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MANX, A 6-D Muon Beam Cooling Experiment

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Motivation for MANX

- There two challenges for muon colliders:
    1. Short lifetimes
    2. Diffuse phase-space production.

- Cooling is required before effective acceleration of muons can take place.

- **Ionization cooling** is sufficiently quick to increase particle density in phase space, but only in transverse dimensions.

- **Emittance exchange** is required between longitudinal and tranverse dimensions.

- The Helical Cooling Channel (HCC) was proposed as a novel innovation for 6-dimensional cooling [Johnson and Derbenev].

- The combination of solenoid, dipole and quadrupole fields that comprise a HCC can be achieved by magnetic rings displaced from each other in a helical pattern, forming a helical solenoid (HS).

MANX at RAL

- MANX is a six-dimensional muon ionization cooling demonstration experiment using a HS implementation of an HCC.
- Goals:
  1. Test HCC Theory and its HS implementation
  2. Verify simulation programs
  3. Demonstrate effective 6D muon cooling.
- Factors out the basic HCC physics from engineering complications (worked on in parallel projects)
  1. Liquid helium in place of liquid or gaseous hydrogen
  2. No RF
- We propose to have MANX follow MICE at the Rutherford-Appleton Laboratory (RAL) as an extension of the MICE experimental program.
  1. MANX spectrometer yields six measurements {*x*, *y*, *px*, *py*, *E*, and *s*} for each particle, where *s* is the path length of particle.
  2. 6D cooling factor of ~ 2.0 in 2m of MANX channel

MANX and Muons, Inc.

MANX is a signature story of Muons, Inc. - several new ideas combine www.muonsinc.com

1. Idea of gaseous energy absorber enables new technology to generate **high accelerating gradients** for muons by using the high-pressure region of the Paschen curve: High Pressure RF Cavity (HPRF)
   - Measurements by Muons, Inc. and IIT at FNAL have demonstrated that hydrogen gas suppresses RF breakdown for high gradients (~60MV/m) in high fields (~ 3.5 Tesla)
   - Hydrogen performs 6X better than LHe
   - Beam tests with HPRF cavity planned at FNAL's Muon Test Area (MTA)

2. Concept of a cooling channel filled with a **continuous homogeneous absorber** to provide longitudinal cooling by exploiting the path length correlation with momentum in a magnetic channel with positive dispersion: Helical Cooling Channel (HCC)
   - Can be extended to the case of magnetic fields that change amplitude along the *z*-axis (the beam direction).
   - For MANX, the beam momentum can change and the conditions for 6D cooling can still be met as a beam slows down in a continuous absorber.

Ionization cooling issues

- 2D Transverse Cooling

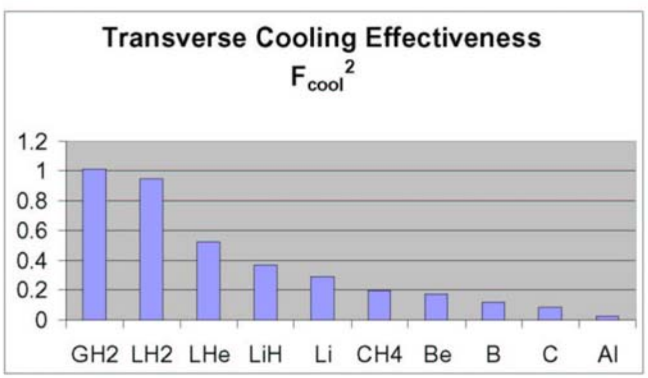
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

and

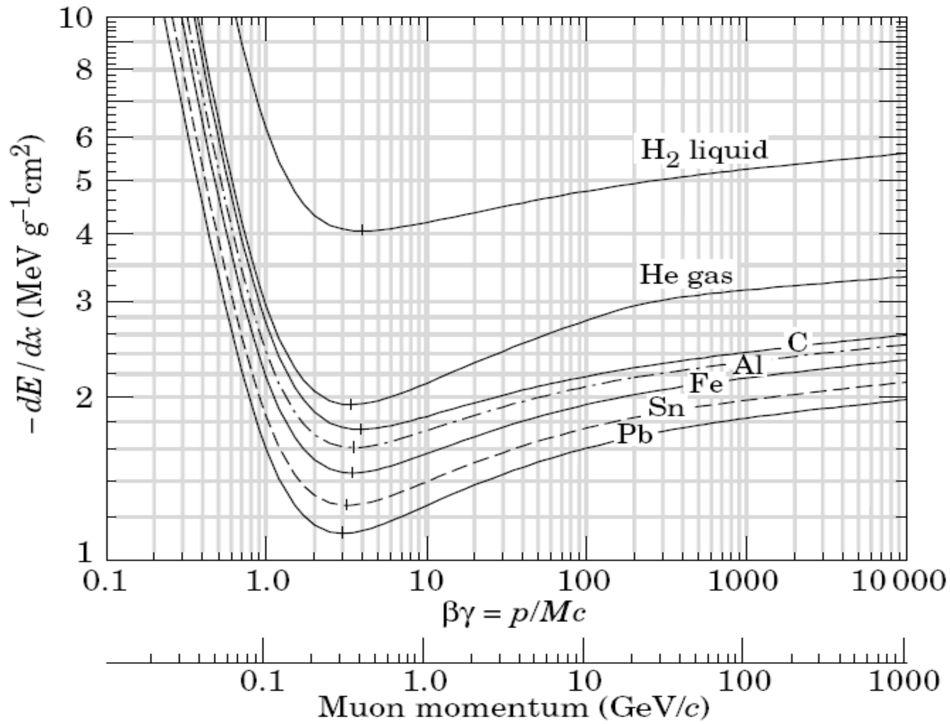
$$\epsilon_{N,\mathrm{min}} = \frac{\beta_\perp (14\ \mathrm{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$

- Figure of merit: $F_{cool}=L_R dE_\mu/ds$

(4D cooling) for different absorbers



- H2 has better heat capacity, viscosity and IC effectiveness



Want $\beta_\perp \approx p/B$ as small as possible

- Reducing p difficult as the slope of dE/dx implies longitudinal heating for p<300.
- Increasing B means **new technology**

Can compensate with more complex dispersion function or absorber shape

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HCC theory evolution

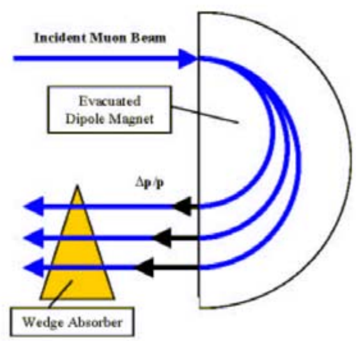


Figure 1. Use of a Wedge Absorber for Emittance Exchange

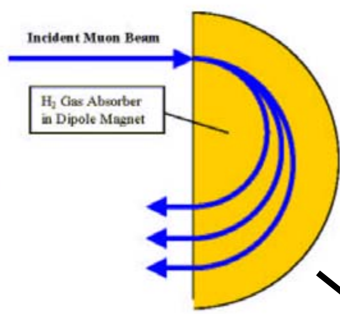
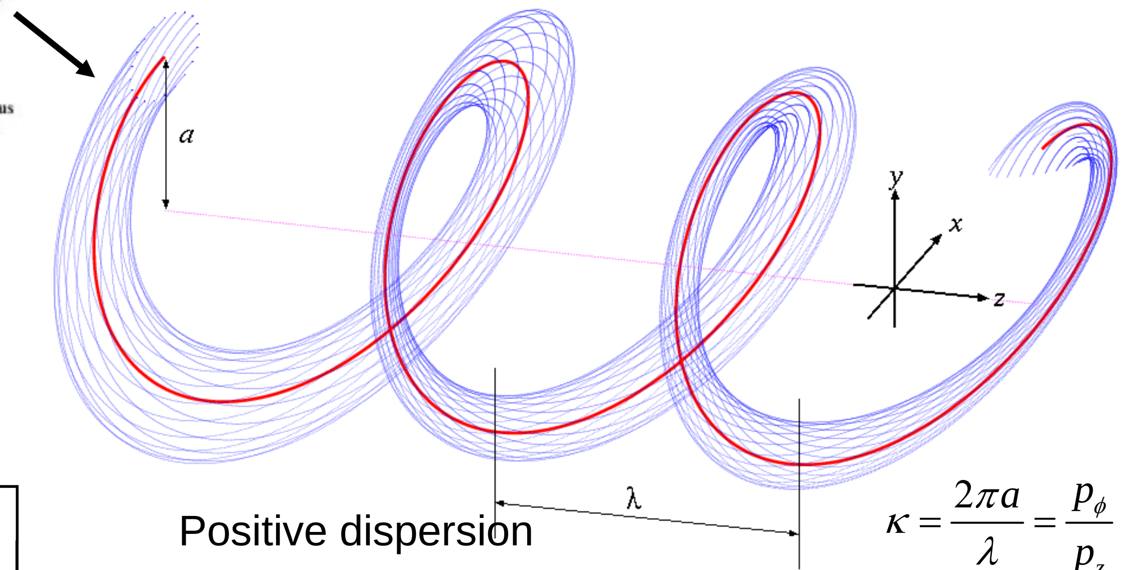


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Dipole ➔ Dipole + Solenoid (+Quad for stability)

$$\left.\begin{aligned} F_{h-dipole} &\approx p_z \times B_\perp; \quad b \equiv B_\perp \\ F_{solenoid} &\approx -p_\perp \times B_z; \quad B \equiv B_z \end{aligned}\right\} \quad f_{central} = \frac{e}{m}(b_\varphi \cdot p_z - b_z \cdot p_\varphi)$$



Positive dispersion

$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

Transforming to the frame of the rotating helical dipole leads to a time and z –independent Hamiltonian, can form relation:

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left[B - \frac{1+\kappa^2}{\kappa} b\right]$$

Manipulate values of parameters to change performance:

$$q \equiv \frac{k_c}{k} - 1 = \beta \sqrt{\frac{1+\kappa^2}{3-\beta^2}}$$

Equal cooling decrement

$$\hat{D} \equiv \frac{p}{a}\frac{da}{dp} = 2\frac{1+\kappa^2}{\kappa^2}$$

Longitudinal only cooling decrement

Characteristics of HCC

- Compactness
- Field homogeneity (continuous solenoid)
- HCC theory straightforward to apply
- Variability in the following:
  - Absorber
  - Fields
  - Channel geometry
  - Coil construction
  - RF or no RF
- HCC R & D is relevant to many stages of MC/NF design
- HCC R & D can be an upgrade to MICE experiment
- HCC techniques relevant to FNAL near and long-term program

Survey of HCC Applications

Ability to cool in any or all dimensions enables many uses

- Pre-cooler*
- Quasi-isochronous p decay channel*
- Muon Collider/Neutrino Factory Front End
- Stopping Muon Beams*
- 6D Cooling for Muon Colliders
- Transition and matching sections*
- Extreme Cooling: PIC and HCC
- Transport to pbar trap*
- Cooling Demonstration: MANX*

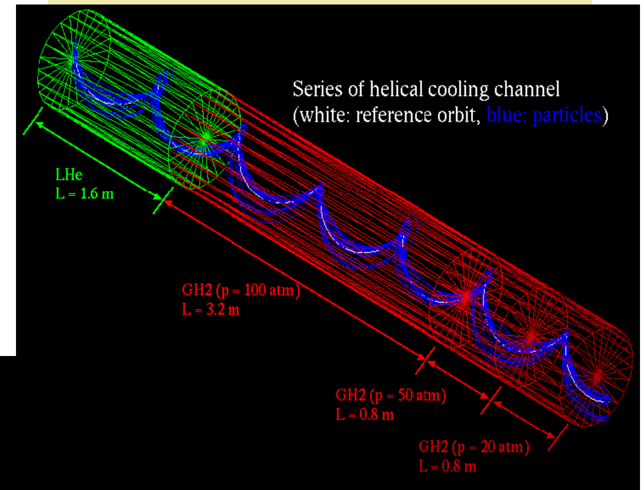
* no RF required

http://www.muonsinc.com/tiki-index.php?page=Papers+and+Reports
for relevant EPAC08 papers and other conference references

HCC Applications

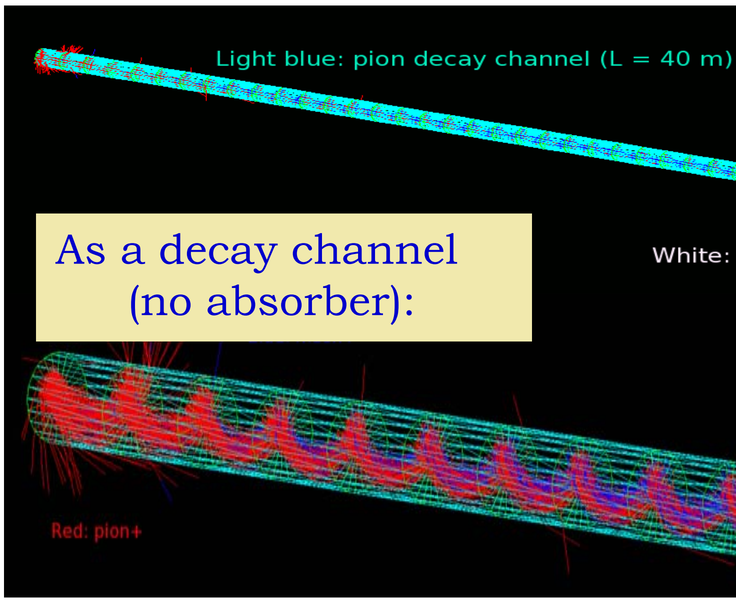
Some examples of parameter manipulation from the Derbenev-Johnson HCC theory to address specific applications:

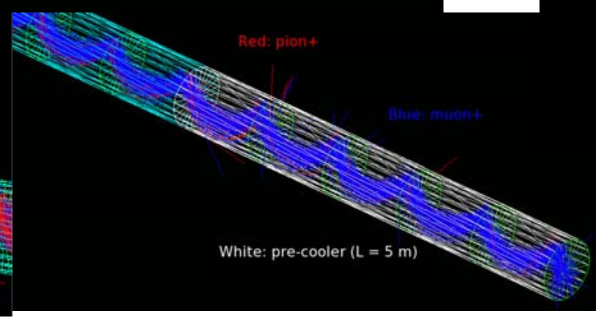
Stopping muons: decreasing absorber density.



As precooler: absorber, no RF.

As a decay channel (no absorber):





As a cooling channel (abs+RF):

Muons, Inc. : Nothing designed today will be used exactly as imagined now

Solenoid + High Pressurized RF

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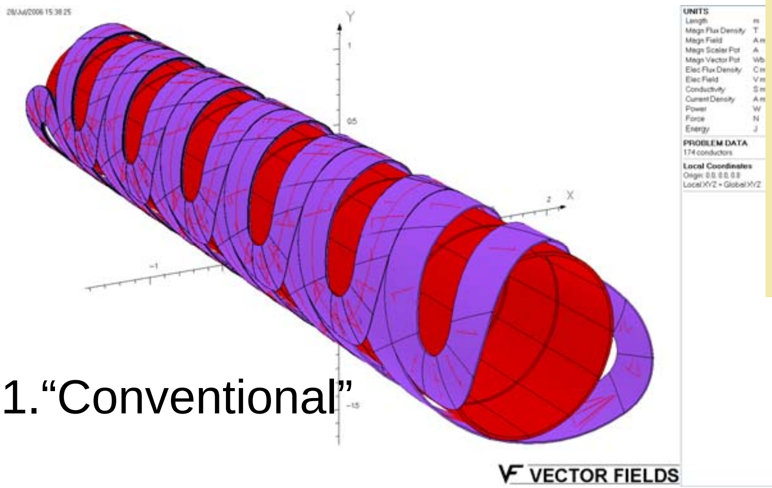
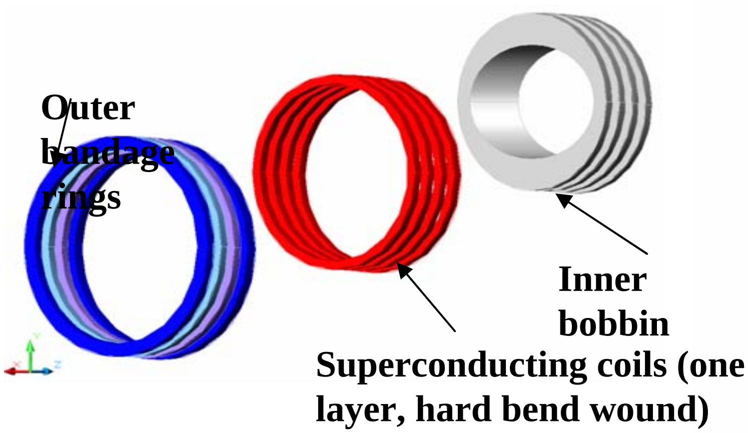
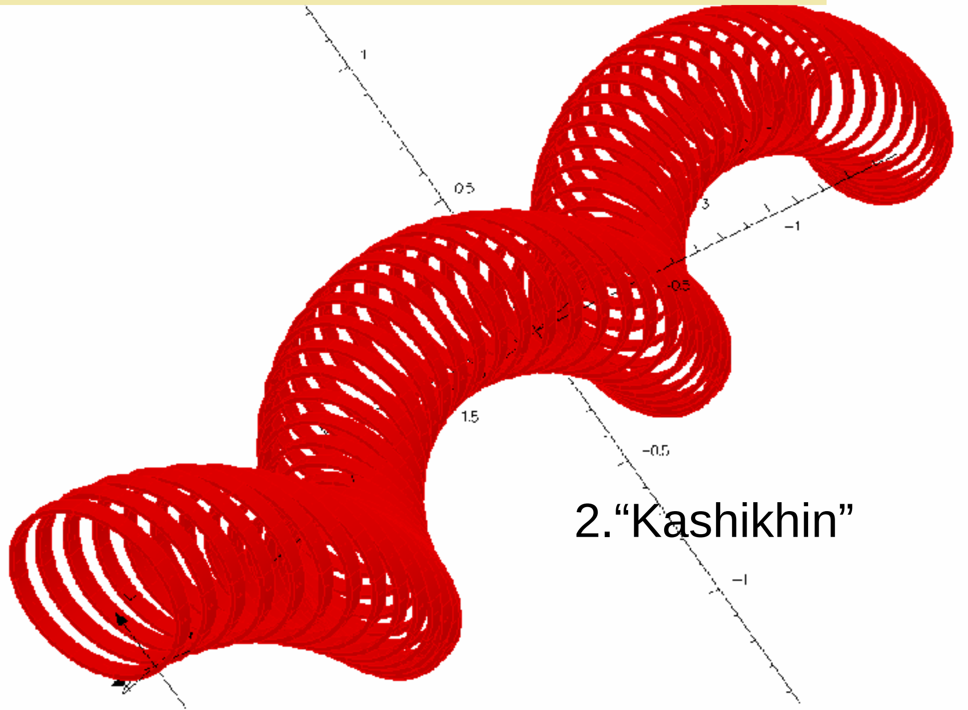
MANX HCC Design Evolution

Combined function magnets:

1. Layered conductors for individual components
2. Individual coils, offsets create dipole, quad components







Can in principle use coil offsets to construct any desired magnetic channel: HCC, matching, etc.

MANX Proposal Masthead

MANX, A 6D MUON BEAM COOLING EXPERIMENT

Robert Abrams[1], Mohammad Alsharo'a[1], Andrei Afanasev[1], Charles Ankenbrandt[1], Emanuela Barzi[2], Kevin Beard[1], Alex Bogacz[3], Daniel Broemmelsiek[2], Yu-Chiu Chao[3], Linda Coney[4], Mary Anne Cummings[1], Yaroslav Derbenev[3], Henry Frisch[5], Ivan Gonin[2], Gail Hanson[4], David Hedin[6], Martin Hu[2], Valentin Ivanov[1], Rolland Johnson[1], Stephen Kahn[1], Daniel Kaplan[7], Vladimir Kashikhin[2], Moyses Kuchnir[1], Michael Lamm[2], James Maloney[6], Michael Neubauer[1], David Neuffer[2], Milord Popovic[2], Robert Rimmer[3], Thomas Roberts[1], Richard Sah[1], Pavel Snopok[4], Linda Spentzouris[7], Melanie Turenne[1], Daniele Turrioni[2], Victor Yarba[2], Katsuya Yonehara[2], Cary Yoshikawa[1], Alexander Zlobin[2]

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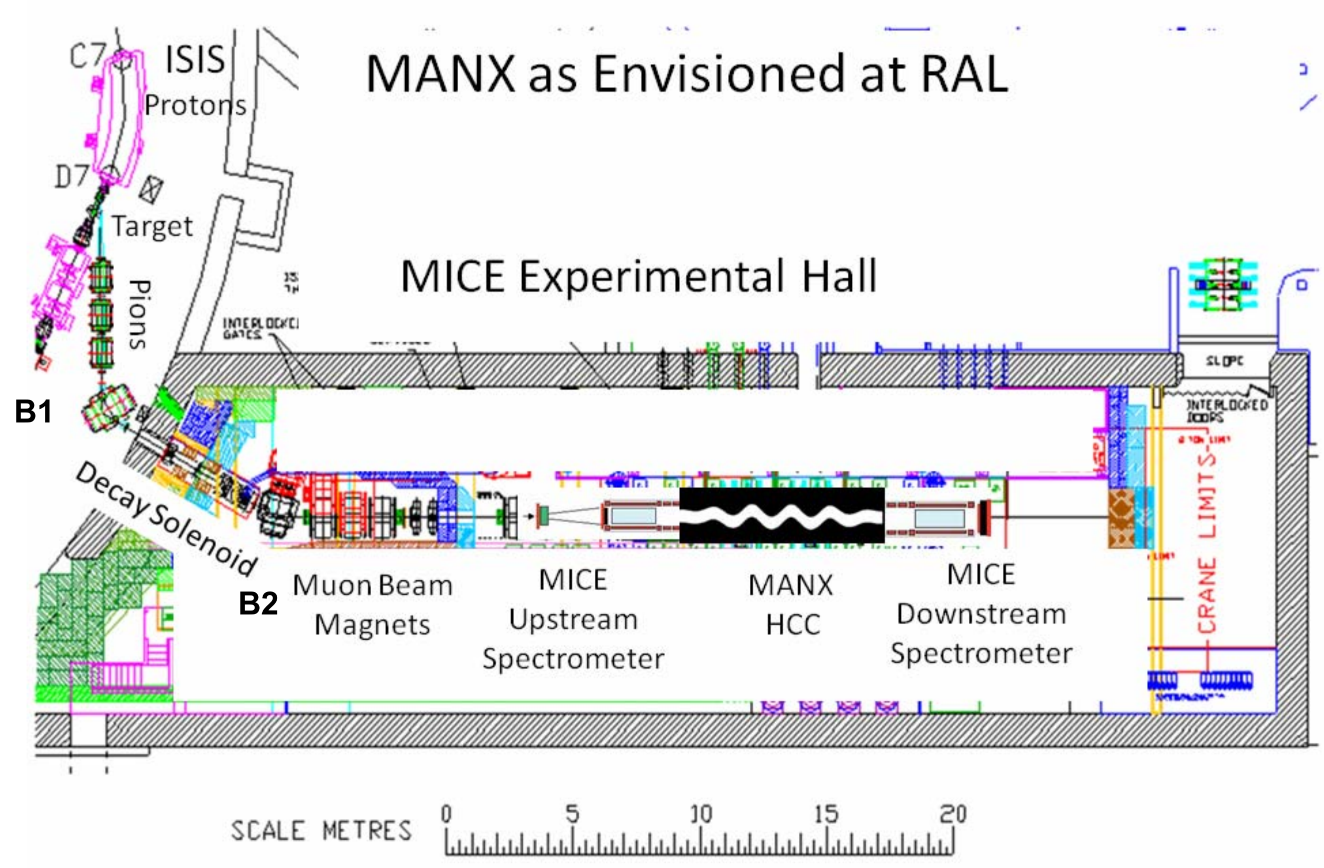
[2]*Fermi National Accelerator Laboratory*
[3]*Thomas Jefferson National Accelerator Facility*
[4]*University of California at Riverside*
[5]*University of Chicago*
[6]*Northern Illinois University*
[7]*Illinois Institute of Technology*

MANX at RAL Plan

- Utilize/adapt existing MICE HW and SW
  - MICE beam line
  - MICE beam instrumentation
  - MICE spectrometers and particle ID counters
  - DAQ and electronics
  - Simulation and analysis SW
  - Infrastructure and facilities at RAL
- Add MANX-specific HW and SW
  - Trackers inside HCC for trajectory determination
  - Faster TOF for better P_L, 6D emittance determination

MANX in RAL Experimental Hall



ISIS: 800 MeV Protons, 50 Hz, 100μs spill
(1x10 mm Ti target, 1 dip per 50 spills)

MICE plans to operate at 140, 200, 240 MeV/c muons
Retune beam for ~370 MeV/c muons for MANX

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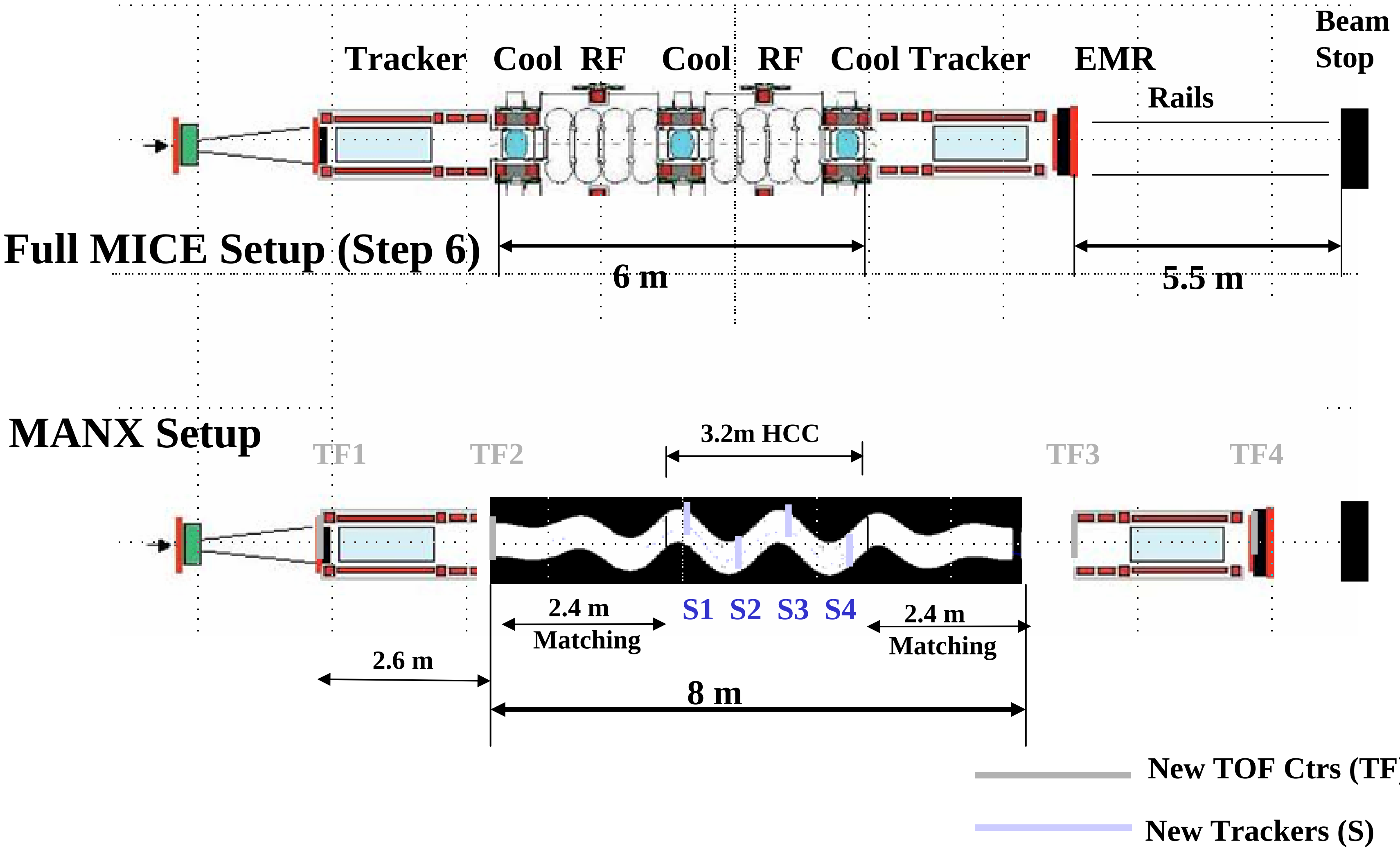
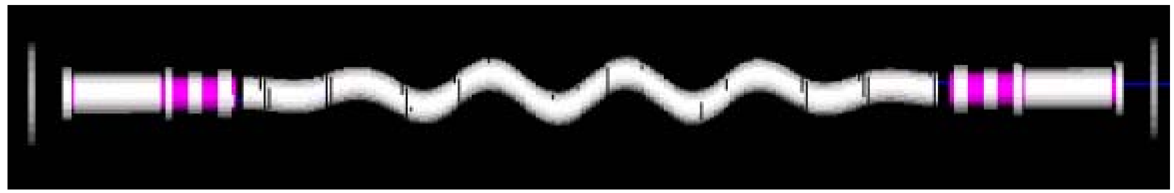
MICE Setup and MANX Apparatus

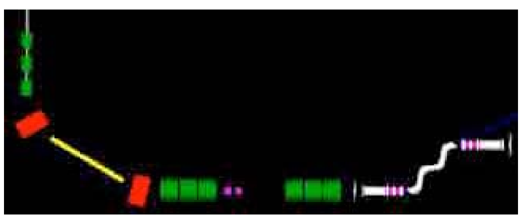


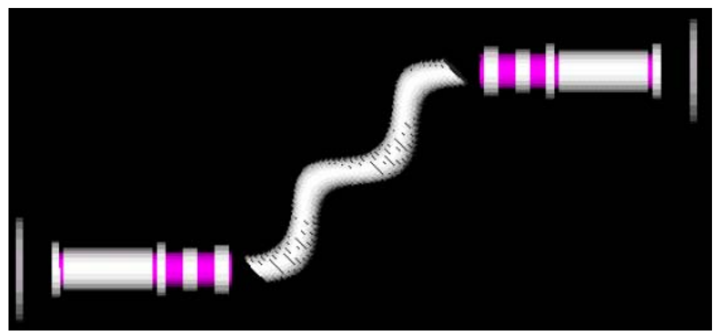
MANX Channel Configurations

1. Baseline Configuration: “Full Matching Sections”

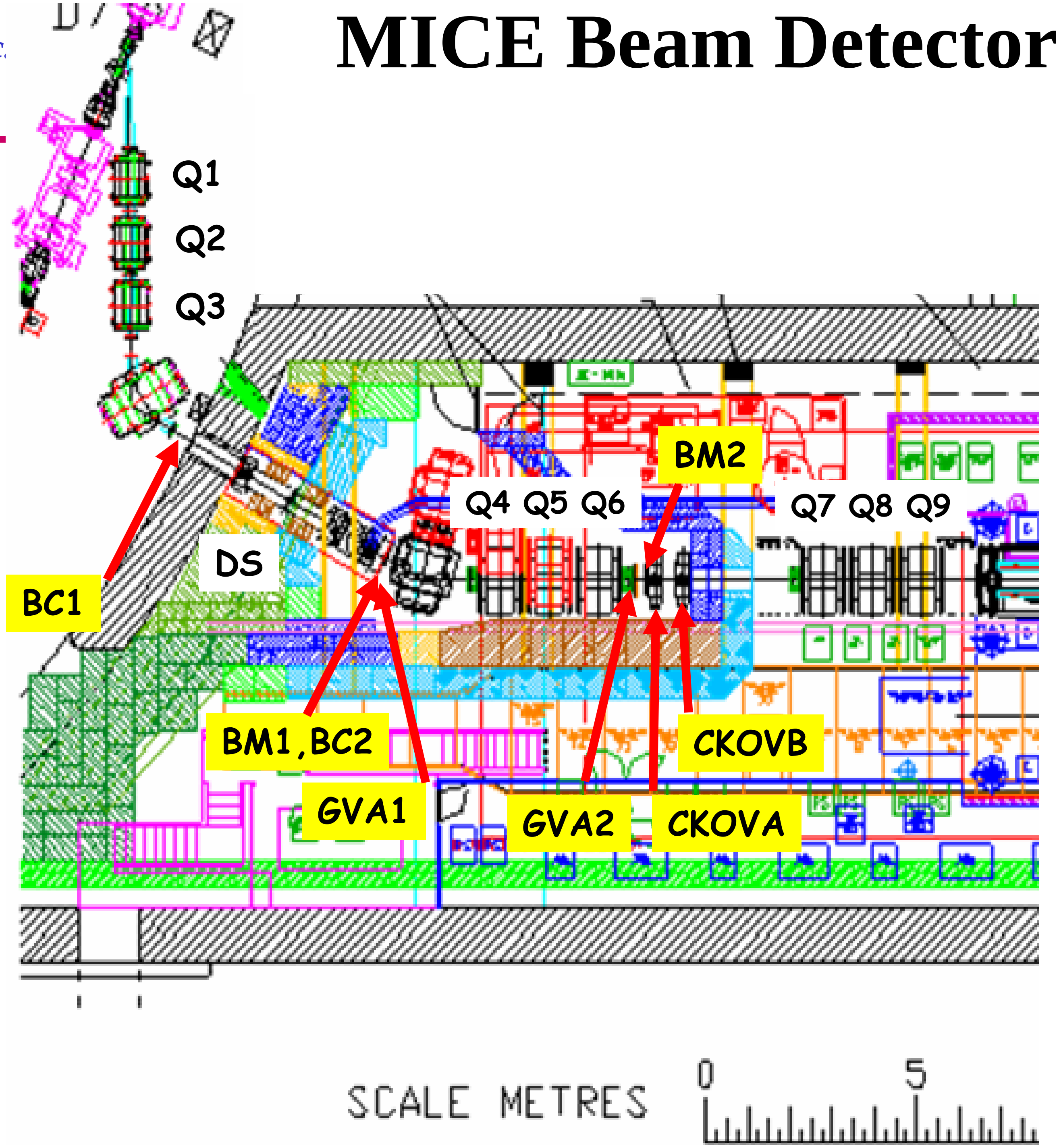


2. Alternate “Off-Axis” Configuration





MICE Beam Detectors



MICE Detectors Useful for MANX

Detector	*Purpose*	*Size (cm^2)*	*Number (Per unit)*	*Type*	*Source*
BM1,2 **BC1, 2** **GVA1, 2**	Beam profile Beam trigger Beam trigger	20x20	(8x + 8y)	Scint fibers Scint ctrs Scint paddle	U. Geneva
TOF 0, 1 & 2	Pi-mu ID, RF timing(MICE) (~70 ps time res)	~40x40	10x + 10y 7x + 7y	BC-420 scint	INFN Milano Pavia
CKOV1,2	Pi-mu ID Trigger	45x45	4 PMTs	Cherenkov Aerogel rad	U. Miss
Trackers (Upstream&Downstream)	Momentum measurement	~17.5 cm active radius	5 stations 2-3 coord per stat'n	Scint Fibers (x, u, v) 4T Solenoid	LBNL, IIT FNAL, UCL RAL, Osaka
KL (Upgraded KLOE EMCAL)	Downstream electron ident	120 x120	4 layers 30/layer	Scint Fibers Pb Foils	INFN Rome
EMR (Electromagnetic Ranger)	Downstream e-mu ID	120 x120	9 layers 9 (x or y) per layer	Scintillator strips	INFN Milan

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MANX Resolution Study

Table 1: Parameters describing the MICE beam adjusted for 350 MeV/c muons.

Parameter	*After 2nd Bend*	*After Diffuser*
P, MeV/c	375	341
σ_P, MeV/c	44	36
σ_X , mm	102	55
σ_Y, mm	56	41
σ_{Px}, MeV/c	11	32
σ_{Py}, MeV/c	7	30
σ_T, ns	0.29	0.47

Table 2: Parameters describing the MANX HCC

Parameter	*Value*
Helical Period	2 meters
Pitch Tangent: $\kappa = P_{\perp}/P_{\parallel}$	0.8
Channel Length	4 meters
Reference Radius	0.255 meters
Initial Solenoid Field	4.5 T
Initial Helical Dipole Field	1 T
Initial Mean Muon Momentum	350 MeV/c
Solenoid Coil Inner Radius	0.25 meters

Case	σ_X	σ_{Px}	σ_{Pz}
	mm	MeV/c	MeV/c
Upstream Mice SciFi Alone	0.74	1.3	1
Downstr. Mice SciFi Alone	0.95	0.94	0.4
MICE plus Matching Planes	2.4	3	1.7

Table 3: Measurement errors expected from SciFi detection planes in MANX.

Case	$\Delta\varepsilon_{TR}/\varepsilon_{TR}$	$\Delta\varepsilon_{6D}/\varepsilon_{6D}$
Upstream MICE SciFi Alone	0.10%	1.44%
Downstream MICE SciFi Alone	0.32%	0.77%
Mice plus Matching Planes	0.28%	1.58%

Table 4: Relative measurement errors for transverse and 6D emittance.

Note: Resolutions for Upstream and downstream MICE cases are calculated at centers of MICE spectrometers.

"MICE plus Matching" resolutions are calculated at entrance to MANX HCC with additional detectors at that location. Without Additional detectors the emittance and position resolutions are much worse.

New MANX Detectors

- Trackers inside HCC
  - Better definition of trajectory inside HCC
  - Measure emittance evolution inside HCC
  - Calibration/verification with empty HCC Fast
- Advanced TOF Counters
  - Better determination of longitudinal component of momentum
  - Improves computation of 6D emittance
  - MICE TOF ctrs → 50-60psec resolution
  - MANX MCP TOF (~10 ps) counters can supplement or supplant MICE TOFs to improve resolution
- Range-out calorimetry in MICE?
  - Particle ID and momentum measurement
  - Installed in final MICE configuration

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Particles Ensembles Studies

Single particle events aggregated offline to approximate collection of beam particles

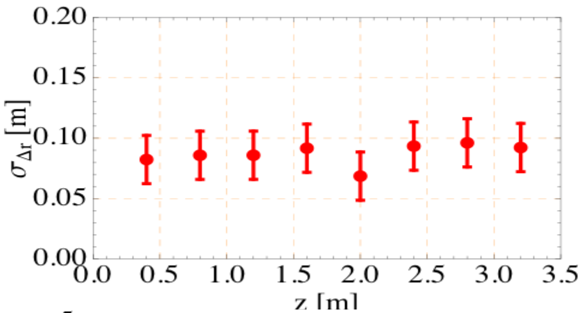


Figure 5: RMS of radial beam distribution in the HCC.

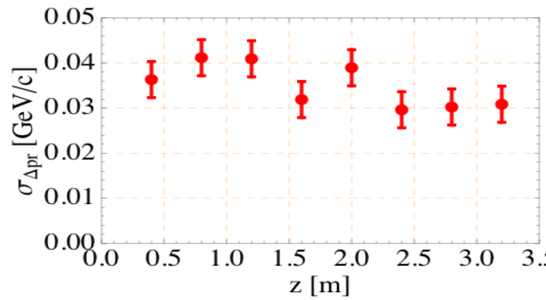


Figure 6: RMS of transverse momentum distribution in the HCC.

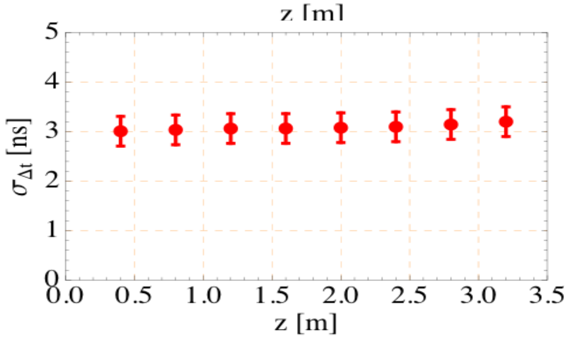


Figure 7: RMS of time spread in the HCC.

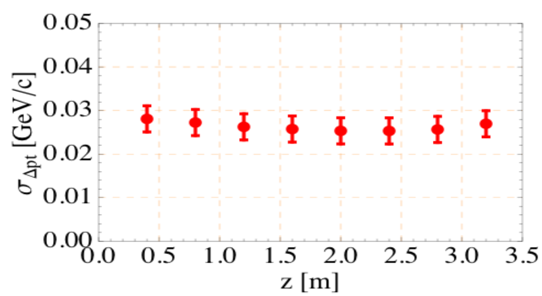


Figure 8: RMS of total momentum distribution in the HCC.

Emittance evolution through HCC

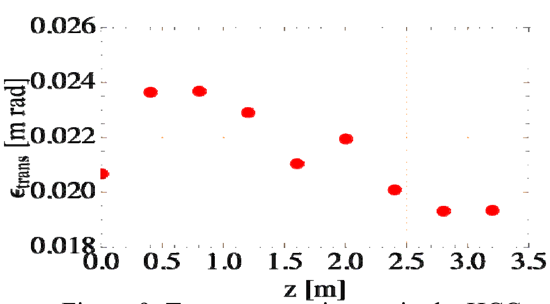


Figure 9: Transverse emittance in the HCC.

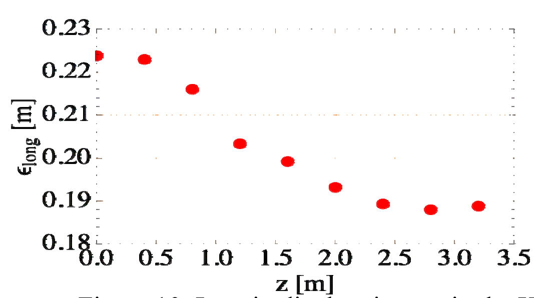


Figure 10: Longitudinal emittance in the HCC.

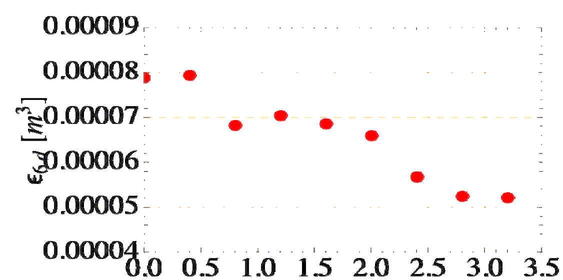
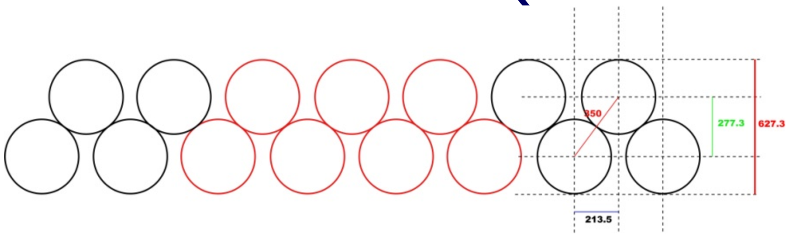
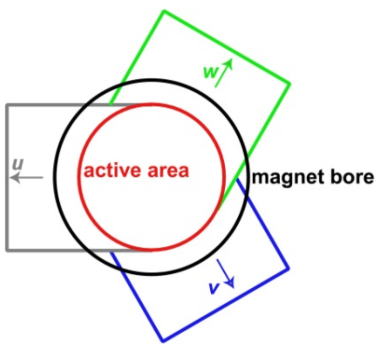


Figure 11: 6D emittance in the HCC.

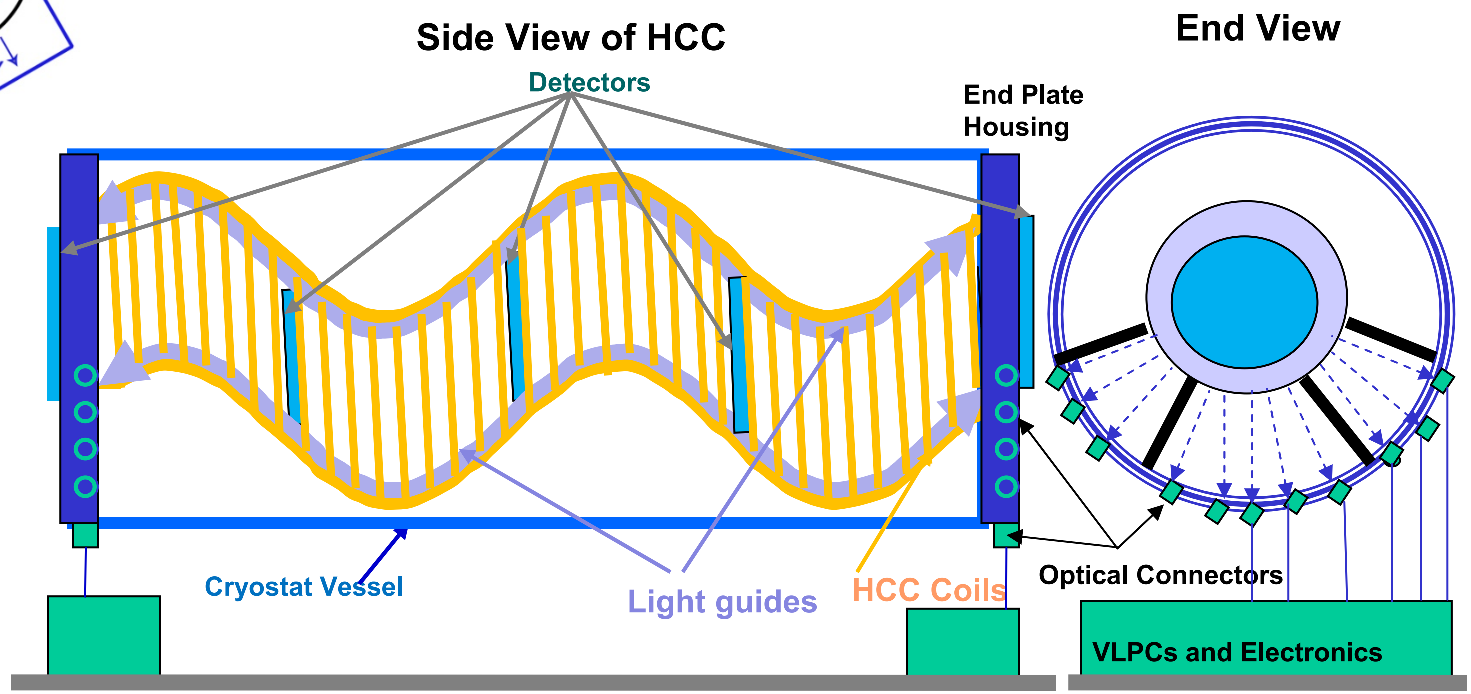
MANX HCC Tracker Design (based on MICE Tracker)



- 0.35 mm Scintillating fibers
- Two overlapping layers per coordinate
- Combine signals in groups of 7
- Resolution ~0.5 mm per 2-layer plane



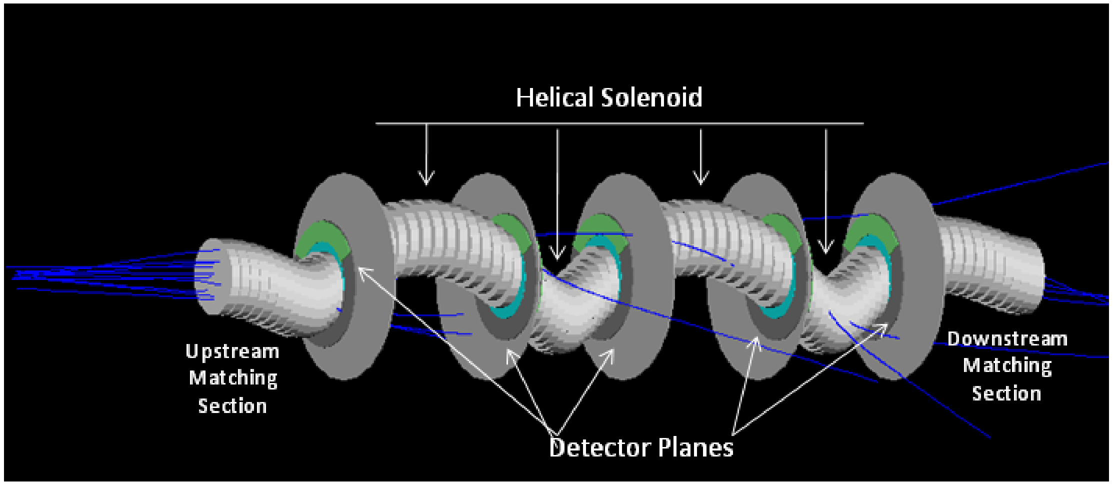
- To cover a 50cm HCC inner diameter requires 306 channels
- Each channel 1.63mm wide, containing 7 fibers (2142 fibers total).
- Each 3-plane station requires 918 channels,
- MANX may use 2-plane stations (x-y or u-v per station)



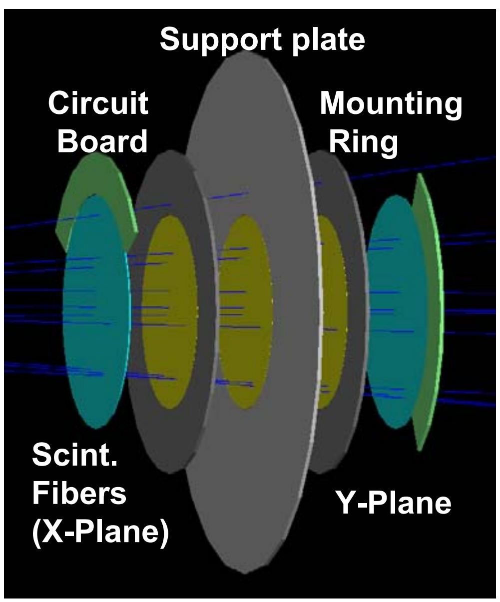
MANX HCC Tracker Concept 1

- Based on MICE tracker design
  - Tracker unit is installed in HCC bore
  - Fiber light guides brought out of bore
  - Optical detectors and electronics outside
- Design Challenges
  - HCC bore is helical, not straight
  - Alignment, positioning, installation, seals
  - Bore is filled with Liquid He, not He gas at STP (as in MICE)

Trackers Inside HCC: Concept 2

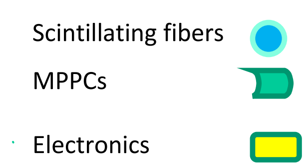


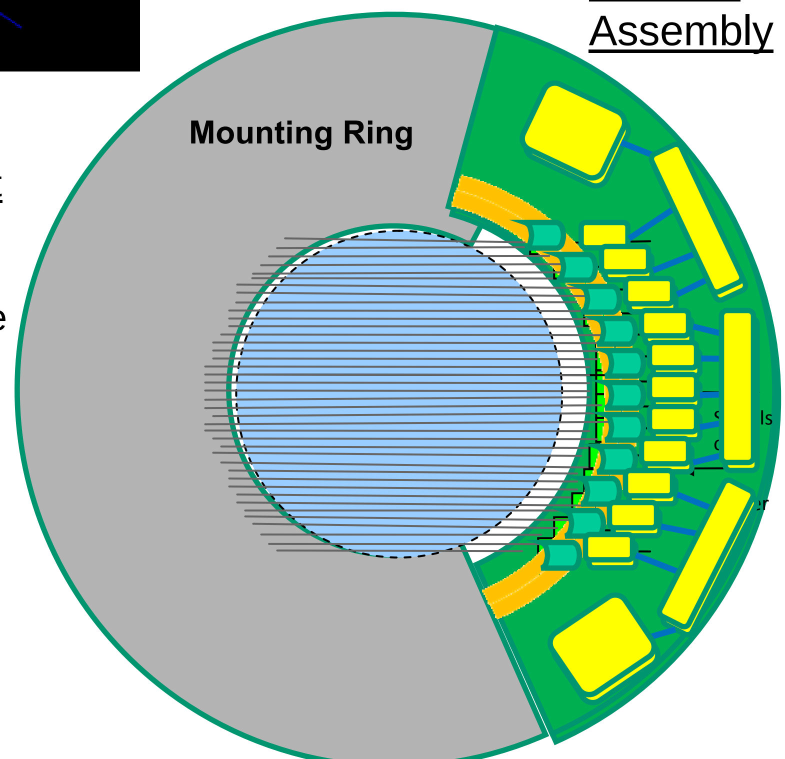
HCC Assembly
- 2 Units between HCC and Matching sections
- 3 Units inside HCC
- Alternate X-Y and U-V units



Exploded View of X-Y Unit
- Support plate built into HCC structure
- Mounting ring removable
- Scintillators/circuit board built on mounting ring

Y-Plane Assembly

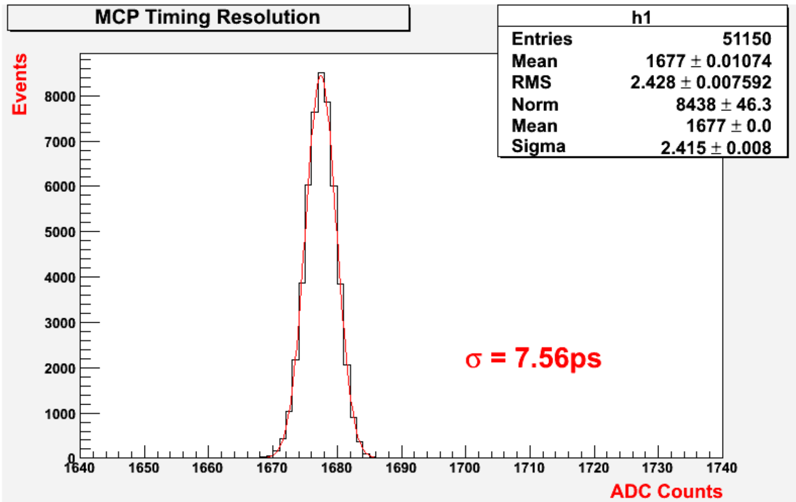




MANX HCC Tracker Concept 2

- Integrated with mechanical design of HCC
  - Build planes into structure of HCC
  - Use scintillating fibers as detectors
  - Mount SiPMs and digitizers within HCC cryostat
  - Extract electrical signals (not light guides)
- Challenges
  - New technology/application
  - Access to electronics for repair/maintenance
  - Heat inside cryostat?
  - Operation at LHe temperature (Electronics at LN2 temperature?)

MCP TOF Counters for Better P_L



Time difference between 2 commercial MCPs, response to laser pulses, intrinsic MCP resolution 4ps (ANL test stand, 408nm)

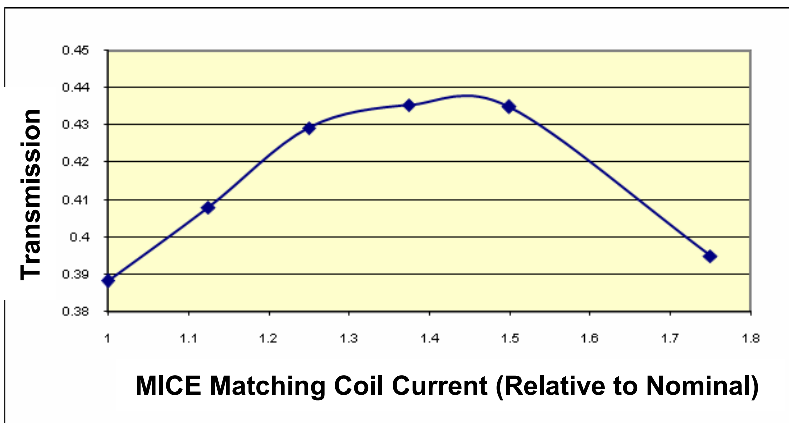
Example:
p = 300 MeV/c muon, γ=3, β = 0.94
For L=3m, t = 10.6 ns
$\Delta p/p = \gamma^2 \Delta t/t$
Then
For Δt = 50 ps resolution: Δp/p = 4.3%
For Δt = 5 ps resolution: Δp/p = 0.43%

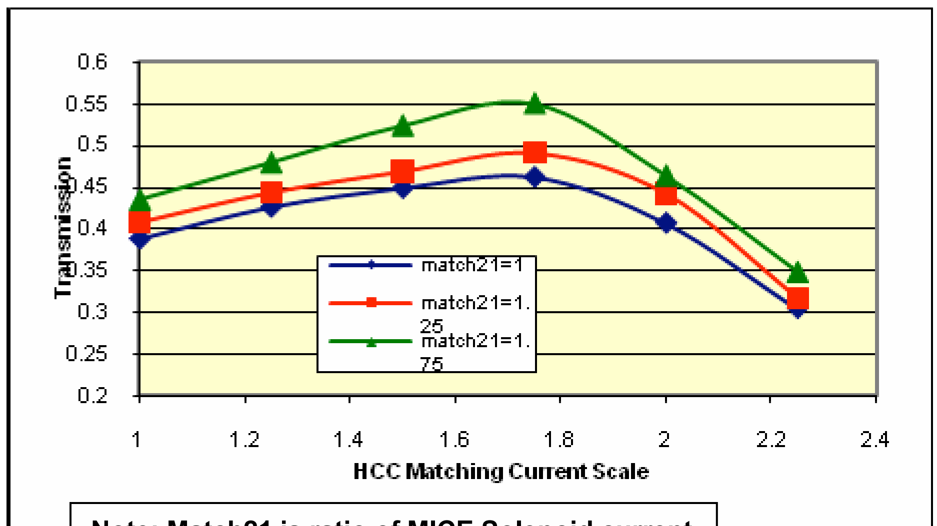
TOF measurement of P_L is complementary to measurement by MICE tracker:
- **MICE tracker measures P_T and infers P_L by track angle, $\Delta P_L/P_L$ ~ 2%.**
- **TOF measures P_L directly (given particle ID), $\Delta P_L/P_L$ ~ 0.5%.**

For MANX: ~50 (5cmx5cm) tiles cover the 40 cm diameter MICE solenoid aperture. Tiles with commercial MCPs ~$5k each at this time.

Results of Transmission Study

- Baseline Configuration: 70% of muons in upstream MICE solenoid survive to the end of the HCC
- Off-Axis Configuration: transmission depends on MICE matching coils current and amount of over-current in first few coils in HCC (LE 55% survival)

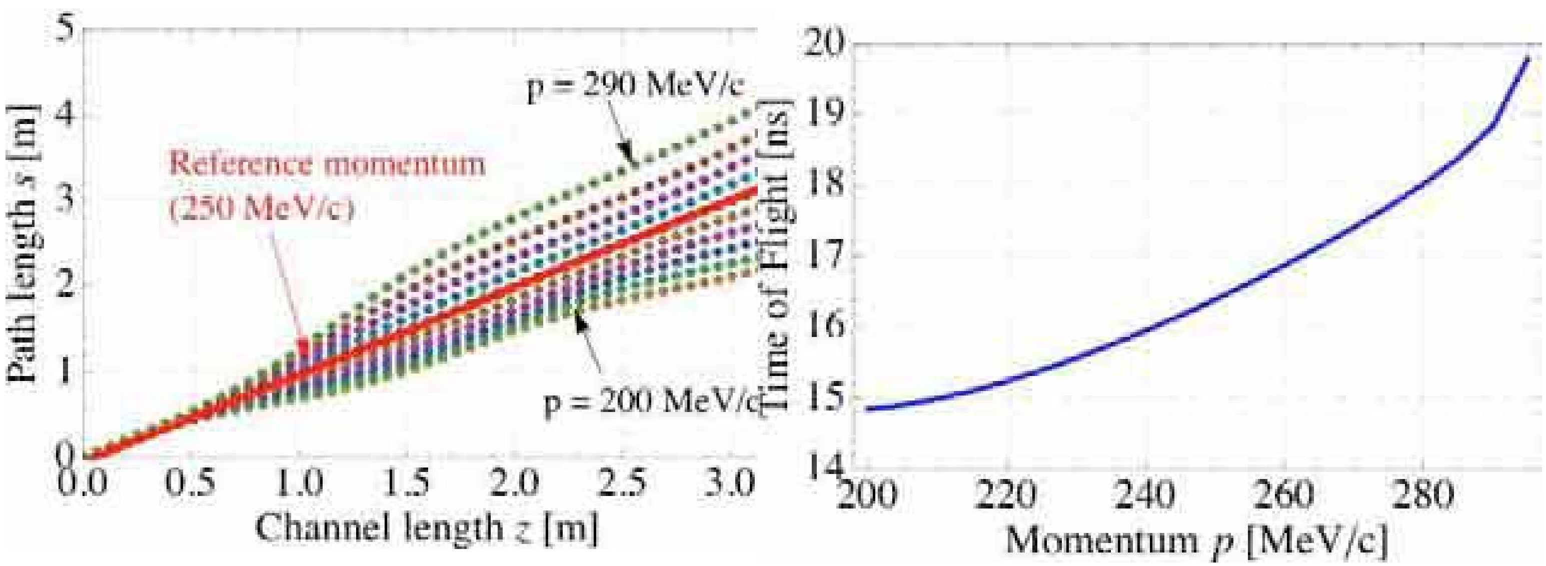




Note: Match21 is ratio of MICE Solenoid current relative to nominal current

PAC09 TOF Study

Trajectories inside 3.2 m long HCC



TOF difference per 10 MeV/c
Momentum difference is ~500 psec.
50 psec resolution should be adequate
for 1 MeV/c momentum resolution.

(Ensembles of Particles also studied: See PAC09 Papers)

Running and Data Estimates (Preliminary)

- About 10,000 events gives a useful sample for emittance measurement, based on simulations
- Expect ~100 μ per spill, ~1% usable for gross emittance calculation, 1 spill/sec
- A single 10,000-event run would take ~3 hours.
- Expect ~ few hundred runs to vary conditions such as different initial emittances, magnet currents, beam momentum, fill with liquid H_2(?), wedge absorbers, etc.
- Longer runs needed to study particular regions of phase space in HCC
- Time is needed for commissioning, calibration, beam tuning, background studies, reconfiguring, etc.

MICE Review Summary

➢ Space-consistency in the MICE hall

- Matched MANX has no obvious space incompatibilities; the space required for the helium system needs to be assessed.

➢ Consistency of time scales and resources

- Quantify effort required to design and install MANX, and to maintain the MICE infrastructure and instrumentation. The timescale looks rather optimistic, given the available resources.
- There is qualified support within MICE, for a second generation experiment at RAL; a strong UK presence would be necessary. *MICE itself could not agree to any next experiment; a new collaboration would be required.*

➢ Use of MICE infrastructure resources

- The MICE LH2 systems would be too small for a LH2-filled HCC
- Due to margins and forces it may not be possible to operate the MICE spectrometers to match into the 6T HCC field required for an input beam of 350 MeV/*c*. *[To confirm]*
- Off-Axis MANX may have engineering difficulties associated with transfer of non-axial forces, and torques on the spectrometer cold masses, also proximity of magnet to MICE magnetic shield wall.

MICE Review (Cont'd)

- Scope and adequacy of proposal in view of existing MICE instrumentation and infrastructure
  - The MICE spectrometers appear more than adequate for transverse measurements; the TOFs could provide a momentum resolution of 1% at 200 MeV/c to 3% at 350 MeV/c, but degraded by straggling.
  - The Cerenkovs would not be adequate at 350 MeV/c. The down-stream PID detectors may be too small, given the space required for the downstream TOFs for longitudinal momentum measurements
  - *A shortened MANX, using a 240 MeV/c input beam, could be a better match to the MICE instrumentation.*
  - To re-use MICE software for MANX effort should soon be devoted to its adaptation and use to demonstrate the performance of MANX with the MICE (or other) instrumentation.
  - Need better estimates of cooling performance in "standard" MICE beam and spectrometers, and more detailed estimates of resolution with TOF counters and internal detector planes in HCC.
  - Cryogenics costs needed: Refrigeration and helium

AAC Review Summary

- AAC Charge and Conclusions/Recommendations
  - Does MANX validate 6D ionization cooling for mu collider?
    - "If successful, MANX would be a great step forward towards the feasibility demonstration of a muon collider".
    - MANX can provide partial validation. of the HCC 6-D ionization cooling scheme. MANX does not address other significant cooling schemes (PIC and REMEX)
  - What is optimal mix of simulations and experiments?
    - Execution of MICE followed by a 6-D cooling scheme with full simulations
    - Results and lessons learned from MICE should be taken into account before one can decide if MANX is the right thing to do
  - Impact of MANX on Mu2e and Project X
    - Application of MANX to Mu2e is "very appealing"
    - Impact of HCC on the Mu2e plan be evaluated within one year

FNAL Support Requested to AAC

- Designing/Building HCC
- Access to lab facilities for fabricating and testing scintillation counters (NIU has some facilities for source testing)
- For HCC tracker concept 1: use of available D0 CFT VLPCs and associated electronics
- Some electronics design and fabrication (possibly supported by joint SBIR projects)
- Use of MTBF for beam tests of detectors
- Mapping of HCC magnetic field
- Use of PREP electronics for tests at Fermilab
- Support for Fermilab participants in MANX

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Work To Do and in Progress

- Address issues and questions raised by AAC and MICE team
- Simulations of 350 MeV/c beam at RAL: tuning, μ rates, backgrounds
- Simulations of full MANX spectrometer including HCC and new detectors
- Reconstruction and fitting of tracks in HCC
- Sensitivity analysis, field accuracy requirements, statistics needed, running time estimates
- Calibration procedure, run conditions
- Review all MICE components for use in MANX
- Analysis refinements and additions to MICE analysis SW
- Design MANX-specific detectors, electronics, and other components