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Quench protection studies updated

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+ the magnet designers in WP5 team!

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EuroCirCol

Outline

1. 40 ms protection delay at 105% of I_{nom}
2. Parametric analyses
3. Protection with heaters (Cosθ)
    - Is the high current the most critical?
4. Failure scenarios and impact of uncertainties
5. Summary

Simulation methods

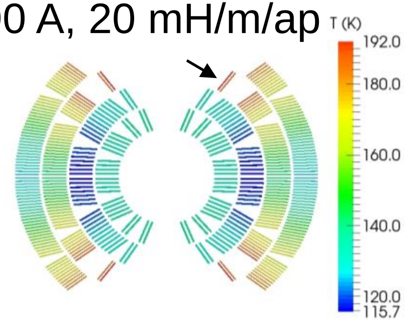
- Current decay and temperatures with Coodi
  - Adiabatic
  - Field map and inductance from ROXIE
  - Quench delays and propagation velocities are input
- Heater delays with CoHDA
  - 2-D simulation of heat conduction from heater to coil
  - Quench onset when cable temperature reaches T_{cs}
    - T_{cs} for cable maximum field, no degradation

1. 40 ms uniform protection delay: Temperatures

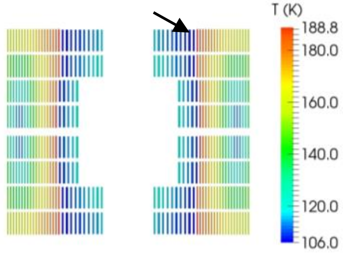
Protection delay includes the detection, etc.

	T_{max} (K)	ΔT (incl. HS) (K)	ΔT (excl. HS) (K)
Cosθ	345	~140	~60
Block	356	~250	~80
CC*	353	~250	~120

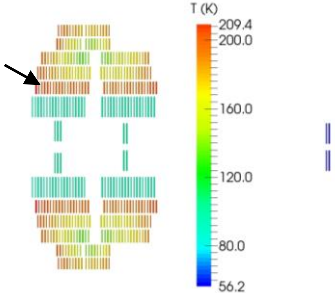
16T_22b-37-optd6f6
11790 A, 20 mH/m/ap



V20ar
12040 A, 18 mH/m/ap



V1h2
15940 A, 32 mH/m/2-ap

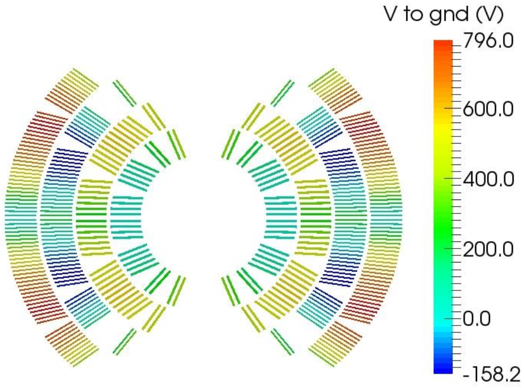


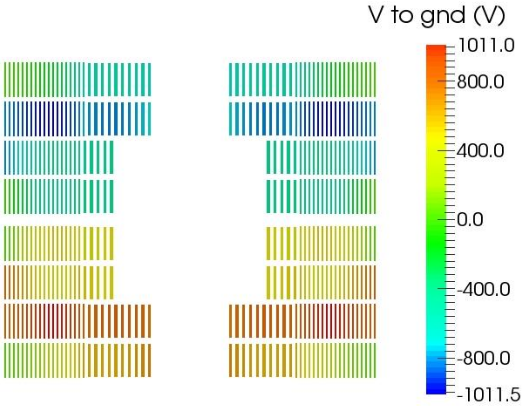
*CC winding order and induct. tbc

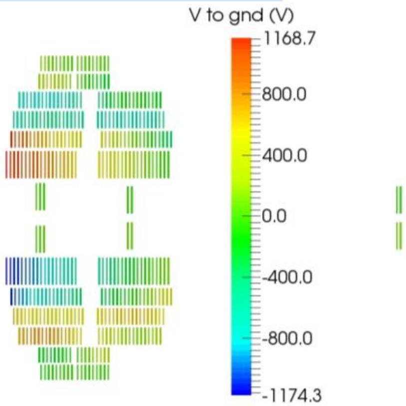
1. 40 ms uniform protection delay: Voltages

	Max to gnd (V)	Max btw turns (V)	Max btw layers (V)
Cosθ	800	90	970
Block	1010	70	880
CC*	1200	80	1860

Initial quench propagation excluded

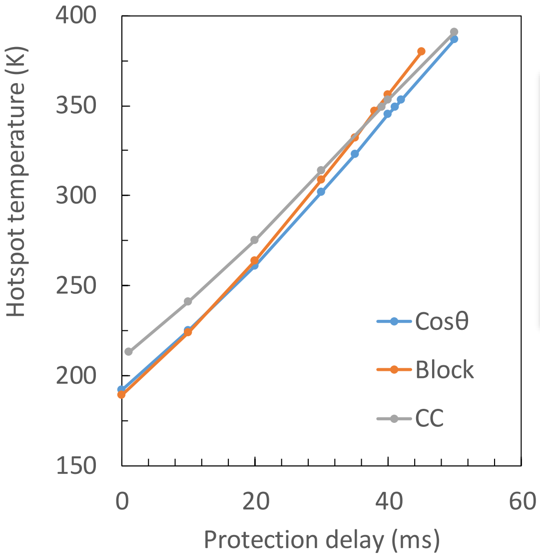






2. Parametric analysis with uniform delay

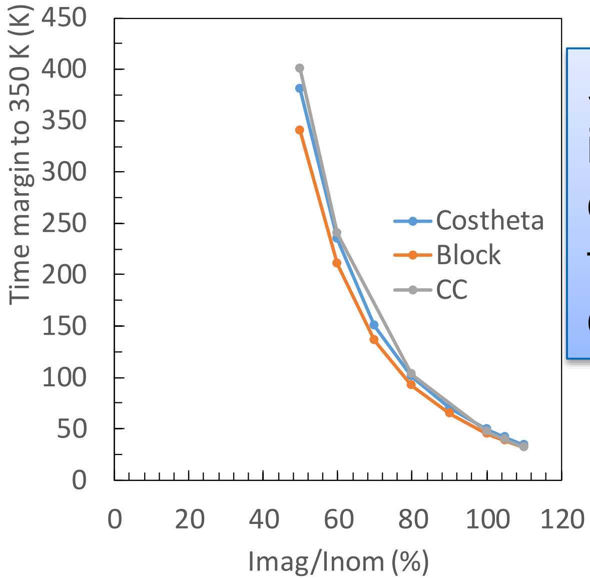
T_{max} vs. Protection delay at 105 %



Similar behaviour in all magnets

Time margin vs. current

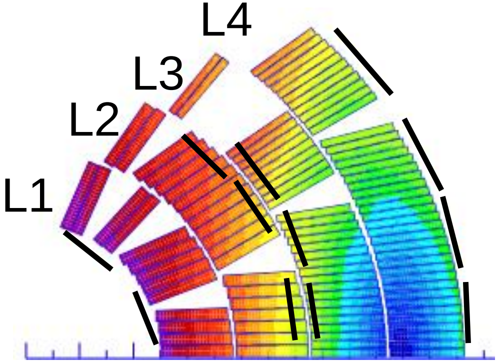
Time margin = protection delay that leads to given T_{max} (see E. Todesco, WAMSDO 2013)



Significant increase of reaction time at low current

3. Cosθ protection with heaters

- Realistic heater design, but not optimized
- Similar to LHC, LARP and HL-LHC technology:
  - 25 µm SS strips with Cu-plating
  - **75 µm polyimide insulation**
- Strip width: 10-14 mm
  - **Strips cover 70 turns out of 101**
- HS length: 3-6 cm, period: 15-35 cm
  - **HS cover 17-20% of turn length**
- ***P*(t=0): 70 -100 W/cm^2, τ_{RC}: 30 ms**



Approximate heater strip locations

HFU	**450 V / 14 mF**
Strips / coil	24
HFU circ. coil	8
Stored E / 2 ap.	45.4 kJ *
900 V units / 2 ap.	16

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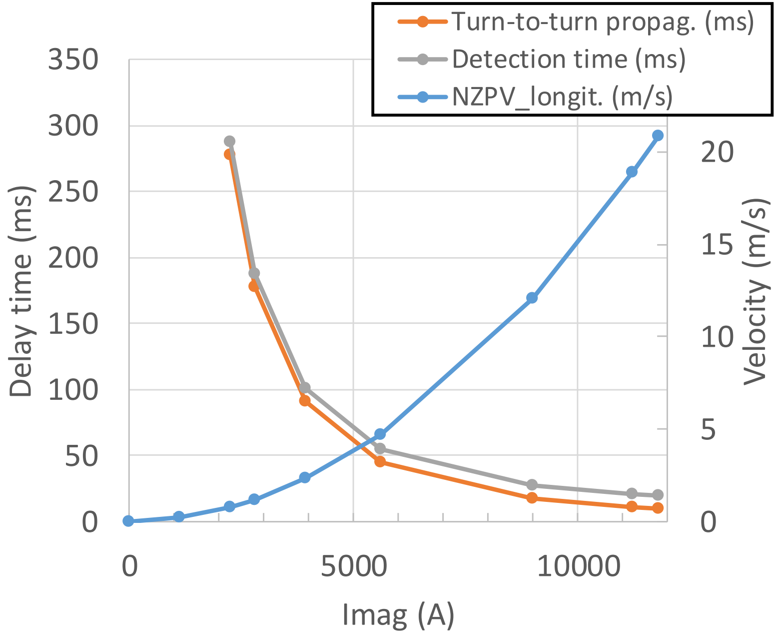
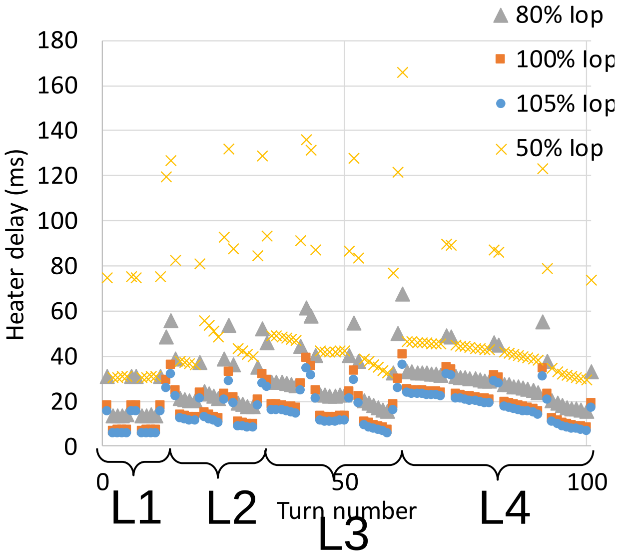
3. Hotspot temperature simulation assumptions

- 20 ms for quench detection (10+10ms)
- 20 m/s longit. NZPV, 10 ms turn-to-turn
  - QLASA: Average longit. 18 m/s, turn to turn: ~4-10 ms
  - Remember pre-heating from heaters!
- At lower current scaled proportionally to I_{mag}^2

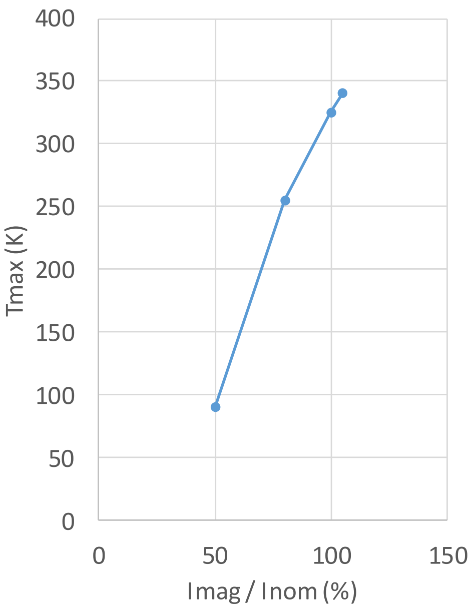


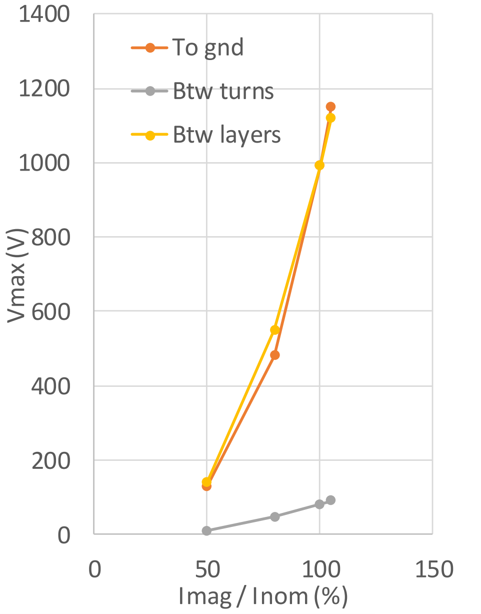
3. Results with heater based protection

Turn heater / quench delays vs. I_{mag}



Hotspot temperature and voltages vs. I_{mag}





⇒ High current the most critical
⇒ Protection at all currents
⇒ Very small margin at high current

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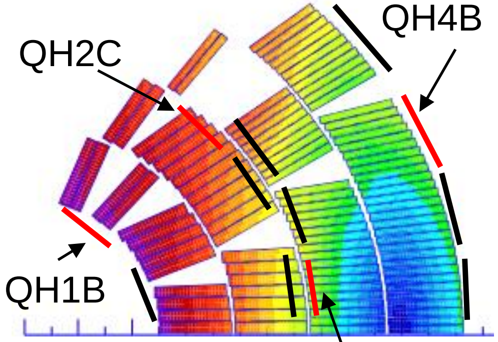
4. Failure scenarios at 105%I_{nom}

	Failing strip in all coil halves	Strips failed	T_{max} (K)	V_{max} gnd (V)	V_{max} turns (V)	V_{max} layers (V)
	Nominal	**0**	**341**	1150	90	1120
Fail1	QH1B	**4**	**349**	1070	100	1250
Fail2	All IL QH's	**8**	**355**	1000	100	1380
Fail3	QH2C	**4**	**346**	1100	100	1200
Fail4	QH2C and QH3A	**8**	**366**	1160	110	1110
Fail5	QH4B	**4**	**355**	1800	100	1100

If 4 strips / magnet fail: T_{max} < 360 K



Nominal:

$\underline{T_{max} = 341\ K}$,
V_{max} to gnd = 1150 V,
V_{max} btw turns = 90 V,
V_{max} btw layers = 1120 V

4. Uncertainties…

- **Heater delays:**
  - Assign heater delay to cable average field:
    - $\underline{T_{max} = 364\ K}$, V gnd = 1290 V, turns = 100 V, layers = 1360 V
- **Material properties:**
  - Use MATPRO properties for current decay (NIST for heater delays):
    - $\underline{T_{max} = 356\ K}$, V gnd = 1480 V, turns = 110 V, layers = 1410 V
- **Heater insulation:**
  - Increase heater insulation to 100 µm:
    - $\underline{T_{max} = 356\ K}$, V gnd = 1240 V, turns = 90 V, layers = 1050 V

4. …Uncertainties

Nominal:

T_{max} = 341 K,
V_{max} to gnd = 1150 V,
V_{max} btw turns = 90 V,
V_{max} btw layers = 1120 V

- **Quench propagation velocity:**
  - NZPV longit. to 15 m/s:
    - **T_{max} = 346 K**, V gnd = 1160 V, turns = 90 V, layers = 1100 V
  - NZPV longit. to 15 m/s AND turn-to-turn speed to 15 ms:
    - **T_{max} = 353 K**, V gnd = 1110 V, turns = 90 V, layers = 1090 V

Not enough margin…

Not easy to find significant improvements with small changes, but

Increasing NZPV longit to 40 m/s: T_{max} = 334 K…
(Corrisponds to halving the periods)

To summarize

- Tmax vs. protection delay quite similar in all magnet options
  - **Time margin 40+/-2 ms in all options to 350 K at 105% I_{nom}**
  - Time margin increases exponentially at low current (340-400 ms at 50% I_{nom})
- In cos*θ* heater-based protection shows potential, but a large number of HFU's may be needed for the redundancy and margin
- **To explore next: Heaters + CLIQ**
  - Heaters to complement CLIQ, analysis needed at all current levels
  - Waiting to use STEAM for this analysis

Appendix: Heater design

	Peak power, RC time constant	HS length / period	Strip width
QH3, QH2C	70 W/cm[2], 30 ms	6/30 cm	10 mm
QH4	100 W/cm[2], 30 ms	6/35 cm	14 mm
QH1 and QH2A-B	70 W/cm[2], 30 ms	3/15 cm	10 mm

4 HFU circuits:

- 1B || 1A || 2A || 2B
- 2A || 3A || 3B || 3C
- 4A || 4B
- 4C ||4D