Low-luminosity D1 for FCC

FCC week 2018 at Amsterdam

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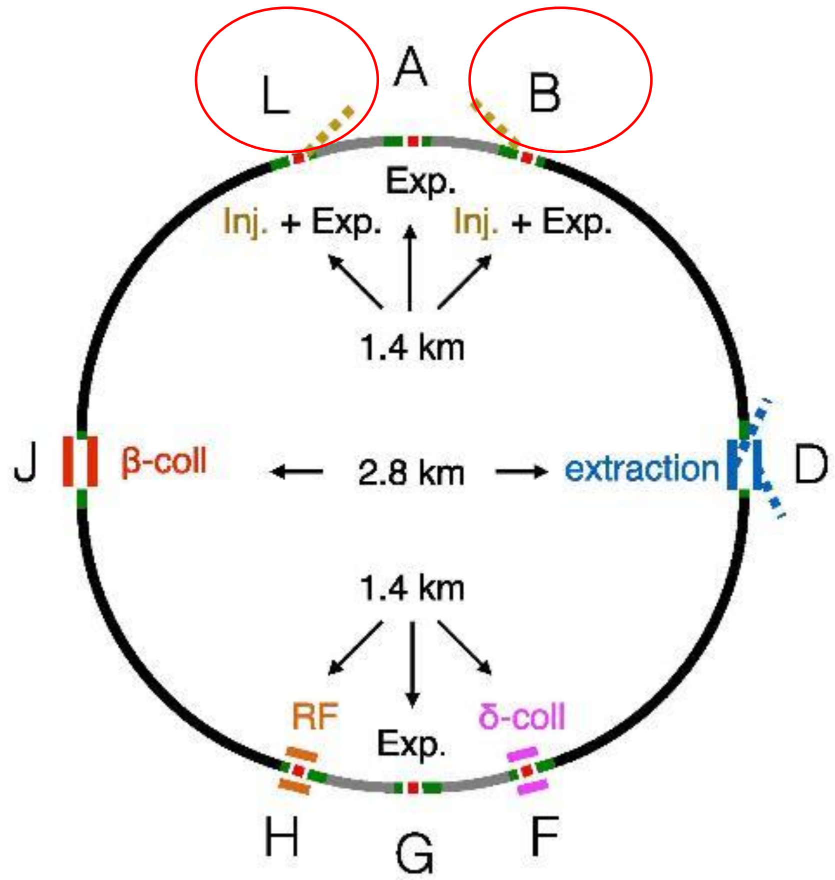
Introduction



- At the present plan, 2 IRs will expected to be open for 'low-luminosity' experiments (β^* = 3 m), which will be combined with the injection regions (**L** and **B**)
- Design study on the separation dipole (D1) has started in KEK since 2015, and now is updated according to the latest design parameters as presented by Daniel

Requirement of D1 for FCC

Presented by
T. Nakamoto (KEK)

FCC-hh magnet parameters

	B / G (T) / (T/m)	B_{peak} (T)	Bore (mm)	Length (units x m)
MB	16	16.4	50	4500 x 14.3
MQ	450	13	50	800 x 6
MQX	225	13	100	
D1	12	13	60	4x2 x 12
D2	10	10.5	60 Single Aperture	4x3 x 10

Inter-aperture distance: 250 mm
Yoke diameter: 700 mm
Stray field: 100 mT

Given by Luca Bottura

FCCweek 2015

March 26, 2015 T. Nakamoto, FCC Week 2015 at Washington, DC 2

FCCweek 2018

	Q1	Q2	Q3	D1	D2
Number of units/IP	4	4	4	4	4
G, *B*	270 T/m	270 T/m	270 T/m	12 T	10 T
L	10 m	15 m	10 m	10.2 m	12.2 m
Aperture	64 mm	64 mm	64 mm	100 mm	60 mm

By D. Schoerling

Parameters on FCC D1

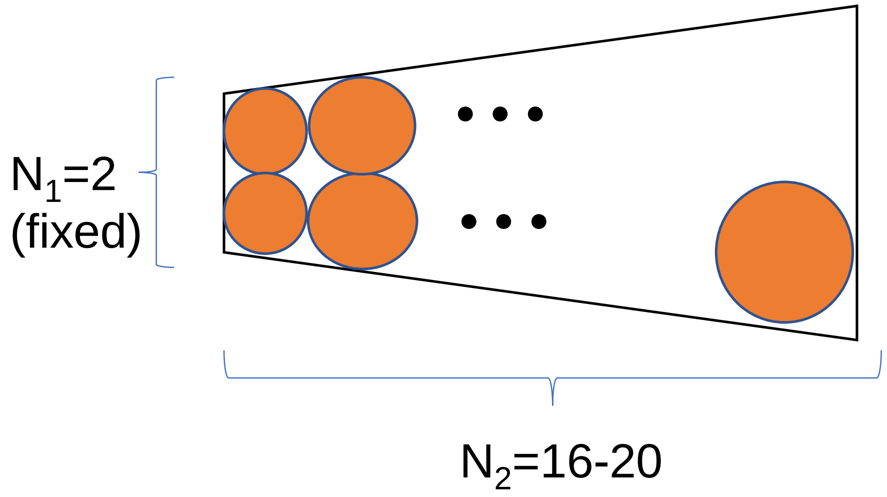
- **Primarily given parameters**
  - Nominal dipole field (B_1) : **12 T**
  - Aperture : **100 mm**
  - Magnet length : **10.2 m**

Consider to use the FCC Nb_3Sn technology as with the 16 T dipole (EuroCirCo1-P1-WP5)

- **Secondarily given parameters** *Ref. A. Ballarino and D. Tommasini in FCC week2017*
  - Strand Φ : **< 1.1 mm**
  - Num. of strands : **< 40**
  - RRR of the copper : **100**
  - Keystone angle : **< 50°**
  - Cable compaction factor : **< 0.14**
  - Working temperature : **1.9 K**
  - Cu/non-Cu : **>1.0:1**

Starting params. for the cable design

- The following variables are tentatively fixed through this study, and will be given feedbacks from the later analyses (quench analysis, 3D modeling etc.)
  - Filament Φ : **20 μm**
  - Cable insulation thickness : **0.15 mm**
  - Compaction factor
    - ✓at the thin edge : **0.10**
    - ✓at the thick edge : **~0.055**
  - Cu/Non-Cu ratio: **1.7-3.0**
- The floating numbers in this study:
  - Num. of strands along the cable highet (N_2) : **16-20**
  - Strand Φ : **<1.1 mm**
  - Keystone angle is calculated according to the # of strands, diameter, and the compaction factor
    - ✓Keystone angle : **0.24-0.32°**



Contraction factor : 0.003 (fixed)

Consideration on the J_E requirement

$$\int_{T_c}^{T_{\max}} \frac{A_{\mathrm{Cu}}}{A} \frac{S(T,B)}{\rho_{\mathrm{Cu}}(T,B,RRR)} dT = \int_0^{t_{\max}} J_{\mathrm{E}}^2(t)dt$$

$$= \int_0^{t_{\mathrm{delay}}} J_{\mathrm{E}}^2(0)dt + \int_{t_{\mathrm{delay}}}^{t_{\max}} J_{\mathrm{E}}^2(0) e^{-2\frac{t-t_{\mathrm{delay}}}{\tau}} dt$$

$$= J_{\mathrm{E}}^2(0) \cdot t_{\mathrm{delay}} + \frac{\tau}{2} J_{\mathrm{E}}^2(0)$$

$$(t_{\max} \to \infty)$$

$$S = f_{\mathrm{Cu}} S_{\mathrm{Cu}} + f_{\mathrm{nonCu}} \boxed{S_{\mathrm{nonCu}}}$$

Volumetric heat capacity of Nb_3Sn (Refered to 'alternative fit' in [1])

Insulation is not included

- A_{Cu} : Copper area (m^2)
- A : Cable area (m^2)
- ρ_{Cu} : Copper resistivity (Ω•m)
- S : Volumetric heat capacity of the cable (J/K•m^3)
- τ : Current decay time constant (s)
- T_{max} : Maximum temperature (K)
- t_{delay}: Detection delay after initial quench start (s)

[1] https://espace.cern.ch/roxie/Documentation/Materials.pdf

T_{max}=350 K, t_{delay} = 40 ms, RRR = 100

J_E (A/mm^2)		600	700	800	900	1000
τ (ms)	Cu/NCu=1.7	155.6	93.6	52.4	24.6	4.7
	Cu/NCu=2.3	213.7	135.8	85.2	50.5	25.7
	Cu/NCu=3.0	265.4	173.8	114.3	75.5	44.3

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A_{Cu} : Copper area (m^2)
A : Cable area (m^2)
ρ_{Cu} : Copper resistivity (Ω•m)
S : Volumetric heat capacity of the cable (J/K•m^3)

To gain τ >100 ms for various Cu/NCu, the first constraint on J_E would approximately be 600 A/mm^2

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Strategy

1. Magnet design is done using ROXIE ver.10.3.1 (on the 2D basis)
   - J_c-B curve of Nb_3Sn is from 'EuroCirCo1-P1-WP5'

2. Optimize the num. of conductors and coil geometry for various cable designs such that multipoles are **below 1 unit** for the nominal dipole field (12T)
   - Cu/NonCu is varied from **1.7 to 3.0**, which is to further be tuned according to the later quench analysis

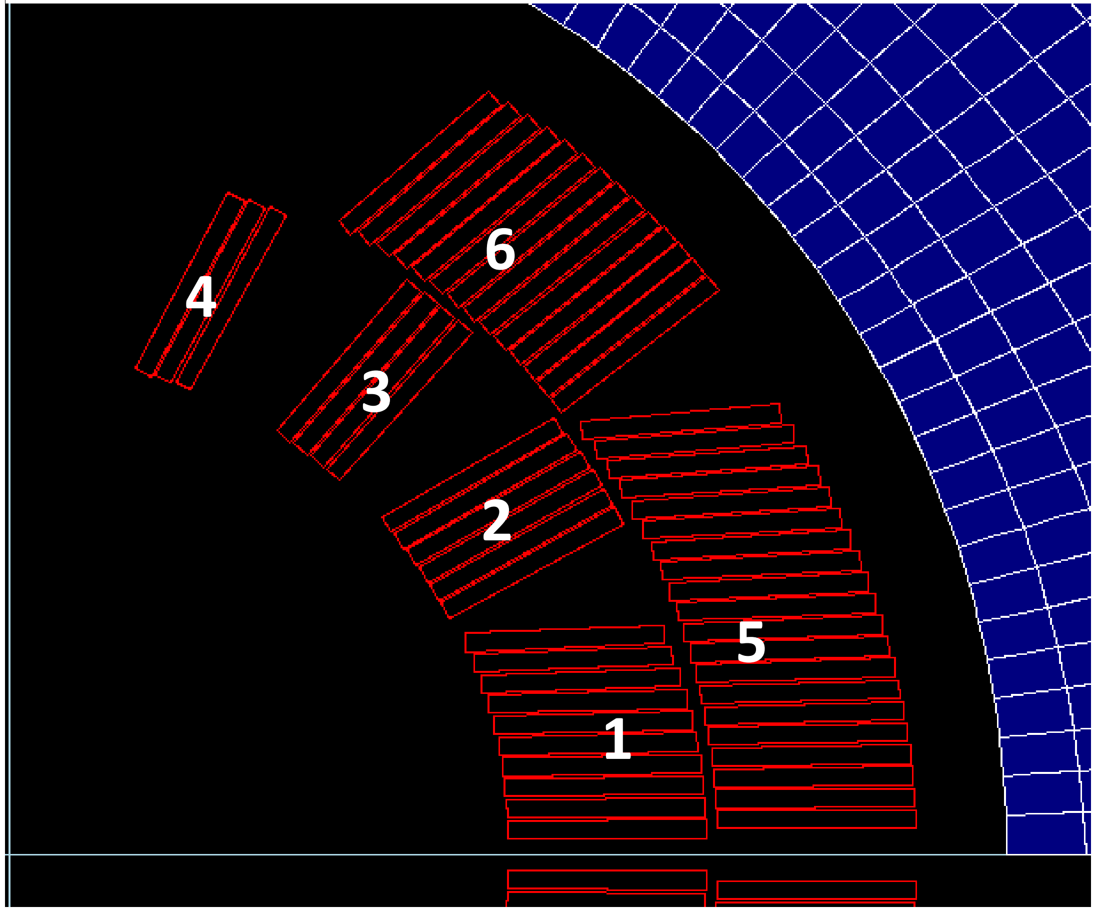
3. Then, see if the resultant J_E is around **600 A/mm²**

4. After the optimization, the quench analyses are performed to give the 2nd feedback to the design study (C)

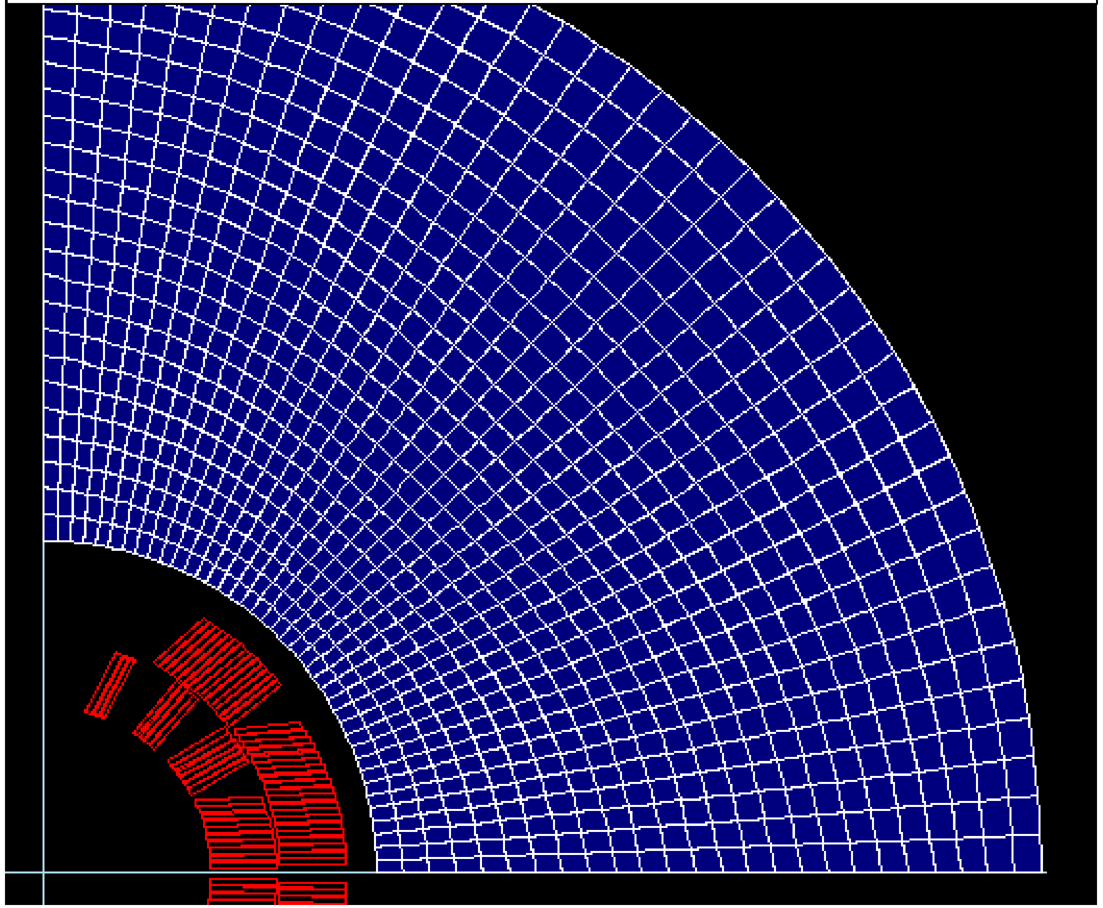
NOTE: The study is still ongoing

KEK first magnet design

Double-layered 6-blocks magnet
(double pancake coil)



Inner (outer) radius of yoke :
100mm (300mm)



No optimization for iron yoke geometry !!
(*e.g.* no HX hole yet)

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After 1st the geometry optimization

Strand Φ (mm)	Total # of strands	Total # of conductors	$B^{nominal}$ (T)	$I^{nominal}$ (A)	J_E (A/mm^2)	B^{peak} (T)		Self inductance (mH/m)
						Inner	Outer	
0.9	32	62	12.002	16100	790.85	12.697	11.576	-
	34	63	12.003	15980	738.78	12.688	11.506	-
	36	63	12.002	16290	711.30	12.631	11.379	-
	38	62	12.004	16820	695.78	12.682	11.325	6.9
	40	63	12.004	16780	659.41	12.611	11.347	7.2
1.0	32	**Under optimization**						
	34	59	12.003	17640	660.60	12.688	11.263	6.3
	36	57	12.001	18450	652.52	12.652	11.323	5.9
	38	**Under optimization**						
	40	**57**	**12.004**	**18890**	**601.11**	**12.620**	**11.147**	**5.8**

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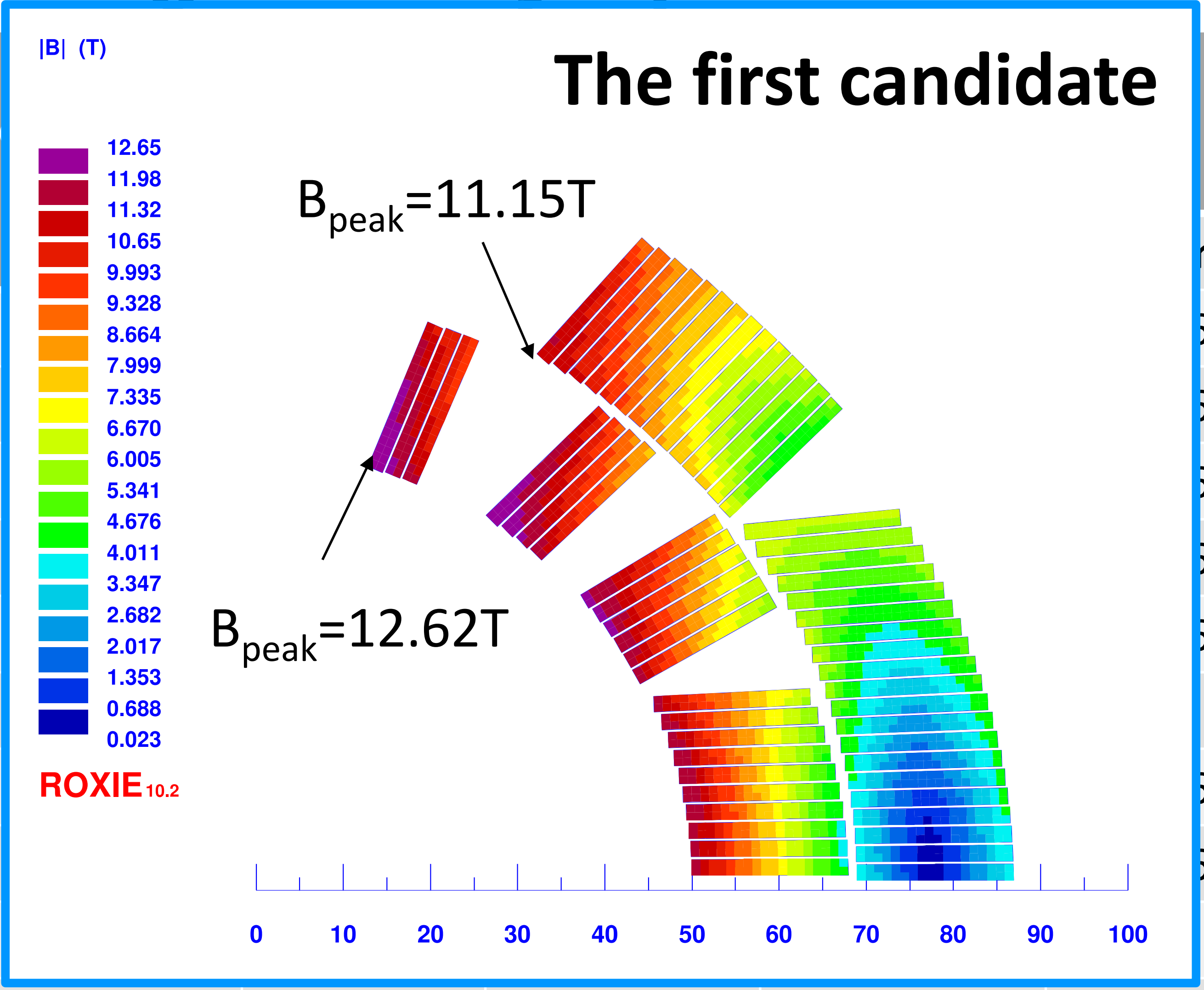
After 1st the geometry optimization

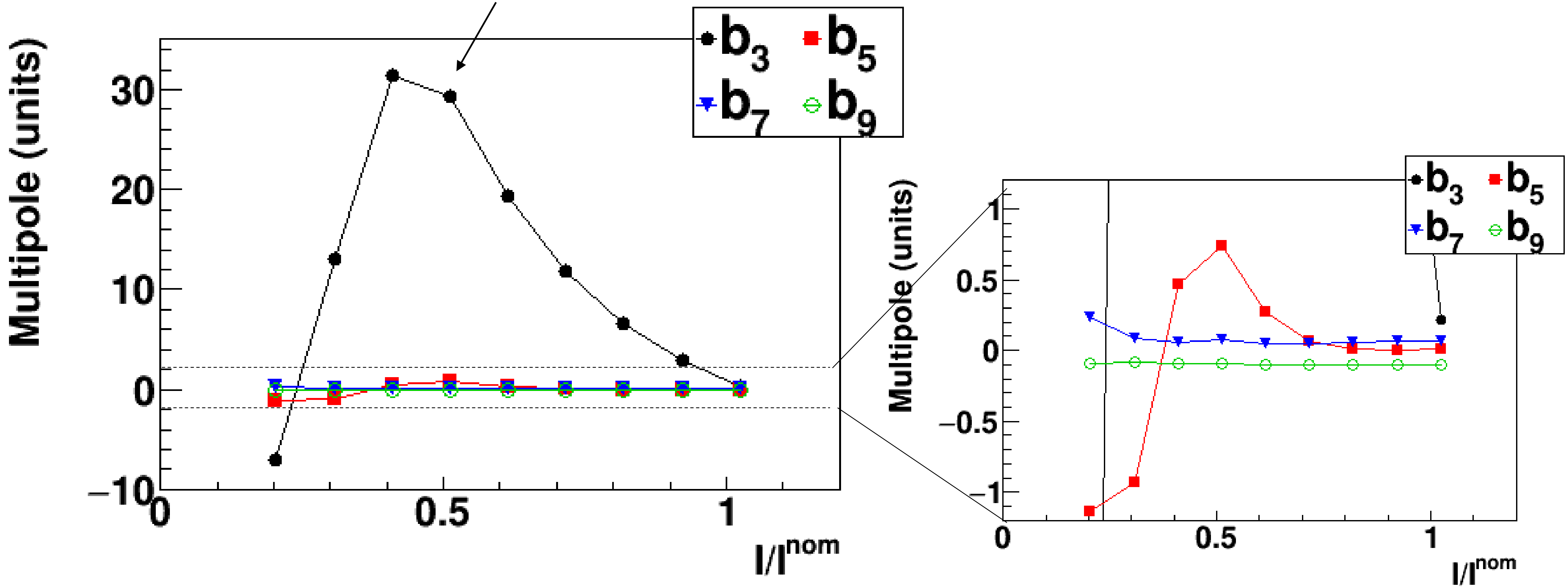
Strand Φ (mm)	Total # of strands	[illegible]	[illegible]	[illegible]	[illegible]	B_{peak} (T)		Self inductance (mH/m)
						ner	Outer	
0.9	32	[illegible]	[illegible]	[illegible]	[illegible]	597	11.576	-
	34	[illegible]	[illegible]	[illegible]	[illegible]	588	11.506	-
	36	[illegible]	[illegible]	[illegible]	[illegible]	531	11.379	-
	38	[illegible]	[illegible]	[illegible]	[illegible]	582	11.325	6.9
	40	[illegible]	[illegible]	[illegible]	[illegible]	511	11.347	7.2
1.0	32	[illegible]	[illegible]	[illegible]	[illegible]			
	34	[illegible]	[illegible]	[illegible]	[illegible]	588	11.263	6.3
	36	[illegible]	[illegible]	[illegible]	[illegible]	552	11.323	5.9
	38	[illegible]	[illegible]	[illegible]	[illegible]			
	40	**57**	**12.004**	**18890**	**601.11**	**12.620**	**11.147**	**5.8**



We get J_E~600A/mm² for (Φ, $N_{strands}$)=(1.0mm, 40)

Harmonics

Large variation in b3 attributes from the smaller yoke inner radius compared to the coil size



All multipoles are within 1 unit at nominal current

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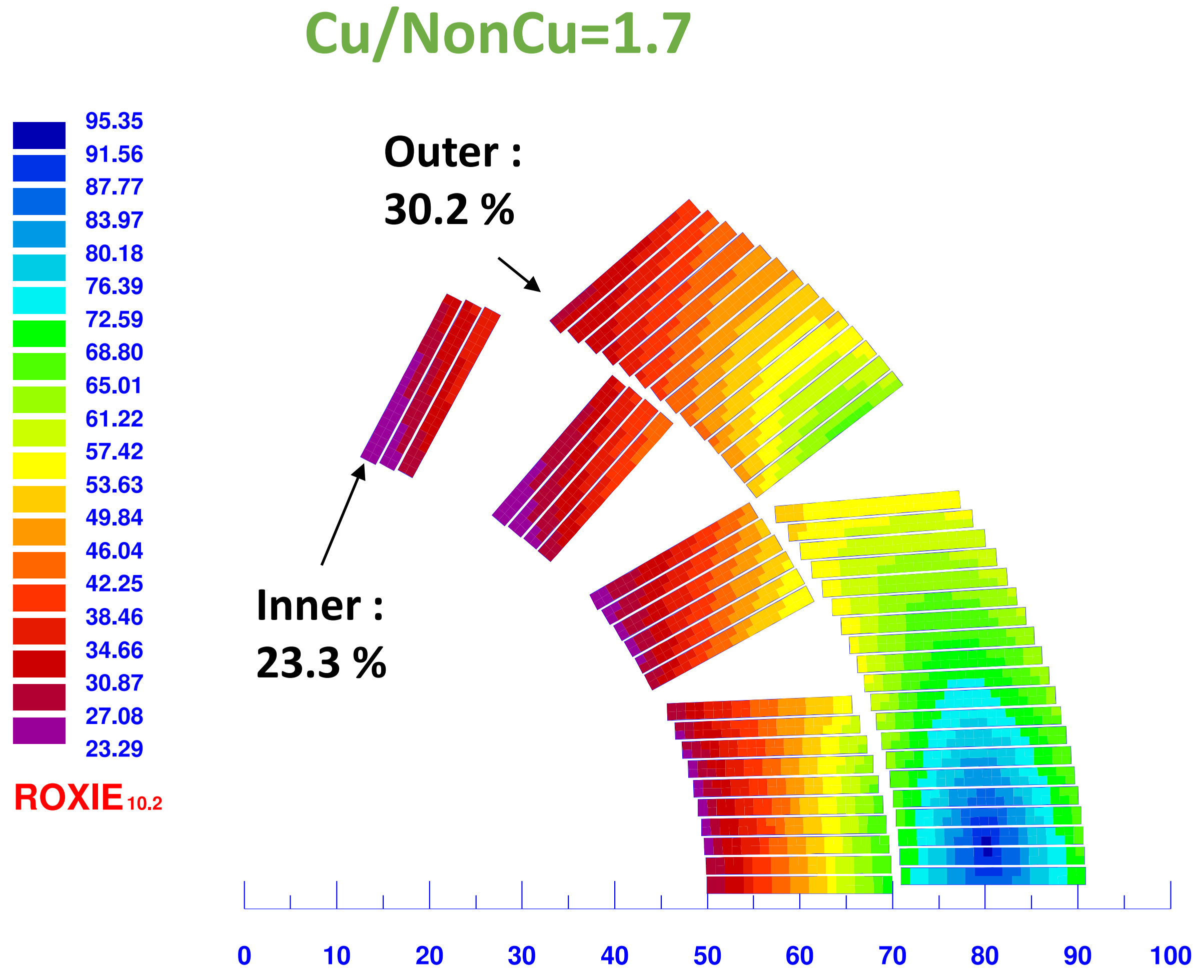
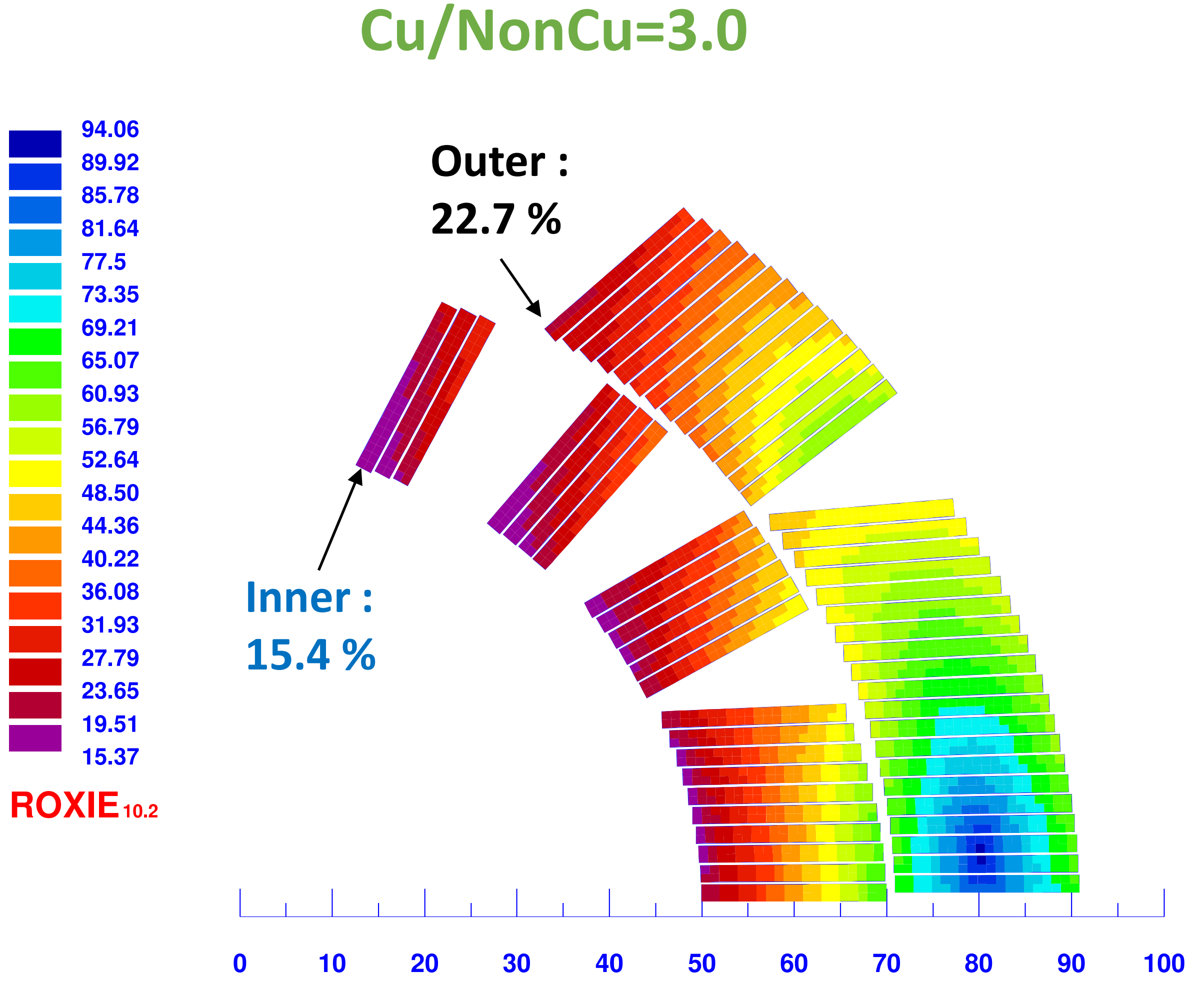
Operation margin





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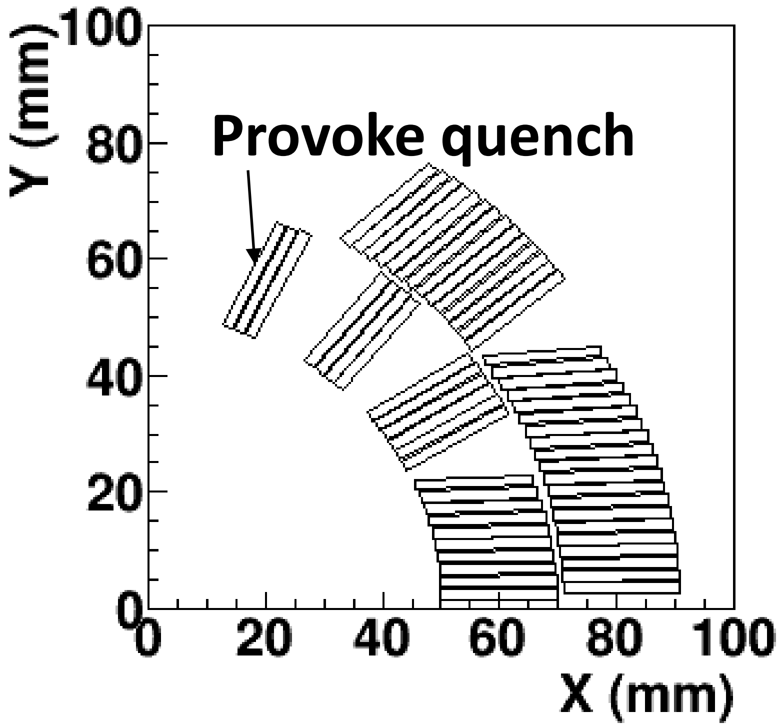
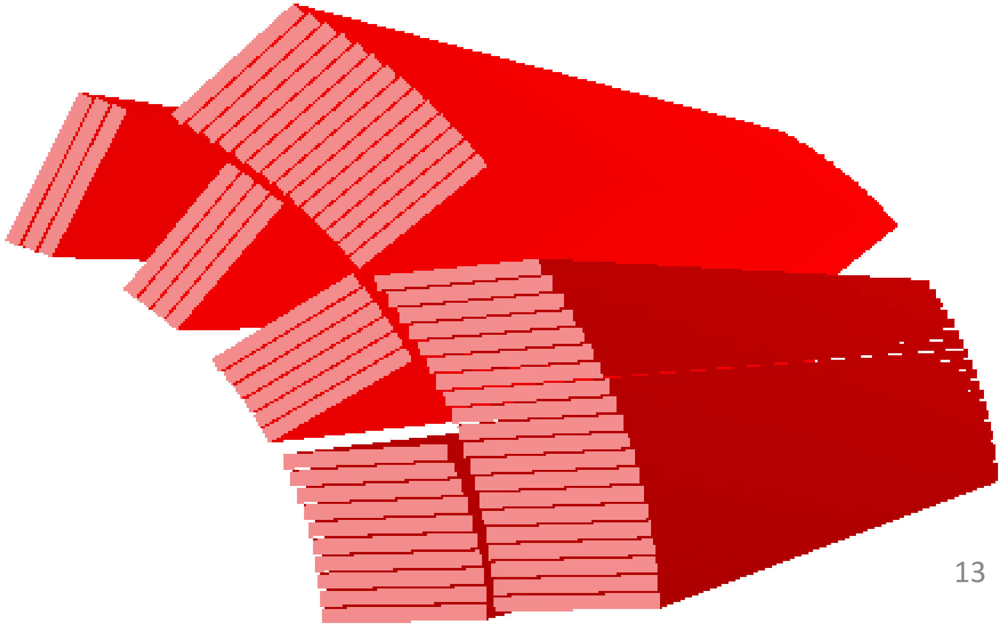
Large Cu/NonCu is still acceptable

Quench analysis

- To give the second feedback on the cable design
  - Tuning of the Cu/NonCu ratio
  - Modeling the magnet from scratch if necessary
- Assume 20 ms delay for the quench detection, and another 20 ms delay for quenching entire coil (**40 ms in total**)
- Quench simulation is performed by the handmade C++ base code (3D analysis)
  - Assume 'adiabatic' condition
  - Operation current is set to 105% of the nominal one
  - Since design of the coil-end is not complete yet, just extrude the straight part, and
    - ✓ Consider heat propagation in the longitudinal and turn-to-turn direction
    - ✓ Not consider the layer-to-layer heat propagation





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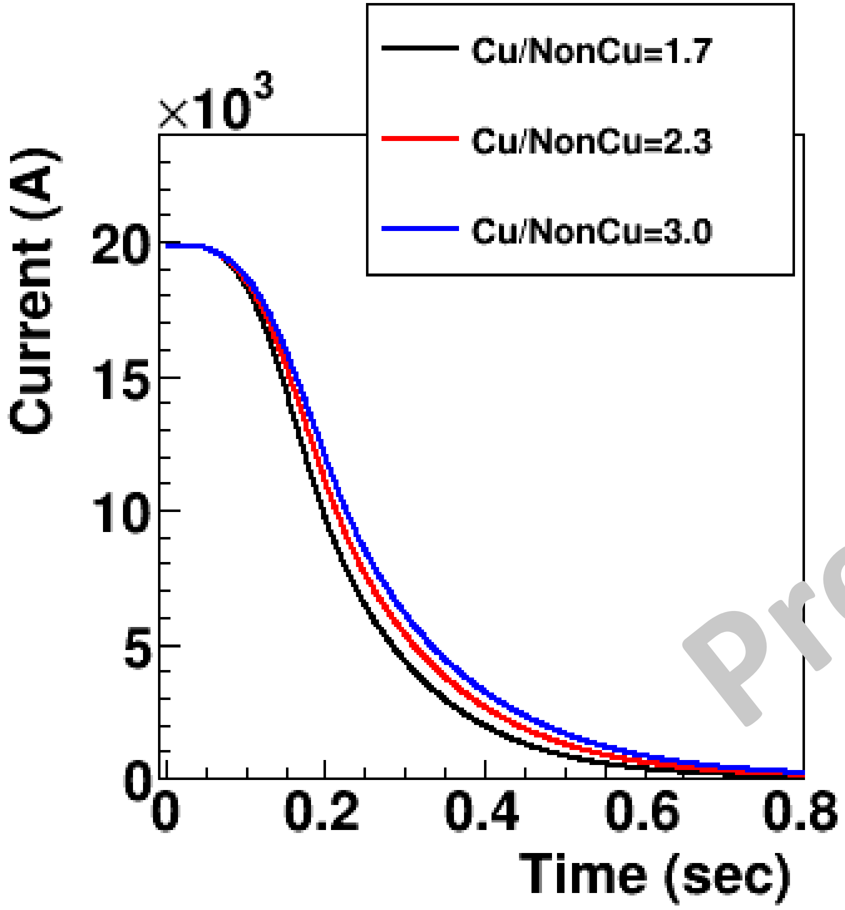
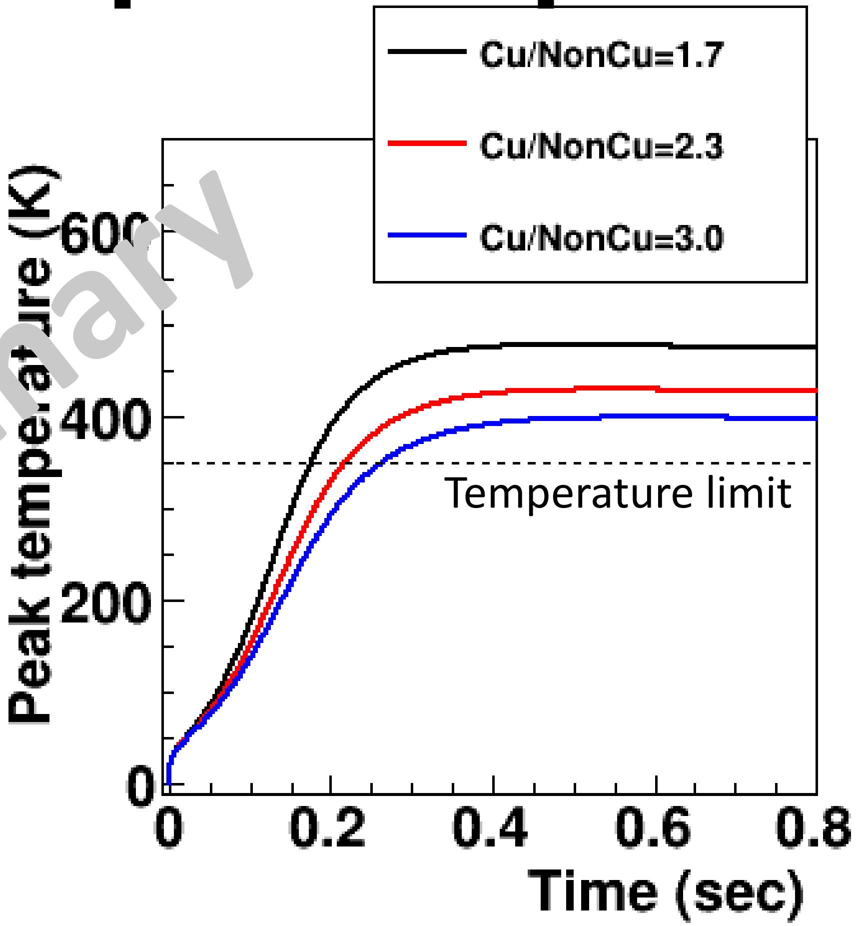
Current profile & Hotspot temperature





Longer current tail due to the lower resistivity for the larger Cu/NCu

Even the large Cu/NCu (=3.0), the magnet cannot be protected as T_{Hot} exceeds 350 K

Further design study and crosscheck with ROXIE will be performed

Conclusion & prospect

- Design study on the FCC D1 magnet is being conducted in KEK
- We found the current magnet design was not suited for the magnet protection, and further study on the design optimization should be done
- **We've just finished the 1st iteration for the present optics target**, and the 2nd iteration will be performed according to the results presented here

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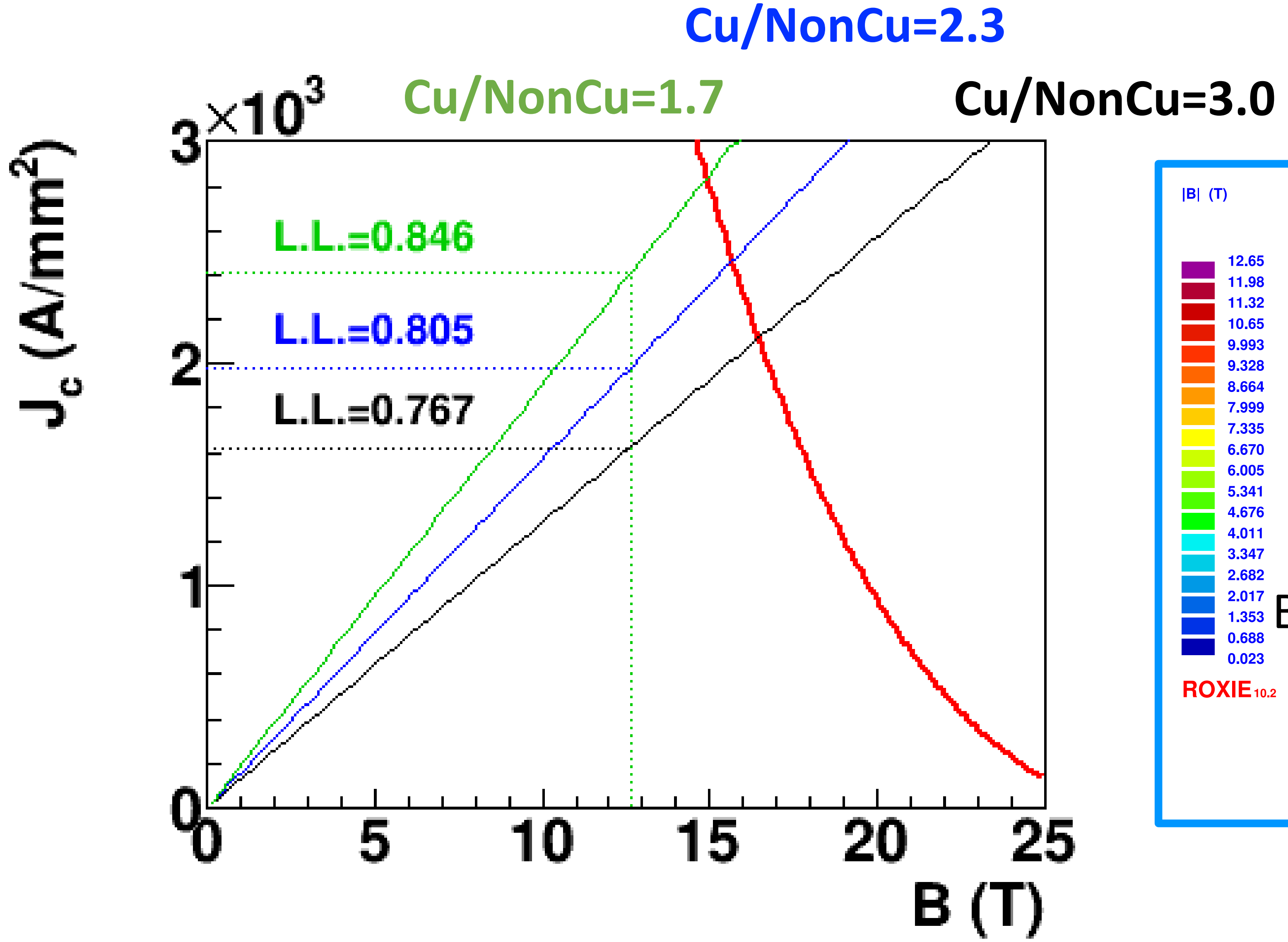
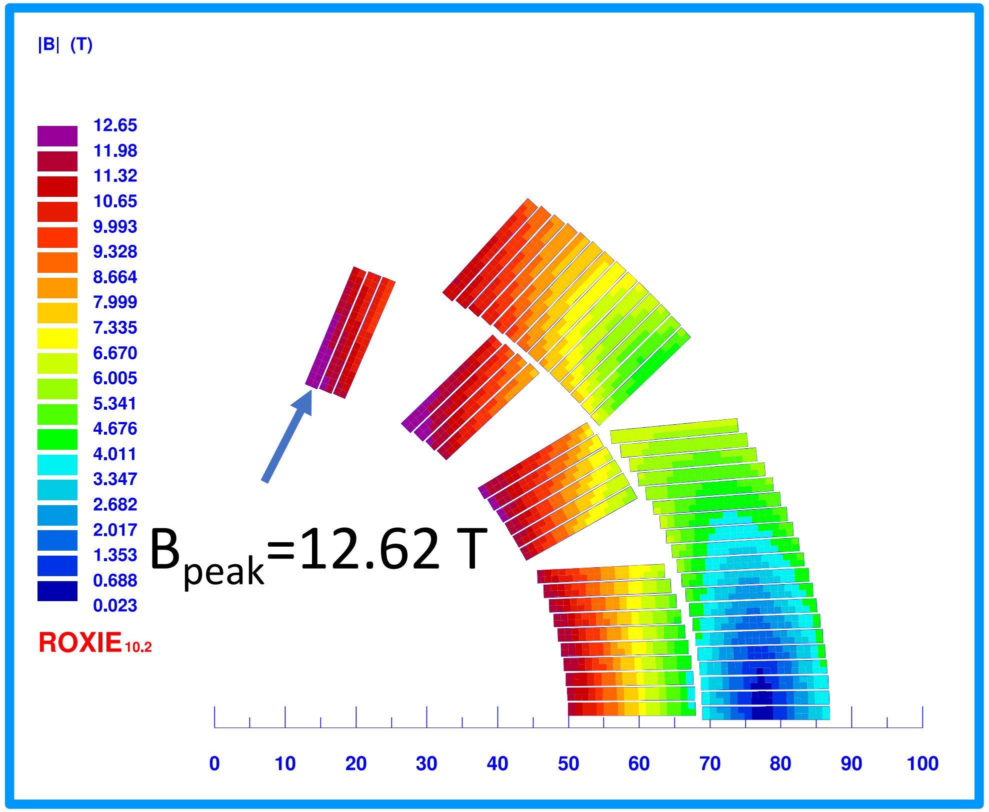
SUPPLEMENT

Load line





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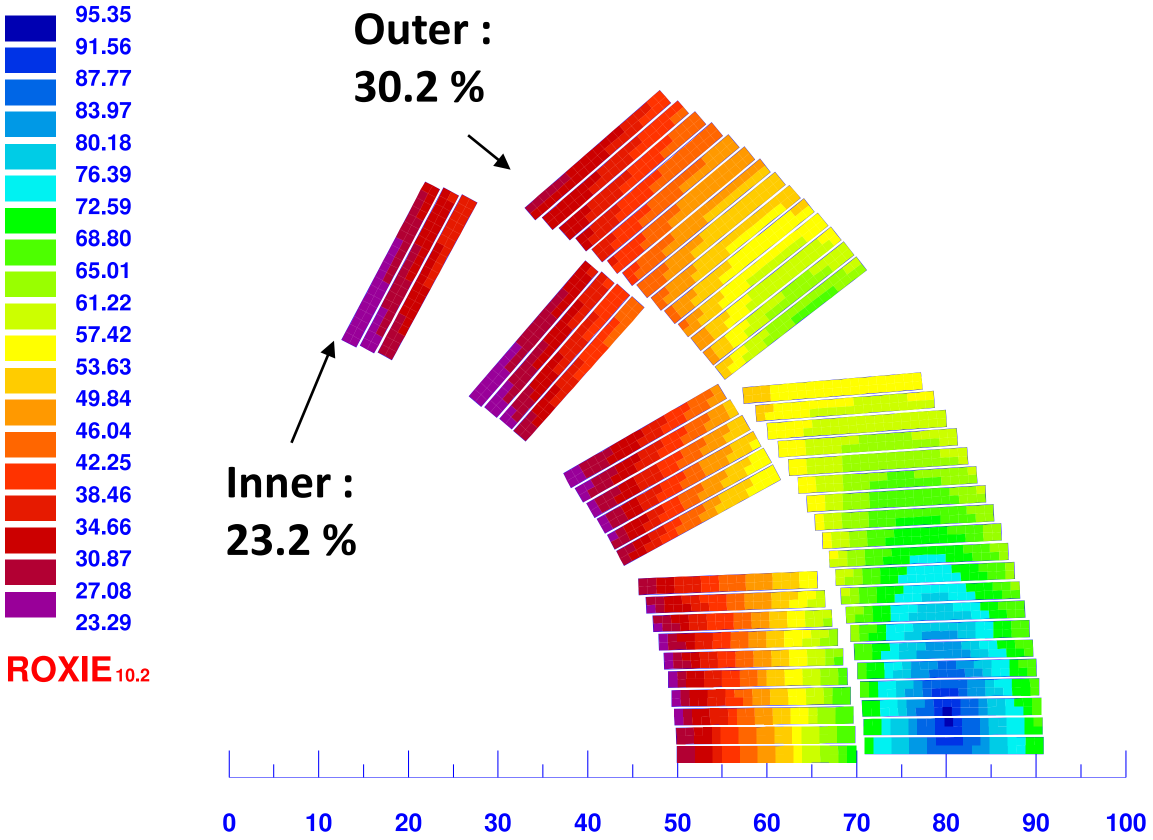
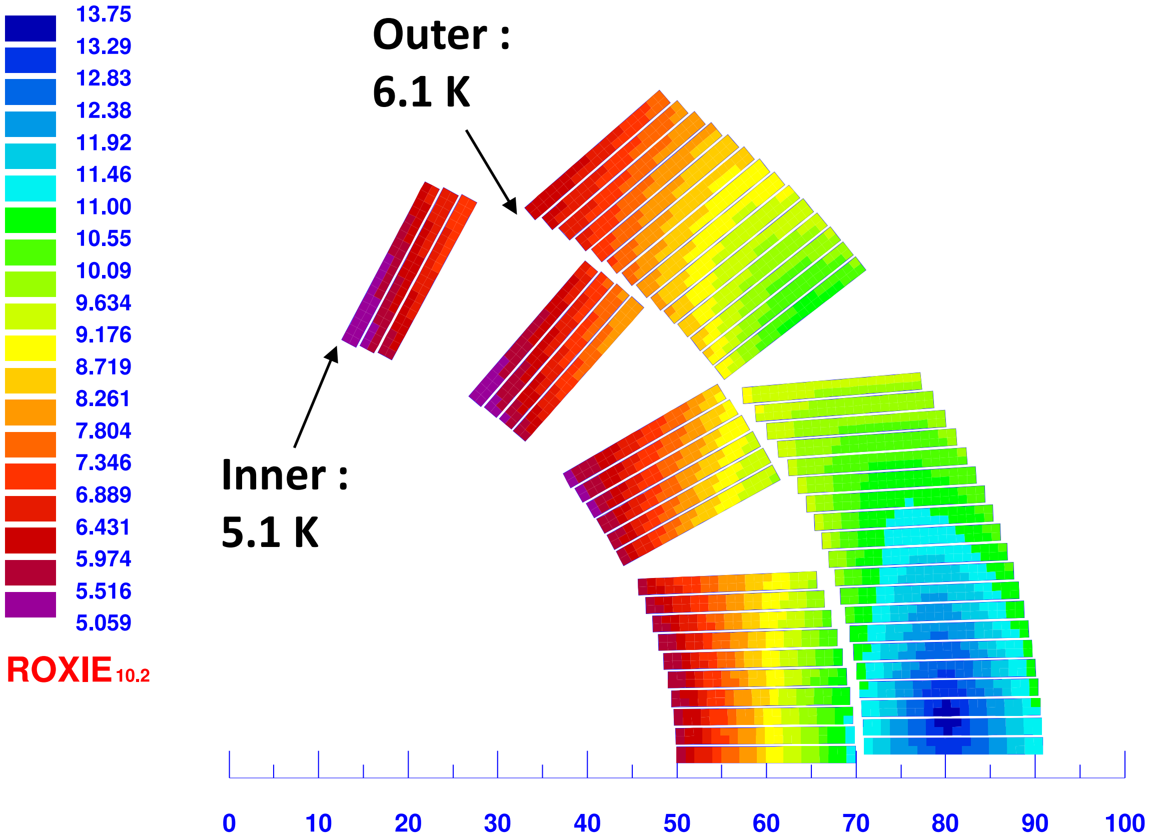
Operation margin (For Cu/NCu=1.7)

Margin to quench (%)

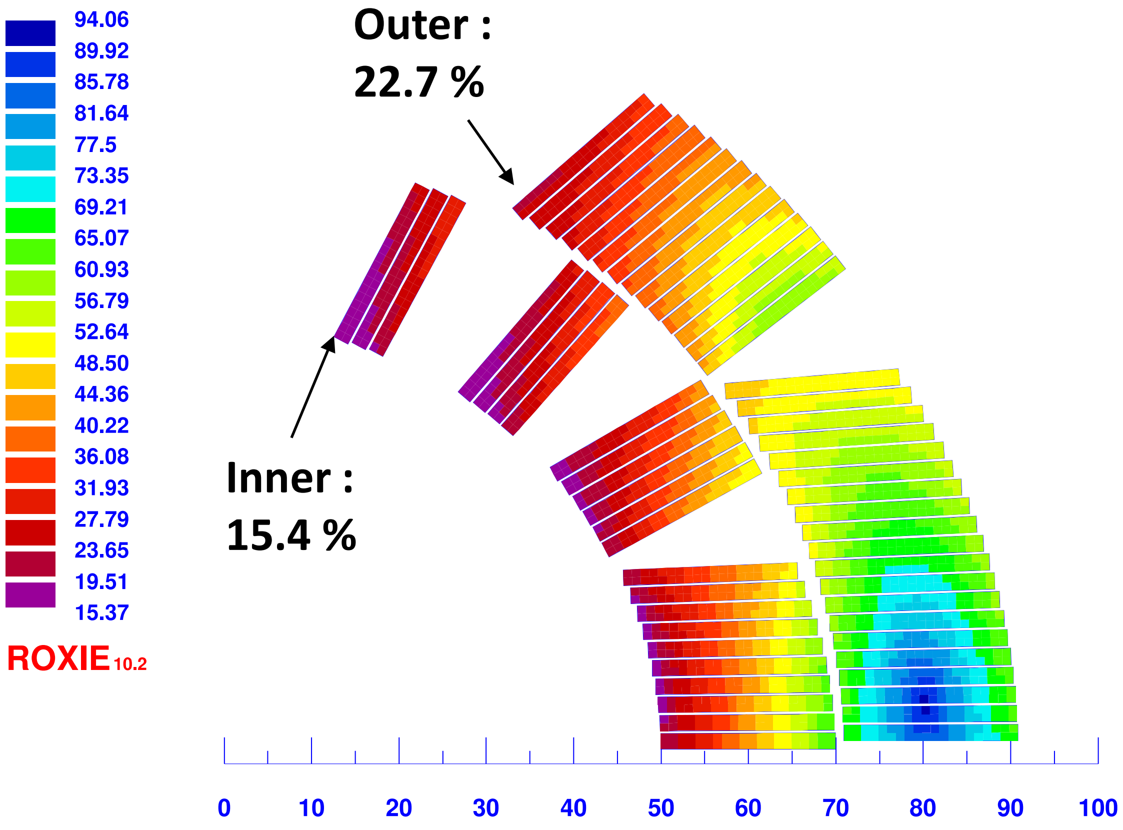


Temperature margin (at T_{op}=1.9 K)

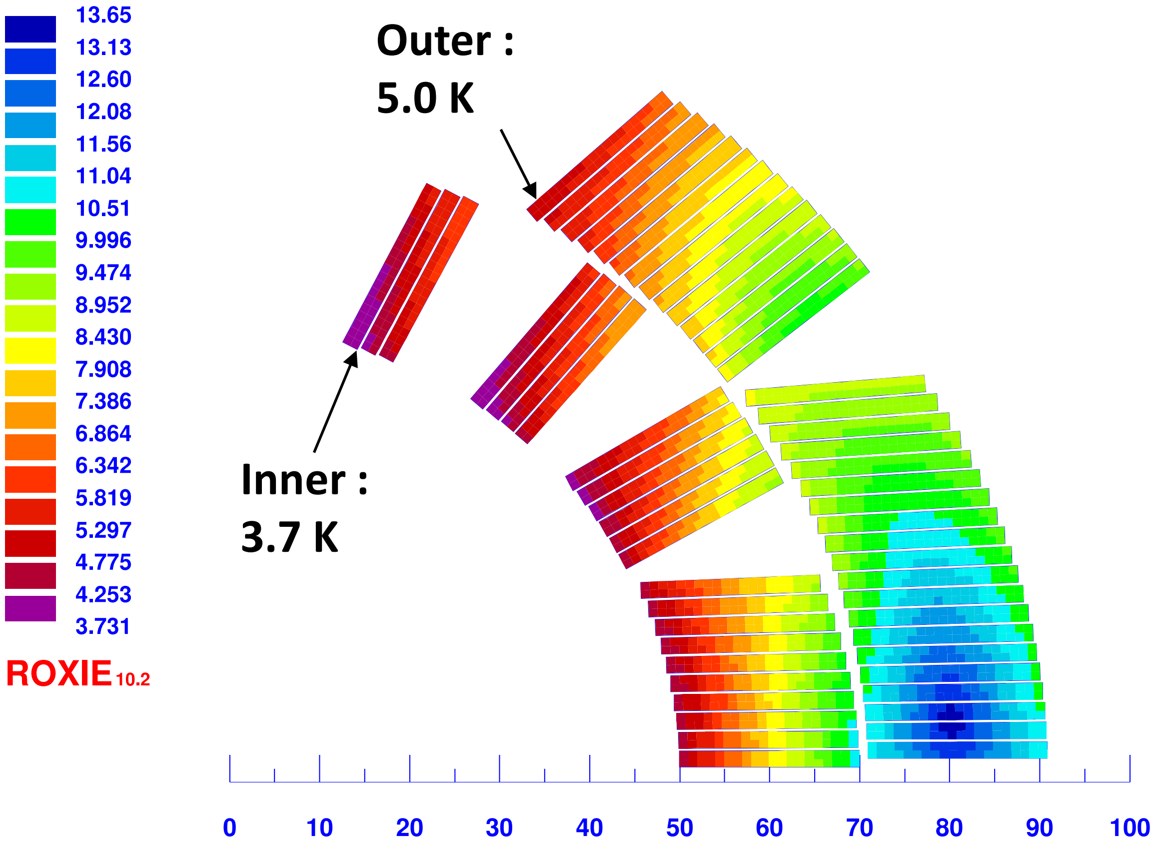


Operation margin (For Cu/NCu=3.0)

Margin to quench (%)



Temperature margin (at T_{op}=1.9 K)



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Snapshot of the present design candidates

Strand Φ (mm)	0.9		1.0		
Num. of strands	38	40	34	36	40
Cable Height (mm)	17.1	18.0	17.0	18.0	20.0
Stored energy at $I=I^{nominal}$ (MJ/m)	0.98	1.0	0.98	1.1	1.0
Self inductance at $I=I^{nominal}$ (mH/m)	6.9	7.2	6.3	5.9	5.8

Large strand/cable size is preferable for reduction of J_E

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