FERMILAB-SLIDES-08-002-PPD

R&D For Mu2e

R. Bernstein
for the Mu2e Collaboration

FNAL PAC Meeting
3 November 2008

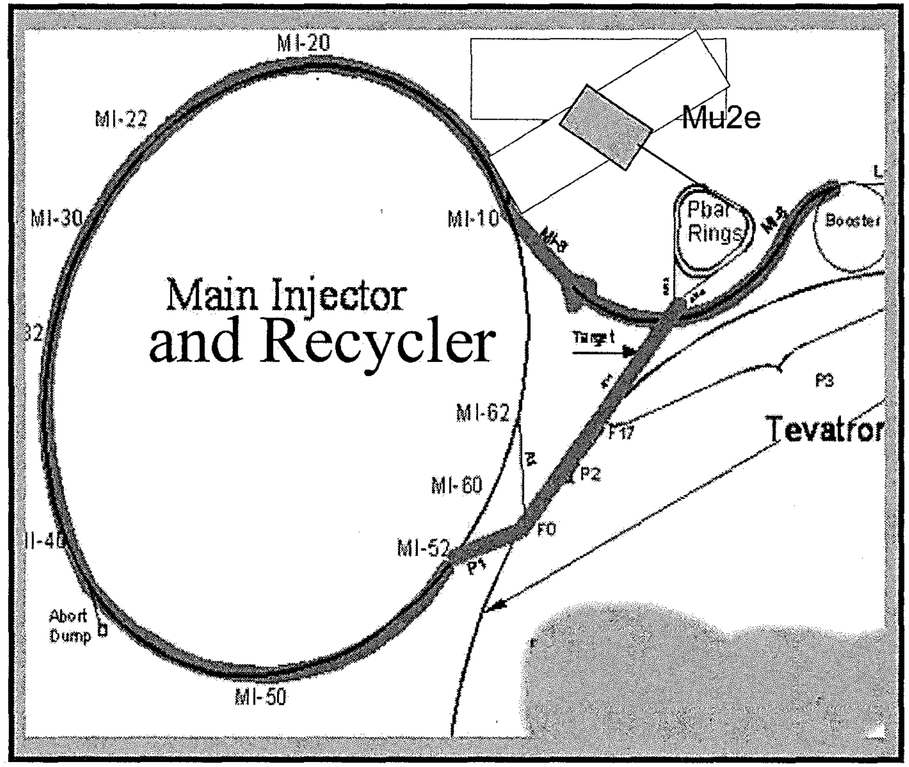
Outline

- Start with a proton in Booster
- Follow all devices along the way to an analyzed conversion electron
- Present R&D Needed at Each Step
  - What are the issues?
  - What is the plan for R&D on that issue?

- Accelerator
  - Boomerang Scheme
  - Accumulator/Debuncher
  - Extinction Scheme
- Solenoids
  - Field Specifications
  - Final Design
  - Monitoring/Measurement
- Detector
  - Tracker
  - Calorimeter
- Others if Time or Questions
  - Booster
  - Machine Energy
  - Trigger and DAQ
  - Civil Construction
  - Cosmic Ray Veto

Boomerang Scheme

- Protons from 8 GeV Booster
- Through existing lines into Recycler
- Out through AP line into Accumulator/ Debuncher
  - Significant changes to A/D
- Slow Extract to Mu2e Hall
- R&D:
  - Recycler extraction design, but is "mirror-image" of NOvA design
  - Slow extraction is new
  - Detailed beamline transport simulation for entire system



Accumulator/Debuncher

- Particle Rates
  - Loss Detection
  - Safety Considerations
- RF Manipulations:
  - Standard techniques but needs detailed optimization
- Extraction
  - Slow Extraction from Debuncher
  - Must understand scheme and losses

Particle Rates For A/D Rings

- Debuncher/Accumulator currently receives approximately 2.5×10^{11} particles per hour

- Mu2e requires $\sim 2 \times 10^{13}$ per second
  - So naively this is x300,000 flux
  - Loss of ~1% yields 290W of beam power in diffuse loss

- Booster currently receives 500 W total diffuse
  - Or 1 Watt/meter, adopted as "rule of thumb"
  - 1% loss leads to 290W/ 510meters in A/D

- R&D Required
  - What is the expected diffuse loss?
  - Passive shielding not enough; need to adapt Booster system
  - Constant energy rings help – specify operating range for magnets for beam permit

A/D Shielding R&D

- A/D Rings do not have enough cover for passive shielding alone (an issue outside enclosure)
  - Fence off area?
  - Interlock buildings?
  - Can We Access Enclosures while Beam is Running?
    - For debugging, maintenance, repair, etc.

- R&D Required:
  - Safety assessment
  - Simulation of transport
  - Measurement of losses both now and in future
    - Do we want special runs in A/D to measure particular loss rates at specific locations?
  - Cost of new shielding/safety system

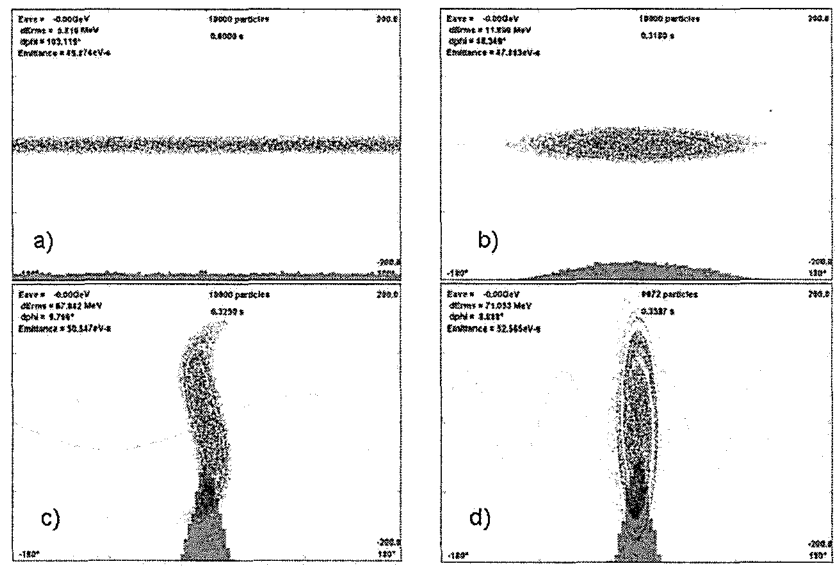
A/D Intensity

- Intensity Limitations
  - Diffuse Losses
  - Point Losses
  - At design intensity, space charge can be appreciable
    - This is potentially a problem because of resultant tune shift
    - Which then may make slow extraction to experiment difficult since slow extraction works by putting beam on resonance
      - Particles not on resonance at same location along circumference
- R&D Required:
  - Assess aperture and impedance after Mu2e changes
    - Understand diffuse and point losses
    - Are there specific regions that require more shielding?
      - e.g., extraction region
  - Simulation of space charge effects
    - Integrated work on space charge and extraction scheme

A/D RF Manipulation

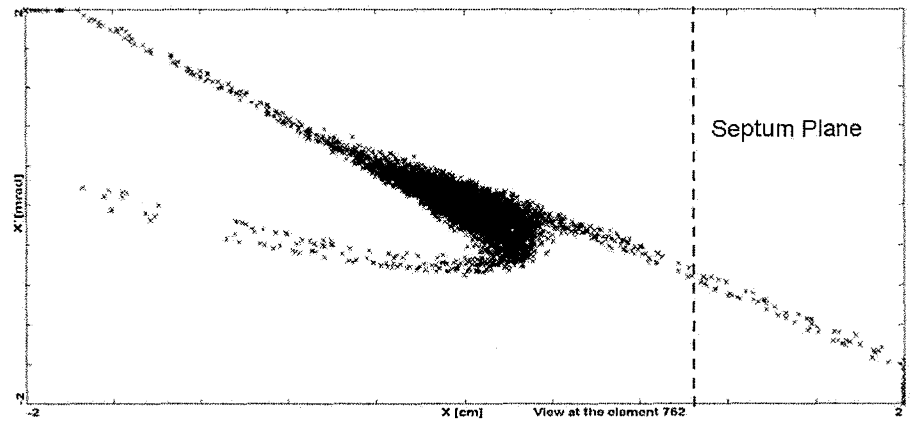
- Accumulator:
  - 53 MHz (h=84), 80 kV (~30-50 kV presently avail.)
  - 625 kHz (h=1), 4 kV (~2 kV presently available)
- Debuncher:
  - 588 kHz (h=1), 40 kV (~0.5 kV at present)
  - 2.35 MHz (h=4), 250 kV (~0.8-2 kV at present)
- R&D Required:
  - Techniques are sound, technology known; cost estimate needs to be performed
  - Need detailed design and optimization

Existing RF voltage not enough but not new technology



Slow Extraction in A/D

- Slow Resonant Extraction
  - Need simulation
  - Need Lambertson/Septa
    - Conceptual Plan exists from Mu2e LOI
- R&D:
  - Study losses here
  - Coupling to tune shift
  - Details of scheme affects civil work and precise extraction point
  - Understand any required reconfiguration
  - New Magnets
  - Instrumentation
  - Cost



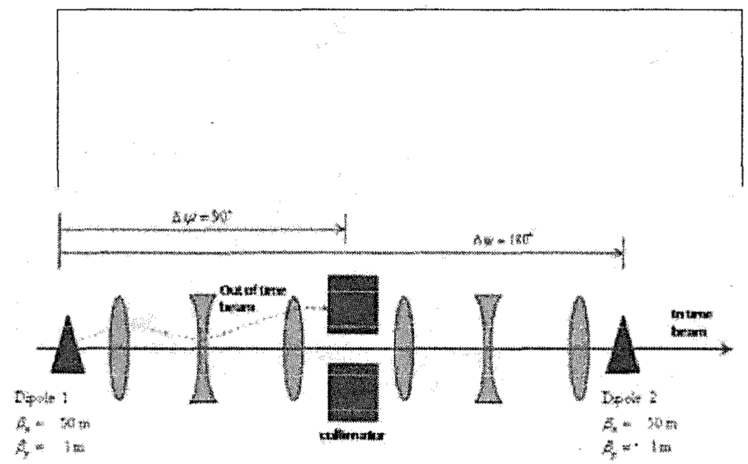
Resonant Extraction Parameters	
Kinetic Energy (GeV)	8
Working tune (ν_x/ν_y)	9.769/9.783
Resonance (ν_x)	29/3
Normalized acceptance (x/y πmm-mr)	285/240
Normalized beam emittance (πmm-mr)	20
β at electrostatic septum (m)	15
β at Lambertson (m)	22
β at harmonic quads (m)	14
Septum Position (mm/σ)	11/4.8
Septum gap/step size (mm)	10
Sextupole Drive Strength (T-m/m^2)	473
Initial Tuneshift	.048
Septum field (MV/m)	8
Septum length (m)	3

Accumulator/Debuncher R&D Summary

- Near-term (3–6 months)
  - Specification of RF systems
  - Simulations of complete scenario
  - Instability assessment
  - Beamline designs for Transfers between machines
  - 3-D simulation of motion with space charge
  - Alternatives and evaluations
- Longer-term (12-18 months)
  - RF R&D – RF system design & prototype
  - Injection/Extraction design
  - Engineering design and cost estimates
- Detailed impact statement for Accelerator Division has been prepared

Extinction Channel

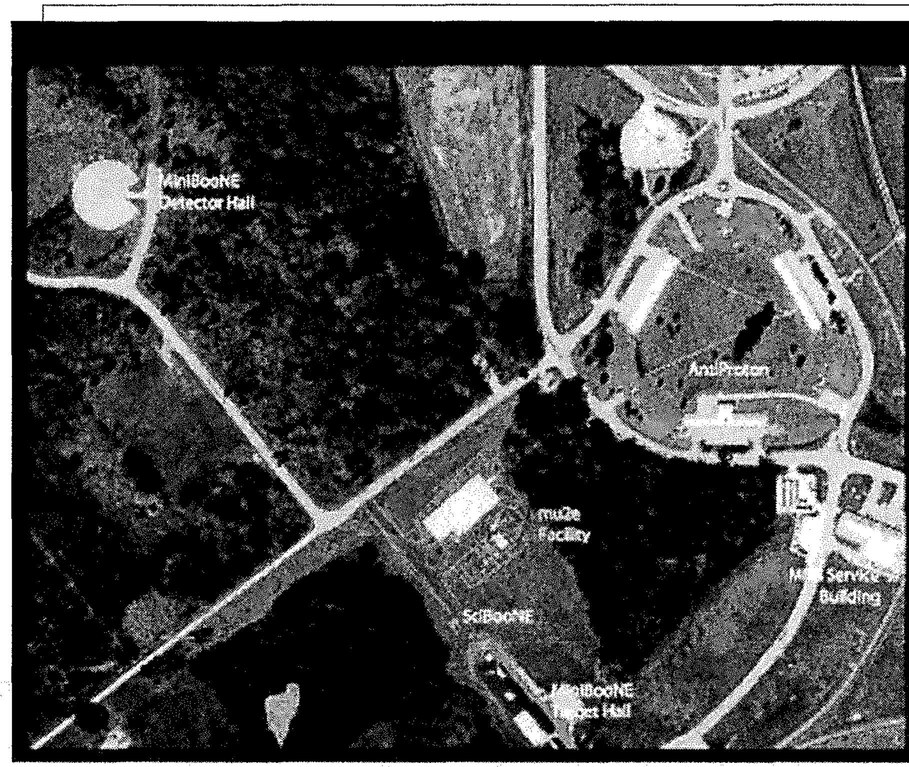
- What Will "Natural" Extinction Be After Beam Manipulation?
- How much additional extinction is required from other methods?
- Is AC-Dipole the Best Scheme?
  - BNL/MECO had different idea
    - Evaluate all options
  - Redundant extinction in pbar rings?
    - *Redundancy is good…*
- Measurement of Extinction
  - Phase advance of AC-dipole current
  - Continuous off-angle telescope
  - *More Redundancy is better…*
- In AC Dipole Scheme:
  - Scraping off collimators
  - Simulations just beginning
  - Where is best place to put it?
    - Interaction among A/D extraction, wetland disturbance, performance of channel
- Understanding interplay between site choice, accelerator, physics simulations required



Extracted Beamline

- Short underground beamline
  - Pipe under creek to avoid wetlands issue
- Extinction Channel between A/D and Mu2e Hall
- Proton beam enters hall and solenoid
- R&D Required:
  - Precise location of extinction channel not set, needs optimization
  - Detailed beam transport underway
  - Details will depend on final depth of building
    - value engineering issue

First-pass design; location not fixed and may affect extinction scheme details



AC Dipole Conceptual Design

- Conceptual Design Report expected Summer 2009
- Collaboration with KEK: spending US-Japan funds now!
  - Ferrites
  - Power leads
  - Prototyping underway

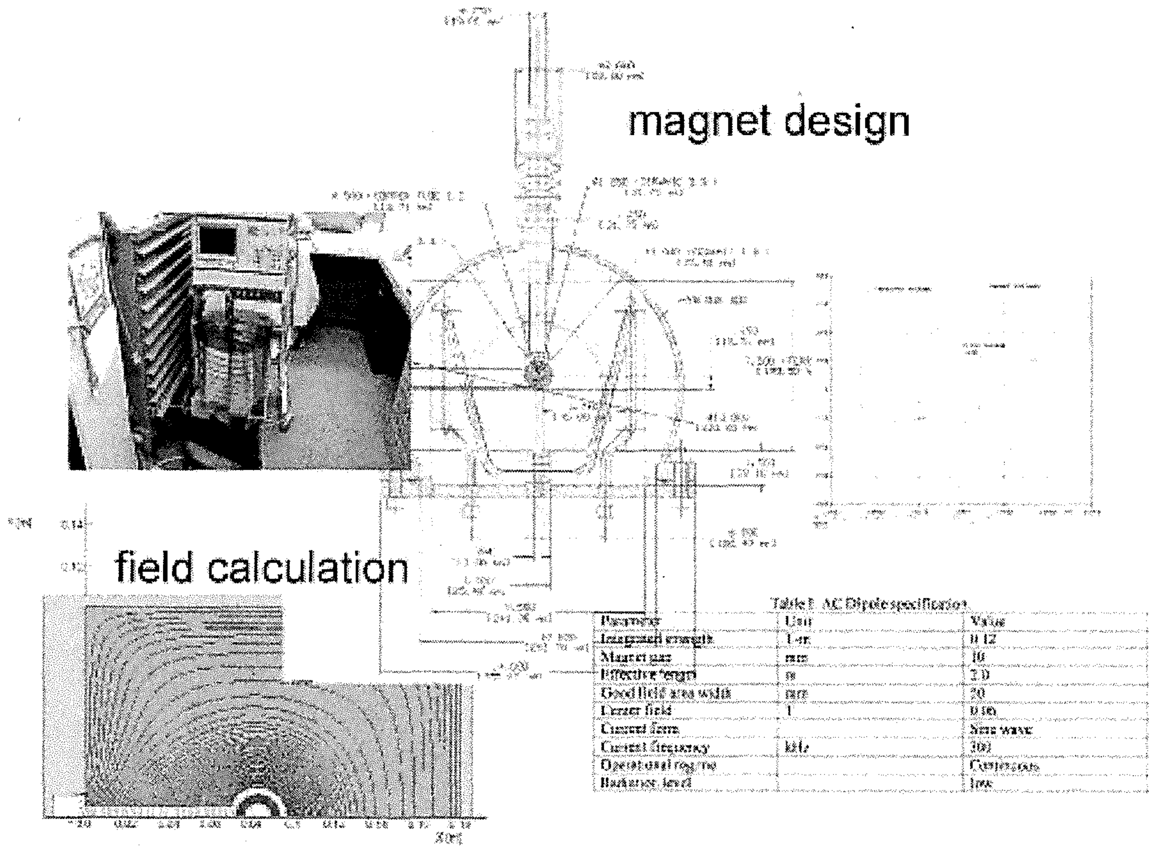


Table I. AC Dipole specification

Parameter	Unit	Value
Integrated strength	T·m	0.12
Magnet gap	mm	10
Effective length	m	2.0
Good field area width	mm	20
Center field	T	0.06
Current form		Sine wave
Current frequency	kHz	300
Operational regime		Continuous
Radiation level		low

Solenoids

Nearly Half the Total Project Cost

Critical Path Item for Schedule

State of Design of Solenoids

- The magnet conceptual design was established with the MECO Magnet Conceptual Design Report (Jun02) and updated through subsequent design changes since the CDR.

- The present baseline benefited from multiple reviews:

▪ Interim design review	Sep01
▪ Final design review	Feb02
▪ Magnet acquisition panel review	Sep02
▪ Presentation to BNL safety committee	Jun03
▪ RSVP review	Oct04
▪ RSVP baseline practice review	Apr05
▪ RSVP baseline final review	Apr05

Conclusion from RSVP Baseline Review:

"The magnet technical baseline design meets all design criteria."

- ***R&D: incorporate existing knowledge, validate, and advance***

Solenoids: R&D on Design

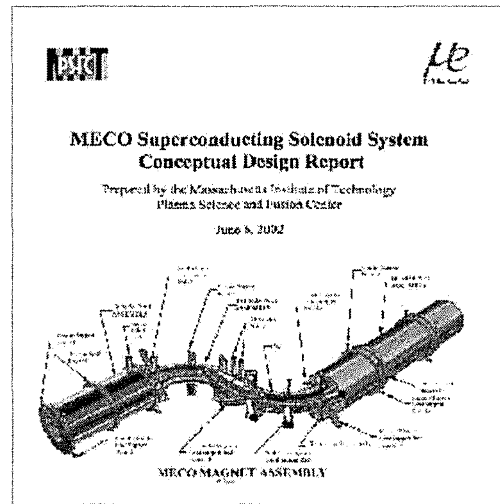
- Start with Advanced Design Work Done by MECO
- Field Specifications:
  - Combination of experimenters, magnet designers, and engineers is required to advance state of field specs
  - Ensure field specifications allow us to meet physics goals
  - critical integration issue across all aspects of experiment
- Re-examinations:
  - How can we assimilate extensive MECO work and therefore not waste time but also have an independent fresh look?
  - Alternate designs
    - COMET probably more costly, and evaluation will take a year or more

Solenoids: Design, Procurement, Installation

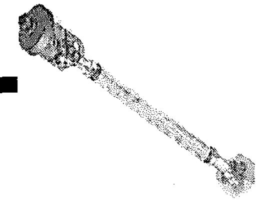
- Final Design and Procurement Strategy
  - Should FNAL be the "general contractor" and have the actual construction done outside? Or a mix?
  - What role should FNAL play in advancing from MIT conceptual design to technical design to final design?
- Installation Issues and Interplay with Civil Construction, Detector System, and Proton Beamline?

Assimilating MECO/MIT Work

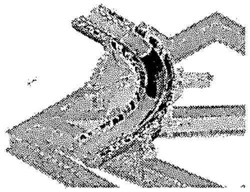
- MIT Plasma Science Fusion Center
  - Prepared a CDR
  - Two of three key engineers have left, one still at MIT
  - Now work for General Atomics
    - Who not coincidentally make superconducting magnets
    - General Atomics is interested in design and/or construction contract
- Meeting 7-8 October 2008
  - All three came to meeting with FNAL TD
  - Presentation of state of design
  - Very well attended (~30 FNAL staff)
  - Extensive technical discussions:
    - Reasons for specific design choices
    - Where they believed design could be improved or advanced
    - Three years of work after CDR was performed and will be made available
    - The former MIT group members will provide additional extensive documentation, solid models, and code
    - Thoughts about "build-to-spec" or "build-to-print" strategy
      - Key for allocation of resources and has cost implications



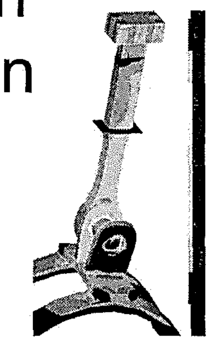
MIT CDR

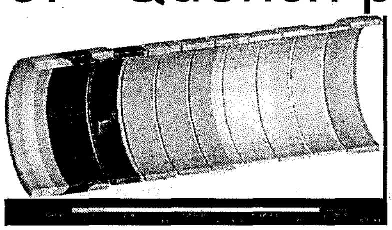


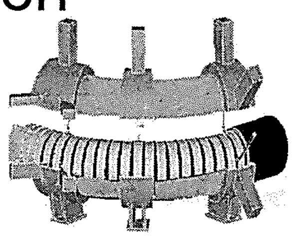
1. Introduction and summary
2. Interfaces

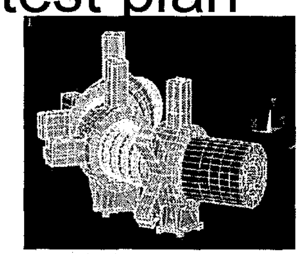


3. Field specifications and field matching
4. Conductor design
5. Coil insulation design
6. Conductor joint design
7. Current lead and bus bar design
8. Quench detection system
9. Quench protection
10. Power supplies, dump resistors and switches
11. Structural design criteria
12. PS structural design
13. TS structural design
14. DS structural design
15. Cryogenic system design
16. Magnet assembly
17. Magnet installation
18. Draft magnet test plan









Updates After CDR Discussed at Meeting

Item	Reason	In Baseline	Last Status
Update the field spec	**Limit transverse fields in TS from PS and DS**	**No**	**TBD**
9 coils -> 11 coils in the PS	Conductor length matching (no internal joints)	Yes	Done
Addition of PS iron and poles	Limits transverse fields in TS from PS	Yes	Done
Addition of DS poles	Limits transverse fields in TS from DS	Yes	Done
He gas cooled radiation shields	Avoid potential explosion issue with ozone buildup in LN2	Yes	Done
Thicker TS vacuum bore tube to support the shields	Structural	Yes	Done
Added TS support frame and enlarged TS support pedestals	Needed for uniform floor loading and to react all coil loads	Yes	Done
Conduction cooled PS coil design	**Eliminate He bath, He loss on quench and quench pressurization**	**No**	**TBD (Not easy)**
Thermal Siphon Cooling in the PS, and possibly in TS and DS	PS heat load encourages thermal siphon	No	TBD
Alternative design for PS hoop load support	Lower cost than machined Al mandrels	No	TBD
SS -> GFRP rods	Lower heat leak	No	TBD
Consider Longer TS bend region coils	Lower winding cost	No	TBD

Solenoid: Technical R&D Issues

- Conductor Choice: *new possibilities*
  - Strong indication that SSC cable inventory is missing
  - Probably ~$3M conductor acquisition required
  - Buying duplicate SSC cable not the best choice
  - May leave as a vendor prerogative
- Magnet Shielding in Transport Solenoids
  - Significant leakage fields (800 gauss within a few meters) may lead to operational difficulty and possible ES&H Issues
- Tuneability of muon beam line in Solenoids
  - Lack of ability to adjust transport field for imperfections/deviations
  - Called out by Tschirhart Committee
  - MECO: achieving field specs is a sufficient guarantee for physics requirements, but we will re-examine
- Cryogenic Issues
  - Cooling of Production Solenoid (conduction cooled design)
  - Use of High Temperature Superconducting Leads?
    - Transition from cold to room temperature for magnet current
- Integration issues related to Fermilab
  - Cryogenics infrastructure/Power supplies/quench protection

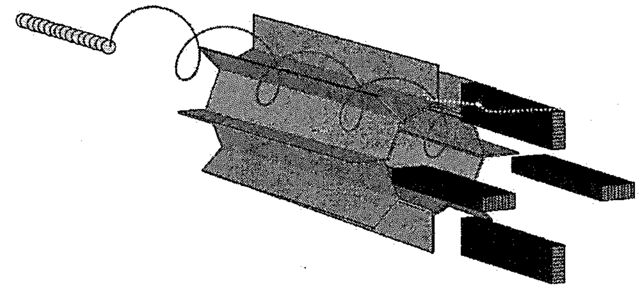
Solenoids: Physics R&D Issues

- Optimization of design:
  - Quality of "magnetic mirror" at production and stopping target and interplay with cost, technical complexity
  - Field gradients: how much can field along line vary?
    - dB_s/dr, dB_s/ds
- Monitoring and Measurement: Significant R&D issue
  - Requirements on muon beam position measurement within solenoids
    - Do we need to place beam position measurement devices inside solenoids to check simulations and time-variations?
    - What measurements are needed?
  - Measurement of field *in situ*
    - Precision required? Engineering: where and how many measurements?
  - Do we then require "correction coils" or other ways to adjust fields based on measurements of beam position measurements or other data?

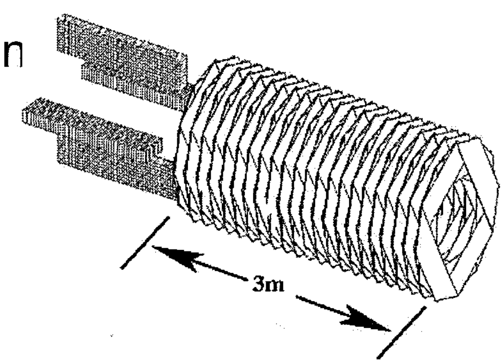
Detector

Tracker and Calorimeter

Detector: Tracker



- Two trackers studied
  - L-tracker
    - Pattern recognition “easier”
    - Challenging to build
  - T-tracker
    - Pattern recognition “harder”
    - Much easier to build but not without challenges
  - R&D Issue:
    - Mu2e will prototype L-tracker
    - Also solving most T-tracker construction problems
    - Parallel software effort



Detector: Tracker

- Tracker
  - L-Tracker Construction
    - Can a low mass, mechanically stable L-tracker be built?
      - Prototyping and design work
    - Can the T-tracker be analyzed?
      - Detailed MC with real effects
  - L-Tracker R&D Issues
    - Mechanical Stability of L-Tracker
    - Maintenance/Repair
      - electronics channels
      - broken wires
  - Prototypes required
    - Smaller scale prototypes at Houston for MECO
    - Pick up and continue their work

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 53, NO. 4, AUGUST 2006

Performance of a Prototype Tracking Detector With Waveform Sampling Electronics

Y. Cui, *Member, IEEE*, K. Lan, *Senior Member, IEEE*, and E. Hungerford

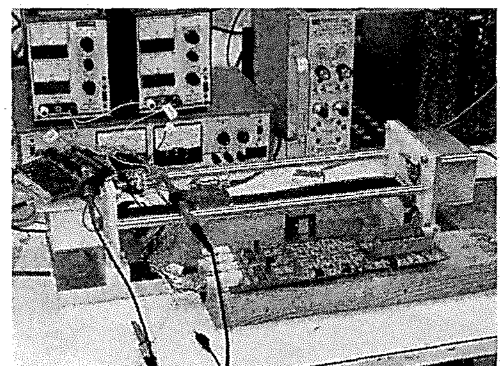
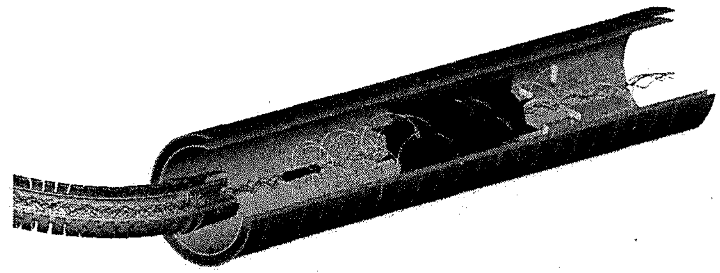
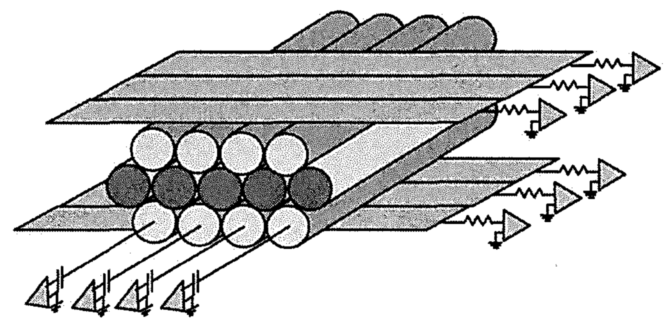


Figure 1.1 The SP-MK1 prototype and its front end electronic set up

Detector: Tracker Details

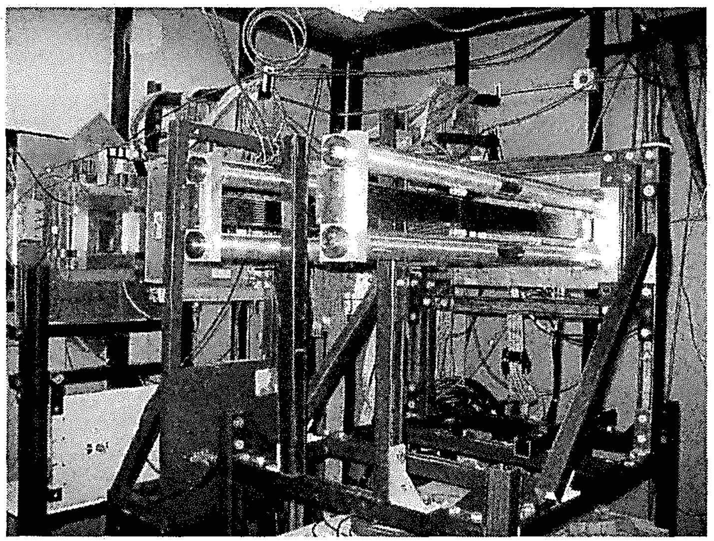
- Straws:
  - Expected Resolution:
    - r/φ: 200 microns
    - Z: 1.5 mm
    - p: ~0.120 MeV/c intrinsic
  - Fast Gas: CF_4-isobutane
    - Almost co-axial with solenoid
    - Prevents multiple hits on wire
- Cathode Readout:
  - 30 cm x 0.5 cm
  - On inner and outer planes
  - 16,640 total



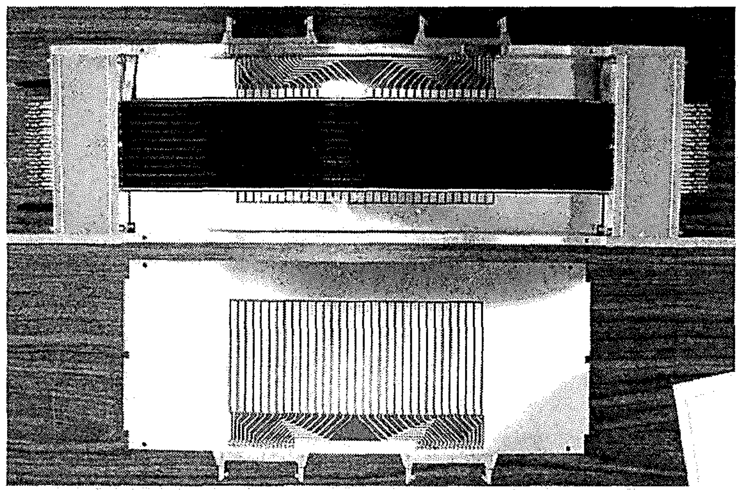


Detector: Tracker R&D Issues

- Design:
  - Strong FNAL group exists and is working with collaboration
    - Mechanical support structure with FEA
    - Gas manifolds and associated infrastructure
    - Electrical readout
  - Full MC of real detector: does it meet or exceed performance specifications?
    - Help from CD in infrastructure already paying off
- Prototyping
  - Which straws?
    - spiral, seamless, polyimide, PEEK
  - Fabricate vane or octant for mechanical stability, mounting, and assembly
  - Full-size prototype
    - for pad readout, crosstalk, noise
    - Leaks, outgassing, resistivity,…



T950 Straw Tracker Test

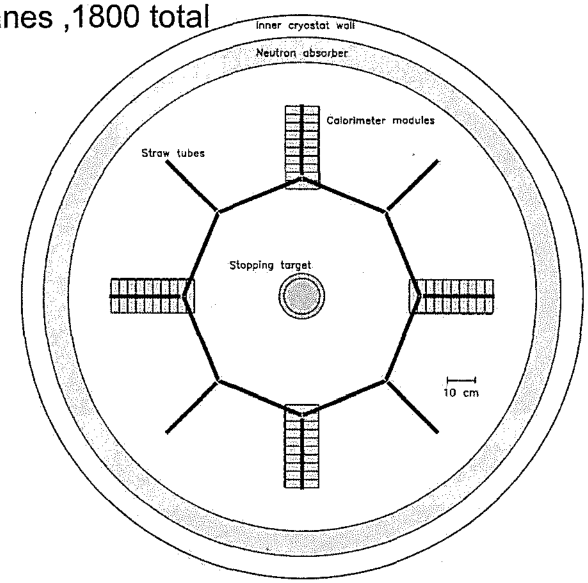


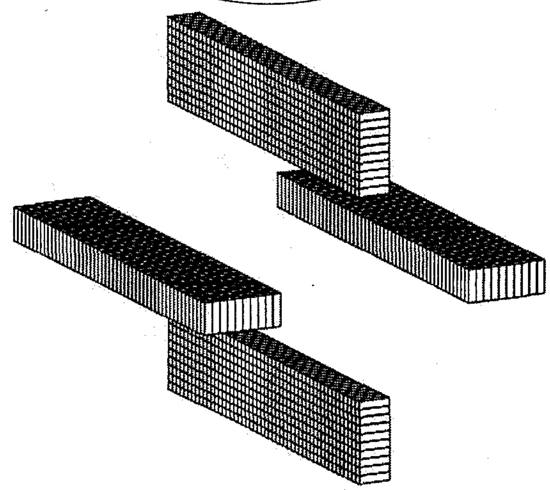
MECO resistive straw prototype

Detector: Calorimeter

- Calorimeter
  - Requirements:
    - Physics:
      - Experiment trigger
      - Independent check of
        - » Energy
        - » Position of extrapolated track
      - Timing
    - Operating
      - Must operate in 10 kG field
      - In Vacuum
      - Survive beam flash
      - Radiation Hard (160 Gy/yr)
  - R&D Issues:
    - Physics:
      - Required resolution
    - What is best choice of calorimeter technology?

•10 x 45 = 450 array of 30x30x120mm^3 $PbWO_4$ crystals
•Four vanes ,1800 total





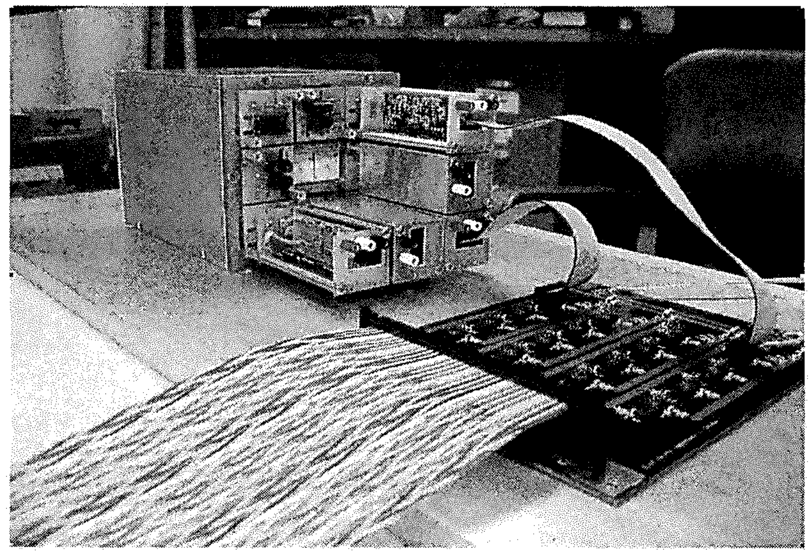
Detector: Calorimeter R&D

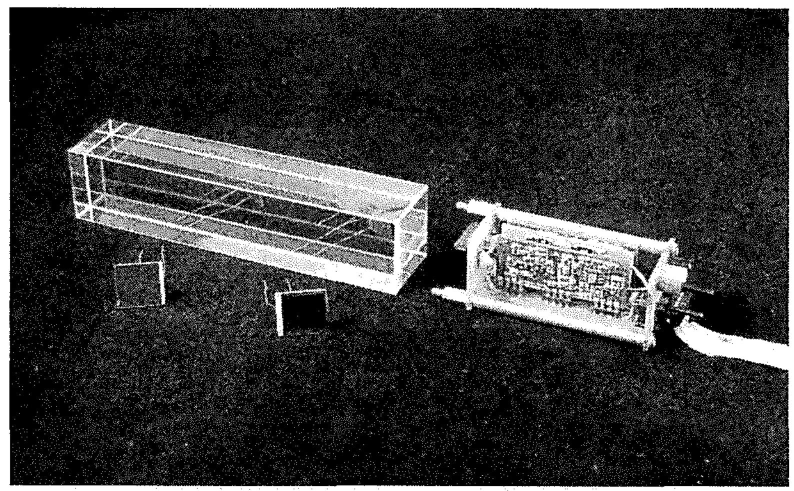
- R&D on Energy Resolution:
  - Recall resolution of tracker ~ 0.1%
  - Is there then any advantage of 1% vs 5% in calorimeter?
    - Energy check to eliminate catastrophic misreconstructions
    - Could reduce some backgrounds with tighter cuts on E/p
  - Requires simulation effort to assess improvements vs. cost vs. complexity

- R&D on Calorimeter Technology:
  - Other crystals possible
  - Better light yield, possibly eliminating need for cooling
    - Large complexity savings

Detector: Calorimeter Prototyping

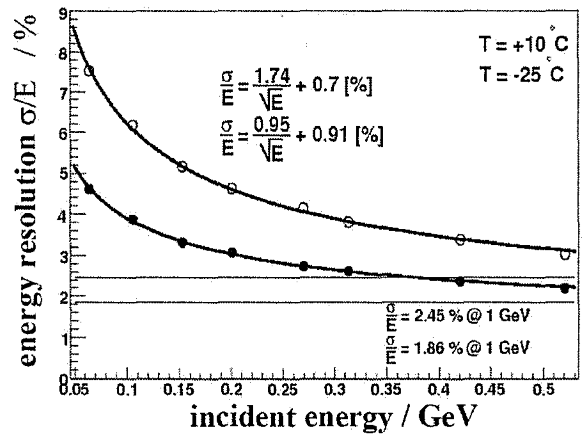
- R&D Prototype at NYU as part of MECO:
  - Low-noise preamplifier designed and fabricated
  - APD+preamplifier characterized and tested
  - Single crystal performance has been demonstrated with cosmic rays: 38 p.e./MeV, electronic noise 0.7 MeV.
  - Pile-up noise expected to be 0.9 MeV
  - Estimated performance with electrons, $\sigma(E) \sim$ 5-6 MeV at 100 MeV, σ(position) < 1.5 cm
- Will pick up and continue R&D

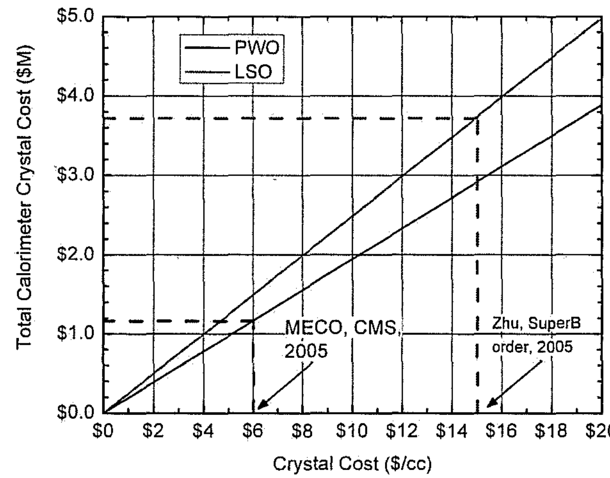




Detector:Calorimeter Crystal Choice

- R&D: Alternative Crystals: more light, less cooling
  - PWO-II
    - Selected for PANDA calorimeter
    - Improvements:
      - Reduced defects
      - Less La and Y doping ⇨ less quenching of primary luminescence yield
      - Fast,
        - □ σ = 1.5 ns @100 MeV @ -25°C
      - Double CMS PWO light yield!
        - □ σ/E = 4% @ 100 MeV @ -25°C
  - LSO: Lu_2SiO_5
    - ~200X light of PWO! $\sigma(E)$ ~ 1% possible
    - Cooling not needed!
    - Cost not prohibitive: \$3M over MECO/$PbWO_4$
    - *Greatly simplifying engineering:*
      - *cost of material vs. cost of cooling design and construction*





See talk by R. Zhu, Fermilab, April 2, 2008.

Simulations: Build on MECO

- Starting with a solid foundation but need modernization
- Must refine our understanding of detector response
  - Detector and backgrounds from beam, stopping target, and beam dump
  - in the context of a specific reconstruction algorithm
    - Optimization of stopping target, tracker, calorimeter, CR veto
- Plans for Auxiliary Measurements
  - Need consistent and complete methods for measuring:
    - resolution and non-gaussian tails
    - response of detector *in situ*
  - Determine what test beam measurements needed to benchmark simulations
- Extinction Channel: what gets out?
- Solenoid Muon Transport: field specifications, backgrounds, particle transport; late-arriving particles?
- This is a significant focus of daily group efforts
  - Simulation group formed and has biweekly meetings (~10 people)
  - Rewriting FORTRAN MECO Monte Carlos in GEANT4/C++ and integrating with beamline/accelerator tools

R&D Conclusions

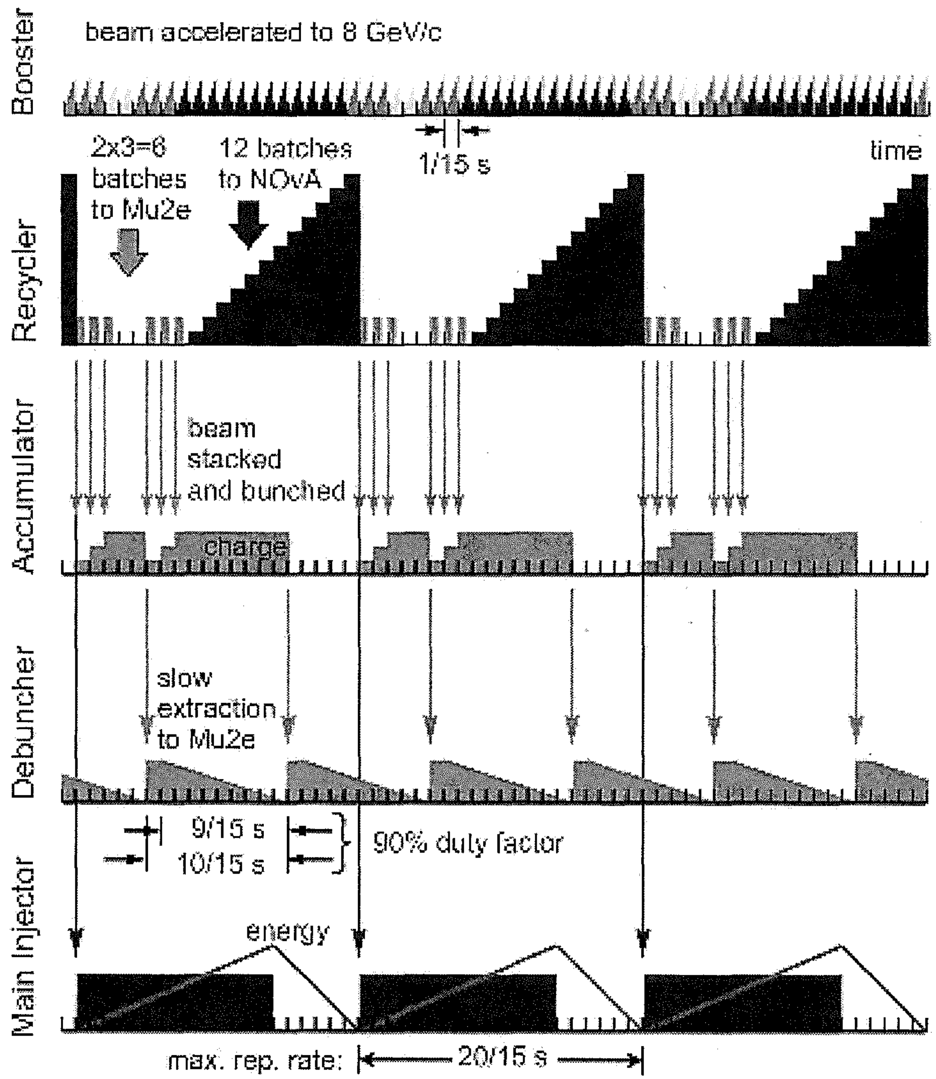
- MECO is a solid, extensively reviewed foundation
  - We are looking for independent validation, improvements on the details, and refinements, not extensive re-design
- We have identified R&D issues for:
  - Accelerator, extinction, solenoid, tracker, calorimeter, simulations
- We have formed sub-groups:
  - Accelerator: complete design starting
  - Extinction: prototyping underway
  - Solenoids: assimilating MECO and moving beyond
  - Tracker: prototyping just starting
  - Calorimeter: best technology?
  - Simulations: have MECO code running and are designing modern, more powerful code
- We are working with Project Management to integrate technical decisions with cost/schedule constraints:
  - *reduce uncertainty, cost, and risk*

Other R&D Topics

- Booster
- Machine Energy
- Trigger and DAQ
- Civil Construction
- Cosmic Ray Veto

Overview of Timeline

- Because of time required to ramp Main Injector magnets, there are available Booster cycles
- Mu2e does not affect NOvA



Booster

- Current Performance of Booster:
  - 4.5-5.0E12 protons/batch
  - Operationally limited to 7.25 Hz
  - Believed 9Hz is achievable with current system
  - Current radiation limits would allow 1.6E17/hr although typically running at 8-9E16/hr (factor of just under two)
- Booster needs upgrade:
  - 15 Hz (AD has agreed to do this)
    - Not considered major project
    - Technique understood and documented: RF upgrades
- R&D Required:
  - Accelerator Division will perform calculations, cost assessment, make plan

Machine Energy

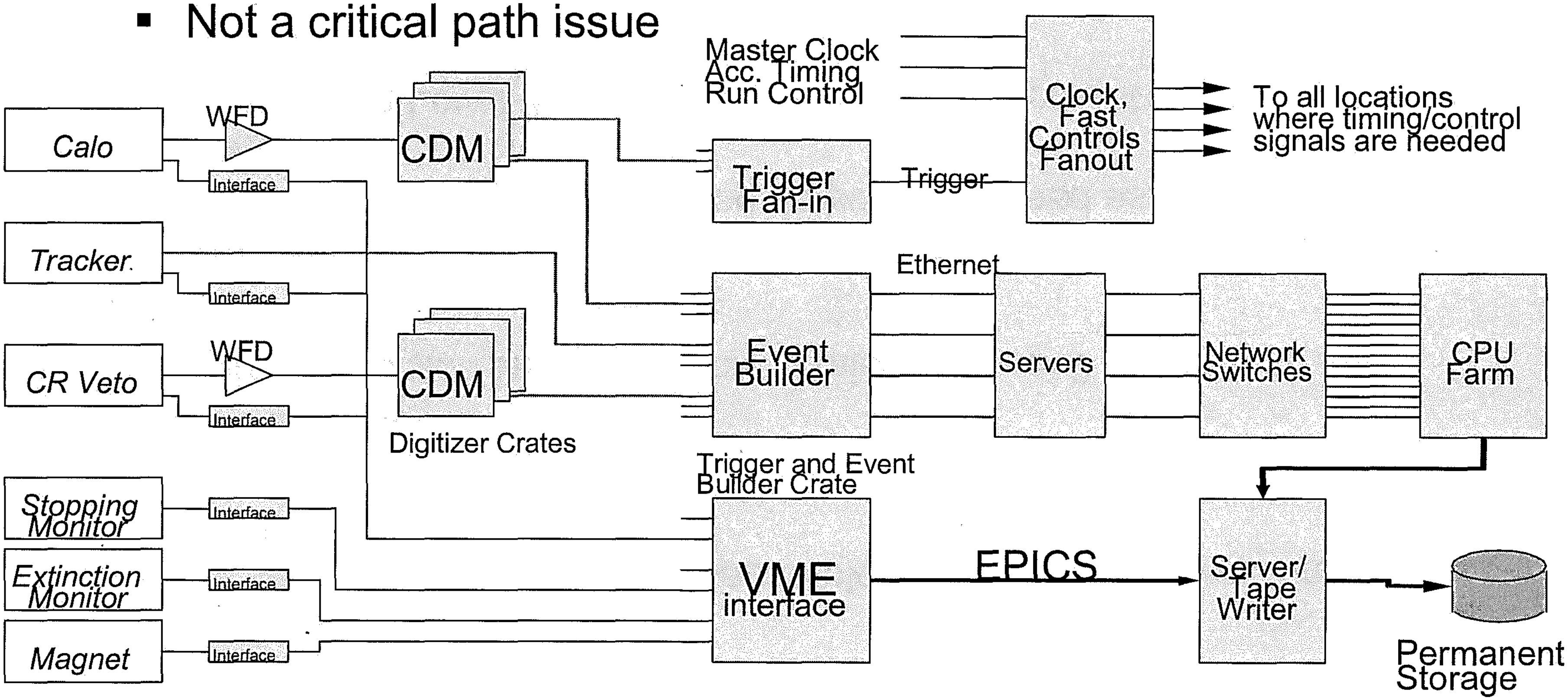
- Is 8 GeV optimum?
  - Antiprotons increase with energy; cross-section not well known, so is it good to lower machine energy?
    - Antiprotons not a significant issue for Mu2e
  - Muon production scales with total beam power, so 25 kW at 5 GeV same as 25 kW at 8 GeV, not much to be gained
- Using Boomerang Scheme:
  - The Recycler is made of permanent magnets, so the energy is fixed.
  - The Booster can extract at pretty much any energy, but the MI-8 line also uses a large number of permanent magnets

Trigger and DAQ

- DAQ scope
  - Digitize hits from various sub-detectors and form pipeline
  - Generate level-1 trigger
  - Build events and load to processor farm
  - Generate level-3 software trigger
  - Define physics data sets and write to permanent storage
  - Separate system for slow control and monitoring
- Level-1 Trigger
  - DIO electrons + pre-scaled calibration triggers
  - 1-10 μs for decision based on trigger sums
  - 1-2 kHz trigger rate: ~ 1 Gbit/s into event builder
- Event Builder
  - Gather digitized data from all subsystems
- Processor Farm
  - Simple algorithms based on tracker information
  - 10 to 100 Hz to storage
  - Event size ~ 50 kbytes: ~ 10 Terabytes a year

Trigger and DAQ

- MECO design from late 1990's/early 2000's
  - Better technology exists
  - Need to re-visit in light of improved technology
  - Not a critical path issue

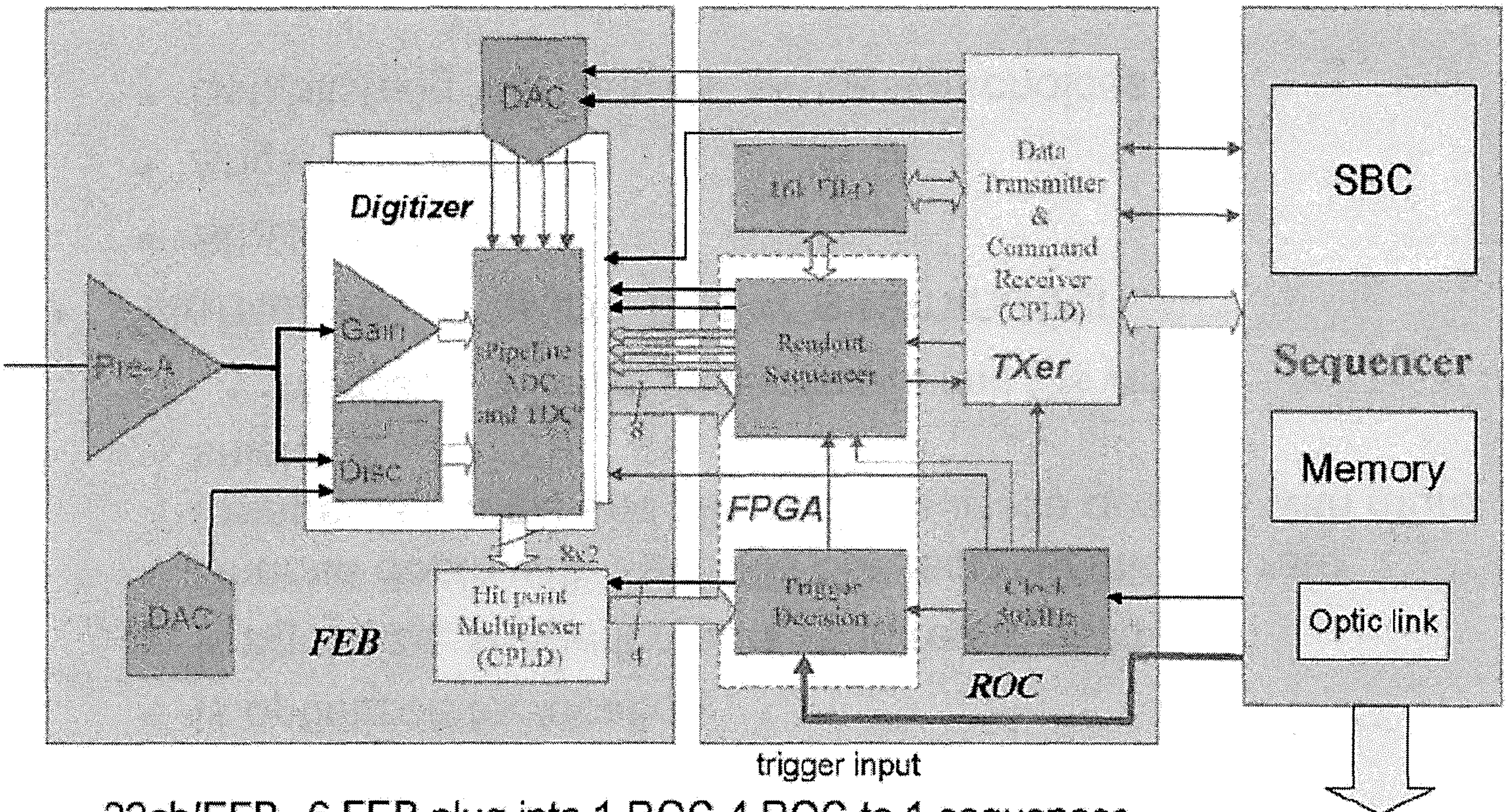


Trigger and DAQ R&D

- Calorimeter APD digitization
  - Inside or outside vacuum?
  - Do we need 500 MSPS (megasamples/sec) speed? Waveform digitization?
- Trigger hardware
  - Trigger decision time: 1 or 5 or 10 microseconds?
- CR Veto PMT digitization
  - Need to mirror calorimeter module but won't need as much precision.
  - Trigger and Level-3 software algorithm development
  - Level-1 trigger algorithms: efficiency vs. noise
  - Level-3 tracking algorithms to reduce background triggers: how robust against hardware failures and tracking systematics?
- Tracker Front End
  - Improvements since 2005 design?

Trigger/DAQ R&D

- Existing FEE: ELEFANT chip, obsolete technology



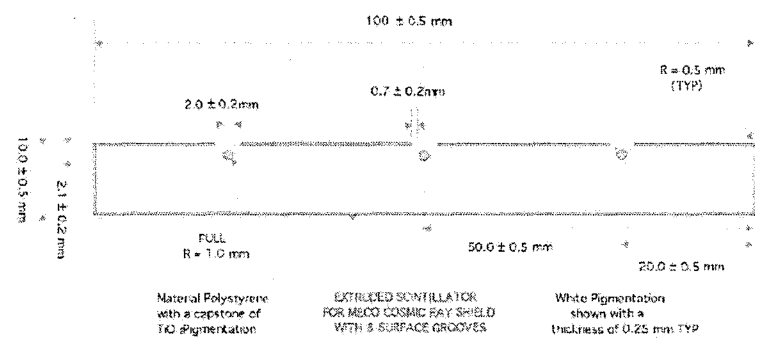
32ch/EFB, 6 FEB plug into 1 ROC,4 ROC to 1 sequencer

Civil Construction

- Ensure design:
  - Is optimized for location
  - Is right size, shape for work required in building
  - Choose depth with tradeoffs between cosmic ray rate (deeper is better) and alternative surface designs with more shielding
    - Interplay with beam design issues and CR veto
- Alternative Location under examination
  - Shallow vs. Deep
  - Angle out of A/D
  - Establishing "derivatives" wrt design choices

CR Veto

- Is scintillator/fiber design optimum?
  - Light levels and efficiency
  - Interplay with depth and accessibility and building design
  - Grooves (MECO) vs holes (Minerva) for fiber
    - Based on Minerva, prefer holes
      - Easier to co-extrude. learned since MINOS
    - Design straightforward



- Physics
  - What level is required?
    - Designed system is 10^{-4}
    - Negligible background
    - What do we really need?
  - Can we save money/cost/complexity?