Intensity Frontier Experiments and Challenges

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Workshop on Detector R&D

Fermilab

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Physics of Interest

- Rare decay/process – searches for physics beyond Standard Model
  - $\mu^+ \rightarrow e^+\gamma$, $\mu^- N \rightarrow e^- N$
    - Search for muon and electron number violation in charged sector
    - Sensitive to many extensions to the Standard Model – supersymmetry, multiple Higgs doublets, ETC, horizontal gauge bosons, lepto-quarks
  - $K_L \rightarrow \pi^0 \nu\bar{\nu}$, $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
    - Also a search for new physics – e.g. SUSY loop contributions to FCNC decay amplitudes

- High precision measurements
  - g-2 of the muon
    - Small corrections to anomalous magnetic moment of muon in diagrams with loops containing new particles
    - Sensitive to similar new physics contributions as CLFV experiments, but without flavor violation, e.g. supersymmetry

- Concentrate on charged lepton flavor violation experiments
  - $\mu^+ \rightarrow e^+\gamma$
    - ongoing experiment [MEG]
    - limited by detector performance
    - examples of detector choices
  - $\mu^- N \rightarrow e^- N$
    - being actively developed at both Fermilab [mu2e] and JPARC [COMET]

Detector Choices Correlated with Beam Properties

- Experiments use very intense beams, often with particular time structure
  - Very low energy muon beams for $\mu^+ \rightarrow e^+\gamma$
    - Uses positive beam, can exploit decays of pions at rest – *surface muon beam* of 29 MeV/c
    - DC beam to reduce instantaneous rates
  - Negative muon beam with very high intensity for muon conversion
    - Large μ/p ratio needed
    - For reasons of background suppression, beam pulsed at ~ 1 MHz

- Beam contamination by electrons and muons is a source of backgrounds with which detectors must deal
  - Primarily detector rate issue for $\mu^+ \rightarrow e^+\gamma$
  - Both physics background and detector rate issue for $\mu^- N \rightarrow e^- N$

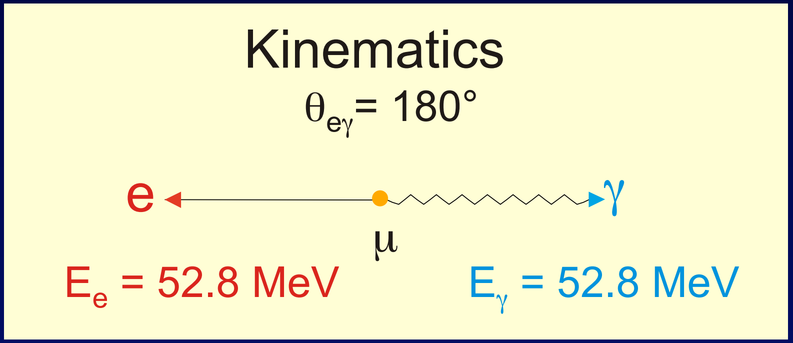
Demands on Detector Systems

- What precision is needed in measured quantities?
  - Low level quantities (time, charge, pulse shape in individual detectors)
  - High level quantities (particle time, momentum, position…)
  - Typically driven by issues of background rejection
  - Often tension between measurement precision and detector material (multiple scattering, energy loss in detectors)

- At what rates must detector elements operate?
  - Driven by acceptances, desired sensitivity, background/signal
  - May be limiting factor in experimental sensitivity
  - Some of highest detector rates in operating experiments have been in intensity frontier experiments (e.g. $K_L \rightarrow \mu e$)

- At what rates must information be digitized, recorded in static memory?
  - Hardware selection: reduce digitization rate, perhaps loss of efficiency
  - Digitize more, higher digital data bandwidth, perhaps increased flexibility
  - Where is data processing and selection done
    - Non-programmable hardware
    - Programmable hardware (FPGA, PLU)
    - Conventional computers

Principal Features of $\mu^+ \rightarrow e^+\gamma$ Experiment

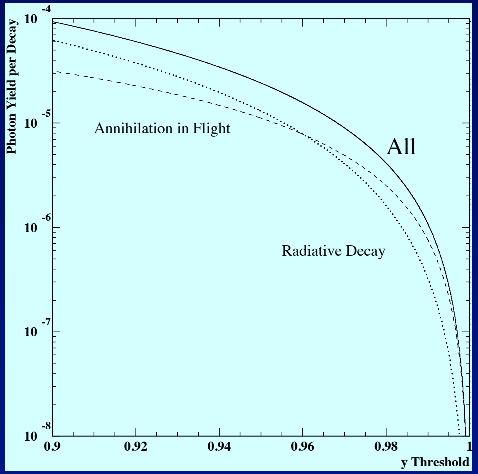


- Stop μ^+ in thin target
  - Measure energies of e^+ (E_e) and γ (E_γ)
  - Measure angle between e^+ and γ ($\Delta\theta$)
  - Measure time between e^+ and γ (Δt)

- Main source of background:
  - Accidental coincidences of
    - e^+ from Michel decay ($\mu^+ \rightarrow e^+ \nu_e \nu_\mu$
    - random γ from rad. decay or annihilation in flight
  - E_γ distribution rises ~linearly from endpoint
  - E_e distribution peaks at ($x = E_e/E_{max} = 1$)

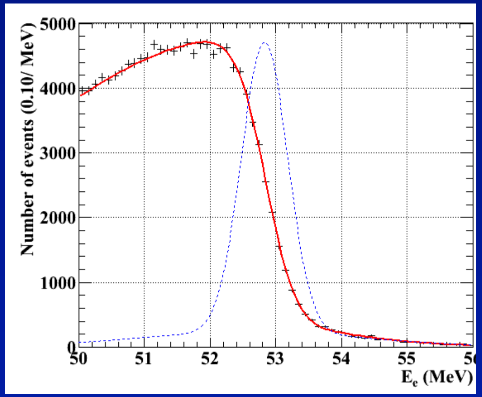
$\Rightarrow$ background/signal $\propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t \times (\Delta\theta)^2 \times$ Rate

signal sensitivity $\propto$ acceptance $\times$ Rate



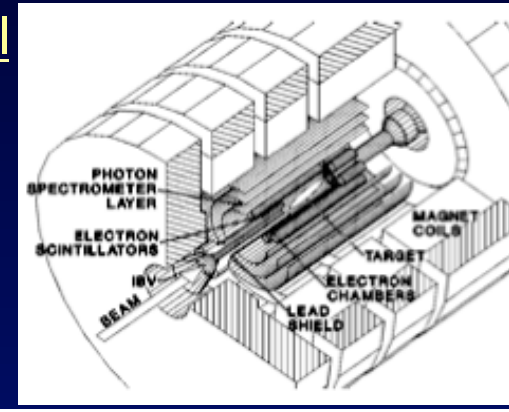
- Must minimize resolution in all measured quantities, maximize acceptance

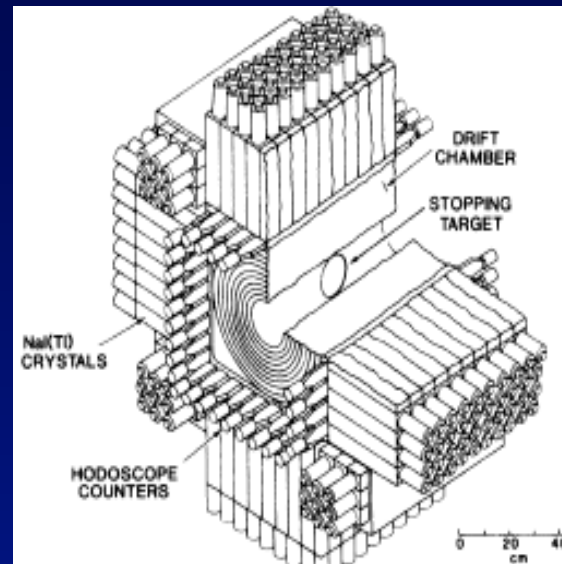
- Tails in angle, time, positron energy resolution primarily represent loss of acceptance, tails in photon energy resolution affects background

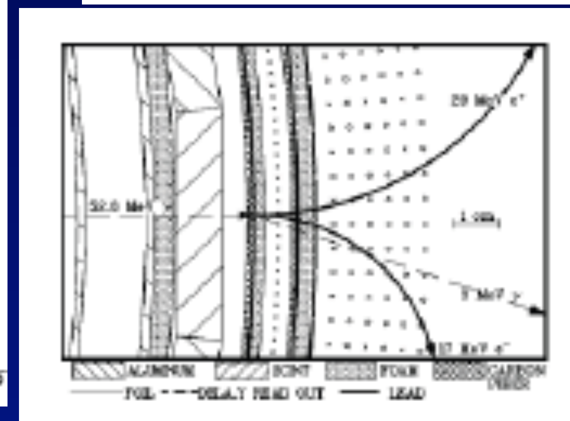


Previous Experience and MEG Goal

- Two primary ways of measuring photon energy:
  - Calorimetric (Crystal Box, MEG)
    - Limited by resolution of calorimeter
    - Large solid angle
    - Possibly poor photon direction measurement
  - Pair produce, measure e^+e^- energy (MEGA)
    - Low acceptance due to thin convertor to reduce energy loss – high rates
    - Very good resolution possible







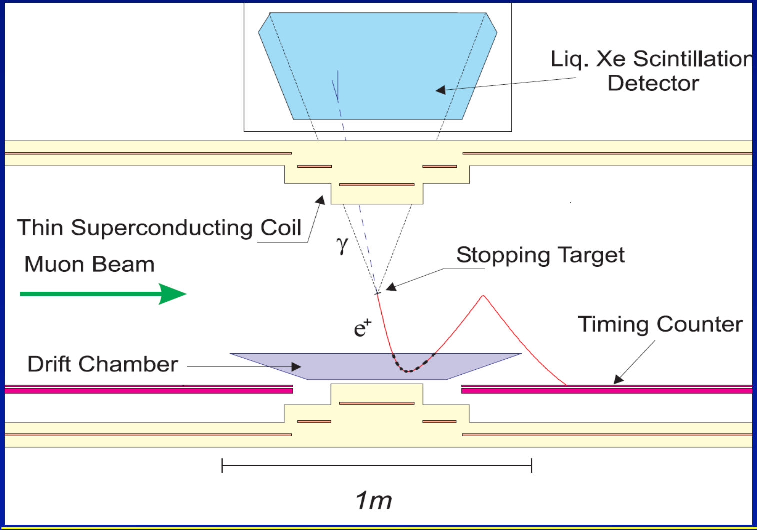
Exp./Lab	Year	σ_{RMS} Resolutions				Stop rate [MHz]	Duty cycle [%]	BR (90% CL)
		E_e [%]	E_γ [%]	Δt_{eg}[ps]	$\Delta\theta_{eg}$[mrad]			
SIN (PSI)	1977	3.7	4.0	590	-	0.5	100	3.6×10^{-9}
TRIUMF	1977	4.3	3.7	2900	-	0.2	100	1×10^{-9}
LANL	1979	3.7	3.4	810	16	0.24	6.4	1.7×10^{-10}
Crystal Box	1986	3.4	3.4	550	37	0.4	(6.9)	4.9×10^{-11}
MEGA	1999	0.51	1.9	610	7	250	(6.7)	1.2×10^{-11}
MEG prop.	2002	0.38	1.7	64	8	30	100	1×10^{-13}

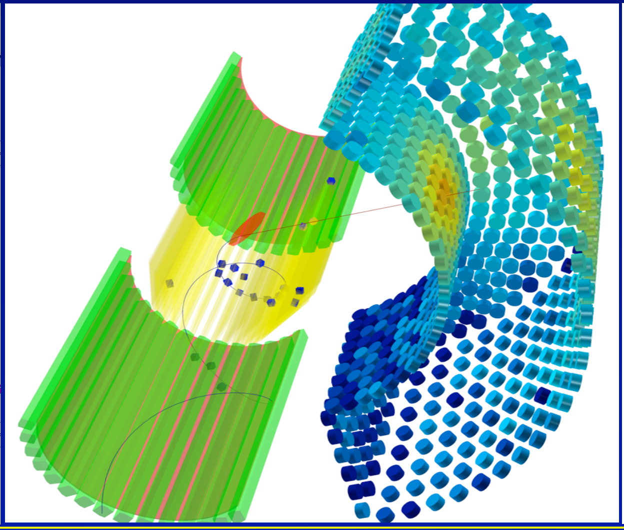
MEG Detection Technique

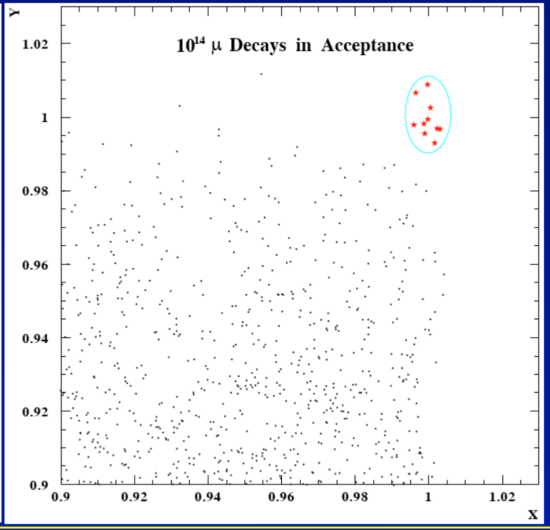
- Original LOI from 1998 (PSI-RR-99-05), proposal in 2002 with goal 10^{-13}
- Muon stop rate of ~3×10^{7} (much lower instantaneous rate than MEGA)

- Detect photon calorimetrically with liquid xenon scintillation calorimeter
  - Energy resolution 1-2%
  - Timing resolution <60 ps
  - Position resolution ~ 5 mm
  - Modest solid angle of ~10% (cost)
- Measure positron momentum with magnetic spectrometer, time with plastic scintillator detector
  - Momentum resolution ~ 0.4%
  - Angle resolution ~ 9 mrad
  - Time resolution ~ 50 ps
  - Acceptance matched to calorimeter

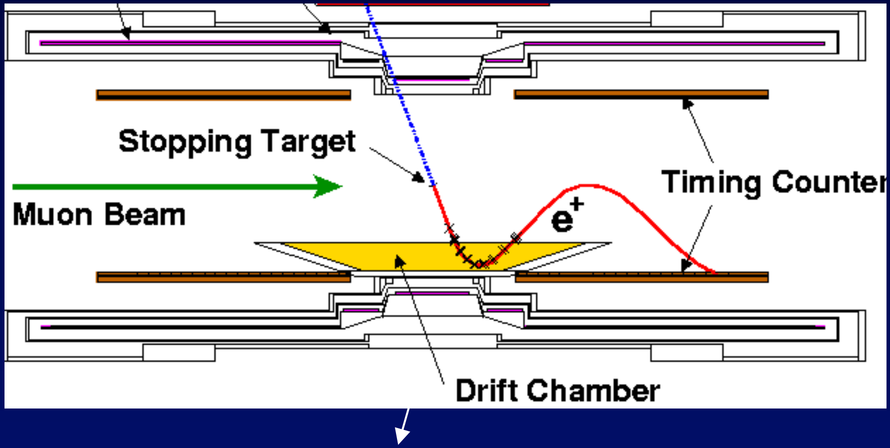
- Significant detector development went into the experiment

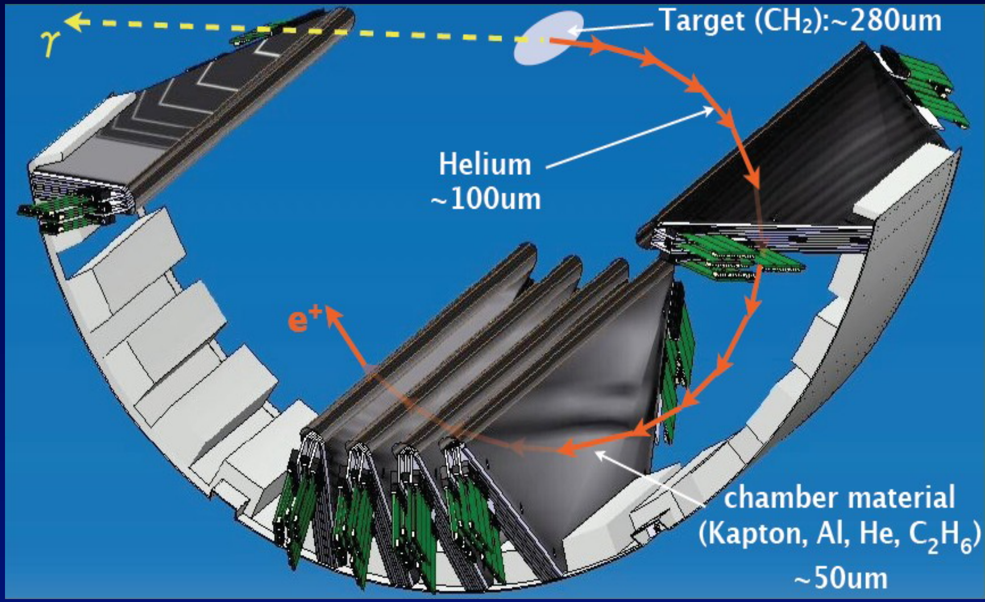




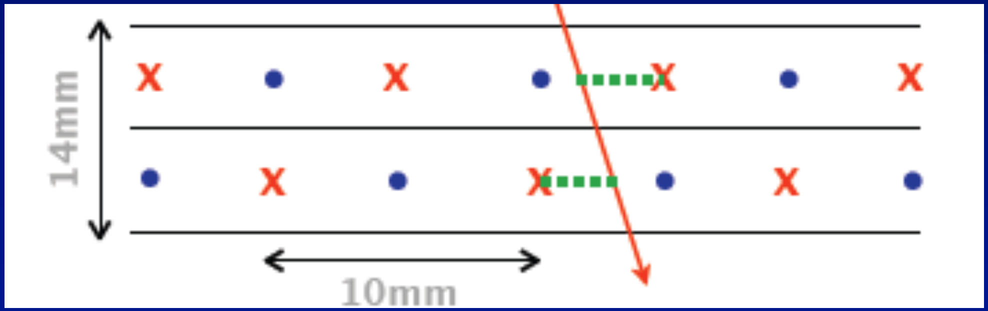


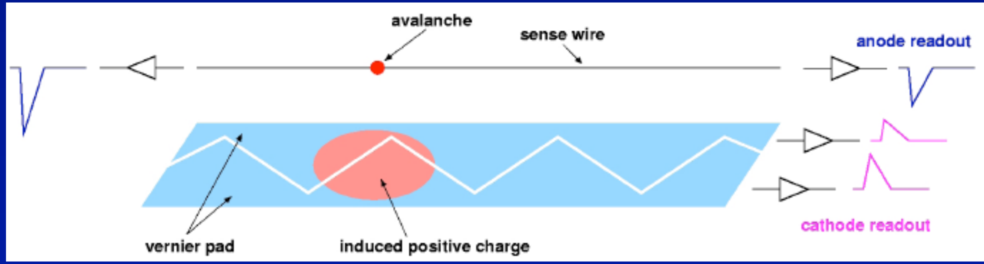
Magnetic Spectrometer Design



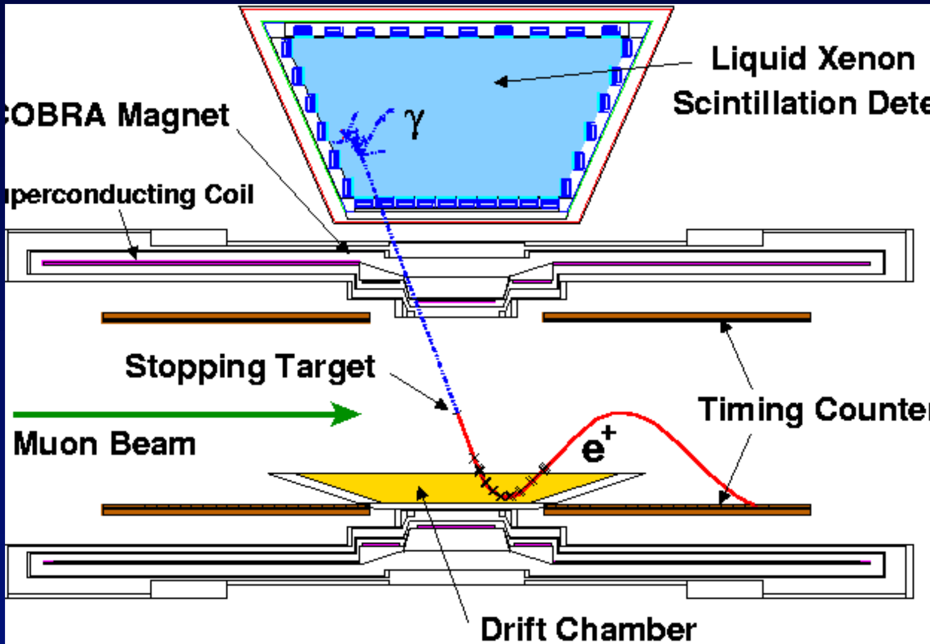


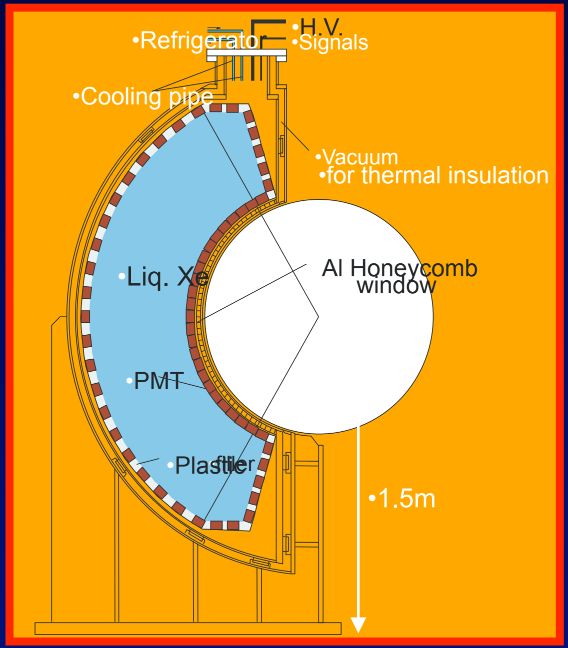
- 16 drift chambers, each 2 layers, 9 cells per layer
- Operated with He-C_2H_6 in He atmosphere to reduce multiple scattering
- Gas containing foils also serve as cathode pads
  - Requires δP across foils to < 0.1Pa
- Radial position from drift time
- Resistive wires for approximate Z by charge division, pattern etched on cathode pads to interpolate Z
- Calculated chamber-to-chamber scattering error equivalent to 300 μm
- Goal: σ_R = 200 μm σ_Z = 300 μm





Liquid Xenon Calorimeter

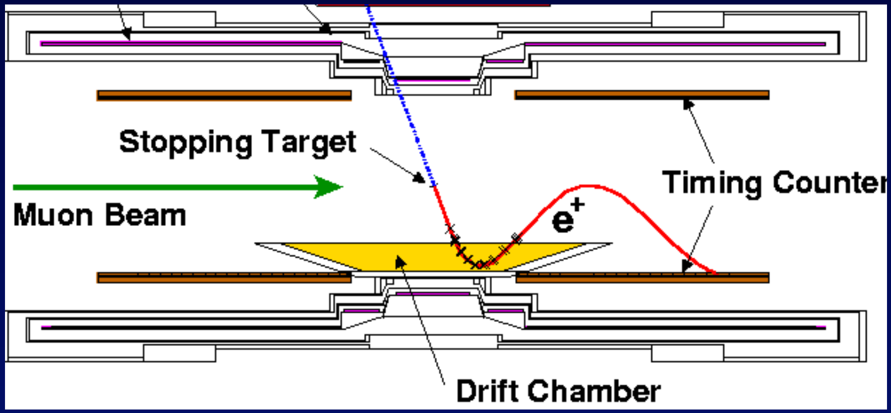


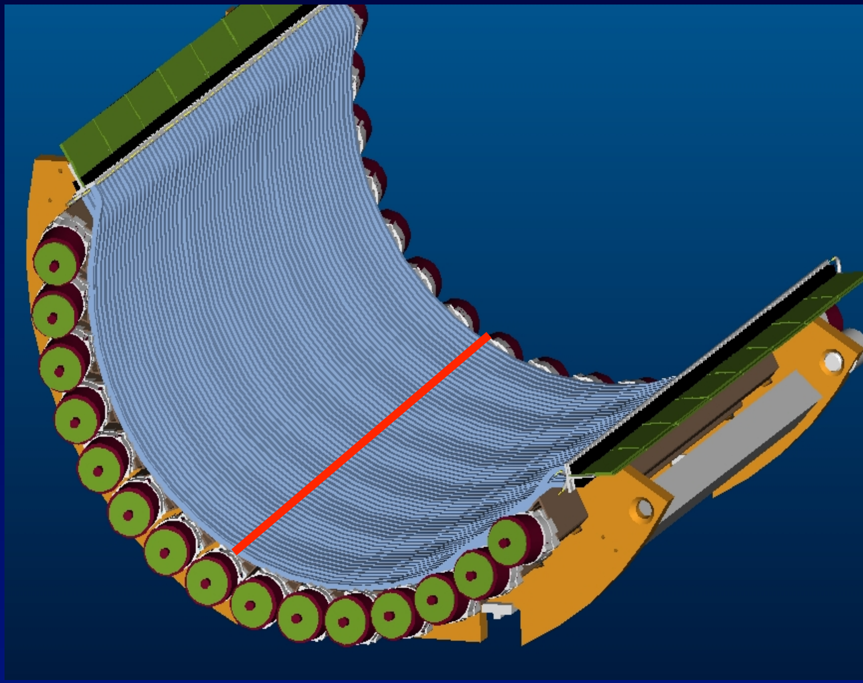


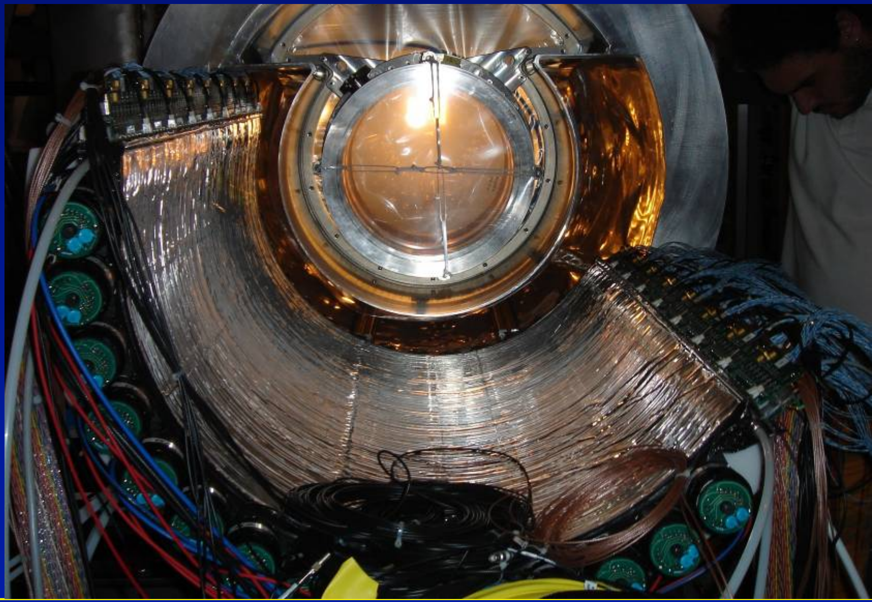
- Relatively high light yield
- No self-absorption of scintillation light: attenuation only from impurities
- ~1000 l liquid xenon (largest LXE volume)
- 860 mesh phototubes on surface, in LXE
- Thin window to reduce photon conversions
- Goal is to measure photon properties:
  - Position: σ_{RMS} = 5 mm
  - Time: σ_{RMS} = 50 ps
  - Energy: σ_{RMS} = 1.2 MeV at 52 MeV

Density	2.95 g/cm^3
Boiling and melting points	165 K, 161 K
Energy per scintillation photon	24 eV
Radiation length	2.77 cm
Decay time	4.2, 22, 45 ns
Scintillation light wave length	175 nm
Scintillation light absorption length	> 100 cm
Attenuation length (Rayleigh scattering)	30 cm
Refractive index	1.74

Timing Counter Design



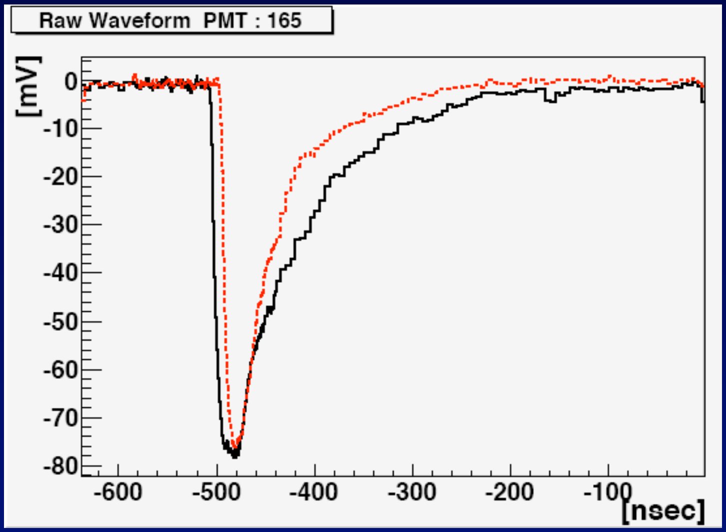


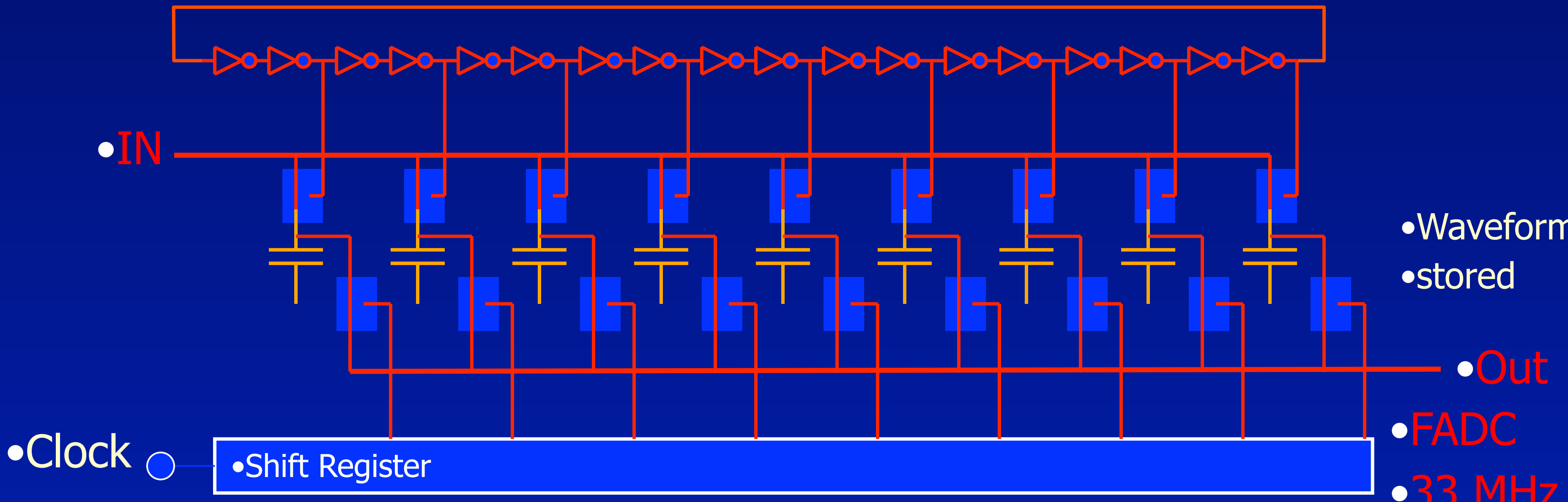


- Primary purpose is trigger and precise measurement of positron time
- 2 layers: 15 constant-ϕ bars, 128 constant-z fibers at each end
- Bars used for timing, R-ϕ position, approximate Z position
  - ~4x4 cm^2, 60 cm long
  - phototube readout with waveform digitizers
- Fibers used for precise z coordinate
  - 5x5 mm^2, cover ~ $\pi/3$ in ϕ,
  - APD readout with waveform digitization
- Goal: $\sigma_t = 40$ ps
- Correct time for track path to < 1 cm

Readout Electronics

- All channels recorded in waveform digitizers (~3500 channels)
- Custom built sampling chip (Domino Ring Sampling)
  - 2.5 GHz sampling rate
    (operated at 500-700 MHz for drift chambers)
  - Sampling depth 1024 bins
  - < 40 ps timing jitter
  - 10 bit FADC (33 MHz, multiplexed 8:1)
  - Onboard calibration
  - Multiple versions, now using DRS4:
    internal time and charge calibration,
    improved temperature performance

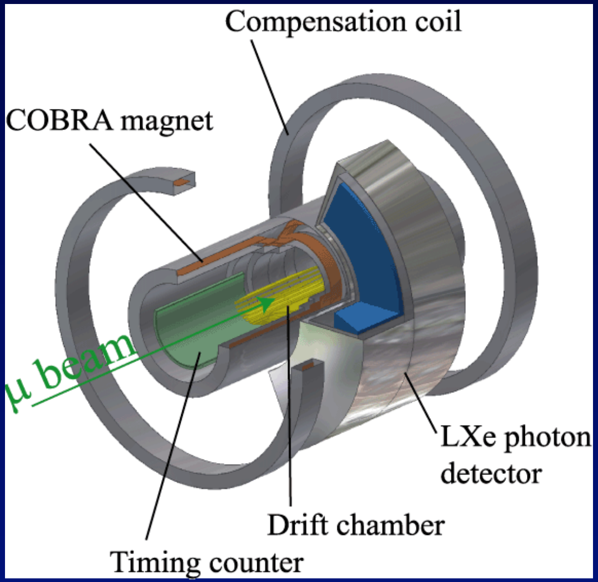




Current MEG Detector Performance

- MEG at PSI is currently collecting and analyzing data
  - MEG resolutions (σ_{RMS})

Quantity	Proposal	Current	
• E_e	0.35	~0.7	%
• E_γ	1.7	~2.8	%
• $\Delta\,\theta_{e\gamma}$	4-5	~12	mrad
• $\Delta t_{e\gamma}$	65	~160	ps



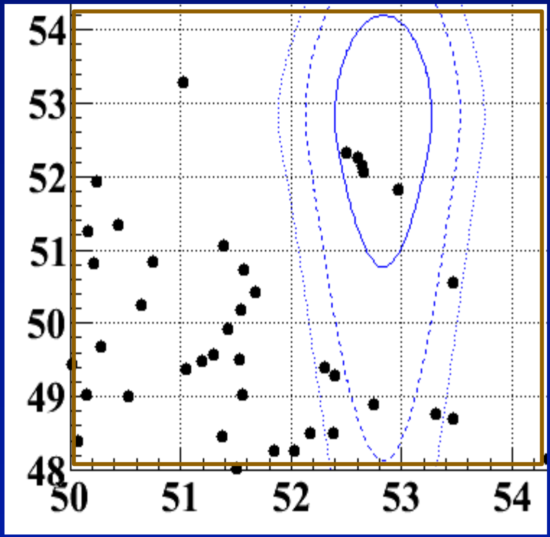
- Expected (proposal) background ~5x10^{-14} at stop rate 3x10^{7}
  Currently worse by factor

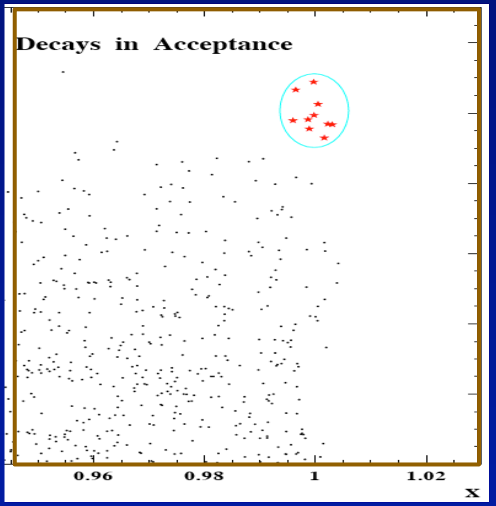
  $(0.7/0.35) \times (2.8/1.7)^2 \times (14/8)^2 \times (160/65) = 100$

- Expected background near 5 x 10^{-12}

- Preliminary results from 2009 data
  $B(\mu^+ \to e^+\gamma) < 1.45 \times 10^{-11}$

- Significant improvements in performance needed to reach goal





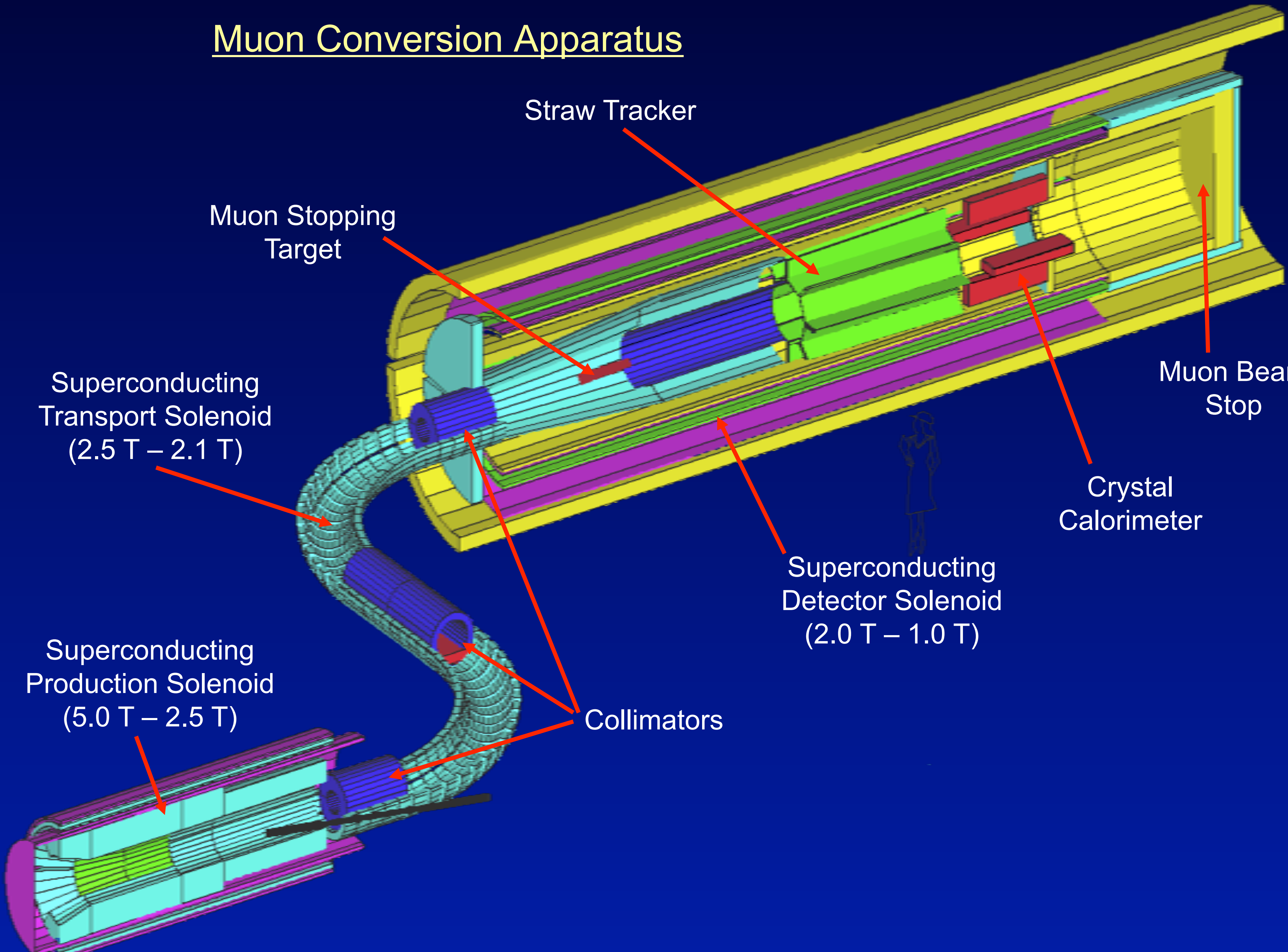
Coherent Conversion of Muon to Electrons ($\mu^- N \rightarrow e^- N$) – mu2e, COMET

- Muons stop in matter and form a muonic atom.
- They cascade down to the 1S state in less than 10^{-16} s.
- They coherently interact with a nucleus (leaving the nucleus in its ground state) and convert to an electron, without emitting neutrinos $\Rightarrow$ $E_e = M_\mu - E_{NR} - E_B$.
- Experimental signature is an electron with E_e=105.1 MeV emerging from stopping target, with no incoming particle near in time.
- More often, they are captured on the nucleus: $\mu^-(N,Z) \rightarrow \nu_\mu(N,Z-1)$
  or decay in the Coulomb bound orbit: $\mu^-(N,Z) \rightarrow \nu_\mu(N,Z)\nu_e$
  (τ_μ = 2.2 μs in vacuum, ~0.9 μs in Al)
- Rate is normalized to the kinematically similar weak capture process:

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N(Z-1))}$$

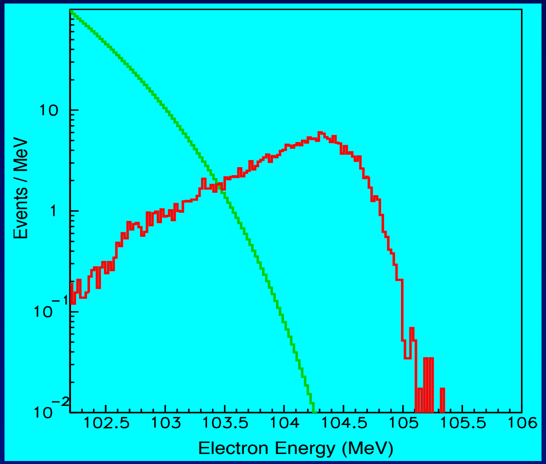
Goal of new experiment is to detect $\mu^- N \rightarrow e^- N$ if $R_{\mu e}$ is at least 2 X 10^{-17} with one event providing compelling evidence of a discovery.

Muon Conversion Apparatus



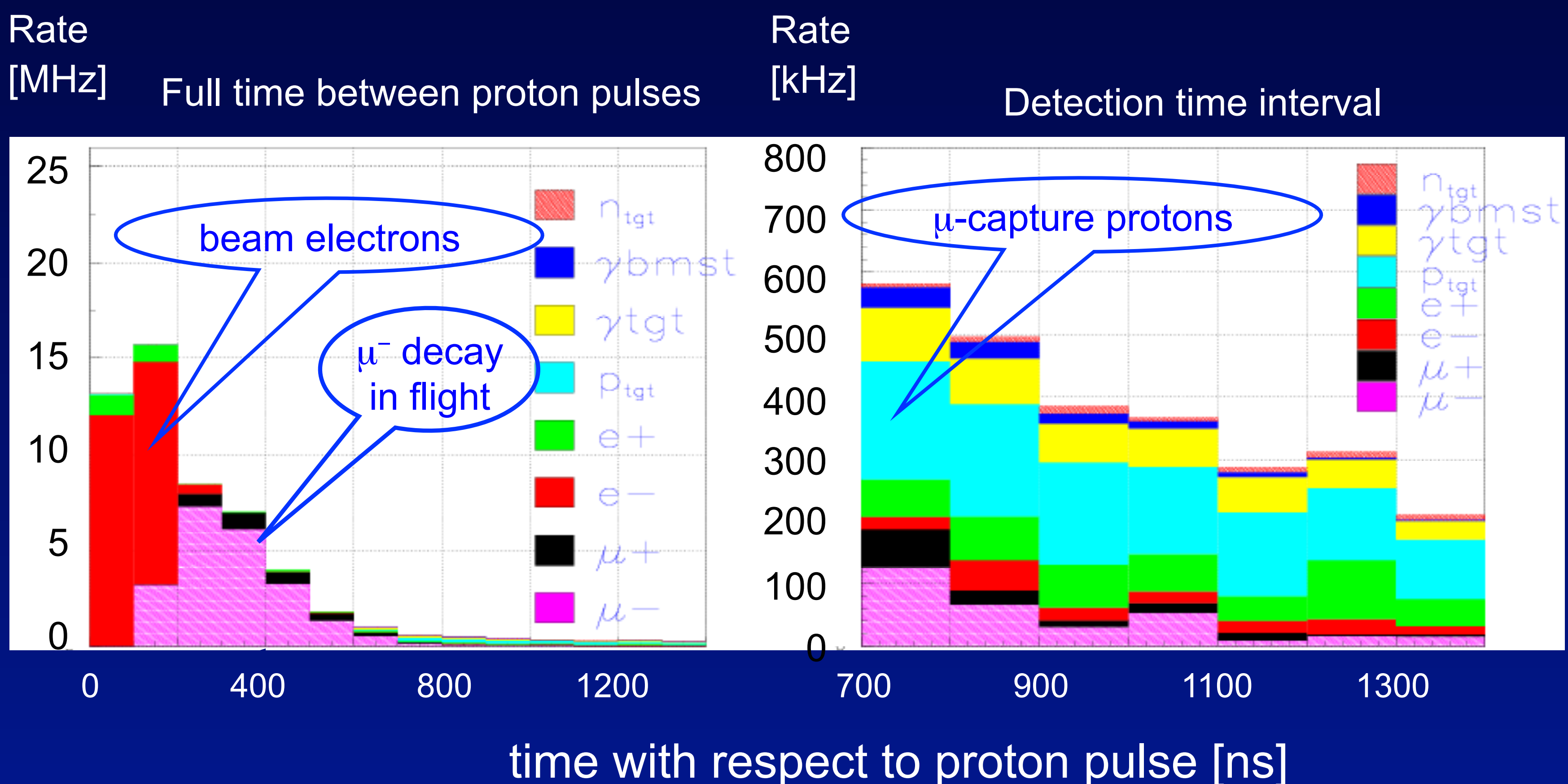
Detector Challenges for Muon Conversion Experiment

- Detector single channel rates and dynamic range – few x 10^5 Hz during signal period
  - *Flash* shortly after pulsed beam strikes production target – electrons
  - Protons (highly ionizing), photons, neutrons from nuclear de-excitation following muon capture
  - Tail of decays of muons in Coulomb bound orbit
  - Use geometry of detectors to mitigate problem



- Physics background rejection
  - Signal is isolated 105 MeV electron consistent with originating in muon stopping target
  - Background from variety of sources
    - High energy tail of muon decay in orbit electron spectrum
    - Electrons from beam sources – muon and pion radiative capture
    - Cosmic ray induced backgrounds
  - Detectors to reduce backgrounds
    - High precision tracking spectrometer – scattering and energy loss straggling limited – 180 keV resolution
    - Sufficient redundancy to reduce high energy tails in momentum resolution to acceptable level
    - Calorimetric detector to provide confirmation of energy, time, position of spectrometer trajectory
- Operating environment
  - Detectors in vacuum – not easily accessible, issues of cooling, breakdown of HV
  - Detectors must operate both in vacuum and at ambient pressure during development
  - Detectors are in high magnetic field, space is expensive
- Data rates
  - Few x 10^4 detector channels operating at few x 10^5 Hz

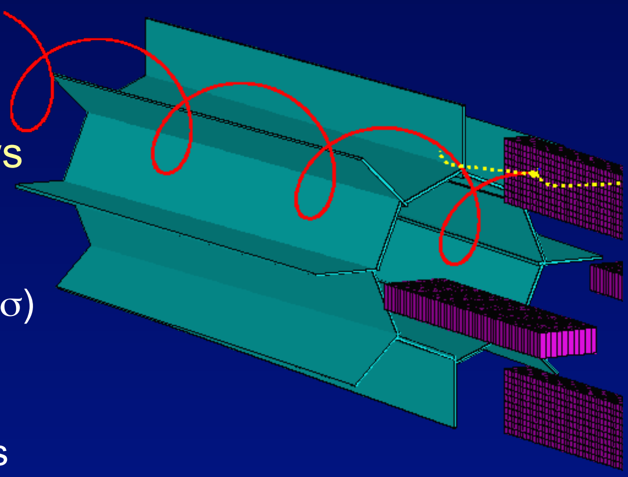
Example of Rate Environment [MECO]

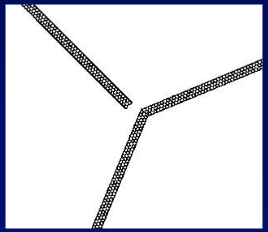


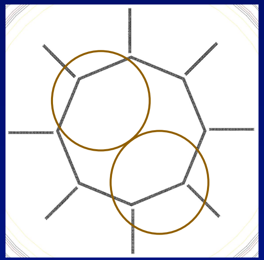
- Very high rate from beam electrons at short times – potential problems with chamber operation
- Protons from μ capture are very heavily ionizing – potential problems with noise, crosstalk

Tracker R&D for $\mu \rightarrow e$ Conversion

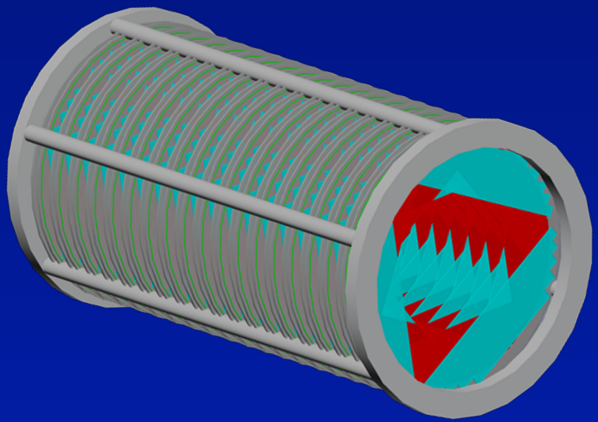
- Tracker requirements from rate, resolution
  - Resolution dominated by energy loss and scattering
  - Rate is dominated by muon capture secondaries and by decay in orbit [DIO]
  - Central resolution function affects dominant background from DIO proportional to σ_E^6
  - Tails in resolution function could result in increased background
- Two rather different geometries possible
  - Axial straw elements – *good* geometry, measurement points concentrated, few straws
    - ~2500 straws – rϕ resolution 200 μm
    - 8 vane and octant modules, 3 layers per module
    - 17000 cathode pads for axial coordinate (1.5 mm σ)
    - Space point by correlating anode and cathode
    - Manifolds, wire support in active area
    - Long straws (~2.6 m) – intermediate wire supports

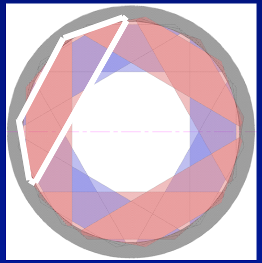


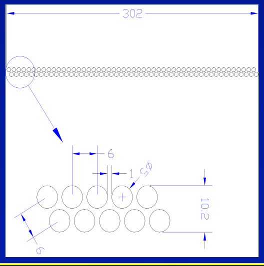




  - Transverse straw elements – no support or readout material in active region, short straws
    - 22000 straws
    - 18 stations x 2 planes x 6 panels with hexagonal geometry
    - Double layer per panel for L/R resolution
    - Space point from stereo reconstruction aided by anode time division for position along wire







Axial Geometry Tracker R&D Challenges

- Mechanical
  - Maintain wire position within straw to ~100 μm
    - 2 intermediate spiral wire supports – reduce mass, volume for acceptance
  - Support structure in space
    - Link modules to maintain geometry
    - Provide axial tension at ends – gas pressure exceeds wire tension when operating
    - Minimize support material – react gravity, axial tension to external frame with carbon fiber in tension
  - Gas tight construction, 6000 m, 4800 connections to manifold with 150 per module end
  - Support of cathode foils
  - Allowing for foil stretching under tension – allow one end to float axially?
- Straw materials
  - Resistive material for outer straw layers
  - Axial voltage drop in straw due to cathode current
- Readout
  - 2400 vacuum electrical feed-throughs, module to solenoid volume
  - Low-mass strip-line cable for anodes and cathodes – in active volume
  - Decouple HV in manifold or at preamp location outside active region?
  - Method to isolate broken wire – fused (ATLAS)
  - Preamp in manifold or outside active region?
  - 19000 vacuum electrical feed-throughs if digitizing outside detector solenoid vacuum
- Analysis
  - Pattern recognition and fitting robust: cathode-anode correlation (charge, time, tracking)

Transverse Geometry Tracker R&D Challenges

- Mechanical
  - Maintain straightness of single, unsupported straw to ~100 μm
  - Allowing for foil stretching under tension
  - Tension straws to allow operation at 0, 10^5 Pa gauge pressure (thin straws)
  - Gas tight construction, 18000 meters, 44000 connections to manifold with 100 per module end
- Straw materials
  - Use of thinner straws desirable – central part of position resolution function limiting with 25 μm straws – recall background proportional to σ_E^6
- Readout
  - 44000 vacuum electrical feed-throughs, module to solenoid volume (or digitize in manifold)
  - Method to decouple broken wire – fused
  - 44000 vacuum electrical feed-throughs if digitizing outside detector solenoid vacuum
  - Time difference on anode wire ends – sub-ns resolution in time difference to be useful
- Analysis
  - Non-local position information (helped by time division)

Straw Material

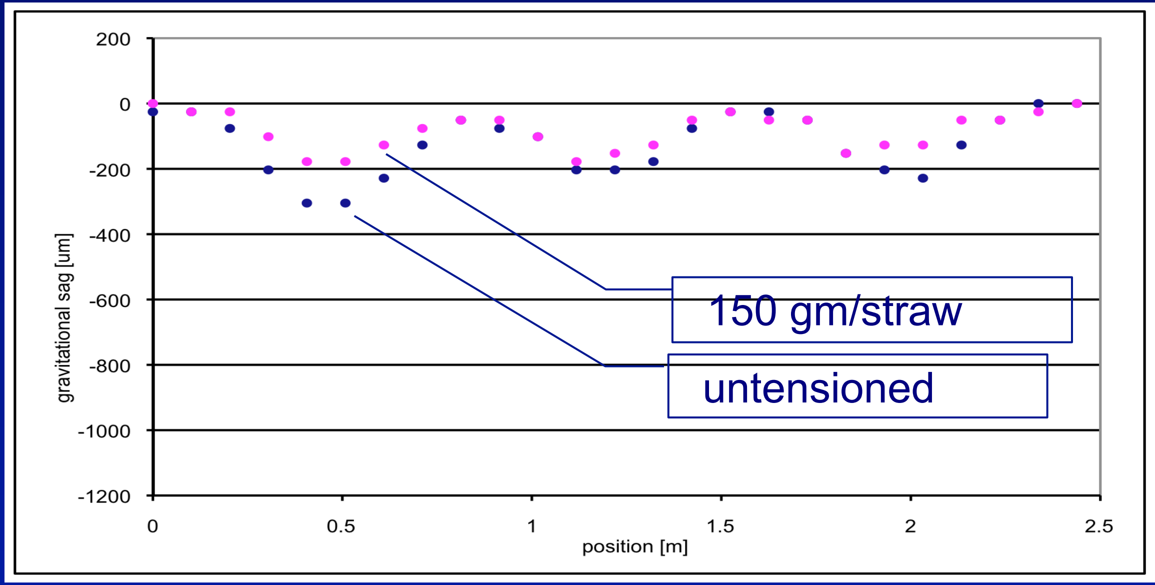
- Conducting with aluminum or copper on substrate
  - Polyester (mylar) non-conducting, spiral wound
  - Polyimide (kapton) non-conducting, spiral wound

- Straw material – resistive
  - Spiral wound carbon loaded polyimide
    - Double wrap with one 25 μm carbon loaded layer, one thinner layer without carbon
    - Possibility of thinner carbon loaded material
    - Problems with variations in resistivity batch to batch
  - PEEK(PolyEther-Ether-Ketone) (30 μm)
    - Good mechanical strength and radiation tolerance
    - Thermoplastic extrusion -> potential to make long tube
    - Proprietary process of forming seamless tubes on a mandrel

- Maintaining straightness
  - Axial tension
  - Support with close-packed arrays
- Expansion under gas pressure (10^5 Pa)
  - Can linear or 2 dimensional arrays be close packed and glued or is space needed for expansion under gas pressure?
- Creep under long-term tension

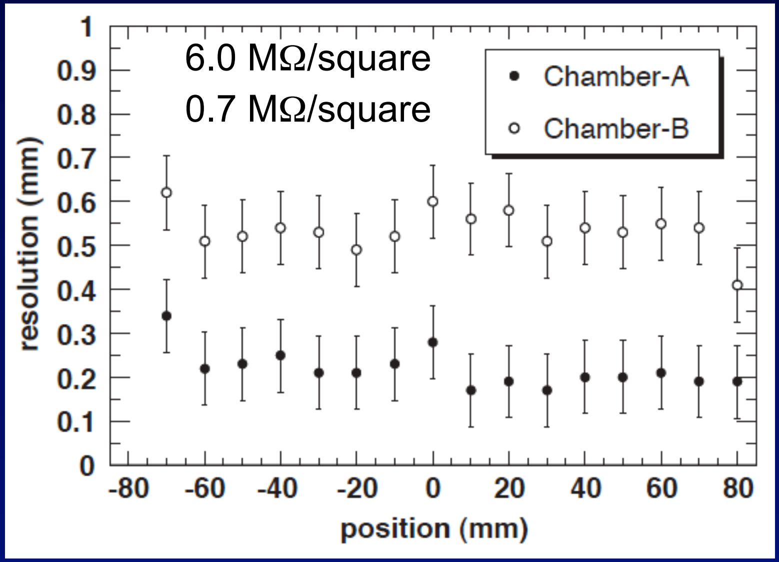
Recent Tests of Close-Packed Array Mechanical Properties

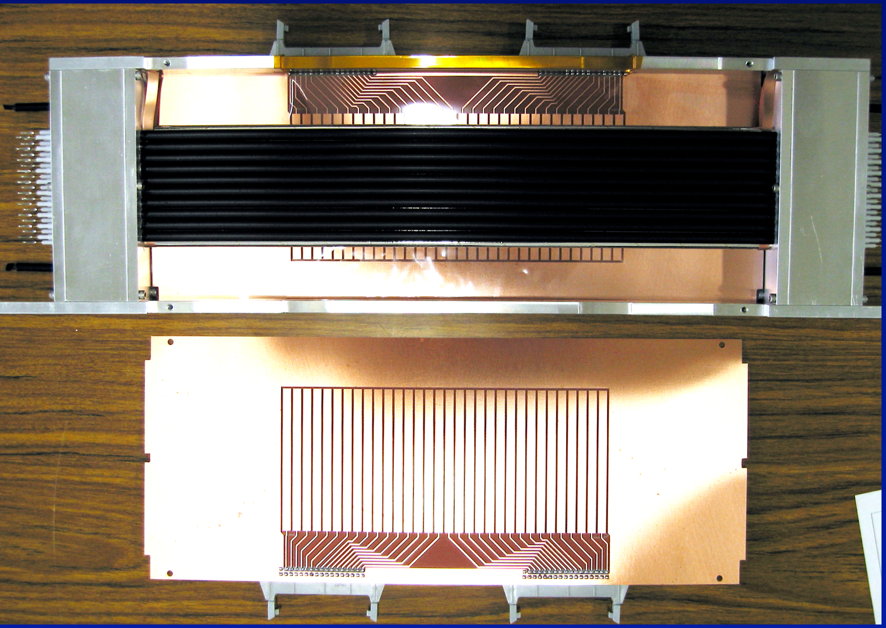
- Early work on long straws [MECO, Houston]
- Recent measurements done at Fermilab [Krider et al.]
- Gluing straws in close packed array significantly reduces deflection under gravity
- Tests done without gas pressure, with three layer, close-packed and glued array
- Axial tension further reduces deflection – comparable to tension from gas pressure

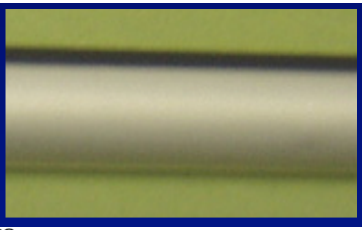


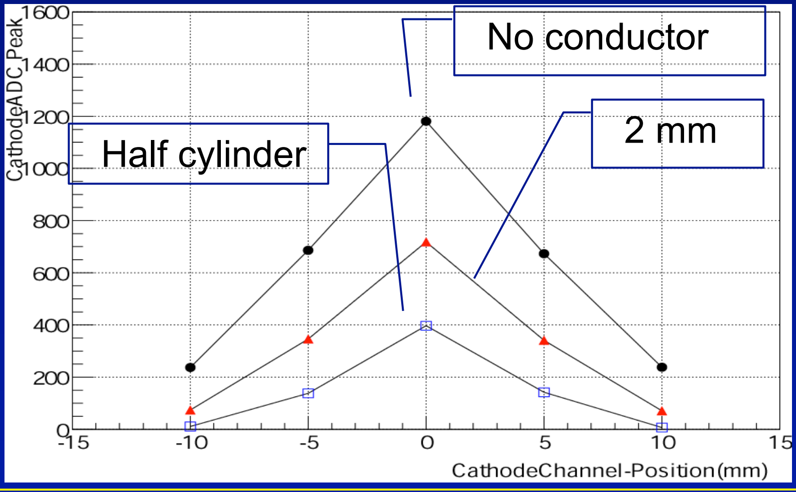
Cathode Pad Resolution with Resistive Straws (Osaka University)

- Required resolution in Z ~1500 μm
- PEEK seamless and carbon loaded kapton spiral wound straws tested
- Measured resolution exceed requirements – 300 to 600 μm depending on resistivity
- Tests also done with aluminum conducting trace for cathode current
    - Conducting strip reduces induced charge, sharpens distribution across pads







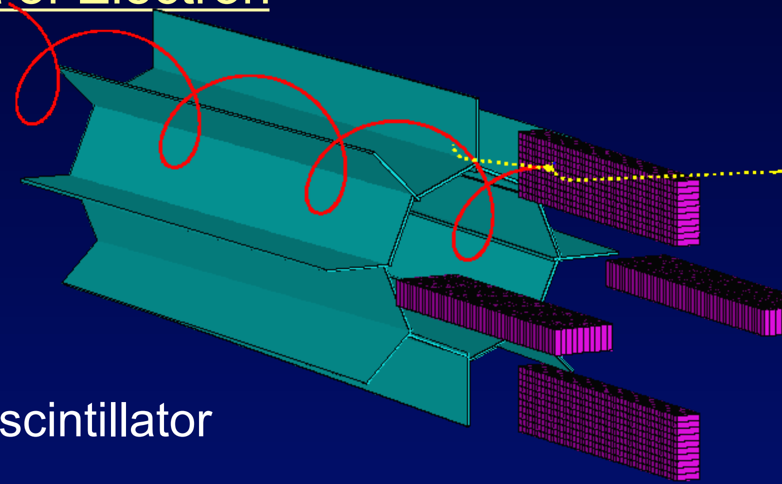


Reducing Straw Mass

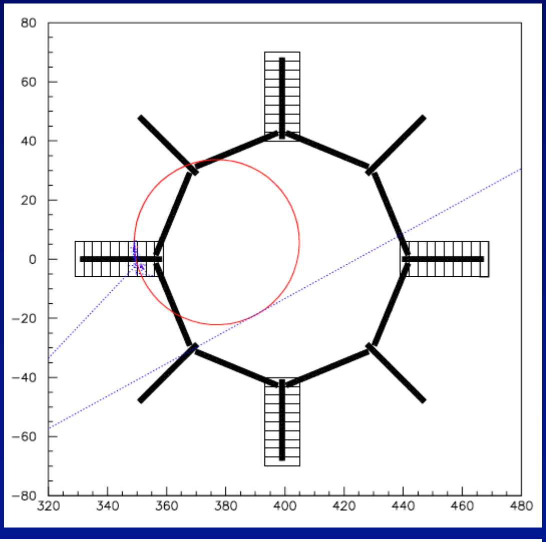
- Yield strength of kapton(mylar) limited by hoop force and 10^5 Pa to ~15(6) μm
- Metalization: copper inside (cathode), aluminum outside (diffusion) to reduce mass
- Reduces radiation lengths a factor of 3 with respect to 25 μm
- Issues with metalization of very thin material
- Probably want to operate with zero overpressure for tests – straws must not collapse under gravity
- Not yet demonstrated that very thin material can be wound into straws

Component	Key Dimension		Density (g/cm^3)	Area (cm^2)	Mass (g/cm)	X_0 (g/cm^2)	$M/X_0/V_{tot}$ (cm^{-1})	
Kapton/Mylar	**6.25**	μm	1.4	9.82E-04	1.37E-03	40.00	1.75E-04	53.6%
Copper	**300**	Å	9	4.71E-06	4.24E-05	12.90	1.67E-05	5.1%
Aluminum	**1200**	μm	2.699	1.88E-05	5.09E-05	24.01	1.08E-05	3.3%
W (20μm)	**25**	μm	19.3	4.91E-06	9.47E-05	6.76	7.14E-05	21.9%
Argon	**50**	%	0.0007595	1.96E-01	1.49E-04	19.55	3.88E-05	11.9%
Ethane	**50**	%	0.00063	1.96E-01	1.24E-04	45.66	1.38E-05	4.2%
Total (one straw)				1.96E-01			3.27E-04	

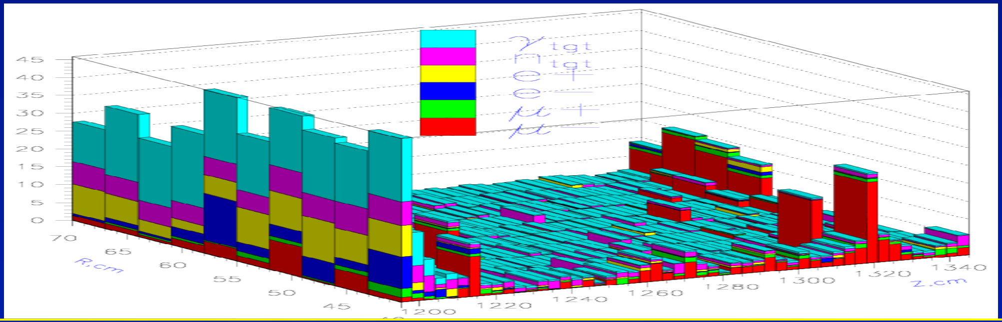
Calorimetric Measurement of Electron



- Confirmation that electron trajectory has associated energy deposition in time and in spatial coincidence
- Used as an event selection tool before events recorded to non-volatile memory
- Significant ambient background – premium on fast scintillator
- Geometry peculiar to experiment – electrons in helical trajectory with pitch angle of 55°
  - Good position and energy resolution when electrons incident on face opposite photo-detectors
  - Premium on high density – minimize areas of front and inner face
- Material choices
  - $PbW0_4$ – fast, shortest radiation length, relatively low light yield
  - BGO – high light yield, slow, relatively high density
  - LSO, LYSO – high light yield, relatively fast, expensive

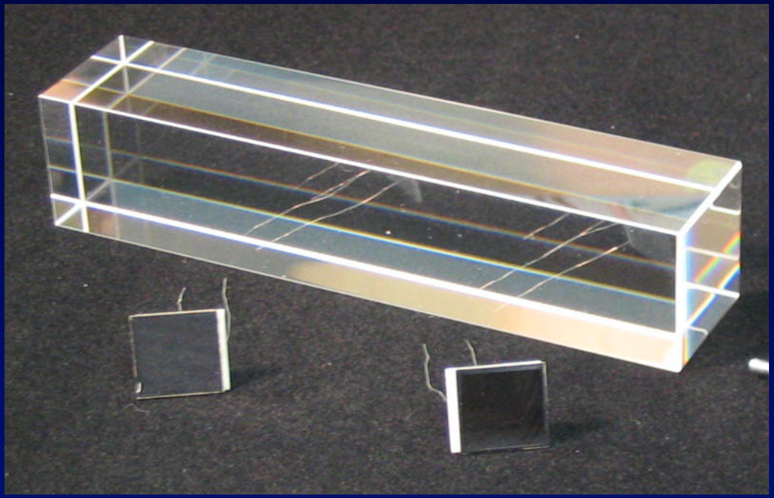


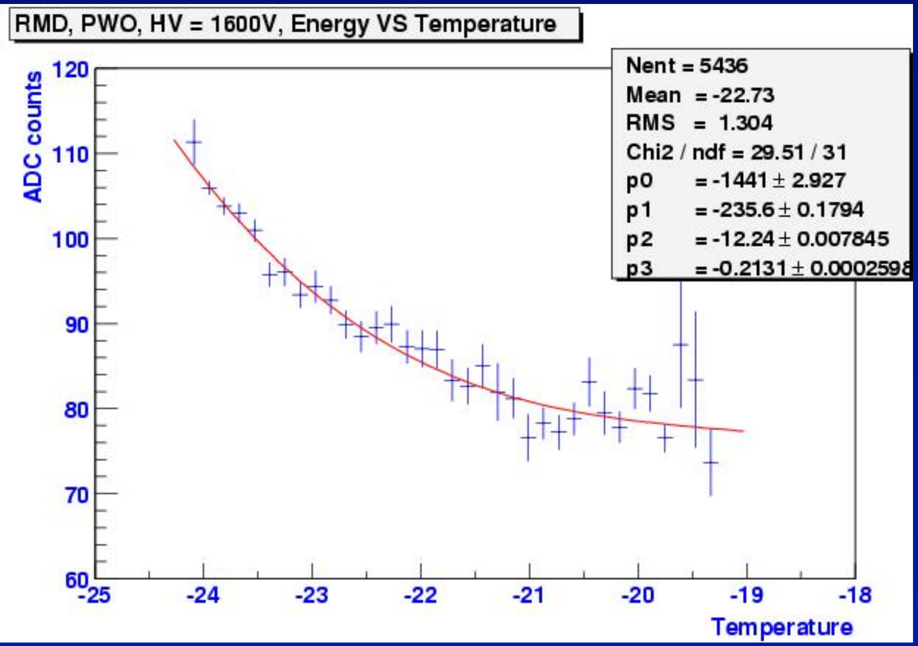
- Detector rates from target and muon beam dump



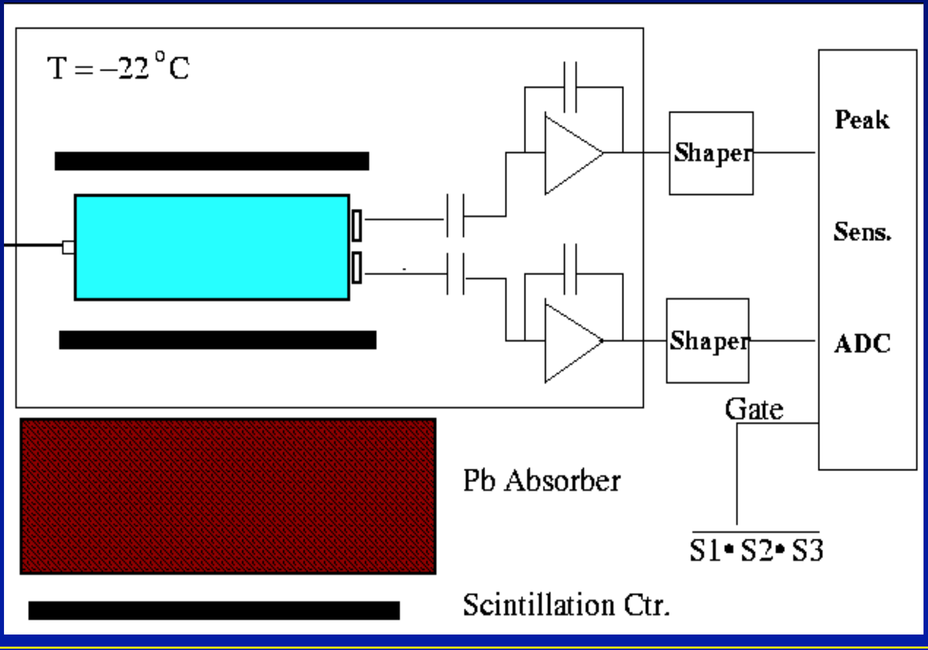
Light Yield for $PbWO_4$ [MECO]

- $3 \times 3 \times 14\ cm^3$ $PbWO_4$ crystals
- Large area (13mm x 13mm) APD from RMD Inc.
- Hamamatsu (5mm x 5mm) APD used by CMS
- Crystal / APD combinations were tested using cosmic rays. The crystals and APDs are cooled.
- Photo-electron yield estimated at 27 pe/MeV per APD when cooled to -24 C
- Newer $PbWO_4$ with larger light yield



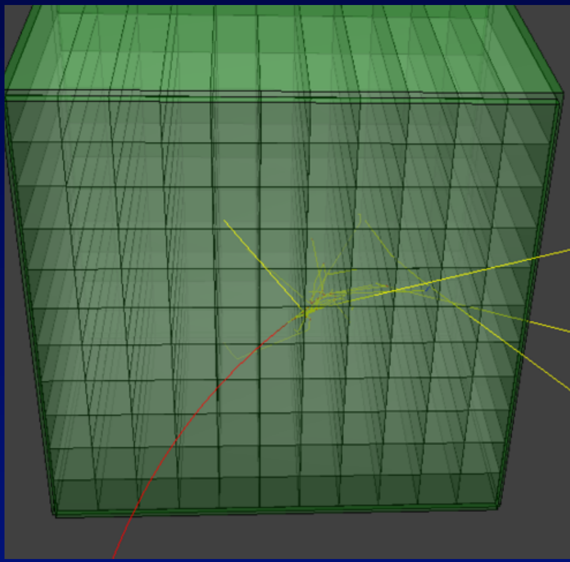


Crystal / APD Test Arrangement

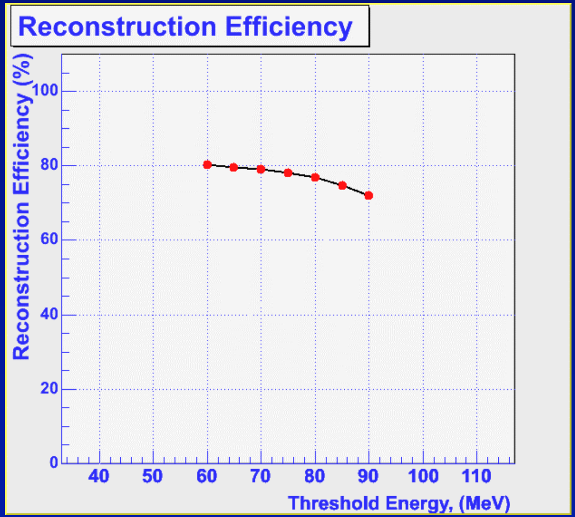


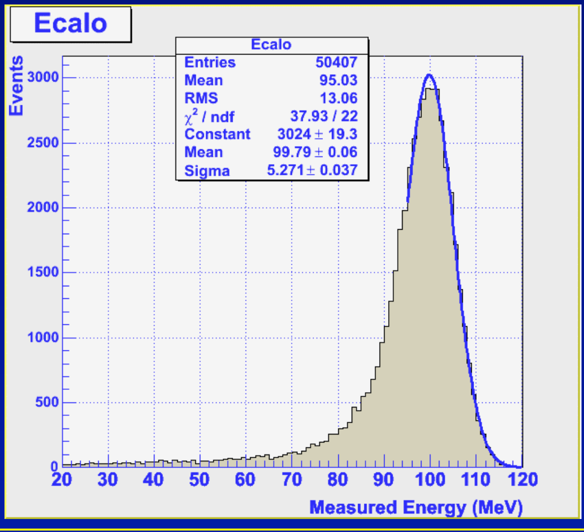
Studies of $PBWO_4$ Performance from Prototype and Simulation

- Signal is 105 MeV electron
  - Range from dE/dx is few cm in dense crystals
  - Can get significant energy loss from albedo and leakage for electrons near edge of calorimeter – low energy tails – GEANT4 studies of LSO crystals [mu2e INFN Frascati]



- Significant R&D done on contributions to energy resolution from all sources [MECO NYU]
  - Photo-statistics using cosmic ray tests
  - Electronics noise using prototype preamps and shapers
  - Pileup from simulation
  - Energy deposition from GEANT – leakage, albedo
  - Total resolution with 2 large area APDS ~5%
  - Acceptance losses for detected energy >80 MeV dominated by electrons striking upstream and inner faces
  - Trigger rates rather low (<1 kHz) for thresholds near 75 MeV
- Might benefit from improved photo-statistics, no cooling if if LYSO could be used, but tradeoffs in cost, density





Data Requirements

- Want time and at least some charge information on all channels
  - Time resolution to ~ 1-2 ns in tracking chamber for position resolution
    - Somewhat better time resolution (few 100 psec) for time division in transverse geometry
  - Similar resolution in calorimeter:
    - Correlate track in spectrometer and signal in calorimeter
    - Distinguish forward and backward going tracks
  - Charge information in tracker: modest resolution needed
    - Correlate cathode and anode signals, interpolate Z coordinate from pad charges in axial tracker
    - Distinguish between signals from electrons and heavily ionizing protons or spiraling photon conversions
  - Charge information in calorimeter
    - Resolution down to few percent

- Channel count dominated by tracker
  - Axial geometry ~2400 anodes, 17000 cathodes
  - Transverse geometry ~ 22000 wires, double ended readout
  - Additional few thousand channels from calorimeter and cosmic ray veto system

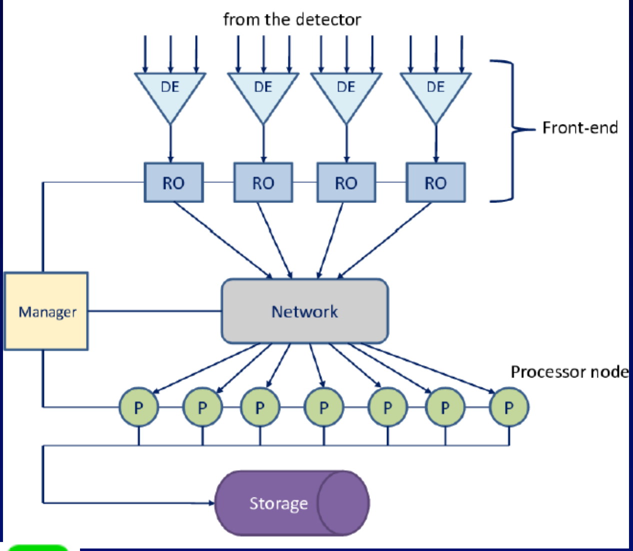
- Typical rates ~300 kHz per channel

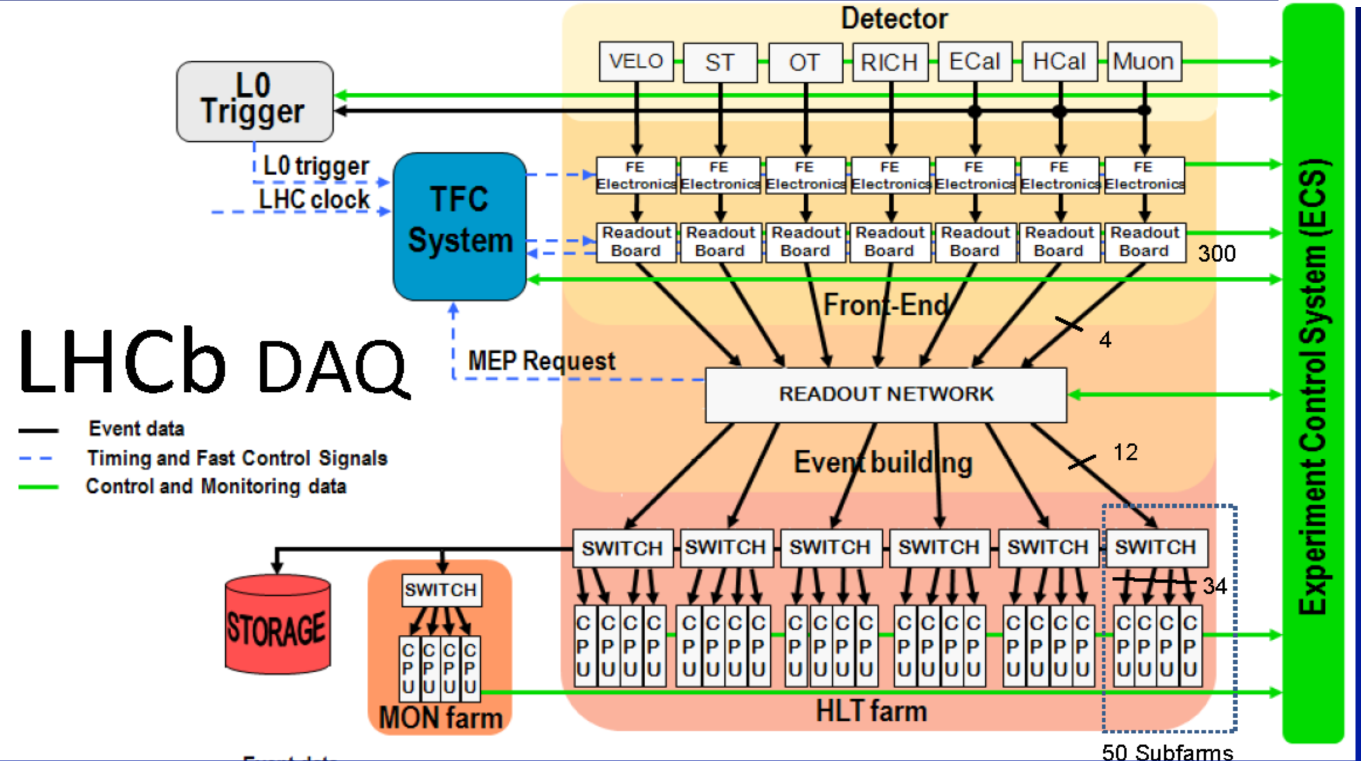
Trigger and DAQ

- What information to store for a hit?
  - Time and limited charge information for all hits
    - Reduces bytes of information per hit, continuous digitization and storage of all hits possible
    - Limits flexibility in signal processing, e.g. technique for hit time determination, integration times for charge
    - Provides increased flexibility in event selection, allows use of high level processors
  - Voltage waveform around the region of interest for selected events
    - Provides for flexible signal processing, can optimize sampling rate for each detector (very useful in MEG)
    - Provides most possible information about hits (e.g. pileup at high rates)
    - Probably cannot continuously sample all waveforms – event selection prior to digitization required
- How to select events?
  - Digitize all information – select events after loading into massively parallel computing farm
    - 120 Gbytes/sec to processor farm – possible with fiber transmission
  - Store information in analog form long enough to select events, then digitize waveform
    - Select events using pipelined signals from fast waveform digitizers (e.g. on calorimeter signals)
    - Minimal deadtime if trigger and readout latency is of order 1 μsec
- Where to digitize: inside or outside vacuum?
  - Outside
    - Analog signals accessible, minimize space and power constraints on digitizers
    - Large number of (20-50k) analog signal cables through vacuum wall
    - Concern about crosstalk, noise on analog cables
  - Inside
    - Increased amount and complexity of electronics not easily accessible – more concern about failure rate
    - Much reduced vacuum signal penetrations through vacuum wall
    - Concern about inducing noise on detectors (e.g. straws) from very high frequency digital signals

Trigger/DAQ with Full Digitized Data Buffer (Streaming Architecture)

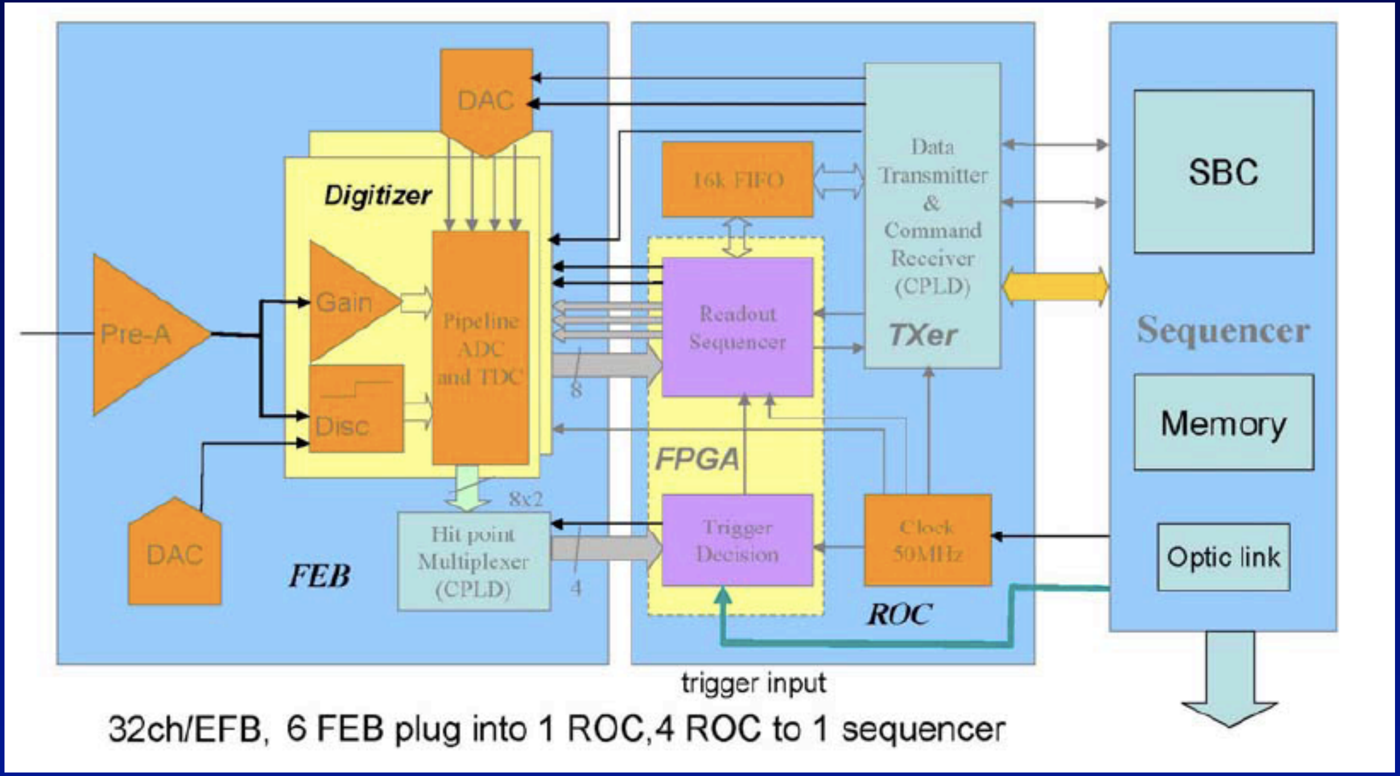
- LHCb is close to fully streaming
  - Some L0 trigger
- Study of fully streaming architecture [mu2e Fermilab, Berkeley]
- Expect improvements in switches, processing power





Digitization for Fully Streaming DAQ

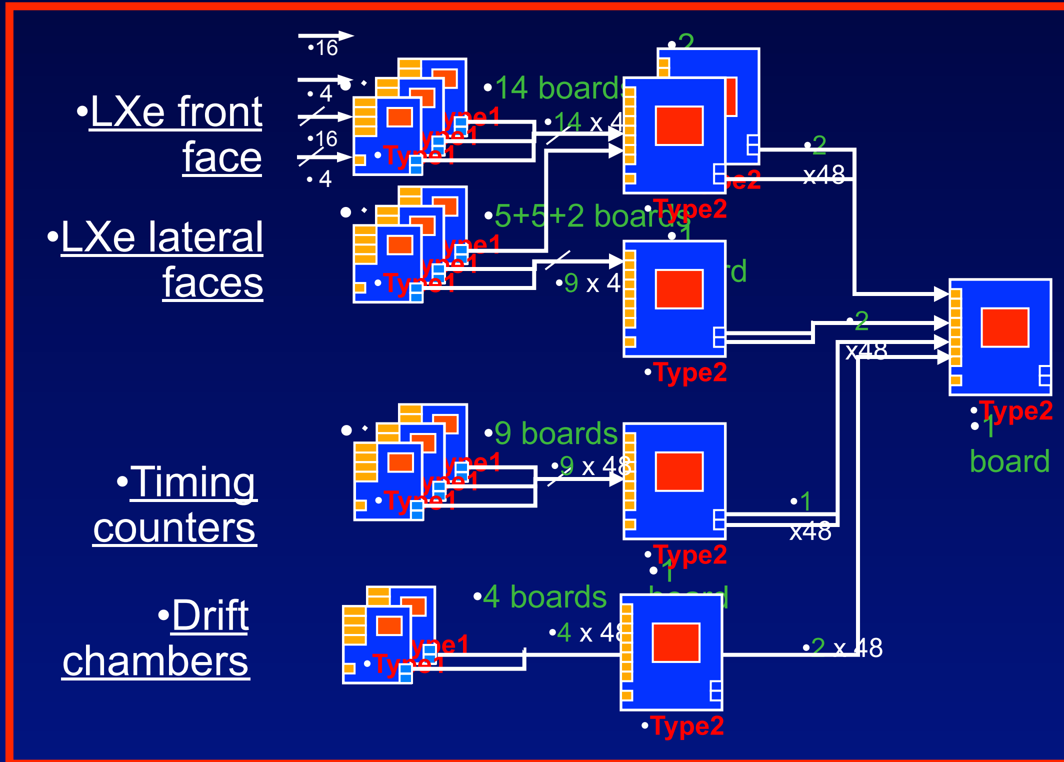
- Data rates for continuous waveform digitazation at required frequency prohibitive
- Digitizers similar to BaBar ELEFANT and JDEM design being studied [MECO Houston, LBNL; mu2e Berkeley, LBNL]

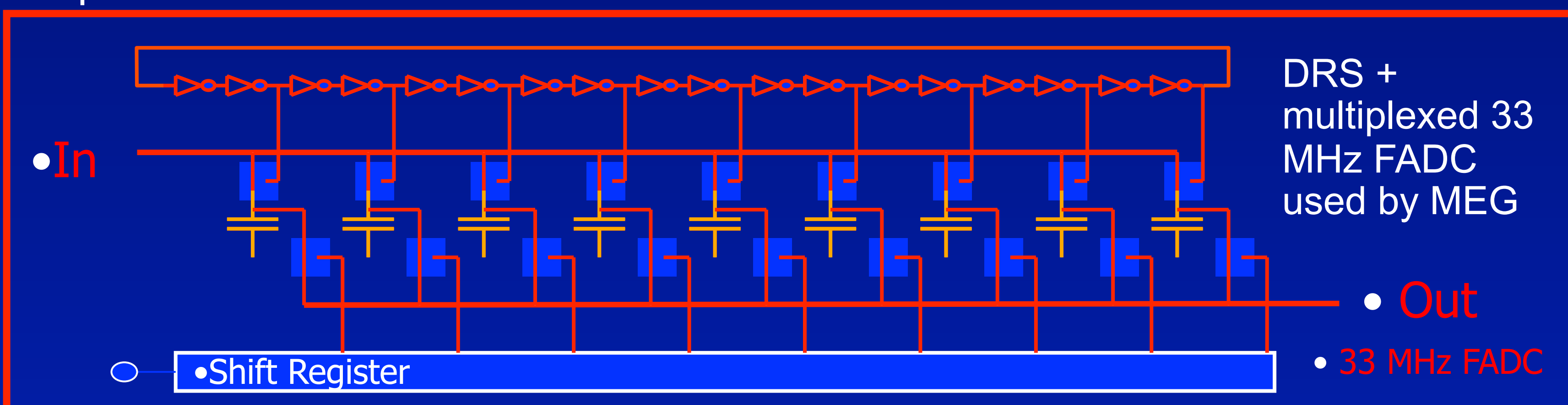


- Additional work on possibility of implementing TDC in FPGAs [mu2e, Fermilab]

Example Trigger/DAQ with Analog Signal Buffer [MEG]

- Trigger in cascaded FPGAs using waveforms digitized in FADCs; latency < 1 μsec
- Analog signals held in ring buffer of capacitors sampling at 0.5-2.5 GHz – fully covers requirement for mu2e
- Data digitization at 33 MHZ by sequentially shifting analog signals to digitizer, multiplexed 8:1– too slow for mu2e
- Modification for higher speed ADCs (100 MHz), not multiplexed





Summary

- Experiments will benefit enormously from increased intensities
- Detector advances critical to realize these improvements
  - Ability to use the increased intensity
  - Improved performance necessary to reduce backgrounds commensurate with improved sensitivity that can be achieved
- The job isn't over when the detector development is done
  - Implementation is likely to be difficult
  - Reality strikes when data is being recorded and analyzed
- In the case at hand, options exist for critical detector components
  - Tracker has multiple geometries in straw chamber implementations
    - Difficult problems in each case
    - Some difficulties can be confronted early, some may be confronted only during commissioning and use
    - Even considerations of a conventional drift chamber [mu2e INFN Lecce] that I did not describe
  - Calorimeter is probably easier in some sense
    - Tradeoffs among different crystals in cost, operational complexity, performance
  - Trigger and DAQ has structural choices
    - Fully streaming vs. analog buffering with short time scale event selection
    - Location of digitizing electronics
- Experiment would benefit from resources to carry R&D farther forward on a number of these issues
  - Largely an issue of financial resources and people