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Powering and protection of the MQXF test facility at FNAL using STEAM-COSIM

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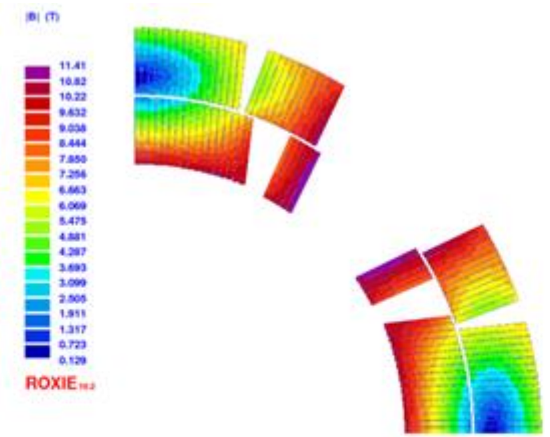
The MQXF magnet

- MQXF is the new low-beta quadrupole for the interaction regions of HiLumi LHC
  – Will be responsible of beam focusing close to interaction points
- Half of these magnets are in production in USA laboratories under the AUP project (BNL, FNAL, LBNL)



- We produce 4.2 m long coils, assemble magnets, and then assemble two magnets in series in one cryostat
  – At FNAL we will test the final cryoassembly in a longitudinal test facility, before final delivery at CERN

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Goals and assumptions of the horizontal test

- During the horizontal test, we will need to:
  - Power and train the magnet to ultimate current (17530 A)
  - Ensure machine-like protection system works as expected
- The protection system needs to be as similar as possible to the one that will be used in machine
- During testing, we have to make sure that all electrical design criteria are addressed during testing, including in failure scenarios

Electrical design criteria

- We have electrical design criteria that define peak voltages that we cannot overcome during testing
  - Voltage to ground, turn-turn voltage, heater-to-coil voltage…

EDMS NO.	REV.	VALIDITY
1963398	5.2	VALID

REFERENCE : LHC-MQXF-ES-0001
US HL-LHC-AUP#: US-HiLumi-doc-879

ENGINEERING SPECIFICATION

ELECTRICAL DESIGN CRITERIA FOR THE HL-LHC INNER TRIPLET MAGNETS

Abstract

This document describes the strategy to be applied in order to define the voltage withstand levels for the MQXF superconducting magnets manufactured both under the US HL-LHC Accelerator Upgrade Project and CERN. The values presented here will be the reference to be used during the reception tests, further qualifications, installation and commissioning as systems in the LHC tunnel.

TRACEABILITY

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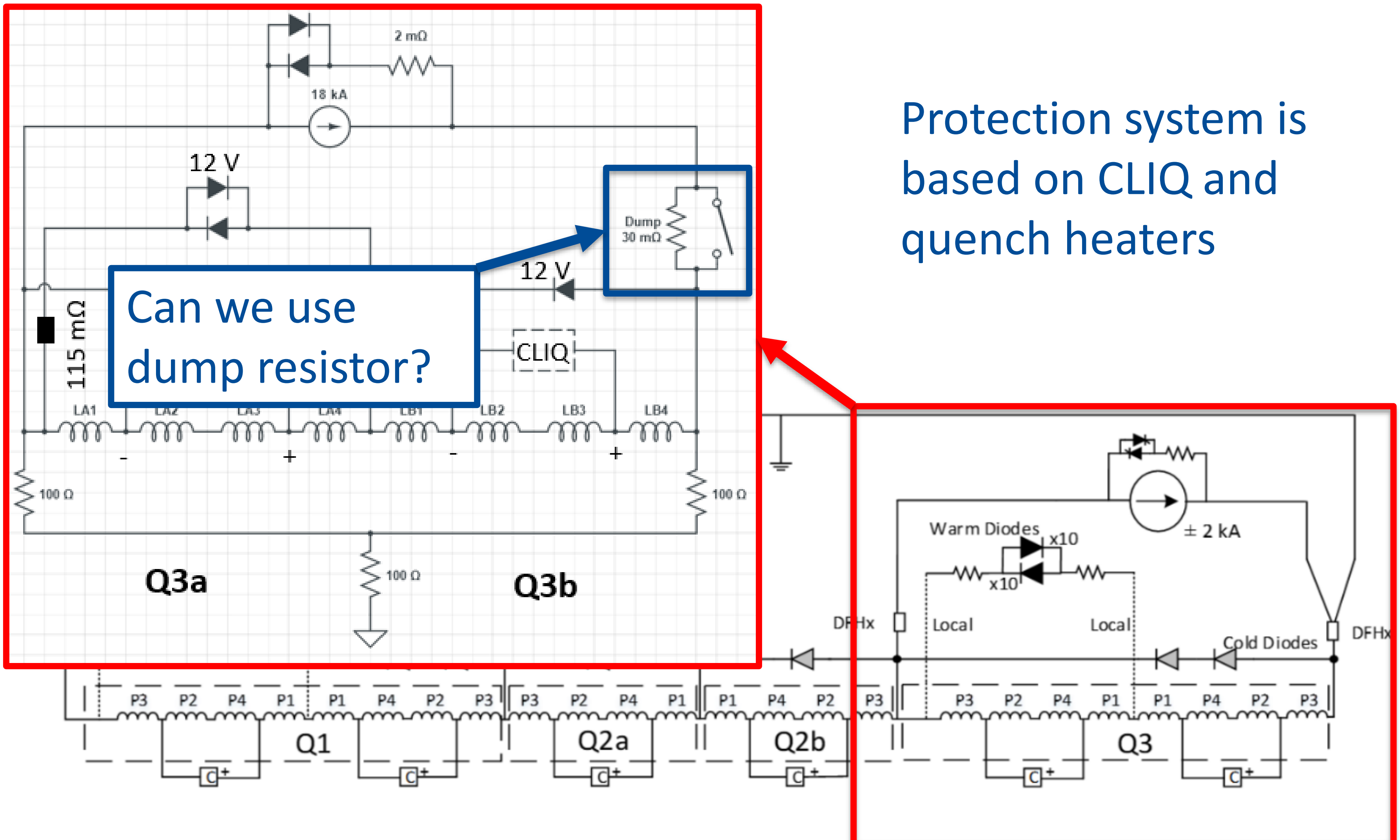
Quench protection circuit

Protection system is based on CLIQ and quench heaters



Simulation needs

- Quench protection system is an intricate circuit
  - Available quench simulation softwares have much simpler built-in circuits

- While it is always possible to make assumptions, we need to
  - Make sure that every point of the magnet addresses electrical design criteria, also in failure scenarios
  - Dimension all components of the circuit in order to make sure that they are within specifications during a quench
    - Diodes, resistors, leads…
  - Understand if we can use a dump resistor safely

- Due to the complexity of the problem, I decided to exploit suitable features of the STEAM network

SING to build the protection circuit

- In order to build the protection circuit, I used the SING Notebook
  - Creates a netlist that can be used as input for LTSpice
    - Circuit solver
  - Using available documentation, I created my personal notebook to create different versions of the horizontal facility FNAL station

- At the end, I got a perfect, parametric representation of the horizontal test station circuit, ready to be solved with a proper circuit solver

CLIQ units

In [13]:

```
# CLIQ unit (units). Here the first port is negative
# Six different library components are used for the six CLIQ units,
# to allow setting six different triggering times
netlist.add(CommentElement("* CLIQ unit (units). Here the first port is negative"))
netlist.add(CommentElement("* Six different library components are used for the six CLIQ units,"))
netlist.add(CommentElement("* to allow setting six different triggering times"))
cliqParameters = a.create_string_array(gateway, ["C_cliq", "R_cliq"])
cliqValues = a.create_string_array(gateway, ["0.04", "0.05"])

cliq1Nodes = a.create_string_array(gateway, ("MAGQ1a_4", "MAGQ1a_2"))
cliq1Attribute = "cliq_unit_1"
netlist.add(ParameterizedElement("xcliqQ1a", cliq1Nodes, cliq1Attribute, cliqParameters, cliqValues))
netlist.add(CommentElement("*"))

cliq2Nodes = a.create_string_array(gateway, ("MAGQ1b_1", "MAGQ1b_6"))
cliq2Attribute = "cliq_unit_2"
netlist.add(ParameterizedElement("xcliqQ1b", cliq2Nodes, cliq2Attribute, cliqParameters, cliqValues))
netlist.add(CommentElement("*"))

cliq3Nodes = a.create_string_array(gateway, ("MAGQ2a_4", "MAGQ2a_2"))
cliq3Attribute = "cliq_unit_3"
netlist.add(ParameterizedElement("xcliqQ2a", cliq3Nodes, cliq3Attribute, cliqParameters, cliqValues))
netlist.add(CommentElement("*"))

cliq4Nodes = a.create_string_array(gateway, ("MAGQ2b_1", "MAGQ2b_6"))
cliq4Attribute = "cliq_unit_4"
netlist.add(ParameterizedElement("xcliqQ2b", cliq4Nodes, cliq4Attribute, cliqParameters, cliqValues))
netlist.add(CommentElement("*"))

cliq5Nodes = a.create_string_array(gateway, ("MAGQ3a_4", "MAGQ3a_2"))
cliq5Attribute = "cliq_unit_5"
netlist.add(ParameterizedElement("xcliqQ3a", cliq5Nodes, cliq5Attribute, cliqParameters, cliqValues))
netlist.add(CommentElement("*"))

cliq6Nodes = a.create_string_array(gateway, ("MAGQ3b_1", "MAGQ3b_6"))
cliq6Attribute = "cliq_unit_6"
netlist.add(ParameterizedElement("xcliqQ3b", cliq6Nodes, cliq6Attribute, cliqParameters, cliqValues))
```

Quench simulation

- Problem: circuit solver can handle time dependand resistant, but, in a quench problem
  - Resistance depends on the current
  - Current depends on the resistance
  - Transient problem, not manageable by simply using a quench software to get the resistance, and use output resistance in the circuit solver software

- STEAM-COSIM can interface a quench simulation software with a circuit solver
  - LEDET + LTSpice
    - Ledet: quench heaters, quench propagation
    - LTSpice: CLIQ, Diodes, Power Supply, leads,…

LEDET input

- I created a MQXF LEDET input
  - LEDET notebook with magnet parameters
  - Handles resistance vs time computation
- Using documentation and available notebooks, I created a notebook that produces a COSIM input for interfacing LEDET input and LTSpice circuit created with SING previously


```
{
    "coSimulationDir": "C:\\cernbox\\RQX_HL-LHC\\COSIM\\Output\\",
    "coSimulationModelSolvers": [
        "PSPICE",
        "LEDET",
        "LEDET",
        "LEDET",
        "LEDET",
        "LEDET",
        "LEDET"
    ],
    "coSimulationModelDirs": [
        "C:\\cernbox\\SWAN_projects\\steam-notebooks\\steam-sing-input\\RQX_HL-LHC\\cosim_model_RQX_HL-LHC\\PSpice\\",
        "C:\\cernbox\\SWAN_projects\\steam-notebooks\\steam-sing-input\\RQX_HL-LHC\\cosim_model_RQX_HL-LHC\\LEDET_1\\",
        "C:\\cernbox\\SWAN_projects\\steam-notebooks\\steam-sing-input\\RQX_HL-LHC\\cosim_model_RQX_HL-LHC\\LEDET_2\\",
        "C:\\cernbox\\SWAN_projects\\steam-notebooks\\steam-sing-input\\RQX_HL-LHC\\cosim_model_RQX_HL-LHC\\LEDET_3\\",
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    ],
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        "LedetInputOutputPortDefinition.json",
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        "LedetInputOutputPortDefinition.json"
    ],
    "convergenceVariables": [
        "I(x_mag_1.L_1)",
        "U_inductive_dynamic_CoilSections_1",
        "U_inductive_dynamic_CoilSections_1",
        "U_inductive_dynamic_CoilSections_1",
        "U_inductive_dynamic_CoilSections_1",
        "U_inductive_dynamic_CoilSections_1",
        "U_inductive_dynamic_CoilSections_1"
```

Final outcome

- Using STEAM-SING, STEAM-LEDET and STEAM-COSIM, i am able to perform a complete quench simulation with CLIQ and quench heaters inside a complex circuit
- I can therefore estimate hot spot temperature with quench simulation software, but also compute peak voltages in every point of the circuit during a quench, and know current/voltage in every circuit component
- I can evaluate effects of failure scenarios and circuit changes on peak voltages

List of simulations

1. No Dump, No CLIQ failures, 12 V bypass diodes on Q3a
2. No Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a

2b. No Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a (Q3a didode resistance is 200 mOhm instead than 115 mOhm)

3. No Dump, No CLIQ failure, no diodes on Q3a
4. No Dump, Q3a CLIQ failure, no diodes on Q3a
5. 30 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a
6. 30 mΩ Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a
7. 30 mΩ Dump, No CLIQ failure, no diodes on Q3a
8. 30 mΩ Dump, Q3a CLIQ failure, no diodes on Q3a
9. 2.5 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a

14. No Dump, Q3a CLIQ failure, no diodes on Q3a, magnet midpoint grounded

18. 30 mΩ Dump, Q3a CLIQ failure, no diodes on Q3a, magnet midpoint grounded

25. 15 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a

26. 15 mΩ Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a

35. 30 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a, 10 ms dump delay

36. 30 mΩ Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a, 10 ms dump delay

Simulation results

	CASE	Peak Q3a Magnet Voltage To-ground [V]	Peak Q3b Magnet Voltage To-ground [V]	Peak magnet midpoint voltage To-Ground [V]	Peak Q3a diodes current [A]	Peak current to-ground [A]	Hot Spot Temperature [K] (a/b)	Energy dissipated into dump resistor* [%]
No Dump	1	459	459	100	$26 \cdot 10^{-3}$	$0.6 \cdot 10^{-6}$	233/233	N/A
	2	434	481	300	1200	$0.25 \cdot 10^{-6}$	279/246	N/A
	2b	435	480	300	1100	$0.25 \cdot 10^{-6}$	279/246	N/A
	3	459	459	100	N/A	$0.6 \cdot 10^{-6}$	233/233	N/A
	4	1238	1227	1238	N/A	$0.25 \cdot 10^{-6}$	263/271	N/A
30 mΩ	5	764	462	462	500	$0.4 \cdot 10^{-6}$	215/229	6.94
	6	671	466	671	700	$0.3 \cdot 10^{-6}$	239/241	
	7	1042	768	768	N/A	$0.5 \cdot 10^{-6}$	231/239	
	8	1744	1240	1240	N/A	$0.2 \cdot 10^{-6}$	237/250	
2.5 mΩ	9	480	460	120	0.1	$0.6 \cdot 10^{-6}$	231/232	
As 4	14	1044	1033	1044	N/A	$0.35 \cdot 10^{-6}$	263/271	
As 8	18	1512	1009	1500	N/A	$0.4 \cdot 10^{-6}$	237/250	
15 mΩ	25	612	463	230	270	$0.4 \cdot 10^{-6}$	224/232	3.58
	26	444	468	444	900	$0.35 \cdot 10^{-6}$	258/244	
30 mΩ 10 ms	35	515	459	459	440	$0.4 \cdot 10^{-6}$	223/233	6.37
	36	703	467	250	800	$0.3 \cdot 10^{-6}$	247/243	

Conclusions

- Using STEAM-SING and STEAM-COSIM I have been able to
  - Produce LTSpice circuit of the FNAL horizontal test facility for MQXF testing
  - Producing LEDET input file of MQXF
  - Producing a cosimulation of LTSpice and LEDET to solve quench protection inside a complex circuit
  - Evaluate quench protection of MQXF inside the FNAL circuit, making sure that it is conform with machine expected performance, and electrical design criteria
  - Evaluate single circuit component behavior during a quench, to ensure that parameters are within specifications