ reduction	**Yes**	Yes
Demonstration of sustainable ionization cooling		
Observation of $\epsilon_\perp$ reduction with re-acceleration		**Yes**
Observation of $\epsilon_\perp$ reduction and $\epsilon_\parallel$ evolution		**Yes**
Observation of $\epsilon_\perp$ reduction and $\epsilon_\parallel$ and angular momentum evolution		Yes†

† Requires systematic study of "flip" optics.

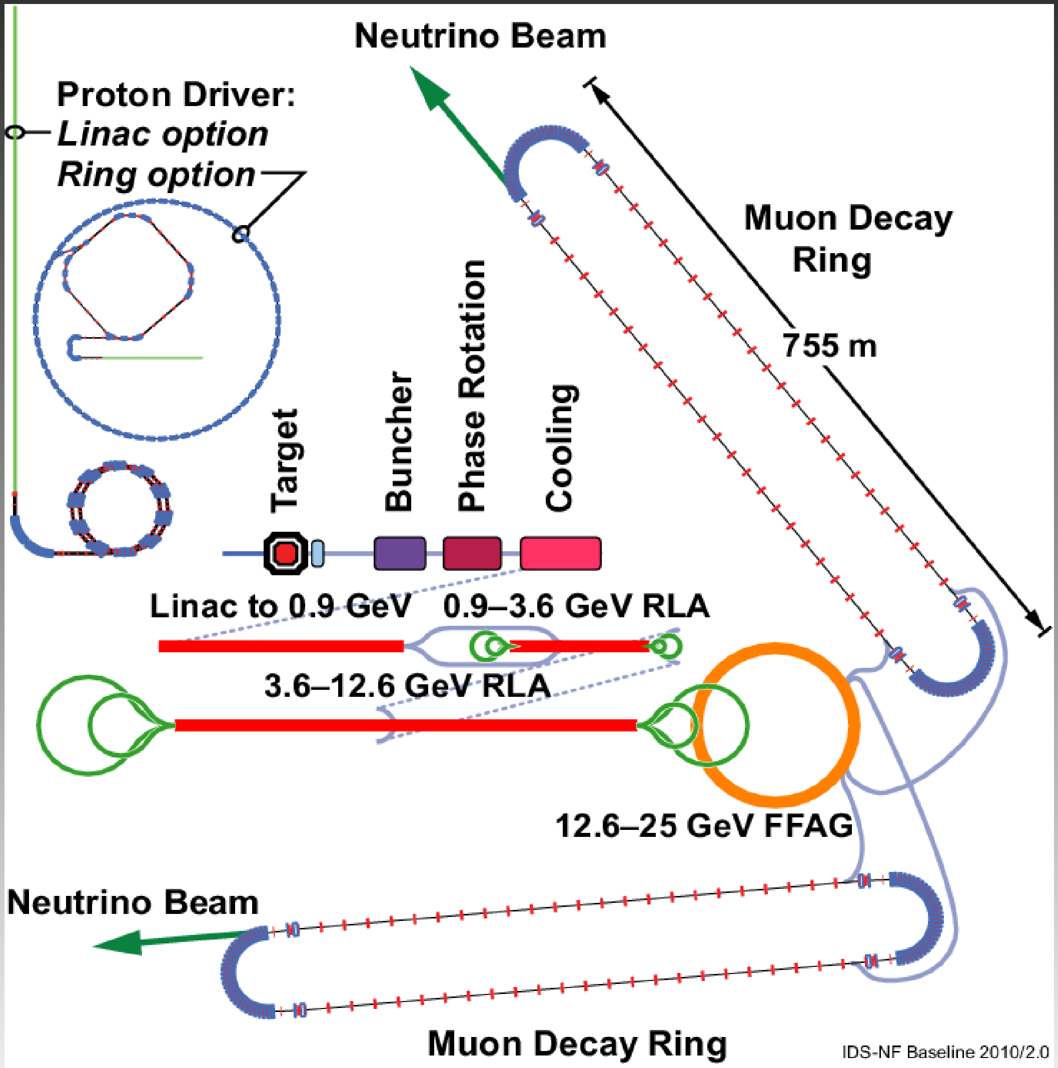
Conclusions

- MICE is a precision experiment: 0.1% relative measurement of muon ionization cooling effect for future neutrino factory and/or muon collider
- MICE is presently preparing for Step IV
- Transition to Step V requires additional AFC, RFCC, and PRY extension
- Much Step V hardware in hand
- Developing techniques to measure the relative phase and amplitude of the RF wrt the muon
- Recent developments in funding agencies will affect scope of MICE Step V

Thank you for your attention

Extra Slides

Motivation:
Neutrino Factory



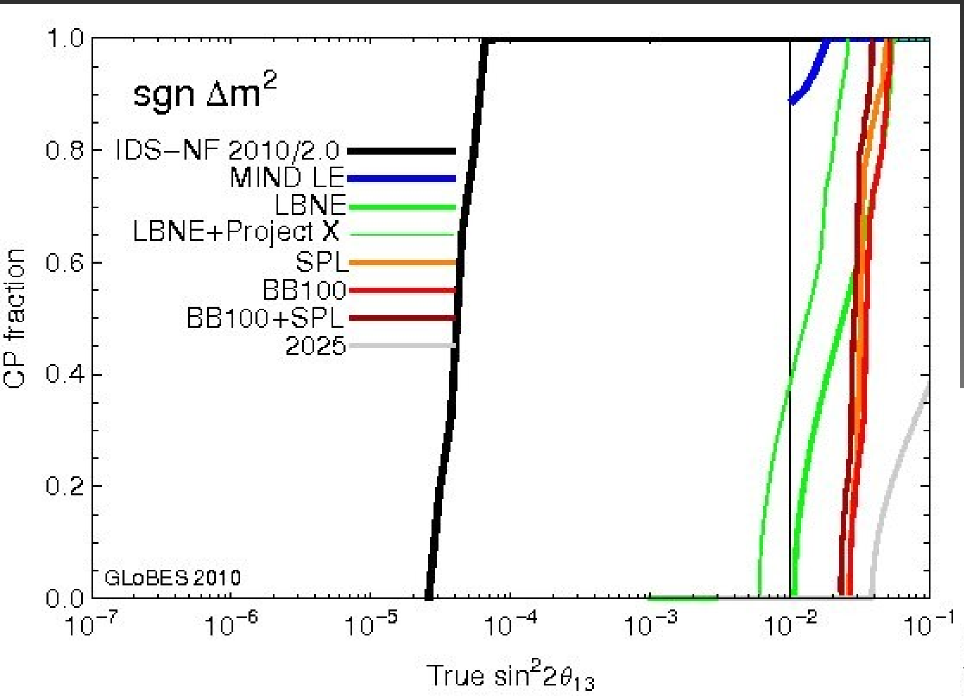
Neutrino Factory:
accelerate muons and store in a ring to produce neutrinos

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

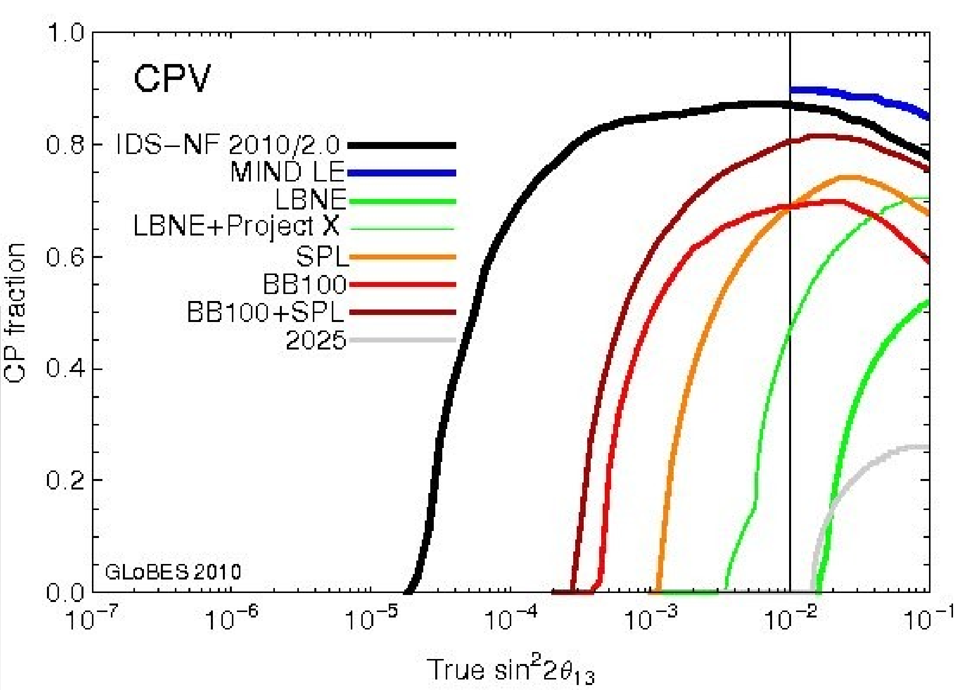
High energy ν_e are *unique* to future facilities.
Golden channel: $\nu_e \rightarrow \nu_\mu$
long baseline oscillations manifests itself by wrong sign muons:

$$\nu_\mu + N \rightarrow \mu^- + X$$

Motivation: Neutrino Factory



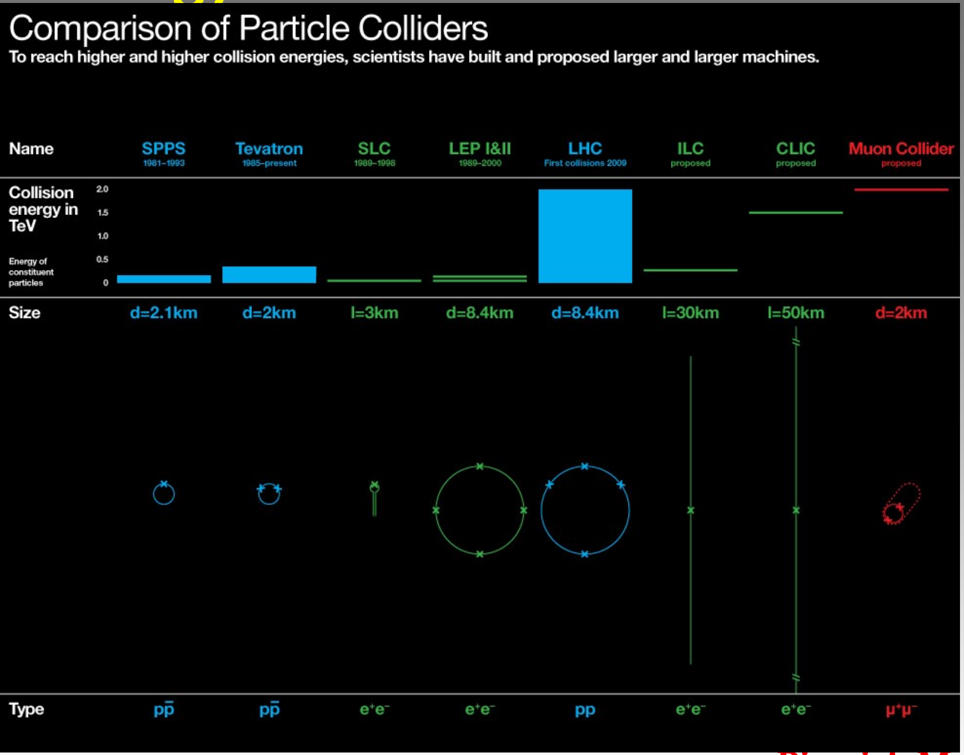
Neutrino Factory

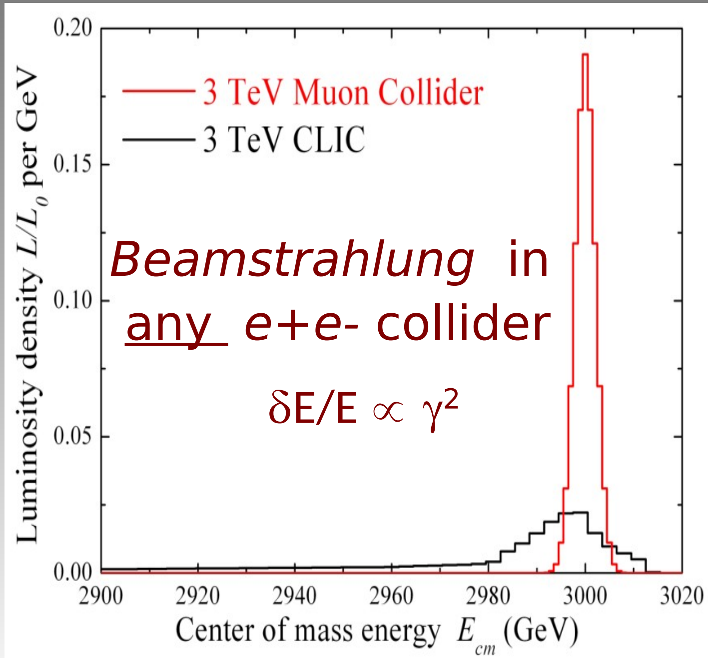


Comparison of neutrino physics reaches for different measurements.

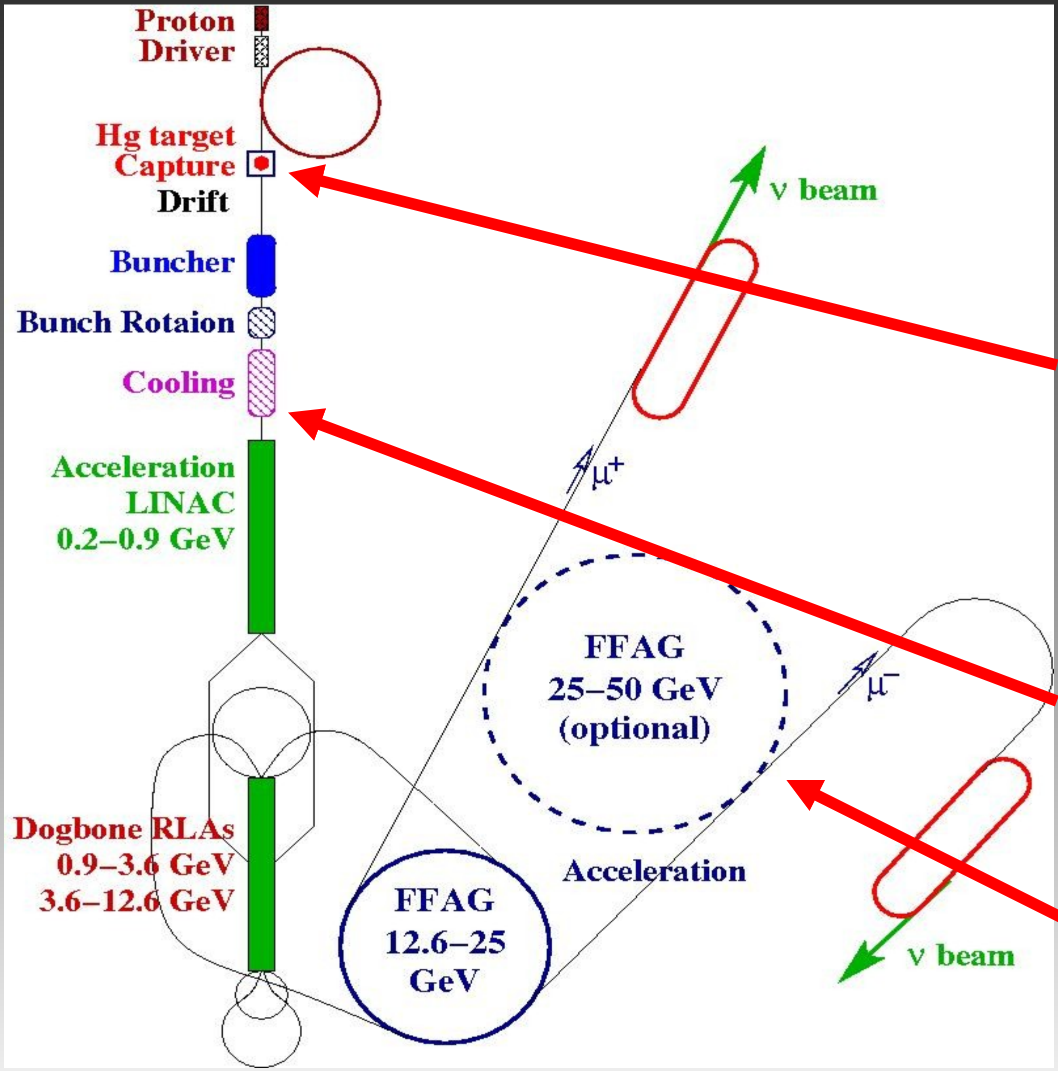
$\mu^+\mu^-$ Collider Basics:

- Center of Mass energy: 1.5-6 TeV (3 TeV)
- Luminosity > 10^{34} cm^{-2} sec^{-1} (350 fb^{-1}/yr)
- Compact ring for 3 TeV – 3.8 km circumference ring
- Energy resolution: 95% luminosity in dE/E ~ 0.1%





Motivation:
Muon Accelerator



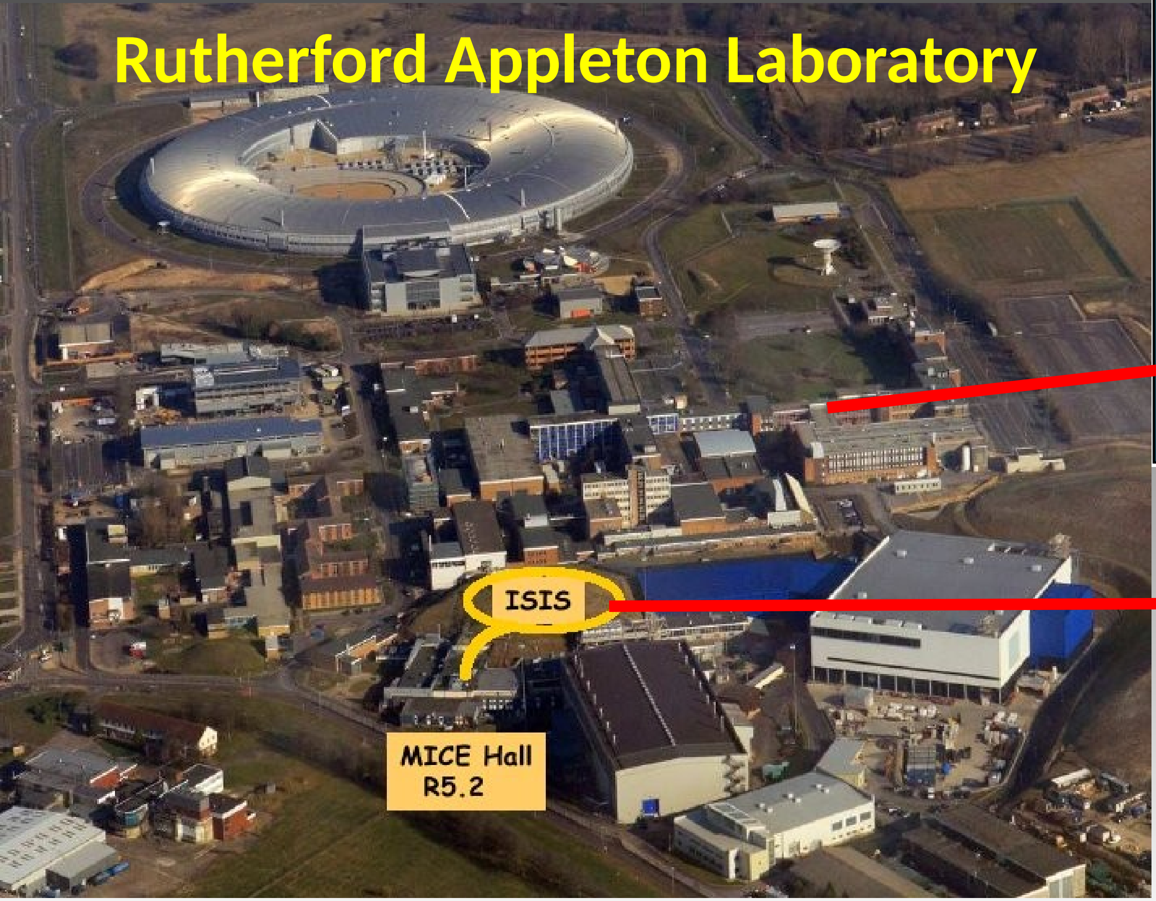
International R&D efforts to meet the challenges

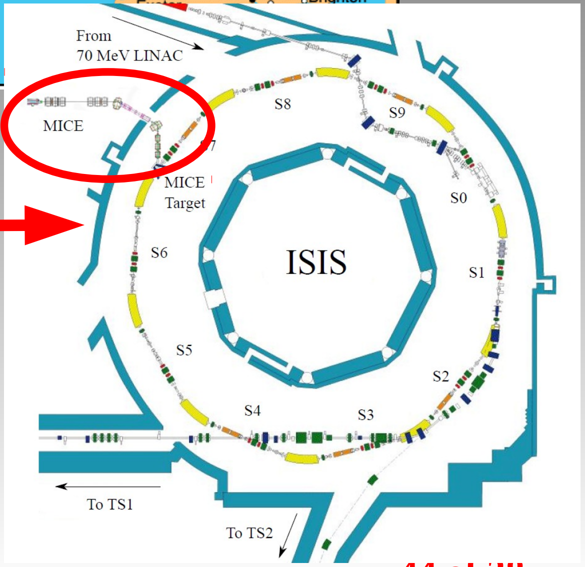
High-power target:
4MW proof of principle
- *MERIT (CERN)*

Fast muon cooling:
- *MICE (RAL)*

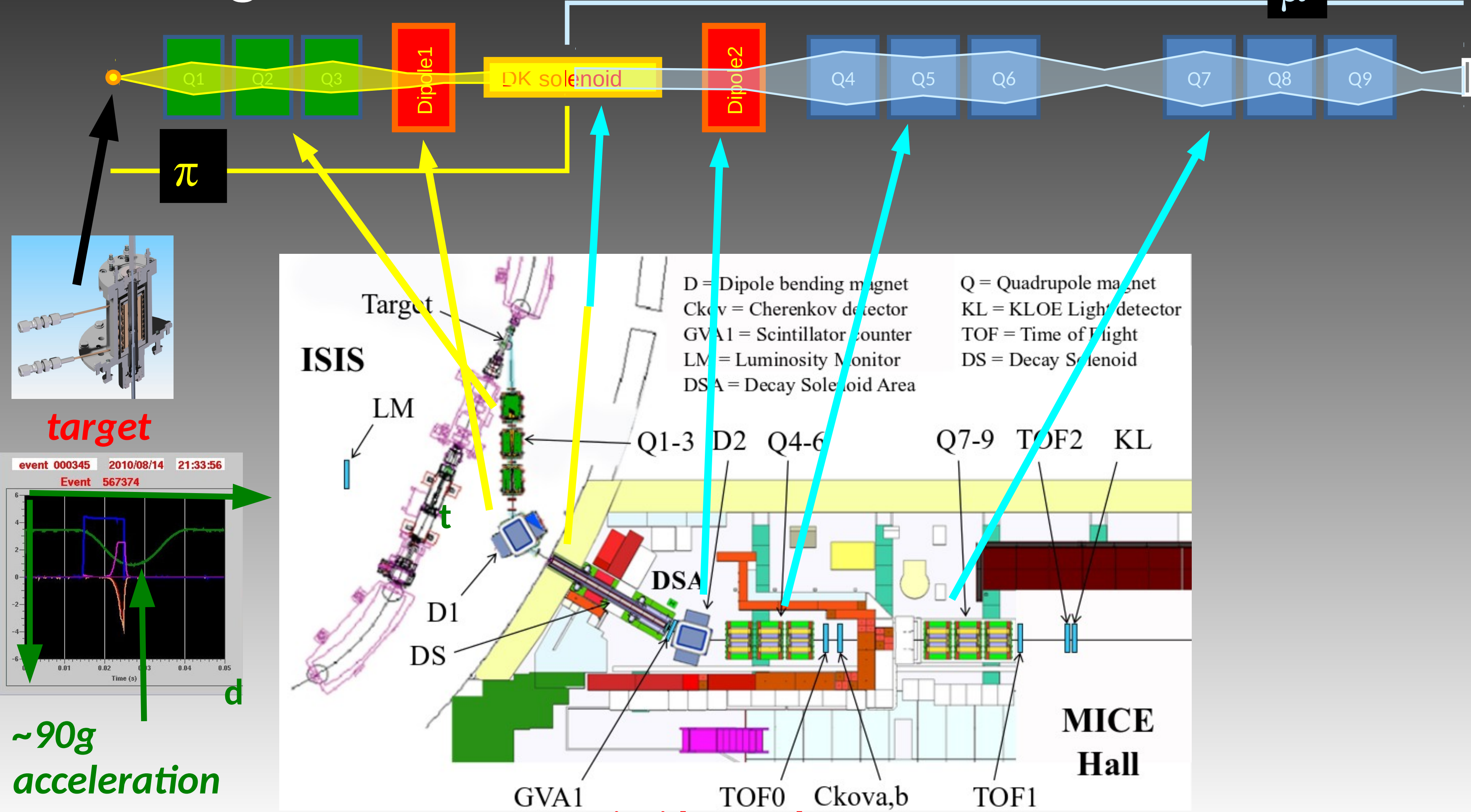
Fast, large aperture accelerator (FFAG)
- *EMMA (Daresbury)*

Description:
The Lab

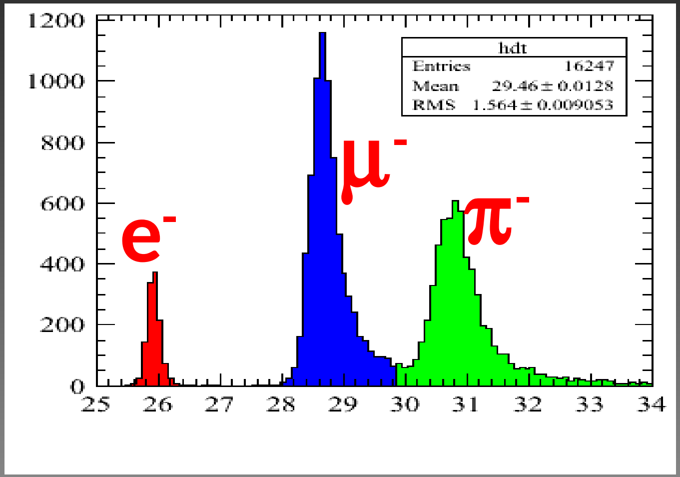




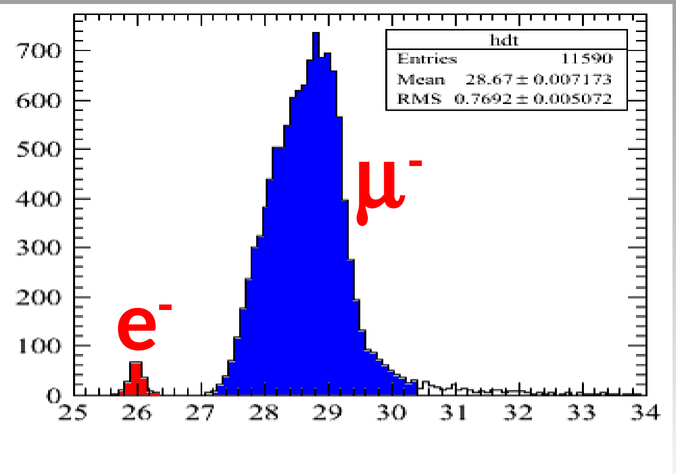
Selecting a muon beam



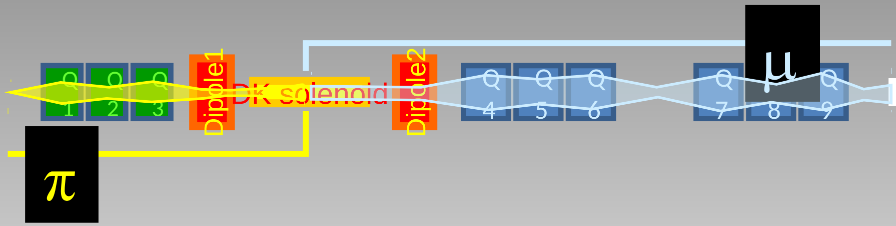
μ direction in π rest frame



$p_1 \sim p_2$: beamline optimized for calibration studies

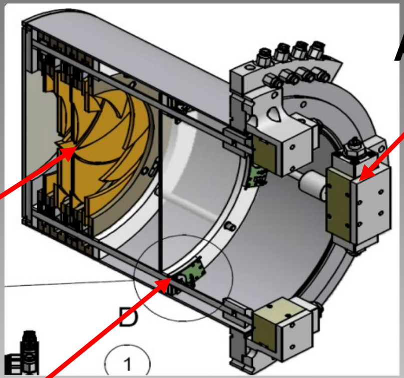


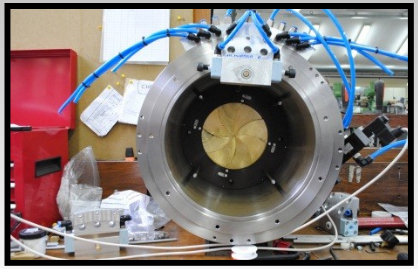
$p_1 \sim 2p_2$: beamline optimized for $\pi \rightarrow \mu$ transmission



Beam Selection

Selecting muon beams for MICE measurements



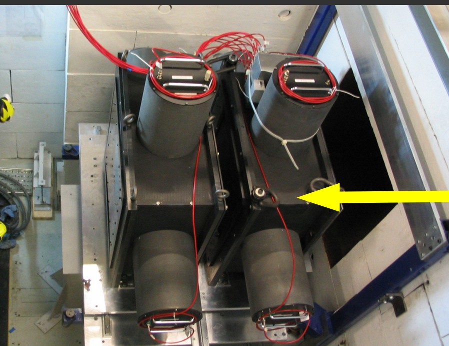


momentum (MeV/c) →

emittance (mm) ↓

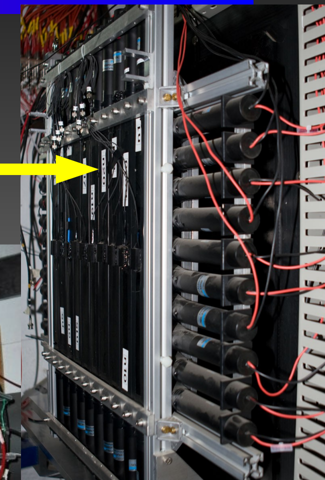
	140	200	240
3	p_{tgt}=321 p_{sol}=185 p_{dif}=151	p_{tgt}=390 p_{sol}=231 p_{dif}=207	p_{tgt}=453 p_{sol}=265 p_{dif}=245
6	p_{tgt}=328 p_{sol}=189 p_{dif}=148	p_{tgt}=409 p_{sol}=238 p_{dif}=215	p_{tgt}=472 p_{sol}=276 p_{dif}=256
10	p_{tgt}=338 p_{sol}=195 p_{dif}=164	p_{tgt}=429 p_{sol}=251 p_{dif}=229	p_{tgt}=486 p_{sol}=285 p_{dif}=267

MICE PID:
Detectors



Upstream PID:
discriminate p, π, μ

- *Time of Flight – ToF0 & ToF1*
- *Threshold Cerenkov*



Downstream PID:
reject decay electrons

- *Time of Flight - ToF2*
- *Kloe-light Calorimeter - KL*
- *Electron-Muon Ranger -EMR*