Lecture 9
Coil Fabrication and Testing

Coil Design/Fabrication Practices

Electrical Safety

Coil Quality Assurance
(*Specifications*)

Introduction

- Magnet design must incorporate practices which protect both the hardware and personnel operating and maintaining the magnet system. This section of the lecture will cover practices adopted at LBNL and used at many of the US accelerator laboratories to ensure safe, reliable operation and long life of accelerator magnets.

- Whether coils are made *in house* or by *vendors*, certain quality standards must be met to ensure that magnets will operate as required.
- Specifications have been developed over the years to ensure magnet coil quality. These include material and fabrication requirements as well as performance tests.
- Rules governing electrical safety differ with different regions. The practices to ensure that magnet systems satisfy state and federal electrical safety requirements in California are reviewed.

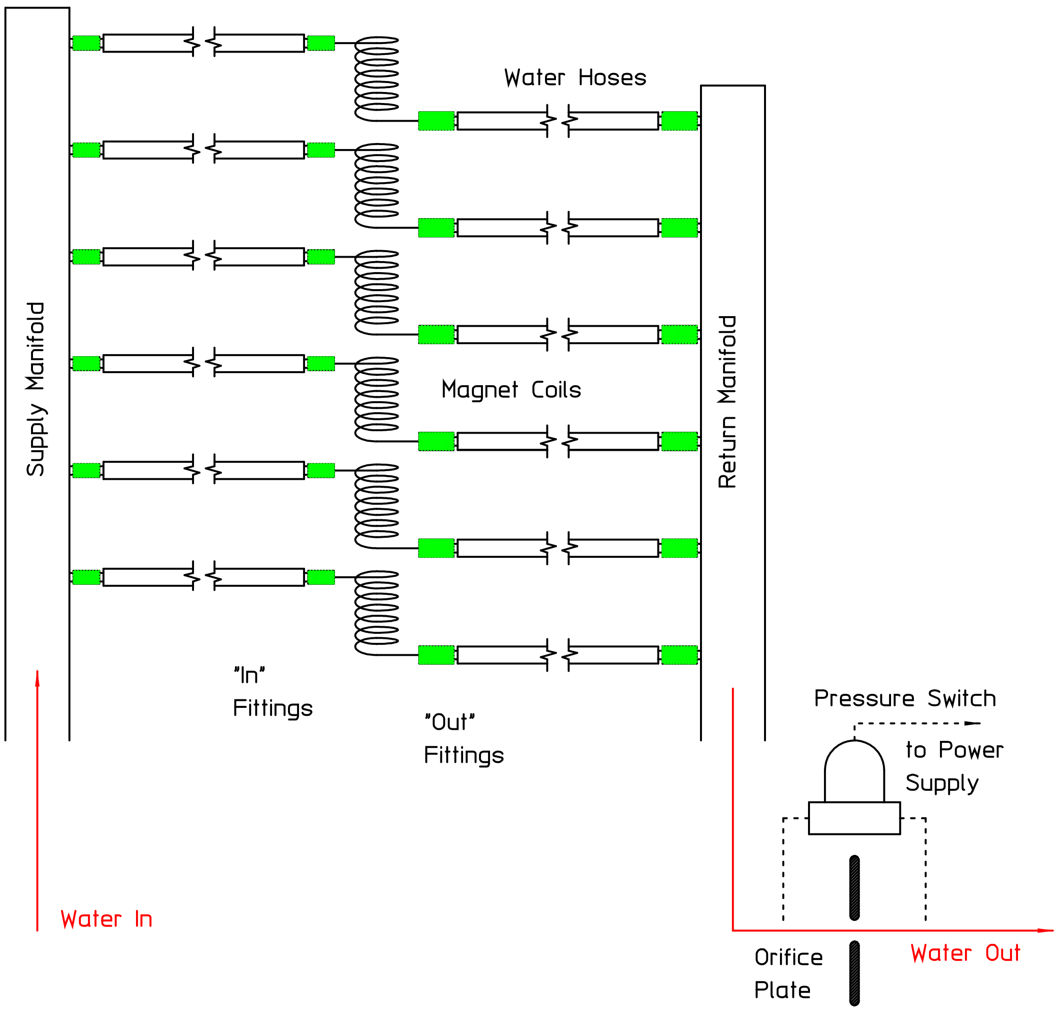
Hydraulic Practices

The accompanying figure illustrates several practices:

•Water hoses should be at least one meter long and use non-conducting material to prevent current leakage from the magnet.

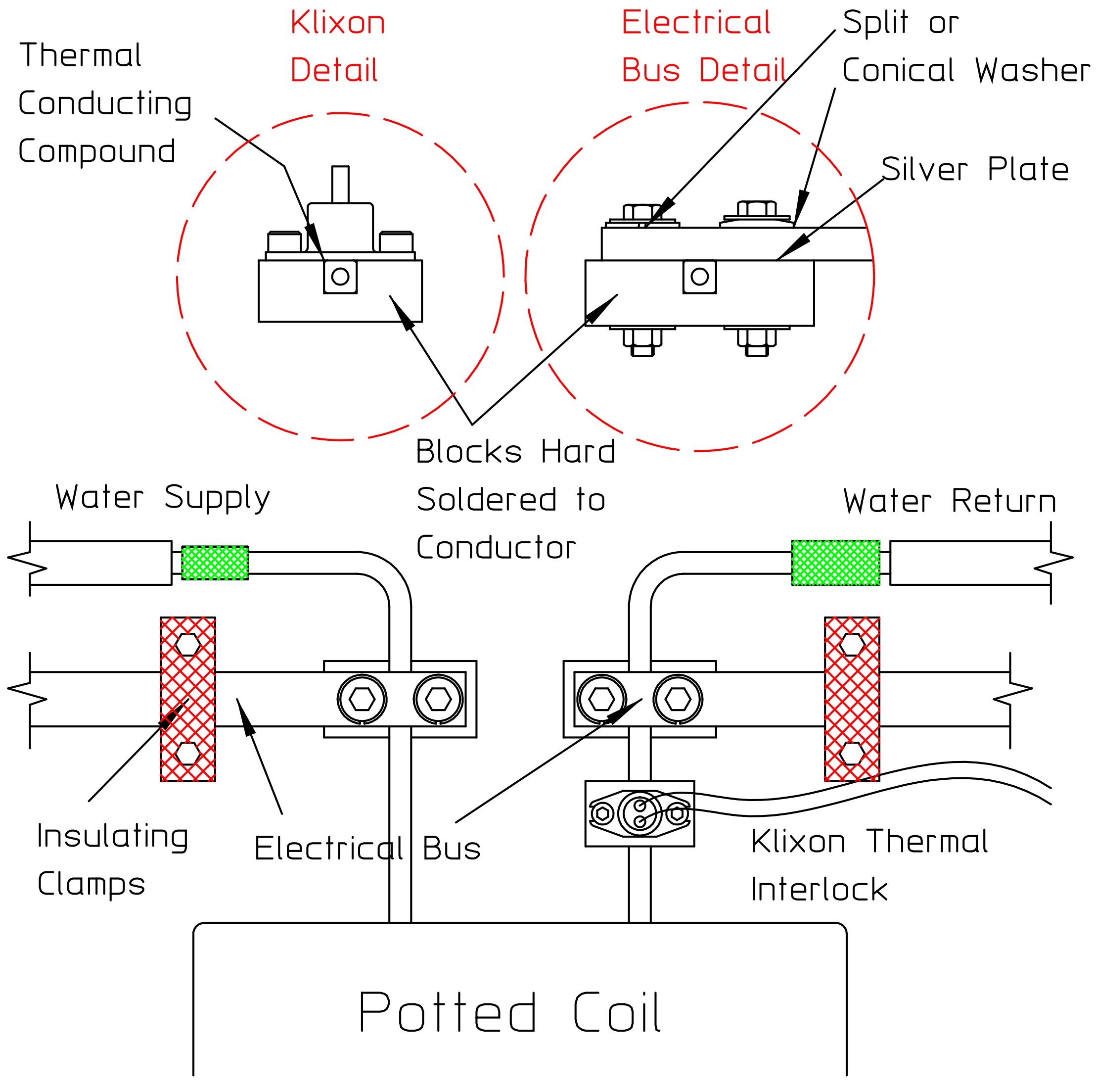
•The water "in" fittings should be smaller than the water "out" fittings. *Why?*

•If a flow interlock (orifice plate) is used, it should be attached to the return manifold. *Why?*



Electrical Practices

The figure illustrates some of the electrical design practices used in a typical magnet coil system.



Klixon Thermal Interlock

- The *Klixon* thermal interlock system is a switch which opens when it senses a temperature higher than its set-point. The thermal interlock system is connected to the power supply and is designed to shut down power if a coil temperature exceeds the interlock set-point.
  - The normal set-point of *Klixons* is about 89^o C. It will generally reset at about 70^o C, although a buyer can request special temperature values for these interlocks.
  - One thermal interlock is installed on *each water circuit*. If a coils has more than one water circuit, multiple interlocks are installed to protect that coil.
  - All the interlocks on one magnet are connected in series.

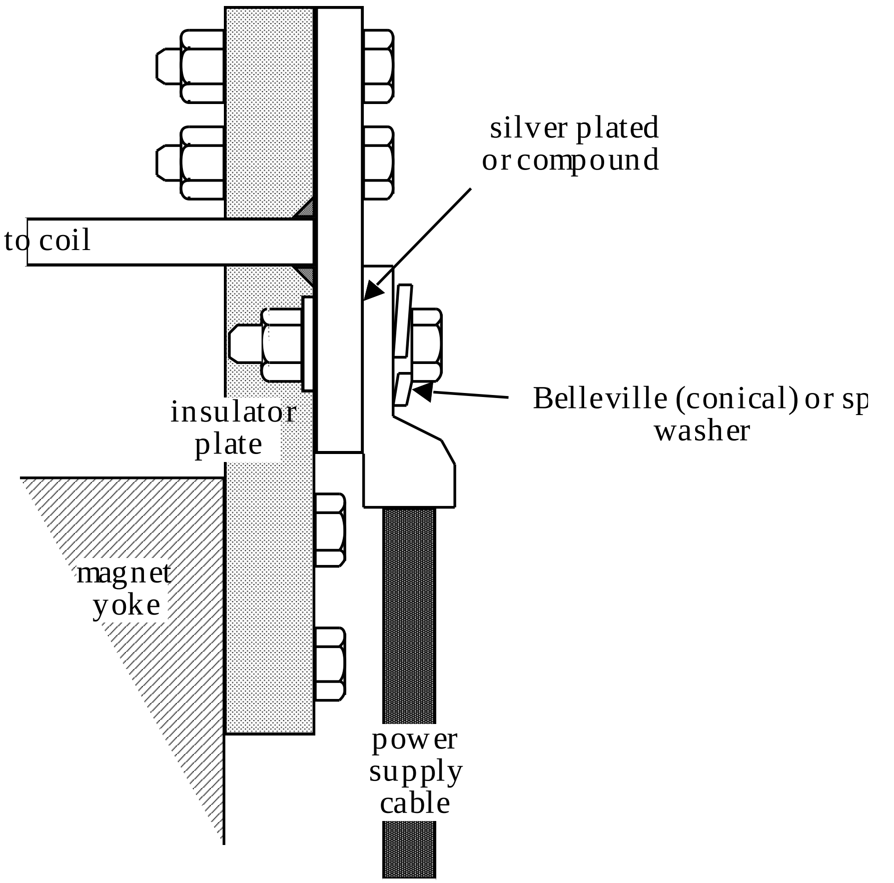
- Interlocks for magnets in power supply series strings *may or may not* be connected in series.
  - If too many elements are connected in a series string, it is difficult to identify the particular magnet or circuit in that magnet. This becomes especially troublesome if the Klixon suffers intermittent failure.
- The Klixon is *preferably* mounted on the water return lead of the coil. *Why?*
- The Klixon is *always* mounted on the current carrying portion of the conductor (inside the electrical connection bus. *Why?*
  - The Klixon is mounted to a block hard-soldered to the conductor. The interface between the Klixon and the mounting block is coated with a thermal conducting paste. *Why hard-solder?*

Internal Electrical Bussing

- Practices for the internal electrical connection separate magnet coils are used to ensure safe and reliable magnet operation.
  - Blocks to the connection of busses to the separate coils are hard soldered to the conductor.
  - The busses are generally air cooled and therefore are sized so that the maximum current density is $\leq$ 1.5 Amps/mm^2.
    - Since the busses are significantly heavier than the coil conductor, with current density $\leq$ 10 Amps/mm^2, insulating support blocks (usually epoxy fiberglass) are attached to the core to support the busses and protect the coil conductor from damage. No mechanical load should be carried by coil leads.
  - The interfaces between the busses and the coil blocks are either silver plated or coated with an electrically conducting compound.
  - Either split or Belleville (conical) washers are used under flat washers and either the bolt head or the nut. *Why?*

Power Supply Connections

- Power Supply cables are very heavy. The design of the bus connection to the cables should be rigid and rigidly attached to the magnet core.
- The cable-bus interface should be coated with electrically conductive material.
- The fastener system should include a split washer or other energy storage device.



Electrical Safety

- Normally, an electrical safety inspection and audit is performed at a facility before it is allowed to turn on. It is extremely important that all electrical safety rules and standards be observed during the *design stage* of the project, since retrofit *after* the components are fabricated installed can be extremely expensive and time consuming.

Lead Insulation and Coil Covers

- Coil covers or careful coil taping is *required* to prevent direct personnel contact with any magnet conductor or bus connection under the following conditions:
  - IV > 150 V-Amperes or I > 30 Amps or V > 130 Volts or when the magnet stored energy is > 5 joules.
  - Coil covers are *recommended* for all magnets regardless of their operating condition since it is difficult to audit safety practices when many different magnets are installed in the typical beamline. The *hot end* of the coil cooling tubes (the fittings) must also be enclosed in the cover.
  - Safety rules require that *any removable section of a coil cover must be attached by at least four screws*.

Electrical Grounding

- Safety rules require all non-electrically powered accelerator components to be electrically grounded.
  - Magnet cores are often assembled from laminations which may or may not be electrically connected to each other or to the core structure.
    - As part of the core assembly procedure, a *single* weld bead is often specified, electrically connecting all magnet laminations together.
    - A *single* connection point is provided to attach a metal strap grounding the magnet core to the support girder or other ground point.

Coil Fabrication Specifications

- Specifications are written to assure coil quality and long life. If magnets are built "in house" or by vendors to designs completed by the customer, detailed specifications must be written. Certain design constraints and tests should be included in these specifications. The following list includes *recommendations* that may or may not be included in the specifications at the discretion of the magnet engineer/designer.

- The specification should require that coils are wound in a clean environment and not in a shop environment where metal chips are present. If metal chips are embedded in the potted coils, they can cause intermittent shorts that are difficult to detect and can be extremely troublesome.
- A single water circuit in a coil assembly should be wound from a *single continuous length* of conductor. Splices “buried” within the potted insulation should not be allowed.

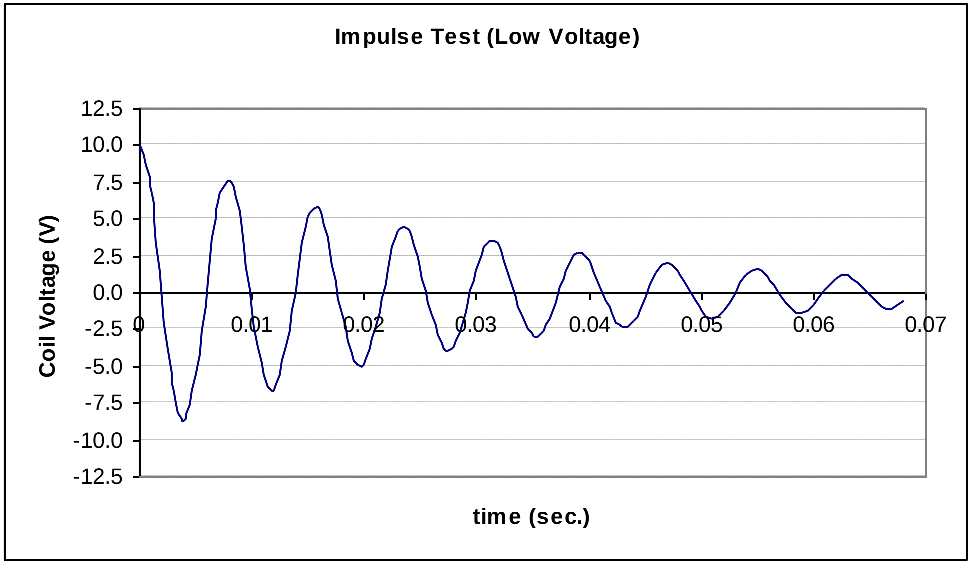
- Hollow aluminum conductors should be tested for leaks prior to winding. Aluminum conductors are usually assembled from four separate pieces which results in a conductor with four seams which run the length of the conductor. Leaks can occur in this type of fabrication. Copper conductor are extruded from a single piece of copper in a identical manner that small diameter tubes are fabricated. Therefore, one seldom encounters leaks in hollow copper conductor.
  - Usually, the leak test is a pneumatic test where the cooling channel is pressurized and the pressure monitored for some time (usually several hours).

- A *ball test* is specified for a conductor *before* it is wrapped into a magnet coil. This test consists of using high pressure air to blow a ball, no more than 80% of the diameter of the conductor hole, through the conductor water flow passage in order to ensure no blockage or collapsed passages.
  - For long conductor lengths, or small cooling hole diameter, this test is omitted. (Pneumatic pressure drops can be very high during this test.)
  - If the conductor vendor supplies long hollow conductor which is spliced, the location(s) of a splice should be clearly marked so that the continuity of the water cooling passage can be ensured.

Coil Tests

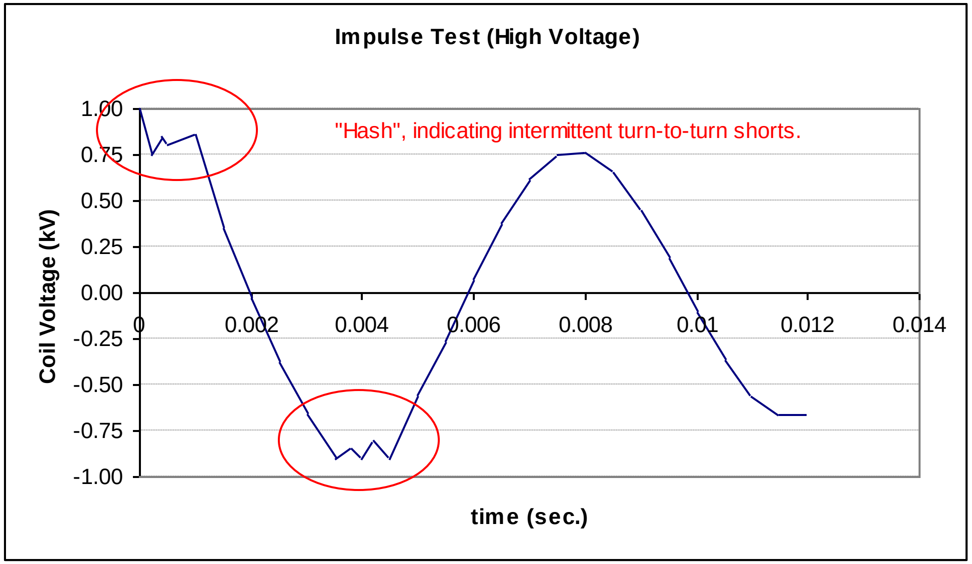
- An impulse test should be specified and photos of the scope trace should be required.
  - The test involves applying a short voltage pulse across a combination of a capacitor and the coil being tested and observing the current waveform detected by a shielded pickup loop in the coil. The waveform will be a damped sinusoidal oscillation. Its frequency and damping rate will depend on the parameters of the coil and the capacitor in the tester. The procedure consists of starting with a low voltage pulse (~ 10 Volts/turn) and increasing the voltage until one reaches 200 Volts/turn or 2 kV maximum and observing the waveform. For the ordinary water cooled coil, the required turn to turn voltage is a small fraction of a volt per turn. Thus, impulse tests at the capacity of the tester (a few kV) is more than sufficient.

- An impulse test is useful to determine whether intermittent shorts will occur since the turn to turn voltage during an impulse will exceed the voltage during DC operation. An impulse test is required in order to detect intermittent turn to turn shorts. This test can only be performed on a coil isolated from metallic surfaces and will not work once the coil is installed on the core. Core eddy currents and the iron permeability will mask the expected behavior of the electrical circuit.



- A *healthy* coil will exhibit the same waveform as the voltage is increased from test to test with only a variation in the amplitude. A *sick* coil will exhibit waveforms whose frequency and/or damping rate changes as the voltage increases or will exhibit *hash* at the peak of the damped sinusoid. A *dead* turn to turn short cannot be detected with the impulse tests unless the waveform can be compared to a good coil of the identical design. Even then, the wave form of a good coil with many turns will vary only slightly from the wave form of a coil with a *dead* turn to turn short of the same design.

Wave form for a coil with an *intermittent* short.



- The impulse test *must* be performed on all coils after potting and prior to installation of a magnet. *Optionally*, an impulse test can be performed *before* it is potted.
  - If the impulse test is performed on a coil both before and after potting, the voltage traces must be identical for the two tests.
  - Specifications should require photographs made of *all* the scope traces (low and high voltage, *optionally* before and *required* after potting) and delivered to the customer as part of the *Quality Assurance* (QA) documentation.

Null Measurements

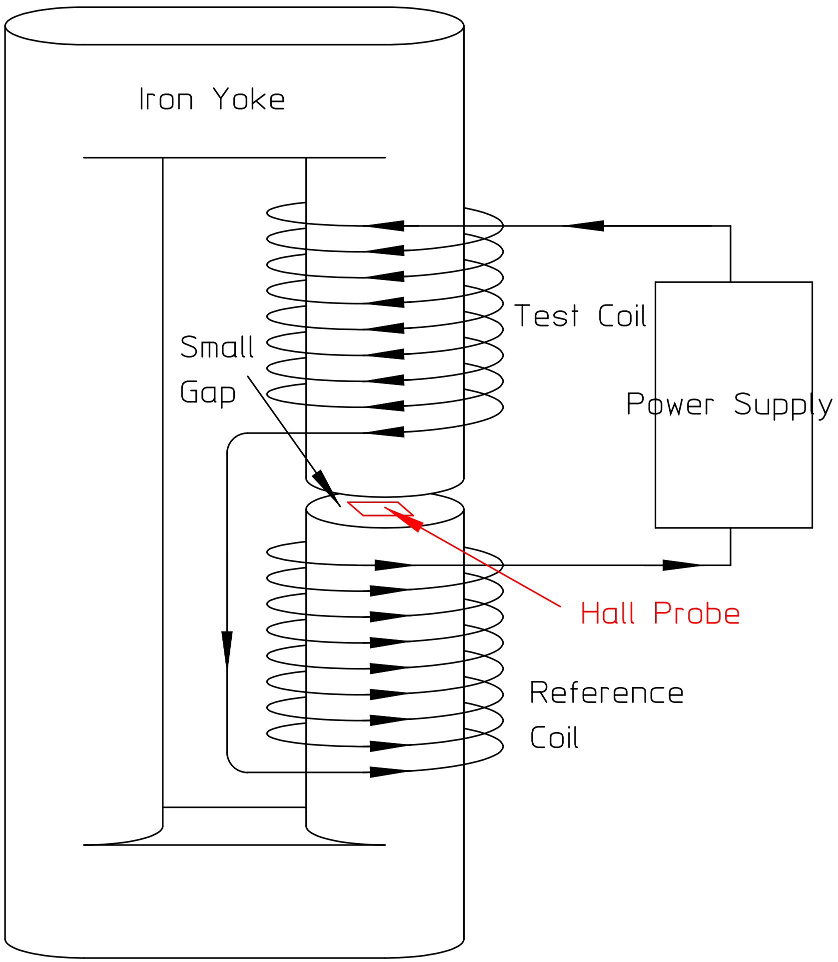
- For coils with a large number of turns, a precise resistance measurement prior to potting often *cannot* reveal the presence of a *dead* turn to turn short. This test is inaccurate since the conductor cross section may vary.
- For coils with a *large number of turns* of small conductor, a *null* measurement with two coils in a magnetic circuit can reveal differences in the number of turns of two otherwise identical coils.

- The coils are connected in opposite polarities
- The error in the number of turns can be measured using a Hall probe.

$$B = \frac{\mu_0 NI}{gap} = \frac{\mu_0 \left(NI_{reference} - NI_{test}\right)}{gap}$$

$$= \frac{\mu_0 I\left[N - \left(N - \Delta n\right)\right]}{gap}$$

$$= \frac{\mu_0 \Delta n \times I}{gap}$$



Hipot Test

- After potting, the coil should undergo a *hipot* test. The techniques used to hipot vary according to design. Vacuum potted coils with impermeable surfaces, can be immersed in salted water. A less risky technique is to wrap the insulated part of the coil in aluminum foil. Specifications normally call for raising the voltage in the coil to twice the operating voltage plus one kV. The maximum drainage current is usually set at 2 mAmps/kV.

Measurements

- *Water flow* calculations made for the preliminary design *may* be unreliable for a coil designed with many tight turns. This is due to the added flow impedance of tight radius turns. Thus, these measurements should be made carefully at the anticipated pressure differential available in the magnet water cooling system and the results compared for a number of coils with the same design *and* with design predictions. The ambient temperature should be recorded at the time of the measurement since the water flow is affected by the water viscosity which change substantially with temperature.
- *Coil resistance* should be carefully measured using a double bridge (so that current is not carried in the coil while measurements are being made) and compared with computed values. The ambient temperature when the resistance measurements were made should be recorded.

QA Travellers

- As part of the *Quality Assurance* procedure for coil fabrication and testing, a form (*Traveller*) is developed which is filled out, signed and dated by technicians performing coil fabrication and testing and signed and dated by the supervisor responsible for the fabrication and testing of coils.

- At a minimum, the Traveller contains the following information:
  - Coil type and *serial number*.
  - Name(s) of individual(s) inspecting and testing conductor and date of task completion.
    - Inspection includes leak tests, ball tests (if required) and locating conductor splices (if any).
  - Name(s) of individual(s) winding, insulating and ground wrapping the coil and date of task completion
  - Name(s) of individual(s) potting the coil and date of task completion
  - Name(s) of individual(s) *finishing* the coil and date of task completion
    - Finishing includes lead bending, soldering Klixon interlock blocks and lead blocks and soldering water fittings.

Coil QA Traveller Data

- In addition to the previously described information, the traveller should include the following measured data.
- Impulse test scope photographs at low and high voltages.
- Hipot test results.
  - Maximum Voltage
  - Measured leakage current (max $\leq$ 5 μAmps)
- Water Flow Test Results
  - Pressure Drop
  - Flow
  - Temperature
- Resistance
  - Value
  - Ambient temperature during measurement

Lecture 10

- Lecture 10 collects “loose ends” which have not been covered thus far.
- The subject of stored energy, and magnetic forces are covered in chapter 7.
- Stored energy is used to compute magnet inductance, which is used to compute power supply requirements for dynamic magnets, magnets with time varying magnetic fields.
- Although other dynamic effects (eddy currents) are covered in this chapter, this is a broad complex subject and will not be covered in the lectures.
- General principles for reducing fringe fields are covered.
- Means of minimizing errors in the magnet integrated field by chamfering to control the fringe fields are discussed.