Low Noise Detector Design

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Outline

- What do we mean by grounding?
- Detector front ends with examples
- Conductivity of carbon fiber and its use in detectors
- Detector construction techniques
- Experiment wide techniques

What is a Ground

- Different meanings for different designs
  - Designer of a large radio transmitter wants lightning protection so his ground needs to transmit thousands of amps from a lightning bolt into the earth
  - Power engineer has the requirement of keeping structures and the center tap of his power transformer at roughly the same potential
  - Detector designers have little need for either of these requirements

Detector Ground Characteristics

- Large capacitance so that noise currents flowing onto the ground do not raise the voltage of the ground.
  - From the detector point of view, this makes the current “disappear”.
  - The 0 voltage also prevents the noise signal from coupling into other detector components.
- It should also have a large surface area so that the current flow is not concentrated.
  - This prevents significant magnetic coupling.

- The vacuum shell for the CMS magnet is a very good detector ground
  - large surface area with no openings
  - It is more than several skin depths thick
    - The resistivity of the stainless steel actually helps since it aids in turning the noise currents into heat
  - It is very close to most sub detectors

Noise Currents

- Noise currents are never a voltage source
  - This means even a relatively poor connection to ground or detector by pass may reduce the noise voltage substantially.
- Inductance almost always dominates resistance for detector noise
  - 1 cm long section of a cooling pipe carrying 100 µA of 10 MHz noise current located 1 cm from a silicon strip will generate a 3500 electron signal in 10 ns through magnetic coupling (assumes 100 ohm amplifier impedance)
  - If the pipe is1 meter long and 5 mm in diameter, it has 7 ohms of impedance at 10 MHz from self inductance
    - Grounding one end of the pipe may not affect the noise pickup

Detectors Are Changing

- Signal levels are getting smaller - often to a few thousand electrons
- Must design the detector from the beginning for good low noise performance

Integrated Detector Design

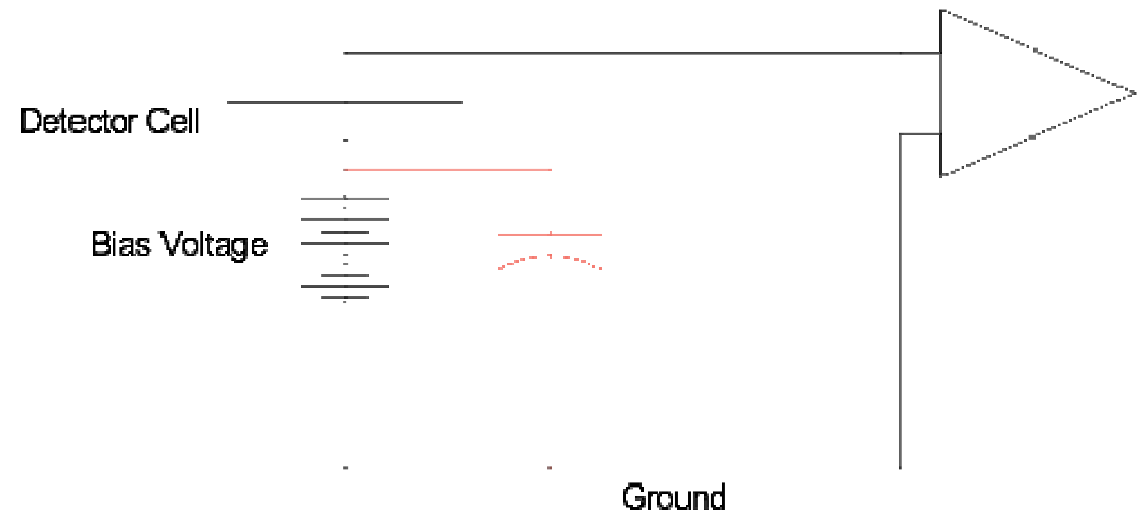
- At these small signal levels mechanical components can have a significant impact on the electrical performance of the detector
- The old way of designing the mechanics and electronics independently and assembling at the end needs to give way to integrated design teams
  - Need common meetings on all aspects of the design

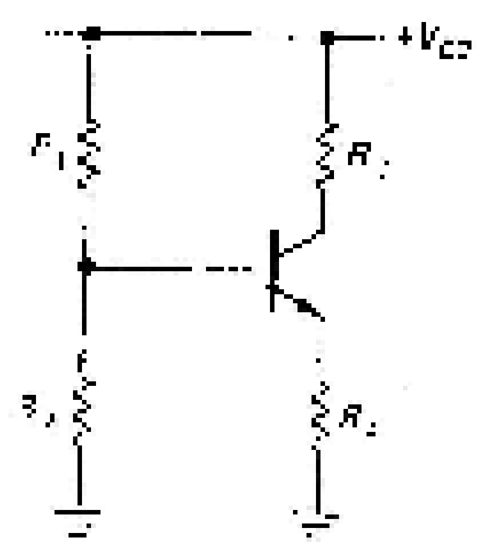
Front End Design

- Describe a few different configurations of front end designs
- Concentrate on the return circuit
- Provide several examples

Simplified Detector Cell

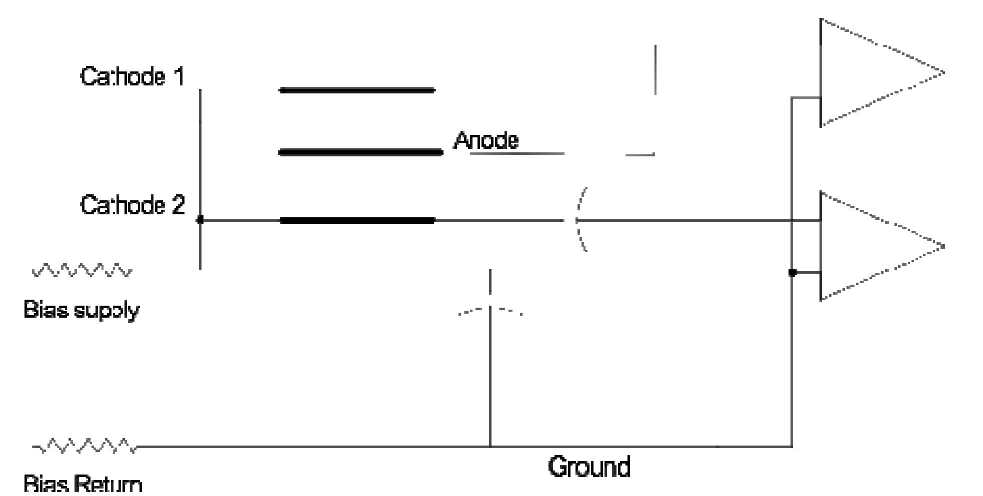
- Detector-preamp system is usually well designed
- Most noise issues associated with ground current return (red in top picture)





Wire Chamber with Cathode Readout

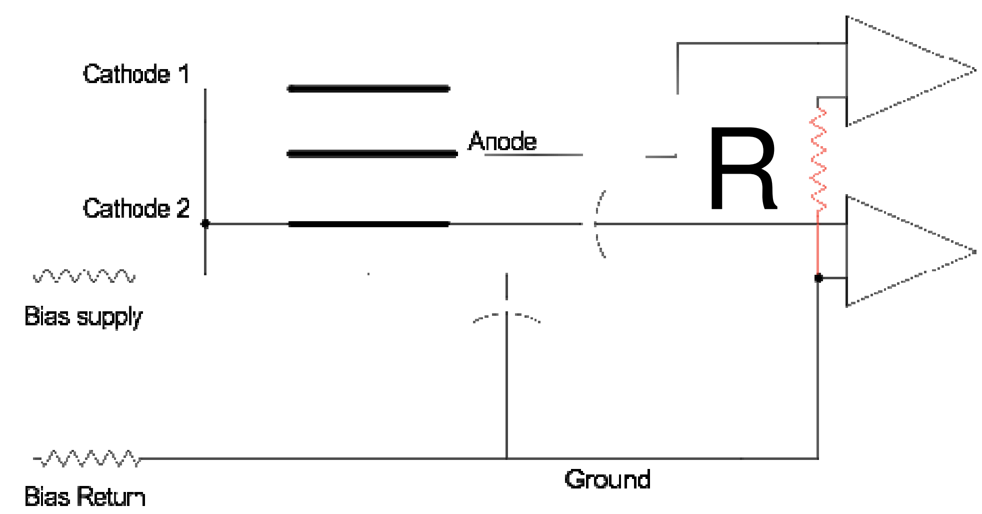
- Simple design
  - High voltage is filtered and isolated by supply resistor
  - Ground loop through HV supply broken by bias return resistor
  - Signal return through one capacitor is local
  - What could go wrong?



Muon Noise

- Large chamber system installed over several months
- Noise was at expected level for chambers when installed
- Noise level increased with time over several months
- Earliest installed chambers were the noisiest.

- Chamber had separate boards for anode and cathode
- HV was sent to only one board
- Connection between boards (ground) was by a screw
- The surface of the screw oxidized with time and increased the value of R
- Ground return was by unknown alternate path
- Noise currents enclosed by this path added to the signal

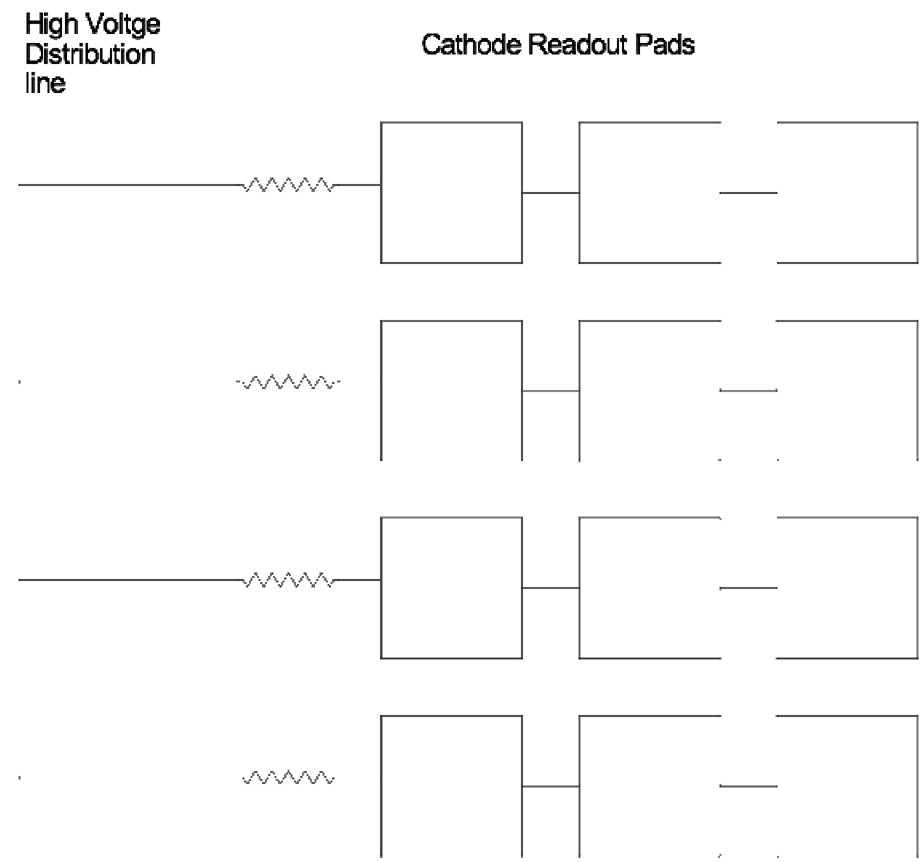


- Breakdown voltage for thin non conducting oxides is proportional to thickness.
    - Smaller signal voltages are blocked by thinner oxides.
- This problem was corrected by adding a dedicated electrical connection between the two boards.
- The R component could be inductive rather than resistive.
    - Impedance of a 20 cm long wire 1 mm in diameter at 40 MHz is 6 ohms from self inductance
- It is very important to control this impedance

Precision Drift Chamber With Cathode Readout

- Design worked perfectly in test beams and on the bench
- When fully instrumented in the experiment, the detector would spontaneously break into a stable oscillation after a variable length of time
- The only way to stop the oscillations was to turn off the power to the preamps

- The high voltage system was graded so that drift velocities were roughly constant across the detector.
- The readout pads and the line that fed the voltage to the pads were etched on a Kapton sheet located directly over the amplifier inputs
- HV distribution line
  - Passed back and forth 32 times across the chamber
  - Open at the far end
  - Terminated in a large resistor at the source end



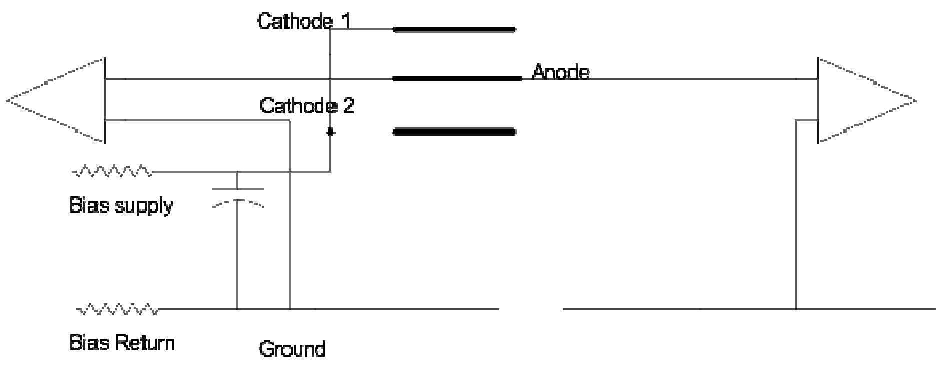
- The long HV feed line was acting as a transmission line resonator
  - delay for signals propagating down and back was sufficient to create positive feed back
  - Line selected unique frequency based on its length.
- Coupling to the pad amplifiers through the resistors was small so feed back in a partially instrumented chamber was too small to cause oscillations.
- Random start times depended on noise pulses generating enough energy in the line

- This effect is present in many cathode readout chambers
  - amplifier bandwidth is too low to respond to any resonance
- Other system components (cooling lines, cables etc) could also resonate
- Effect is more important for large detectors with high bandwidth amplifiers

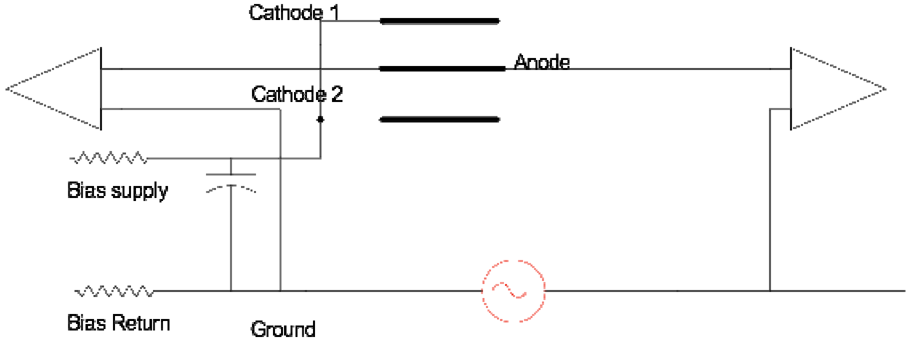
Readout From Both Ends of a Detector With a Common HV Plane

- Often used to determine track coordinate along the wire.
- The high voltage is usually fed from one end only

- This example is similar to the muon system describer earlier but now there is no resistor at all
- Return current is through the cables to the digitizer rack and back to the preamp
  - Delay was long enough to cause positive feedback so the preamps oscillated
  - Moving the cables changed the inductance and thus, the total delay so oscillation depended on cable position.



- Solution was to add an external connection between the grounds
- Unlike the muon system this connected two different grounds together creating a ground loop
- If capacitors had been installed on the other end, the ground loop would even be through the HV plane which is even worse
- Need either good ground plane or local ground isolation for the preamps - discussed later



Grounding for Detectors With Remote Preamps

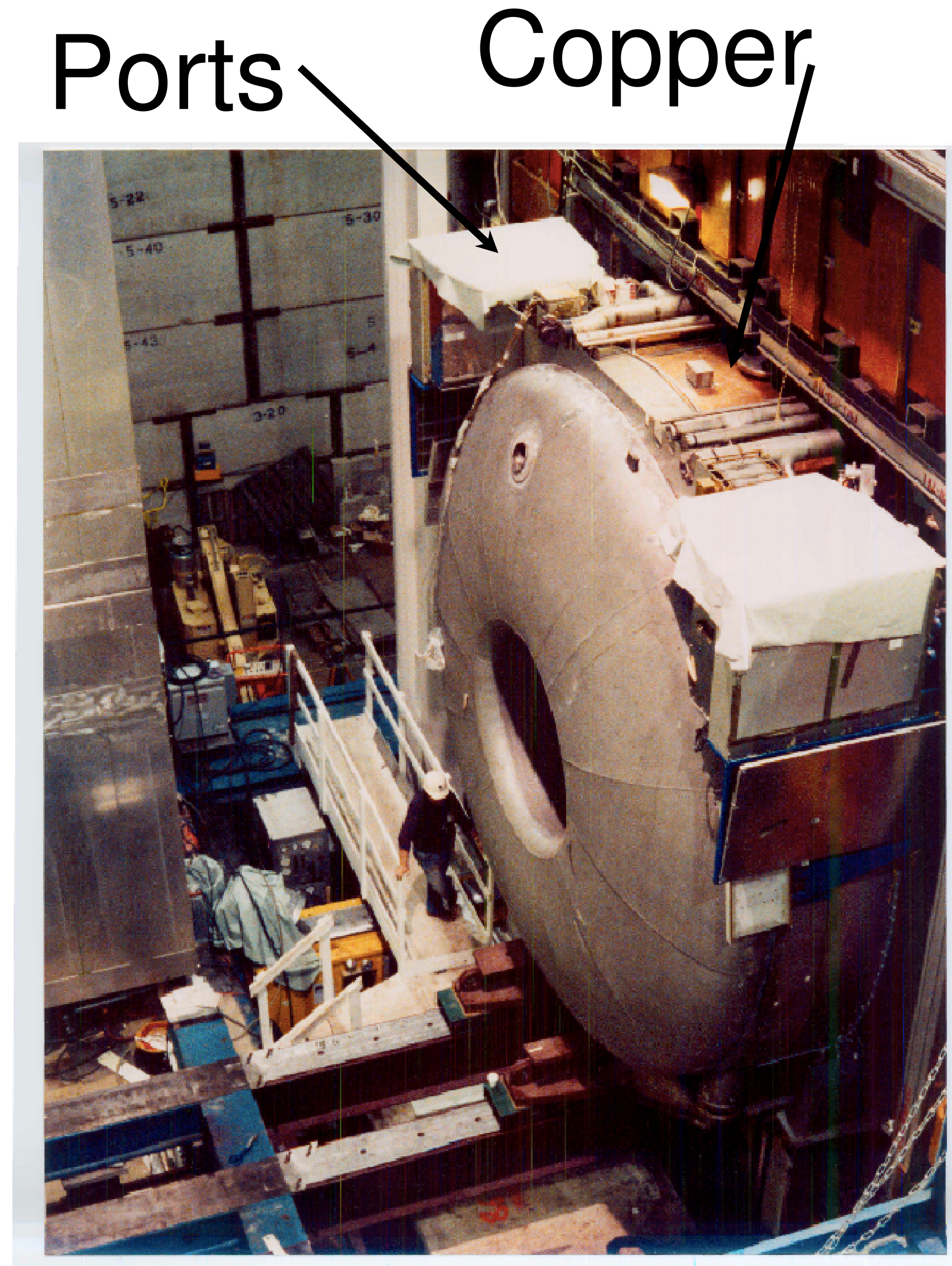
- This is the case where the the preamp is not close to the sensor
    - D0 liquid argon calorimeter with multiple signal and high voltage ports
    - D0 Layer 0 silicon detector with readout chips connected to the sensor with an analog cable

Return Path

- Must minimize the inductance in the signal return path
- Wide thin conductor gives the lowest inductance, i.e., a ground plane

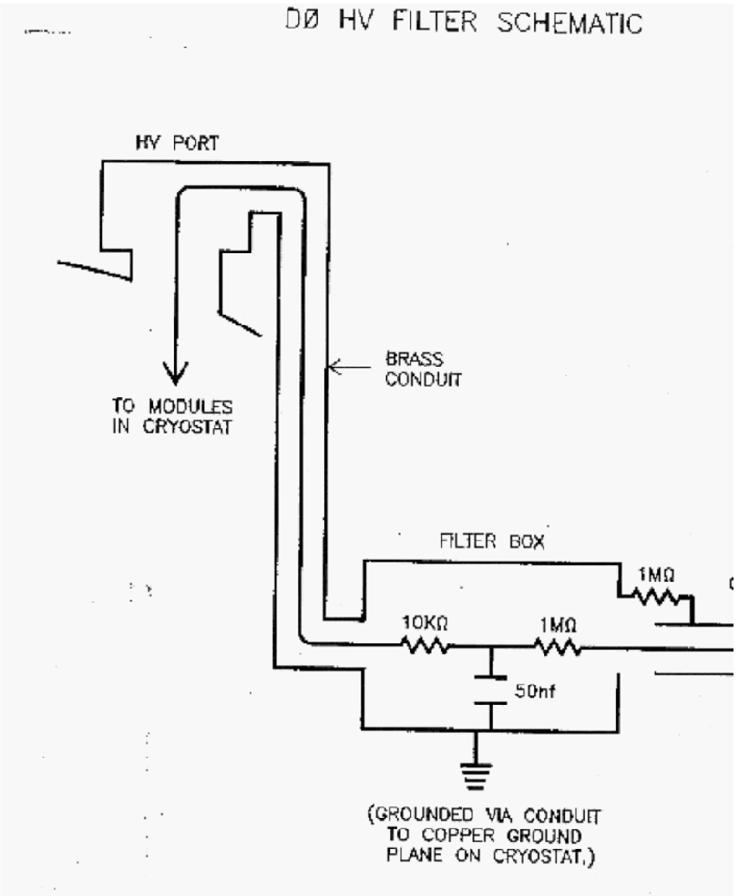
D0 Calorimeter

- 4 preamp ports
- 2 HV ports
- HV port feeds multiple preamp ports
- Need good interconnect
- Copper shell over top of calorimeter for ground plane



Calorimeter HV

- Design works well for return current
- Preamps and digitizers are located at two different locations
  - Ground is similar but not identical at the two locations
  - Correlated double sample eliminates most noise

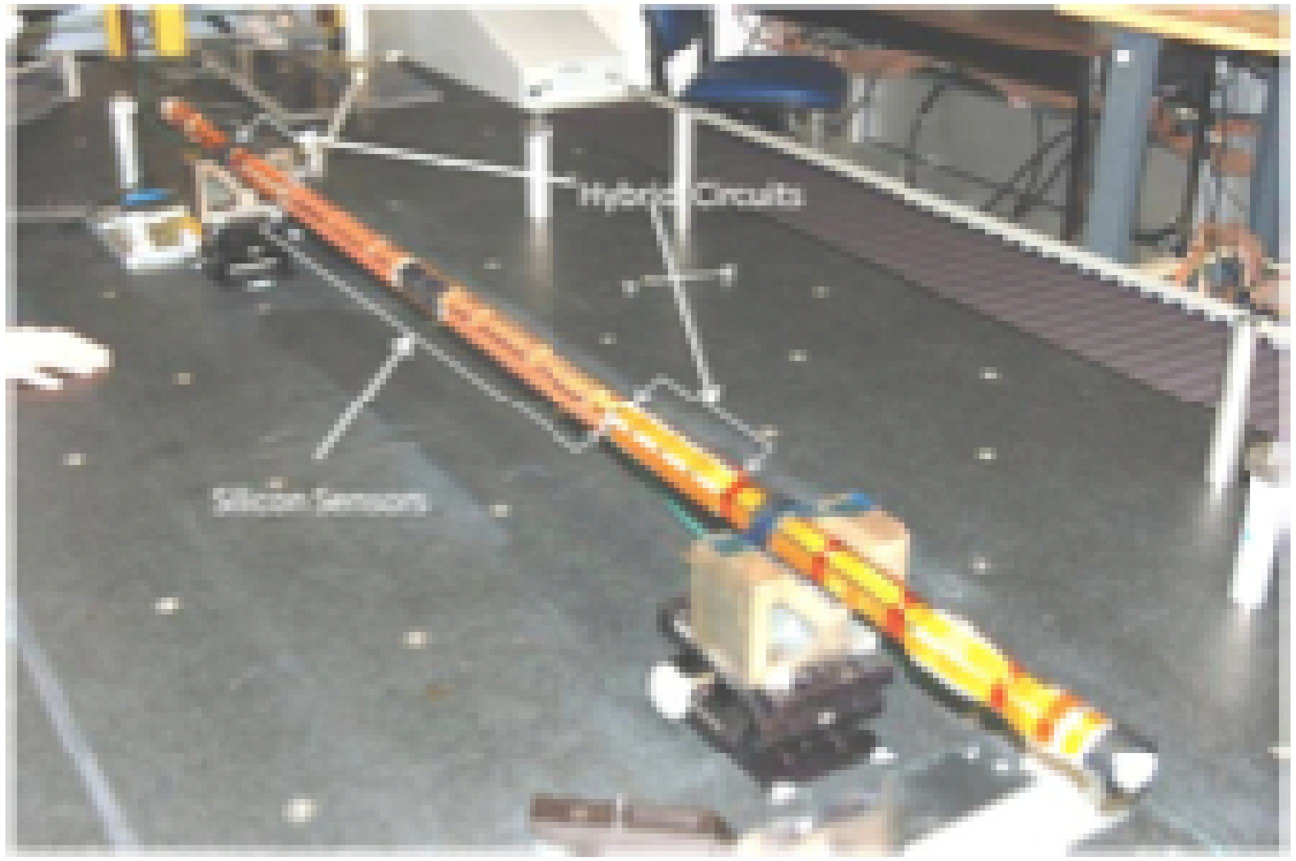


Calorimeter Shielding

- Inner layer muon system is used as a faraday shield for the preamps
  - Very sensitive to noise from muon readout
  - Limit calorimeter preamp bandwidth so they do not see the muon readout noise
  - Muon chamber failures often cause calorimeter noise.
- Modern design would put the digitizers on the same ground plane so this problem would not exist.

Layer 0 silicon detector

- Radius of detector is too small to mount chips on the sensors
- 300 mm analog cables
- All carbon fiber structure
- Need to create a ground plane under sensor and hybrid with little increase in mass



High Modulus Carbon Fiber

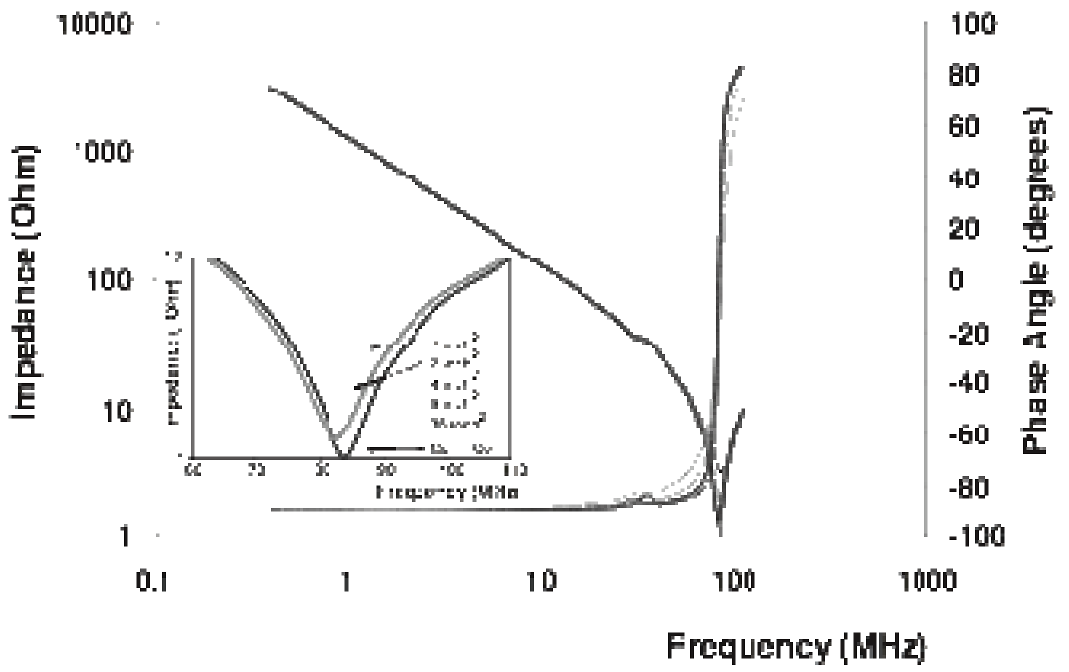
- Remarkable material for detectors
  - several times stiffer than steel
  - low mass
  - easily formable into complex shapes
  - surprisingly good electrical conductivity at high frequencies

Carbon Fiber Electrical Conductivity

- Constructed 6 inch by 6 inch parallel plate capacitor with 1/4 inch thick FR4 dielectric
- Bottom plate is copper
- Top plate is either carbon fiber or copper
- Connection to carbon fiber is by copper tape glued to surface of CF plate
- NIM A 550 (2005) 127

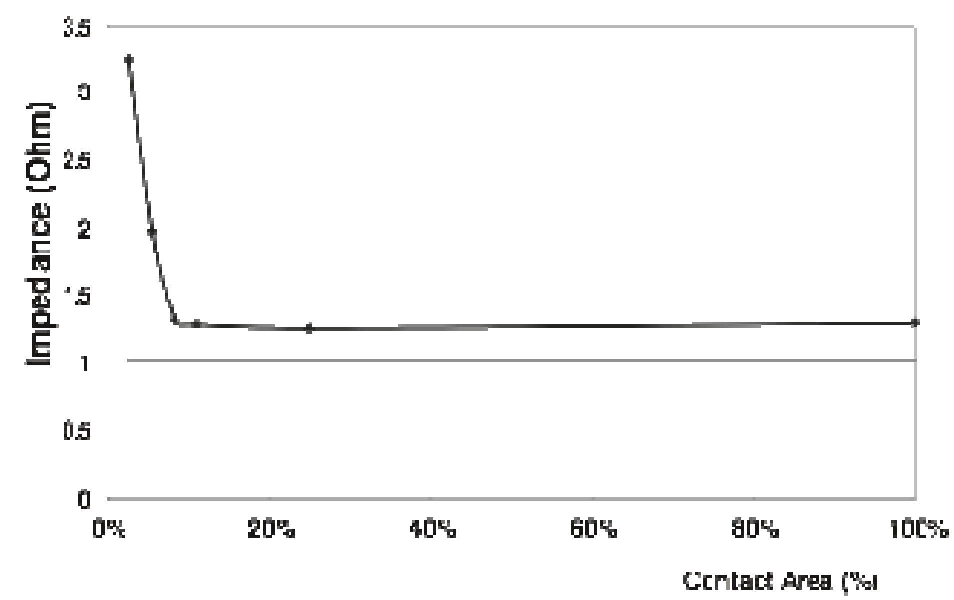
Impedance Measurement

- Inset in plot is a blow up of the region with the lowest impedance
- The data is taken with different areas of copper tape on the carbon fiber plate
- The carbon fiber - copper capacitor is within a factor of 2 of the all copper one



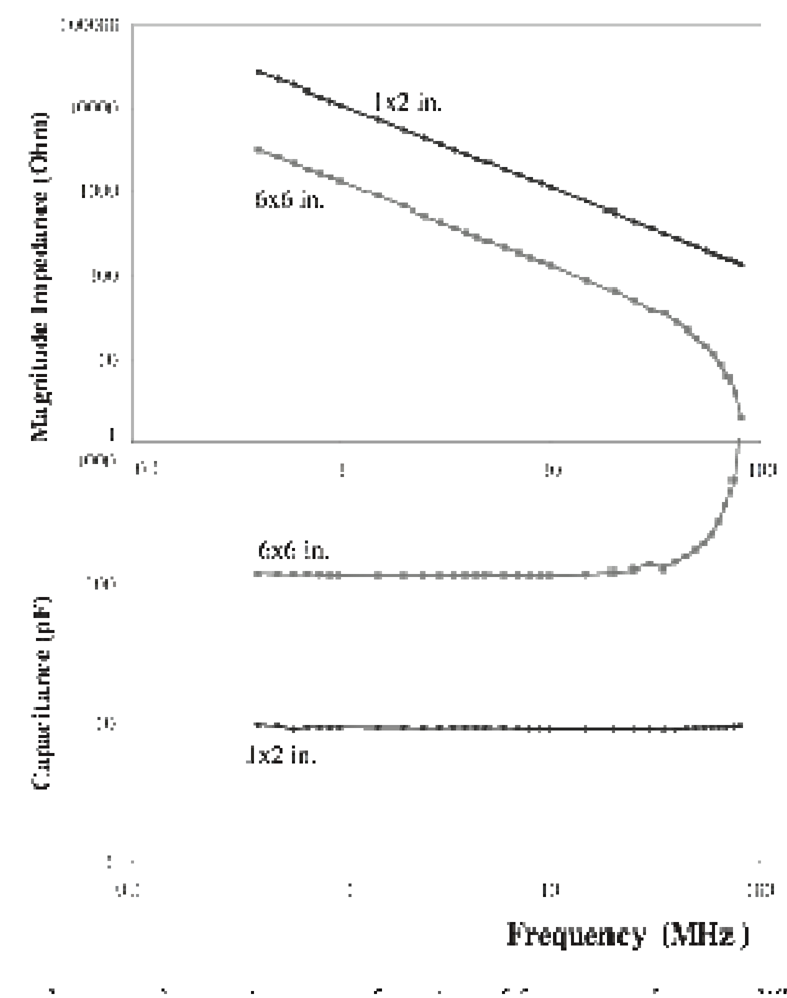
Impedance Versus Copper Tape Area

- Data is plotted at minimum of previous figure
- Indicates that less than 20% copper coverage is required for good coupling to carbon fiber



Data Check

- Copper tape pasted directly of the FR4 - no carbon fiber
  - Upper curve is 1 by 2 in copper tape
  - Lower curve is all copper capacitor
  - Very different from previous plot
  - Data consistent with area ratio
- Conclude that Carbon Fiber is a good conductor at high frequency

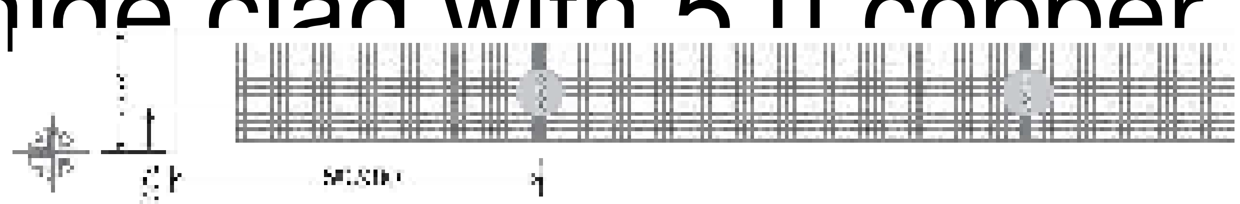


Implications

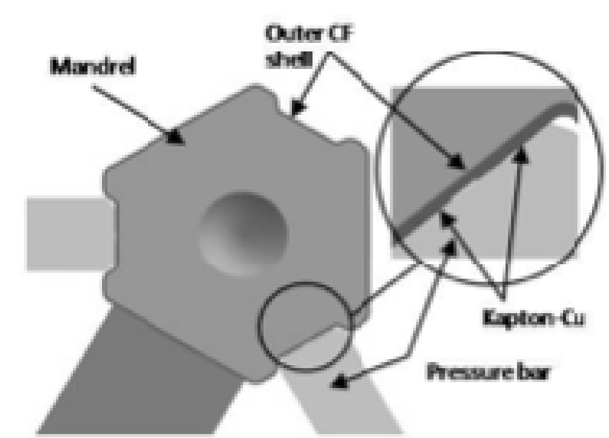
- Can not ignore any carbon fiber structures when doing the electronics design
- Can use the support structure to great advantage in designing grounding and shielding structures for a detector

Coupling to Carbon Fiber

- Data shows that we need only about 20 % contact.
- Skin depth limits the useful thickness
- Best method appears to be to etch a mesh pattern on 50 μ thick polyimide clad with 5 μ copper



- Copper side is placed next to the carbon fiber
- Standard printed circuit vias are used to make contacts on the other side of the mesh for external connections
- Polyimide is then co cured with the carbon fiber to make the mechanical structure.



Layer 0 Ground Plane

- ~30 mm diameter cylinder
- Less than an ohm of impedance between sensor and chip at 10 MHz
  - It holds both sensor and chip at same potential so even if ground plane is slightly noisy, no noise is measured.
- Metallic plane with these properties would have added too much mass

Ground Isolation

- The layer 0 detector is read out from both ends
- Mechanical requirements did not allow a dielectric break between the two read out sections
  - Creates a ground loop through the carbon fiber
- Break the ground loop by isolating the local grounds at each end
  - Add extra protection even with a ground plane

- Mass constraints and readout chip design did not allow on detector ground isolation
- Put in a small circuit board about 2 meters from end of detector to do this
- 3 components for isolation
  - circuit board
  - digital signals
  - power

Circuit Board

- One half of board was world ground and other half local detector ground
- Minimize trace overlap between the two sections
- Achieved 278 ohm impedance at 7 MHz for a bare board
    - Reduced to 33 Ohms with all components and cables installed

Power

- Use separate power supplies dedicated to each side of detector.
- Supplies are chosen to have good AC isolation to external ground

Digital Lines

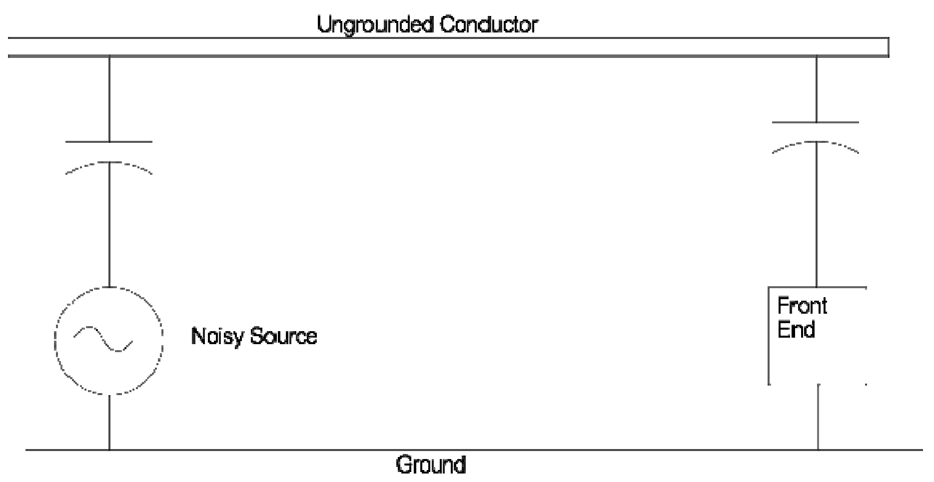
- Tried various isolators such as opto isolators
- All failed for such things as speed, operation in a magnetic field etc.
- Chose simple differential driver and receiver

Performance

- 6 boards in parallel so overall ground isolation is 33/6 =5.5 Ohms
- Parallel connection is at end of 2 meter cable so we can add cable self inductance of the cables to get more than 10 ohms.
- Measured common mode noise is about 3% of MIP

General Detector Issues

- Need to control (ground) the potential of all metallic parts
  - create unwanted connections via capacitive coupling



Aluminum

- Oxidizes immediately
  - oxide is a good insulator
- Two methods for connections
  - Mechanical such as star washers
    - Needs to be gas tight to prevent oxide formation
  - Plating
    - Alodine: no mechanical size increase but scratches easily
    - Tin: some mechanical size increase but fairly rugged

Adhesives

- Often see detectors glued together
- Need to provide good interconnect to prevent ungrounded conductors
- Conductive epoxy without plating Aluminum is usually not adequate

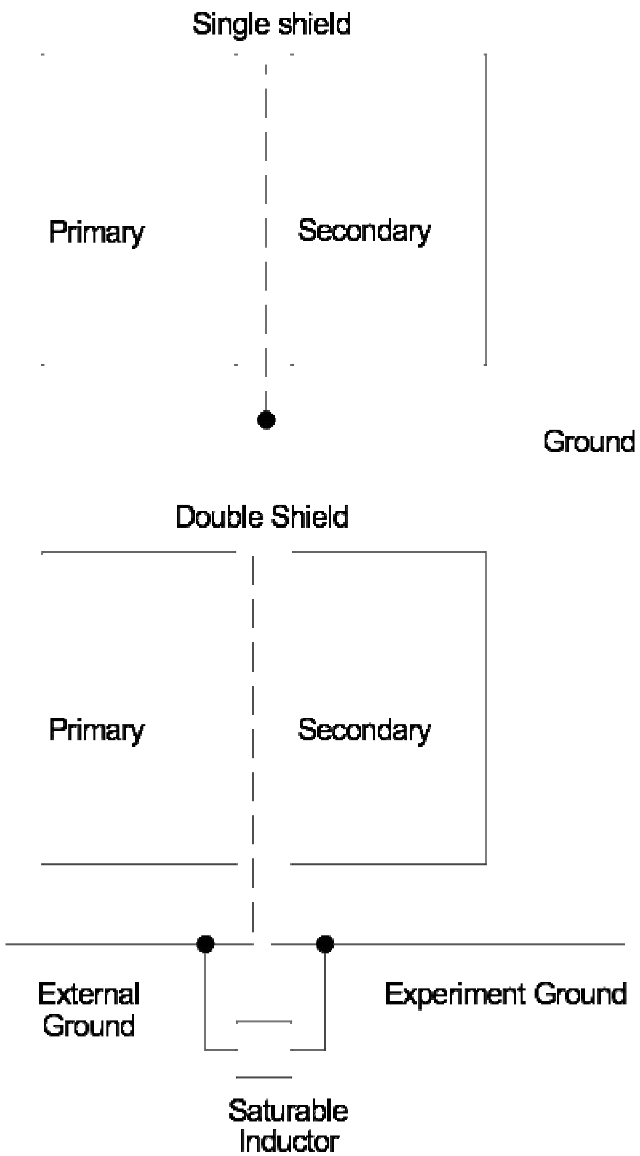
Experiment Wide Techniques

- Power Distribution
- Cable plant
- Racks and counting house infrastructure
- Global grounds

Transformers

- Transformers come with 0, 1 or 2 Faraday shields
  - shield is typically a copper screen wrapped around one of the coils to stop capacitive coupling.
  - One shield is a screen between the coils
  - Two shields usually have screens wrapped individually around the primary and secondary.
- One shield reduces capacitive coupling by about a factor of 100 and 2 shields reduce the coupling by about a factor of 1000.

- The shield for a single shielded transformer is simply connected to the ground plane
- Two options for double shielded one
    - Direct connection to ground
    - Isolated ground connection
        - Serious safety problem since a shorted transformer could raise the secondary ground to secondary voltage potential
        - solution is an iron core inductor wrapped with enough turns so that a small current saturates the inductor resulting in low impedance for a transformer short.



- Minimum number of shielded transformers is one per sub detector.
    - provides good isolation between systems
- In a large sub detector one might want multiple transformers to isolate segments
    - We are doing this for the NoVA experiment

Cable Plant

- Separate trays for AC, Detector power and signals
- Covered and well grounded trays for detector cables are best.
    - A substitute is a grounded sheet of copper at the bottom of the tray
    - Provides a low impedance ground plane over the route

Grounding Cable Shields

- No hard and fast rule. It depends on the available ground.
- If grounds are equal, I prefer to ground at the rack (off detector) end because any energy picked up by the shield is removed from the detector.
- In CMS the superconducting magnet is a better ground than the racks so ground at detector end
    - Also need to move unwanted power off the detector so we need to minimize inductance to ground

Racks and Infrastructure

- I prefer to weld the racks together and to the support structure
- This is most important if cables are grounded at the racks
  - Normal rack paint is a good insulator at low voltages
- Rack mounting strips should be tin plated
  - Standard option on most commercial racks

Global Grounds

- Design for the NoVA neutrino detector
  - Work in progress
- NoVA is all plastic device filled with liquid scintillator
- No obvious metallic structure to use as large capacitor
  - The only large metallic structure is an access catwalk
- They will almost certainly need a good ground

Ufer Grounds

- Developed by Herbert Ufer for US Army during WW II.
  - Developed to provide protection for munition storage areas from lightning and static charge
- Basic idea is to use the reinforcing rod in concrete as a low impedance path to earth ground
  - Experiments do not have any current flow
  - Concrete connection depends on ions around the rods in moist concrete
  - Likely that this will also provide good capacitance

Ufer2

- Some evidence that this is the case from work at D0
  - Solved a magnet noise problem by connecting the ground to the concrete floor via the track plates that the detector rolls on.

NoVA

- Weld the catwalk together
  - catwalk serves as connection to experiment electronics
- Connect rebar in wall adjacent to cat walk into a grid
- Tie the catwalk to this grid at roughly 1/10 wavelength of upper frequency of preamp.
- Probably won’t know if this works until the experiment is installed

Summary

- Design of the ground return is essential for good detector noise performance
  - Most errors are found in this area
- Support structures (especially Carbon Fiber) can be important parts of the detector electronics.
- Need careful attention to detail through out the design and construction process.