Impulse testing of coils and magnets: present experience and future plans

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Impulse testing for LARP magnets

LARP impulse tester:

DWX-05 Winding Tester (ECG-Kokusai)

• 0.1-5 kV impulse voltage range
• 0.01 μF internal capacitor

• Impulse testing is a key electrical qualification procedure used by LARP for the past HQ, LQ and present MQXF series.

• It is the only available technique to access turn-to-turn and layer-to-layer insulation strength

• It is sensitive probe to shorts between coil winding and structural parts that are inaccessible for direct probing

• Impulse waveform oscillation frequency and decay rate contain a comprehensive information about coil L, C, R and overall integrity.
Present QXF impulse test schedule

1. **Individual coils**: impulse tests at 500 V, 1000 V, 1500 V and then with 100 V steps up to **2500 V**, 3 test pulses applied at each step.

2. **Assembled coil pack** before insertion into the iron yoke: impulse test on individual coil from 100 V to 500 V with steps of 100 V, 3 pulses per step.

3. **Assembled magnet**: impulse tests at 500 V, 1000 V, 1500 V and then with 200 V steps up to **2000 V**, 2 test pulses applied at each step.

   Apparently, the magnet test is **less stringent**, than the coil test...
A proposal for “sectional” magnet testing

**Problem:**

Quench protection simulations show up to 50 V peak voltages turn-to-turn in MQXF. A 50-turns coil then needs to be impulse tested at 2.5 kV (or higher??) to achieve this voltage. Then the full magnet requires 10 kV! Moreover, those numbers are for the helium gas conditions; in air the test voltage should be substantially higher...

**Proposal:**

1. **Impulse test magnet coils individually, using the “CLIQ” leads.** This should allow to increase the turn-to-turn test voltage up to required 50 V (seen in quench simulations) using ¼ of the impulse voltage we would otherwise need to apply to the full magnet.

2. **Do it right after the cold test, when the magnet is already warm, but still sits in the cryostat in helium gas.** The voltage breakdown threshold should be lowest at this condition. If we qualify each coil at 50 V turn-to-turn, this should automatically qualify the entire magnet.

**Is it feasible?**

(G. Ambrosio)
(1) We need to know the turn-to-turn voltage distribution in the coil under test, and understand the effect of the floating portions of the winding.

(2) At 1 bar (760 Torr) the minimum of the Paschen curve for He corresponds to a 25 μm gap. One can vary the cryostat pressure to “scan” the relevant gap range.
Pulse transient

Free coil oscillations

HV discharge test zone

Energy loss / period variation test zone

**Principle of the impulse test**

- **I**: SCR* closes, charged capacitor C is connected to the coil
- **II**: SCR opens, capacitor C is disconnected from the coil

* Silicon Controlled Rectifier

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* Image of a circuit diagram showing a charged capacitor C connected to a coil through a silicon controlled rectifier (SCR), leading to various test zones.

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* Image of a graph showing a pulse transient and free coil oscillations, with labels for coil voltage (inverted), control voltage, HV discharge test zone, and energy loss/period variation test zone.

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* Text highlighting the sequence of events:
  - SCR* closes, charged capacitor C is connected to the coil.
  - SCR opens, capacitor C is disconnected from the coil.
Once SCR closes, the capacitor charge $q=CU_0$ redistributes between $C$, $C_p$ and $C_g$. Then: $U_{test} \sim U_0 C / (C+C_p+C_g)$

When setting a master waveform, the tester sequentially increases internal $U_0$, until $U_{test}$ equals to the set test voltage. 

In case $C_p+C_g >> C$ the required $U_{test}$ may be not reachable.
Relevance of the two test “zones”

I - High voltage test zone

- Insulation failure between the coil winding and the structural elements
- Turn-to-turn insulation failure

- Both types of failure are characterized by a sudden increase in high-frequency voltage noise ("flutter"), and a significant waveform shape variation

- If an intermittent short to structure is formed during the test, the waveform period will suddenly change, and stay changed into the “free oscillation” region.

“Qualification” – prior to the magnet test

II - Energy loss / period variation test zone

- Degradation of the insulation resulting in a capacitance change (waveform period)
- “Solid” shorts to structure, or between the turns (waveform period)
- Significant increase in losses due to eddy currents, hysteretic effects, resistivity, or corona discharge (waveform decay rate)

“Consistency check” – post test and during magnet operation
Impulse testing: good coil examples

86-turn “air core” solenoid

LARP HQ Coil 15

No new features appear as impulse voltage increases, and waveform period is independent of the test voltage.
Impulse testing: coil failure examples

Turn-to-turn short suddenly forms during the high voltage phase of the test; the waveform period subsequently increases into the low-voltage zone.

Multiple intermittent spikes, instabilities due to insulation failure. Loss has suddenly increased on the third impulse, resulting in the drop of waveform amplitude.

HQ Coil 3

Turn-to-turn breakout failure

HQ Coil 18

Inter-layer short, corona discharge

3 consecutive pulses
Effect of the stray capacitance ($C_g$)

Original “master” waveform

“High” end shorted to structure

Period increased

“Low” end shorted to structure

No period change
LARP LQ magnet

All coils are separate (no “pizza box”)

Capacitance of another coil connected to the positive end increases waveform period
Effect of the inductive coupling loss

Master curve (red) – lead “x” is floating
Impulse test (white) – lead “x” is connected to the “hot” end

Period decreased, as the dynamic inductance of the probed half-coil half is lowered by the shorted other half of the coil.
Electrical compensation of the floating ends

Proposal:

Test two electrically adjacent coils in parallel; effect of the rest of the magnet is eliminated by grounding the symmetric grounding of the remaining CLIQ leads.

These three tests allow testing of coils turn-to-turn insulation at nominal (for single coils testing) voltage within the assembled magnet, and not affected by the stray L and C.
Testing magnet wired to the test facility

Same approach allows for testing the magnet while connected to the power supply of the test facility. An optional capacitor across the coils that are not being tested may be necessary (to eliminate inductive pickup to the tester and HV spike on the PS).

Coils can be continuously monitored with impulse test during magnet operation, if protection resistors are used.
Voltage distribution in the coil under test?

A self-resonant coil can be potentially treated as an open *transmission line*, with a distribution of inductances and capacitances along the length defined by the geometry and environment.

A simplest equivalent circuit:

A possible close analog: dipole antenna
Impulse voltage amplitude was probed between the ground terminal and every 5th turn of the coil using an oscilloscope probe.

Turn-to-turn voltage was found to follow a superposition of an “S-shaped” and linear dependences.
Impulse test at 100 V. The outer layer (B2) is at ground, the inner layer (A2) is “high”.

Impulse tester waveform

Oscilloscope waveform
Impulse voltage distribution in the HQ coil

- Non-linear voltage distribution!
- Turn-to-turn voltage increases towards the pole
Localizing electrical breakdowns

By comparing voltage distribution along the coil winding with that of the “reference” coil, and by monitoring impulse waveforms on insulated structural parts (central island, endshoes), the locations of insulation breakdown, turn-to-turn, layer-to-layer and coil to structure shorts can be determined.
Work in progress

- Simulations (M.M., E.R.)
  - Use QXF mutual inductance matrix calculated by ROXIE + estimates for the capacitances (turn-to-turn, layer-to-layer) to generate a realistic equivalent schematics
  - Study transient oscillations using circuit simulator, and generate voltage distribution plots for various test configurations
  - Create an optimized test schedule consistent with the 50 V turn-to-turn requirement

- Measurements
  - Measure impulse voltage distribution along the V-taps and structural parts
  - Turn-to-turn measurement using a “practice” QXF coil (in progress at FNAL)
Thank you!