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Paschen Breakdown Considerations for the DUNE ND 5 Coil Magnet

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Near Detector Workshop: Magnet Systems

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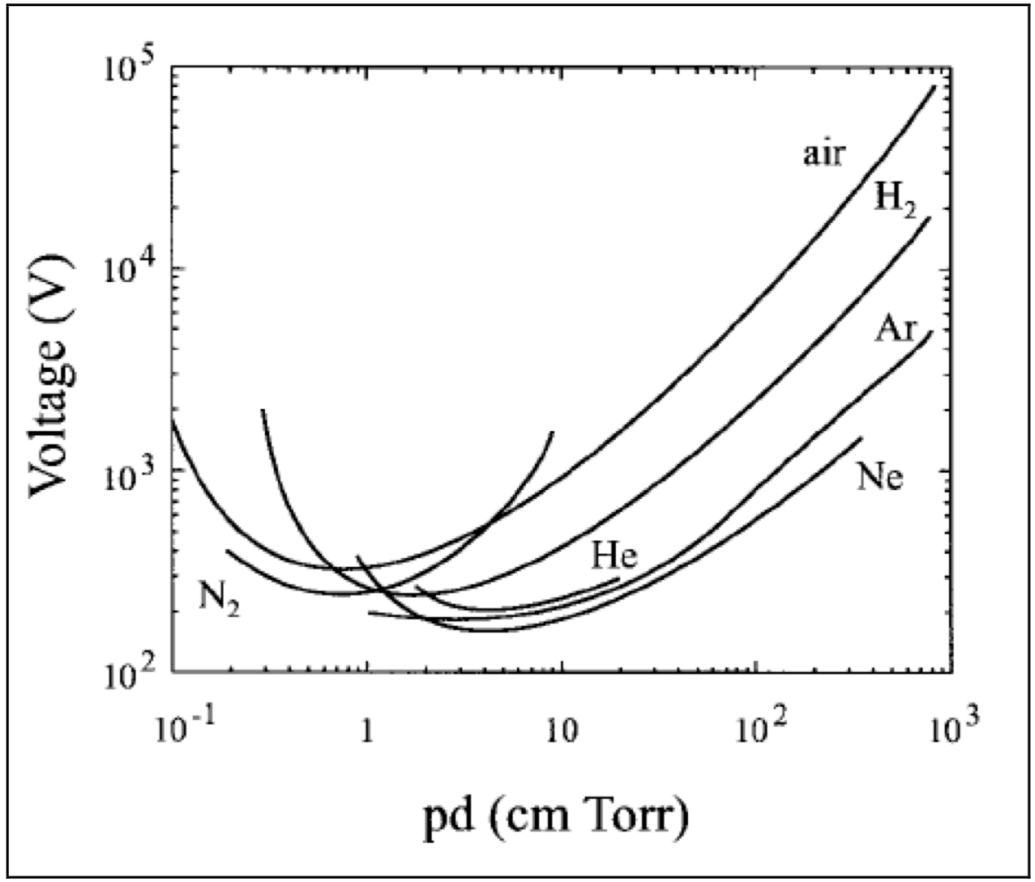
Why is Paschen Breakdown of Interest?

- Of interest to a cryogenic engineer because of significant Paschen mitigation efforts on the Mu2e experiment utilizing cryogenic resources I'd prefer not to repeat
- Both high vacuum and atmospheric pressure are very efficient dielectrics
  - ~20 kV/cm in air
- However at intermediate pressures there is the Paschen minimum
  - Breakdown can occur at "low" voltages and surprising distances
    - Breakdown voltage a function of the product of pressure and distance
  - As low as ~160 V in helium gas at 4 Torr x 1 cm
    - Material, roughness, shape, cleanliness, oxide, etc impact exact value
  - For every voltage (above the minimum) there are infinite combinations of pressure and distance at which breakdown could occur

Why is Paschen Breakdown of Interest?



He has the lowest minimum breakdown voltage but N2 and Air also break down at low voltages

	Minimum Voltage	Pressure x Distance
Gas	Volts	Torr x cm
Air	330	0.6
Helium	160	4
Nitrogen	250	0.7

What Risk Does Paschen Breakdown Present?

- Paschen breakdown scenario
  - Helium used for cooling leaks into the insulating vacuum
  - Pressure rise increases heat load
  - Magnet quenches
  - Quench protection switches to dump resistor
  - Coils go to several hundred volts as energy is extracted
  - Combination of
    - Imperfect local electrical insulation
    - Local pressure and distance to ground lead to Paschen breakdown
  - Arcing and the potential for severe damage to the magnet
- A low probability but high risk scenario

Insulating Against Paschen Breakdown

- Must ensure gas does not contact a bare surface at voltage
- Difficult to design a resistant geometry
  - Not dependent upon pressure alone (P x d)
  - Difficult to define a minimum safe distance to conductors
- Entire current carrying system inside the insulating vacuum must be Paschen proof
  - Insulation must not only be initially perfect but protected during installation and survive thermal cycles
- Atmospheric hi-pot testing may not reveal flaws due to air's 20 kV/cm dielectric strength
- Paschen breakdown voltage increases ~20% at cryogenic temperatures (room temperature tests conservative)

Mu2e Experiment and Paschen Breakdown

- Paschen breakdown identified as a risk to the Mu2e solenoids after the design was mature
  - Mitigation very difficult and costly when not considered early in the design
  - Suggest DUNE ND decide approach early
  - Middle ground approach chosen by Mu2e
    - Test Paschen proofing techniques and small assemblies
    - But don't Paschen test large final assemblies
  - Mu2e cryogenics WBS includes:
    - HTS power leads located in Feed Boxes (cryogenic valve boxes)
    - Superconducting bus in the transfer lines from Feed Boxes to Solenoids
    - Why a cryogenic engineer is concerned about this….

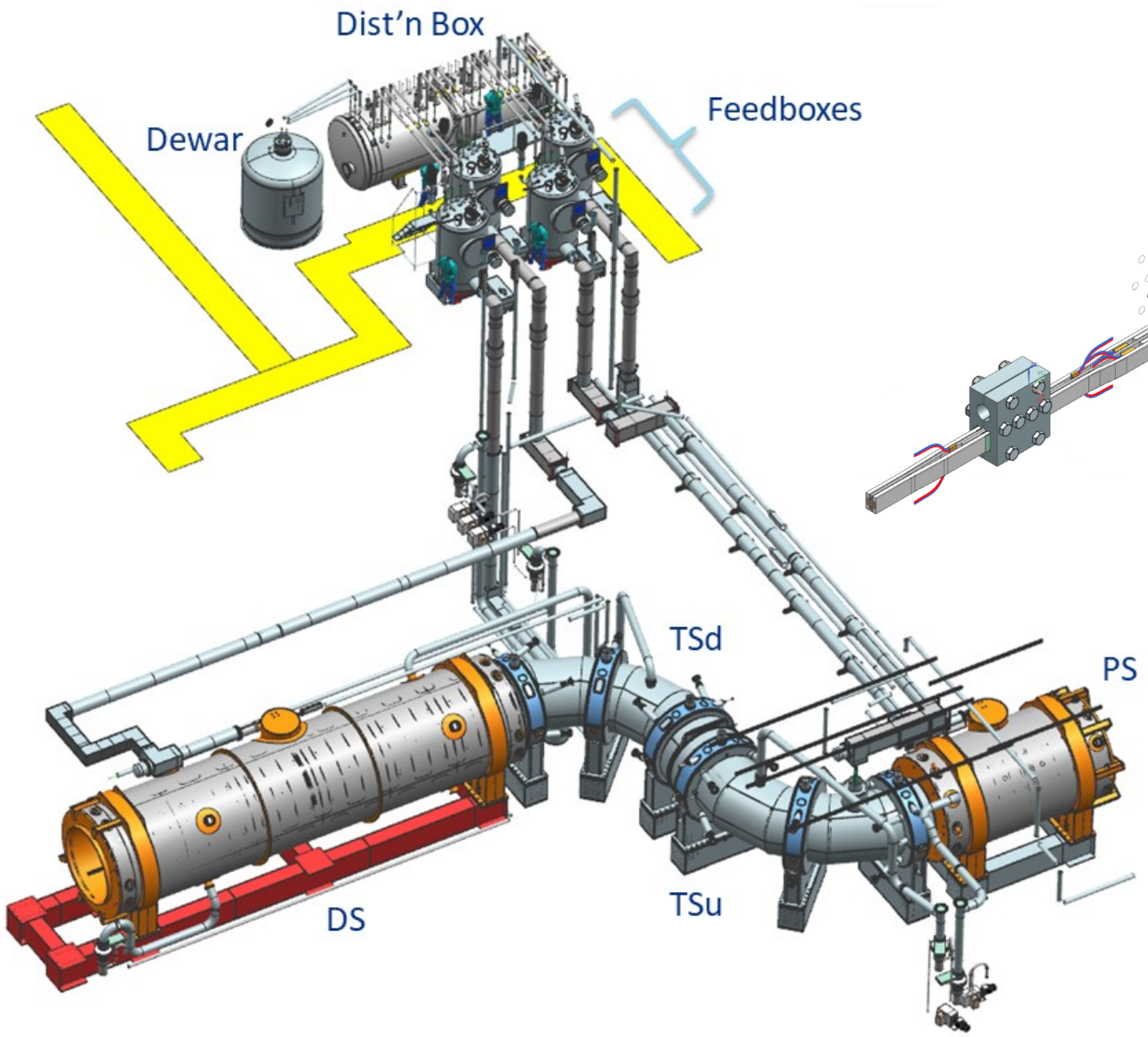
Mu2e Experiment and Paschen Breakdown

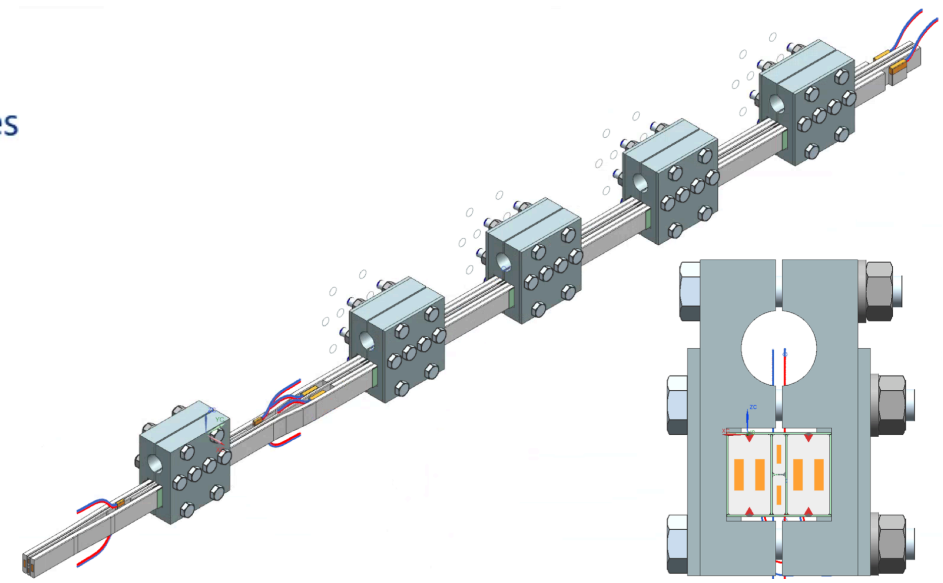
- HTS power leads
  - Mu2e repurposed vapor cooled HTS power leads (Tevatron)
    - See Sandor's talk
  - Converted from vapor cooling to conduction cooling
    - Easier to integrate conduction cooled leads into the experiment
    - Breakdown not an issue in an atmospheric helium bath
  - Paschen test stand was developed for the HTS leads
    - Pressure sweeps hard vacuum to atm pressure with He gas
    - Voltage sweeps to above extraction voltage
    - Paschen breakdown occurred….
    - Numerous iterations and modifications required
    - Insulating bare surfaces, non-conductive fasteners, potting instrumentation connectors, etc
  - Paschen breakdown was mitigated after significant effort

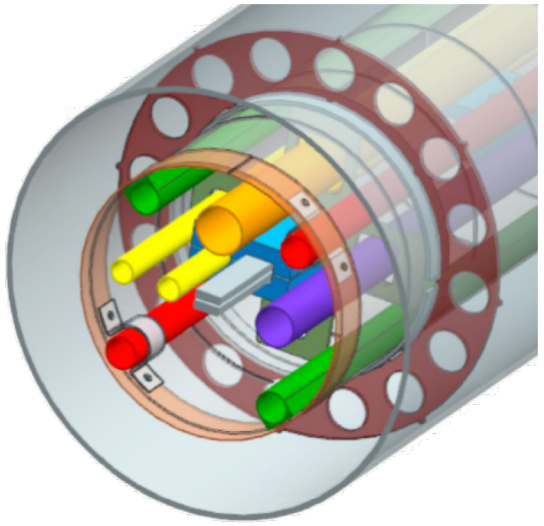
Mu2e Experiment and Paschen Breakdown

- Transfer Line superconducting bus
  - Feed Boxes with HTS power leads and cryogenic services are located in accessible area outside experiment shielding
  - Transfer Lines run 10s of meters from FBs to solenoids
  - Conductors (aluminum stabilized NbTi)
    - Routed thru the center of the cryogenic TLs
    - Common insulating vacuum between FB, TL, Solenoid
    - Conduction cooled by clamping to cooling pipes
    - Conductor surfaces exposed to insulating vacuum
    - Insulating scheme developed using the Paschen test stand
      - Conductors wrapped with adhesive Kapton tape
      - Sprayed with a varnish
      - Thermal cycled, bent, clamped and then Paschen tested
    - Insulation technique verified to be Paschen proof and repeatable
    - But not practical to Paschen test entire TL assembly

Mu2e Experiment and Paschen Breakdown







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ITER Experiment and Paschen Breakdown

- ITER is Paschen testing magnets and power feed systems
  - Numerous published papers
  - See paper “Paschen Tests in Superconducting Coils: Why and How” J. Knaster and R. Penco IEEE Transactions on Applied Superconductivity Vol 22 No. 3 June 2012
    - Details an approach for a Paschen testing campaign
  - Expensive to fully test an entire magnet and support systems
    - Vacuum vessel required to house magnet
    - Cameras necessary to locate any breakdown
    - Thermal cycling prior to testing
      - Cryogenic system, cooldown constraints
    - If breakdown does occur how to repair?
    - May have to be performed at multiple manufacturing or assembly steps to ensure robustness (issue of the last connection)
    - All supporting systems must be tested

Avoiding the Risk of Paschen Breakdown Entirely

- Limit the magnet extraction voltage to less than the Paschen minimum
  - Eliminates the risk of Paschen breakdown and associated mitigation costs
  - Conductor stabilizer optimized to limit heat generated/temperature rise during low voltage extraction
  - Is this possible for the DUNE 5-Coli Helmholtz?

Summary

- The Paschen breakdown approach should be decided early in the design cycle
  - Likely to be an issue raised during funding agency reviews
- 1st option - operate with the low probability but potentially large consequence of a breakdown
  - Numerous large solenoids not “Paschen proofed” have operated successfully
- 2nd option - design and test for Paschen breakdown
  - Expensive to Paschen test a large magnet and support systems
- 3rd option – extract energy at a voltage less than the Paschen minimum