QXF heater design

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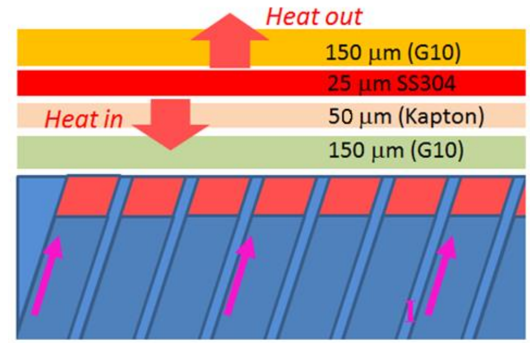
Outline

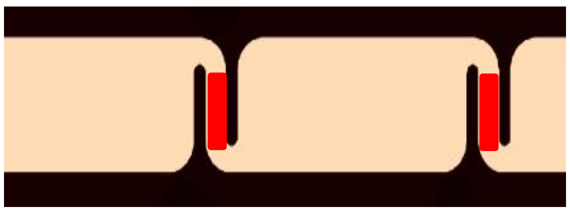
- Heater design challenges and goals
- “Stainless only” heater design for SQXF / LQXF
- Copper plated design options for the OL
- Copper plated design options for the IL
- Summary of the designs and future work

Basic concepts

Active protection: upon detecting the quench, the goal is to create the largest normal zone in the shortest possible time



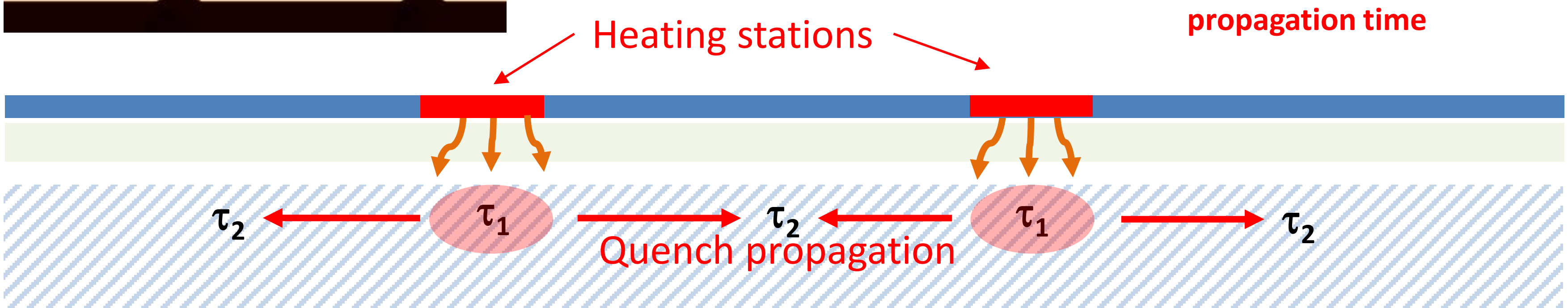
Uniform strip (τ_1, τ_2=0)



Strip with heating stations (τ_1, τ_2)

τ_1 – thermal diffusion time (heater delay)

τ_2 – quench propagation time



- Large spacing L between the heating stations -> higher surface power density -> shorter τ_1, but longer τ_2 of the quench propagation between the heated areas
- Small spacing L between the heating stations > smaller heater power -> longer τ_1, but shorter τ_2 of the quench propagation between the heated areas

Heater design steps for QXF

- Establish a set of operational and dimensional design criteria

  We agreed that SQXF and long QXF should share same design criteria to ensure the above statement is valid and the SQXF heater performance is relevant to the long QXF.

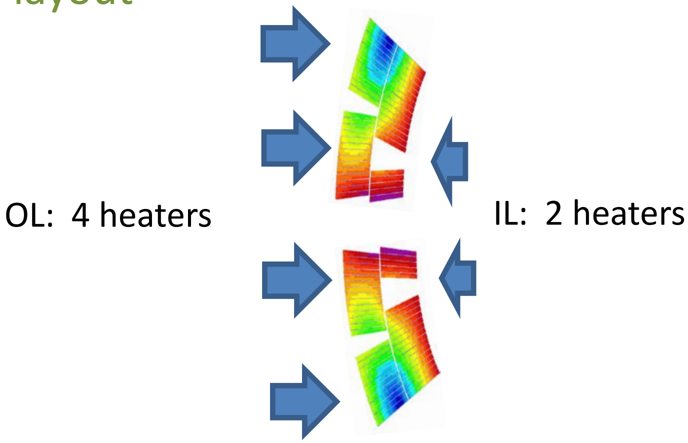
- Determine heater time delays through experiments and simulations
- Design heater patterns to satisfy the minimal protection requirements
- Further optimize heater efficiency and layouts based on recent performance tests (HQ, LHQ) and simulations

Our goal is to learn the most about long QXF protection from the SQXF heater performance. We will use SQXF to validate and optimize the final QXF design.

SQXF vs QXF

Patterns were developed individually for the short (1 m) and long (~6.7 m) QXF model, sharing the same:

- Heater material (SS304) and Kapton trace thickness (50 micron)
- end-to-end heater configuration and layout

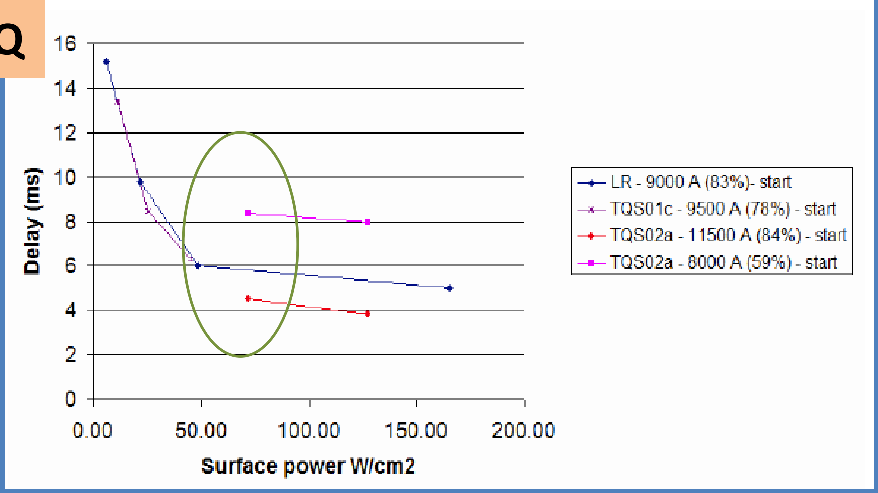


- heating station geometry
- concept behind periodicity of the heating stations - it is derived from the twist pitch of the cable
- power per heating station (in SQXF, we will set it to match the long QXF equivalent by choosing an appropriate HFU voltage)

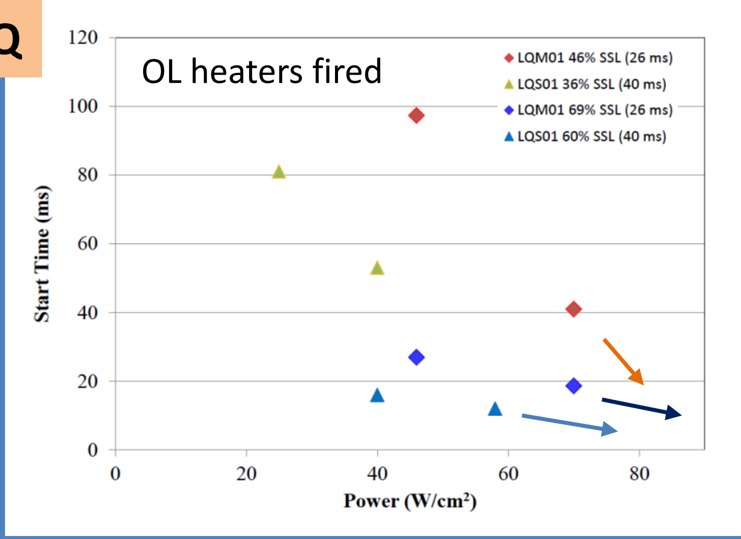
Input: quench delay vs heater peak power density

Experiments

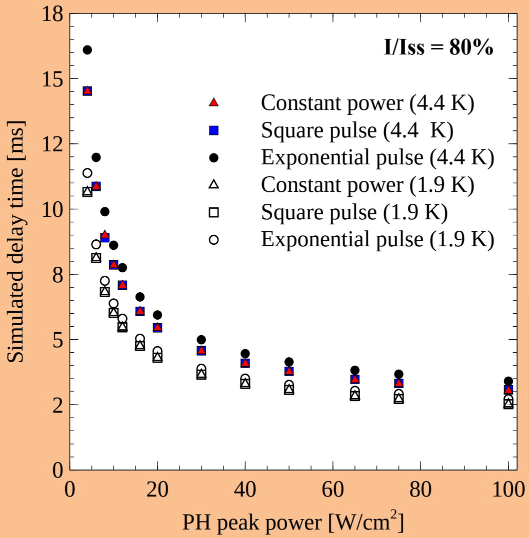
TQ



LQ

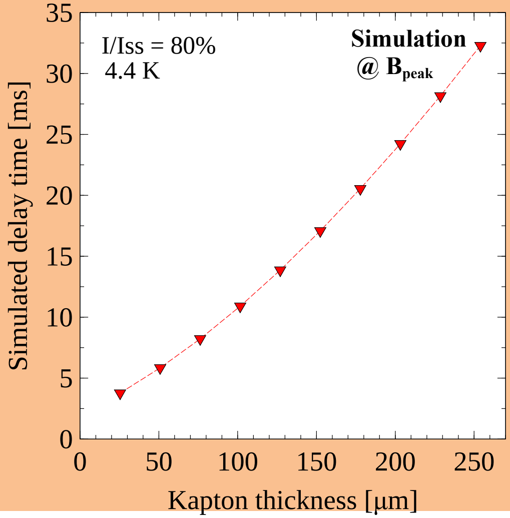


Simulations



T. Salmi WAMSDO 2013

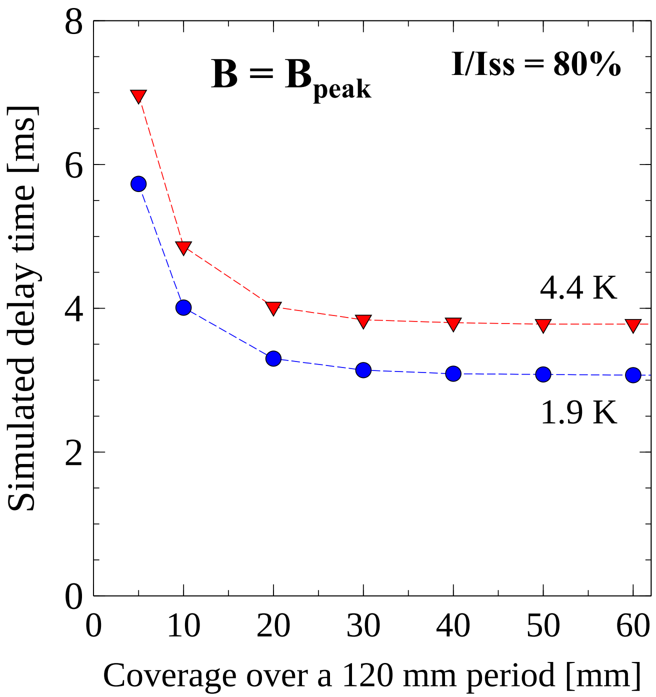
Power density > 50 W/cm² is desirable



Delay increases by 60% when Kapton layer thickness is increased from 25 µm to 50 µm

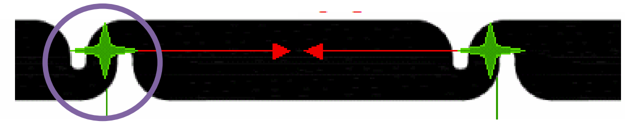
Heater delay simulations vs HS coverage and period

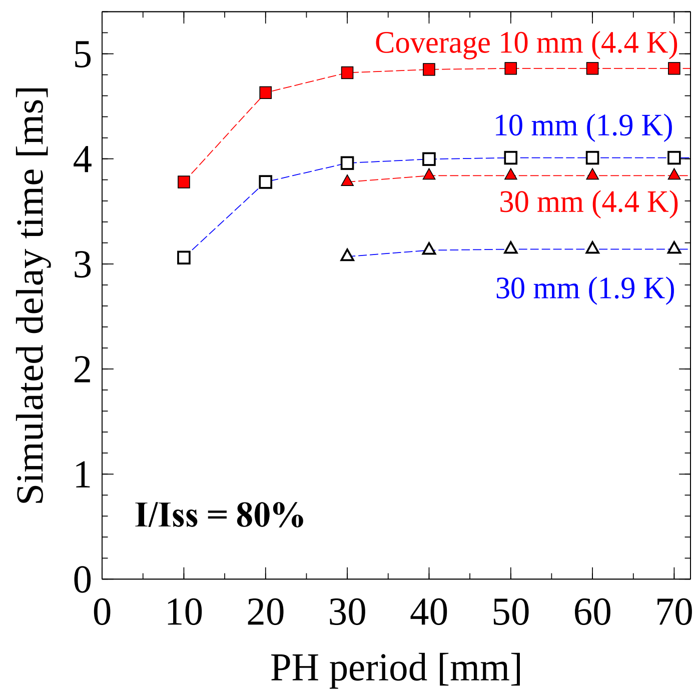
WAMSDO 2013, T. Salmi



Coverage = length of heating station segment along the cable

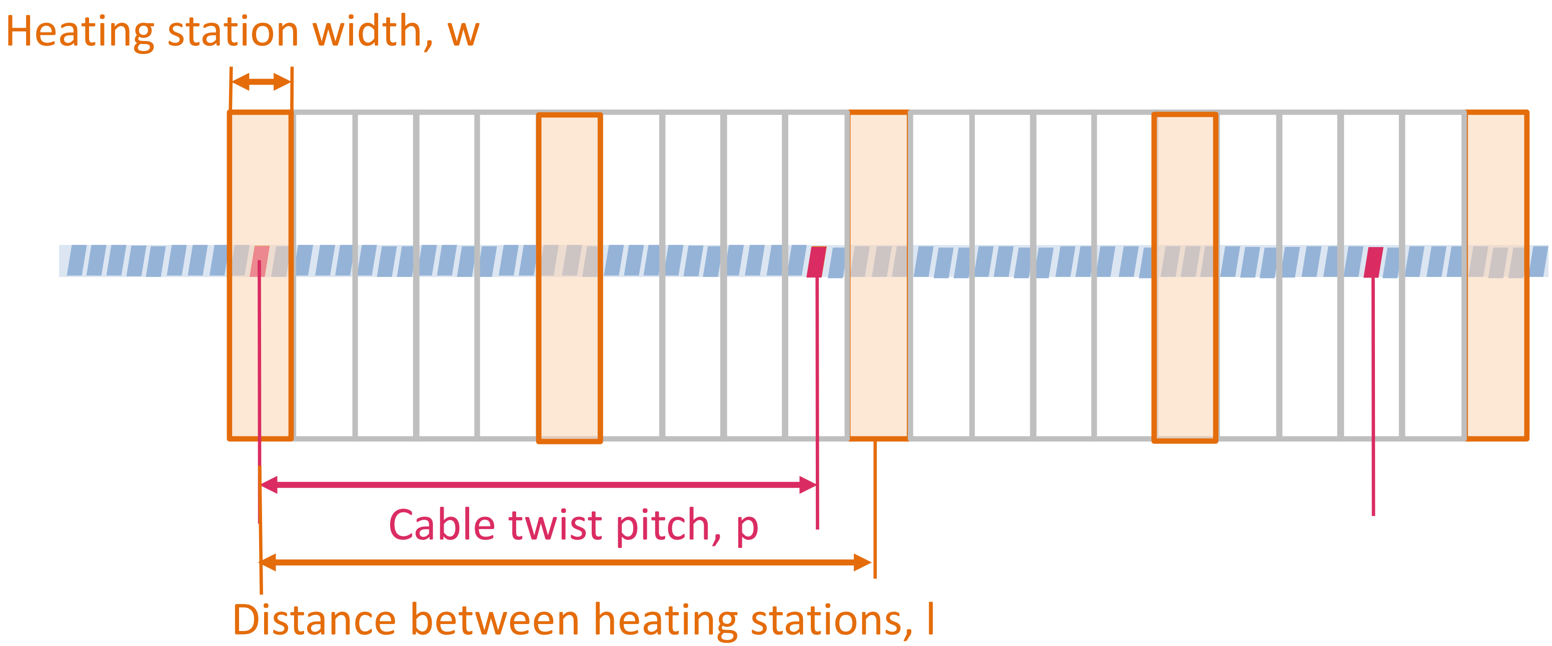
Period = Distance between heating stations





By going from ~10 mm wide heating station to a continuous strip, one can gain ~1 ms of the heater delay time (equivalent to ~0.25 MIITS at 16 kA). HS length > 20 mm is desirable.

Matching the cable twist pitch



If $p = 2nw$ and $l = (2n+(-)1)\,w$, then the supercurrent in all strands of the cable segment of length L= n l can be “interrupted” *simultaneously* by the normal zones created with *n* heating stations.

- **This approach can potentially improve heater efficiency, as all cable strands will get resistive and start dissipating heat at once**

SQXF/LQXF agreed heater design parameters

Peak power density:	50-150 W/cm^2
HFU voltage:	up to 450 V
HFU current:	up to 220 A
HFU capacitance:	4.8-19.2 mF
Distance between heating stations: (Could be related to the transposition pitch of 109 mm)	up to 120 mm

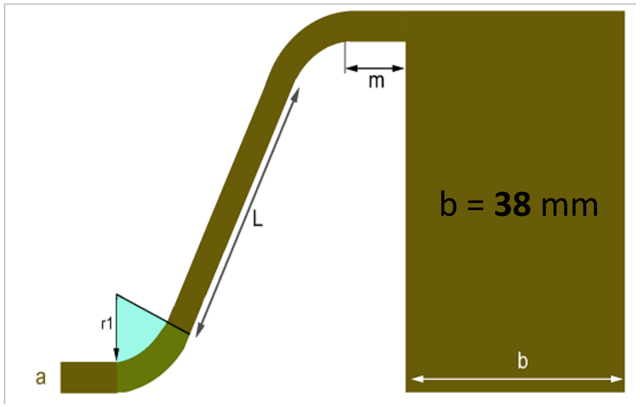
Trace parameters:

Kapton Insulation thickness:	50 µm
Stainless Steel thickness:	25 µm
Copper thickness:	10 µm
Glue thickness:	up to 25 µm

Coil surface coverage by trace: < 50 % IL

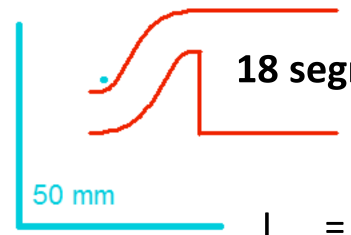
Distance from heater to coil or voltage taps: **4 mm or more**

SQXF outer layer, “SS only” design



a = 10.48 mm (=> **12.11** mm along the cable)
r1 = 3 mm ; L = **15** mm; α = 60 deg; m = 3 mm
$\rho = 5 \cdot 10^{-7}\ \Omega$ m, d = 25 μm

$H_{OPMT} = H_{IPMT}$ = 23.7 mm

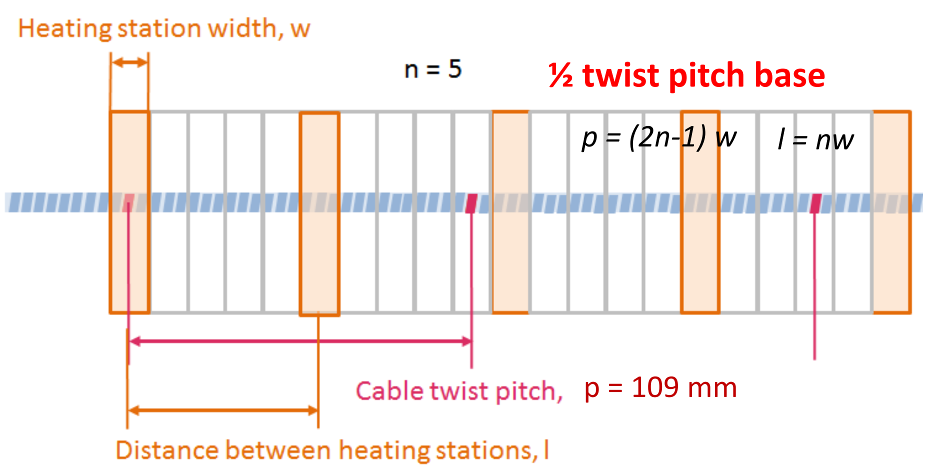


18 segments
(Per 1.075 m)

L_{seg} = 60.7 mm

R_{heater} = 1.48 Ω

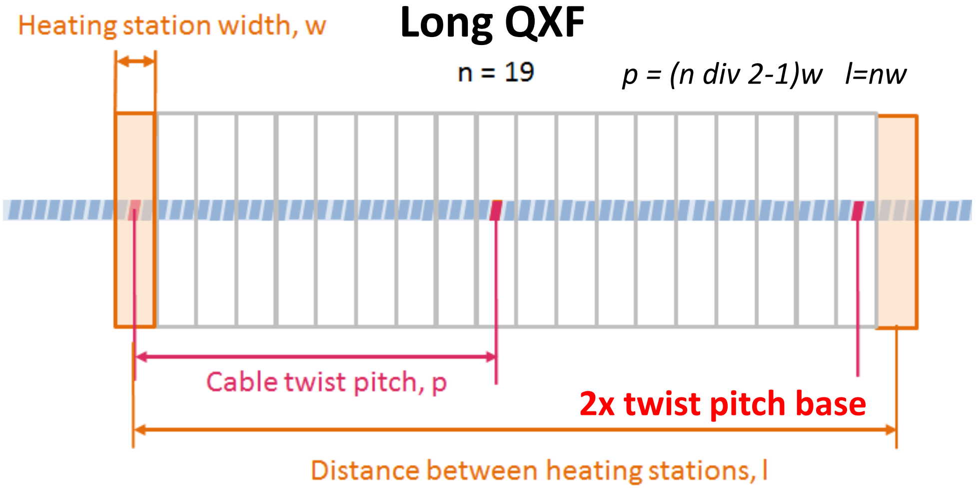
At **100** V =>
67 A and 82 W/cm² per straight portion of the heating station



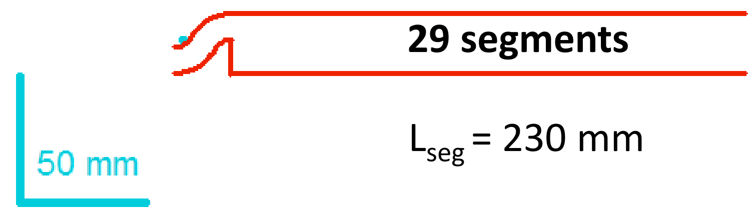
5 segments (303.5 mm length) will provide simultaneous quenching of all strands.

To satisfy the 4 mm gap between heaters and coil boundaries / Vtaps requirement, the choice was made for the ~24 mm wide heater pattern, allowing placing two heater strips of identical geometry per each coil side.

Long QXF "SS-only" option for the OL



(Per 6.70 m)



L_{seg} = 230 mm

$H_{OPMT} = H_{IPMT}$ = 23.7 mm

⇓

R_{heater} = 6.49 Ω

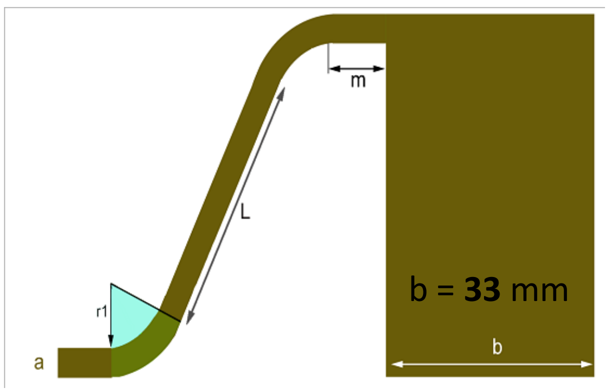
At **450** V =>
69 A and 87 W/cm^2
per straight portion
of the heating station

One will need to increase the period of the heater pattern to 230 mm (2x twist pitch +1 station) in order to be within the required range of power densities. This in turn will add ~10 ms to the heater total delay due to increased quench propagation time between the HS.

SQXF inner layer, "SS only" design

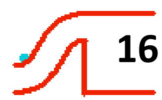
L_{IMMT} = 30.75 mm and L_{IPMT} = 9.19 mm
Entire inner layer: 45.51 mm

If we were to place two separate heaters for the inner layer like we did for the outer layer, the only feasible heater structure for the pole multi-turn L_{IPMT} would be a straight strip. Even then, at 6.7 m length and 9.2 mm width its resistance will be ~14.6 Ω – too high! Therefore, we **combined mid-plane and pole block heaters in one that spans across the spacer** and portions of both (pole and mid-plane) multi-turns. It occupies ~65% of the trace width along the winding.



a = 10.48 mm (=> 12.11 mm along the cable);
r1 = 3 mm; L = **15** mm; α = 60 deg; m = 3 mm

H_{seg} = 30.75 mm

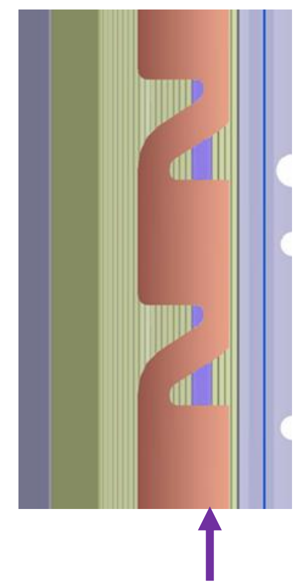


16 segments
SQXF (1.0 m)

L_{seg} = 61.3 mm

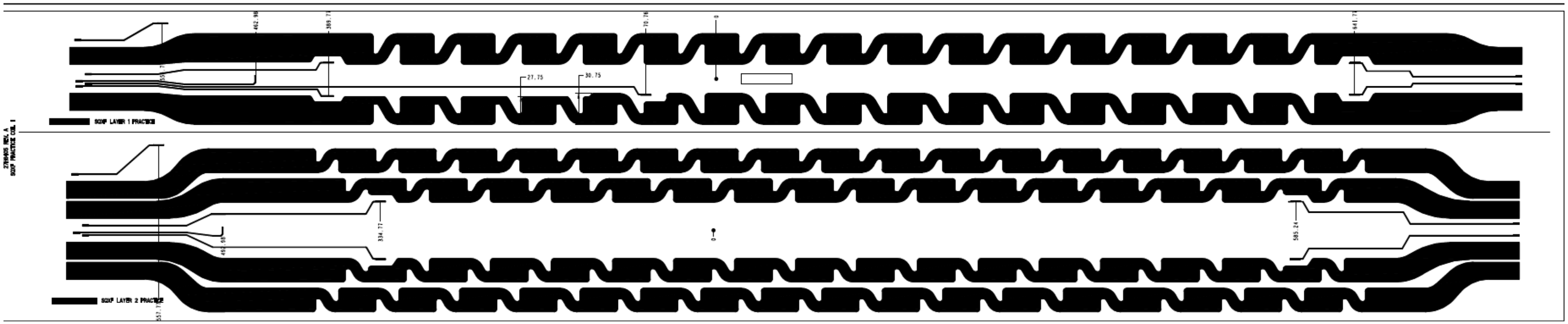
R_{heater} = 1.42 Ω

5 segments (303.5 mm length) will provide simultaneous quenching of all strands.

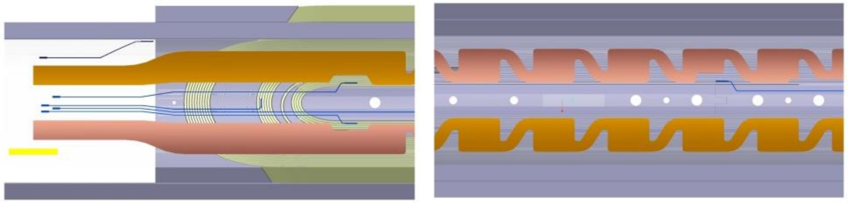


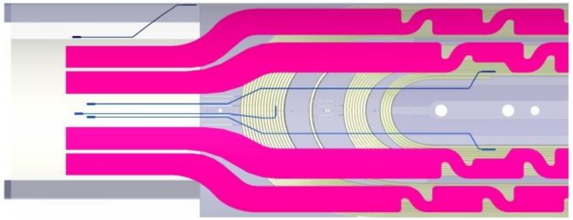
wedge

SQXF final trace for Coil 1



D. Cheng

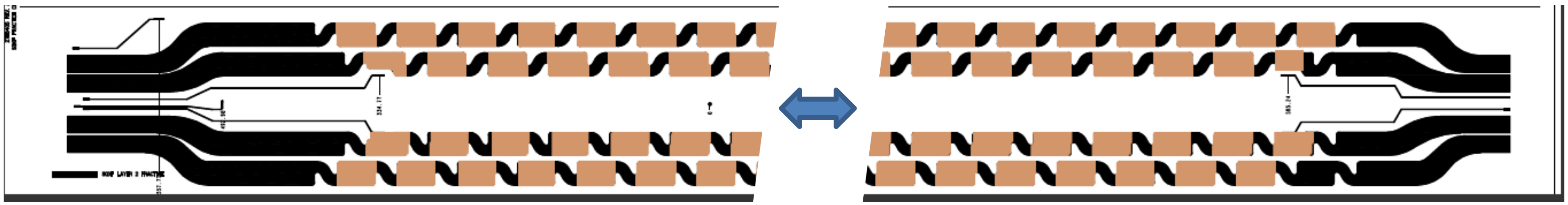




- The masks were produced and one trace was manufactured. Hipot test of the trace is pending.

Can the SQXF design be directly used for LQXF?

YES – by applying copper plating



6.7 m

The SQXF original design extended to 6.7 m length yield ~110 heating stations and the net resistance of 9.1 Ohm => 49 A (at 450 V) and 45 W/cm^2 per heating station – too low. But we can scale up the length of the original heating station design, by plating copper only on the wide portions of the heater:

If we plate the "pads" with 10 micron of Cu, the net resistance will drop to 5.6 Ω => 80 A (at 450 V) and 116 W/cm^2

Assuming ρ_{Cu}= 3.6 10^{-9} Ω m (at 100 K)

This is still an option for the long QXF

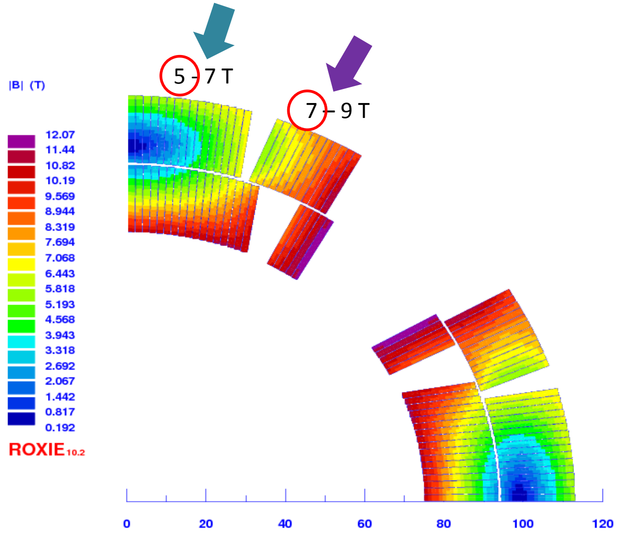
Copper plating: a game changer?

One can possibly form heating stations in the **straight** SS strip by selectively applying copper plating

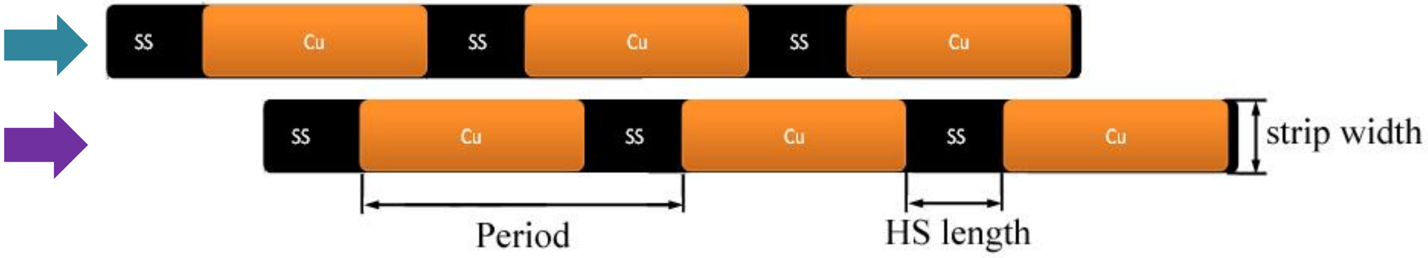
- ❑ Advantage: easier fabrication, larger heating stations (so potentially smaller delay), more power delivered overall
- ❑ Disadvantage: higher heater currents, continuous coverage along the turns may favor bubbles (IL only)
- ❑ Open questions: electrical integrity, current uniformity

- Furthermore, many "hybrid" solutions are possible, that can be optimized for the winding layout, field distribution, etc…

OL “Cu-plated” design, option 1



- 2 separately powered strips / coil side
- Strip width 20 mm
- HS length and period optimized using CoHDA
  - 7 T and 5 T @17500 A
  - NZPV = 5 m/s



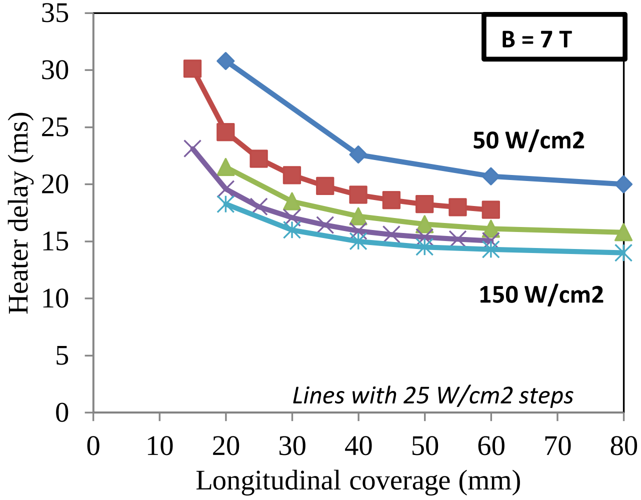
T. Salmi

Optimization results for the OL

- Optimization is done by minimizing the sum of (PH delay + quench propagation time between the HS).

7 T – 20 mm wide strip

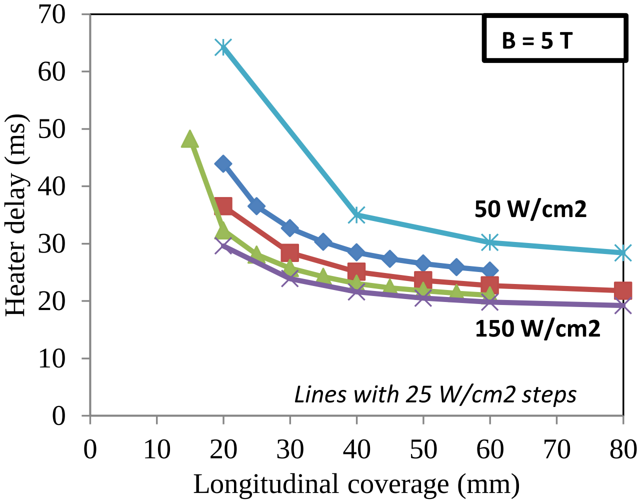
Power (W/cm2)	LHS (mm)	Period (mm)	PH delay (ms)	Tot. Delay (ms)
50	60	106.7	20.7	25.4
75	40	88.2	19.1	23.9
100	30	106.70	18.5	23.22
125	30	87.2	17.1	22.8
150	30	96	16	22.6



5 T – 20 mm wide strip

Power (W/cm2)	LHS (mm)	Period (mm)	PH delay (ms)	Tot. Delay (ms)
50	80	142.2	28.4	34.6
75	55	121.3	25.9	32.5
100	40	103.00	25.1	31.4
125	40	116.2	23.2	30.6
150	40	128.4	21.6	30.4

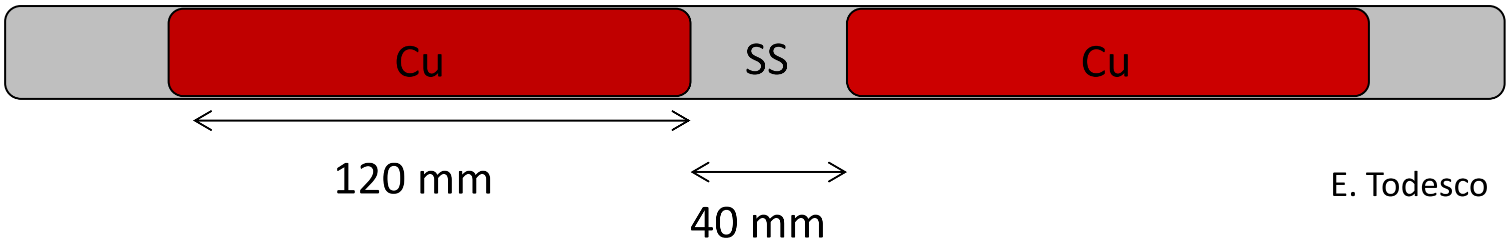
Negligible difference..



Adjustment of the period to match the cable twist pitch is to be done here…

T. Salmi

"Cu-plated" OL design, option 2

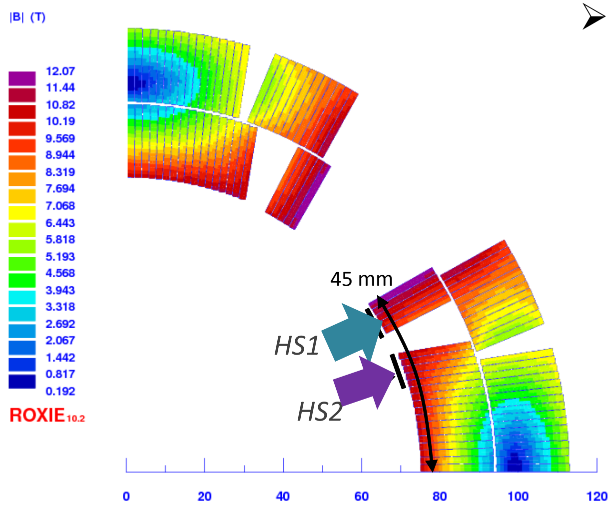


E. Todesco

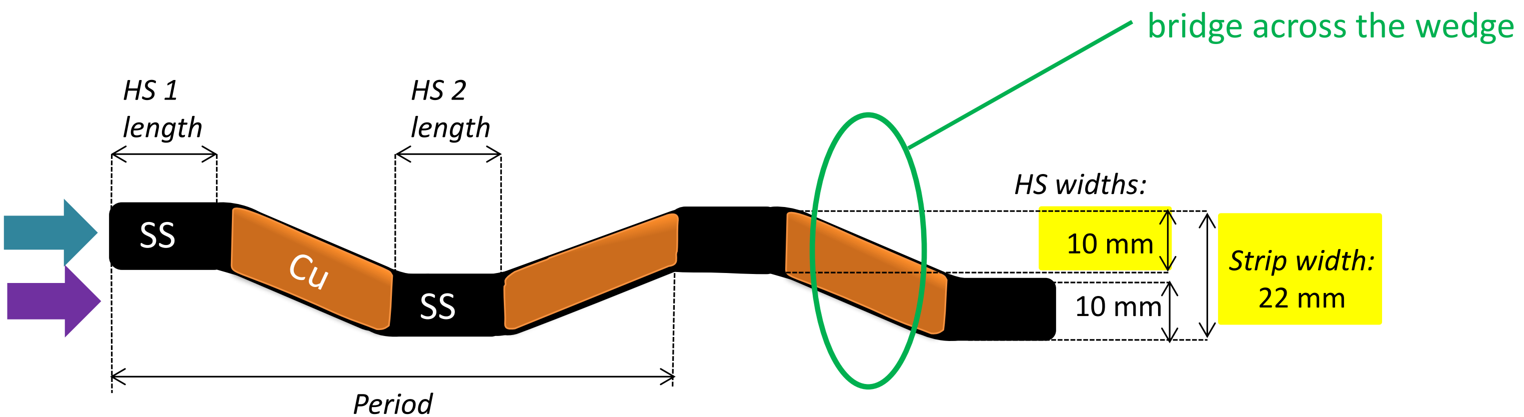
- Power up to 200 W/cm^2 (at 200 A)

QXF				
		short	US	CERN
Magnet length	(m)	**1**	**4**	**7**
Heater width	(mm)	**20**	**20**	**20**
Heater thickness	(mm)	**0.025**	**0.025**	**0.025**
Station length	(mm)	**40**	**40**	**40**
Station distance	(mm)	**120**	**120**	**120**
Station resistance	(Ω)	0.04	0.04	0.04
SS resistivity	(Ωm)	5.0E-07	5.0E-07	5.0E-07
Cu resistivity	(Ωm)	5.0E-09	5.0E-09	5.0E-09
Cu resistance	(Ω)	3.0E-03	3.0E-03	3.0E-03
Cu thickness	(mm)	0.010	0.010	0.010
Number of stations	(dimless)	6	25	43
Total resistance	(Ω)	0.26	1.08	1.85
Voltage	(V)	**52**	**215**	**370**
Current	(A)	**200**	**200**	**200**
Power	(W/cm^2)	**200**	**200**	**200**

“Cu-plated” IL design, option 1: “snake” pattern

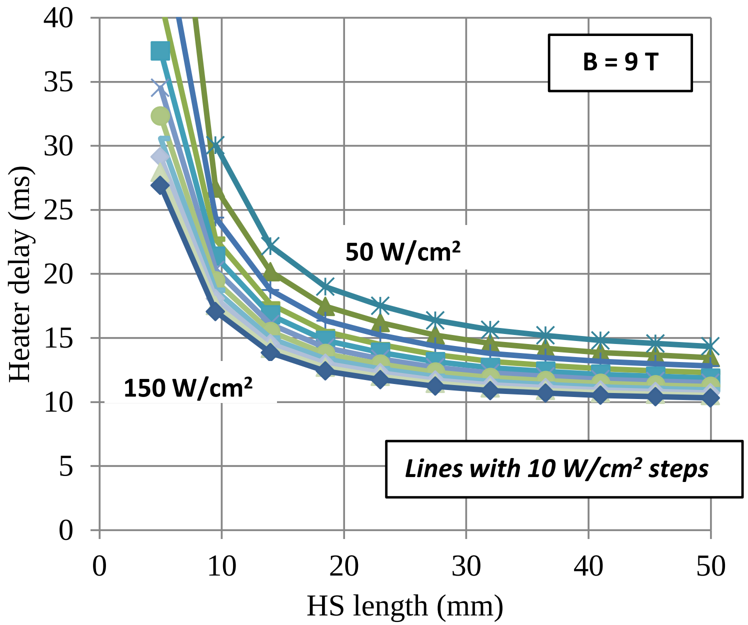


- Strip full span = 22 mm (leaving > 50 % free at thecoil midplane), covering
  - 4 turns on pole block (~7.2 mm)
  - 5 turns on midplane block (~9.2 mm)
    - Heating station (HS) width = 10 mm
    - HS length and period optimization (CoHDA)
      - B = 9 T, NZPV = 10 m/s



T. Salmi

Dimensional optimization



- **Optimization is done by minimizing the sum of (PH delay + quench propagation time between the HS).**

Result (adjusted for the pitch length of 109 mm):

- **HS length = 18.32 mm**
- **period = 91 mm**

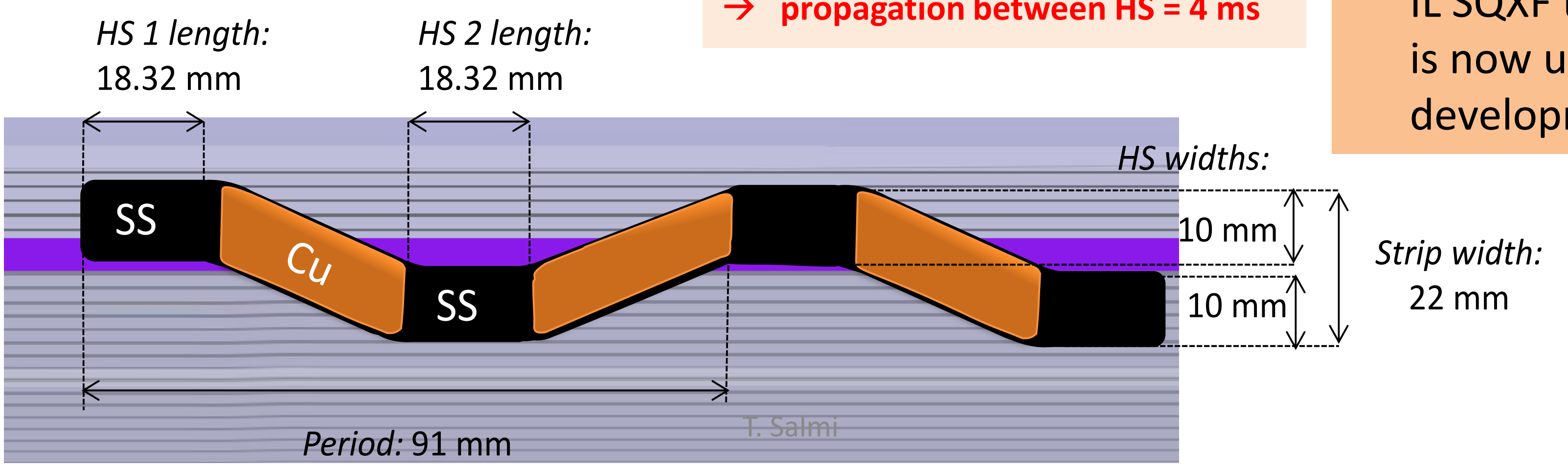
τ_{RC} = 36 ms, R = 5.6 Ω, I = 80 A

P(0) = 130 W/cm²

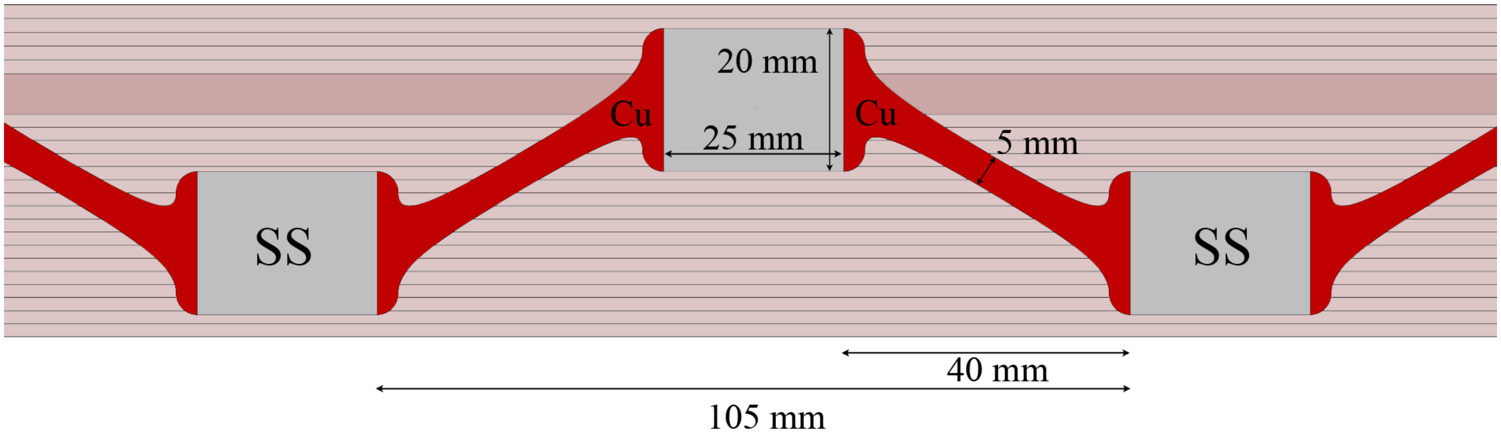
→ **PH delay = 13 ms,**

→ **propagation between HS = 4 ms**

- The CAD version of the IL SQXF trace is now under development



“Cu-plated” IL design, option 2



E. Todesco

- Reduced width of the copper-plated bridges (more space available for holes)
- Increased width of the heating station
- Cooper-plated terminals of the heating stations to improve current flow uniformity

		short	US	CERN
Magnet length	(m)	1	4	7
Heater width	(mm)	20	20	20
Heater thickness	(mm)	0.025	0.025	0.025
Station length	(mm)	25	25	25
Station distance per turn	(mm)	105	105	105
Station resistance	(Ω)	0.025	0.025	0.025
SS resistivity	(Ωm)	5.0E-07	5.0E-07	5.0E-07
Cu resistivity	(Ωm)	5.0E-09	5.0E-09	5.0E-09
Cu resistance	(Ω)	0.0056	0.0056	0.0056
Cu width	(mm)	5	5	5
Cu thickness	(mm)	0.010	0.010	0.010
No. of stations per turn	(dimless)	7	30	53
Total resistance	(Ω)	0.43	1.84	3.24
Voltage	(V)	64	275	487
Current	(A)	150	150	150
Power	(W/cm^2)	112.5	112.5	112.5

Comparative parameter table for the IL designs

”Cu” - IL Option 1 (Tiina)

		short	US	CERN
Magnet length	(m)	**1**	**4**	**7**
Heater width	(mm)	**10**	**10**	**10**
Heater thickness	(mm)	**0.025**	**0.025**	**0.025**
Station length	(mm)	**18.3**	**18.3**	**18.3**
Station distance per turn	(mm)	**72.7**	**72.7**	**72.7**
Station resistance	(Ω)	0.0366	0.0366	0.0366
SS resistivity	(Ωm)	5.0E-07	5.0E-07	5.0E-07
Cu resistivity	(Ωm)	5.0E-10	5.0E-10	5.0E-10
Cu resistance	(Ω)	0.0002	0.0002	0.0002
Cu width	(mm)	9.4	9.4	9.4
Cu thickness	(mm)	0.010	0.010	0.010
No. of stations per turn	(dimless)	10	43	76
Total resistance	(Ω)	0.74	3.17	5.59
Voltage	(V)	**59**	**253**	**448**
Current	(A)	**80**	**80**	**80**
Power	(W/cm^2)	**128**	**128**	**128**

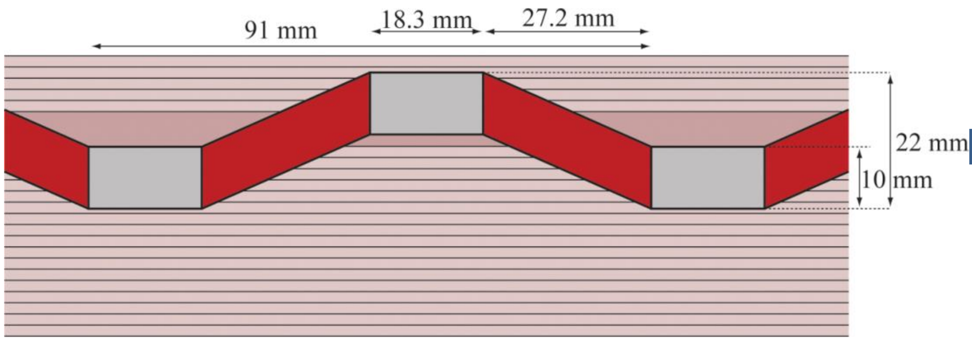
”Cu” - IL Option 2 (Ezio)

		short	US	CERN
Magnet length	(m)	**1**	**4**	**7**
Heater width	(mm)	**20**	**20**	**20**
Heater thickness	(mm)	**0.025**	**0.025**	**0.025**
Station length	(mm)	**25**	**25**	**25**
Station distance per turn	(mm)	**105**	**105**	**105**
Station resistance	(Ω)	0.025	0.025	0.025
SS resistivity	(Ωm)	5.0E-07	5.0E-07	5.0E-07
Cu resistivity	(Ωm)	5.0E-10	5.0E-10	5.0E-10
Cu resistance	(Ω)	0.0006	0.0006	0.0006
Cu width	(mm)	5	5	5
Cu thickness	(mm)	0.010	0.010	0.010
No. of stations per turn	(dimless)	7	30	53
Total resistance	(Ω)	0.36	1.53	2.71
Voltage	(V)	**61**	**261**	**461**
Current	(A)	**170**	**170**	**170**
Power	(W/cm^2)	**144.5**	**144.5**	**144.5**

Comparison of the delays (simulation)

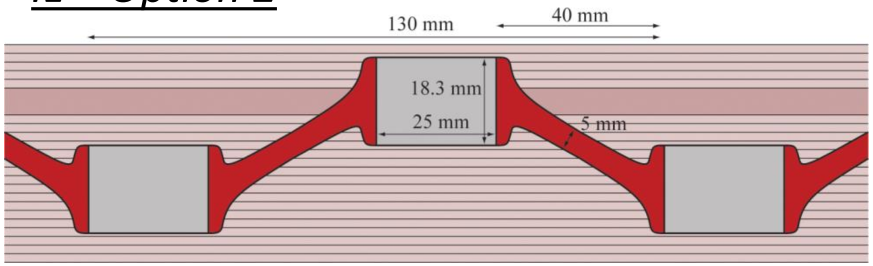
__Simulation for 100 W/cm^2, τ = 47 ms__
__Heater delays at nominal current__

__IL – Option 1__



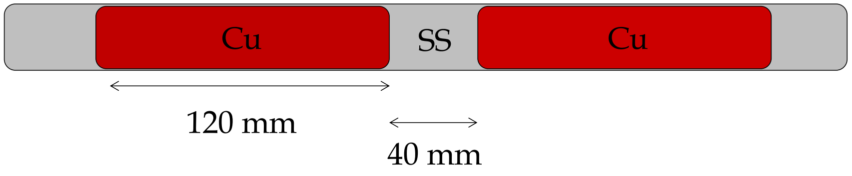
- First delay = 9 ms
- Average* delay = 12 ms

__IL – Option 2__



- First delay = 9 ms
- Average* delay = 11 ms

__OL__

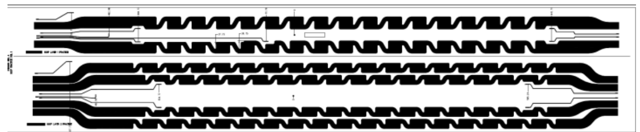


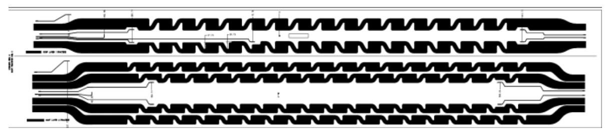
- First delay = 12 ms
- Average* delay =
  - 20 ms (LF block)
  - 14 ms (HF block)

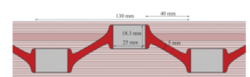
T. Salmi

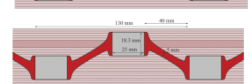
*Using medium field (no quench propag. incl.)

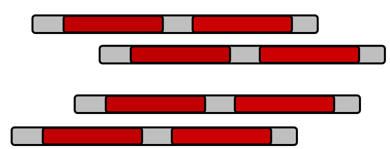
Current status summary and planning











	CAD	Trace
Coil 1: LARP		
➢ IL :“SS only”	V	V
➢ OL: “SS only	V	V
Coil 1: CERN		
➢ IL :“SS only”	V	x
➢ OL: “SS only”	V	x
Coils 2-3: LARP		
➢ IL: “Cu plating” option 1	In progress	x
➢ OL: “SS only”	V	x
Coils 2-3: CERN:		
➢ IL: “Cu plating” IL, option 2	x	x
➢ OL: “Cu plating” OL option 1 or 2	x	x

Remaining questions

- Low field / low current performance

  It appears that much longer heating station (or more power) is needed to initiate quench at < 5 kA. Additional optimization and/or alternative solutions may be needed for the OL mid-plane block heater strip.

- Formation of "bubbles" under the IL heater trace

  Bubble formation was observed routinely in LQ coils under the "wide" portions of the inner layer SS heater element. It is unclear if increasing the heating station length along the cable will induce same type of problem

- Is "more power and larger area" always a good approach for improving protection performance? Or can one do a better job (or same job with less current / stress/ heat gradients) using targeted heat deposition through a better layout optimization? Side-by-side testing is needed to answer this question.