



The MECO Experiment at BNL

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University of California, Irvine

April 22, 2004

Review of Brookhaven National Laboratory
Particle Physics Program

Goal of This Talk



- Remind reviewers of the physics motivation and the status of related experiments that bear on the same physics
- Remind reviewers of the experimental techniques and critical requirements
- Go through the systems, indicating status of each and the needs of the collaboration
- Point out the areas in which BNL Physics Department, C-AD, and other Departments' personnel are making contributions

MECO Collaboration



Boston University

J. Miller, B. L. Roberts

Brookhaven National Laboratory

K. Brown, M. Brennan, G. Greene,
L. Jia, W. Marciano, W. Morse,
P. Pile, Y. Semertzidis, P. Yamin

University of California, Irvine

C. Chen, M. Hebert, W. Molzon,
J. Popp, V. Tumakov

University of Houston

Y. Cui, E. V. Hungerford,
N. Klantarians, K. A. Lan

University of Massachusetts, Amherst

K. Kumar

Institute for Nuclear Research, Moscow

V. M. Lobashev, V. Matushka

New York University

R. M. Djilkibaev, A. Mincer,
P. Nemethy, J. Sculli, A.N. Toropin

Osaka University

M. Aoki, Y. Kuno, A. Sato

Syracuse University

R. Holmes, P. Souder

College of William and Mary

M. Eckhause, J. Kane, R. Welsh

Active BNL Personnel (UCI funding / BNL funding)

Wuzheng Meng – Liaison Physicist

Dave Phillips – Liaison Engineer

Jon Hock – mech. engineer

Bill Leonhardt (Ph) – mech. engineer

Mike Iarocci* – cryo engineer

Dan Weiss – vacuum engineer

Peter Wanderer (SMD) – magnet engineer

Active MIT Personnel

Brad Smith – Magnet Subsystem Manager

Alexi Radovinsky – engineer

Peter Titus – mechanical engineer

What Will Observation of $\mu^- N \rightarrow e^- N$ Teach Us?

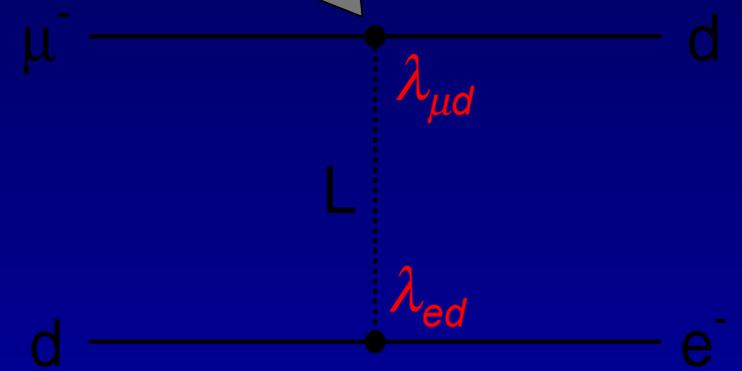
Discovery of $\mu^- N \rightarrow e^- N$ or a similar charged lepton flavor violating (LFV) process will be unambiguous evidence for physics beyond the Standard Model.

- For non-degenerate neutrino masses, ν oscillations can occur. **Discovery of neutrino oscillations required changing the Standard Model to include massive ν .**
- Charged LFV processes occur through intermediate states with ν mixing. Small ν mass differences and mixing angles \Rightarrow expected rate is well below what is experimentally accessible.
- **Charged LFV processes occur in nearly all scenarios for physics beyond the SM, in many scenarios at a level that MECO or PSIMEG will detect.**
- Effective mass reach of sensitive searches is enormous, well beyond that accessible with direct searches.



$$\Gamma(\mu^- N \rightarrow e^- N) \propto \left[\frac{\Delta M_\nu^2}{M_W^2} \right]^2$$

One example of new physics, with leptoquarks



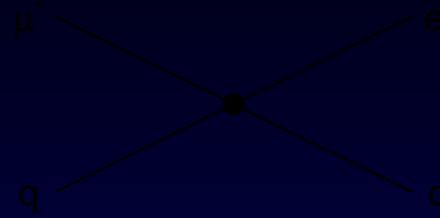
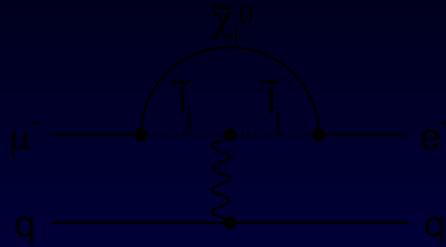
$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')} = 10^{-16}$$

$$\Rightarrow M_L = 3000 \sqrt{\lambda_{\mu d} \lambda_{e d}} \text{ TeV}/c^2$$

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

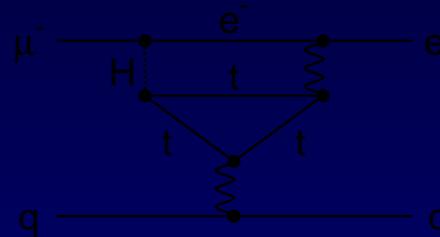
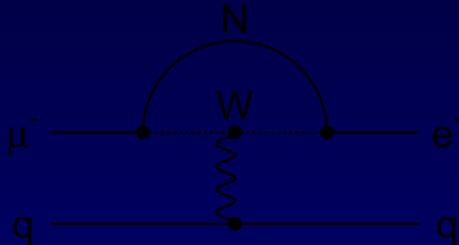


Compositeness

$\Lambda_C = 3000 \text{ TeV}$

Heavy Neutrinos

$$|U_{\mu N}^* U_{eN}|^2 = 8 \times 10^{-13}$$

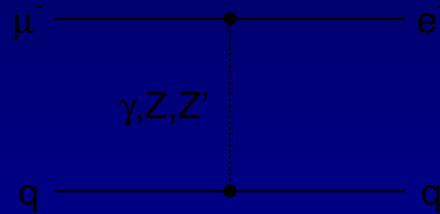
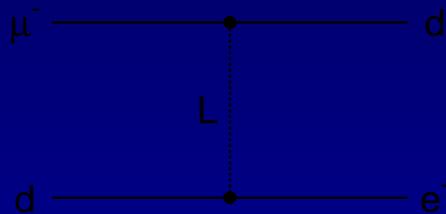


Second Higgs doublet

$$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$$

Leptoquarks

$$M_L = 3000 \sqrt{\lambda_{\mu d} \lambda_{e d}} \text{ TeV}/c^2$$



Heavy Z', Anomalous Z coupling

$$M_{Z'} = 3000 \text{ TeV}/c^2$$

$$B(Z \rightarrow \mu e) < 10^{-17}$$

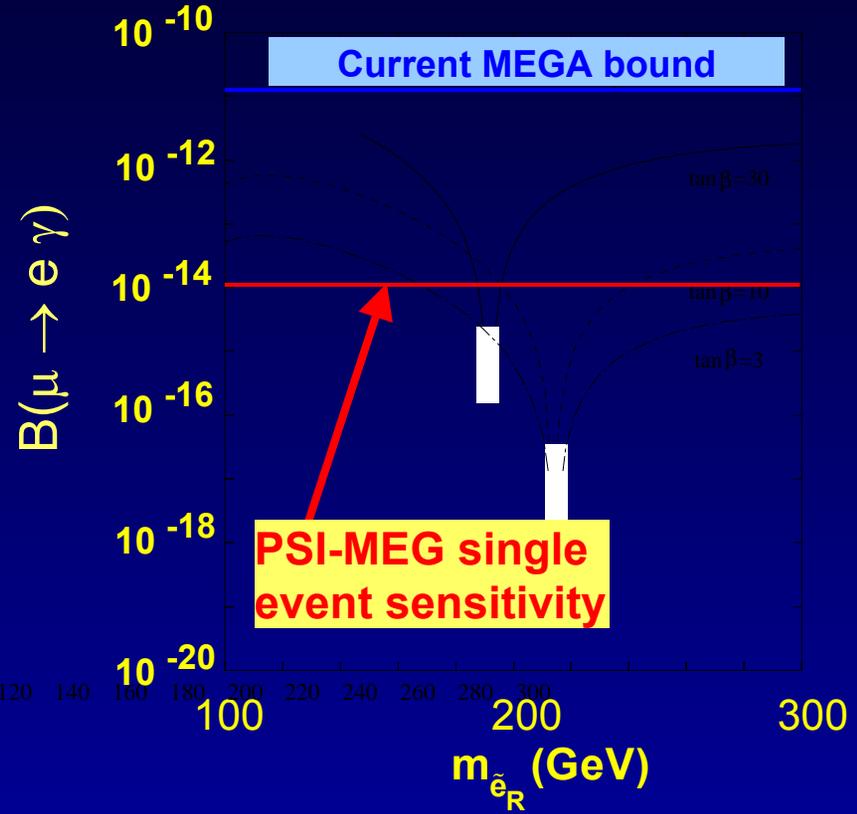
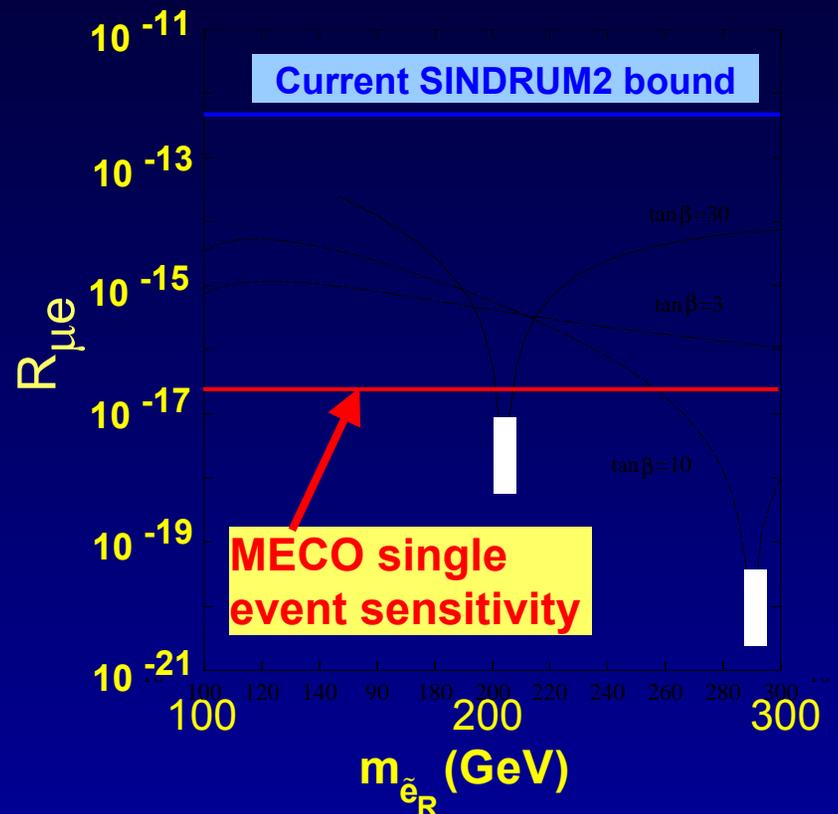
After W. Marciano

Supersymmetry Predictions for LFV Processes



- From Hall and Barbieri
 - Large t quark Yukawa couplings imply observable levels of LFV in supersymmetric grand unified models
- Extent of lepton flavor violation in grand unified supersymmetry related to quark mixing
- Original ideas extended by Hisano, et al.

Process	Current Limit	
$\mu^- N \rightarrow e^- N$	10^{-12}	
$\mu^+ \rightarrow e^+ \gamma$	10^{-11}	
$\tau \rightarrow \mu \gamma$	10^{-6}	10^{-9}



Expected Signal and Background in MECO Experiment



Background source	Events	Comments
μ decay in orbit	0.25	S/N = 4 for $R_{\mu e} = 2 \times 10^{-17}$
Tracking errors	< 0.006	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	No scattering in target
μ decay in flight	0.04	Scattering in target
Radiative π capture	0.07	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	10^{-4} CR veto inefficiency
Total Background	0.45	With 10^{-9} inter-bunch extinction

Background calculated for 10^7 s running time at intensity giving 5 signal event for $R_{\mu e} = 10^{-16}$.

Sources of background will be determined directly from data.

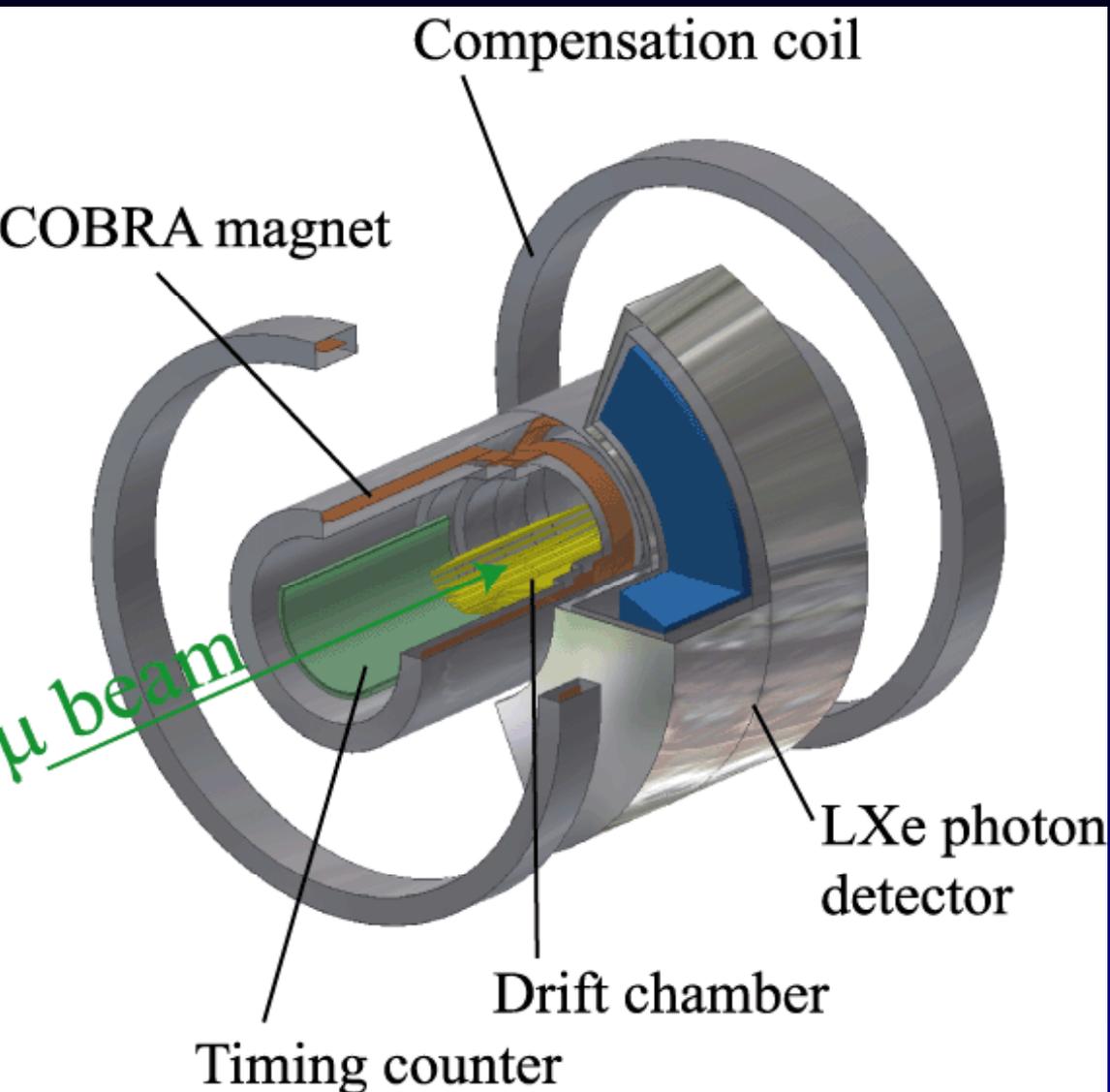
5 signal events with 0.5 background events in 10^7 s running if $R_{\mu e} = 10^{-16}$

Recent understanding of AGS operating schedule and conditions reduces proton flux and running time per year.

Factors affecting the signal rate	
Running time (s)	10^7
Proton flux (Hz) (50% duty factor, 740 kHz μ pulse)	4×10^{13}
μ entering transport solenoid / incident proton	0.0043
μ stopping probability	0.58
μ capture probability	0.60
Fraction of μ capture in detection time window	0.49
Electron trigger efficiency	0.90
Acceptance, selection criteria efficiency	0.19
Detected events for $R_{\mu e} = 10^{-16}$	5.0

The Competition: MEG: $\mu^+ \rightarrow e^+ \gamma$ Experiment at PSI

Search for $\mu^+ \rightarrow e^+ \gamma$ with sensitivity of 1 event for $B(\mu \rightarrow e \gamma) = 10^{-14}$



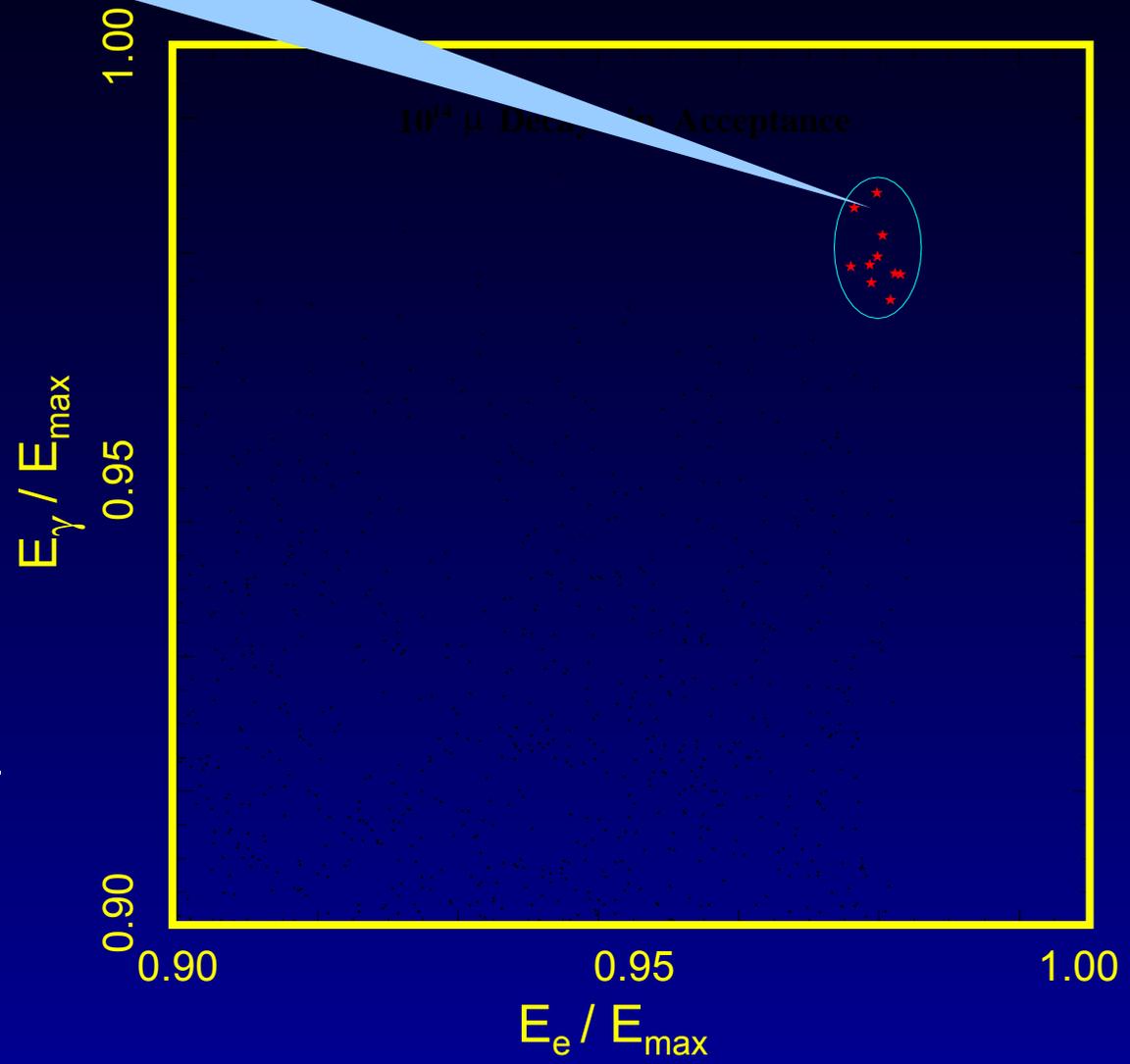
ICEPP, Univ. of Tokyo	Japan
Waseda University	Japan
INFN, Pisa	Italy
IPNS, KEK, Tsukuba	Japan
Paul Scherrer Institute	Switzerland
BINP, Novosibirsk	Russia
Nagoya University	Japan

Expected MEG Sensitivity



Signal for $B(\mu^+ \rightarrow e^+ \gamma) = 10^{-13}$

- Backgrounds calculated with Gaussian resolution functions with conservatively chosen widths.
- **~0.5 background events expected**
- Sensitivity goal is now reduced to $\sim 10^{-13}$
- Expecting to take data in 2006



1. Muon Decay in Orbit –

- $E_{\max} = E_{\text{conversion}}$ when neutrinos have zero energy
- $dN/dE_e \propto (E_{\max} - E_e)^5$
- Sets the scale for energy resolution required: ~200 keV

Muon decay
in vacuum:

$$E_e < m_\mu c^2/2$$

Muon decay in
bound orbit:

$$E_e < m_\mu c^2 - E_{\text{NR}} - E_{\text{B}}$$

2. Radiative Muon Capture: $\mu^- N \rightarrow \nu_\mu N(Z-1) \gamma$

- For Al, $E_\gamma^{\max} = 102.5 \text{ MeV}/c^2$, $P(E_\gamma > 100.5 \text{ MeV}/c^2) = 4 \times 10^{-9}$
- $P(\gamma \rightarrow e^+e^-, E_e > 100.5 \text{ MeV}/c^2) = 2.5 \times 10^{-5}$
- Restricts choice of stopping targets: $M_{Z-1} > M_Z$

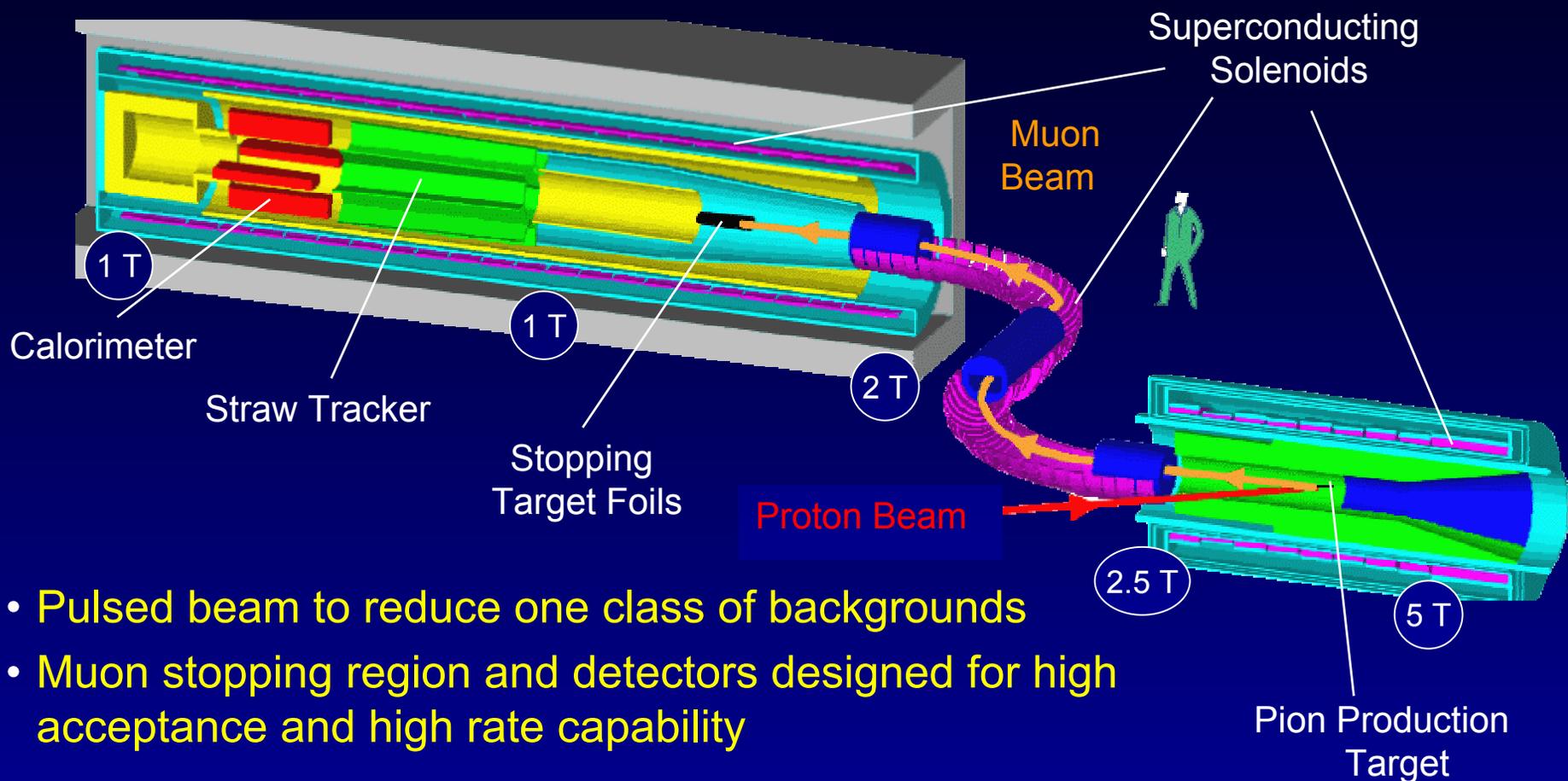
3. Radiative Pion Capture: $\pi^- N \rightarrow N(Z-1) \gamma$

- Branching fraction $\sim 1.2\%$ for $E_\gamma > 105 \text{ MeV}/c^2$
- $P(\gamma \rightarrow e^+e^-, 103.5 < E_e < 100.5 \text{ MeV}/c^2) = 3.5 \times 10^{-5}$
- Limits allowed pion contamination in beam during detection time, sets requirement for a pulsed beam

Features of MECO



- 1000-fold increase in μ beam intensity over existing facilities
 - High Z target for improved pion production
 - Axially-graded 5 T solenoidal field to maximize pion capture



- Pulsed beam to reduce one class of backgrounds
- Muon stopping region and detectors designed for high acceptance and high rate capability

How Have We Allocated Resources?

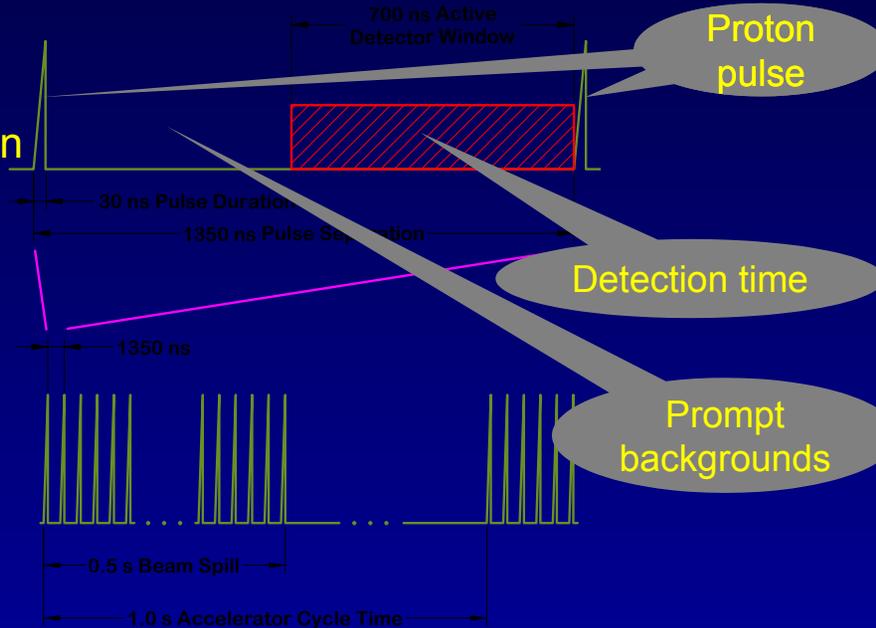
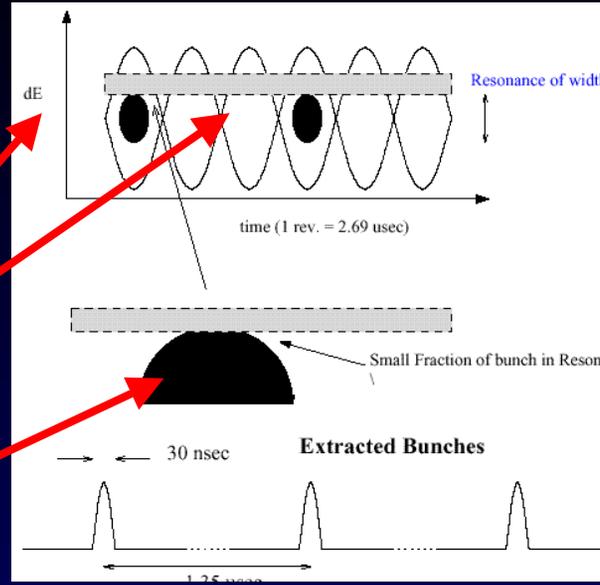


- **Try to keep critical path items on schedule.**
 - Magnet system was (and still is) critical path item. Current estimate is 42 months from signing engineering design contract to operating system. Try to keep design moving even without MREFC start. This has been an NSF priority in their request to Congress
- **Try to retire technical and cost risk as early as possible.**
 - Fund items that will allow technology choices to be made, prove systems that are technically risky, etc.
 - Examples are tracking system and calorimeter system
- **Give priority to funding design work that will allow construction funds to be used efficiently when available – this has been a moving target.**
- **Give priority to keeping collaboration intact by providing funding for items on which collaborating institutions are actively working, using their base funding grants.**
- **Give reduced priority to funding items that are not on the critical path and for which the outcome is not in doubt and there is a clear path to doing the necessary engineering.**
- **Allocation scheme has certain problems.**
 - We risk missing some critical items if unforeseen problems arise after thinking and design work starts.
 - With inadequate resources, more items develop inadequate schedule contingency as no work is done on them – everything eventually becomes critical path.
 - As people are brought on board, increasing fraction of available resources goes to keeping them paid, leaving no resources for them to do anything.

Intense, Pulsed Proton Beam from AGS for MECO (WBS 1.1)



- MECO goal: 8 GeV beam, 4×10^{13} protons per second.
 - Current problem – intensity limited to 2×10^{13} due to activation limits in booster. Sensitivity loss of factor of 2 if unsolved.
- Cycle time of 1.0 s with 50% duty factor
- Revolution time = $2.7 \mu\text{s}$ with 2 of 6 RF buckets in which protons are trapped and accelerated
 - 1.35 μsec pulse spacing
- Resonant extraction of bunched beam
- Very good extinction needed
 - $< 10^{-9}$ protons between bunches for each proton in bunch
- Stopped muon lifetime matched to pulse spacing:
 - aluminum or titanium



Michael Brennan of C-AD is AGS Modifications Subsystem Manager – currently no funding exists for design of AGS modifications, tests to reduce losses and understand beam.

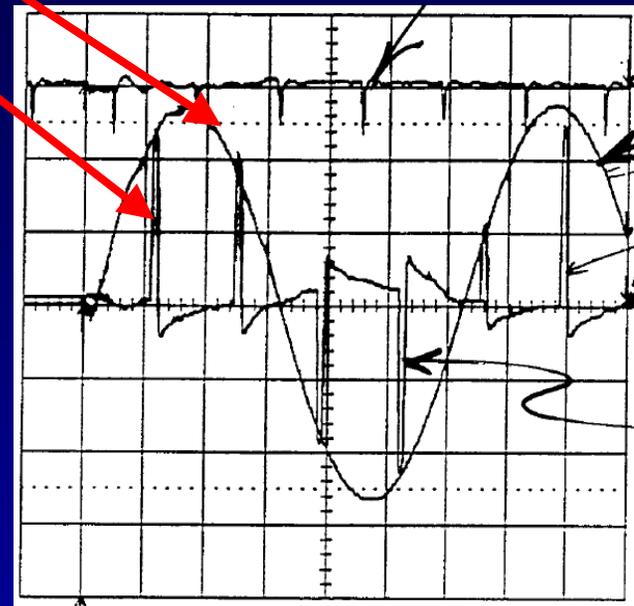
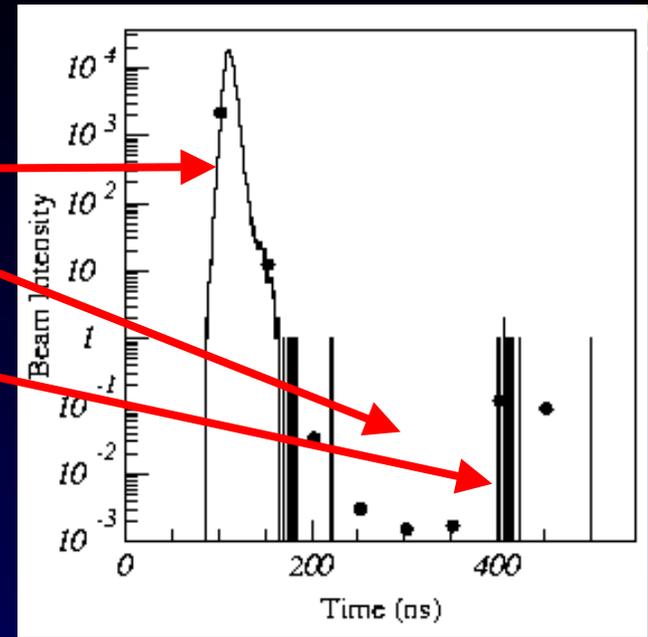
Extinction measurements:

- Initial test at 24 GeV with one RF bucket filled yielded $<10^{-6}$ extinction between buckets and 10^{-3} in unfilled buckets
- A second test at 7.4 GeV with a single filled bucket found $<10^{-7}$ extinction

Improvements in extinction in the AGS:

- 40 kHz AC dipole used to destabilize all orbits
- Fast kicker magnets to cancel effect of AC magnet for particles in buckets (field shown inverted).
- Some early tests done
- Changes needed
 - Modifications to kicker for continuous operation
 - Controls modifications

Additional, extensive facility renovation and improvements for increased reliability during extended, high current running currently under study

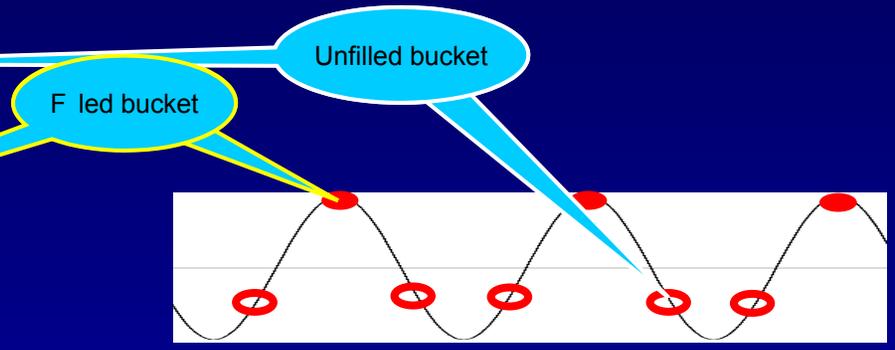
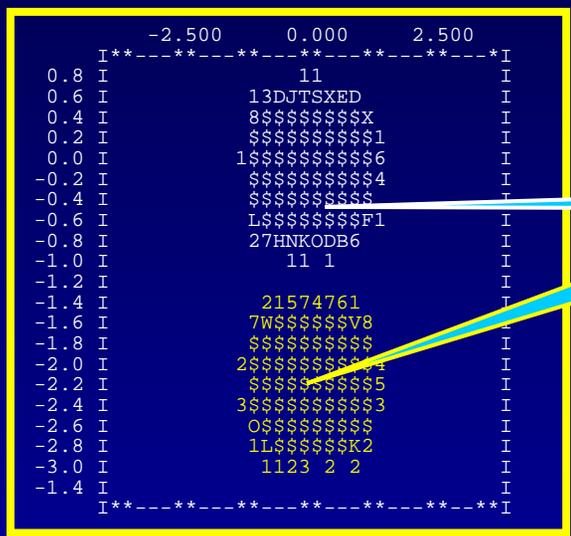
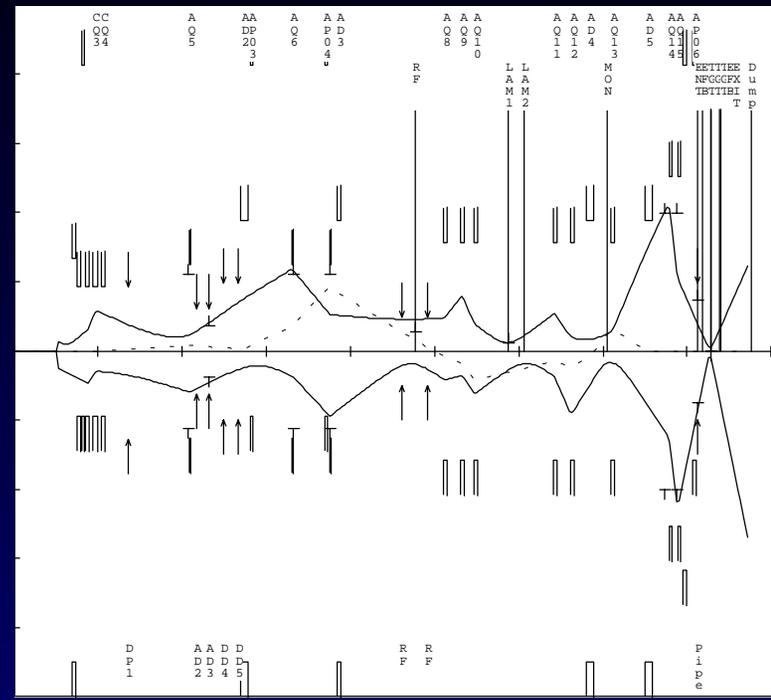


magnetic kick

Proton Beamline (WBS 1.2)

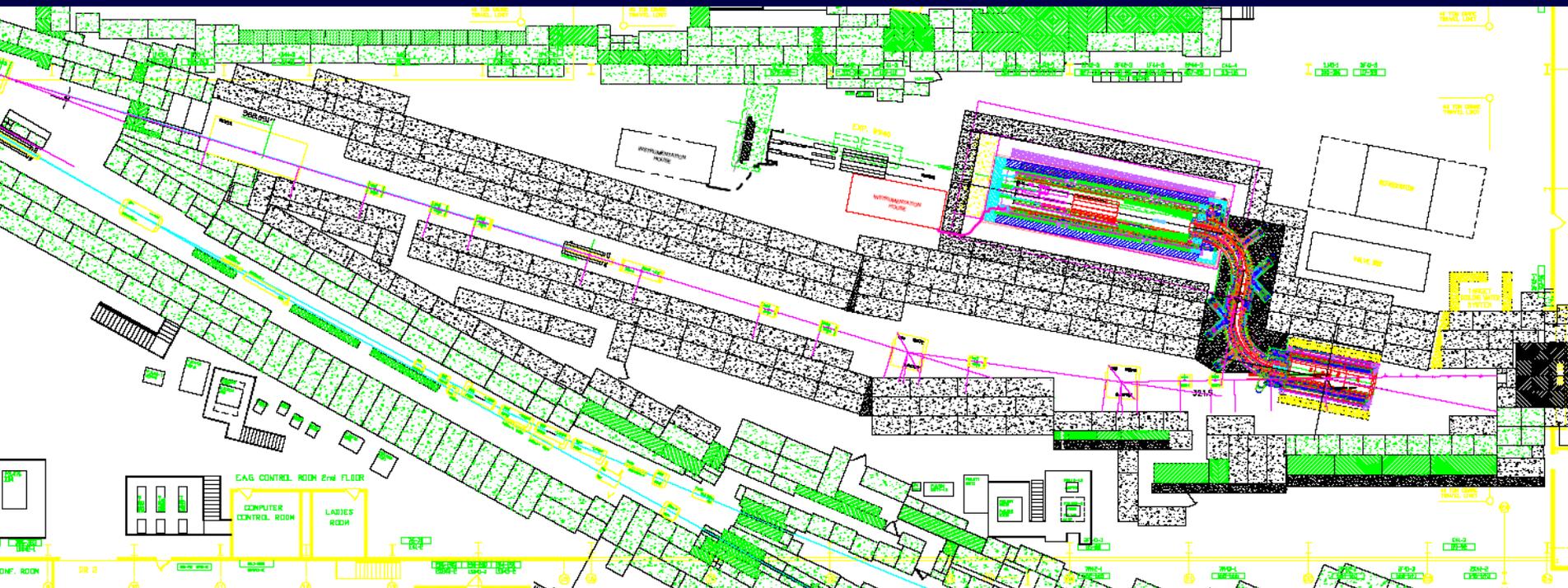


- K. Brown (BNL) is Proton Beamline Subsystem Manager
- Proton beamline is designed for achromatic transport of 8 GeV protons to muon production target (**Phil Pile and Kevin Brown**)
- Includes RF modulated magnet plus Lambertson septum magnets to separate filled buckets from other particles in beam
 - Pre-conceptual design of RFMM done at UCI
 - Stripline magnet with ferrite return yoke
 - Provides ~2.1 mrad separation between filled/unfilled buckets (uniform 75 Gauss field, 5 m long)
 - Resonantly driven at 771 kHz, Q of ~100, for efficient operation
 - Plan to do conceptual design study of total system



Additional Proton Beamline Work

- Shielding design in progress (Dave Phillips)
- Potential extraction aperture limitations recently found (K. Brown)
- Instrumentation design in progress (Kevin Brown)
- Possible complete redesign/simplification of switchyard being considered – potential for up-front spending to reduce significantly operating cost and increase operating reliability (Phil Pile)
- Significant facility refurbishment/modification under study
 - Considered necessary for extensive high intensity running

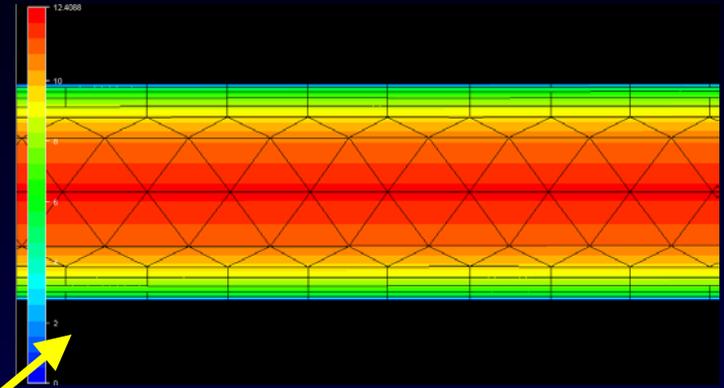
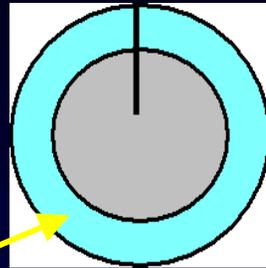


Production Target and Heat Shield (WBS 1.3)

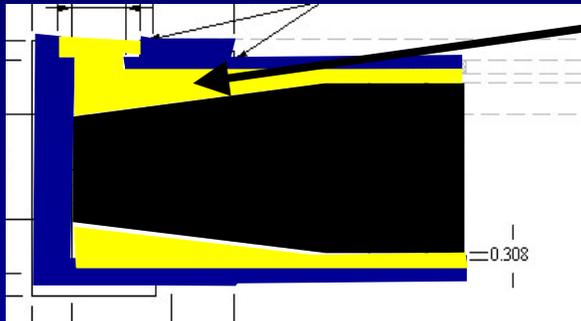
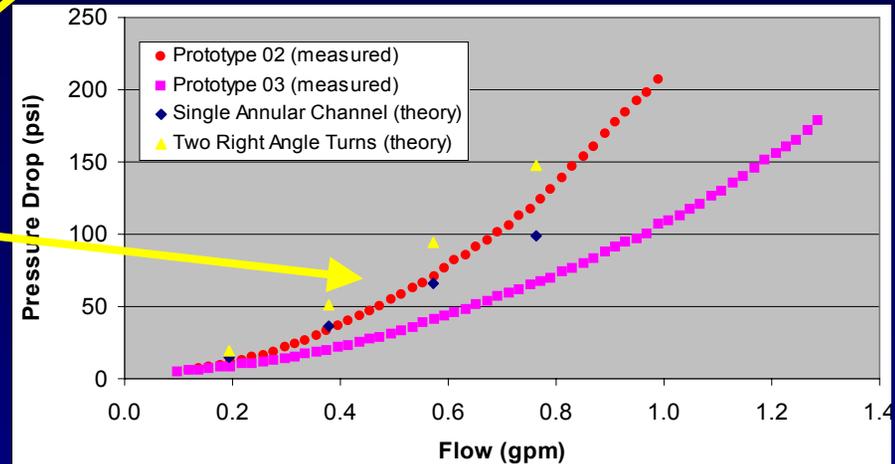


Production target region designed for high yield of low energy muons:

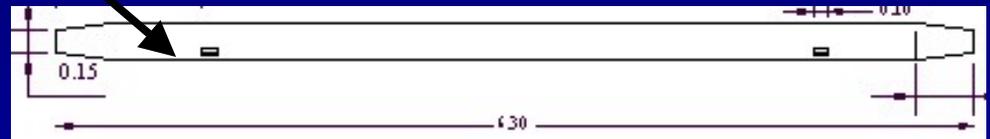
- High Z target material
- Little extraneous material in bore to absorb π/μ
- Diameter 0.6 - 0.8 mm, length 160 mm
- ~5 kW of deposited energy
- **Water cooling in 0.3 mm shell surrounding target**
 - Simulated with 2D and 3D thermal and turbulent fluid flow finite element analysis
 - Target temperature well below 100° C
 - Pressure drop is acceptable (~10 Atm)
 - Prototype built, tested for pressure and flow



Fully developed turbulent flow in 300 μm water channel

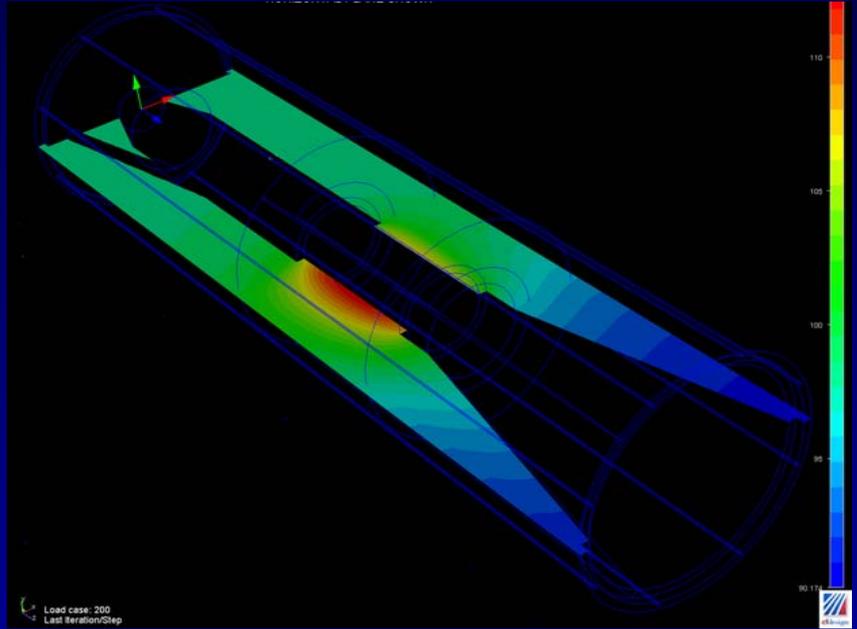
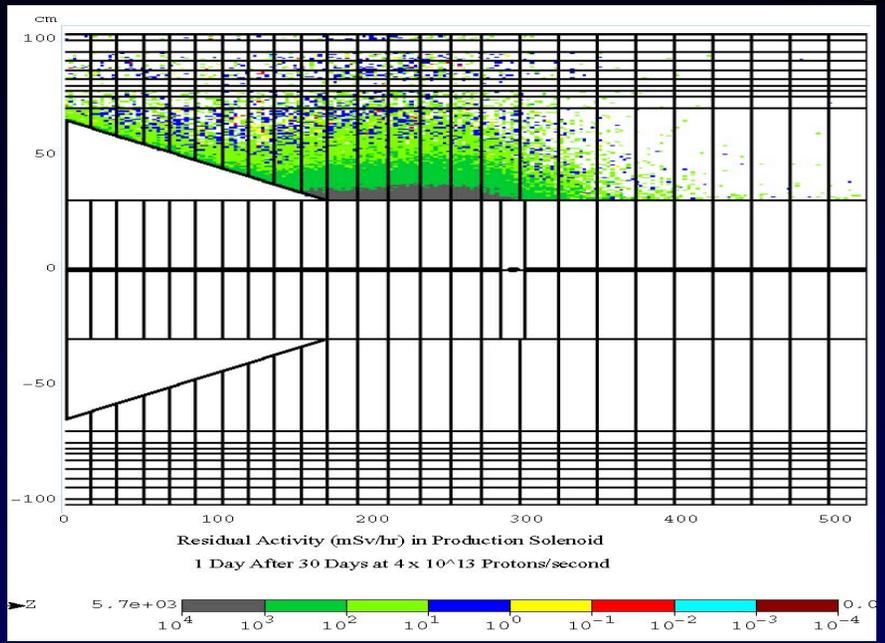


inlet detail target rod



Target Heat Shield

- **Protects solenoids from radiation load**
 - Optimized to reduce total load on magnet cold mass to ~100 W (UCI)
 - Approximately 10 kW of power deposited
 - Combination of copper and heavymet
 - Supported off PS cryostat inner wall
- **Work on construction technique and water cooling mechanism**
 - Structural and thermal analysis by **Jon Hock** (BNL -- UCI contract)
- Study of activation levels by **Peter Yamin** (BNL)



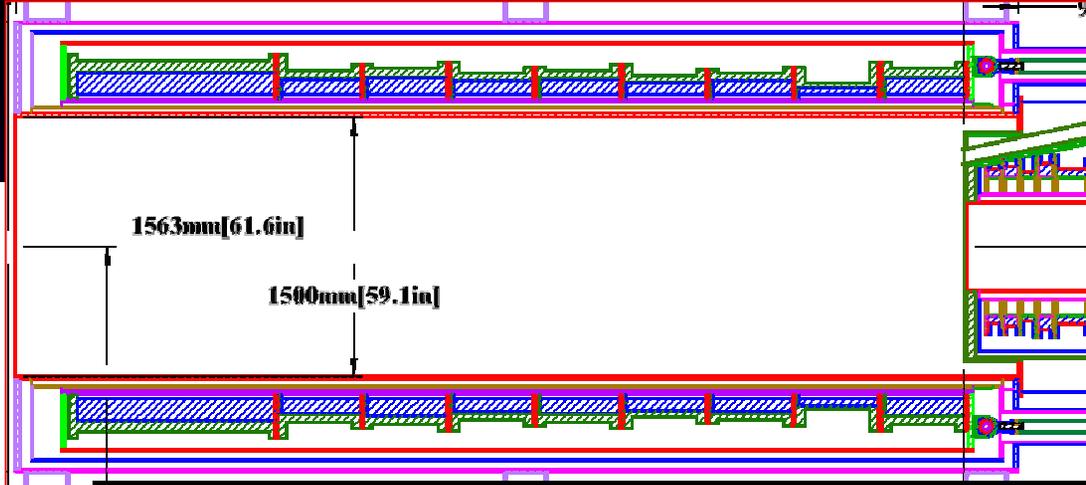
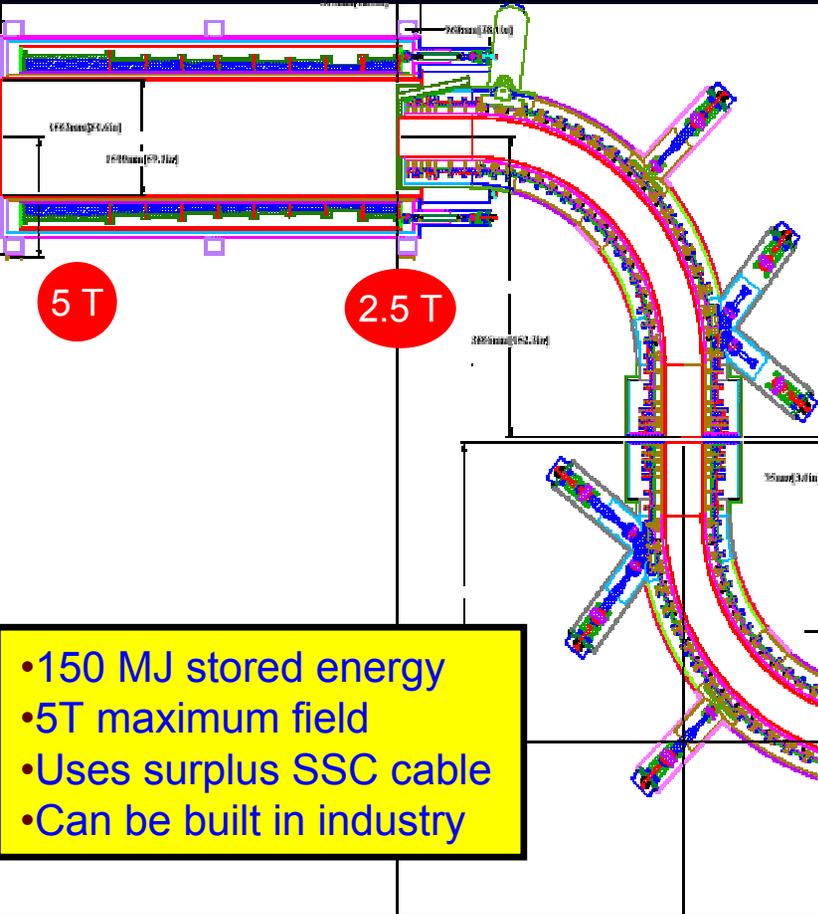
Thermal analysis by Jon Hock (BNL)

Installation gantry concept by Jon Hock

Short history of development

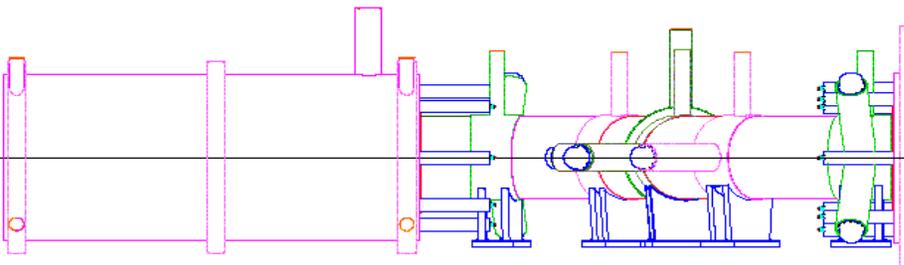
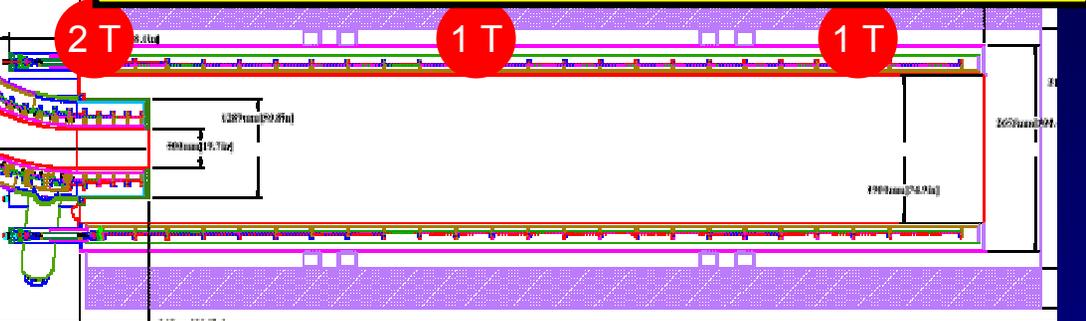
- Group at National High Magnetic Field Laboratory at FSU did a pre-conceptual design study of magnet system.
- Group at MIT Plasma Science and Fusion Center was chosen by competitive bid to do a conceptual design study, following advice of a Magnet Review Committee appointed by MECO.
- A conceptual design report was issued. The work was internally reviewed twice (interim and final review) by a panel of experts appointed by MECO.
- A Magnet Acquisition Panel convened jointly by BNL and MECO endorsed an acquisition plan involving a commercial, build-to-specification procurement.
- Three *industrialization studies* were completed with private industrial concerns.
 - Insulation system for the coils and joints – recommended epoxy and other material choices for radiation hard fabrication
 - Winding, impregnation logistics, fabrication cost and schedule – concluded that the magnets can be built commercially within the nominal 41 month schedule for a price consistent with our expectations
 - Refrigerator/liquefier— refurbish or buy new recommendation
- At MECO's request, **multiple Laboratory safety committees reviewed the conceptual design.**
- An agreement was reached with an experienced procurement group at LLNL to work with UCI to procuring the magnet system, with UCI to write the contract.
- A detailed *Magnet Acquisition Plan* has been drafted (MIT/UCI/LLNL).
- A *Statement of Work* and *Technical Specification* for the magnet engineering design, construction and installation have been drafted and **reviewed by many people at BNL including SMD, C-AD, and safety committees.** Recommendations of these various groups have been incorporated into the documents.
- An RFP for the procurement has been drafted.
- A first meeting with potential vendors was held at MT18 Conference in October in Morioka.

MIT Plasma Science and Fusion Center Conceptual Design of MECO Magnet System

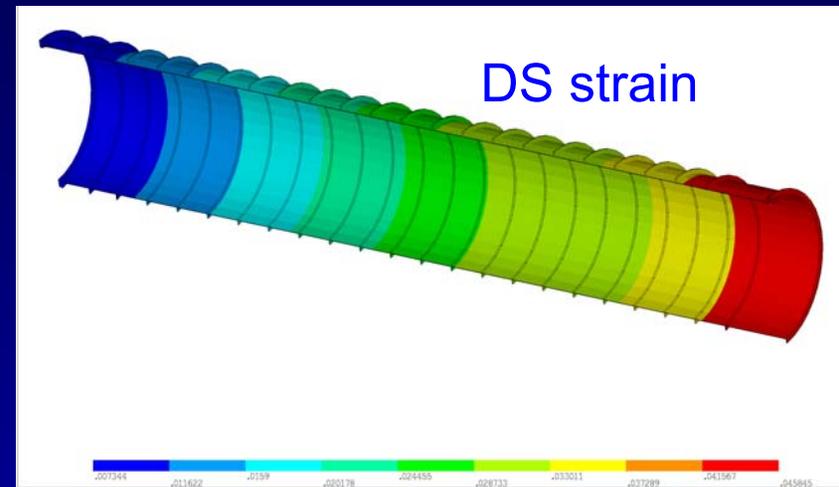
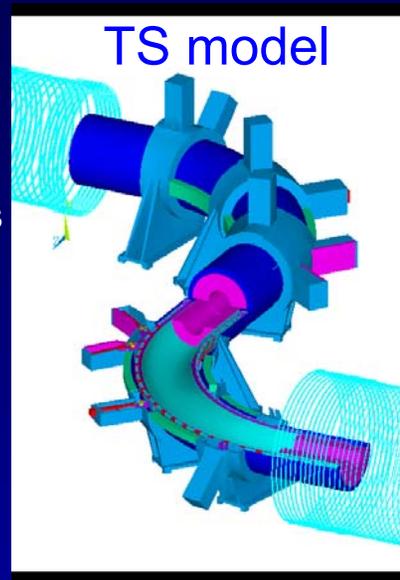
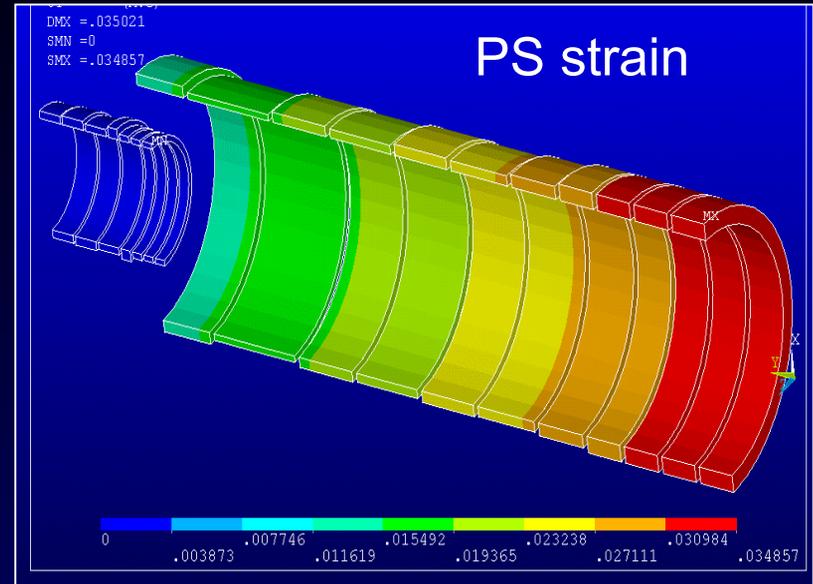


- Very detailed CDR completed (300+ pages)
- Complete 3D drawing package prepared
- TS and SOW for commercial procurement developed
- Industrial studies contracts let and completed

- 150 MJ stored energy
- 5T maximum field
- Uses surplus SSC cable
- Can be built in industry



- The structural models of PS, TS and DS magnets have been updated from the CDR to incorporate some changes and to evaluate effects of modulus and coefficient of thermal contraction variations and deadweight effects.
 - New PS iron return yoke and partial pole piece incorporated to reduce fringe fields and provide ground water shielding
 - PS coil lengths and builds revised to improve manufacturability
 - DS partial iron pole piece incorporated to reduce fringe fields
 - TS cryostat pedestals widened to better react bending stresses
 - Downstream TS horizontal support modified to accommodate DS pole
- Studies done to understand required manufacturing tolerances (MIT/UCI)
 - Cumulative and non-cumulative machining tolerances and assembly tolerances
 - Coil winding tolerances
 - Materials tolerances
 - Alignment tolerances
 - Preliminary conclusion is that all tolerances are well within typical capabilities of vendors
- Redesign of 80 K thermal shields to allow He gas cooling
- Planned cable tests
 - Short sample conductor tests
 - Test of soldering cable in conduit
 - Extracted strand tests of cable
- Work to define installation interfaces (Dave Phillips)

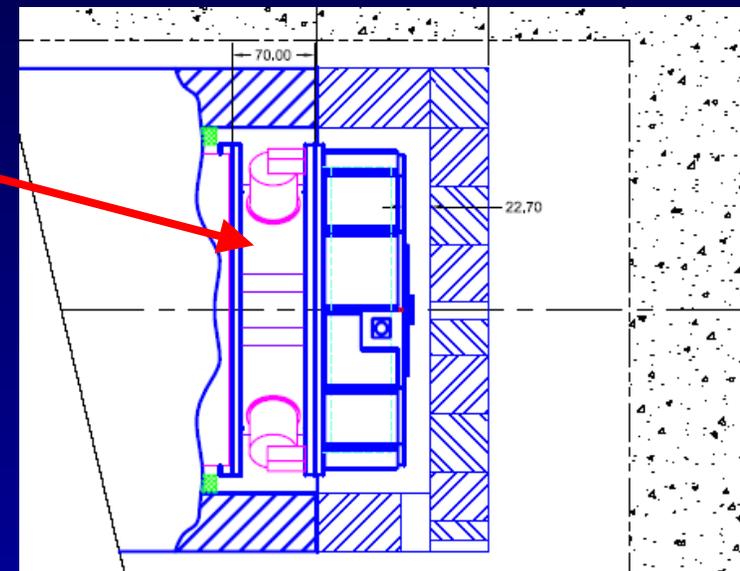
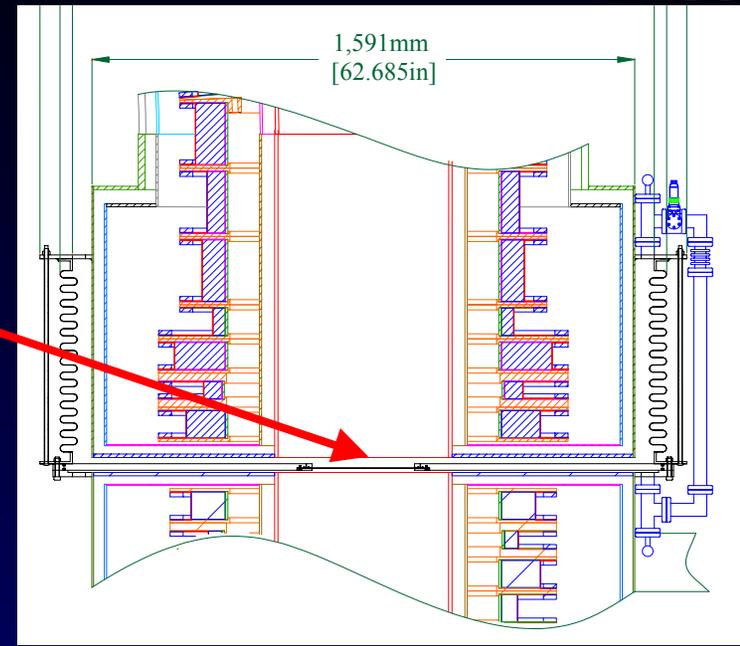


Magnet Acquisition Plan

- Assumes the final design, fabrication, installation and acceptance testing will be performed by a commercial vendor or a team of vendors.
- Identifies method as Best Value Source Selection
- Identifies firms with required capabilities or known to have an interest:
 - Alahlam Ltd.
 - Ansaldo Superc
 - ACCEL
 - Babcock Noell Nuclear GmbH
 - Cryogenic Ltd.
 - General Atomics
 - Hitachi
 - Mitsubishi Electric Corp.
 - Oxford Instruments
 - Sigmaphi
 - Space Cryomagnetics
 - Toshiba
 - Wang NMR Inc.
- Establishes a fixed price, contract as the preferred option – allows for industry feedback at draft RFP stage
- Discusses possibility of splitting out high cost risk interface items and/or installation
- Establishes management information requirements – reporting, QA, etc.

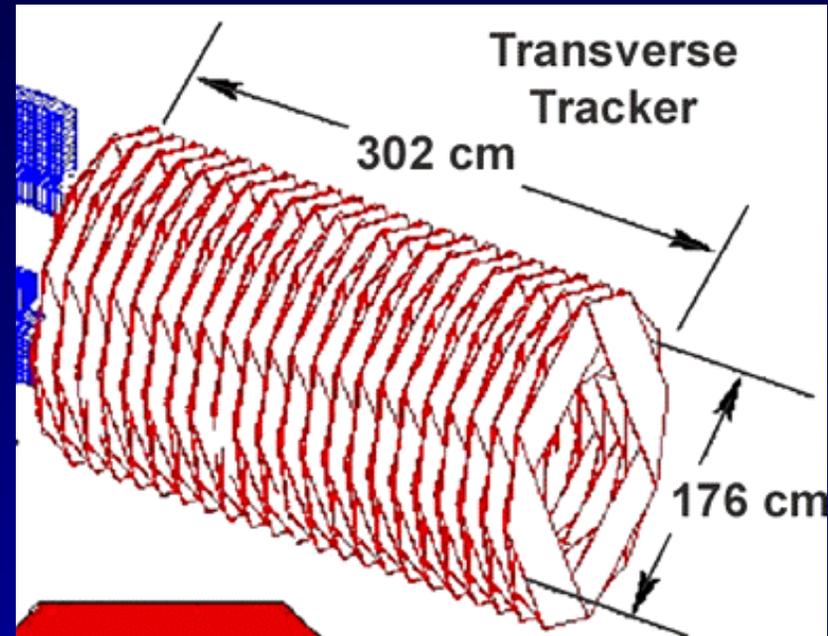
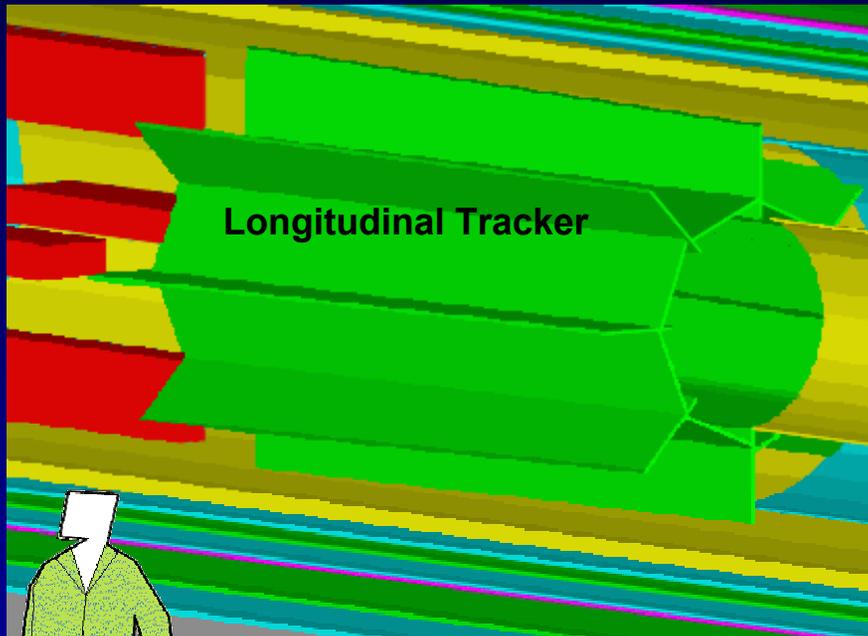
Muon Beamline (WBS 1.5)

- Primarily for magnet interface purposes – not a critical path item
- **W. Morse** (BNL) is subsystem manager
- Work on vacuum window at midpoint of transport solenoid by **Dan Weiss** (UCI contract)
 - Interaction with MIT/UCI on specification
 - Separates dirty PS vacuum from clean DS vacuum
 - Serves as antiproton absorber
 - Conceptual design complete
- **Work on vacuum system and TS end flange closure**
 - Vacuum spec and pump selection by J. Popp (UCI) and Dan Weiss (BNL / UCI contract)
 - Mechanical design/layout by P. Nemethy (NYU) and Bill Leonhardt (BNL Physics BNL/UCI support)
- **Studies of radiation levels in DS region and effect of boron and lithium loaded polyethylene by Peter Yamin.**



Tracking Detector (WBS 1.6)

- Two tracker geometry options are being considered
 - Longitudinal geometry with ~3000 3m long straws oriented nearly coaxial with the DS and 19000 capacitively coupled cathode strips for axial coordinate measurement
 - Transverse geometry with ~13000 1.4 m straws, oriented transverse to the axis of the DS, readout at one or both ends
 - Both geometries appear to meet physics requirements



Seamless Straw Development (Osaka)

• Seamless straws

- Thickness : 25 μm
- Diameter : 5 mm
- Material : Polyamide + Carbon
- Resistance : 6 M Ω /sq

• Advantages

- No Adhesive
- Thinner
- More uniform thickness and resistance
- Less out-gassing and leakage in vacuum

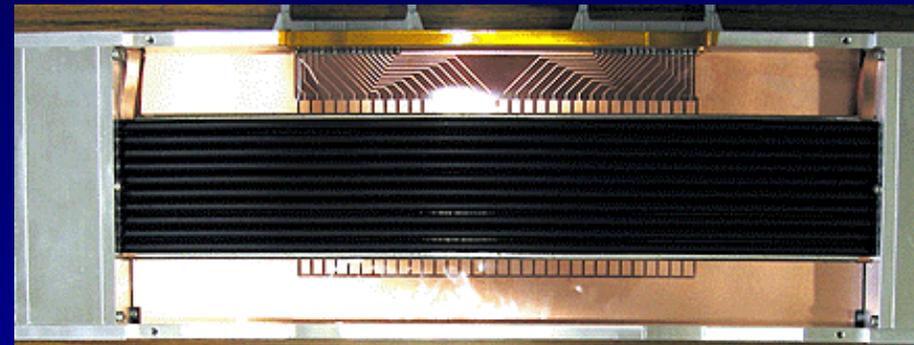
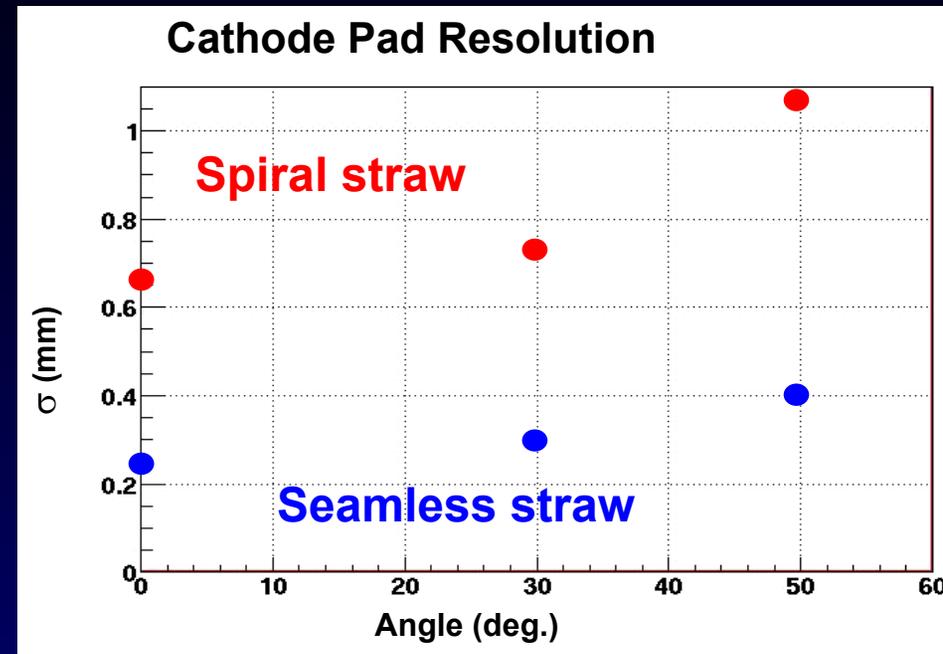
• System built and tested in Japan

• Cathode pad resolution

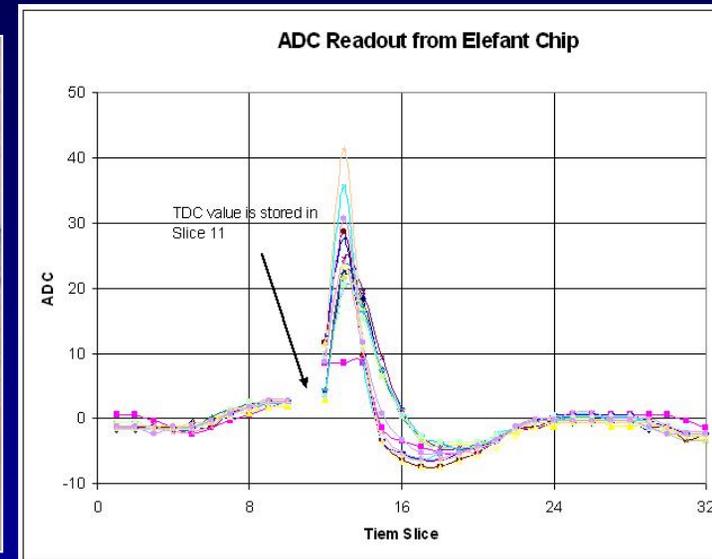
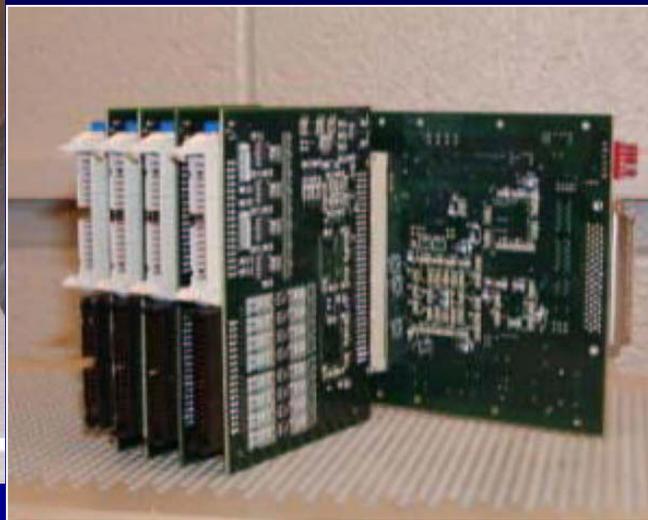
- Seamless Straw (4M Ω /sq) Resolution
 $\sigma = 0.4$ mm at 60°
- Spiral Straw (0.5M Ω /sq) Resolution
 $\sigma = 1.1$ mm at 60°
- Design goal ($\sigma = 1.5$ mm) is achieved

• Seamless straw anode performance

- Drift Distance Resolution
 $\sigma = 70$ μm at 60°
- Efficiency > 95% except near walls
- Design goal ($\sigma = 0.2$ mm) is achieved



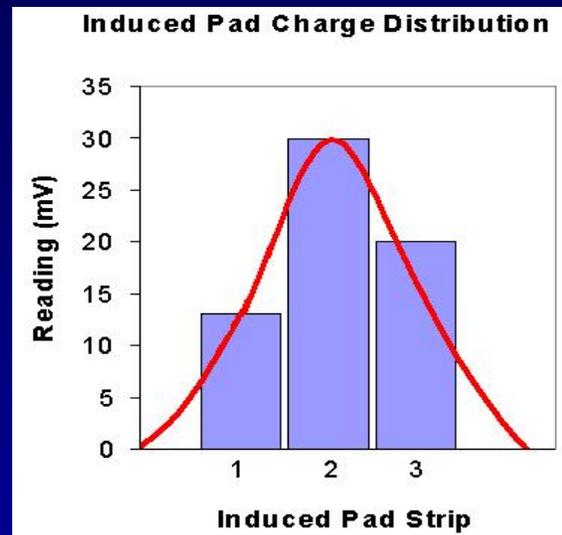
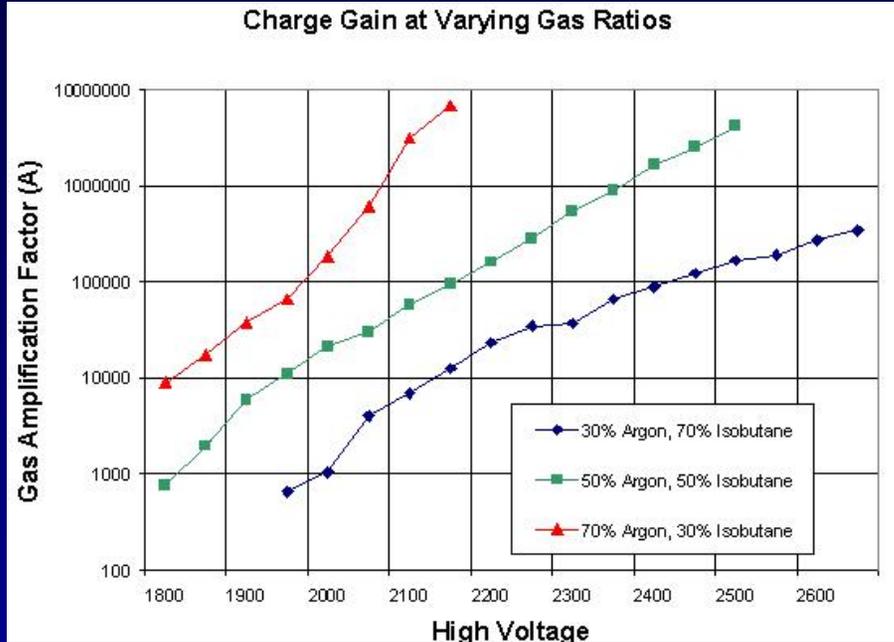
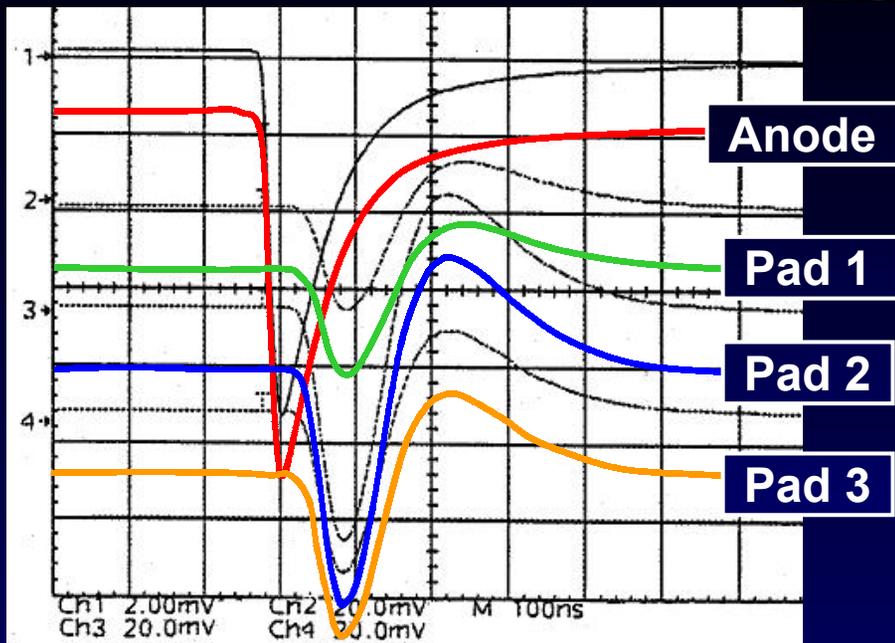
- **Studies provide input to select geometry and readout architecture**
 - Full-length longitudinal vane prototype remains a work in progress at Houston as mechanical stability and straw bonding issues are resolved
 - Electronics design and prototype work at Houston has progressed to testing prototype preamplifier, digitizer, and controller boards as a system using the current version of BaBar's Elephant chip with very promising results.
 - Work beginning on updating Elephant chip design to current technology
 - Simulations of both the longitudinal and transverse geometries continue, indications are that either geometry might work from a physics standpoint



Data From Prototype Chambers

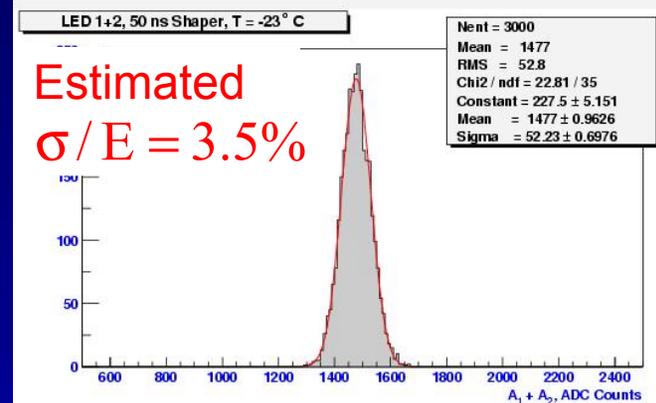
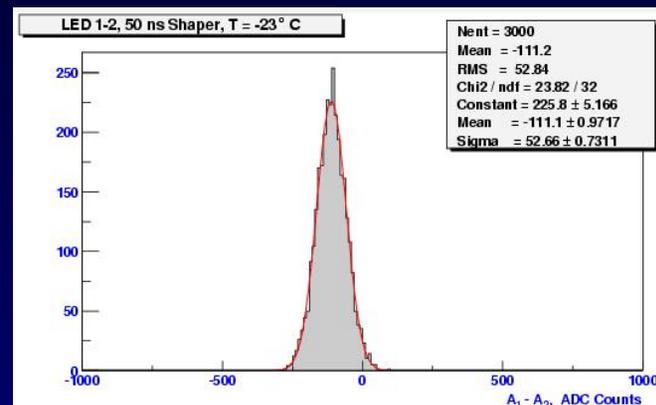
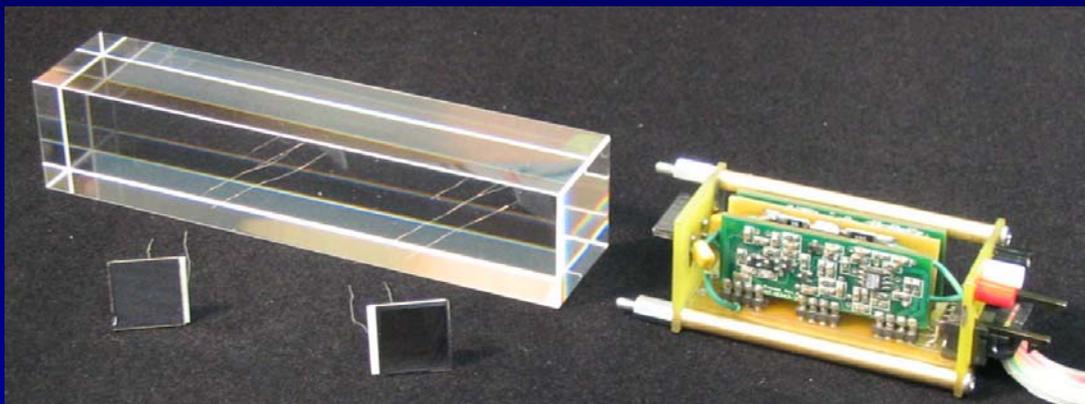


- Studies of charge distribution on pads, gas properties, and several amplifier options
- Selected ASD-4 as the leading amplifier candidate and determined the optimal straw resistivity to be 0.5 – 1 MΩ/sq



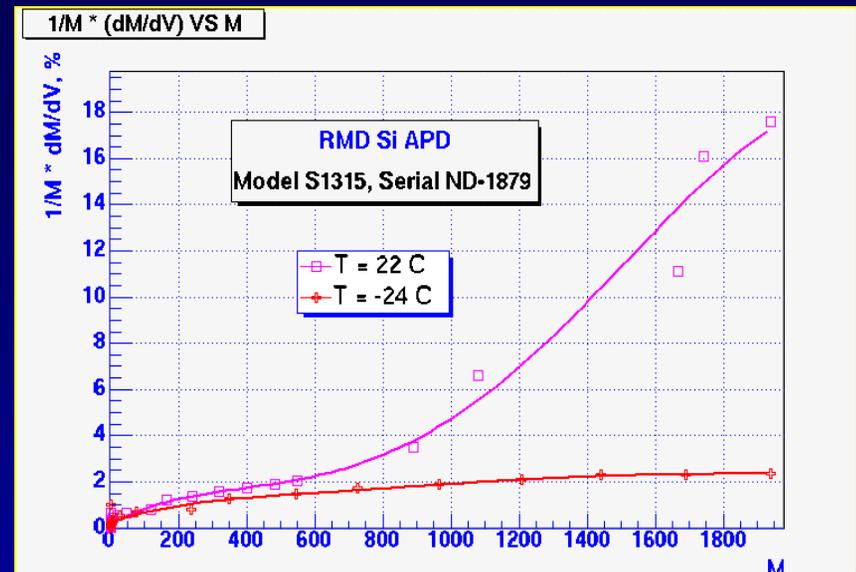
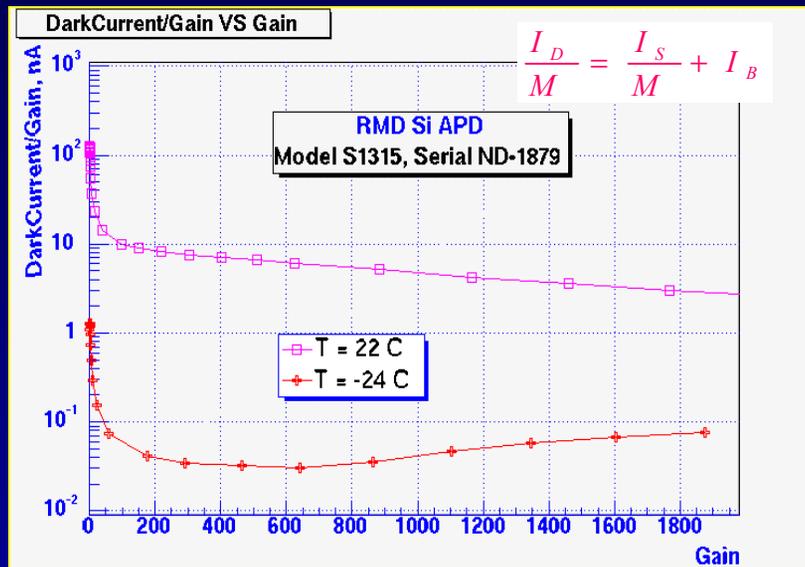
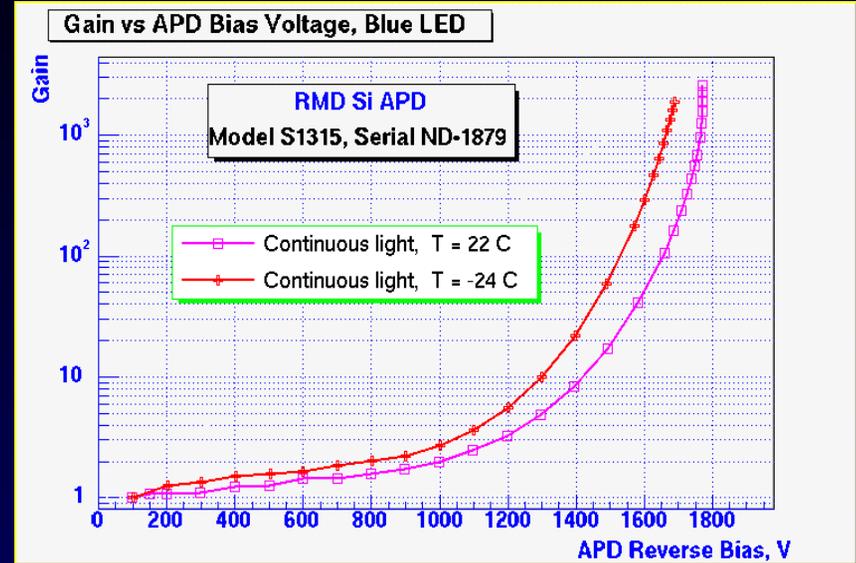
Calorimetric Electron Detector - NYU (WBS 1.7)

- Bench tests of PbWO_4 crystals cooled to -23°C and large area avalanche photodiodes continue at NYU using electronics designed and built in house
- Indications are that this material will meet MECO resolution requirements, demonstrating 20-30 photo e-/MeV (as compared with CMS' 5 pe/MeV)
- We need to verify the system performance via beam tests of an 8x8 crystal array
 - If true we can sharply reduce the contingency on the Calorimeter that covered the possibility of using BGO crystals
 - Further it appears that we can make use of fewer (larger) crystals allowing reductions in APD, and associated HV and readout channel counts (1152 crystals vs. 2000 originally)



Parameters of RMD APD

- The parameters of one RMD APD used in the studies are shown in the plots.
- Gain, gain stability, and dark current performance improve significantly with cooling.



Cosmic Ray Shield (WBS 1.8)

- Extensive testing at William & Mary has established a combination of scintillator, wavelength shifter, and multi-anode PMT that will meet MECO's 99.9% cosmic ray veto efficiency requirement
- Extrusion of ~100 4m slats this summer at Itasca – similar to MINOS design
- Test slats will be assembled into a prototype module this Fall
- Further concerns with rates (e.g. from neutrons) to be addressed

Trigger and DAQ (WBS 1.9)

- No engineering has gone into the Trigger or DAQ to date due to lack of resources.
- A fraction of the support for Boston University's Electronics Design Facility (EDF) will be devoted to start design for the system and cost it.

- **Current Status**
 - Full time Project Manager on board
 - No other project office personnel
- **Critical needs in MECO management structure:**
 - Chief Mechanical Engineer – Candidates are being considered now; the person will lead integration effort and contribute to critical design needs in short term.
 - Chief Electrical Engineer – Attempting to identify candidates for the same type of integration and critical design jobs.
 - Cost and Schedule Manager – aid the PM in developing cost and schedule documentation. The person will work with integrated cost and schedule software (e.g. Primavera).

Summary

- There has been substantial progress in systems where we have been able to apply resources.
- A number of systems are (or soon will be) at the stage where construction funds can be efficiently spent.
- Lack of pre-project development and R&D funds have been the limiting factor in developing the designs of most systems.
- Lack of engineering and project manpower means less reliable cost estimates and resulting higher contingency required in the current cost estimate.
- Many systems are close to being baselined, some with technology choices still to be made.
- The critical path subsystem (the solenoids) have benefited from internal funding priority; nonetheless, they are being delayed (currently day for day) by a combination of less than adequate funding and procedural difficulties.
- Some unforeseen problems with intensity limitations and with available running hours per year threaten to stretch the required years of running and decrease the ultimate MECO sensitivity.

What Can This Committee Do?



- Encourage the Laboratory to support the experiment as much as possible.
 - Structure responsibilities of senior physicists such that they can devote intellectual effort to the experiment.
 - Encourage the DOE and Lab to appreciate the potential benefits of a successful experiment as well as the risks of possible failure.
- Encourage the DOE (both NP and HEP) to provide appropriate support to the collaborating institutions.
 - Physicists in Physics Department
 - Physicists in C-AD and SMD
 - University groups supported by both NP and HEP
- Encourage the Laboratory and the DOE to recognize that there is more than one way of doing business and to be flexible in interactions with the experiment (e.g. costing of limited periods of running with RHIC).
- Encourage the Laboratory and the DOE to find a way to make adequate running time available (presumably at NSF cost).