DE LA RECHERCHE À L'INDUSTRIE

Conceptual Design Review of R2D2

2

- Magnetic Design and Preliminary Protection -

https://indico.cern.ch/event/1003865/

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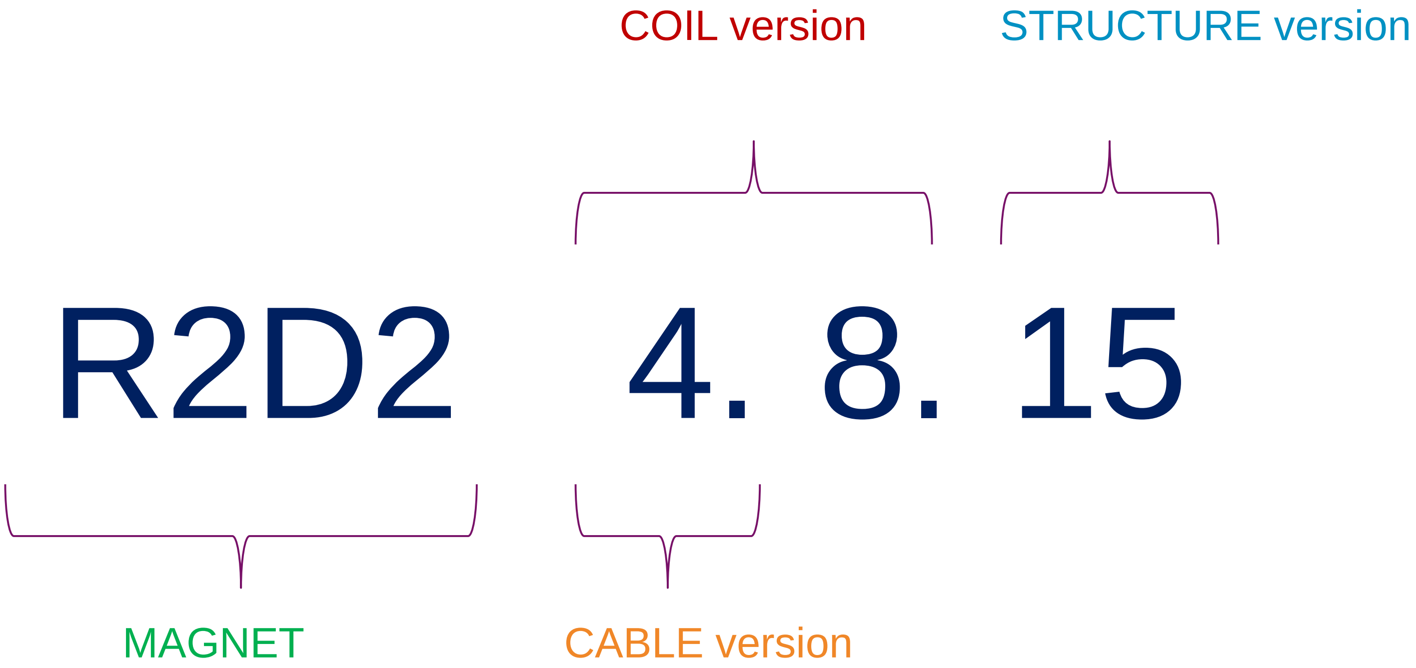
08/03/2021

HOW NOMENCLATURE WORKS



COIL version

STRUCTURE version

R2D2 4. 8. 15

MAGNET

CABLE version

- V1 = FCC 1500 A/mm² @ 16 T 4.2 K
- V2/V3 = intermediary versions
- V4 = F2D2 1200 A/mm² @ 16 T 4.2 K
- V5 = mock-ups cables for tests
- V6 = F2D2 1000 A/mm² @ 16 T 4.2 K

CABLES CONSIDERED FOR THE DESIGN

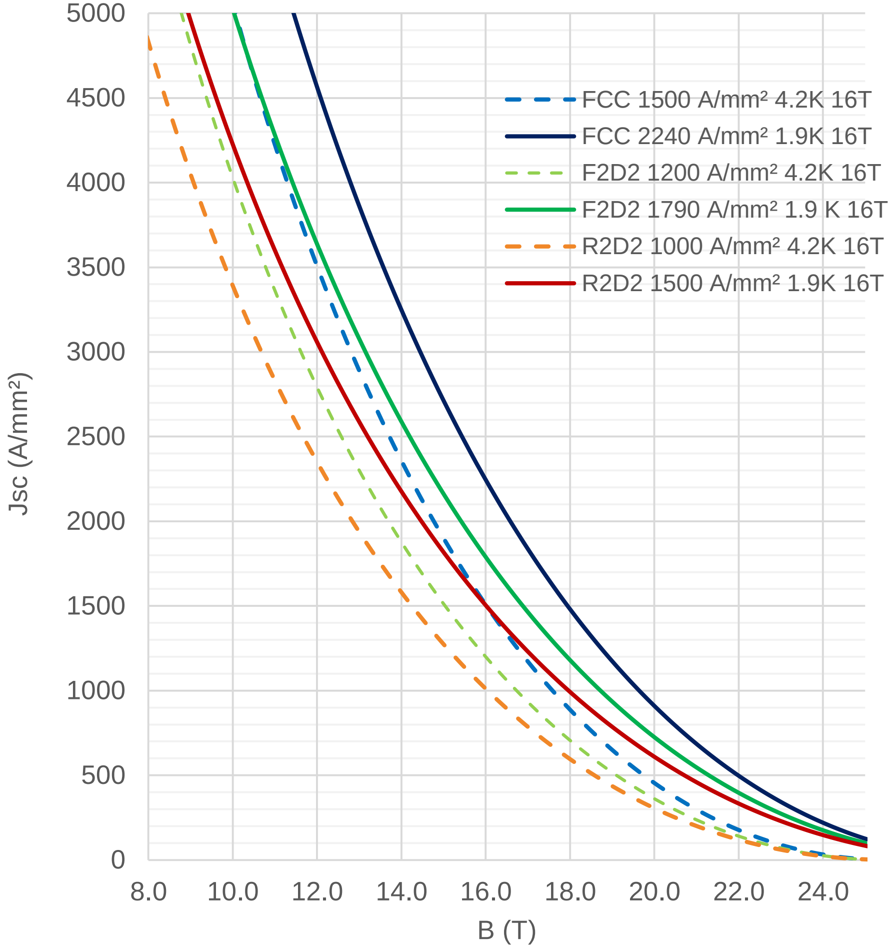
See presentation 4

Expected Parameters	HF	LF
# strands	21	34
ø strands	1.1 mm	0.7 mm
Pitch angle	16.5 deg	16.5 deg
Transposition pitch	85.0 mm	85.0 mm
Cu/Sc ratio	0.8	2
Insulation	0.15 mm	0.15 mm
Expected Dimensions (reacted & insulated)	2.36 x 13.04 mm	1.61 x 13.04 mm

Same geometric dimensions

Different J_c

Expected Critical Current Density Curves

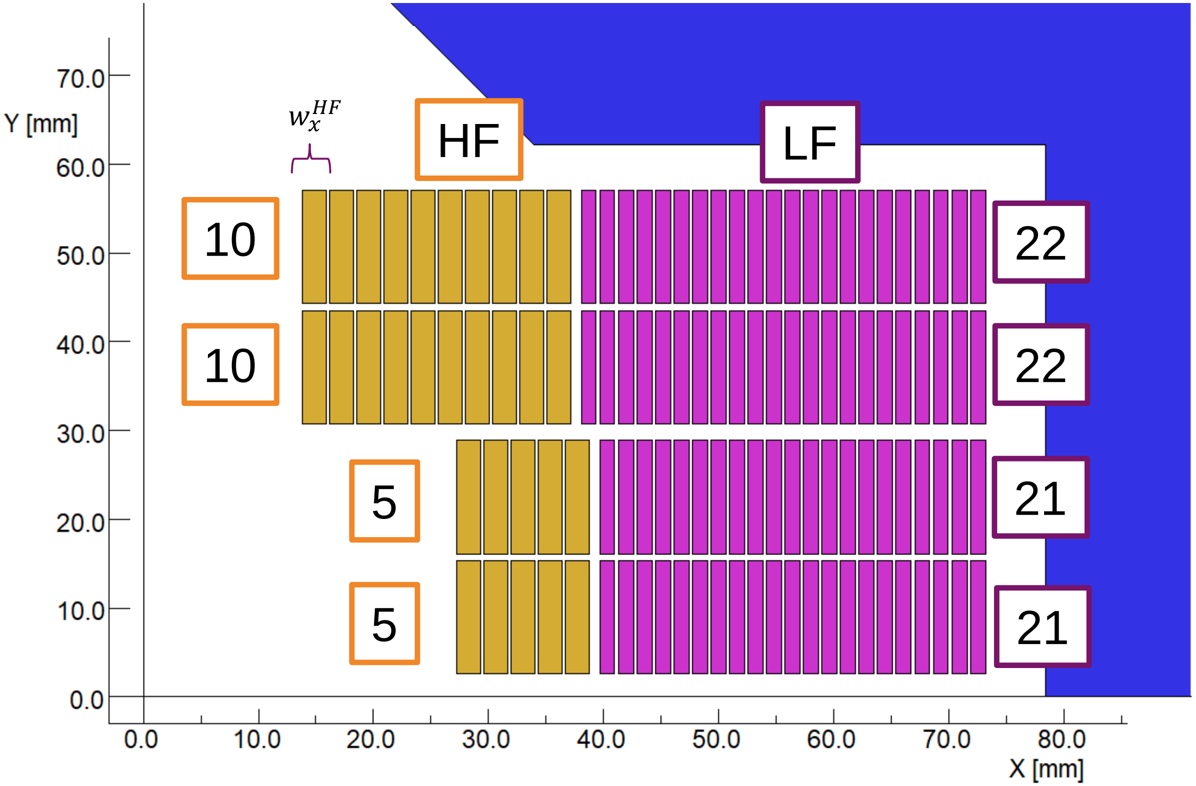


FROM F2D2 V4.8.15…

 # turns from ECC Block Dipole design

COIL 4.8

- Bore radius = 25.0 mm
- Min post radius R_i = 13.69 mm
- R_i/w_x^{HF} = 6.9 (ECC Specs)



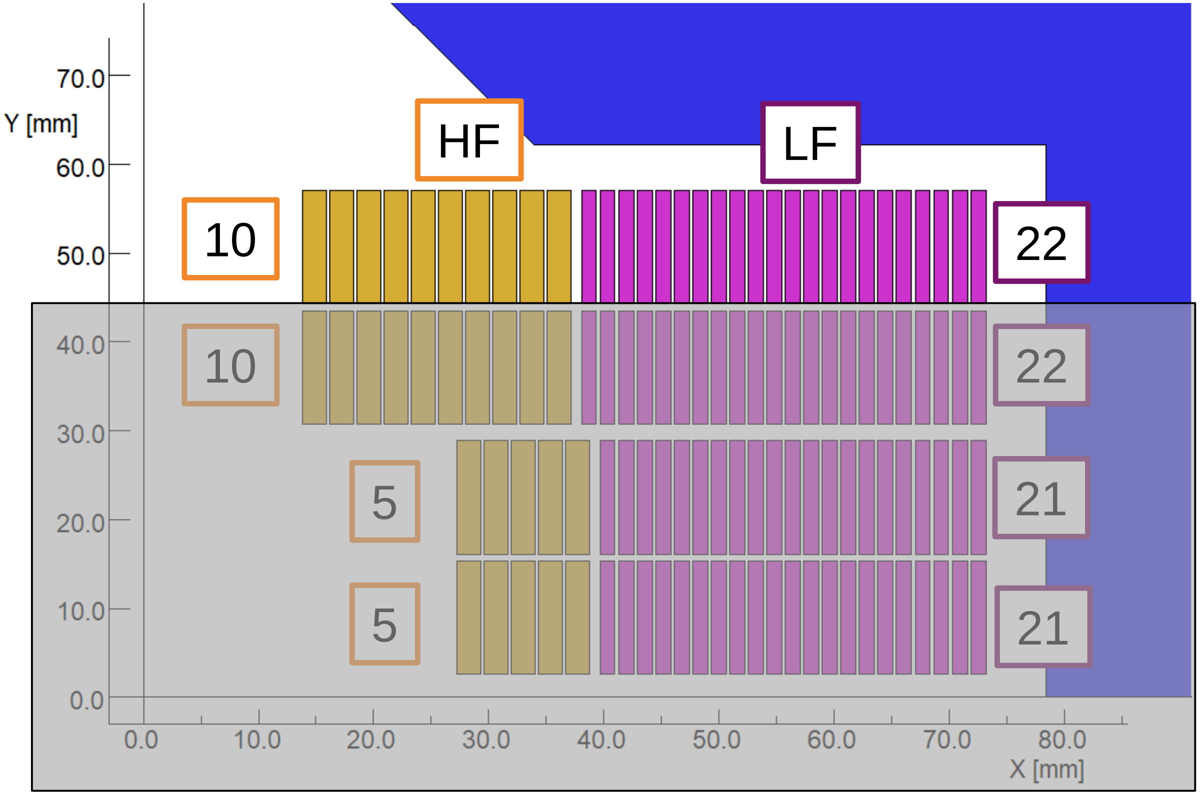
…To R2D2 v4.8.15

GOAL

- Lower the risk
- Study the grading

HOW (part 1)

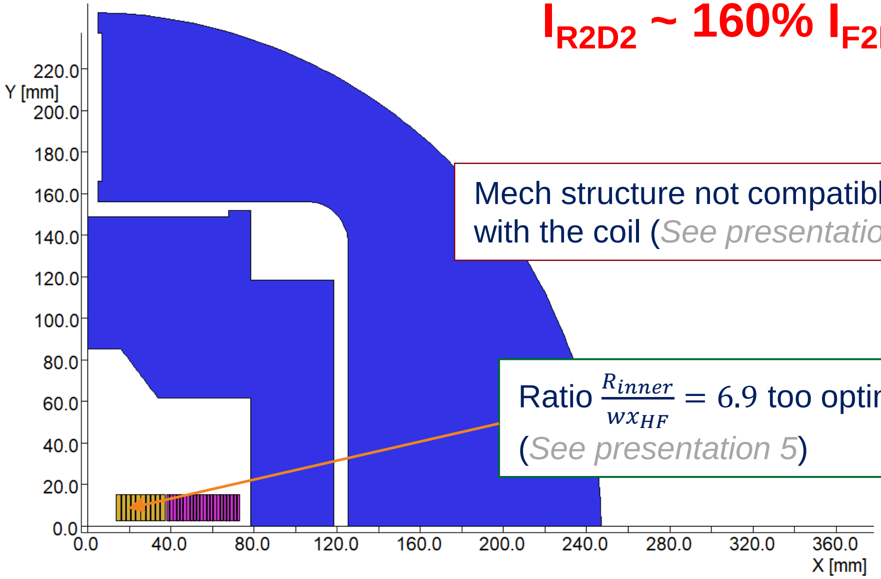
- Racetrack single layer
- Coil 10HF 22LF
- Same F2D2 structure



R2D2 v4.8.15: First Results & Main Issues

Not optimized

I_{R2D2} ~ 160% I_{F2D2}



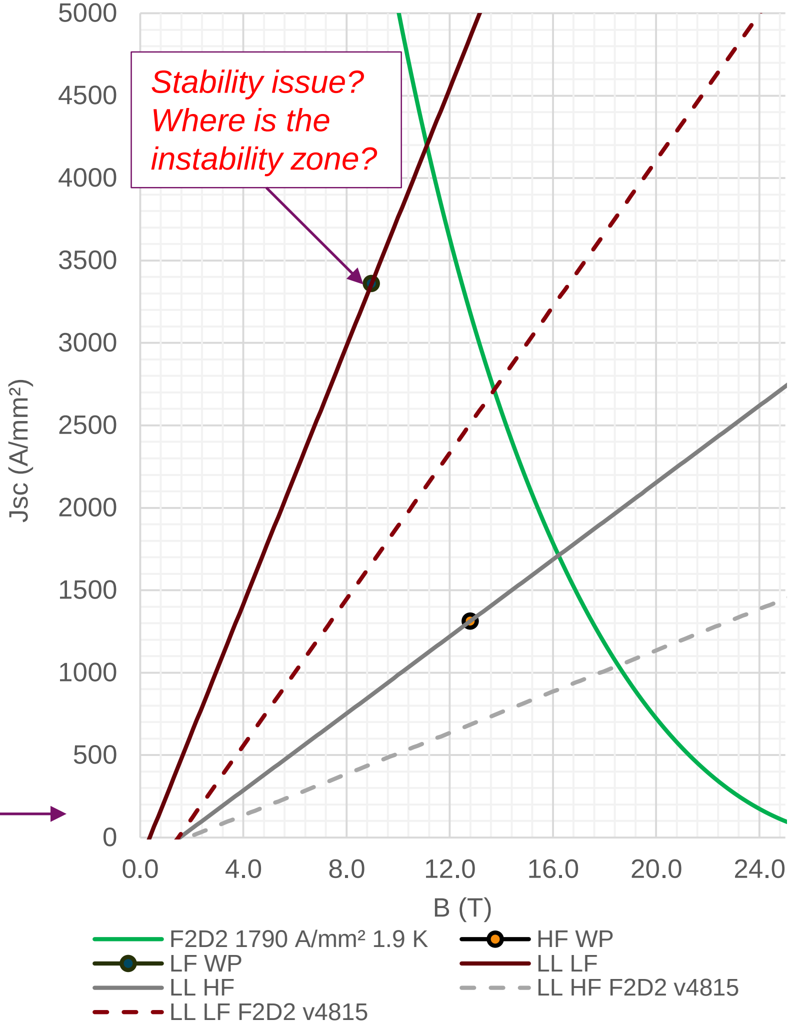
Mech structure not compatible with the coil (*See presentation 3*)

Ratio $\frac{R_{inner}}{wx_{HF}} = 6.9$ too optimist? (*See presentation 5*)

V 4.8.15	Nominal @ 1.9 K 14 % LL margin
I	15917 A
LL margin HF / LF	22.4 % / 14.0 %
B @ (0,0)	11.46 T
B peak HF / LF	12.61 T / 9.77 T

Grading not optimized

Critical Current Density Curves and Load Lines
R2D2 v4815 @1.9 K



Stability issue? Where is the instability zone?

R2D2 V 6.14.R2: 2D DESIGN CRITERIA

Optimization Criteria 2D:

A. Ratio $\frac{R_{inner}}{wx_{HF}} = 6.9$ → Ratio $\frac{R_{inner}}{wx_{HF}} = 10$

B. Instability (?) on the cables
→ 20% cable performance degradation to increase the RRR J_c = @1000A/mm² 4.2 K 16 T
→ First tests @ 4.2 K and after 1.9 K

C. LL margin = 14% too risky
→ Optimized Grading @ 4.2 K LL margin = 20%

D. Max hotspot temperature ~ 350 K
(See presentation on quench)

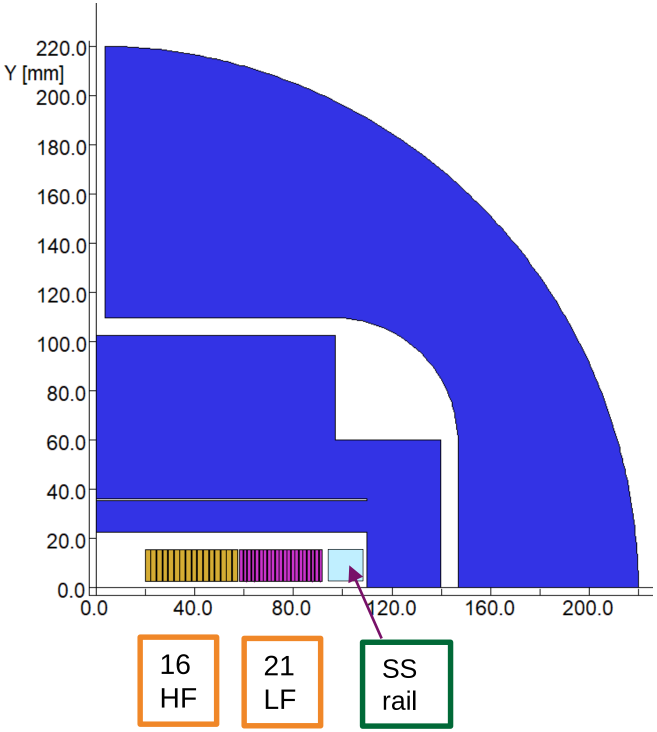
E. Grading not optimized
→ change of the coil pack

F. Dedicated Mechanical structure
→ iron adapted for the mechanics and not for field quality

Coil
4.8 → 6.14

Structure
15 → R2

- Smaller Yoke
- Smaller Y-Pad, X-Pad
- Rail in Iron → SS

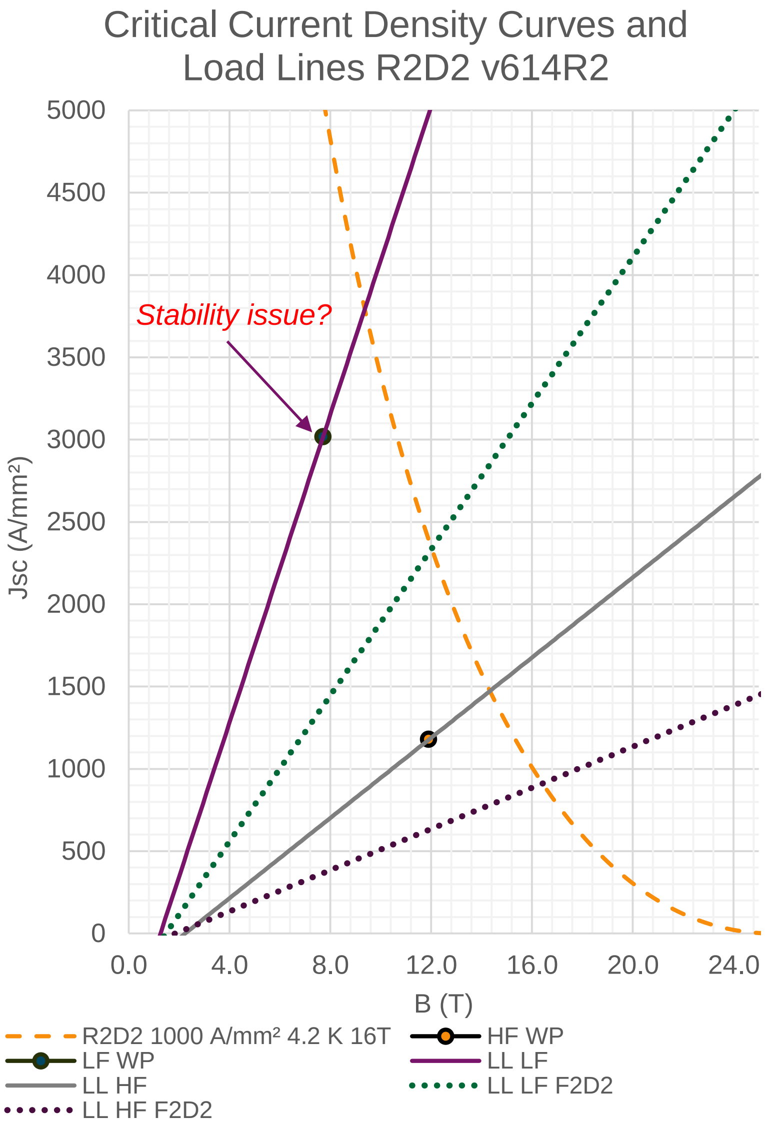


R2D2 v 6.14.R2 – Performances @4.2 K

R2D2 cable 1000 A/mm2 @ 16T 4.2 K FCC Fit

	Nominal	SS
I	13772 A	17215 A
LL margin HF / LF	20.0% / 20.45%	0.0 % / 0.72%
B @ (0,0)	10.42 T	12.46 T
B peak HF	11.82 T	14.27 T
B peak LF	7.68 T	9.49 T
Energy density $\varepsilon_{4.2K}$	474 KJ/m	725 KJ/m
Energy mass density	15.9 KJ/kg	23.8 KJ/kg
Inductance	4.79 mH	4.55 mH
J_{Cu} HF / LF	1472 / 1508 A/mm²	1853 / 1886 A/mm²
Fx HF / LF	1698 / 112 kN/m	2497 / 61 kN/m
Fy HF / LF	-469 / -752 kN/m	-744 / -1101 kN/m
E/L HF / LF	41 / 77 kJ/m	61 / 114 kJ/m

Consequences due to J_{Cu} shown after Lorentz Forces impact in presentation 3

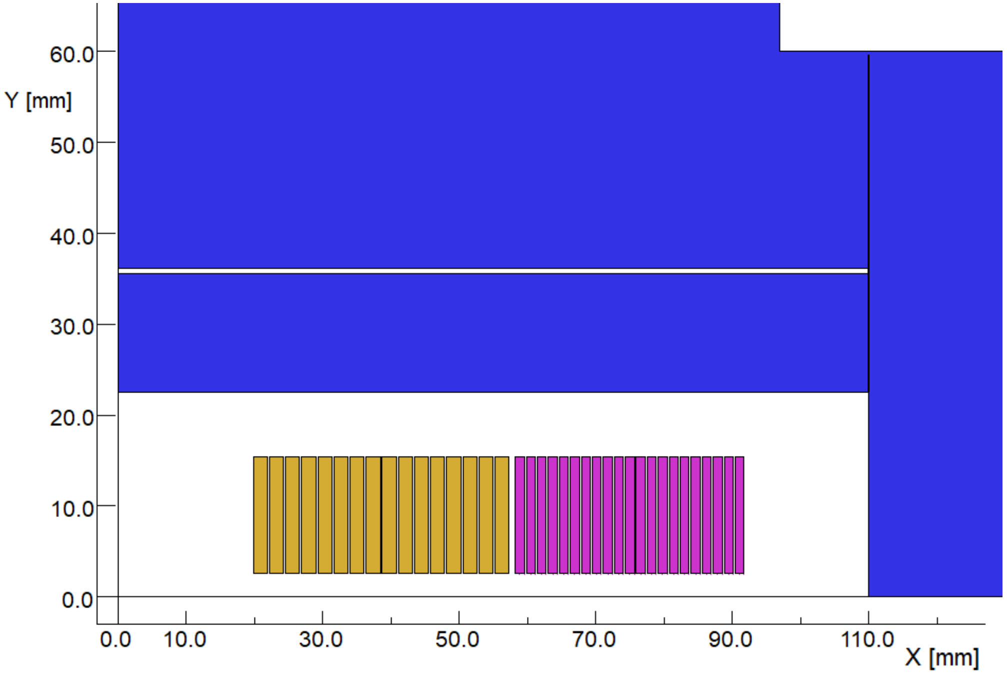

Critical Current Density Curves and Load Lines R2D2 v614R2

R2D2 V 6.14.R2 – GRADING OPTIMIZATION

Grading optimization

Coil pack dimensions	R2D2 4.8.15 (mm)	R2D2 6.14.R2 (mm)
HF	26.58 X 13.04	37.76 X 13.04
LF	35.42 X 13.04	33.81 X 13.04
TOT	59.62 X 13.04	72.17 X 13.04
R_{in}	13.69	19.69

Dimensions for the insulated reacted cables

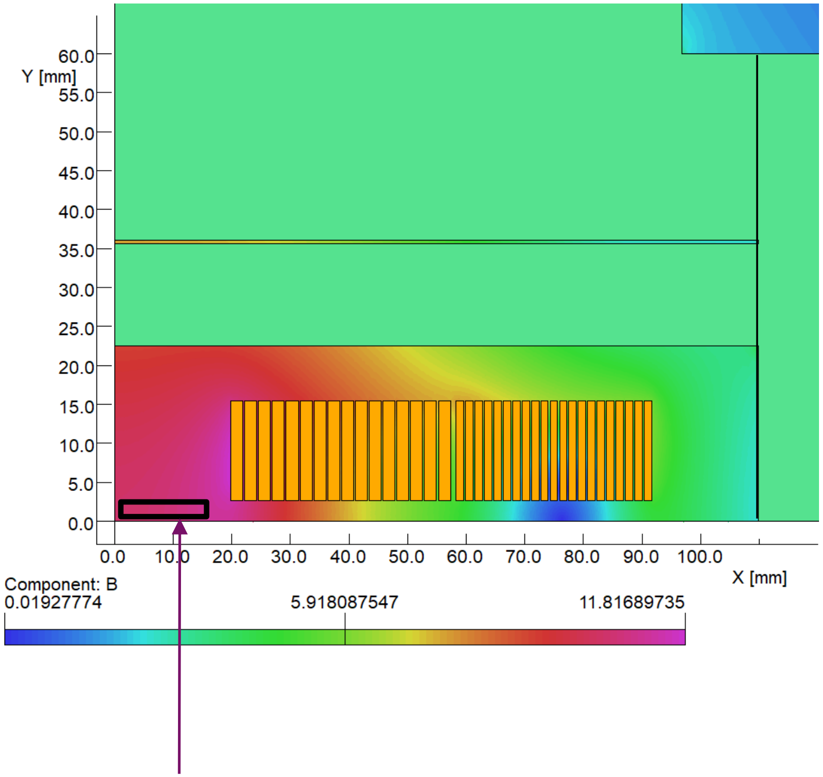


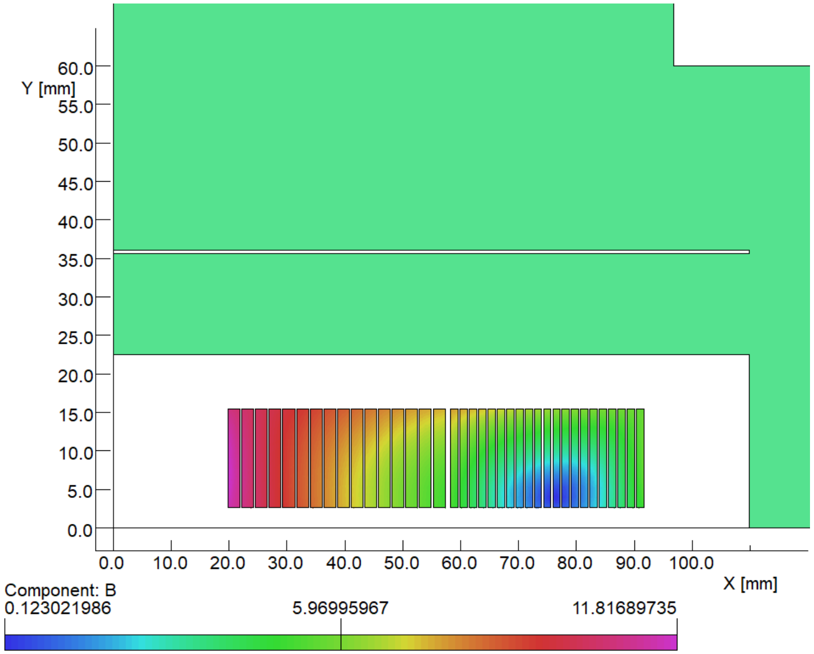
16 HF **21 LF**

Δy midplane = 2.5 mm

R2D2 v 6.14.R2 – B Field Maps @4.2 K

Operative temperature = 4.2 K





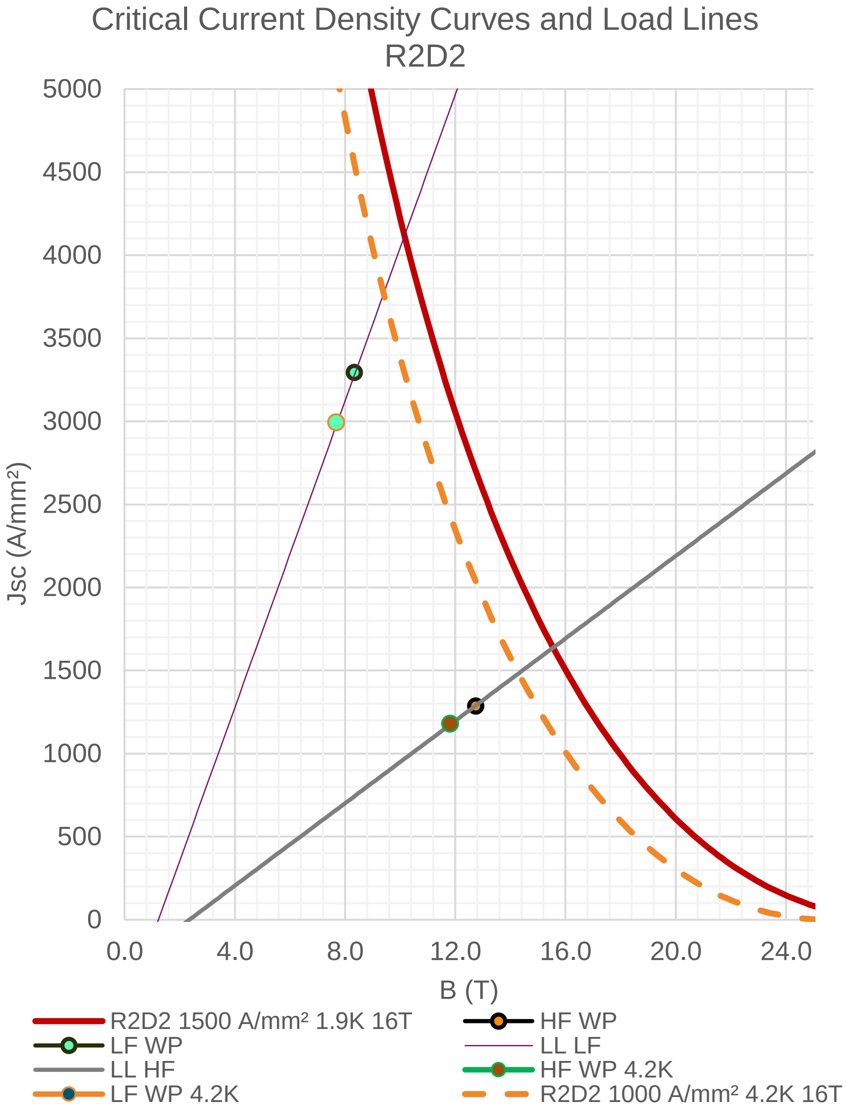
Accessible area for measurements (~30 X 5 mm) → B = 10.42 T

R2D2 v 6.14.R2 – Performances @1.9 K

R2D2 cable 1489 A/mm2 @ 16T 1.9 K FCC Fit

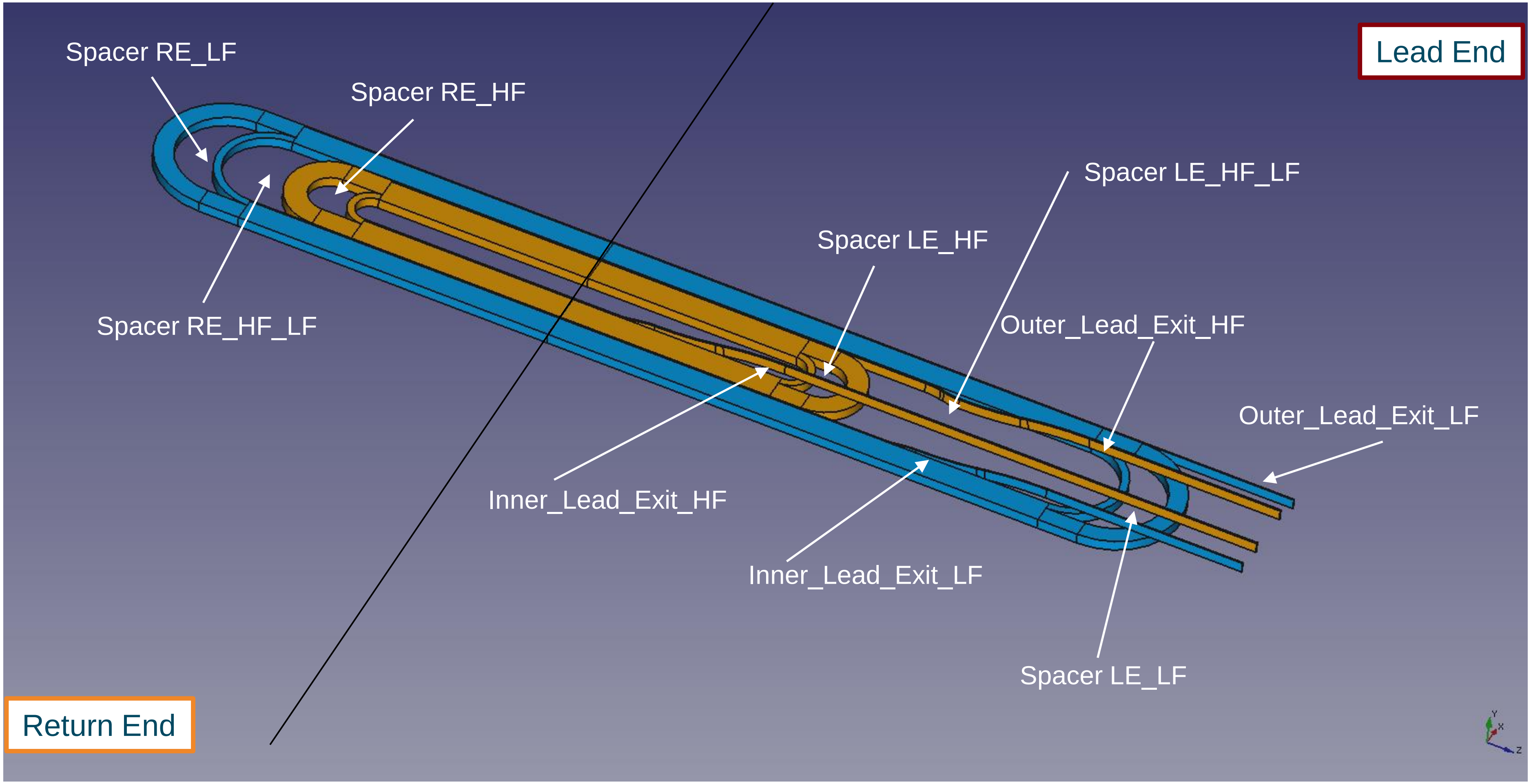
	Nominal	SS
I	15055 A	18819 A
LL margin HF / LF	20.9% / 20.0%	0.9 % / 0.0%
B @ (0,0)	11.15 T	13.29 T
B peak HF	12.69 T	15.23 T
B peak LF	8.32 T	10.21 T
Energy density $\varepsilon_{1.9K}$	553 KJ/m	818 KJ/m
Energy mass density	18.43 KJ/kg	27.25 KJ/kg
Inductance	4.69 mH	4.32 mH
J_{Cu} HF / LF	1627 / 1667 A/mm²	2034 / 2084 A/mm²
Fx HF / LF	1978 / 97 kN/m	2920 / 25 kN/m
Fy HF / LF	-683 / -1101 kN/m	-894 / -1447 kN/m
E/L HF / LF	56 / 106 kJ/m	71 / 133 kJ/m

Consequences due to J_{Cu} shown after Lorentz Forces impact in presentation 3



R2D2 V 6.14.R2 3D DESIGN – COILS TOPOLOGY

Same geometry implemented in OPERA



R2D2 V 6.14.R2 – 3D OPTIMIZATION CRITERIA & BENDING CONSTRAINS

Optimization Criteria 3D:

A. B_{peak} on the straight length for HF and LF

B. Total length = 1300 mm + 200 mm exit leads

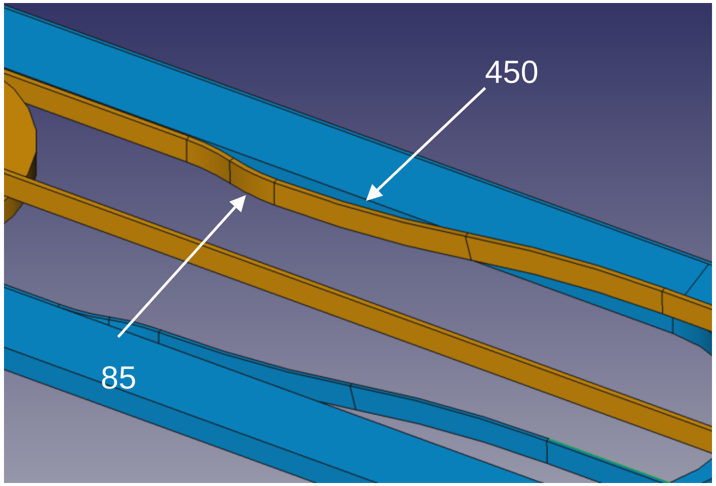
C. Turns distributions in spacers must minimize the B_{peak}

D. Iron is adapted to minimize B_{peak} in the exit leads

Radii

- Hard-way (validated) = 450 mm (*See presentation 5*)
- Easy-way leads = 85 mm (Fresca 2 value)

Conservative, but it is a delicate zone



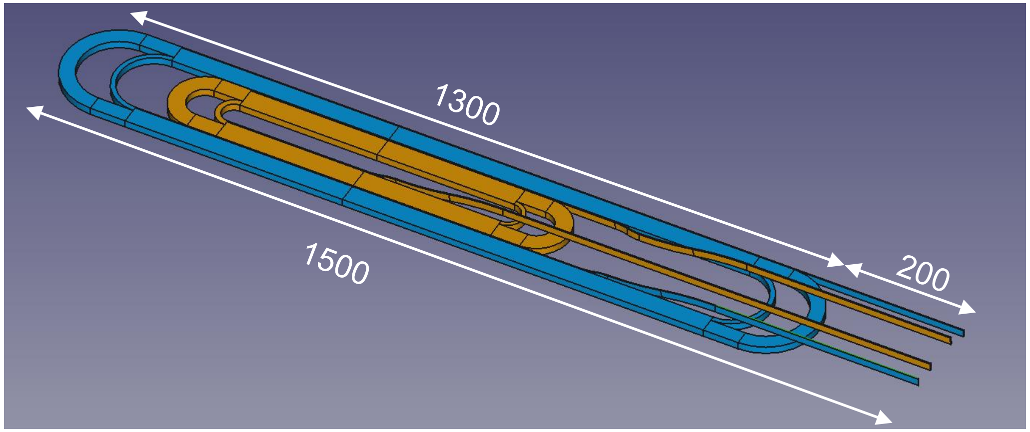
R2D2 V 6.14.R2 – OVEN COMPATIBILITY AND COIL LENGTH

Oven homogeneous length:

- - 2 K ≤ ΔT ≤ 2 K → 1500 mm by specs

R2D2 length:

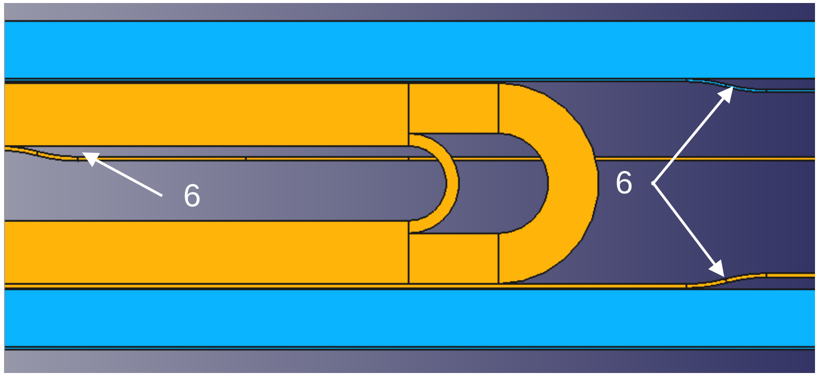
- 1300 mm head to head
- 1500 mm in total (200 mm or more for the Nb_3Sn exit leads)

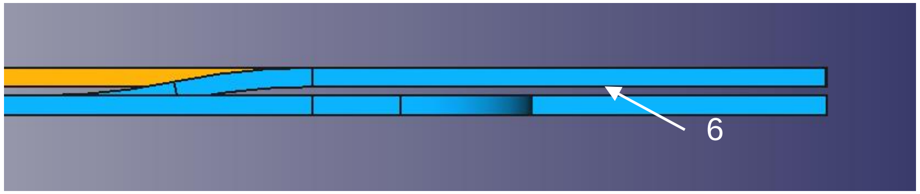


Exit Leads:

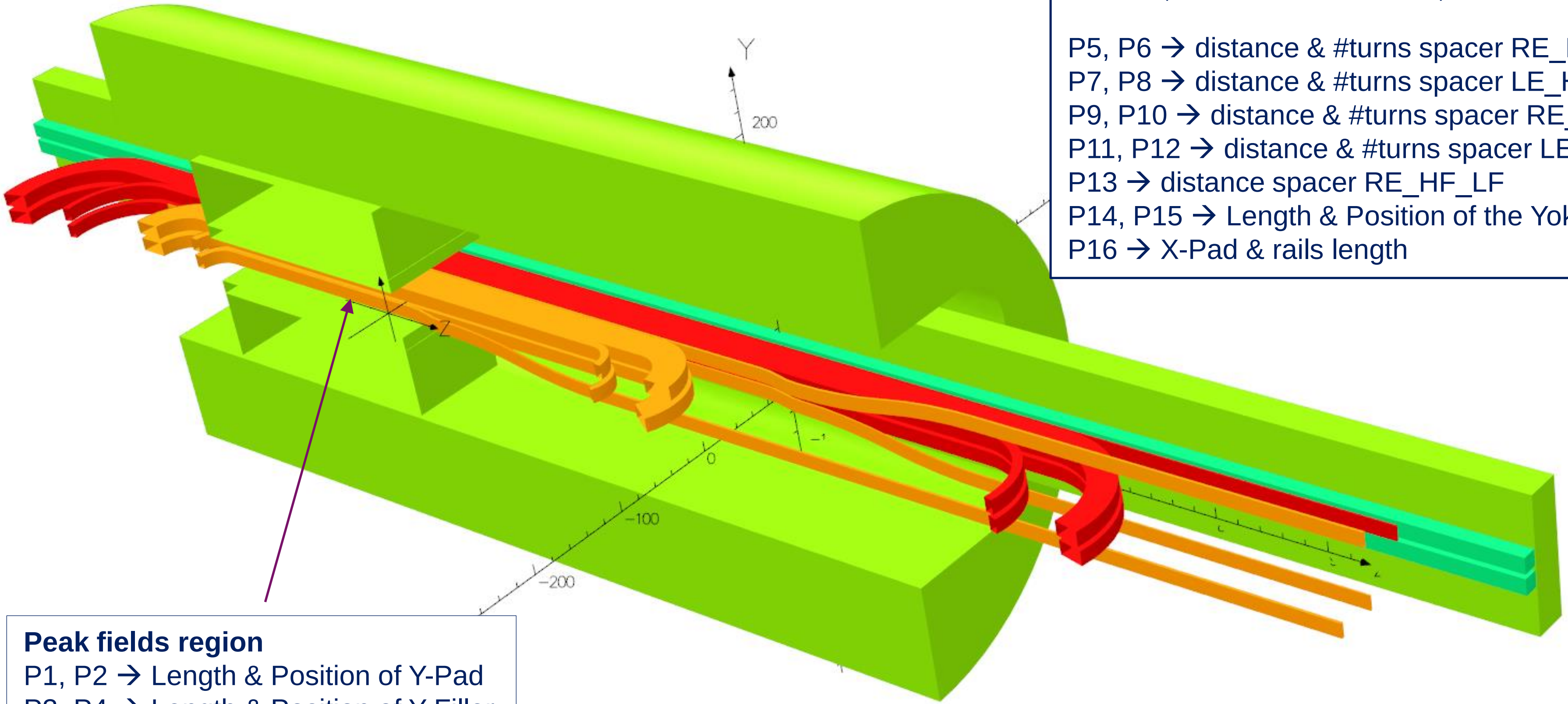
- Chicane separation from coils = 6 mm (for insulation and mechanics)
- Exit leads separation from coils = 6 mm (for insulation & instrumentation, same value as Y-Filler)

Exit leads lengths are fixed by those parameters + radii





R2D2 V 6.14.R2 – 3D OPTIMIZATION

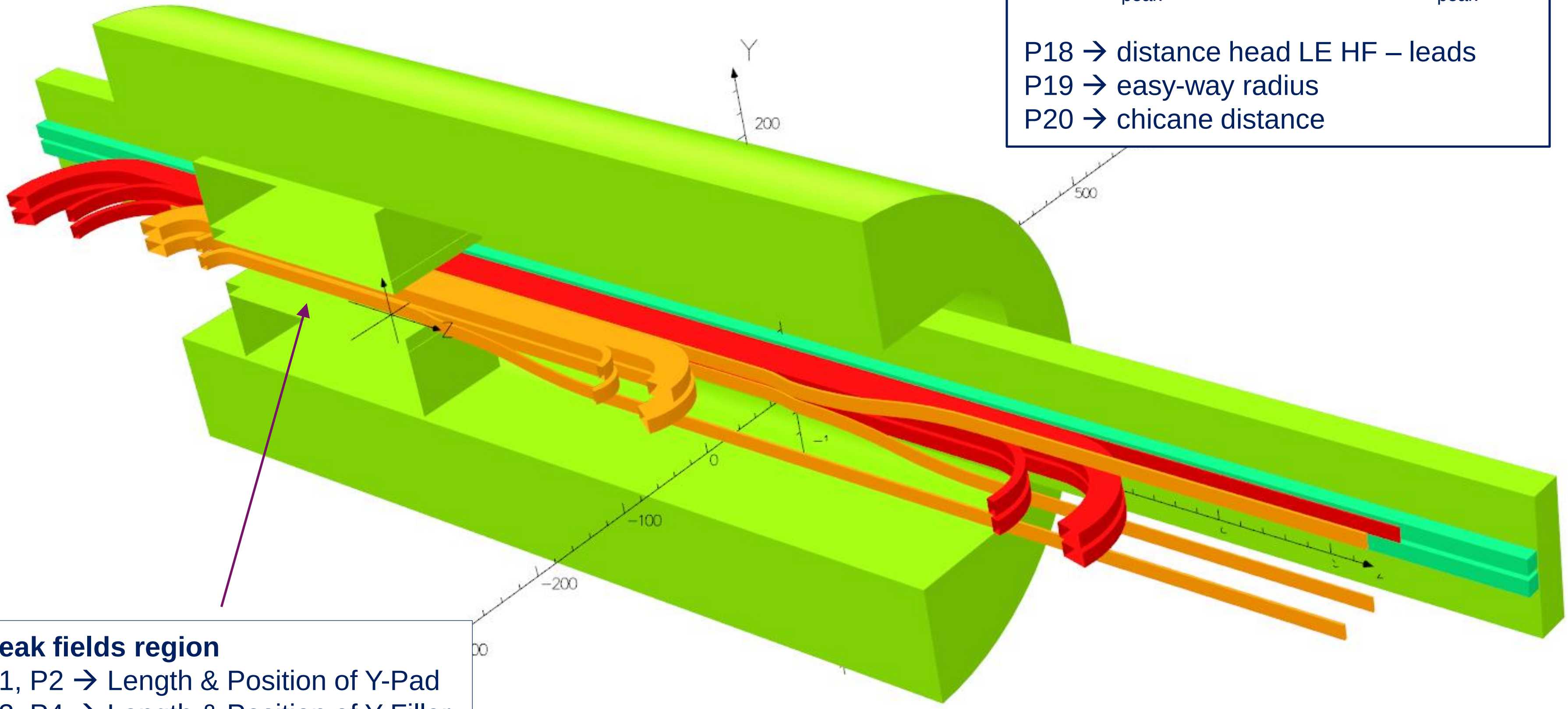


Spacers fields
C2 → B_{peak} spacer RE_HF < B_{peak} HF
C3 → B_{peak} spacer LE_HF < B_{peak} HF
C4 → B_{peak} spacer RE_LF < B_{peak} LF
C5 → B_{peak} spacer LE_LF < B_{peak} LF

P5, P6 → distance & #turns spacer RE_HF
P7, P8 → distance & #turns spacer LE_HF
P9, P10 → distance & #turns spacer RE_LF
P11, P12 → distance & #turns spacer LE_LF
P13 → distance spacer RE_HF_LF
P14, P15 → Length & Position of the Yoke
P16 → X-Pad & rails length

Peak fields region
P1, P2 → Length & Position of Y-Pad
P3, P4 → Length & Position of Y-Filler
C1 = Largest possible zone

R2D2 V 6.14.R2 – 3D OPTIMIZATION

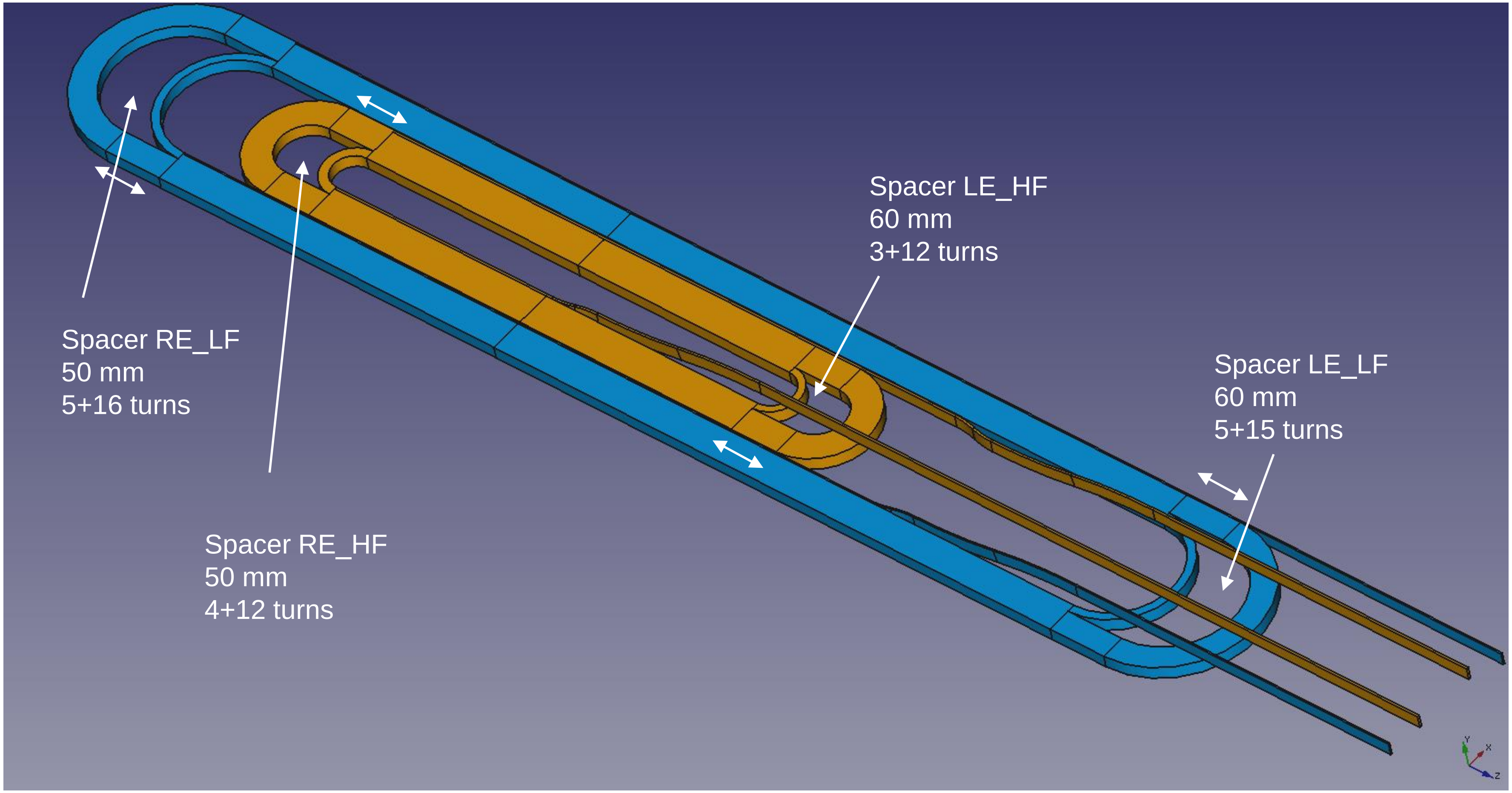


Lead exit fields
C6 → B_{peak} inner lead exit HF < B_{peak} HF
C7 → B_{peak} outer lead exit HF < B_{peak} HF
C8 → B_{peak} inner lead exit LF < B_{peak} LF
C9 → B_{peak} outer lead exit LF < B_{peak} LF

P18 → distance head LE HF – leads
P19 → easy-way radius
P20 → chicane distance

Peak fields region
P1, P2 → Length & Position of Y-Pad
P3, P4 → Length & Position of Y-Filler
C1 = Largest possible zone

R2D2 V 6.14.R2 – 3D GEOMETRIC RESULTS ON COIL



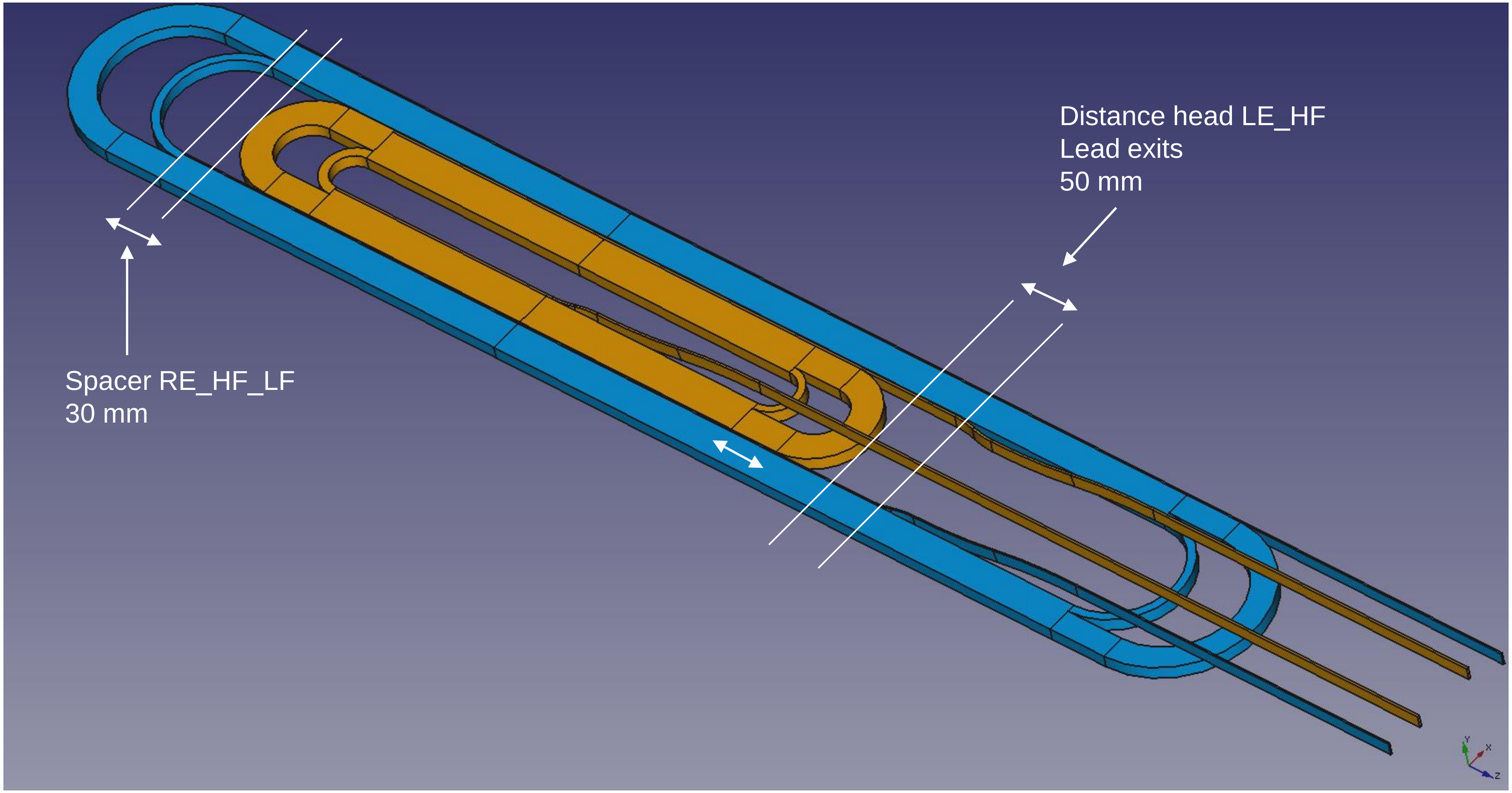
Spacer LE_HF
60 mm
3+12 turns

Spacer RE_LF
50 mm
5+16 turns

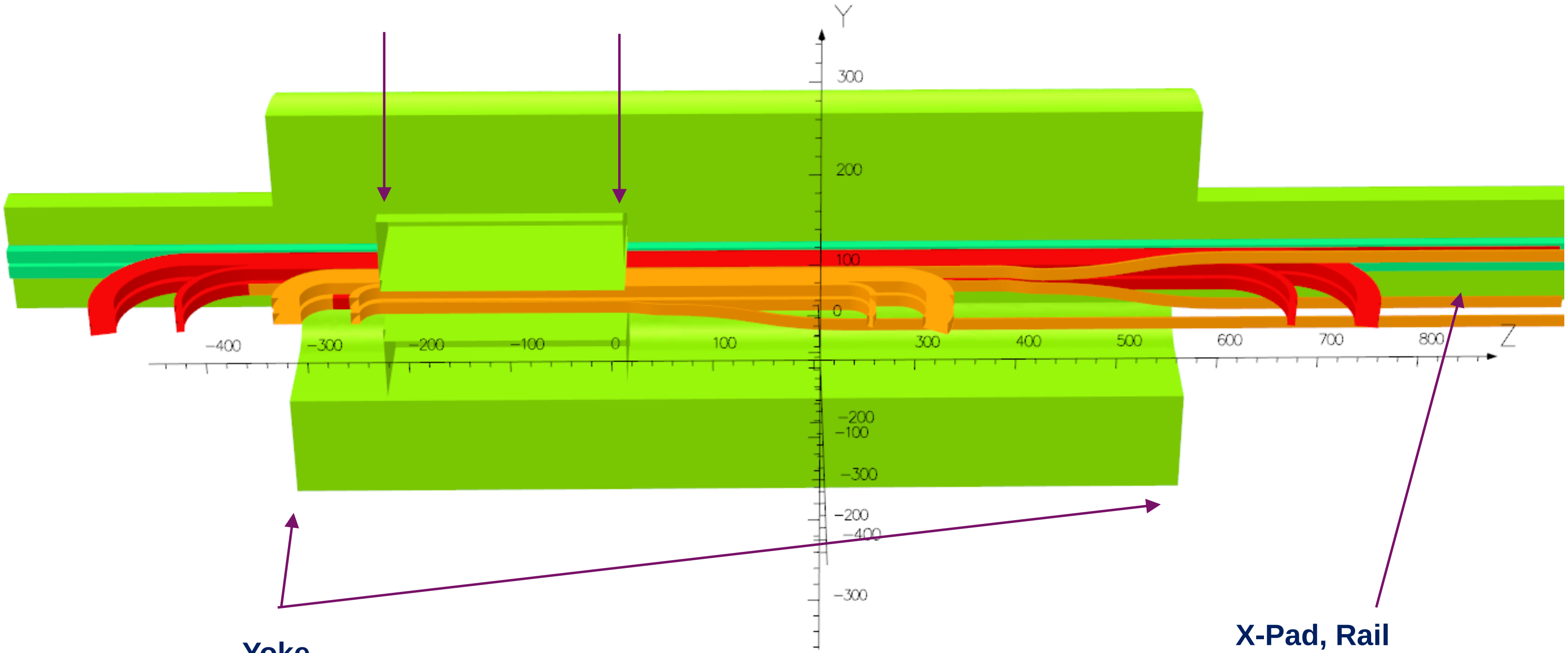
Spacer LE_LF
60 mm
5+15 turns

Spacer RE_HF
50 mm
4+12 turns

R2D2 V 6.14.R2 – 3D GEOMETRIC RESULTS ON COIL



R2D2 v 6.14.R2 – 3D GEOMETRIC RESULTS ON IRON

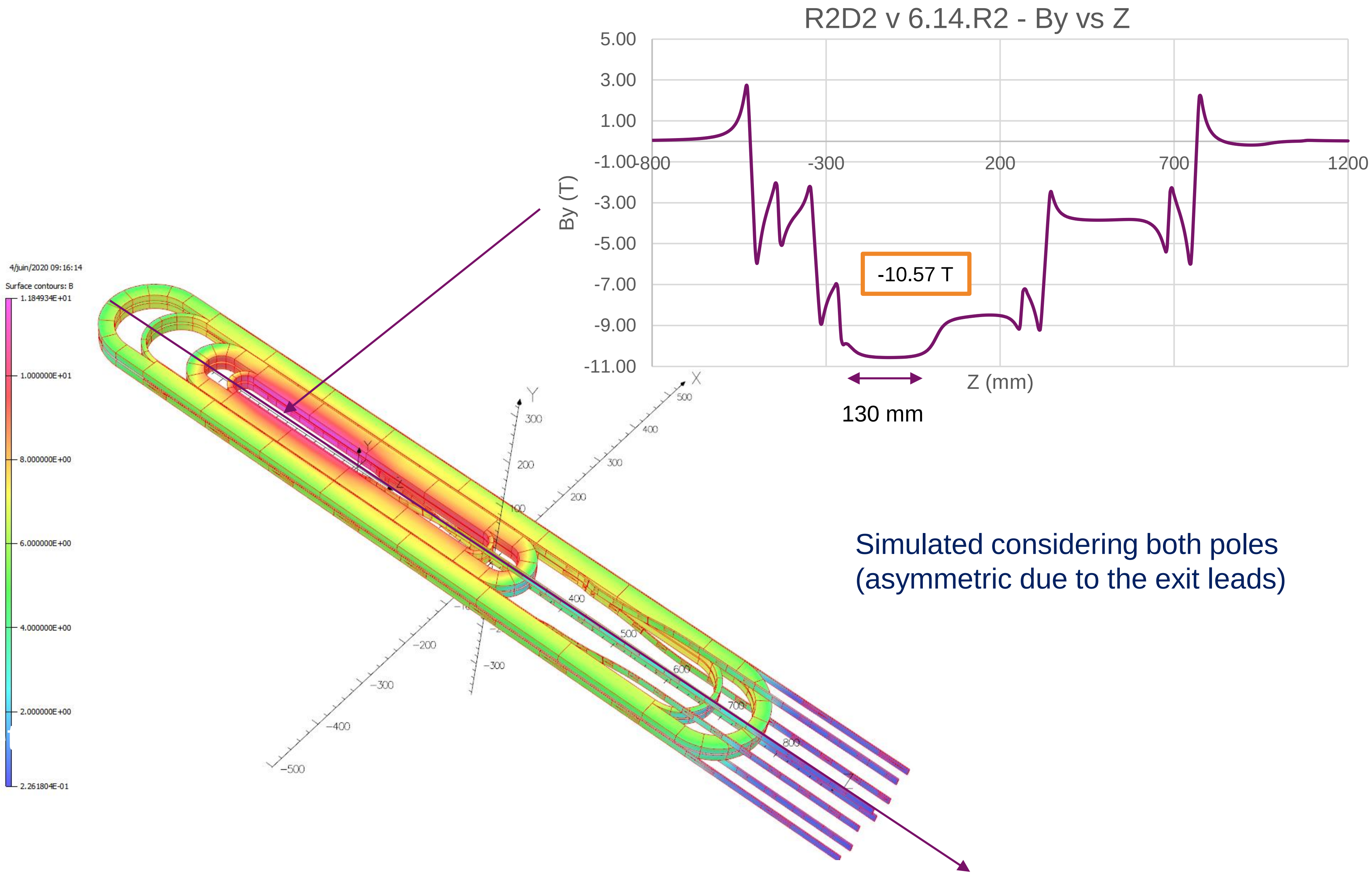


Y-Pad, Filler
Z- = +10 mm from head RE_HF
Z+ = beginning of the chicane inner exit lead HF

Yoke
Z- = end of head RE_HF
Z+ = -100 mm beginning of the head LE_LF

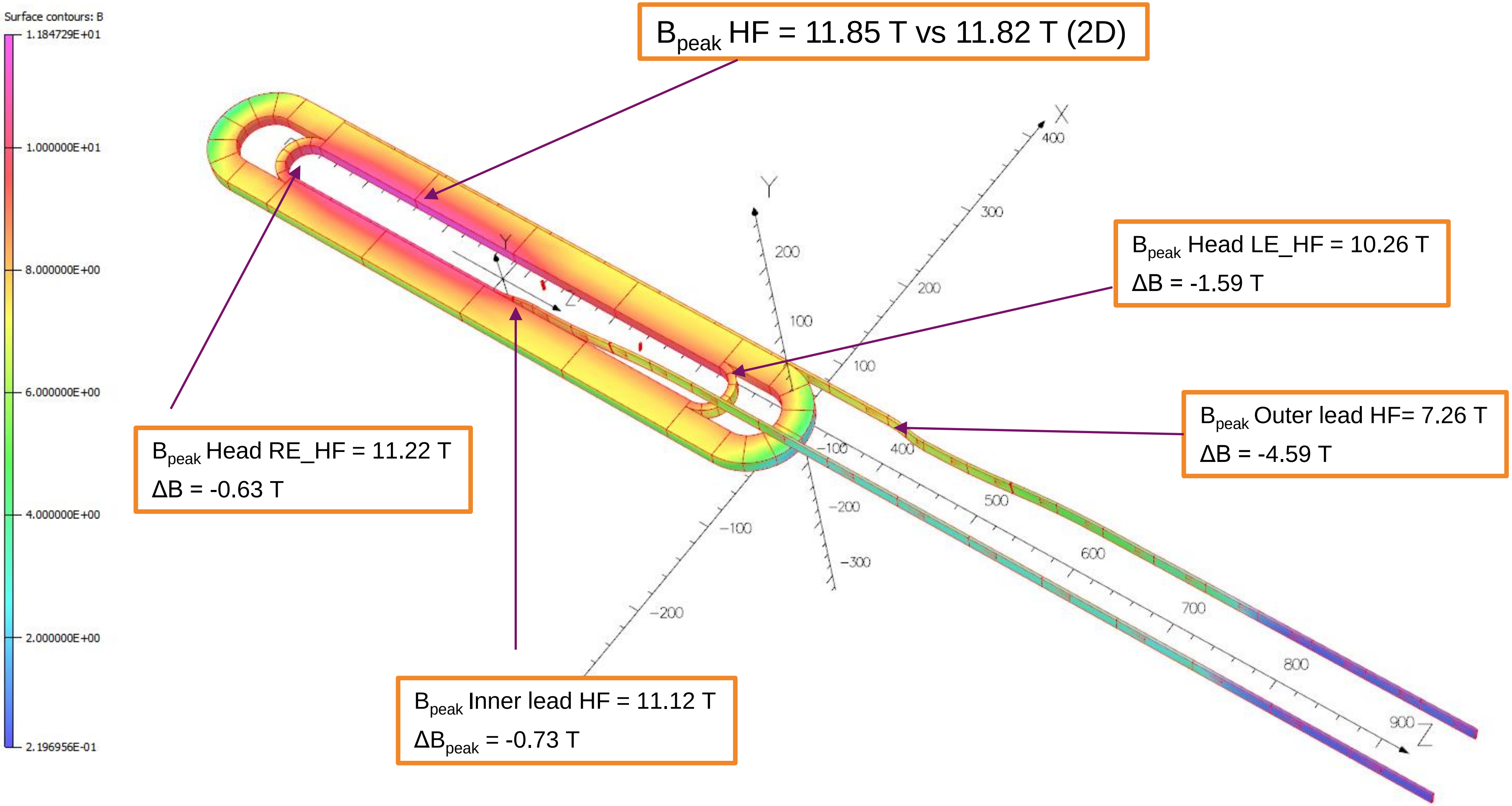
X-Pad, Rail
No influence → length to be decided according to assembly convenience

R2D2 v 6.14.R2 – Expected NOM Performance @4.2K



Simulated considering both poles (asymmetric due to the exit leads)

R2D2 V 6.14.R2 – 3D MAGNETIC RESULT SUB-COIL HF



B_{peak} HF = 11.85 T vs 11.82 T (2D)

B_{peak} Head LE_HF = 10.26 T

ΔB = -1.59 T

B_{peak} Outer lead HF= 7.26 T

ΔB = -4.59 T

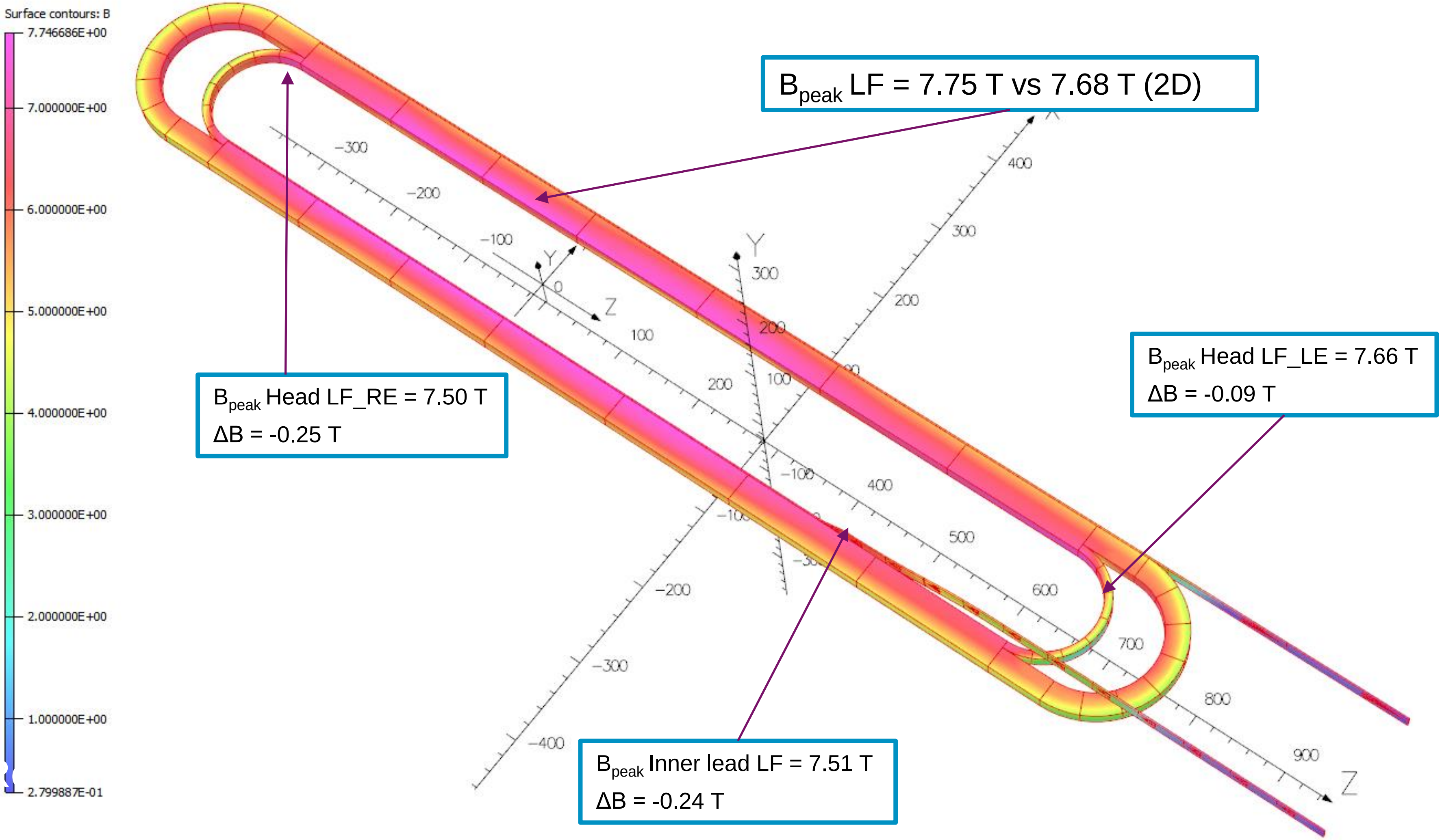
B_{peak} Head RE_HF = 11.22 T

ΔB = -0.63 T

B_{peak} Inner lead HF = 11.12 T

ΔB_{peak} = -0.73 T

R2D2 v 6.14.R2 – 3D MAGNETIC RESULT SUB-COIL LF



B_{peak} LF = 7.75 T vs 7.68 T (2D)

B_{peak} Head LF_RE = 7.50 T
ΔB = -0.25 T

B_{peak} Head LF_LE = 7.66 T
ΔB = -0.09 T

B_{peak} Inner lead LF = 7.51 T
ΔB = -0.24 T

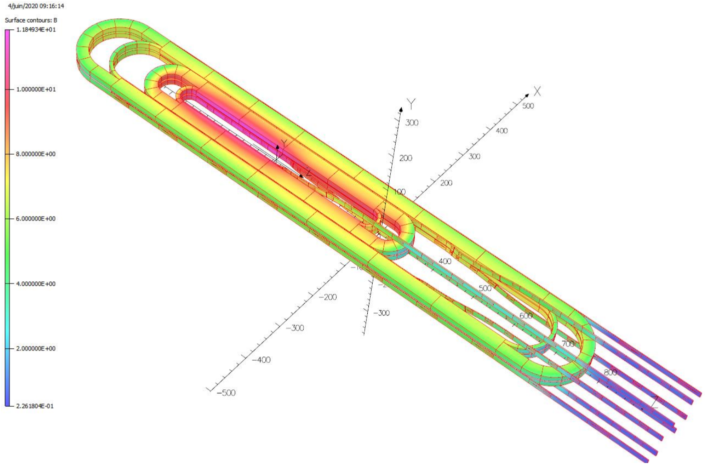
CONCLUSIONS FOR THE MAGNETIC DESIGN

R2D2 GOALS:

- Demonstrate the grading with the cable geometries forecast for FCC
- Validate the conductors behaviour especially at high current
- Validate the quench behaviour in critical condition
- Possible to reach ~10.5 T on the main axis

SMALL MAGNET, BUT NOT AN EASY ONE:

- Small margins on the LF sub-coil due to grading
- Instability issue may arise (conductors caracterization needed)
- Exit-leads are complex, require space and play a main role in the magnet performance
- Very high current → **protection must be mastered and it drives the performances of the magnet**



PROTECTION : QUENCH CRITERIA

Criteria	F2D2	R2D2
Max Hot Spot Temperature	350 K	350 K
Max Voltage btw layers	1200 V	1000 V
Max Voltage to ground	1200 V	1000 V
Max quench detection delay	20 ms	20 ms
Max quench protection delay	20 ms	20 ms
Detection voltage	10 mV	10 mV
Protection Circuit 1st Option	CLIQ+Heaters	CLIQ+Heaters+ Rdump
Protection Circuit 2nd Option	Heaters	CLIQ+Heaters+ Rdump
Max Thermal Stress allowed	Same as MECH	Same as MECH

The conservative approach adopted for R2D2 is maintained also for protection

R2D2 – HOT SPOT CRITERIA

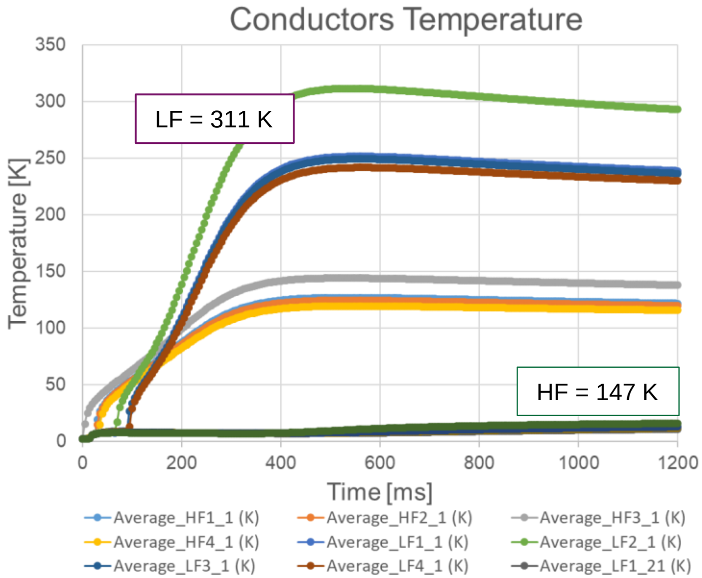
I_{R2D2} ~ 150% I_{F2D2} → protection has a key role in designing

How to rapidly evaluate the impact of protection on the design?
With the spreadsheet developed for ECC by T. Salmi, with the dump resistance option

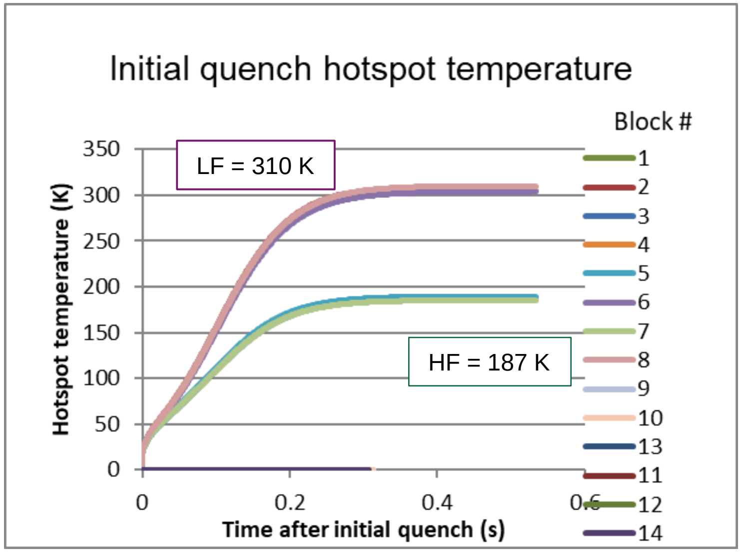
F2D2

2.5D COMSOL Simulation

The contribution of dimensionality (*Wilson – Superconducting magnets*) and geometry on the hot-spots can be seen as if there is a $R_{dump} = \frac{1000\ V}{I}$ in the spreadsheet



ΔT_{LF} ~ 0 K
ΔT_{HF} ~ 40 K



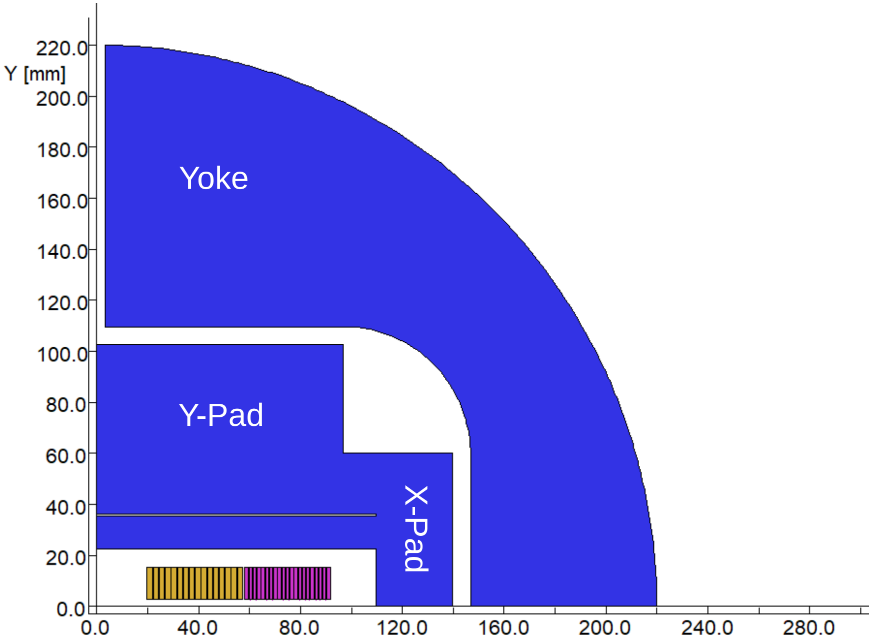
R2D2 – ANALYTICAL CALCULATION HYPOTHESIS

One of the criteria in the magnetic design

Max hotspot temperature ~ 350 K

Hypothesis:

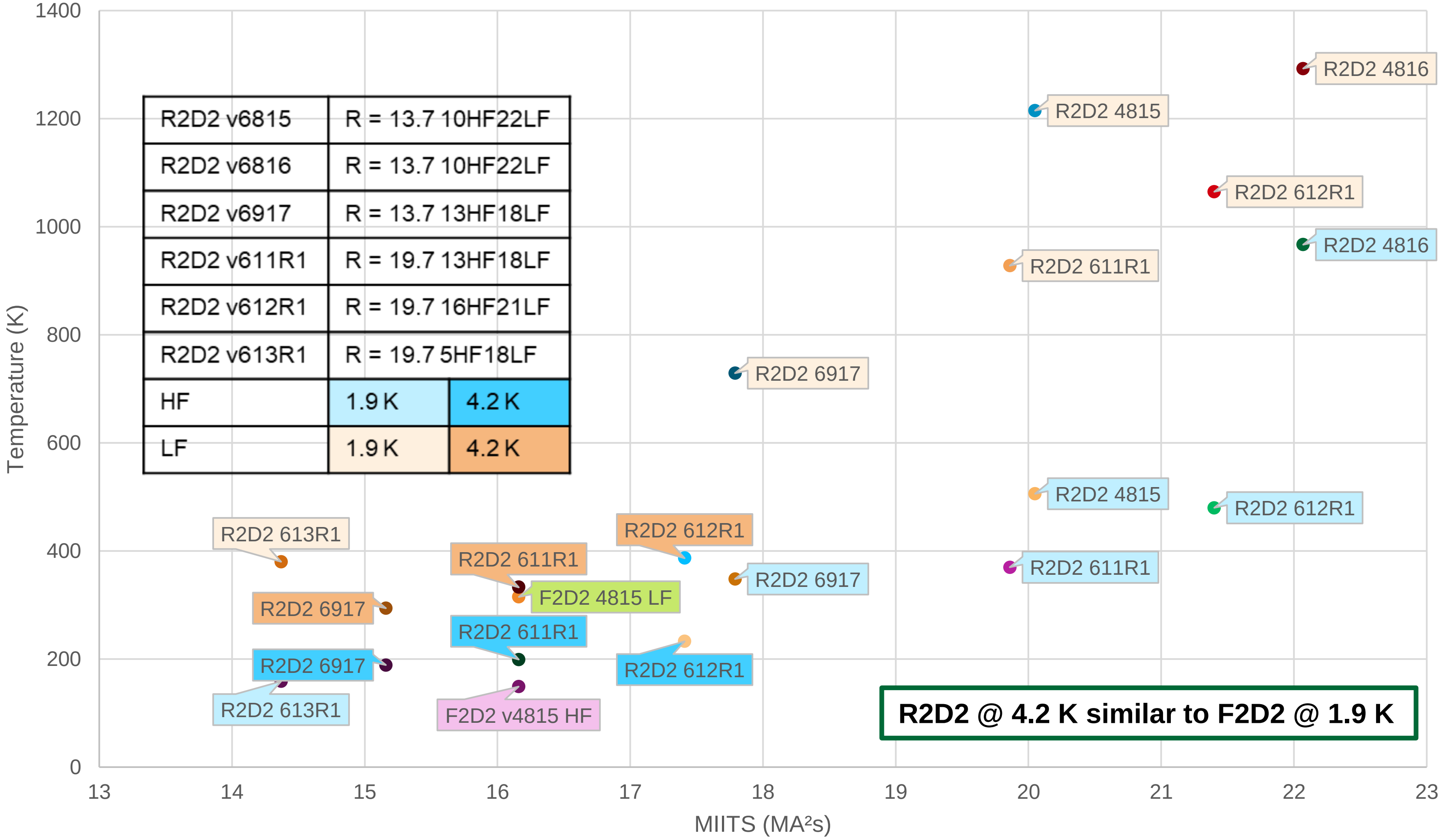
- Adiabatic Regime
- Every coil has a quench heater
- No quenchback
- Rdump = 1000 V / I_0
- No Differential inductance
- Magnetoresistivity
- Detection delay = 20 ms
- Heater activation delay = 20 ms



Approximative evaluation, but it can give a direction in the design

R2D2 – Hot Spot vs MIITS

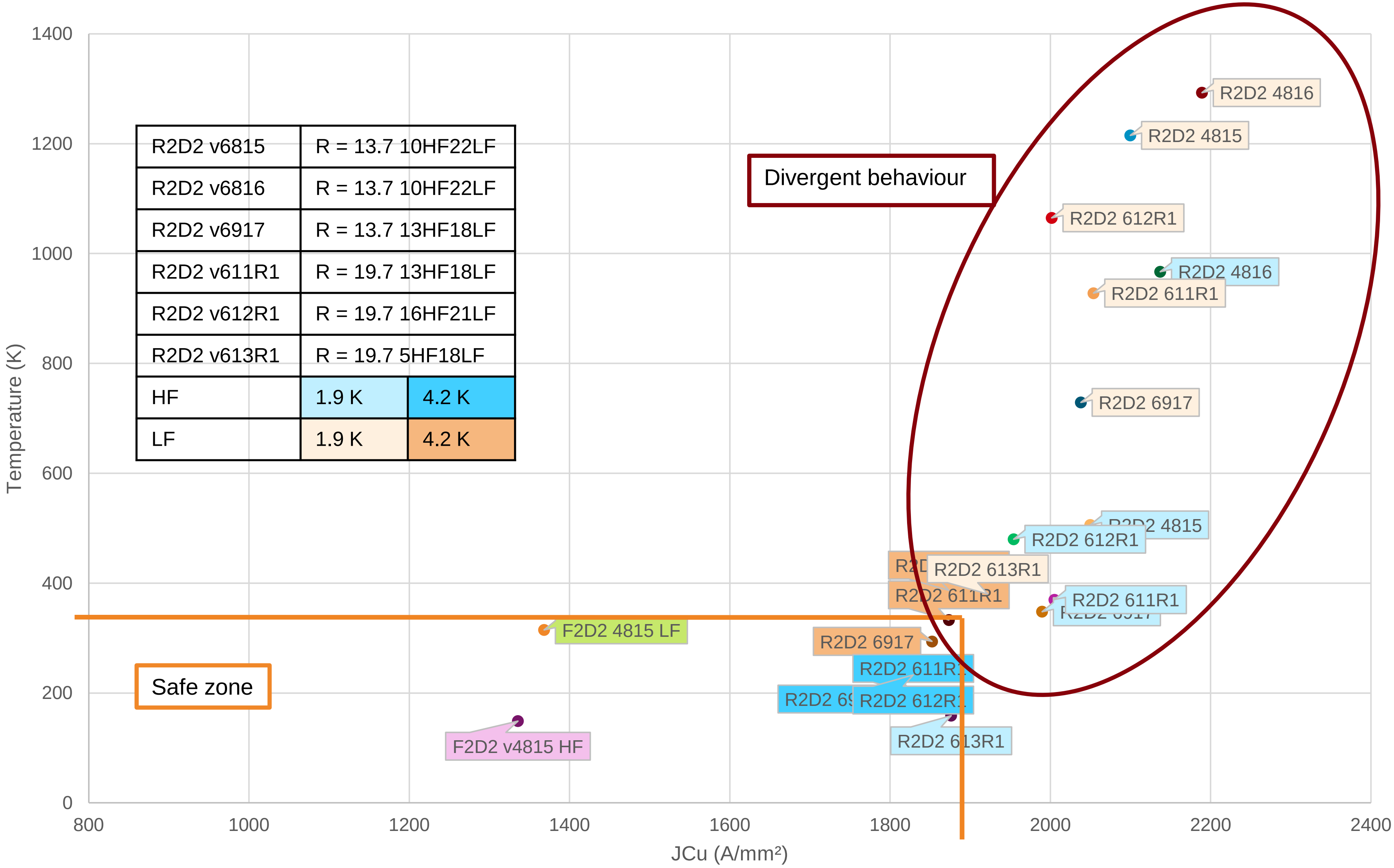
The hot spot criteria has been used from v4.8.15 to v6.13.R1 to understand the best performance zone



R2D2 v6815	R = 13.7 10HF22LF	
R2D2 v6816	R = 13.7 10HF22LF	
R2D2 v6917	R = 13.7 13HF18LF	
R2D2 v611R1	R = 19.7 13HF18LF	
R2D2 v612R1	R = 19.7 16HF21LF	
R2D2 v613R1	R = 19.7 5HF18LF	
HF	1.9 K	4.2 K
LF	1.9 K	4.2 K

R2D2 @ 4.2 K similar to F2D2 @ 1.9 K

R2D2 – HOT SPOT VS J_{CU}



R2D2 v6815	R = 13.7 10HF22LF	
R2D2 v6816	R = 13.7 10HF22LF	
R2D2 v6917	R = 13.7 13HF18LF	
R2D2 v611R1	R = 19.7 13HF18LF	
R2D2 v612R1	R = 19.7 16HF21LF	
R2D2 v613R1	R = 19.7 5HF18LF	
HF	1.9 K	4.2 K
LF	1.9 K	4.2 K

R2D2 v 6.14.R2 – Performances @4.2 K & Ultimate WP

	Nominal	SS	Ultimate WP
I_0	13772 A	17215 A	16500 A
LL margin HF / LF	20.0% / 20.45%	0.0 % / 0.72%	4.15 % / 4.50 %
B @ (0,0)	**10.42 T**	**12.46 T**	**11.98 T**
B peak HF	11.82 T	14.27 T	13.67 T
B peak LF	7.68 T	9.49 T	9.05 T
Energy density $\varepsilon_{4.2K}$	474 KJ/m	725 KJ/m	649 KJ/m
Energy mass density	15.9 KJ/kg	23.8 KJ/kg	21.3 KJ/kg
Magnetic length	785 mm	785 mm	785 mm
Inductance @ I_0	4.79 mH	4.55 mH	4.63 mH
Fx HF / LF	1698 / 112 kN/m	2497 / 61 kN/m	2321 / 74 kN/m
Fy HF / LF	-469 / -752 kN/m	-744 / -1101 kN/m	-683 / 1101 kN/m
E/L HF / LF	41 / 77 kJ/m	61 / 114 kJ/m	56 / 106 kJ/m
J_{Cu} HF / LF	1472 / 1508 A/mm²	1853 / 1886 A/mm²	1783 / 1827 A/mm²
Hotspot HF / LF	**104 K / 141 K**	**260 K / 450 K**	**210 / 350 K**

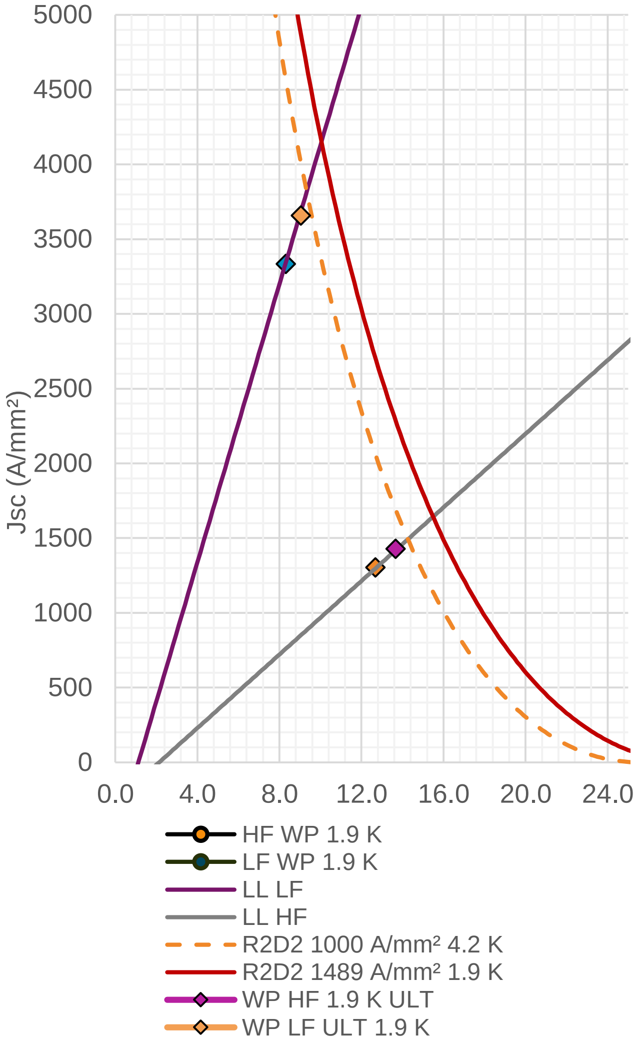
The Ultimate Working Point is the one where the magnet can operate safely

R2D2 V 6.14.R2 – PERFORMANCES @1.9 K & ULTIMATE WP

	Nominal	SS	Ultimate WP
I	15055 A	18819 A	16500 A
LL margin HF / LF	20.9% / 20.0%	0.9 % / 0.0%	12.85 % / 11.3 %
B @ (0,0)	**11.15 T**	**13.29 T**	**11.98 T**
B peak HF	12.69 T	15.23 T	13.67 T
B peak LF	8.32 T	10.21 T	9.05 T
Energy density	553 KJ/m	818 KJ/m	649 KJ/m
Magnetic length	785 mm	785 mm	785 mm
Fx HF / LF (kN/m)	1978 / 97	2920 / 25	2321 / 74
Fy HF / LF (kN/m)	-683 / -1101	-894 / -1447	-683 / 1101
E/L HF / LF (kJ/m)	56 / 106	71 / 133	56 / 106
Inductance	4.69 mH	4.32 mH	4.63 mH
J_{cu} HF / LF (A/mm^2)	1627 / 1667	2034 / 2084	1827 / 1783
Hotspot HF / LF	**135 K / 203 K**	**580 K / 1192 K**	**233 K / 350 K**

Not possible to go to SS

Lorentz Forces impact in presentation 3



Critical Current Density Curves and Load Lines R2D2

R2D2 V 6.14.R2 – CONCLUSIONS

Protection is the main issue for R2D2 due to the high current density in the copper

- Similar MIITS of F2D2 if it operates at 4.2 K
- It seems not possible to operate at SS 1.9 K
- Detailed simulations with COMSOL are ongoing to understand better its behaviour

R2D2 NEW GOAL : being a magnet to test

- The quench behaviour in simple graded coils and the impact of the departing point
- The quench in very different conditions without putting at risk the magnet
- Push-up the limits in high-current
- Test the technologies (heaters, CLIQ, …) and especially their response rapidity (20 ms) towards FCC goals
- Collaboration with Tampere University started

DE LA RECHERCHE À L'INDUSTRIE

BACKUP SLIDES

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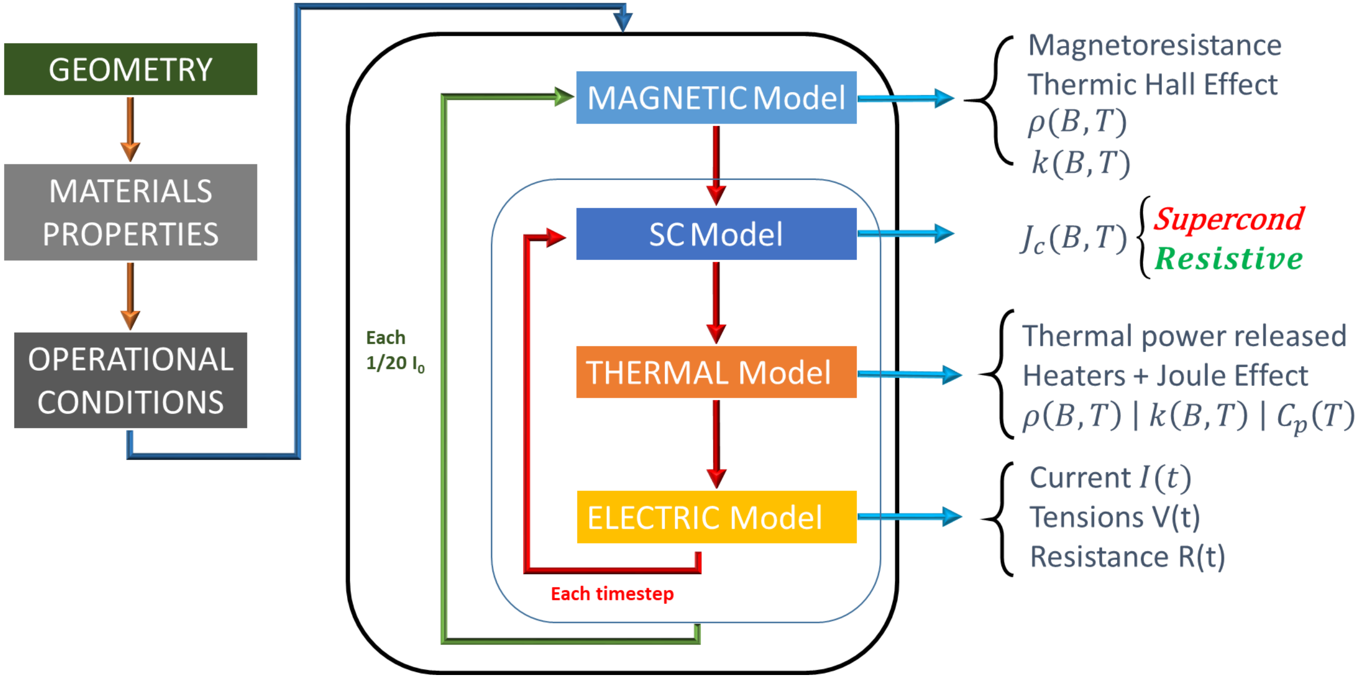
NEXT STEPS : COMSOL QUENCH MODEL

For F2D2:



GEOMETRY

MATERIALS PROPERTIES

OPERATIONAL CONDITIONS

Each 1/20 I_0

MAGNETIC Model

SC Model

THERMAL Model

ELECTRIC Model

Each timestep

Magnetoresistance
Thermic Hall Effect
$\rho(B,T)$
$k(B,T)$

$J_c(B,T)$ *Supercond* / *Resistive*

Thermal power released
Heaters + Joule Effect
$\rho(B,T) \mid k(B,T) \mid C_p(T)$

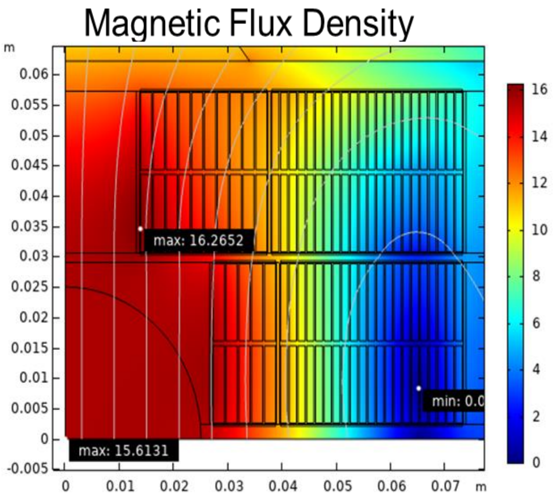
Current $I(t)$
Tensions V(t)
Resistance R(t)

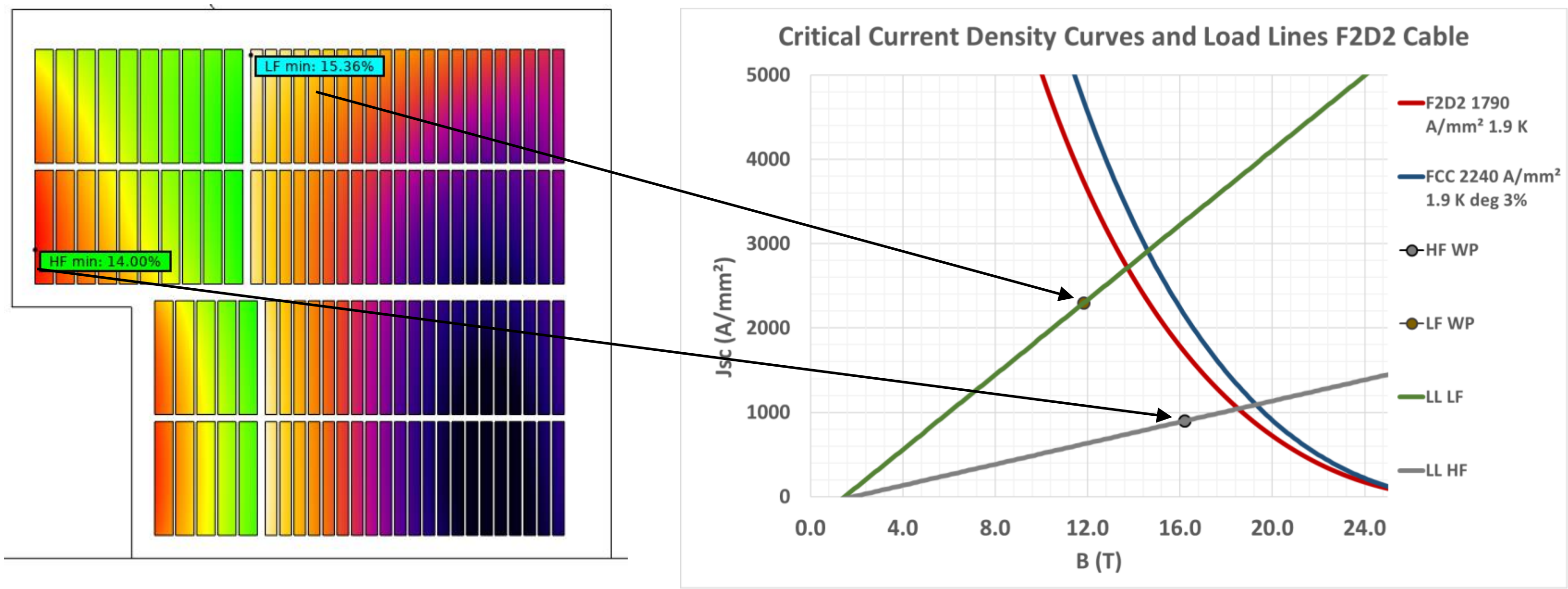
THE MAGNETIC MODEL

Comparison analysis with OPERA (reference model)

- Very good agreement on Bx, By
- Same LL margin for both cables
- Different magnetic energy $\Delta E \sim 12\%$

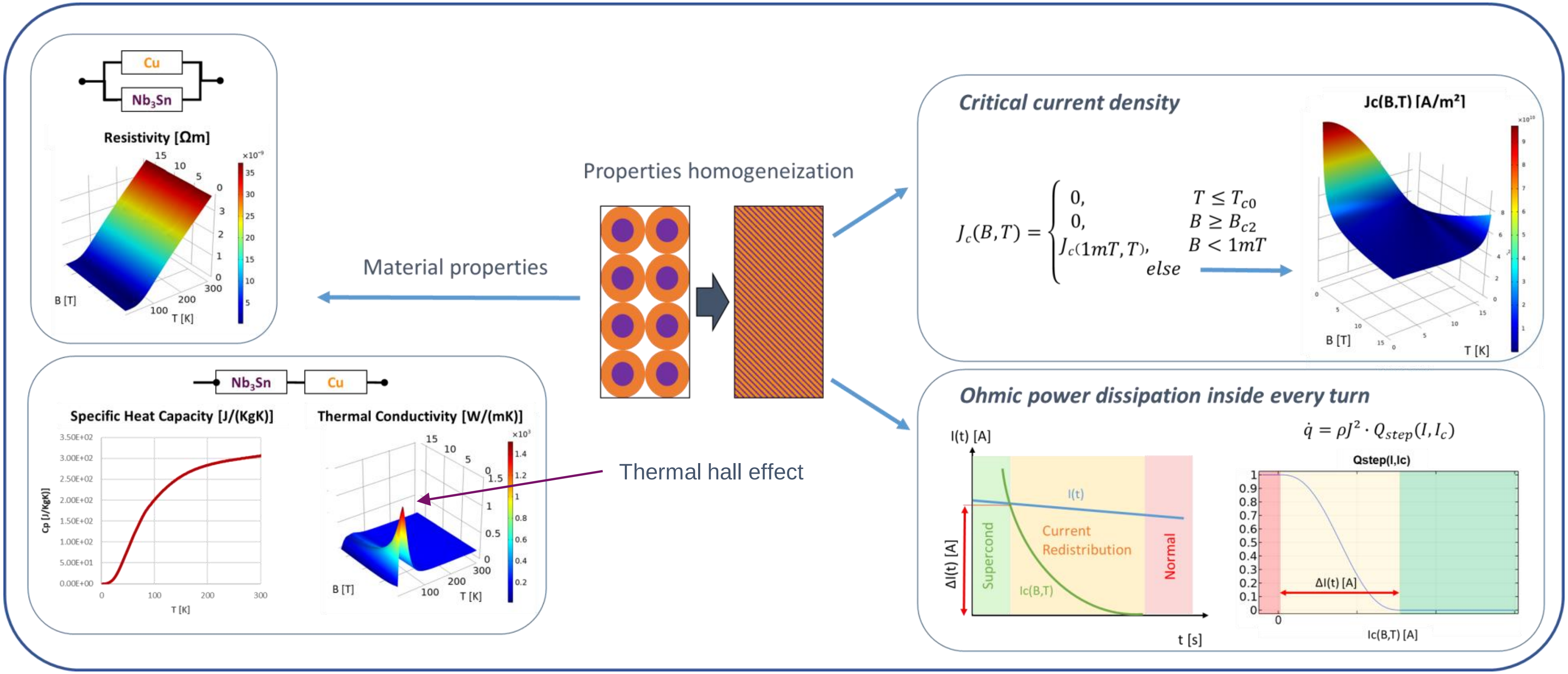
Values for Bx, By directly calculated by COMSOL
Differential inductance imported by OPERA





CABLE MODELLING & SC MODEL

Material properties homogeneization and model for current redistribution inside every turn



Critical current density

$$J_c(B,T) = \begin{cases} 0, & T \leq T_{c0} \\ 0, & B \geq B_{c2} \\ J_c(1mT,T), & B < 1mT \\ & else \end{cases}$$

Ohmic power dissipation inside every turn

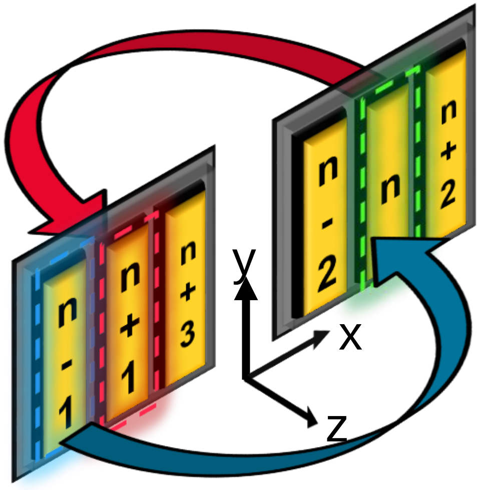
$$\dot{q} = \rho J^2 \cdot Q_{step}(I, I_c)$$

THE THERMAL MODEL

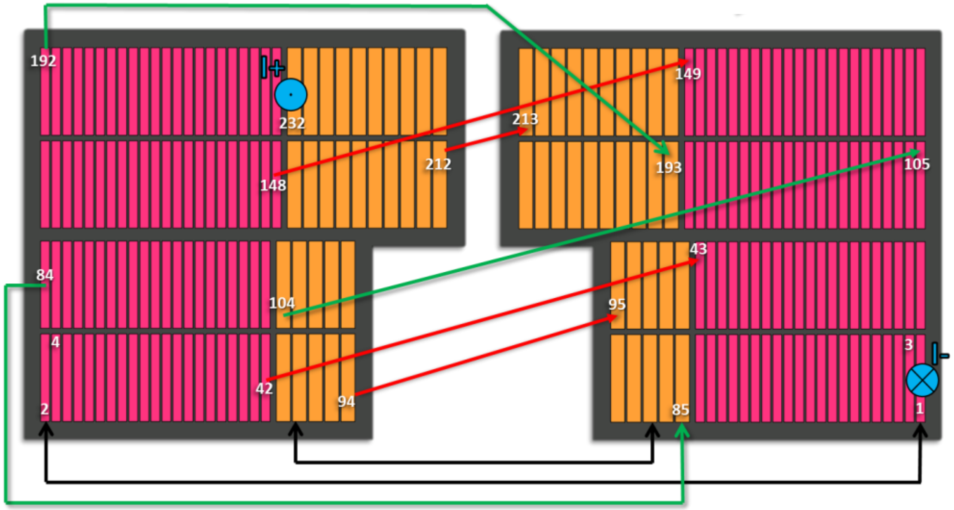
2D heat equation by COMSOL + 1D Axial heat propagation

$$\frac{\dot{Q}}{A_n} = \frac{1}{A_n}\left[\frac{T_{n-1} - T_n}{L_{LE}\left(\frac{1}{k_{n-1}A_{n-1}} + \frac{1}{k_n A_n}\right)} - \frac{T_n - T_{n+1}}{L_{RE}\left(\frac{1}{k_n A_n} + \frac{1}{k_{n+1}A_{n+1}}\right)}\right]$$

Heat conduction / cable surface



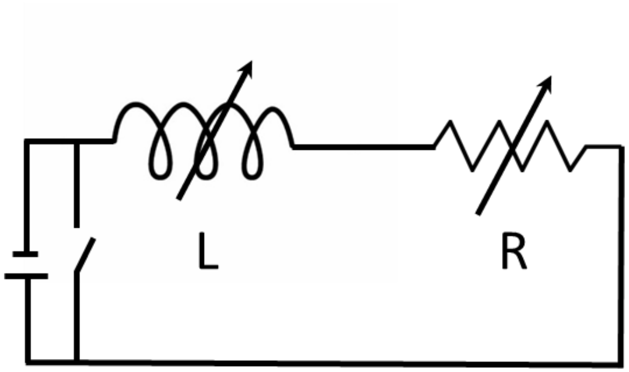
Connections
Layer Jumps
Joints



232 thermal connections

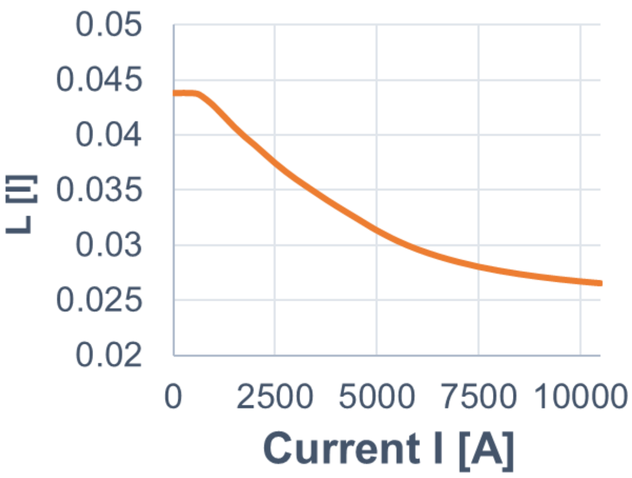
THE ELECTRIC MODEL

The circuit implemented

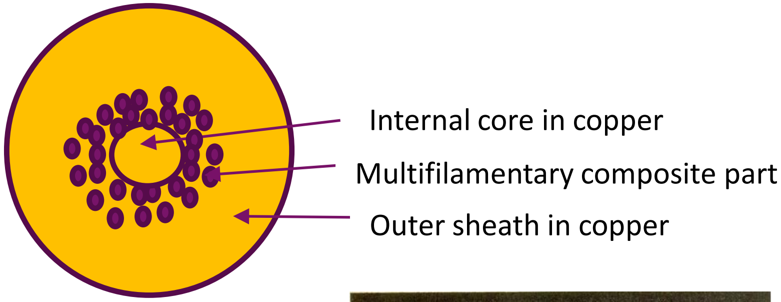


$$\begin{cases} V(t) = R(t)I(t) - L(I,t)\dfrac{dI}{dt} \\ R(t) = \displaystyle\int_z \left(\iint_S \frac{1}{\rho(B,T,t)} dS \right)^{-1} dz \\ L(I,t) = \dfrac{2U(t)}{I^2(t)} \end{cases}$$

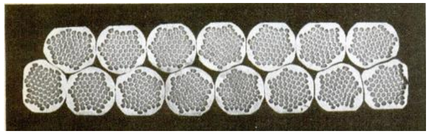
Differential Inductance L(I)



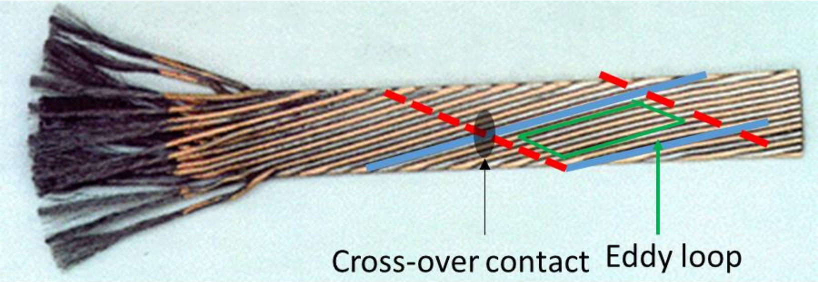
THE AC LOSSES



Strand geometry



Strands of a Rutherford cable



A. Devred. T. Ogitsu, Influence of eddy currents in superconducting particle accelerator magnets using Rutherford type cables, 1995, pp. 1-30.

$$P_{intra}{}^{k} = 2 * N_l \frac{2\pi(R_3)^2}{\mu_0} \left| \frac{dB_t(z_t{}^{k})}{dt} \right|^2 t_s{}^{k}$$

$$\mathrm{t_s}^{\mathrm{k}} = \tau_{\mathrm{core}} + \tau_{\mathrm{composite}} + \tau_{\mathrm{sheath}}$$

$$P_{inter}{}^{k} = 2 \frac{N_l}{L_c{}^{l}} r_c \sum_{p=1}^{N_l} i_p{}^{2}$$

$$\sum_{p=1}^{N_l} i_p{}^{2} = \left(i_1{}^{2} S_2 - \frac{1}{N_l r_c} \frac{d\phi_k}{dt} (S_3 - S_2) + (\frac{1}{N_l r_c})^2 \left(\frac{d\phi_k}{dt} \right)^2 (S_4 - 2S_{3+} S_2) \right)$$

$L_c{}^{l}$	Twist pitch of the cable per layer
i_p	Cross-over current for a given current line
N_l	Number of strands per layer
r_c	Cross-over resistance
k	Index of turns

HEATERS MODELLING

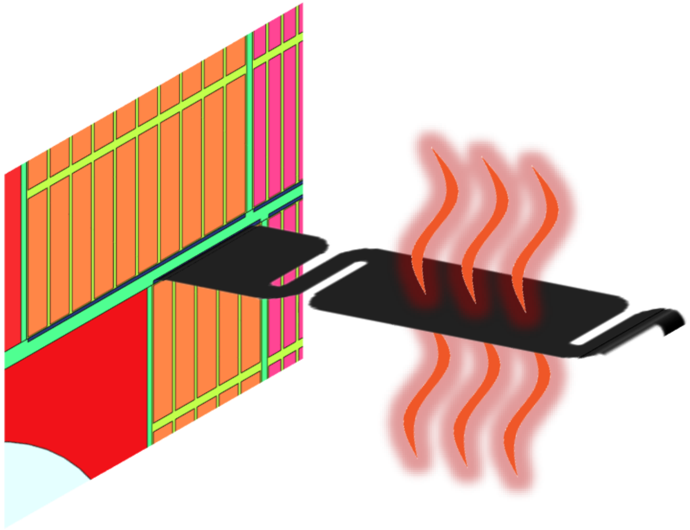
Heaters power dissipation modelled as RC circuit

$$\boxed{\dot{q}(t) = \frac{\frac{V_0^2}{R}\, e^{(-2t/_{RC})}}{Vol_{heater}}}$$

$$\begin{cases} V_0 = 2V \\ C = 20mF \\ R_{HF} = 1\Omega \\ R_{LF} = 0{,}5\Omega \\ I_0 = 4\ A \end{cases}$$

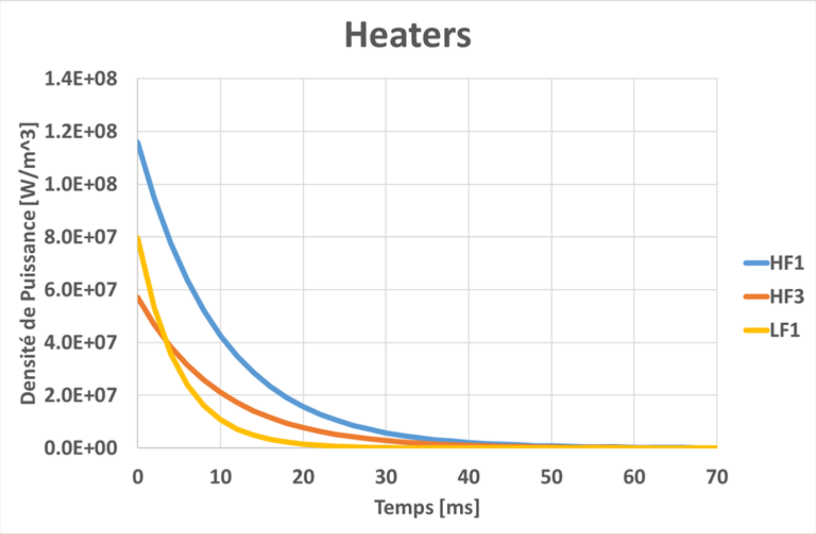
RC Circuit

$$\begin{cases} I_{heater}(t) = I_0 e^{(-t/_{RC})} \\ V_{heater}(t) = RI(t) \\ P_{heater}(t) = RI^2(t) \end{cases}$$

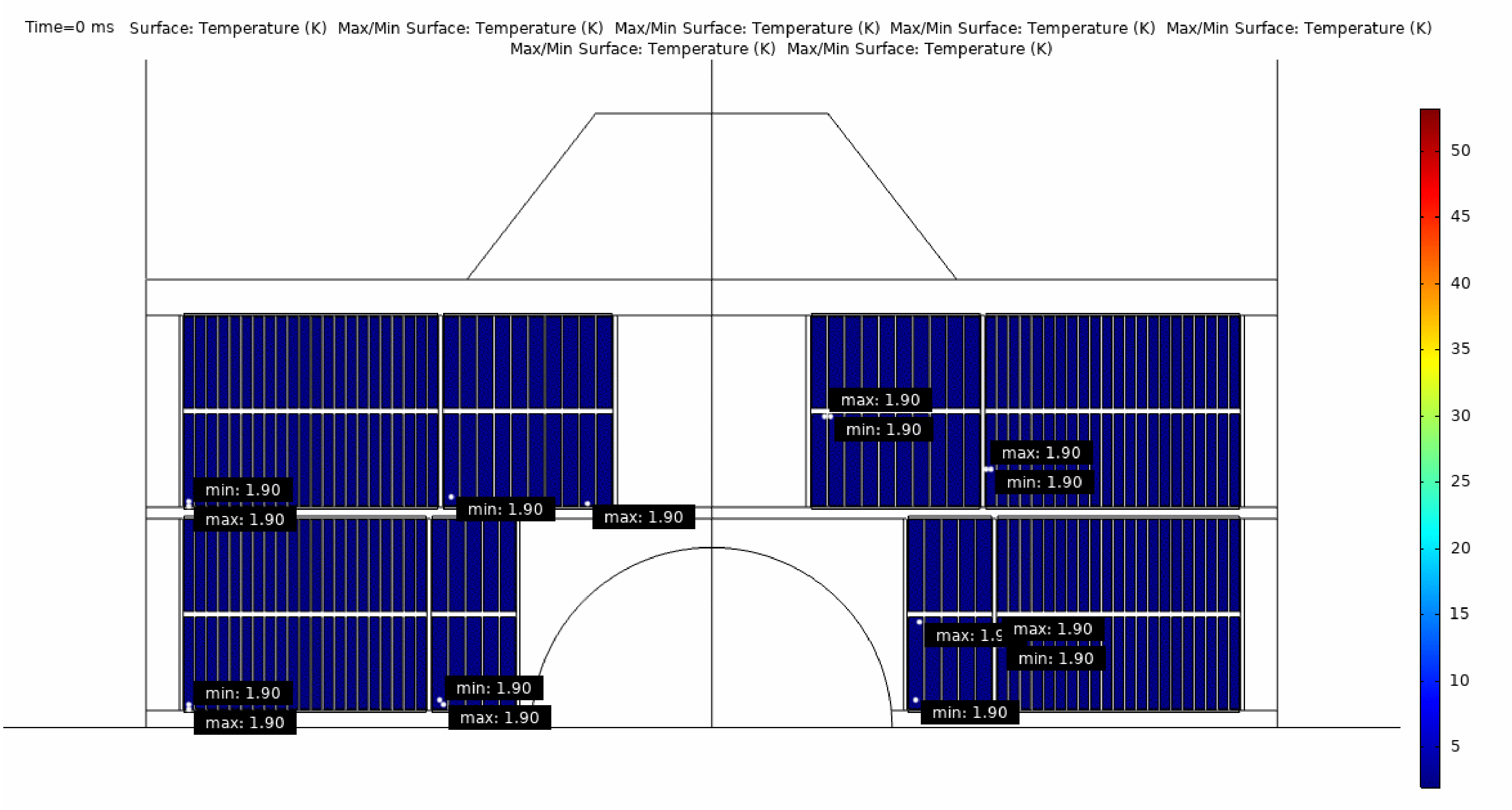


$60 < P/S < 150\ [^{W}/_{cm^2}]$

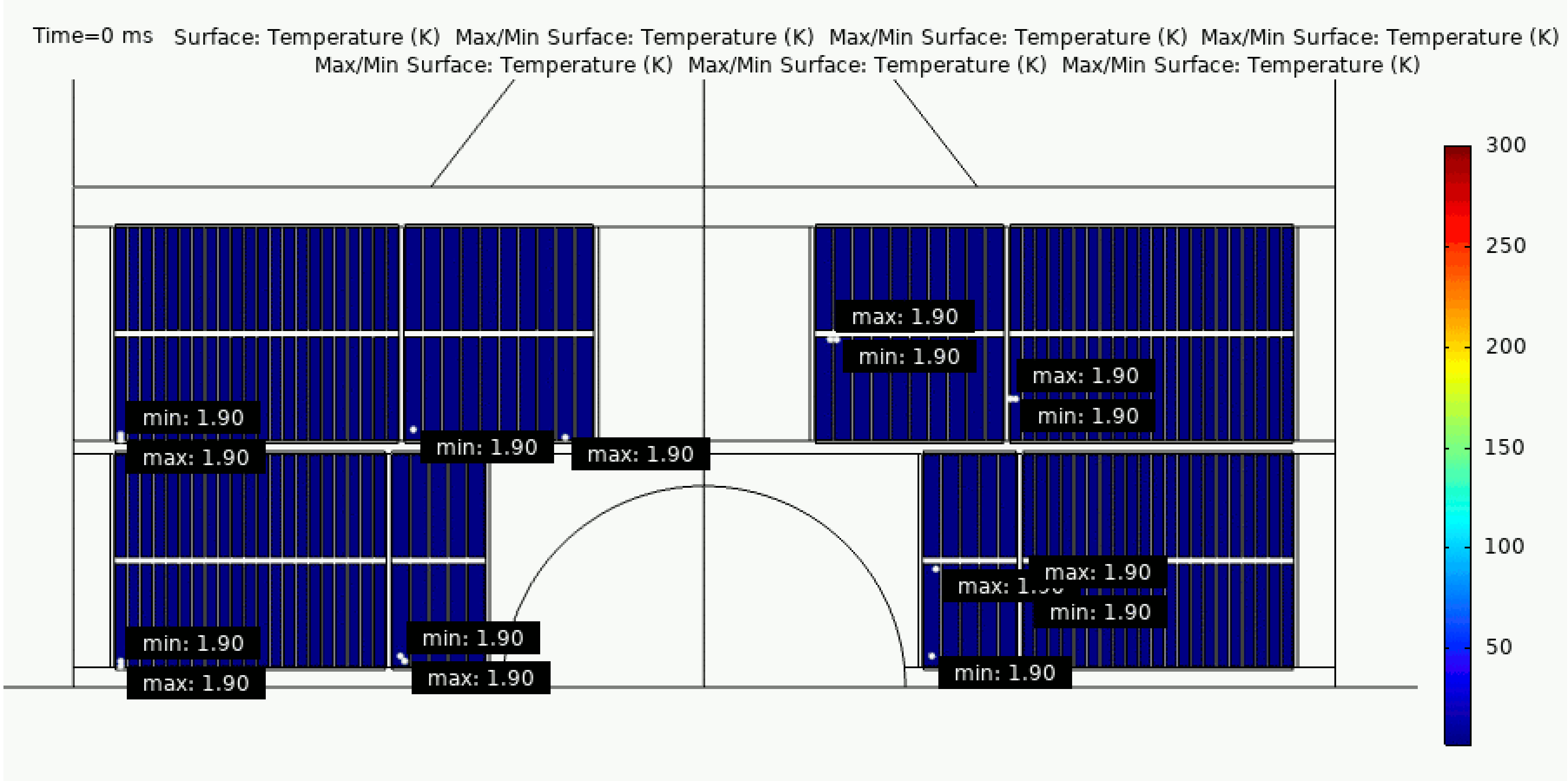
T. Salmi *et al.*, "Suitability of Different Quench Protection Methods for a 16 T Block-Type Nb3Sn Accelerator Dipole Magnet,"



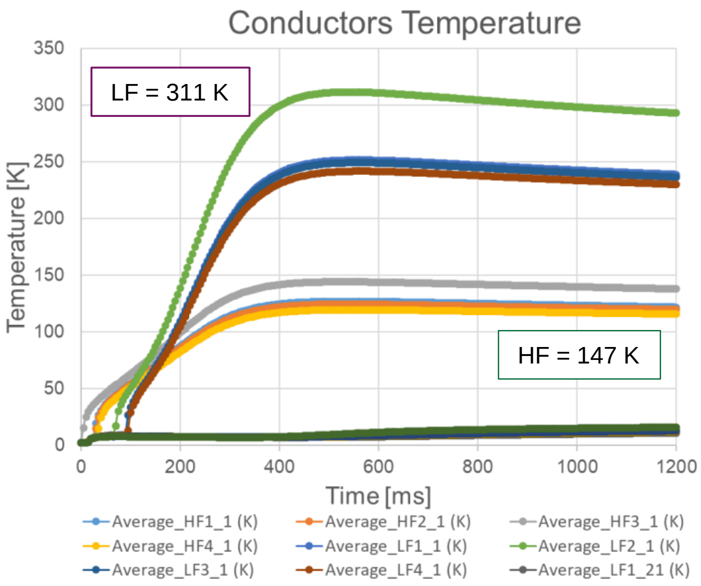
SIMULATION RESULTS – QUENCH START

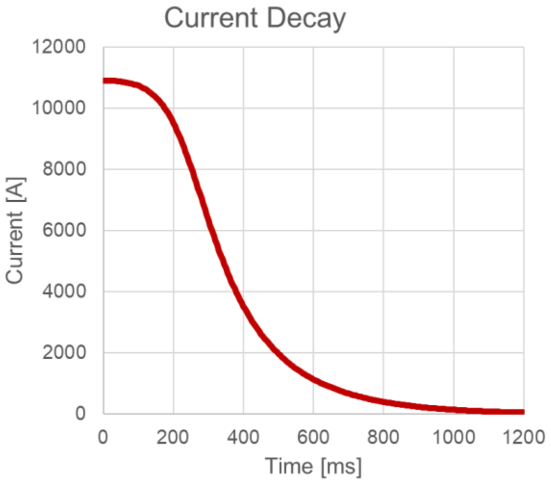


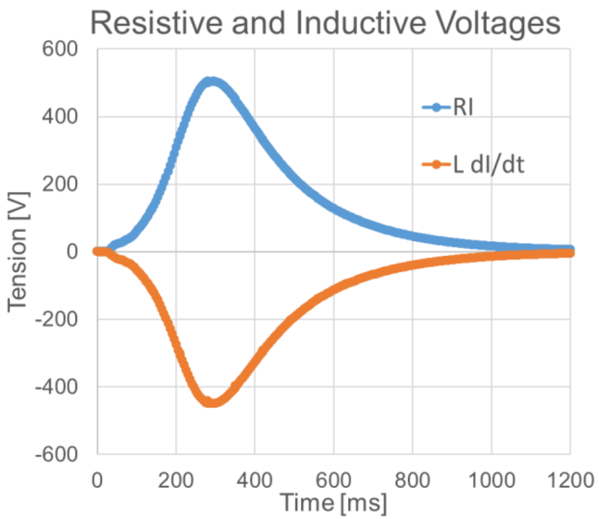
SIMULATION RESULTS – HOT-SPOT TEMPERATURE

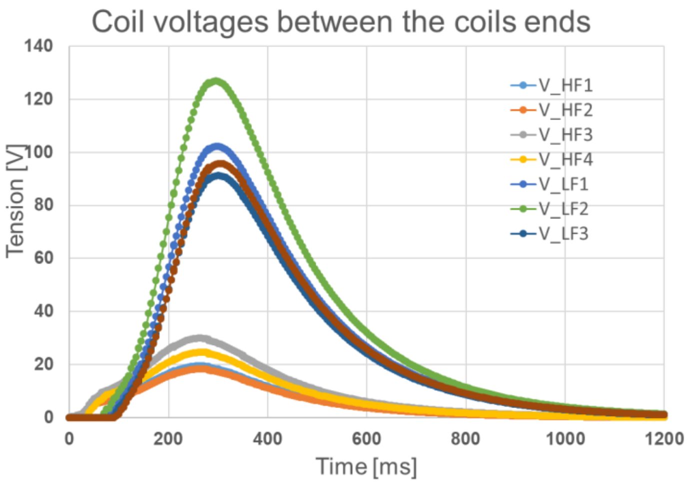


SIMULATION RESULTS WITHOUT AC LOSSES


Conductors Temperature

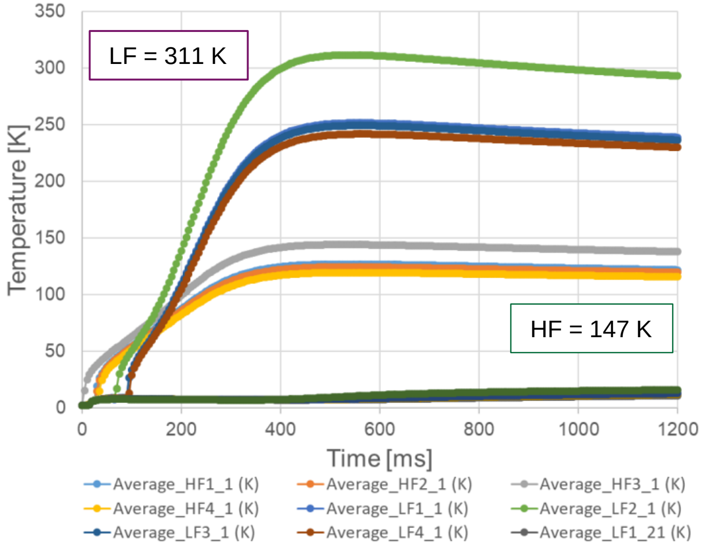

Current Decay


Resistive and Inductive Voltages

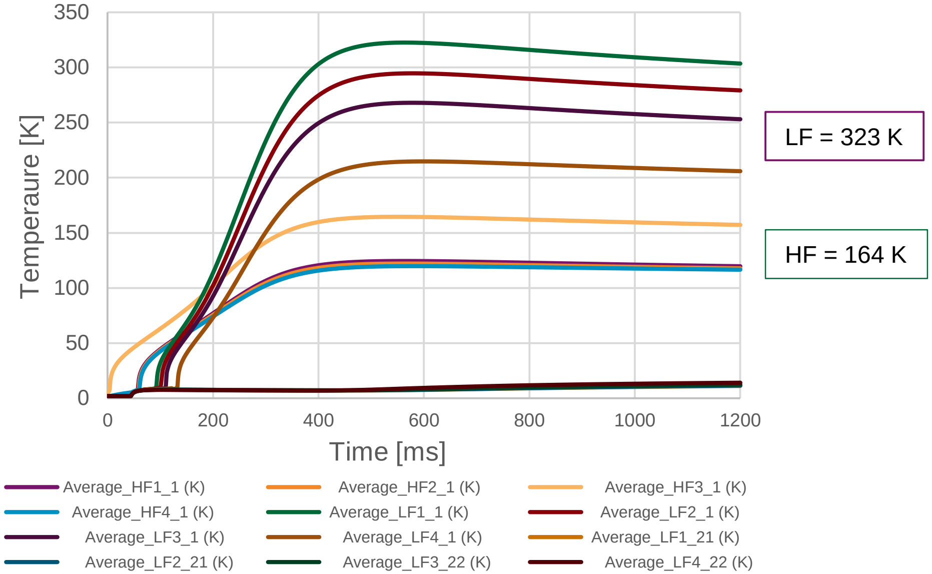

Coil voltages between the coils ends

SIMULATION RESULTS WITH AC LOSSES

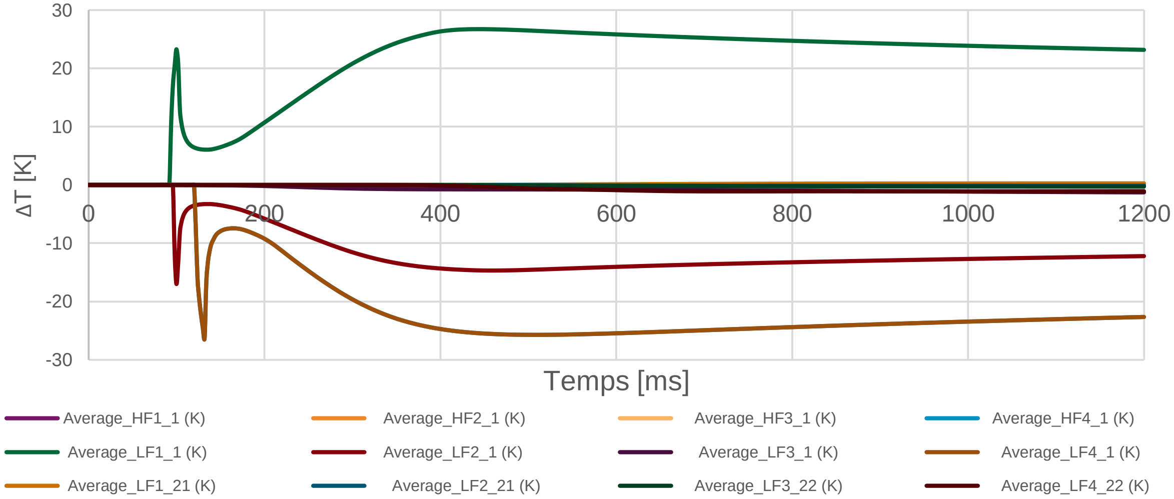
WITHOUT AC LOSSES



WITH AC LOSSES



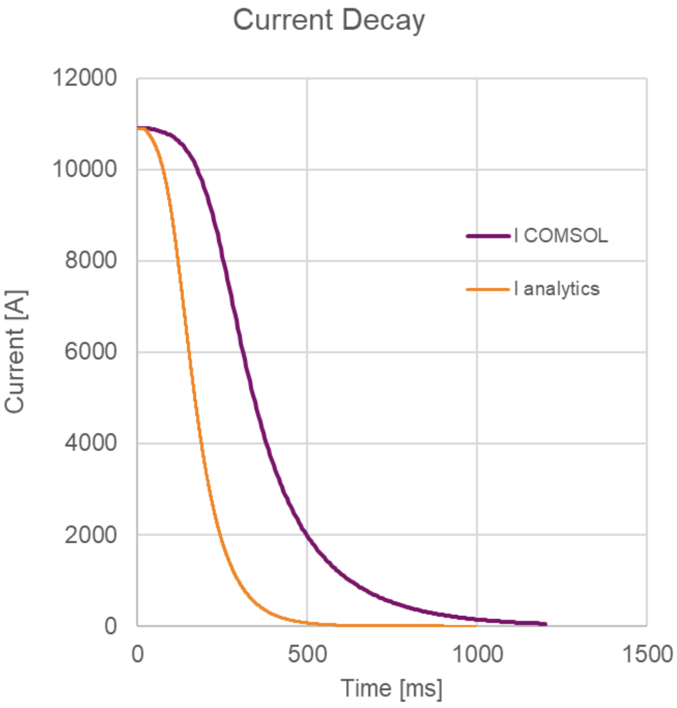
TEMPERATURE DIFFERENCE BTW THE MODELS



COMPARISON WITH ANALYTICAL CALCULATIONS

Hypothesis:

- Adiabatic Regime
- Every coil has a quench heater
- No quenchback
- No Rdump
- No Differential inductance
- Magnetoresistivity
- Detection delay = 20 ms
- Heater activation delay = 20 ms



$$\tau_{analytics} = 196.5\ ms$$
$$\tau_{COMSOL} = 396.0\ ms$$

Current decay is slower in COMSOL than in the spreadsheet

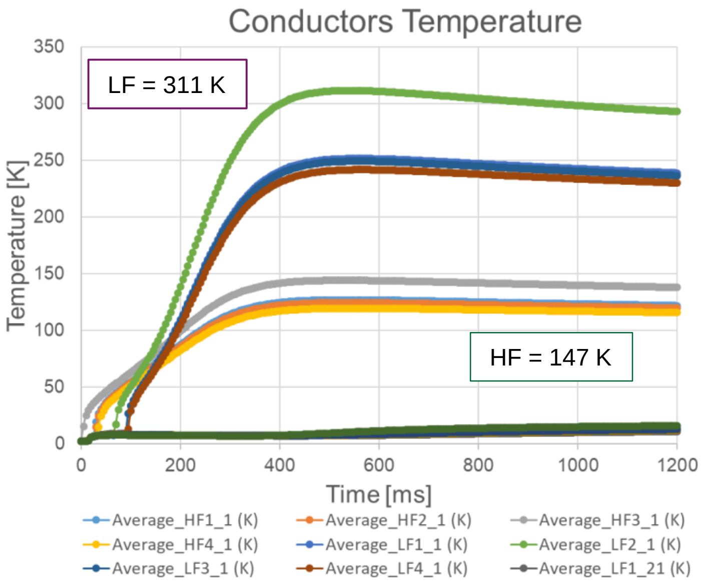
Effect due to

- The dimensionality of the problem already forecast in literature (*See Wilson – Superconducting magnets*)
- Differential inductance

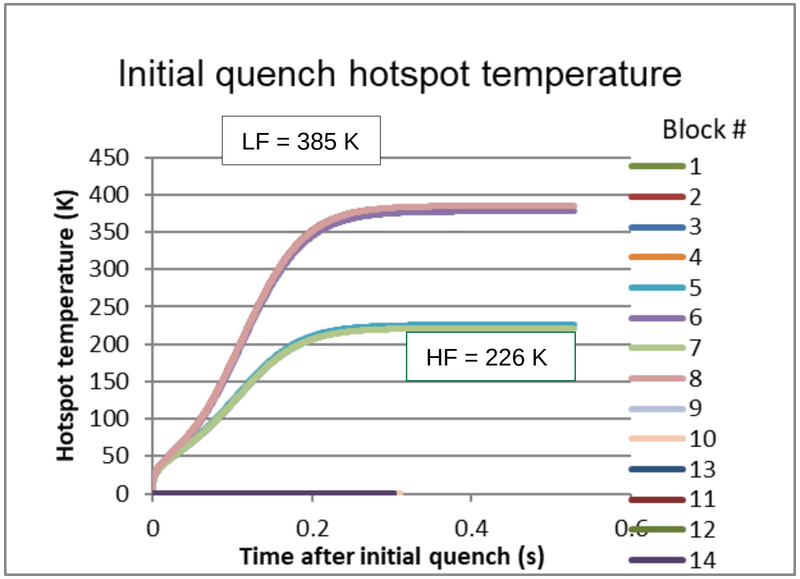
Effects on the hot-spots (the mech structure in COMSOL helps sharing the heat)

Calculations made using T. Salmi ECC Spreadsheet

Comparison With Analytical Calculations



ΔT ~ 75 K

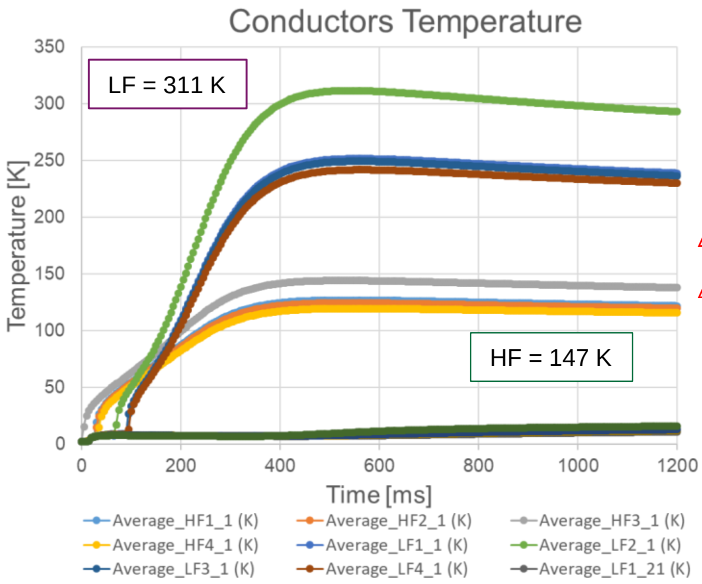


Difference due to :

- Dimensionality of the problem
- Geometry
- Starting point (defined in COMSOL)

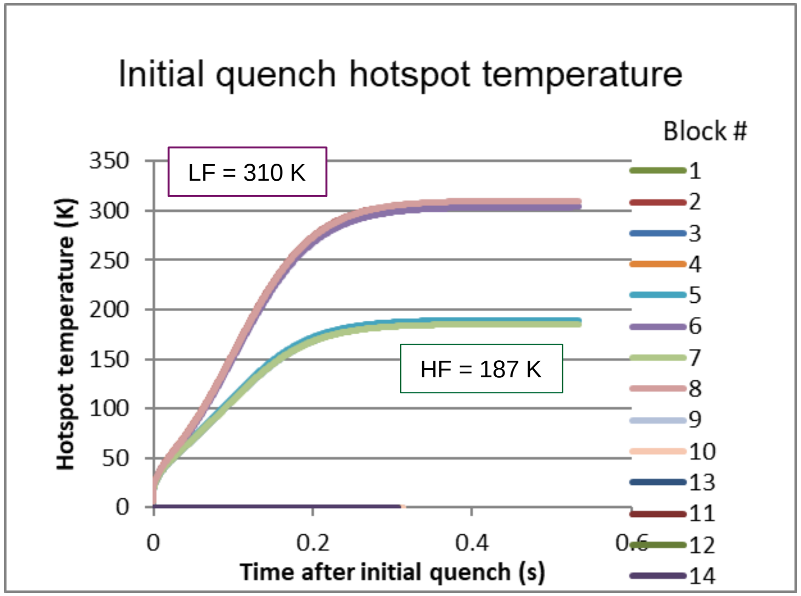
COMPARISON WITH ANALYTICAL CALCULATIONS

The contribution of dimensionality and geometry on the hot-spots can be seen as if there is a $R_{dump} = \frac{1000\,V}{I}$ in the spreadsheet



ΔT_{LF} ~ 0 K

ΔT_{HF} ~ 40 K



CONCLUSIONS

A 2.5 D FEM multi-physics model has been made with COMSOL for F2D2 and it is ongoing for R2D2

Caracteristics

- It couples 4 different models (MAG, SC, THERM, ELECT)
- It considers:
  - the magneto-resistance
  - the thermal-hall effect
  - the current redistribution inside the conductors
  - AC-losses

Results at 1.05 I_{nom}

- Hot-spot temperature well within the criteria (311K LF, 147K HF vs 350K)
- Voltages are well within the criteria (<600 V vs 1200 V max)

Next step

- Include CLIQ
- Simulate different scenario

A special thanks to L.R. Vieira and Y. Ameslon, our internships who worked on the model.