Update On Powering Of Inner Triplet Circuit

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6th HL-LHC Collaboration Meeting

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Input from contributors of the Magnet Circuit Forum: Felix Rodriguez Mateos, Emmanuele Ravaioli, Susana Izquierdo, WP2, WP3, WP6a, WP6b, WP7, WP9, WP15, WP16, WP17

https://espace.cern.ch/project-HL-LHC-Technical-coordination/MCF

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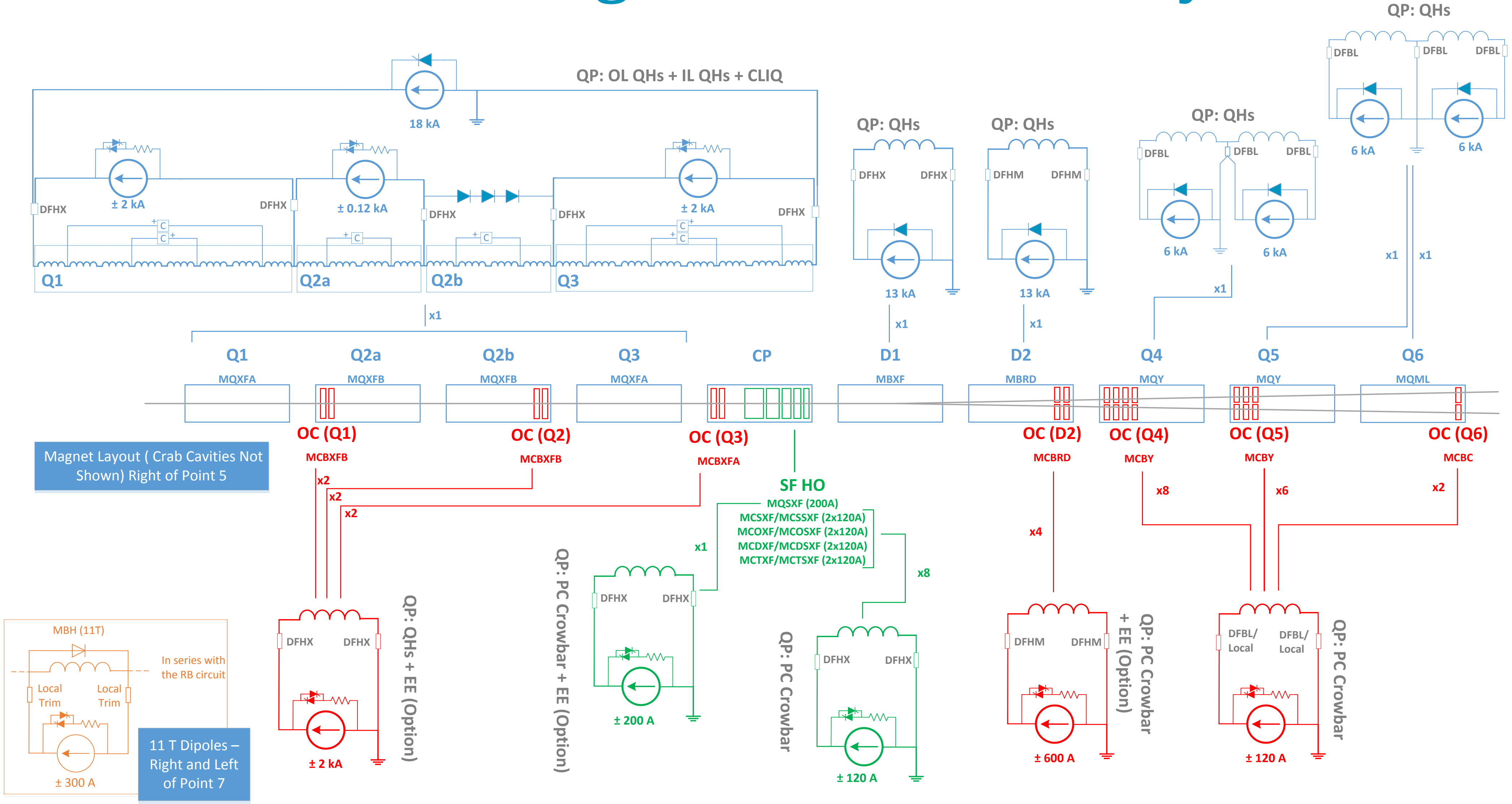
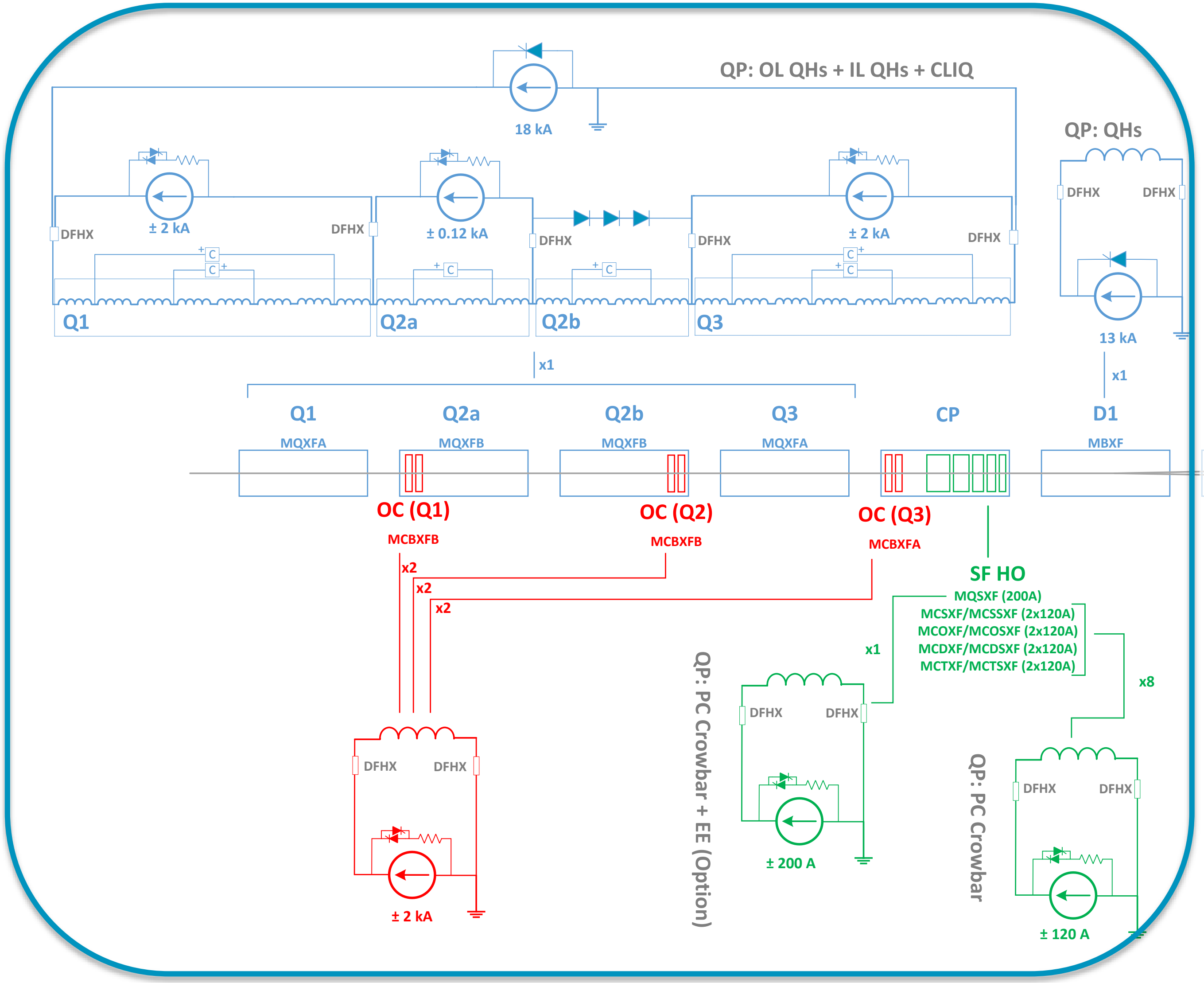


Magnet Layout (Crab Cavities Not Shown) Right of Point 5

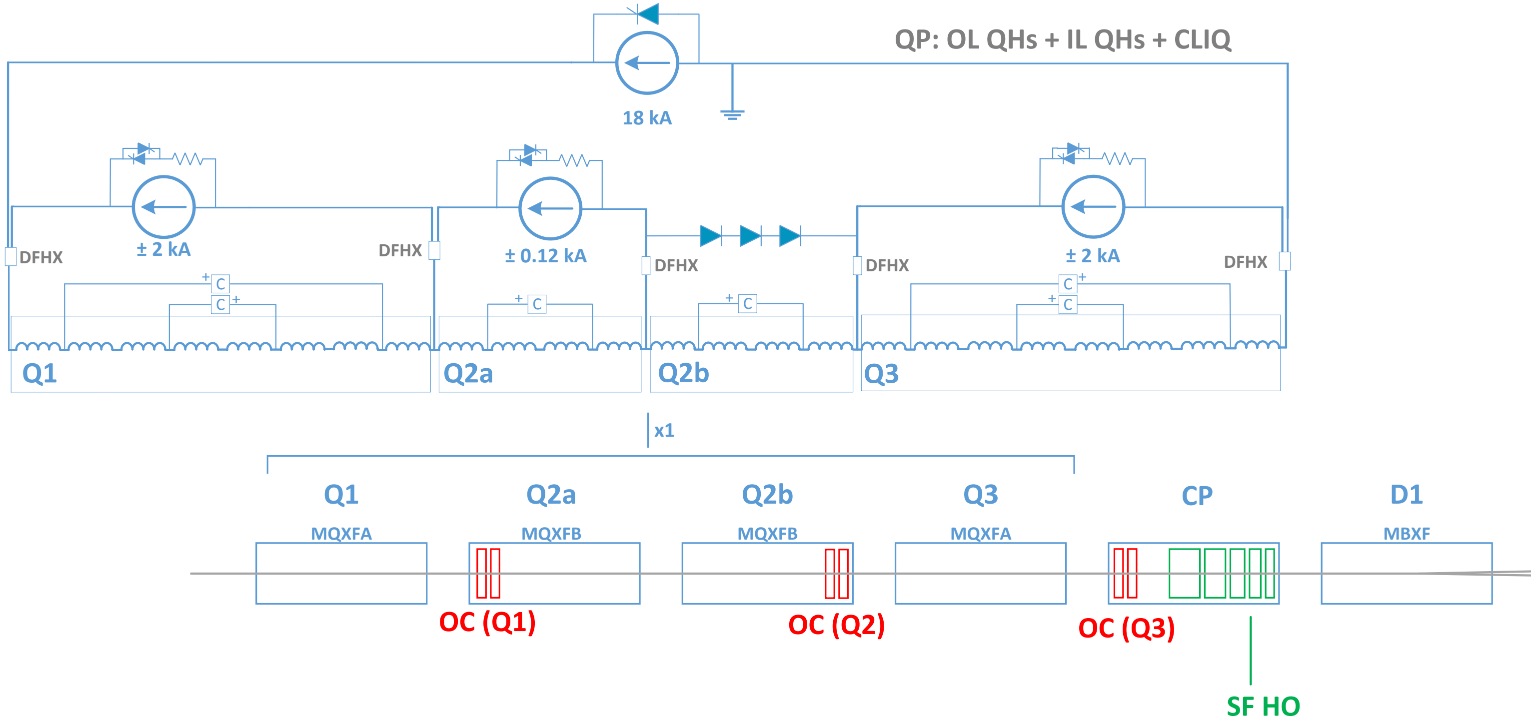
11 T Dipoles – Right and Left of Point 7

HL-LHC Inner Triplet Circuits



- **Definition:**
  - All circuits powered by the DFHX
- **Main Circuits:**
  - Main quadrupole circuit: Q1, Q2a, Q2b, Q3
  - D1 circuit
- **Orbit Correctors of MQ:**
  - MCBX
- **Superferric High Order Correctors**
  - MQSX
  - MCSX/MCSSX
  - MCOX/MCOSX
  - MCDX/MCDSX
  - MCTX/MCTSX

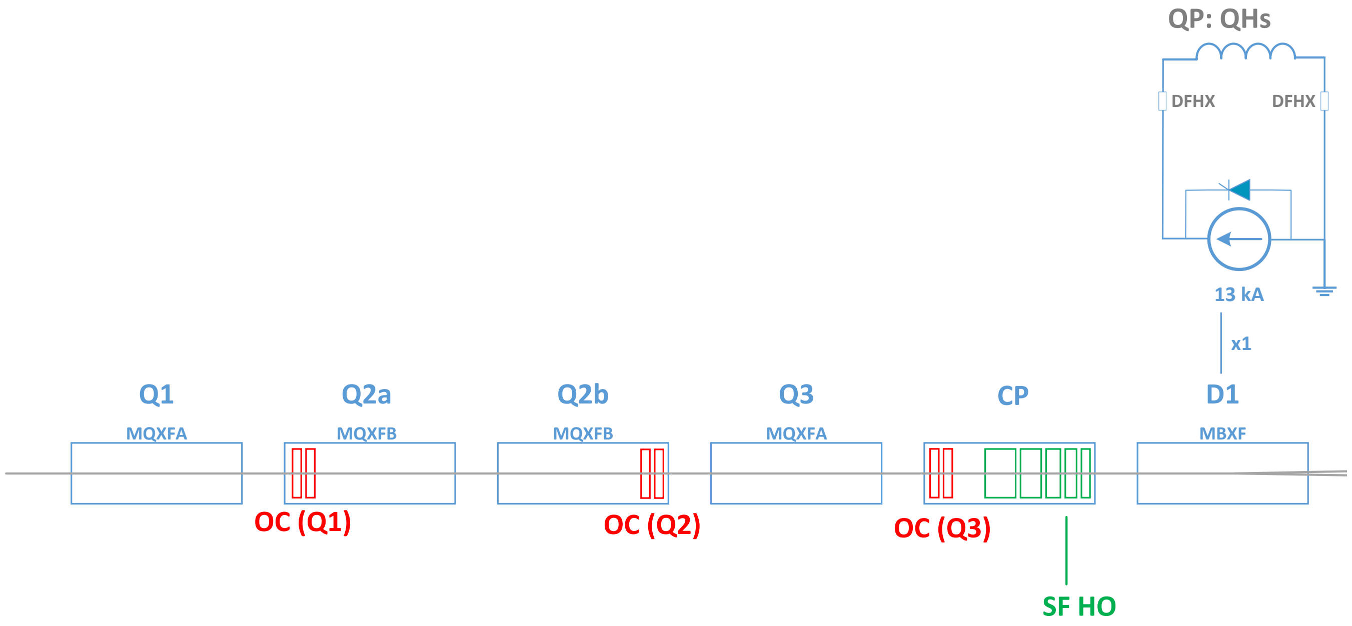
HL-LHC Inner Triplet Circuits



- MQ Circuits:
  - 1 main circuits per IP
    - 18 kA / Unipolar in Current – 2Q
  - 3 trim circuits par IP
    - 2 x 2 kA / Bipolar in Current – 4Q (Q1 and Q3)
    - 1 x 0.12 kA / Bipolar in Current – 4Q (Q2a)

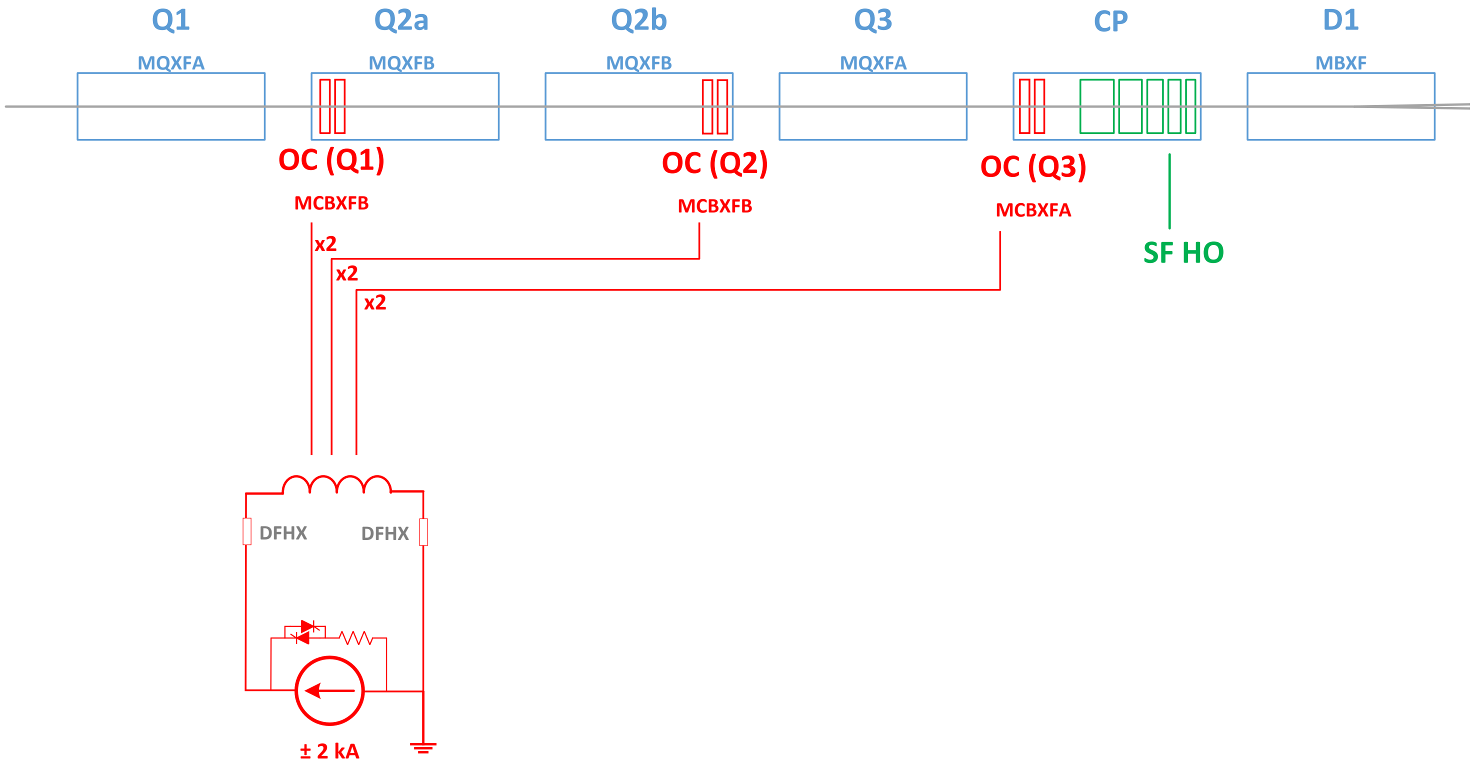
- Magnet Protection (E = 41 MJ):
  - Outer Layer Quench Heaters
  - CLIQs
  - Inner Layer Quench Heaters

HL-LHC Inner Triplet Circuits



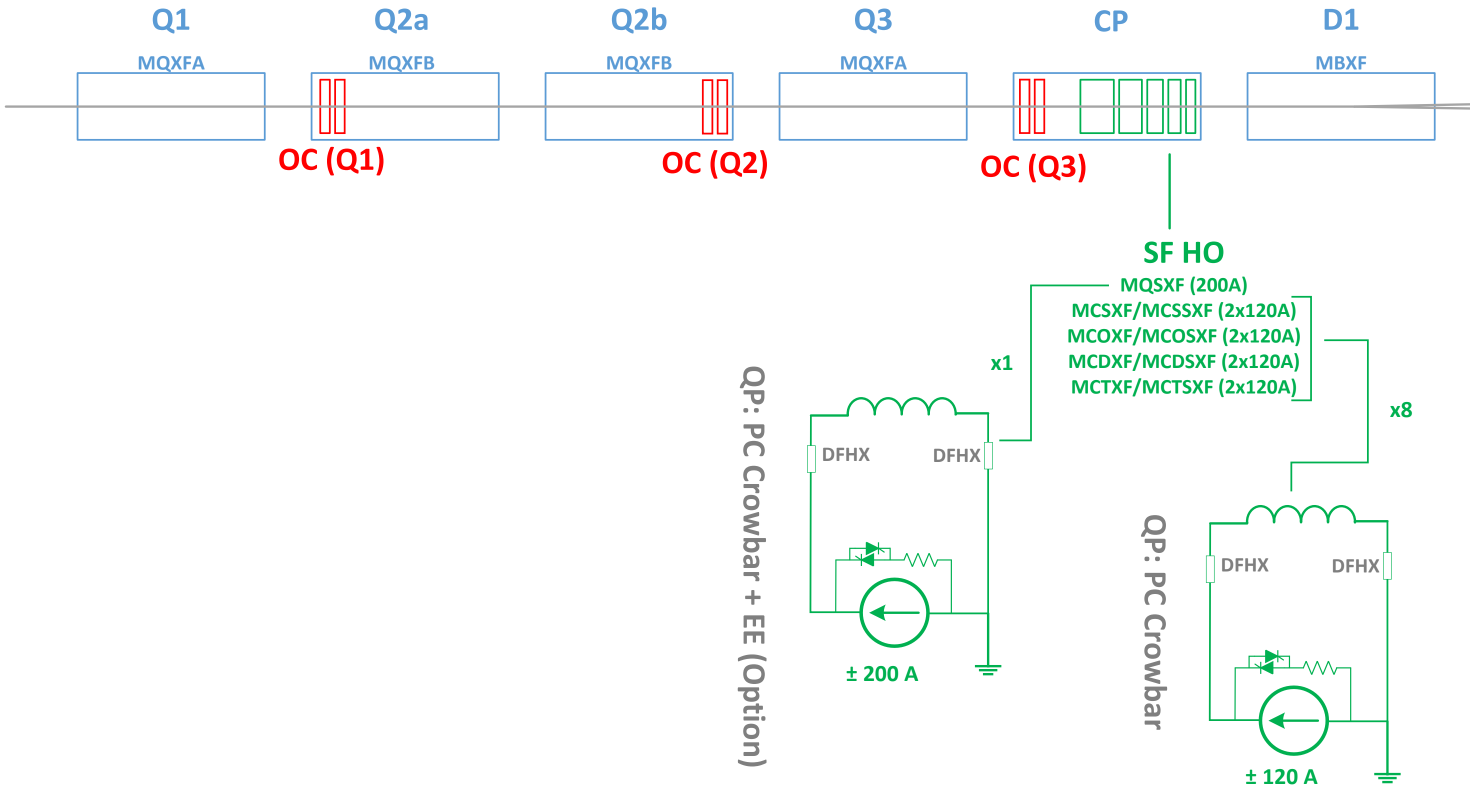
- D1Circuits:
  - 1 circuits per IP
  - 13 kA / Unipolar in Current – 1Q
- Magnet Protection:
  - Quench Heaters (E = 2.3 MJ)

HL-LHC Inner Triplet Circuits



- Orbit Corrector Circuits:
  - 6 circuits per IP
  - 2 kA / Bipolar in Current – 4Q
- Magnet Protection:
  - Quench Heater (baseline)
  - Energy Extraction (Option – 90 to 320 kJ)

HL-LHC Inner Triplet Circuits



- SHOC Circuits:
  - 9 circuits per IP
  - 0.12 or 0.2 kA / Bipolar in Current – 4Q
- Magnet Protection:
  - PC crowbar (E < 2 kJ)
  - Energy Extraction (Option)

HL-LHC Inner Triplet Circuits

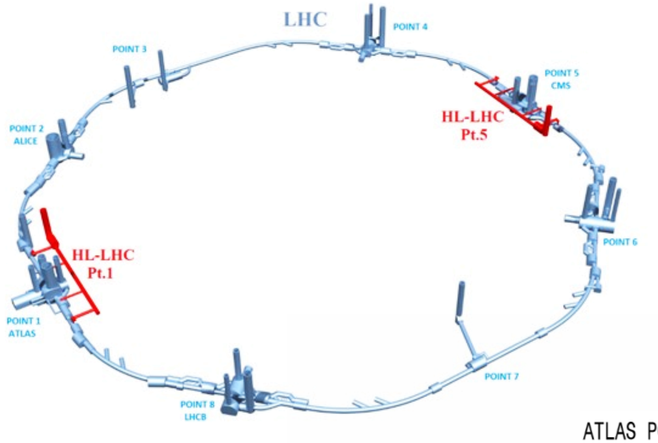
Circuits for HiLumi	Magnet Type	Number of circuits per IP side	I_nominal (7 TeV) [kA]	I_ultimate [kA]	L per circuit [mH]	R per circuit [mΩ]	Time constant [s]	E [kJ]	Protection
Triplet Q1, Q2a, Q2b, Q3	MQXFA / MQFXB	1	16.5	17.82	255	0.264	965.91	40487.9	OQH + CLIQ + IQH
Trim Q1	-	1	2	2	69	1.44	47.92		
Trim Q3	-	1	2	2	69	1.44	47.92		
Trim Q2a	-	1	0.12	0.12	58.5	13.372	4.37		
Orbit correctors Q2a/b - vertical	MCBXFB	2	1.6	1.73	59	1.512	39.02	88.3	QH (+ EE)
Orbit correctors Q2a/b - horizontal	MCBXFB	2	1.47	1.59	135	1.656	81.52	170.6	QH (+ EE)
Orbit correctors CP - vertical	MCBXFA	1	1.6	1.73	109	1.728	63.08	163.1	QH (+ EE)
Orbit correctors CP - horizontal	MCBXFA	1	1.47	1.59	247	1.728	142.94	312.2	QH (+ EE)
Superferric, order 2	MQSXF	1	0.182	0.2	1247	9.853	126.56	24.9	PCC
Superferric, order 3, normal and skew	MCSXF / MCSSXF	2	0.105	0.12	118	13.372	8.82	0.8	PCC
Superferric, order 4, normal and skew	MCOXF / MCOSXF	2	0.105	0.12	152	13.372	11.37	1.1	PCC
Superferric, order 5, normal and skew	MCDXF / MCDSXF	2	0.105	0.12	107	13.372	8.00	0.8	PCC
Superferric, order 6	MCTXF	1	0.105	0.12	229	13.372	17.13	1.6	PCC
Superferric, order 6, skew	MCTSXF	1	0.105	0.12	52	13.372	3.89	0.4	PCC
Separation dipole D1	MBXF	1	12	12.96	27	0.27	100.00	2267.5	QH

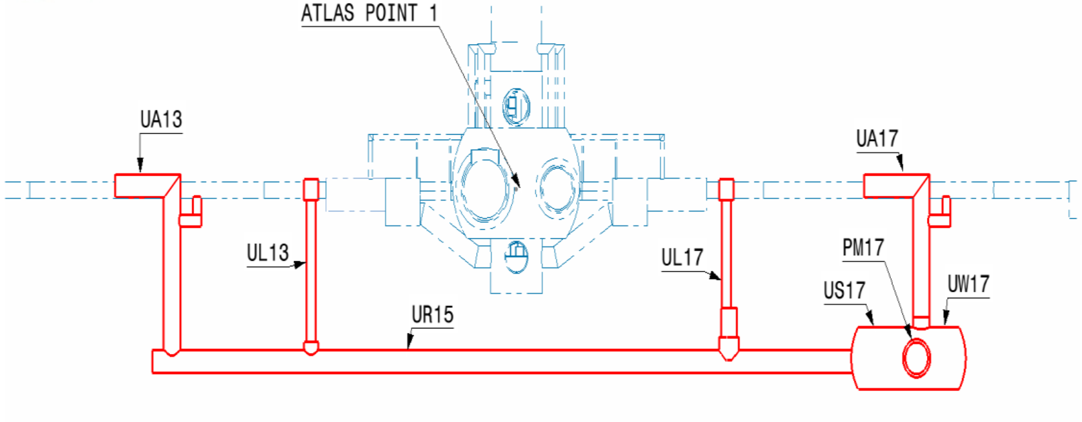
02

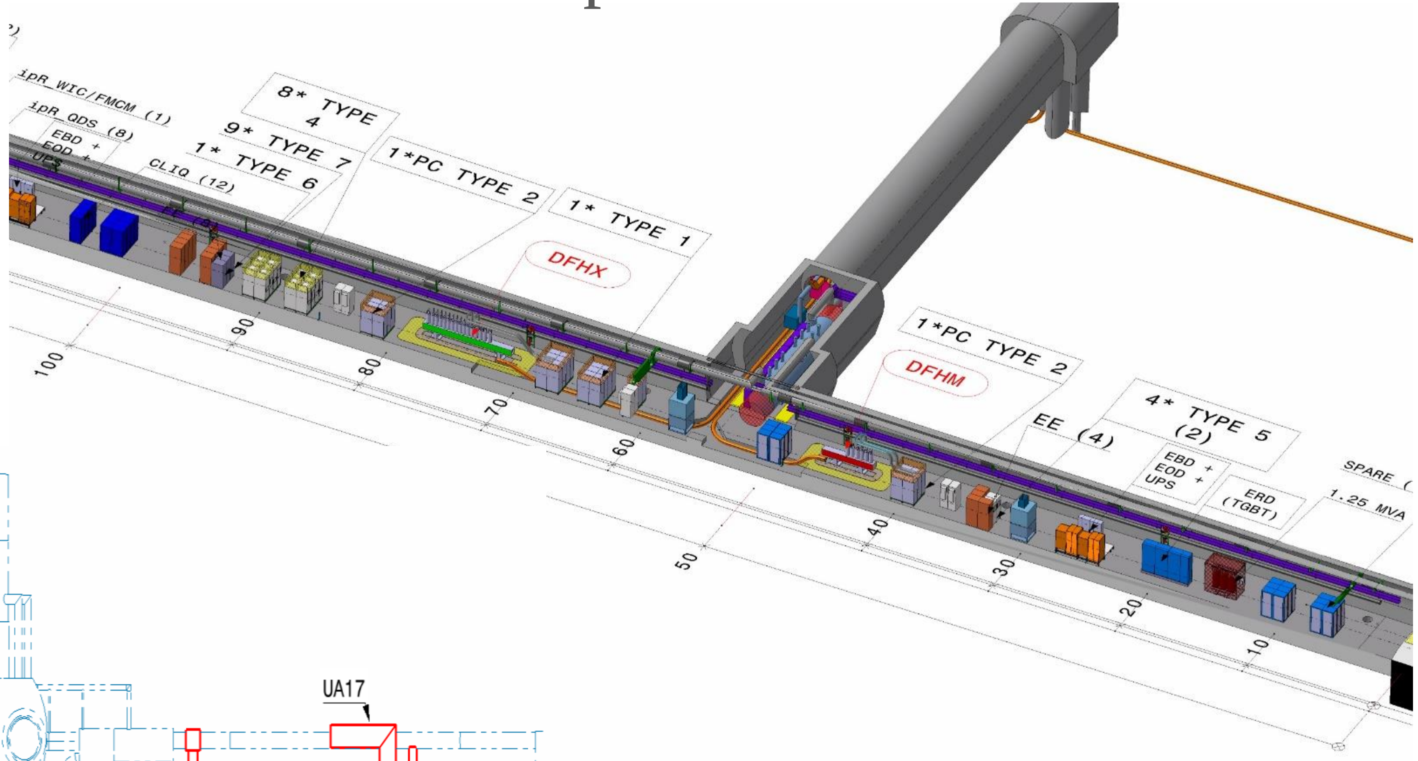
Powering of the Main Quadrupoles Circuit

Power Converters for the MQ Circuit

- Inner triplet PCs will be placed in the URs at points 1 and 5

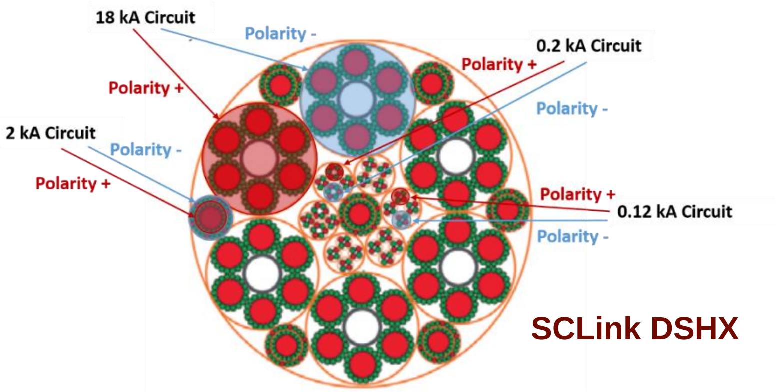


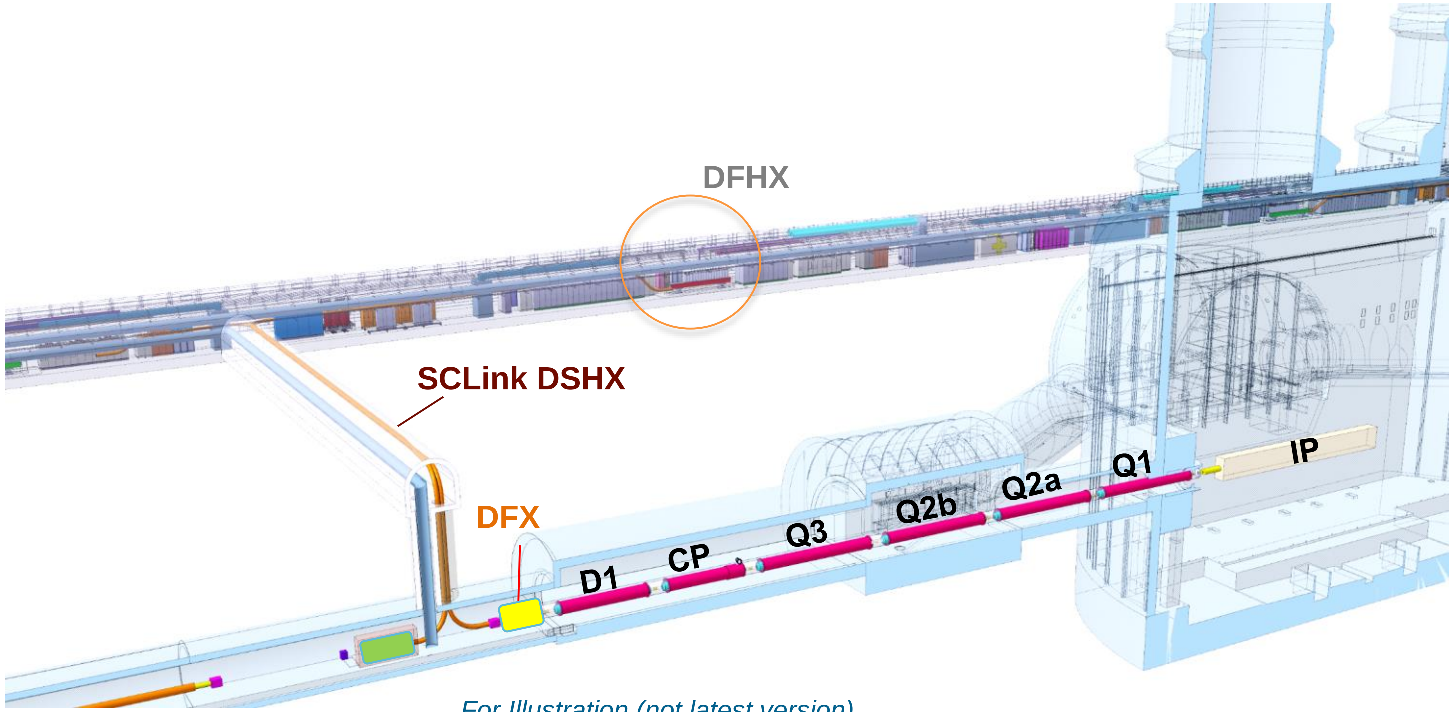




Cold Powering of the MQ Circuit

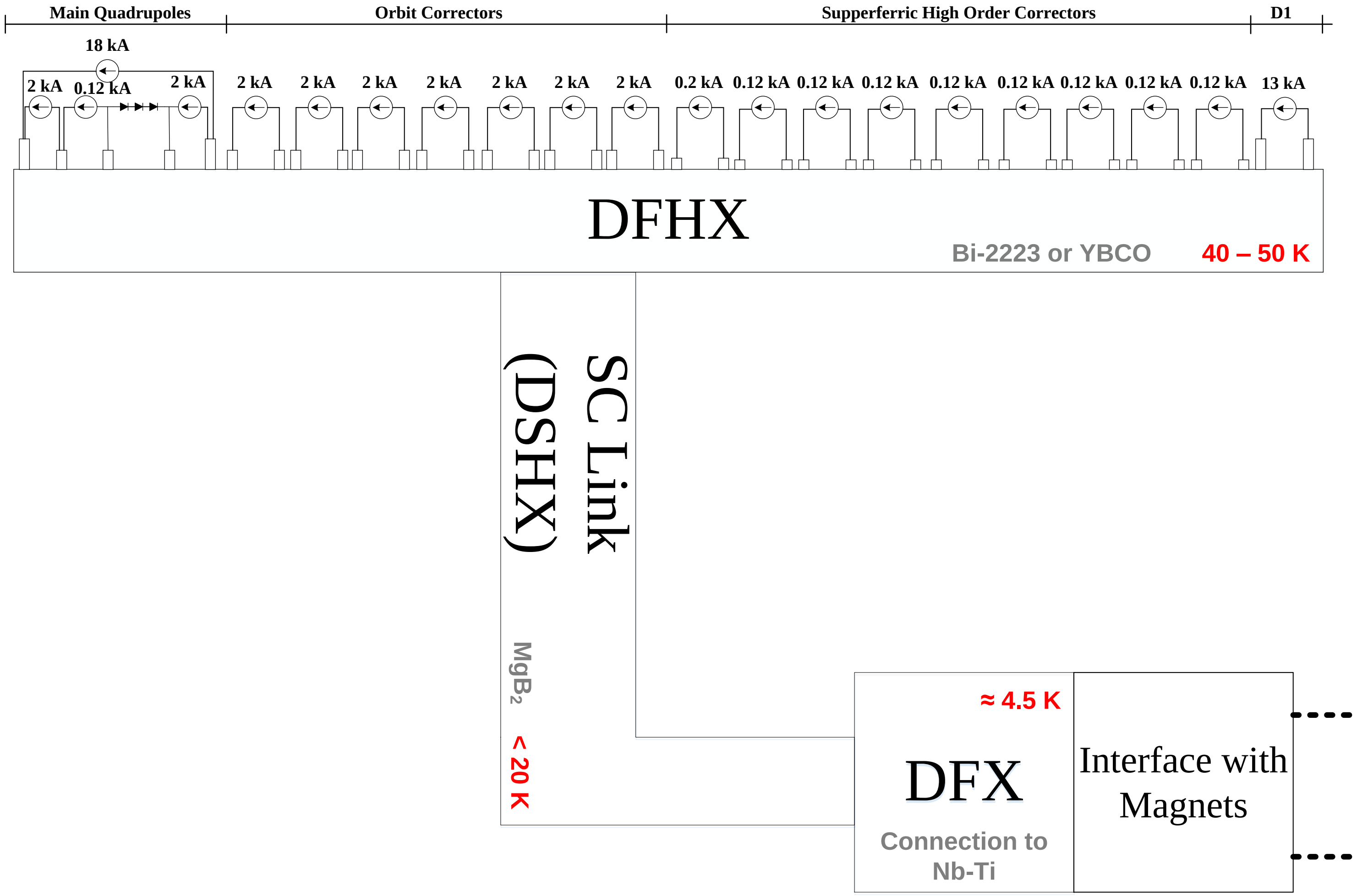
- PCs → DFHX → DSH (SC Link) → DFX → Magnets (via busbars)





For Illustration (not latest version)

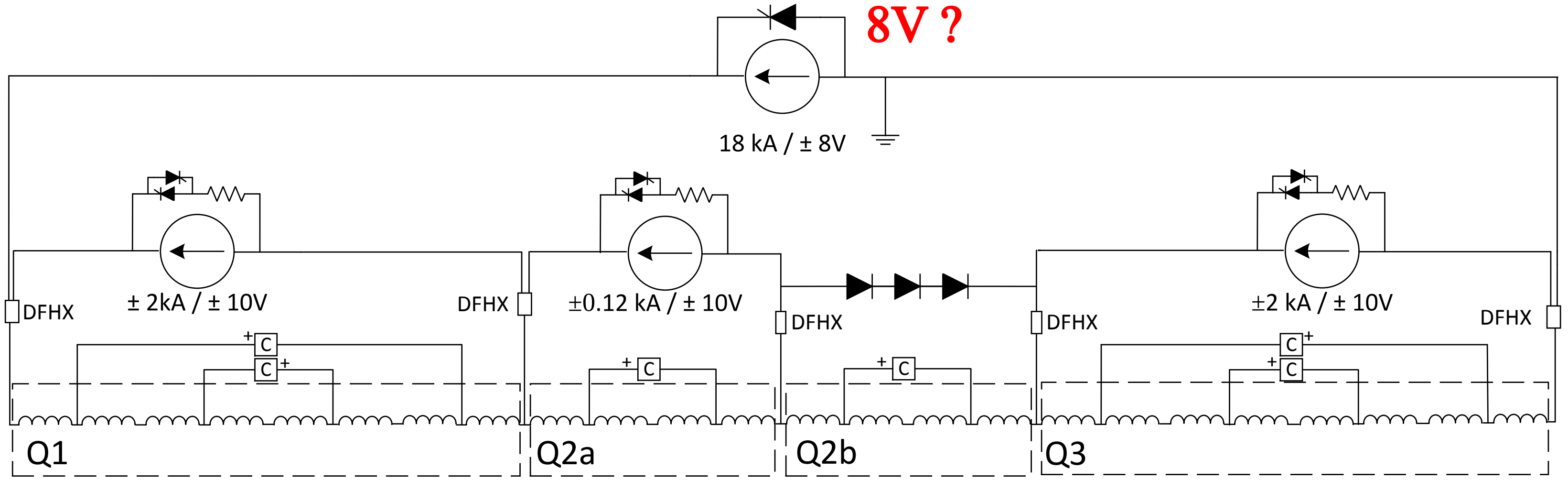
Cold Powering of the MQ Circuit



Gas Helium Cooling in DFHX and DSHX

Liquid Helium Cooling in DFX

Powering of the MQ Circuit



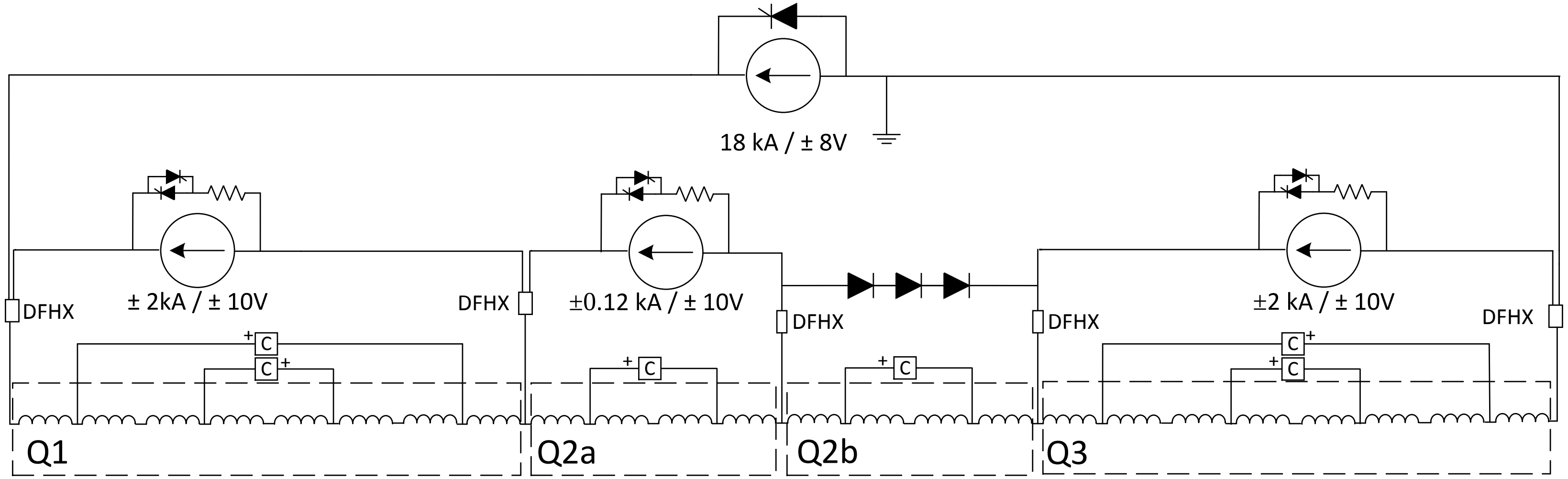
- 1 Main Power Converter:
  - Q1, Q2a, Q2b and Q3 powered in series
  - [18 kA / ±8 V]
- 3 Trim Power Converters:
  - 2 x [±2 kA / ±10V] (Q1 and Q3)
  - 1 x [±0.12 kA / ±10V] (Q2a)
- τ = 1 ks
- Total Energy of 41 MJ
- Warm Diodes over Q2b for Quench Protection (not necessary for warm powering)

Circuits for HiLumi	Magnet Type	I_nom (7 TeV) [kA]	I_ultimate [kA]	L per circuit [mH]	R per circuit [mΩ]	Time constant [s]	di/dt* [A/s]	V_PC [V]	E [kJ]	R Crowbar [mW]
MQ (Q1, Q2a, Q2b, Q3)	MQXFA / MQFXB	16.5	17.82	255	0.264	965.91	13.8	**±8.2**	40488	?
Trim Q1	MQXFA	2	±2	69	1.44	47.92	1.5	±3.9	10956	tbd
Trim Q3	MQXFA	2	±2	69	1.44	47.92	1.5	±3.9	10956	tbd
Trim Q2a	MQXFB	0.12	±0.12	58.5	13.372	4.37	0.1	±2.4	9288	tbd
Q2b	MQXFB			58.5			13.8	±0.8	9288	

* Estimated value to be verified by WP2

Powering of the MQ Circuit

- Maximum Output Voltage of Power Converters



V_qx = R_qx * I_qx + L_qx * didt_qx + L_q1*didt_q1 + L_q2a*didt_q2a + L_q3*didt_q3 ~ 8.2V

V_q1 = R_q1 * I_q1 + L_q1 * didt_q1 + L_q1*didt_qx ~ 3.9 V

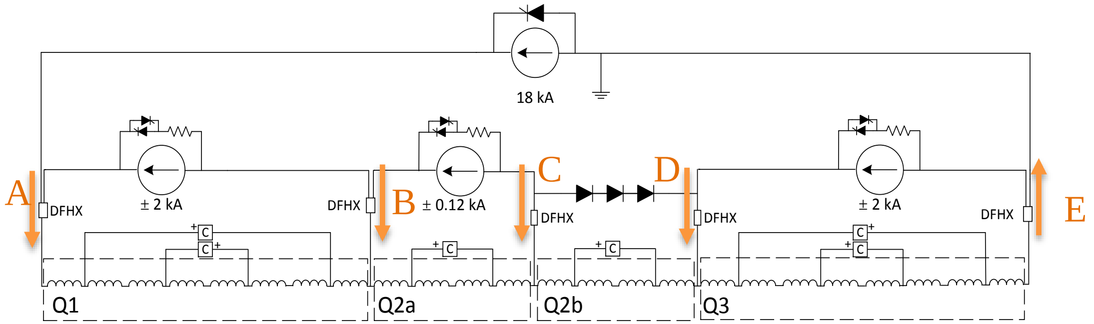
V_q2a = R_q2a * I_q2a + L_q2a * didt_q2a + L_q2a*didt_qx ~ 2.4 V

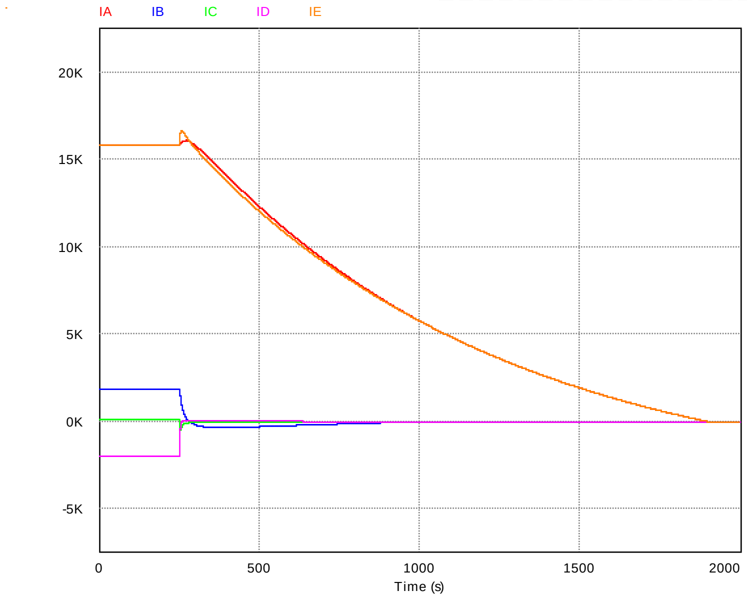
V_q3 = R_q3 * I_q3 + L_q3 * didt_q1 + L_q3*didt_qx ~ 3.9 V

V_q2b = + L_q2b*didt_qx ~ 0.8 V

Powering of the MQ Circuit

- Powering Failure Simulation (No Quench)

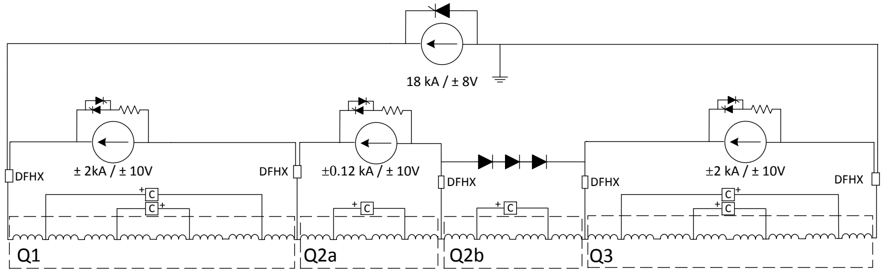


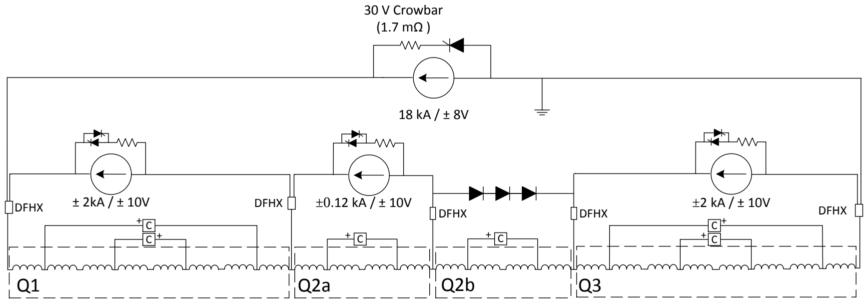


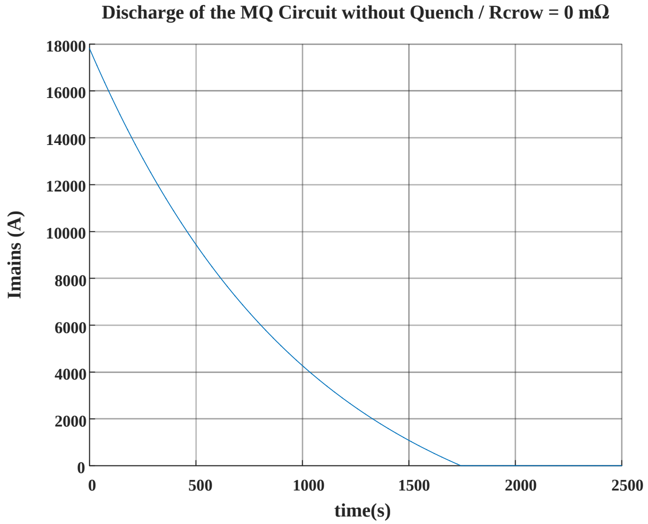
- No Looping Current in Trim Circuits Even if Crowbar Resistances = 0 due to Relatively High Trim Cable Resistance:
  - RcableQX = 0.264 mΩ
  - RcableQ1 = 1.44 mΩ
  - RcableQ2a = 13.4 mΩ
  - RcableQ3 = 1.44 mΩ

Powering of the MQ Circuit

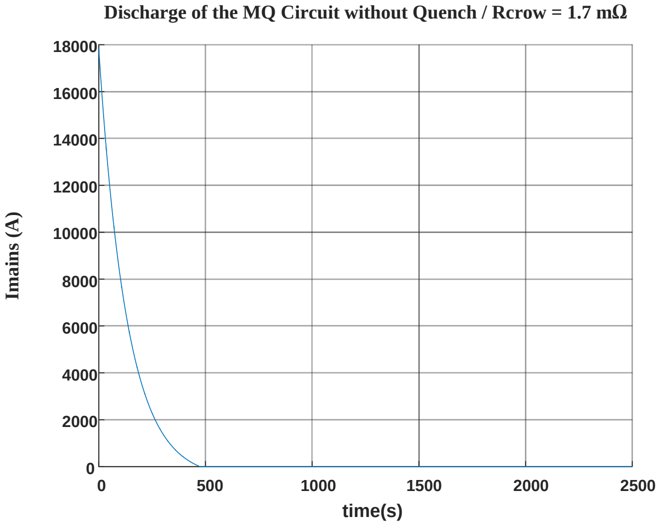
- Water Failure and Main Converter Crowbar Resistance






Discharge of the MQ Circuit without Quench / Rcrow = 0 mΩ

Introduction of 30 V Crowbar Resistance


Discharge of the MQ Circuit without Quench / Rcrow = 1.7 mΩ

- Energy Dissipated in Free-Wheeling Thyristor = 11.5 MJ
- Energy Dissipated in DC Cables = 30 MJ → **ΔT = 86 °C in case of water failure**

- Energy Dissipated in Free-Wheeling Thyristor = 2.12 MJ
- Energy Dissipated in DC Cables = 5 MJ → **ΔT = 15 °C in case of water failure**
- **Energy Dissipated in Crowbar Resistance = 34 MJ**

03

Quench Protection of the Main Quadrupole Circuit

Quench Protection of the MQ circuit

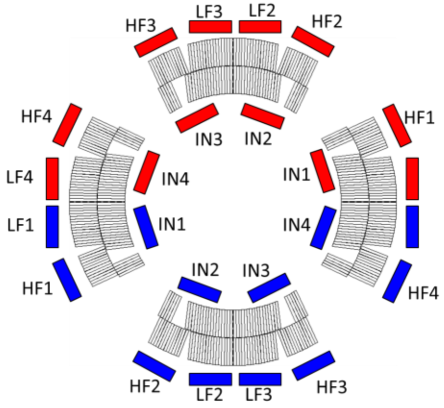
- Outer layer (OL) quench heaters
  - In the baseline
  - Can protect the magnet at all current levels (T_{max}=320 K) and provide some redundancy.

- Inner layer (IL) heaters
  - In the baseline
  - In combination with the OL quench heaters, the hot spot temperature can be reduced by 90 K (T_{max}=230 K).
  - Work in progress to address issues of reliability (linked to coil manufacturing).

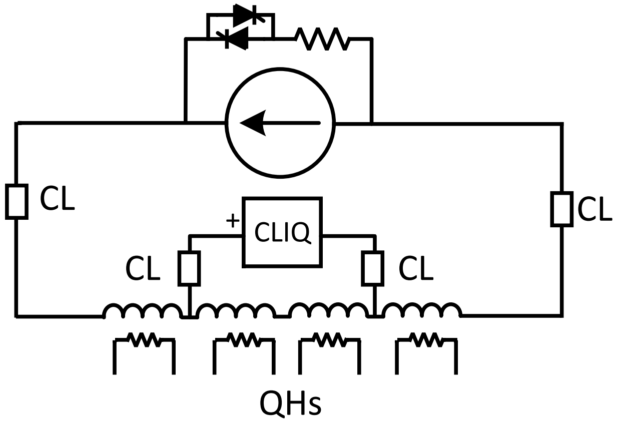
- CLIQ
  - In the baseline
  - In combination with the OL quench heaters, the hot spot temperature can be reduced by 90 K (T_{max}=230 K)
  - Work in progress to address open questions:
    - Assess the long-time reliability and availability
    - Impact on other elements of the circuit, for instance the superconducting link.

Quench Protection of the MQ circuit

- Quench heaters (OL or IL)
  - Quench provoked by thermal diffusion.
  - Electrically separated from the coils.

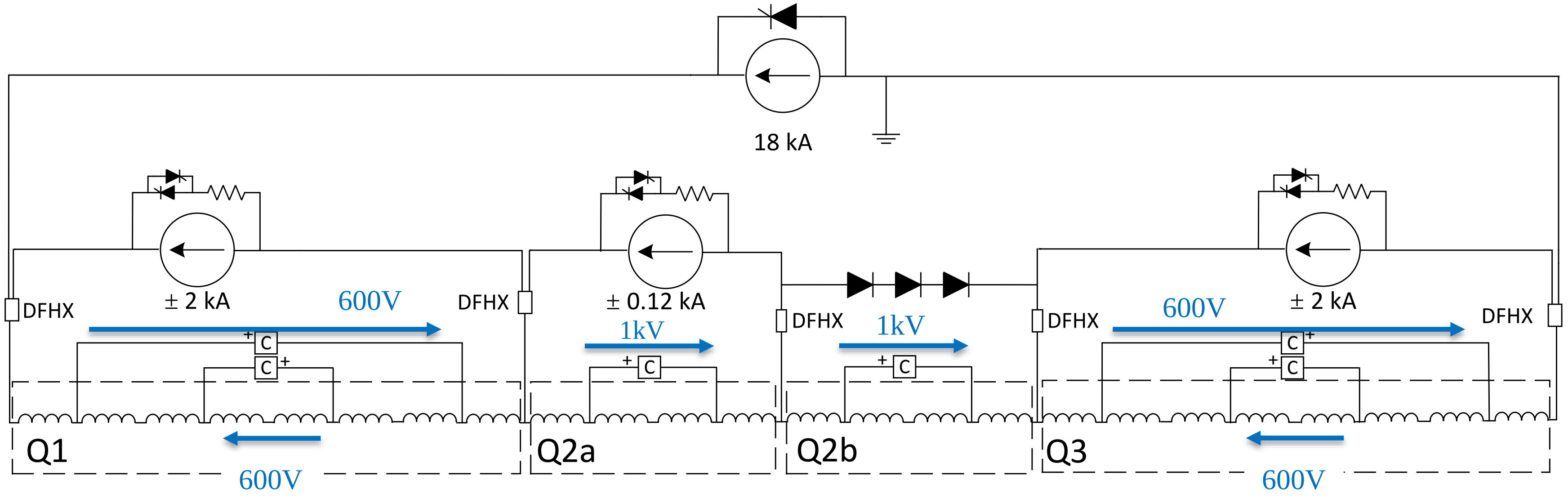


- CLIQ
  - Quench propagation by current oscillations.
  - Electrical interaction with the powering circuit (warm and cold)



Quench Protection of the MQ circuit

- CLIQ
  - 2 x 600V CLIQ units per MQXFA magnet
  - 1 x 1 kV CLIQ units per MQXFB magnet



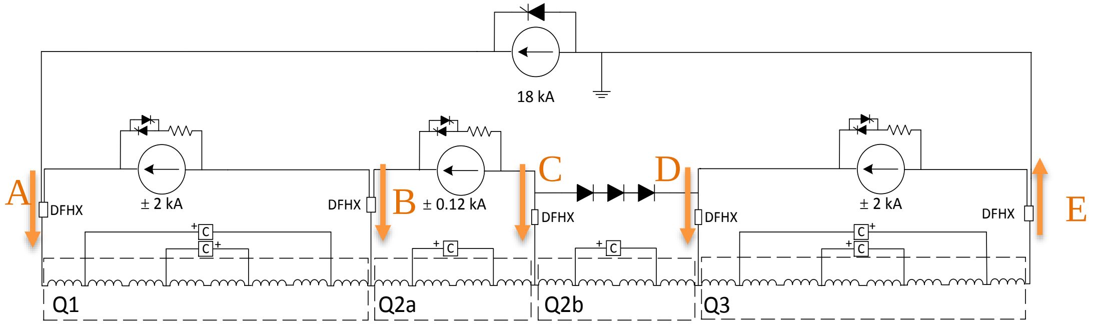
- 2 magnets in series
- 300 V per pole

- 1 magnet
- 500 V per pole

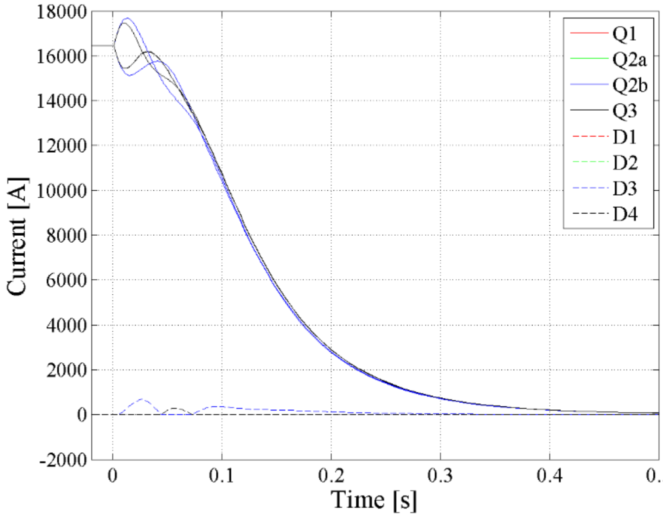
- 2 magnets in series
- 300 V per pole

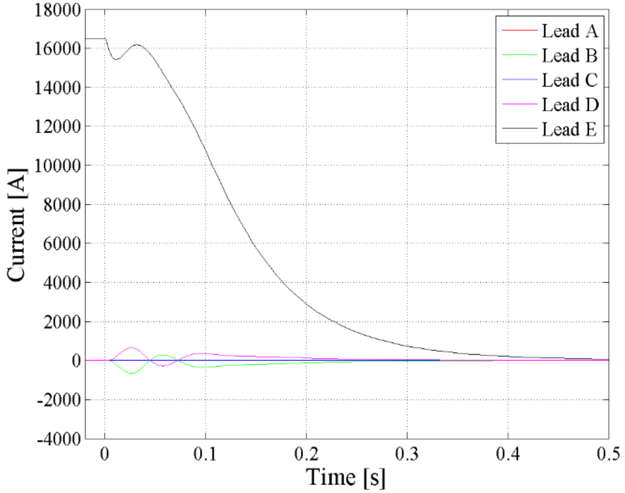
Quench Protection of the MQ circuit

- Quench Simulations: Synchronised Quench without Initial Trim Currents



I_{ms} = 16.5 kA
I_{ts1} = 0 A
I_{ts2a} = 0 A
I_{ts3} = 0 A

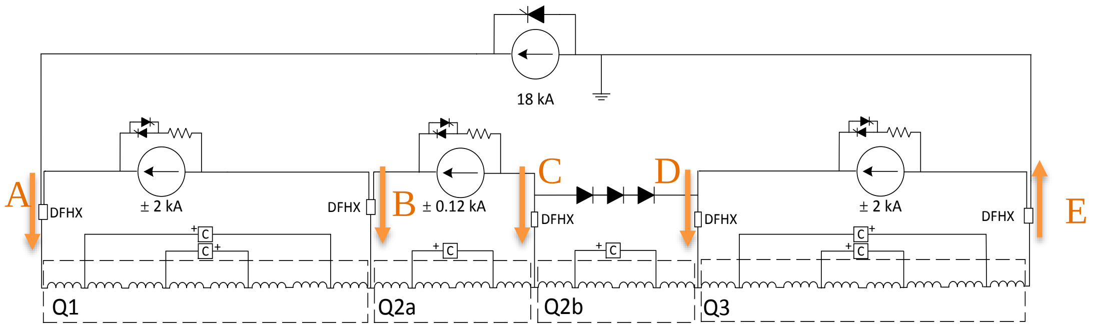




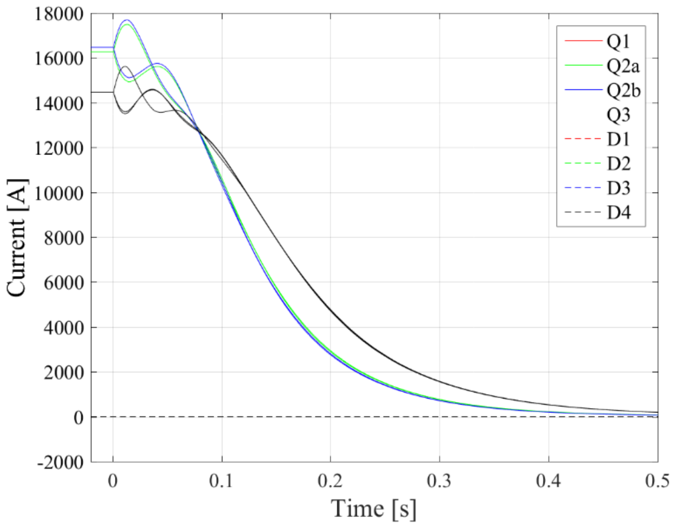
- The behaviour of the magnets are similar (Quench resistance development)
- No issue if the quenches of the 4 MQ are synchronised
- No over-current through leads

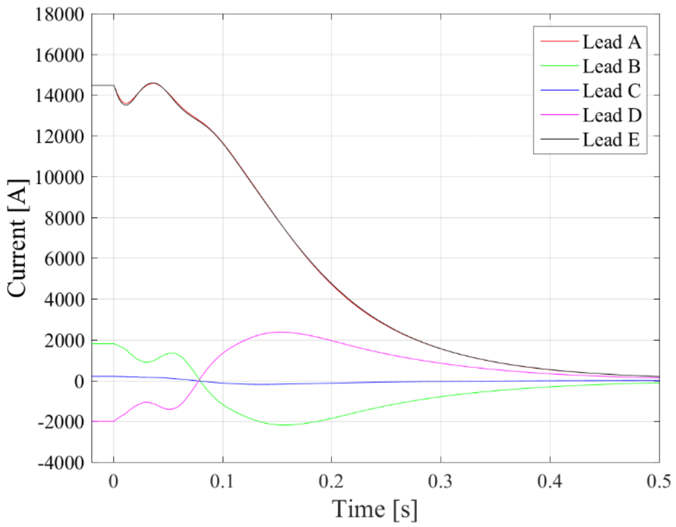
Quench Protection of the MQ circuit

- Quench Simulations: Synchronised Quench with Initial Trim Currents



$I_{ms} = 16.5$ kA
$I_{ts1} = -2$ kA
$I_{ts2a} = -0.12$ kA
$I_{ts3} = -2$ kA



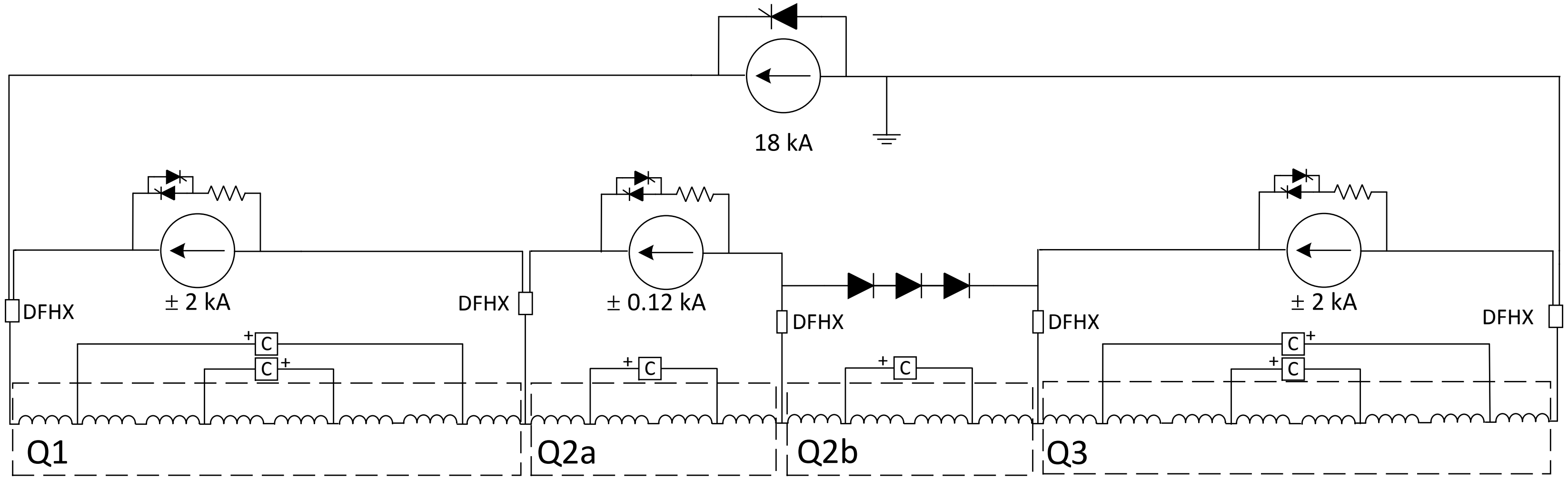


Currents estimated through the SC Link/Leads:

- Leads B and D see 2 kA
- Lead C sees 0.1 kA

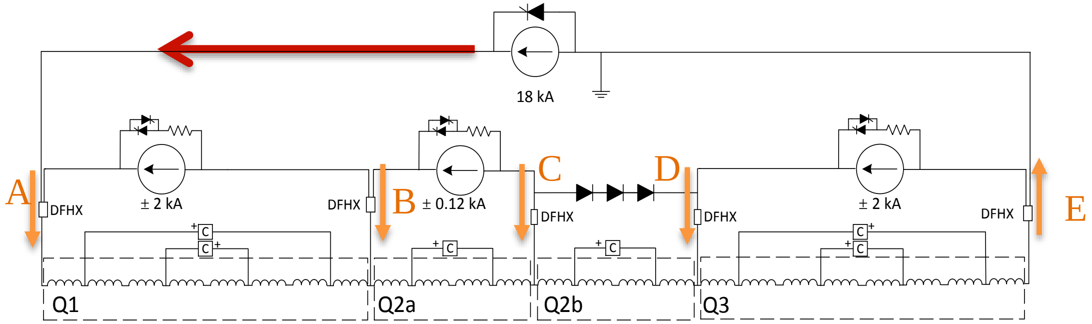
Quench Protection of the MQ circuit

- Quench Simulations: Worst Case Scenario Considered (Conservative Case)
  - Case of the non-detection of a quench is not considered
  - The case considered is one full magnet (i.e. 4 poles) quenches by effect of beam
  - Quench protection system needs:
    - 15 ms to detect the quenchion
    - +1 ms to fire the CLIQ modules (16 ms after the quench)
    - +5 ms to fire the QH (20 ms after the quench)



Quench Protection of the MQ circuit

- Quench Simulations: Worst Case Scenario Considered



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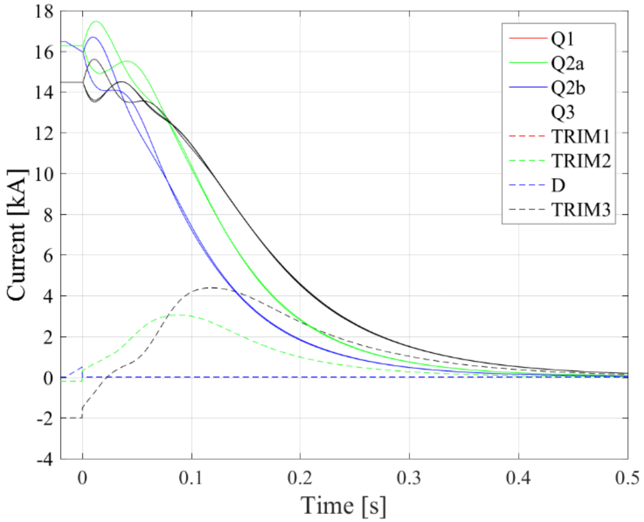
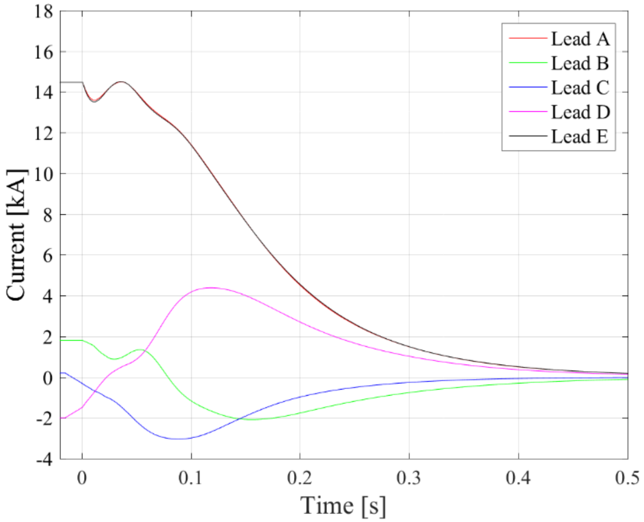
$I_{ts1} = -2$ kA
$I_{ts2a} = -0.12$ kA
$I_{ts3} = -2$ kA



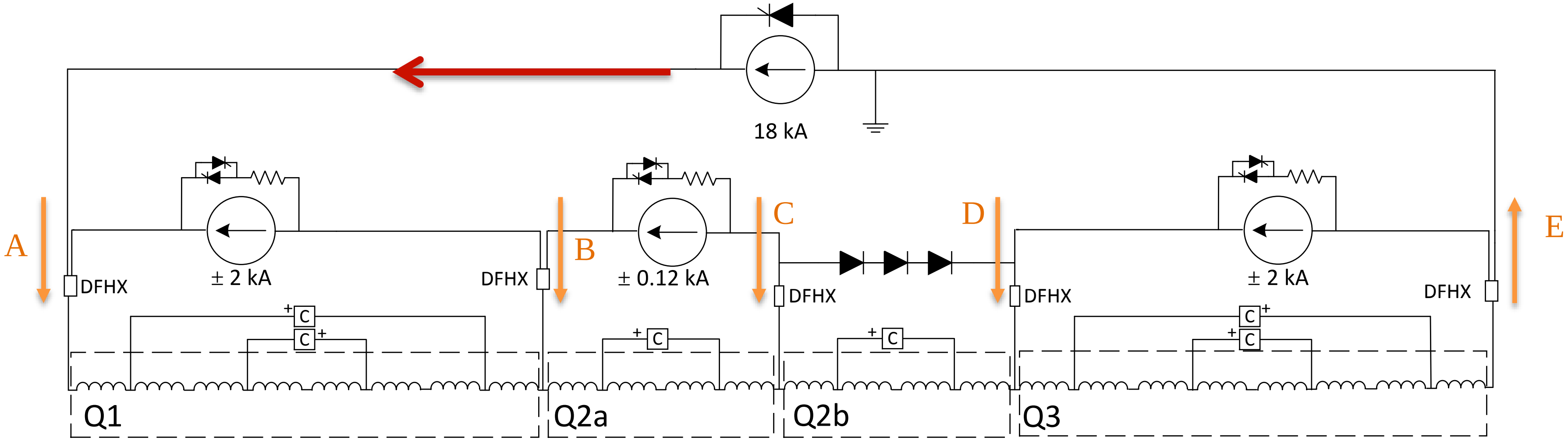


High overcurrent through the SC Link/Leads:

- Leads B and D see 4.4 kA for an eq. time = 120 ms
- Lead C sees 3.2 kA for an eq. time = 100 ms

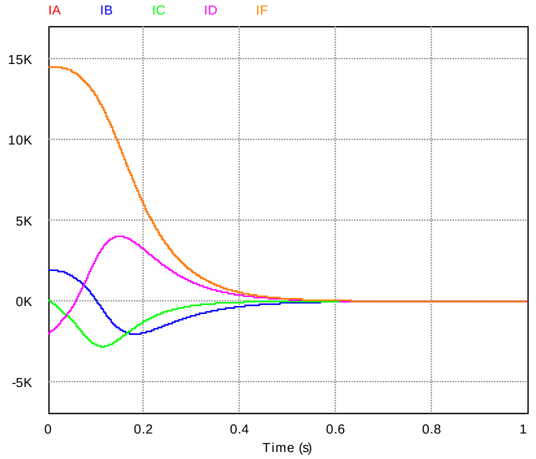
Quench Protection of the MQ circuit

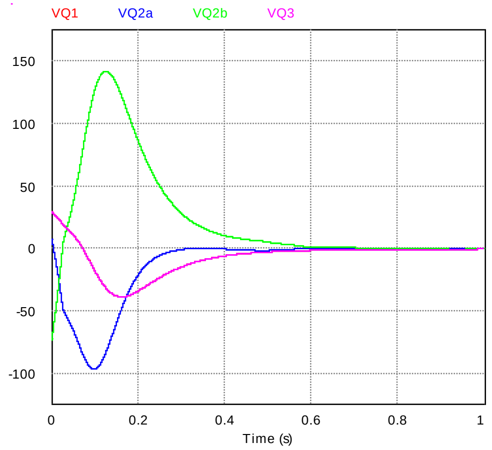
- Quench Simulations: Worst Case Scenario Considered
  - Attempt 1 to reduce the currents through the leads: Increasing the crowbar resistances



RcrowQ1 = 15 mΩ
RcrowQ2a = 80 mΩ
RcrowQ2b = 80 mΩ
RcrowQ3 = 15 mΩ

I_ms = 16.5 kA
I_ts1 = -2 kA
I_ts2a = -0.12 kA
I_ts3 = -2 kA

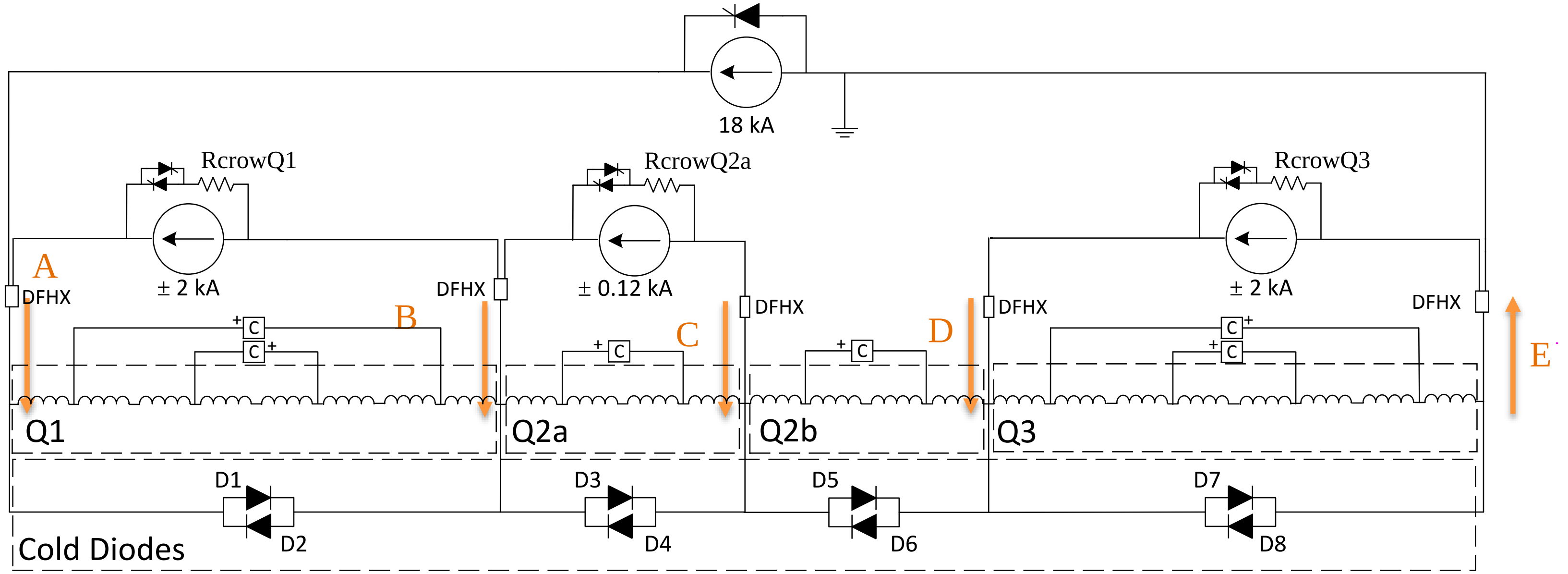




Maximum current decrease of less than 200A in the trim circuits → Low impact (MIITS and current peaks)

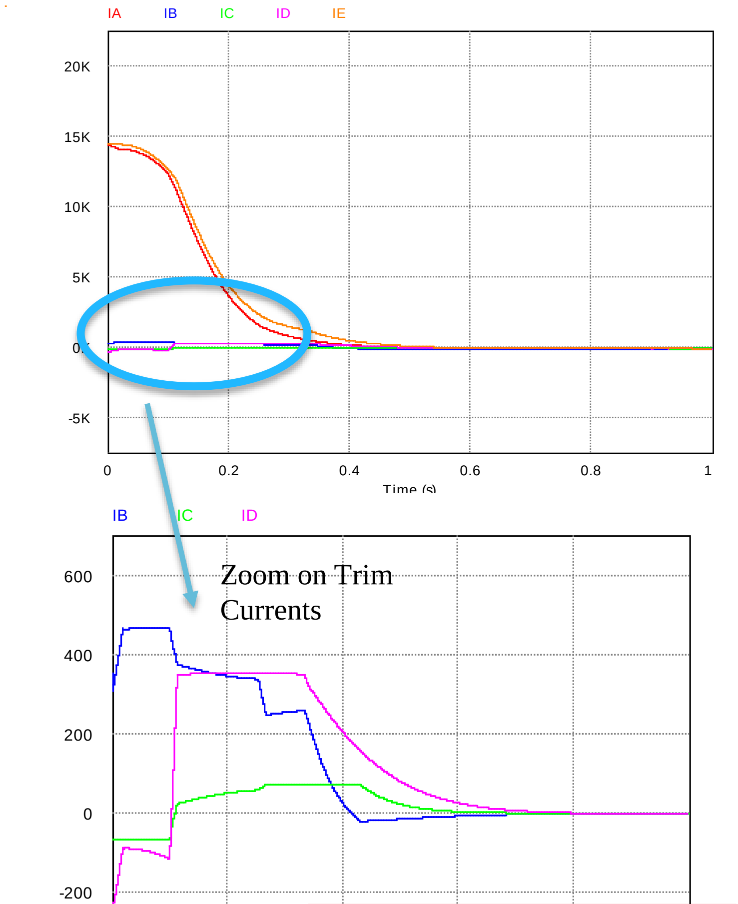
Quench Protection of the MQ circuit

- Quench Simulations: Worst Case Scenario Considered
  - Attempt 2 to reduce the currents through the leads: Introducing cold diodes



RcrowQ1 = 15 mΩ
RcrowQ2a = 80 mΩ
RcrowQ3 = 15 mΩ
Diode Vf = 6 V

I_ms = 16.5 kA
I_ts1 = -2 kA
I_ts2a = -0.12 kA
I_ts3 = -2 kA



Zoom on Trim Currents

$I_C <= Vf/0.08\Omega <= 75 A$
$I_B < 500 A$
$I_D < 400 A$

Cold diodes Status

- Long development programme was conducted for the LHC
- Design aspects:
  - Radiation tolerance
  - Electrical properties (turn-on, forward and reverse voltage characteristics)
  - Thermal property (endurance for long time constants and long term behavior)
  - Cryogenic temperature operation
- Main issue for inner triplet diode integration: Radiation tolerance
  - Radiation resistance limit for the LHC diode (diffusion type): **~2 kGy, 10^{13}n.cm^{-2}**
  - Epitaxial diodes (tested more than 20 years ago) up to **~ 50 kGy, 10^{15} n.cm^{-2}**
    - Studies interrupted when revised (much lower) radiation calculations were presented, together with the success with diffusion diodes
    - Needed to stack them to have sufficient margin for ramping, had reduced reverse voltage capabilities and were much more expensive

Proposed Solutions

- These results are being confirmed at present
- If results are confirmed, two solutions could be considered:
  - Cold diodes with present equipment design
    - More compact than dipole diodes since time constants are 1000 times lower
    - Studies undergoing for radiation exposure in the inner triplet zone (till the DFX)
    - Complex integration
  - Redesign of equipment to withstand the high transitory over-currents
    - Over-currents of 2-3 kA in leads for an equivalent time of 100-150 ms
- Adding a resistance in the crowbar of the main converter may have implications to be analyzed.
- Final layout due date: End of the 2016 in the MCF

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Conclusion

Conclusion

- IT circuits powering scheme has been presented
- IT main quadrupole circuit is complex due to its interconnectivity
- Circuit layout definition is in final stage
- Protection scheme to be finalized when tests are done
- For quench detection and protection instrumentation, see R. Denz’s talk

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Thanks for your attention

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