Considerations about twisted stack cable for HTS insert

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Outline

- Motivation
- Magnet design based on stack cable hypothesis
- Considerations about stack cable weaknesses
- Sensibility of field homogeneity on current distribution

Insert dipole objectives :

- Inner diameter : 40 mm
- Outer diameter : 100 mm
- Flux density B_0 : 5 T in 13-15 T background
- Field quality : $< 5*10^{-4}$ B_0 unit

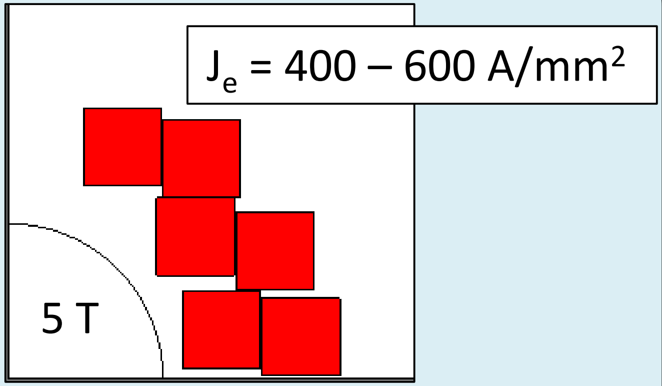
Insert dipole objectives :

- Inner diameter 40 mm
- Outer diameter 100 mm
- Flux density B_0 5 T in 13-15 T background
- Field quality $< 5*10^{-4}$ B_0 unit
- Current density J_e > 340 likely 400 – 600 A/mm^2 (20 T, 4,2K)
- Mechanical stress 100 MPa
- Operating current 5 – 10 kA

Magnet design optimization must lower operating current density
Need for compact cable

Stack cable interest :

Magnet design

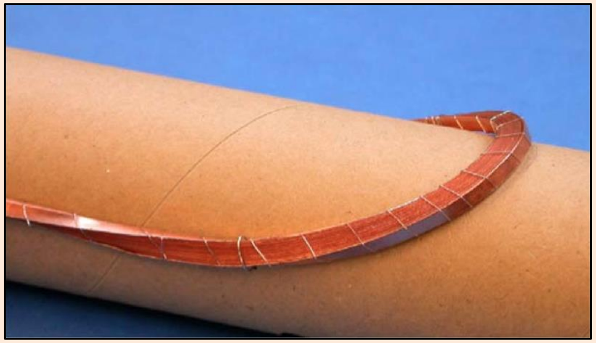


Square blocks : more room for coil topology optimization

Easy to upscale : large current

Tensile/compressive stress = as tape

Cable design



M.Takayasu (MIT), IEEE vol.23 No.3 2013

Easy to make, low cost

Good contact with thermal stabilizer and/or mechanical support

No lost space.

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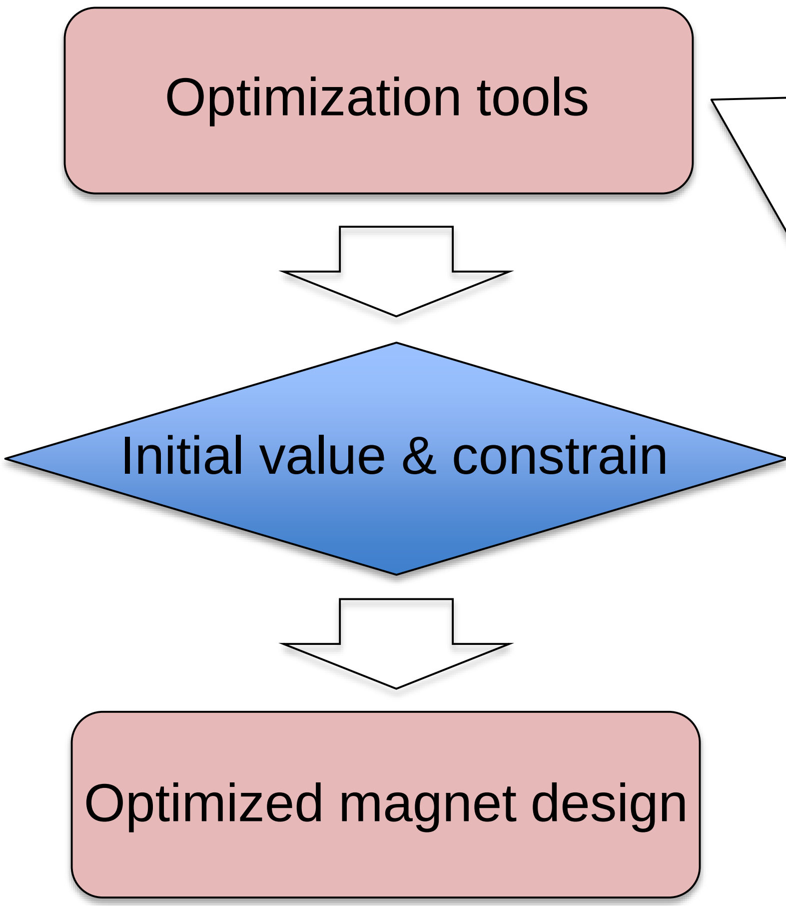
Weak points : bending and above all transposition

Magnet design : What can we get ?



Analytical model

Using 'fmincon (Find Minimum of Constrained Nonlinear multivariable function)' of MATLAB optimization tools. It's much faster to gain results than numerical model.

Electromagnetic equation

Equation for block-coil

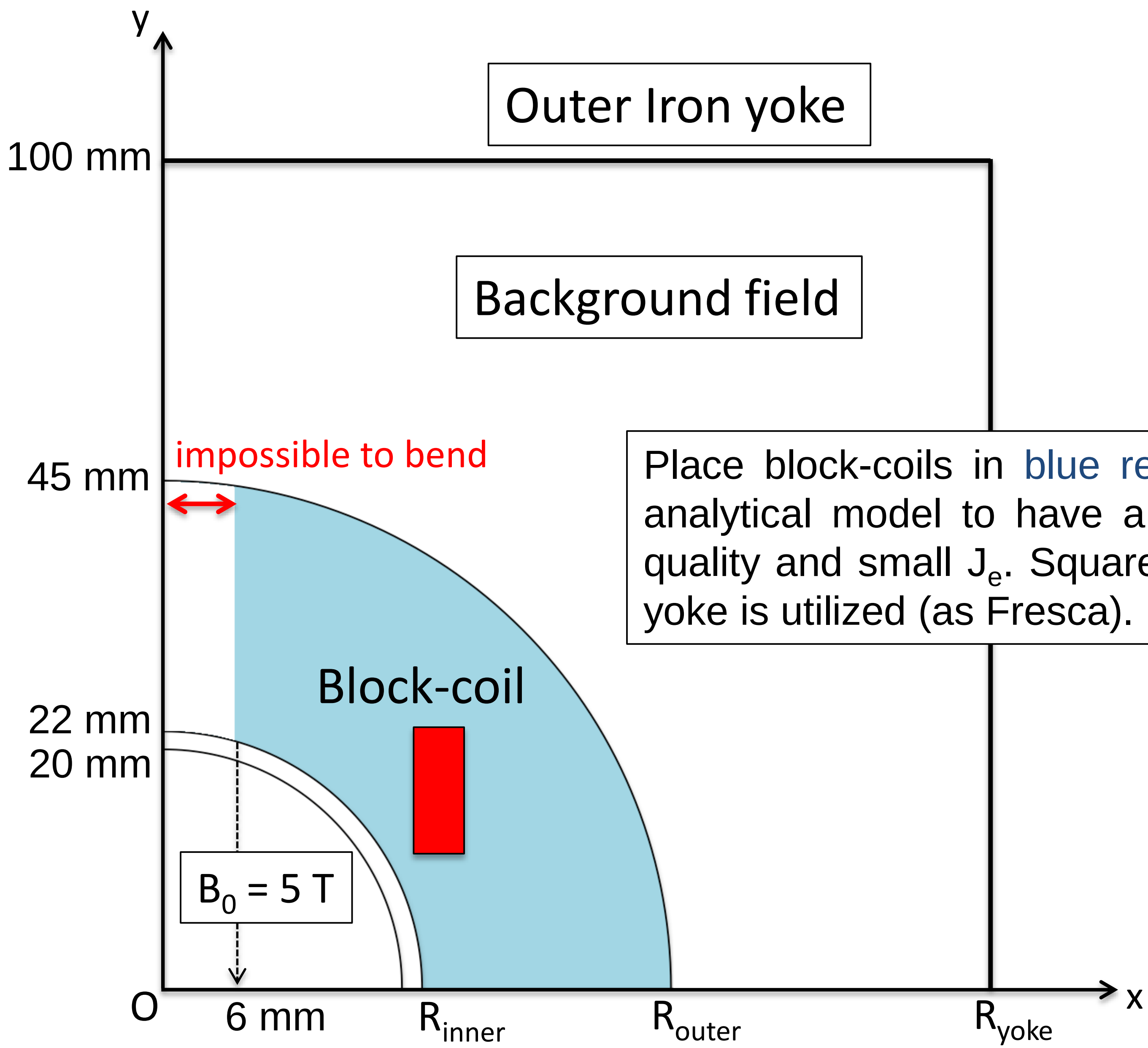
$$B_{y,bloc}(x,y) = \frac{\mu_0 J}{4\pi}\left[\left[(y-b)\ln R^2 + 2(x-a)\arctan\left(\frac{y-b}{x-a}\right)\right]_{a_1}^{a_2}\right]_{b_1}^{b_2}$$

same as CEA

Equation for field quality

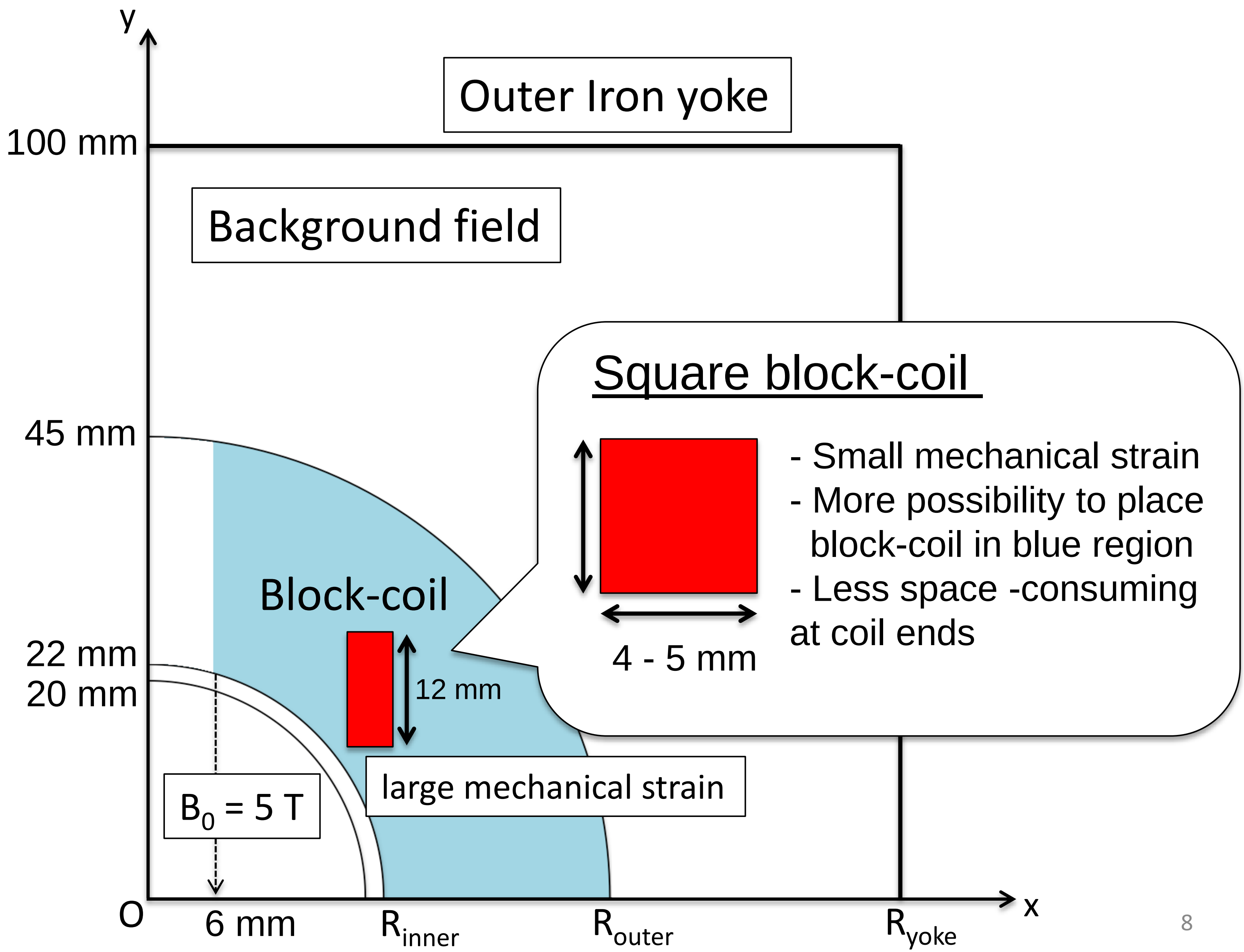
$$B_n = \frac{\mu_0 I}{2\pi r_c}\left(\frac{r_0}{r_c}\right)^{n-1}\cos(n\varphi_c)$$

Initial value & constrain for magnet design



Place block-coils in blue region using analytical model to have a good field quality and small J_e. Square outer iron yoke is utilized (as Fresca).

Block-coil design



Optimization tools for magnet design

Optimization tools

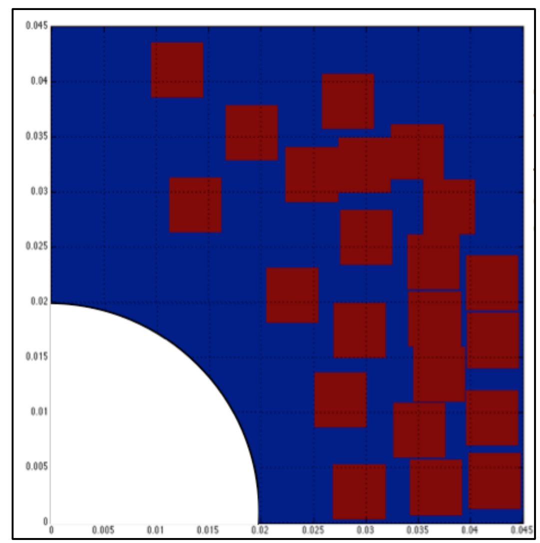
Initial value & constrain

Optimized magnet design

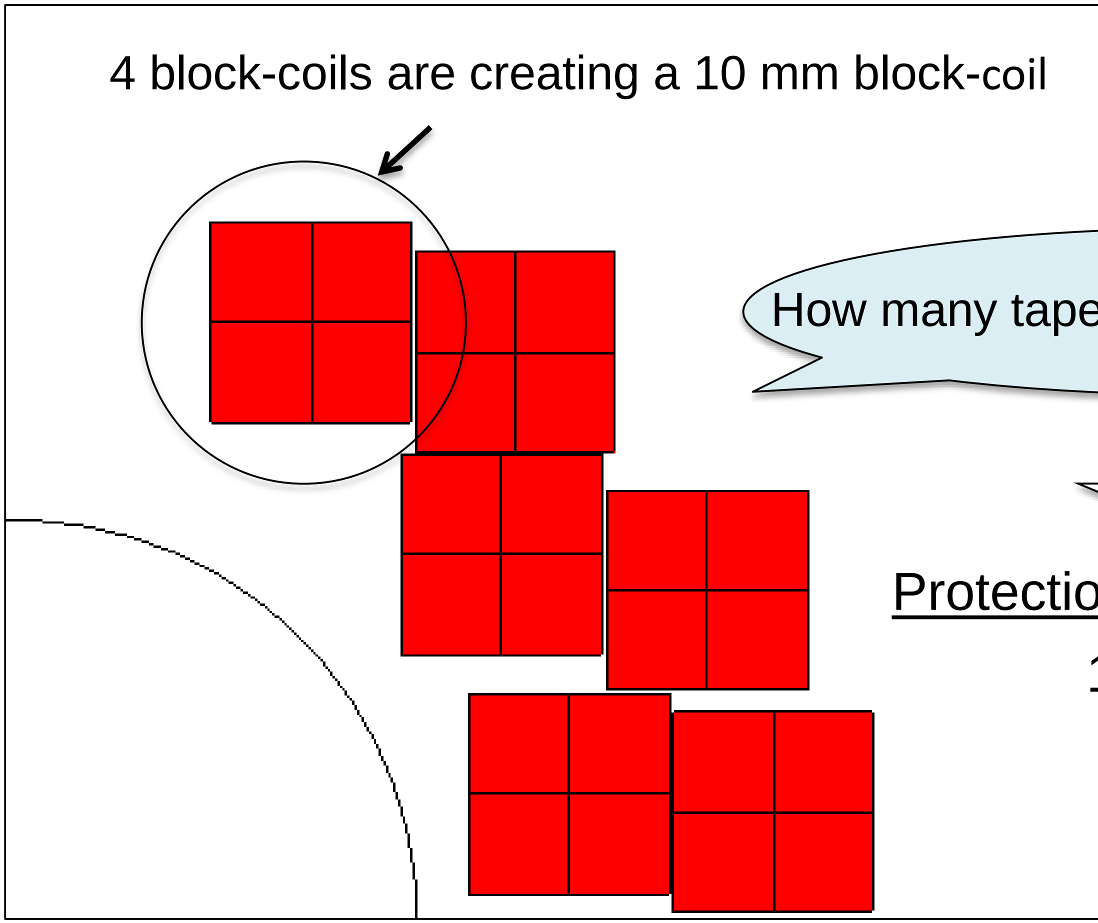
Objective

To obtain good field quality while having small current density J_e. We choose one of the best optimized magnet design that is feasible in terms of manufacturing.

example



First optimized magnet design

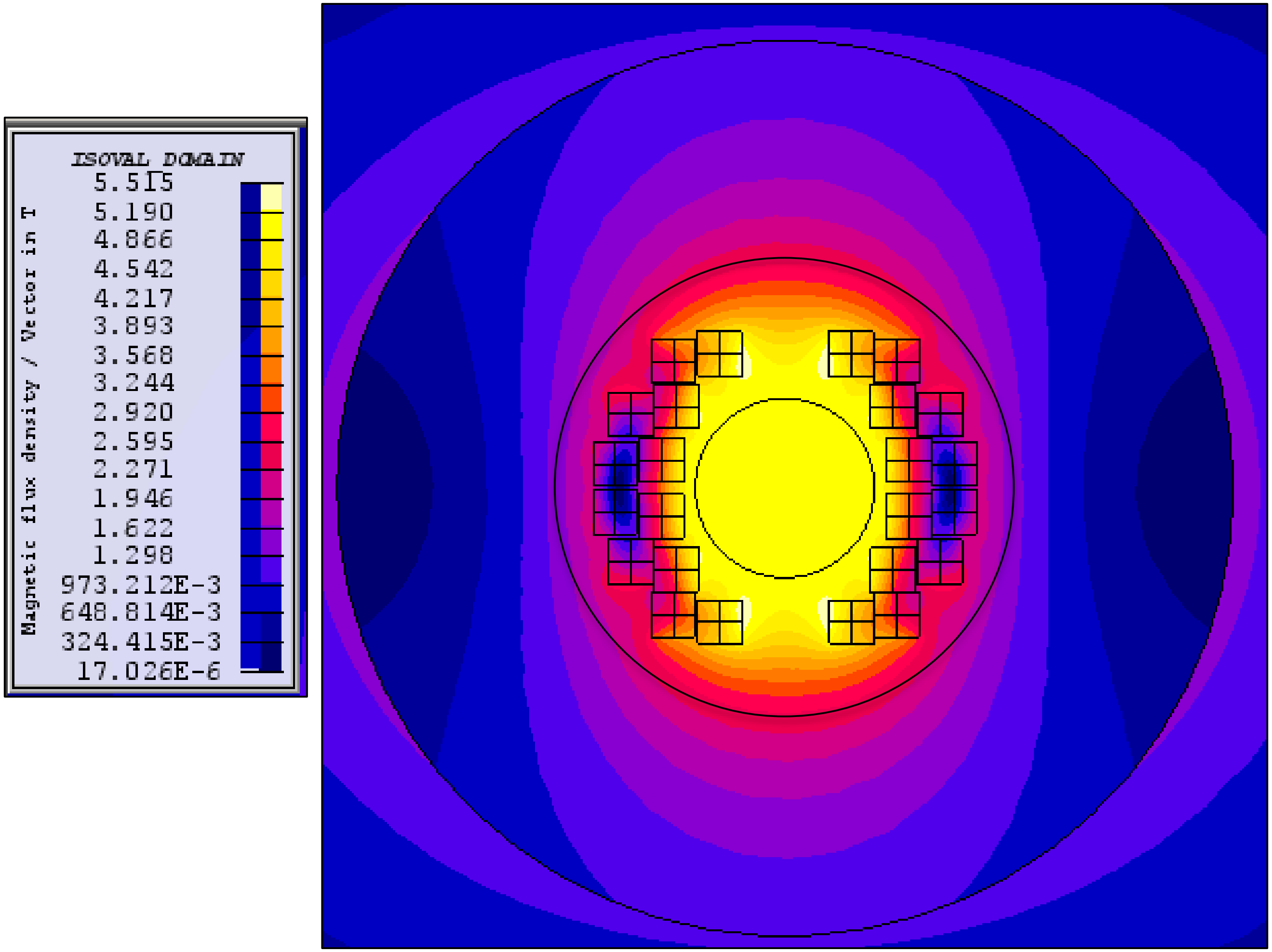


How many tape in parallel in a block-coil?

<u>Protection & Detection scheme</u>

$1 \leqq N_{para} \leqq 30$

First optimized magnet design



Block-coil design

Width, Thickness

5 mm

Conductor area

2400 mm^2

Magnet design

Field quality

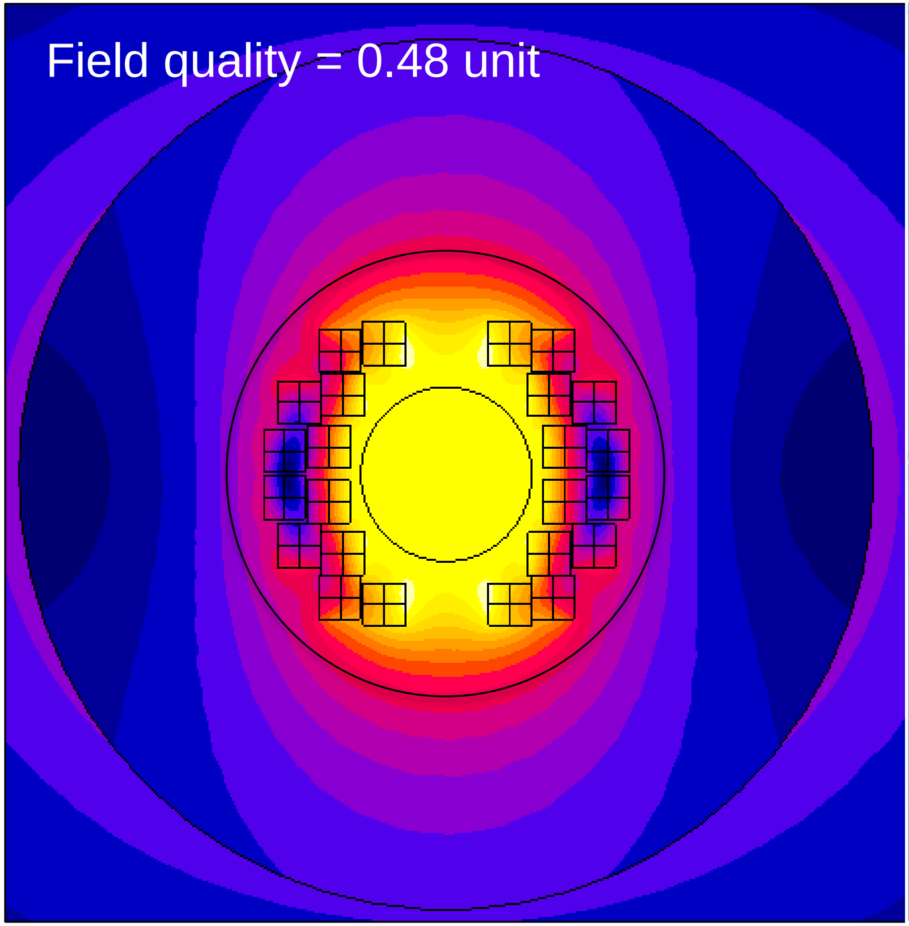
0.48*10 $^{-4}B_0$

Current density J_e

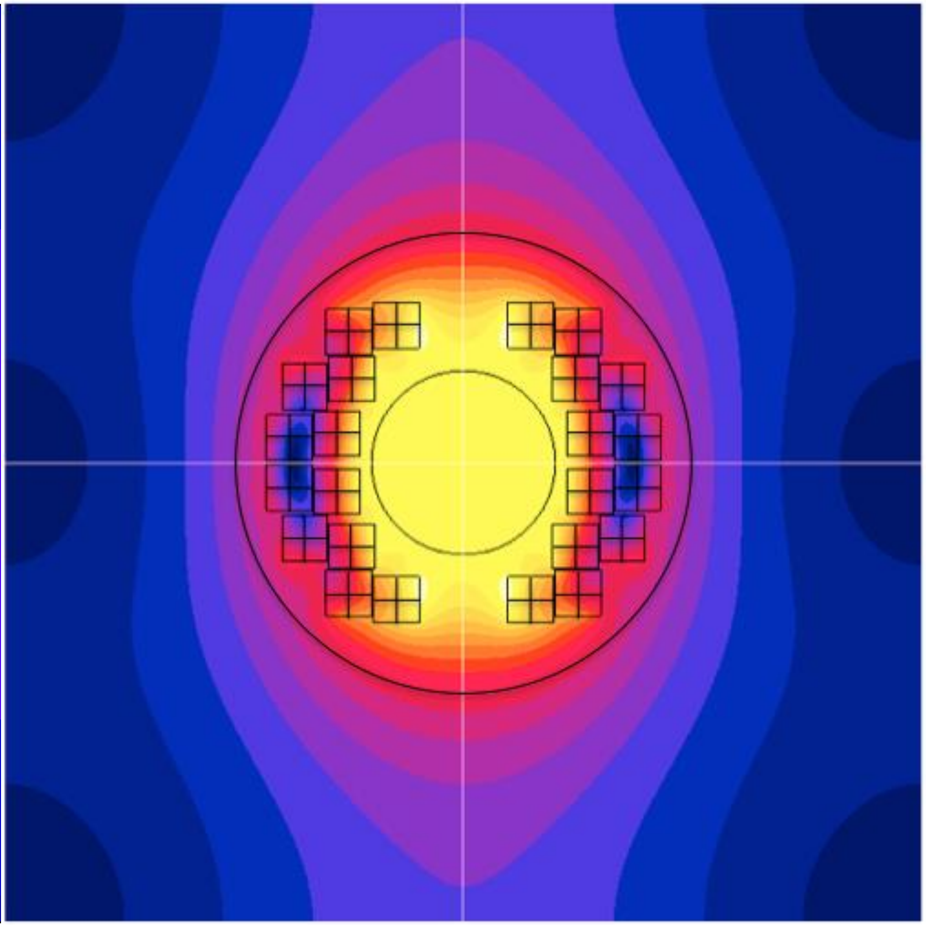
397 A/mm^2

First optimized magnet design

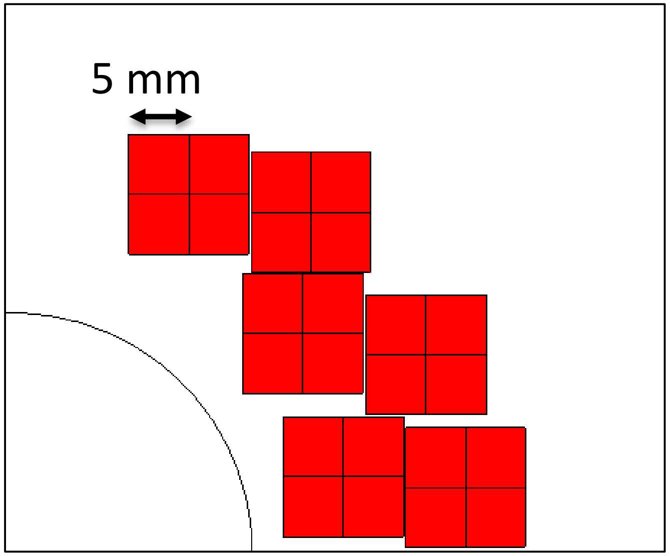
Round outer iron yoke



Rectangular outer iron yoke (Fresca II)



First optimized magnet design : comments



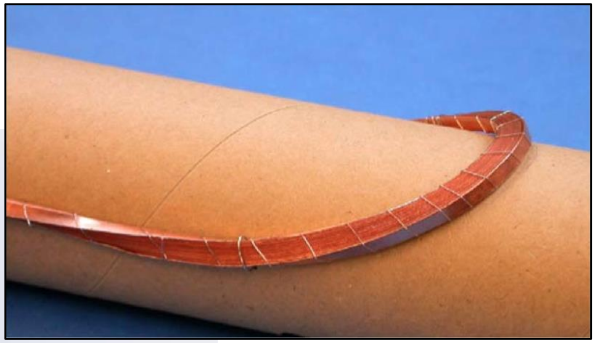
Current density J_e = 400 A/mm²

Iop = 10 kA fro a 5 x 5 mm cable

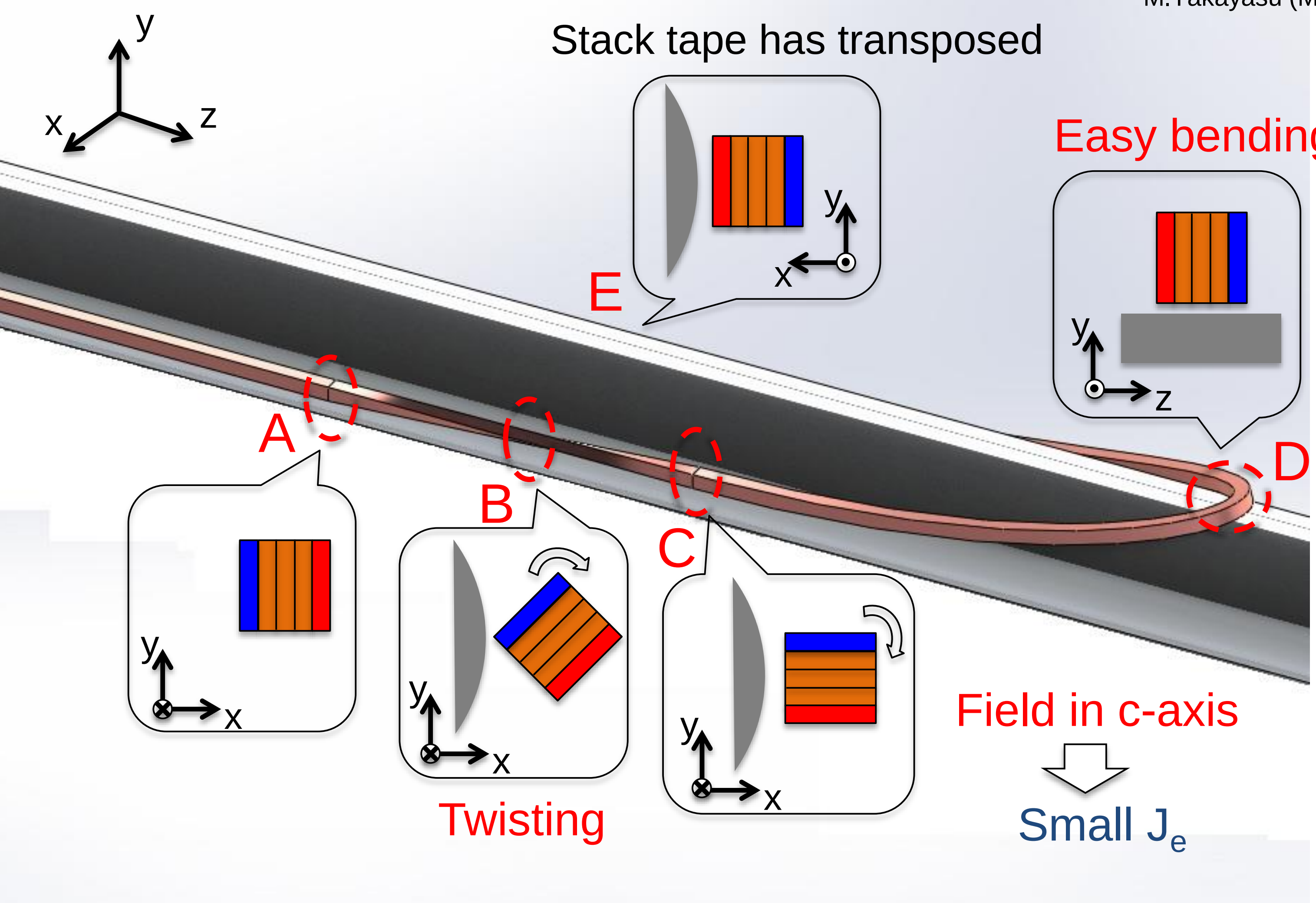
Is it necessary ? If not we can go to smaller cables : 3,5 x 3,5 => 5 kA

- Significant decrease in Je compared to designs with less blocks : room for manoeuvre (larger margins, more stabilizer, reinforcement)
- Blocks may be tilted to follow field lines
- How is bending going at the heads ? Better if the width is small
- Transposition is a problem : where do we twist and what does it change ?

Stacked cable twisting



M.Takayasu (MIT), IEEE vol.23 No.3 2013

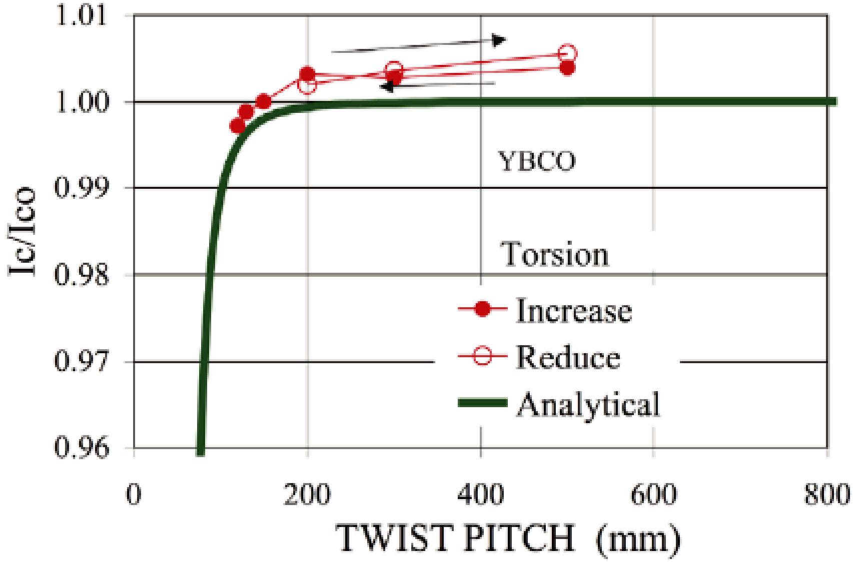


Twisted stack cable issues

- Twisting generate strain
- Part of the cable is fully in c-axis orientation
- Twist occurs one time per turn
- Twisting is not a full transposition

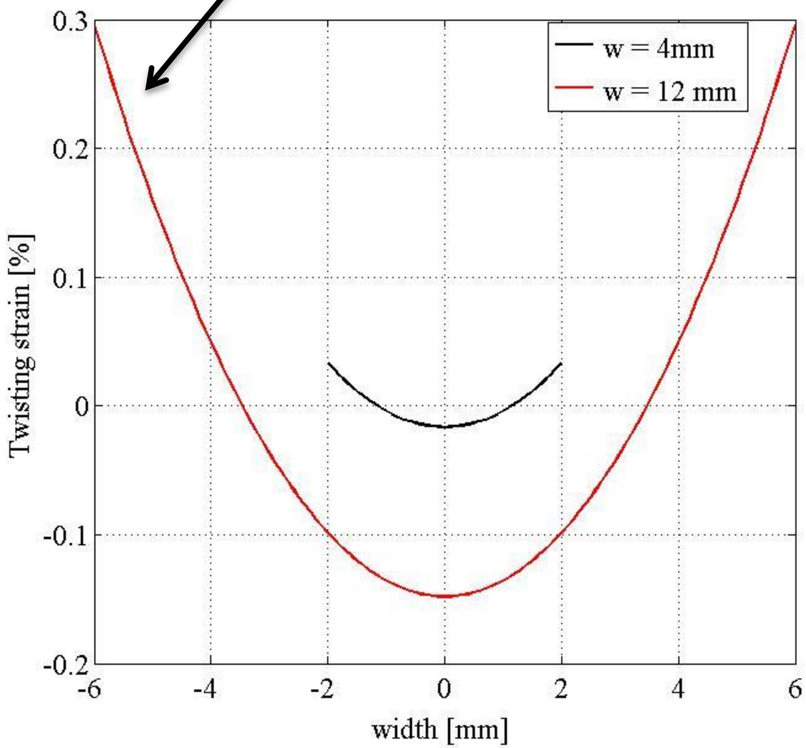
Twist stack cable issues

- Twisting generate strain



M Takayasu et al, Supercond. Sci. Technol. **25** (2012)

Mechanical strain is already large and reaching critical strain 0.33 %.



Twisting pitch = 100 mm, Twisting angle = 90º

It seems managable (small widths better)

Twist stack cable issues

- Part of the cable is fully in c-axis orientation

⇨ 3D study of coil ends is needed to evaluate the local field value (ongoing)

The combination of outsert and insert field can be optimized,

The coil ends of each must not be at the same position. The possibility of an insert longer than the outsert will be studied

Finally, transverse field may be acceptable if Je stays in the range of 400 A/mm^2

Twist stack cable issues

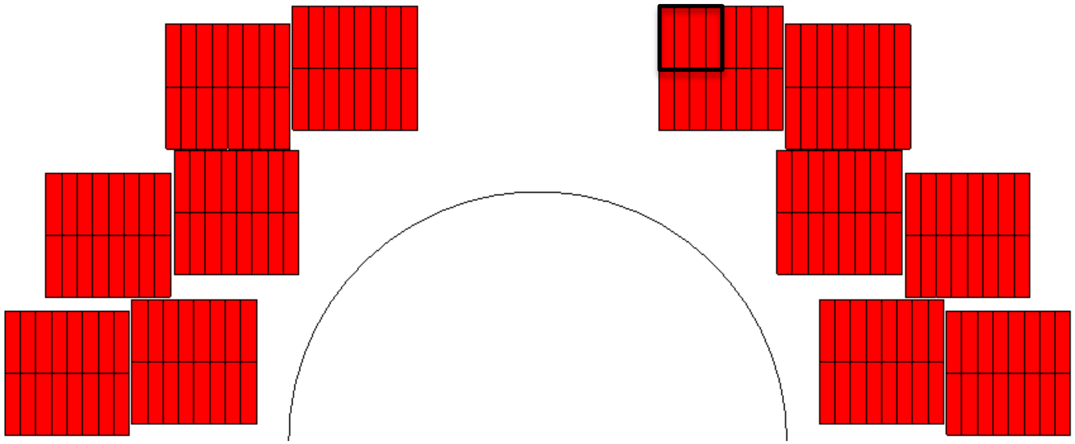
- Twist occurs only one time per turn
- Twisting is not a full transposition

The current distribution in the cable must be studied, with its impact on field homogeneity and losses.

AC losses in CC are largely studied for power applications, and some design tools are available. Behavior in slowly varying high field are well none in principle, but practically evaluating the effects is a challenge.

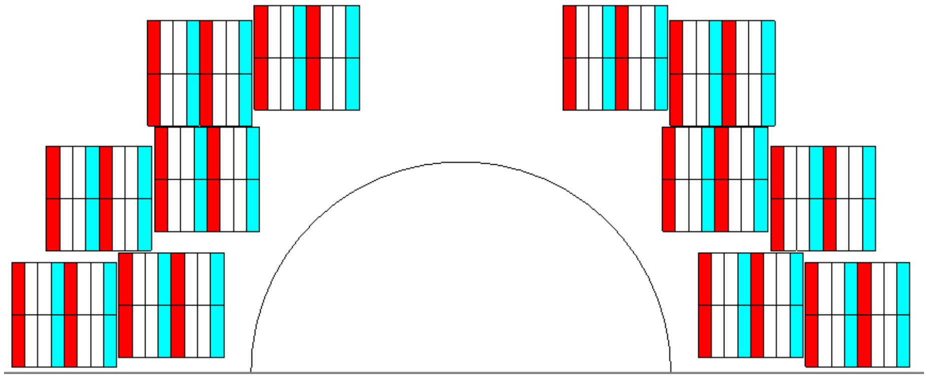
Especially, experiments are needed to validate the modelling

Current transposition effect : First evaluation

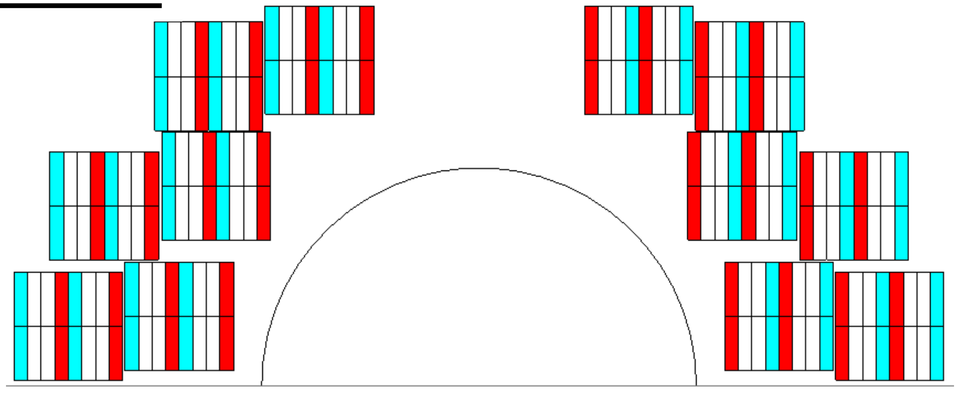


2D simulations in AC…
With copper !

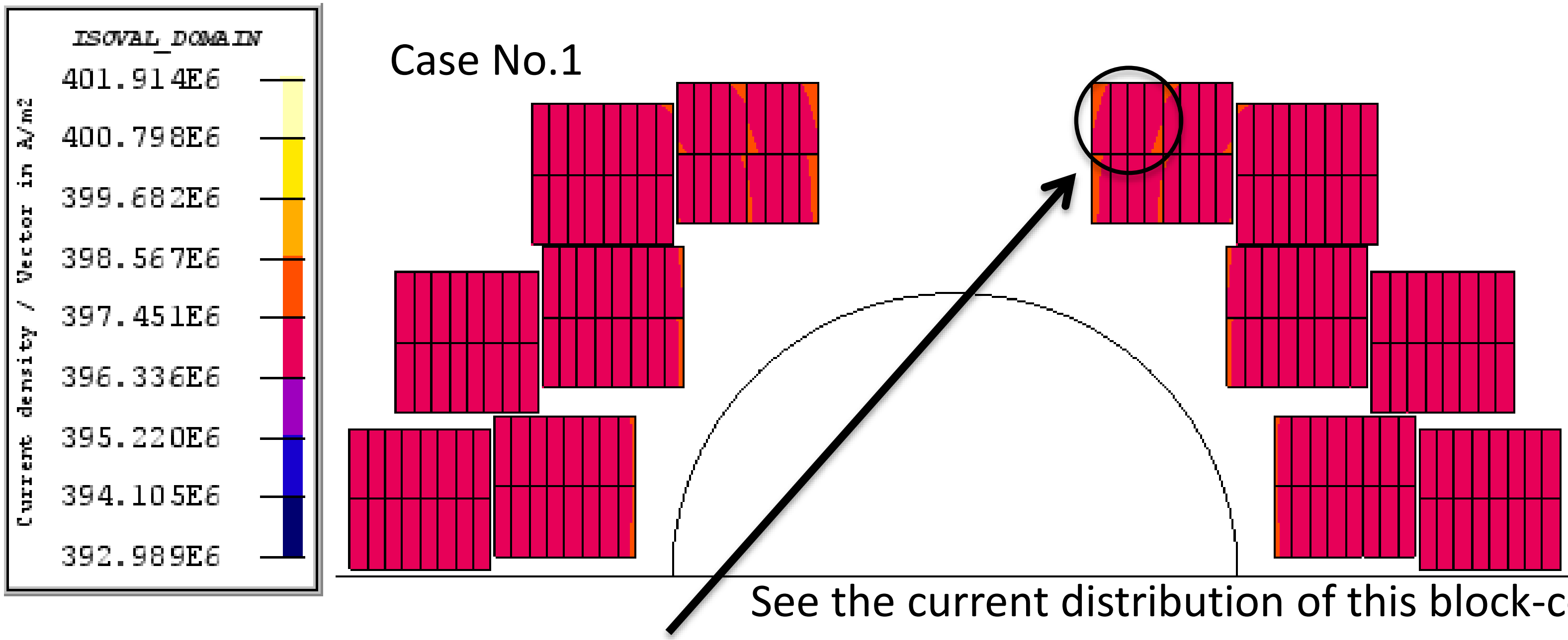
CT



Not CT

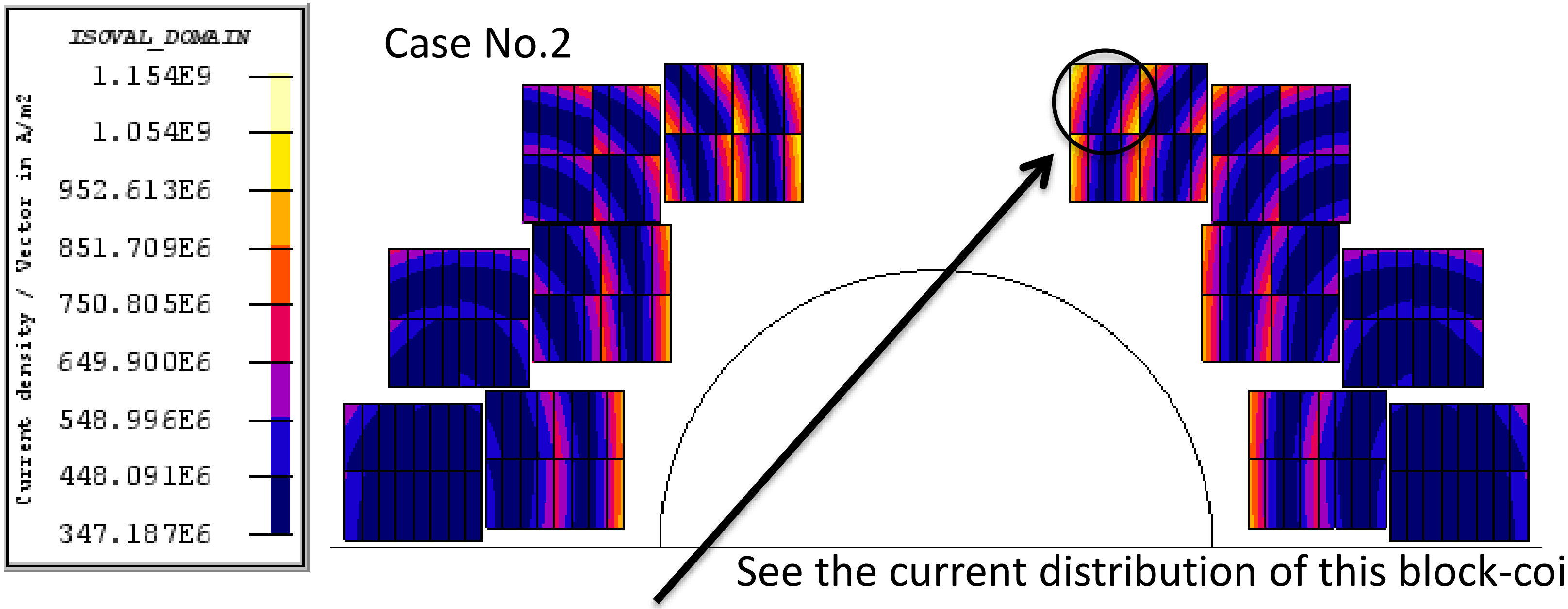


No Current transposition



Case No.	Current distribution				Field quality $10^{-4}*B_0$
	1	2	3	4	
1	25 %	25 %	25 %	25 %	0.48
2	29.6%	26.9%	22.9%	20.6%	2.2945
3	35.1%	28.5%	20.3%	15.4%	5
4	50.9%	35.6%	13.1%	0.4%	13.1

No Current transposition



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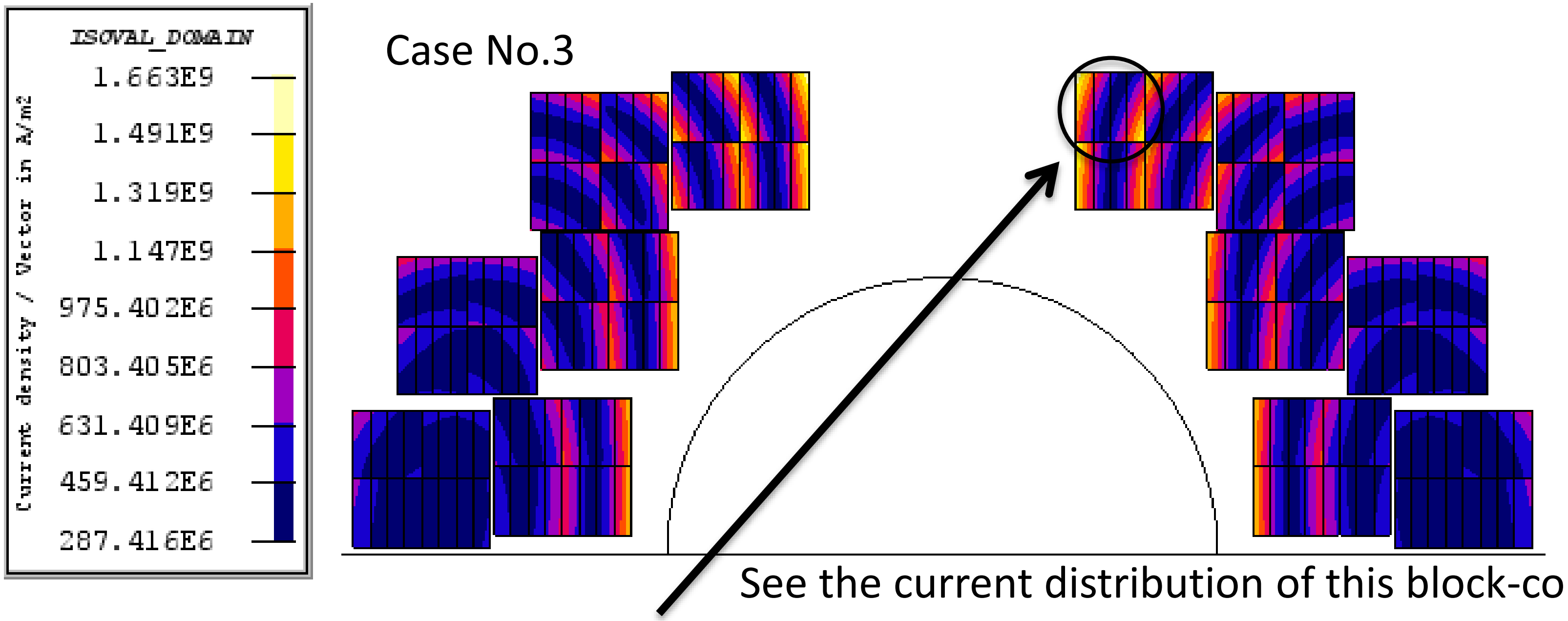
3	35.1%	28.5%	20.3%	15.4%	5
4	50.9%	35.6%	13.1%	0.4%	13.1

No Current transposition



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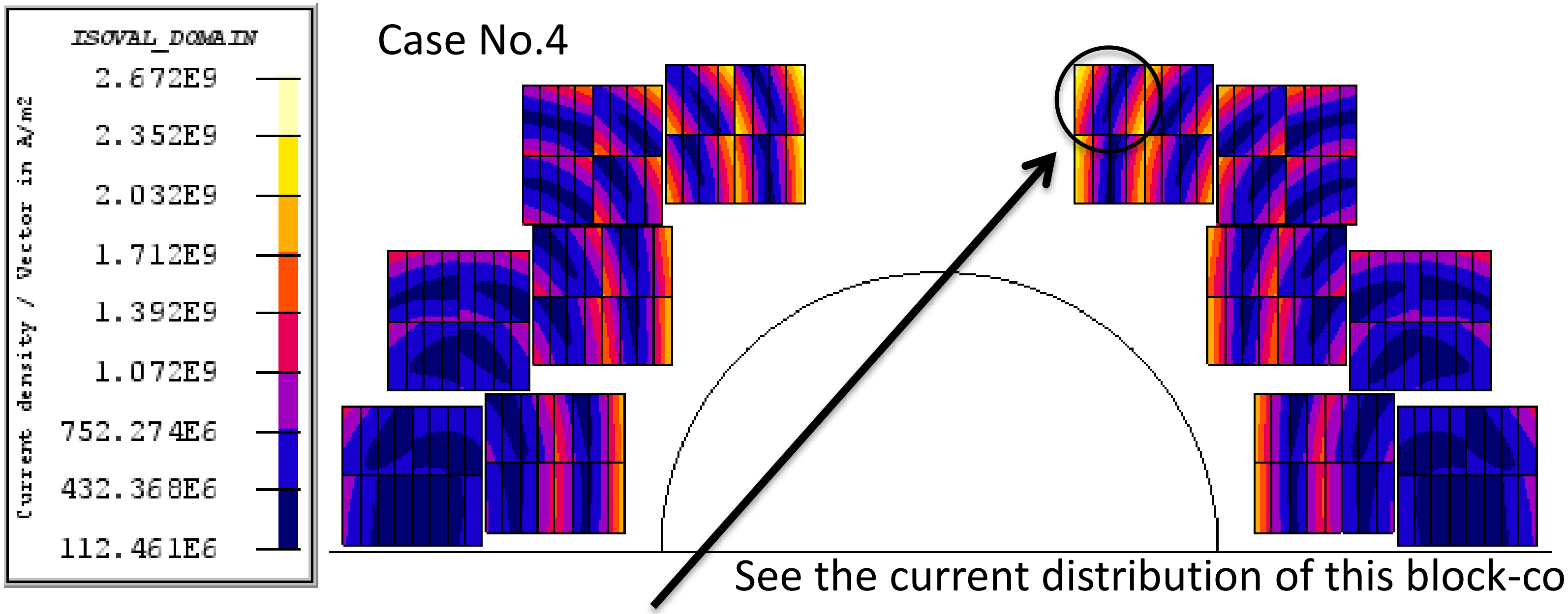

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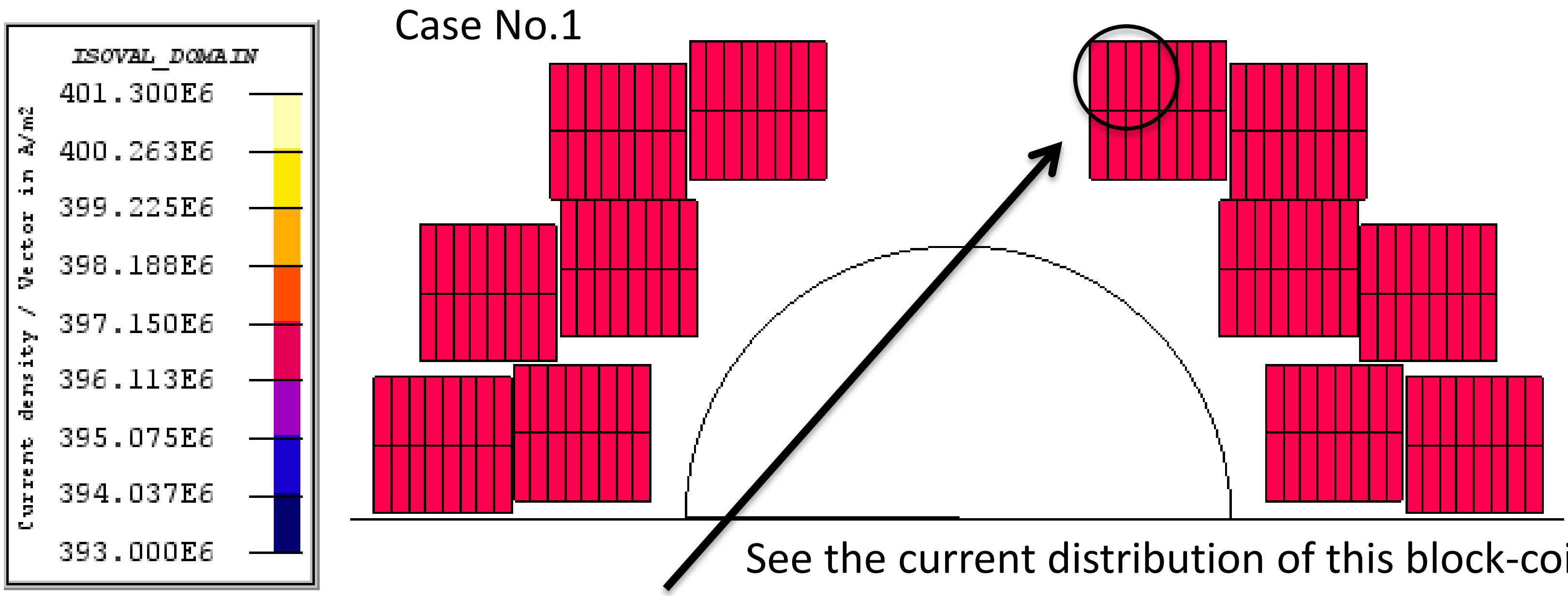
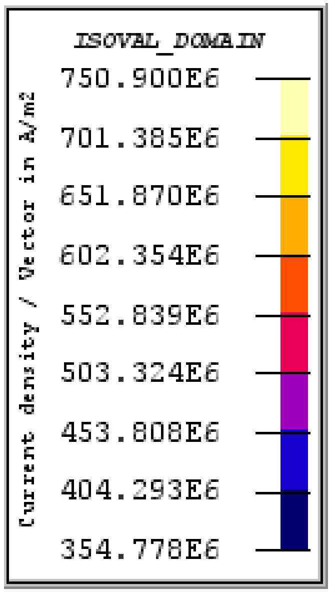
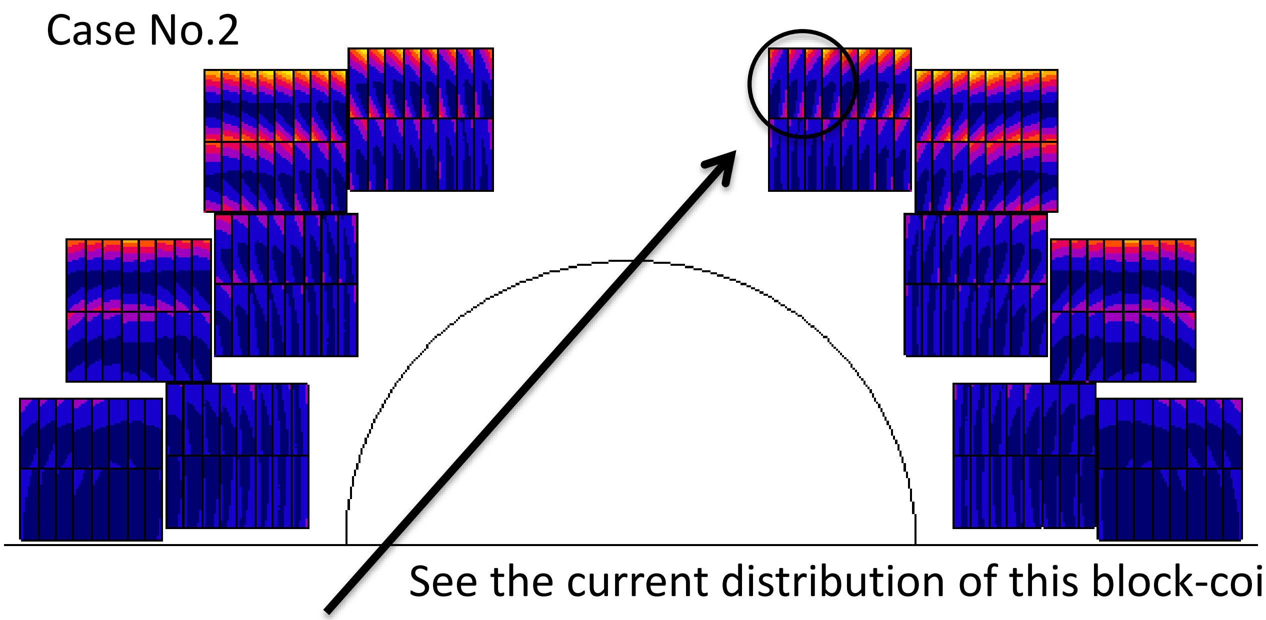
With Current transposition



Case No.	Current distribution				Field quality $10^{-4}*B_0$
	1	2	3	4	
1	25 %	25 %	25 %	25 %	0.48
2	25.1%	24.9%	24.9%	25.1%	0.48
3	25.1%	24.9%	24.9%	25.1%	0.48
4	26.4%	23.6%	23.6%	26.4%	5.8

With Current transposition





Case No.	Current distribution				Field quality $10^{-4}*B_0$
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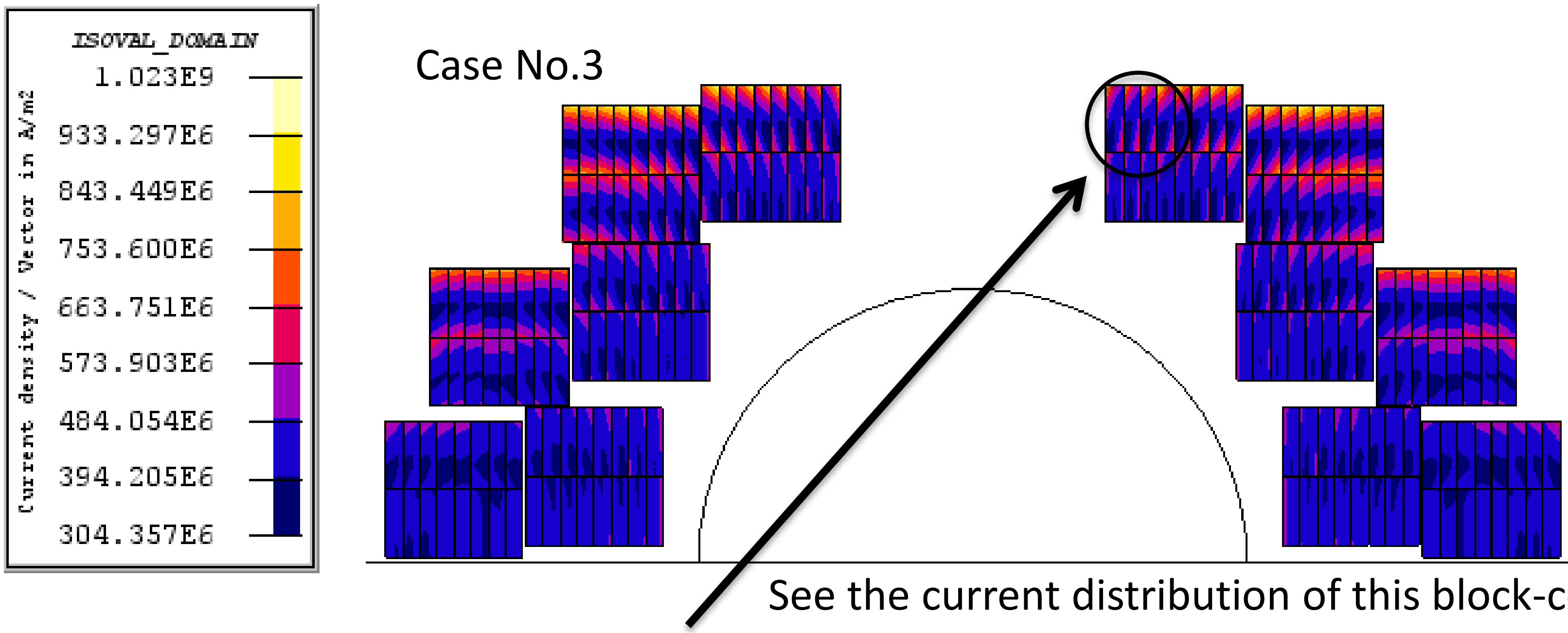
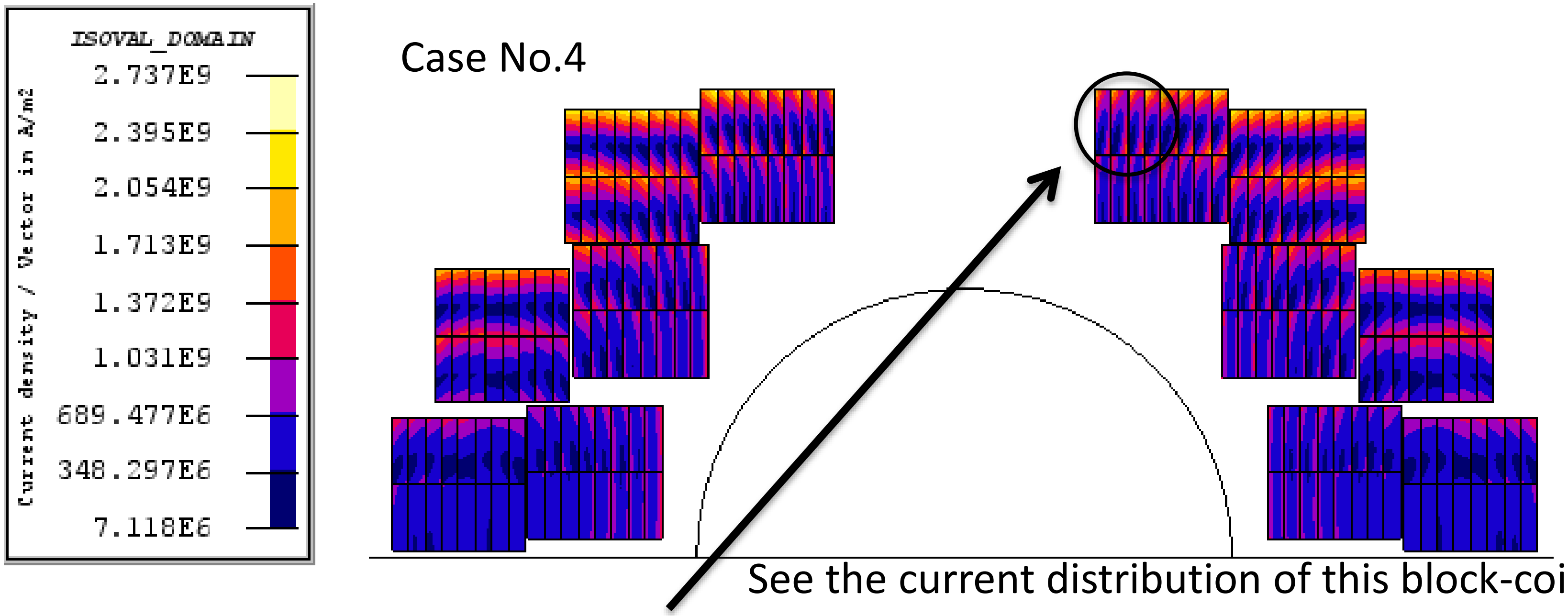
With Current transposition



See the current distribution of this block-coil

Case No.	Current distribution				Field quality $10^{-4}*B_0$
	1	2	3	4	
1	25 %	25 %	25 %	25 %	0.48
2	25.1%	24.9%	24.9%	25.1%	0.48
3	25.1%	24.9%	24.9%	25.1%	0.48
4	26.4%	23.6%	23.6%	26.4%	5.8

With Current transposition



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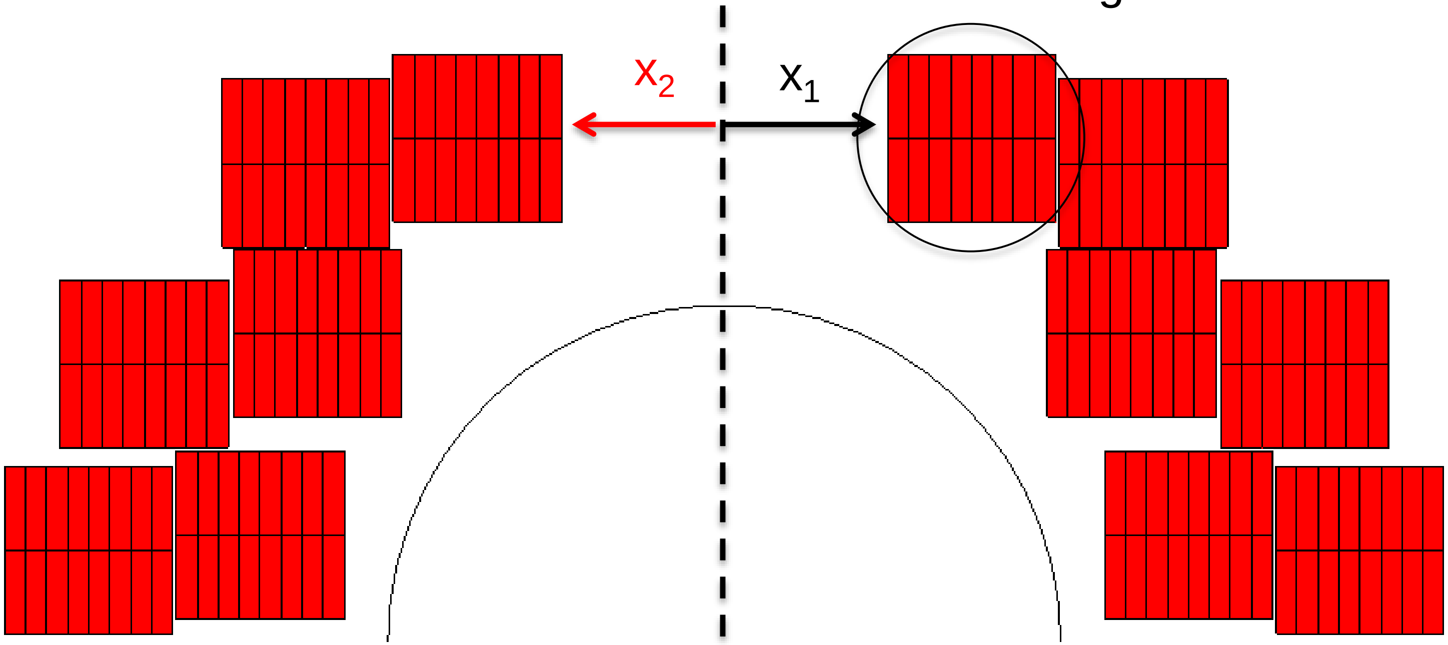
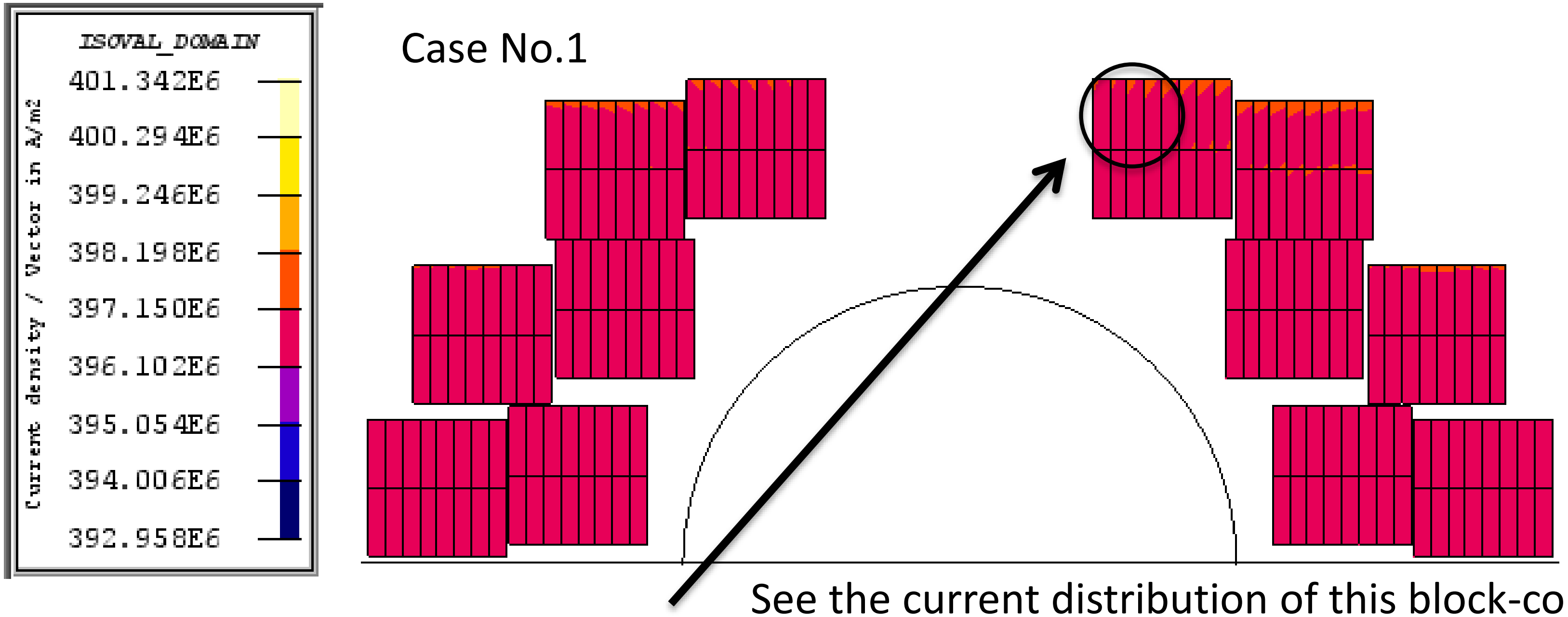
4	26.4%	23.6%	23.6%	26.4%	5.8

Current transposition – sensibility to displacement

Moving 4 block-coils for 0.1 mm

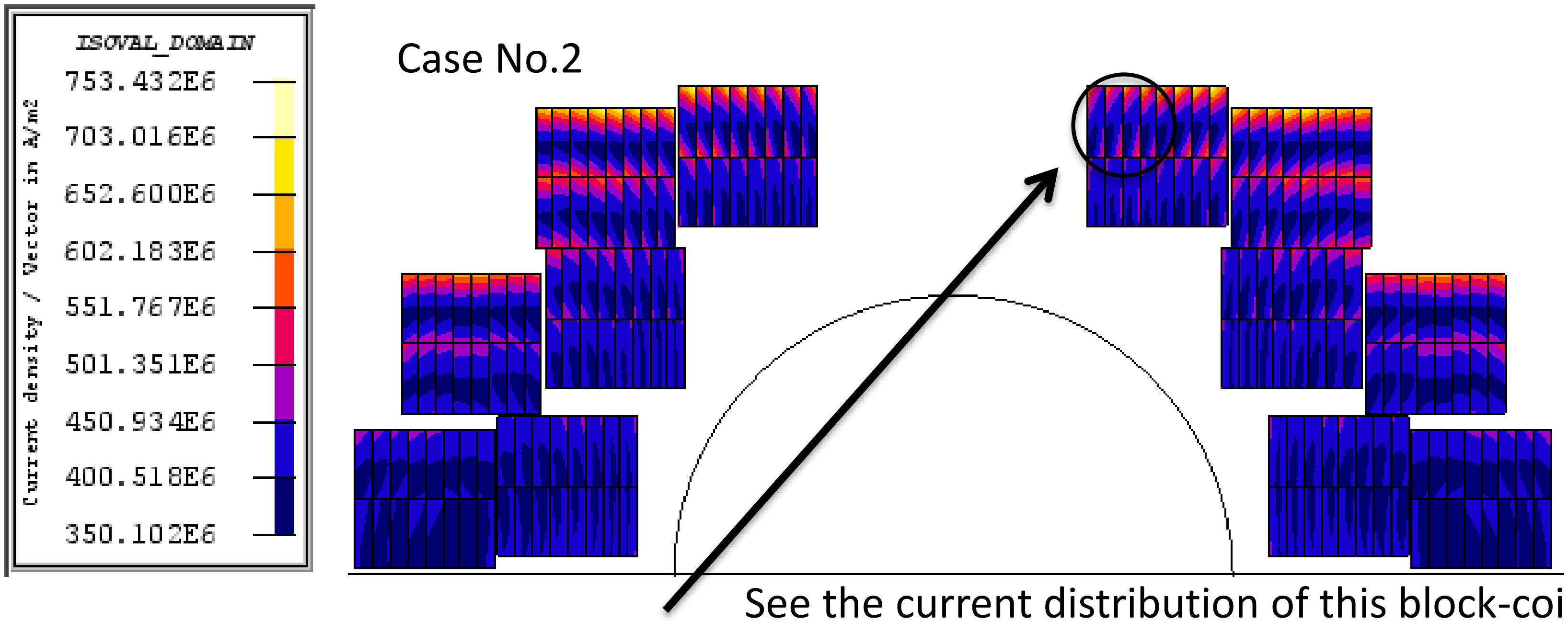


Current transposition – sensibility to displacement



Case No.	Current distribution				Field quality $10^{-4}*B_0$	Field quality (aligned)
	1	2	3	4		
1	25 %	25 %	25 %	25 %	0.48	0.48
2	25.1%	24.9%	24.9%	25.1%	2.69	0.48
3	25.1%	24.9%	24.9%	25.1%	2.93	0.48

Current transposition – sensibility to displacement



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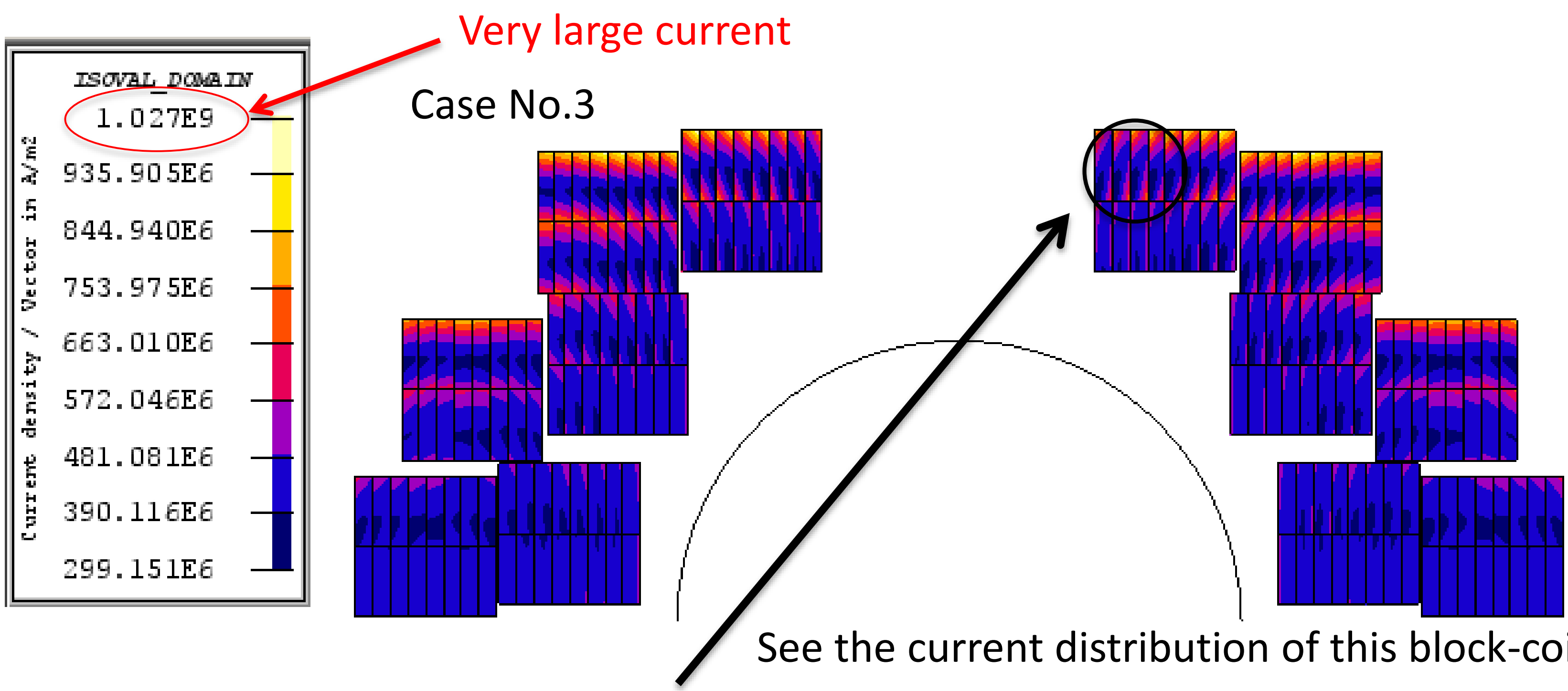
2	25.1%	24.9%	24.9%	25.1%	2.69	0.48
3	25.1%	24.9%	24.9%	25.1%	2.93	0.48

Current transposition – sensibility to displacement



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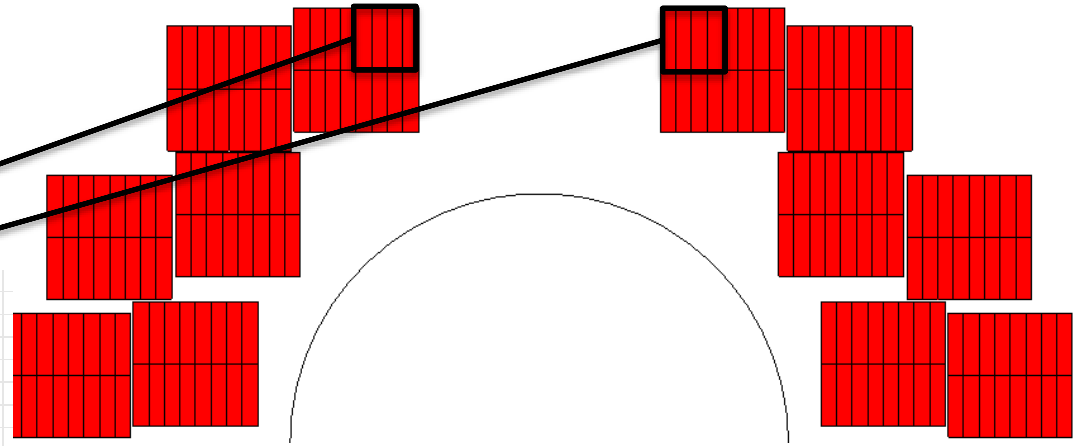
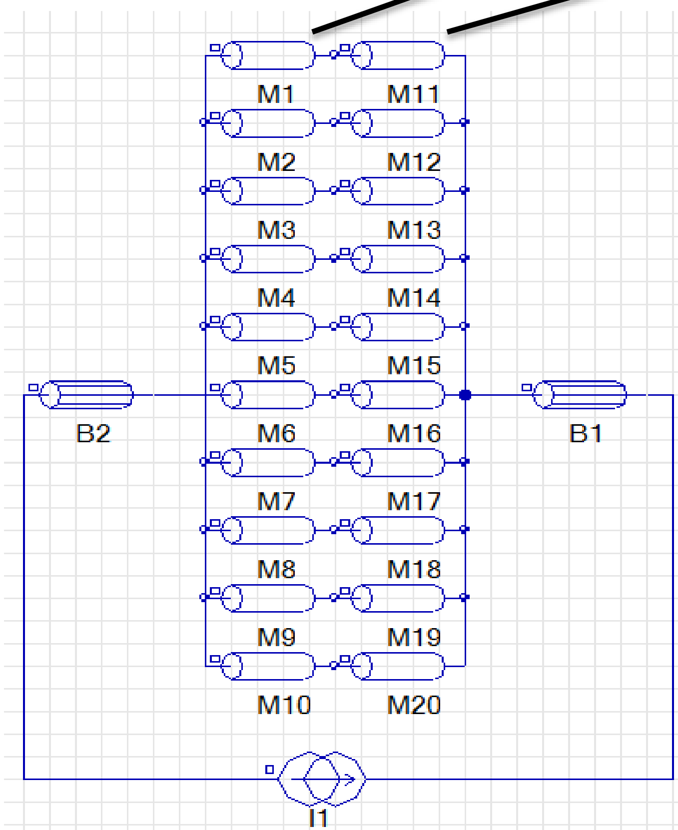
3	25.1%	24.9%	24.9%	25.1%	2.93	0.48

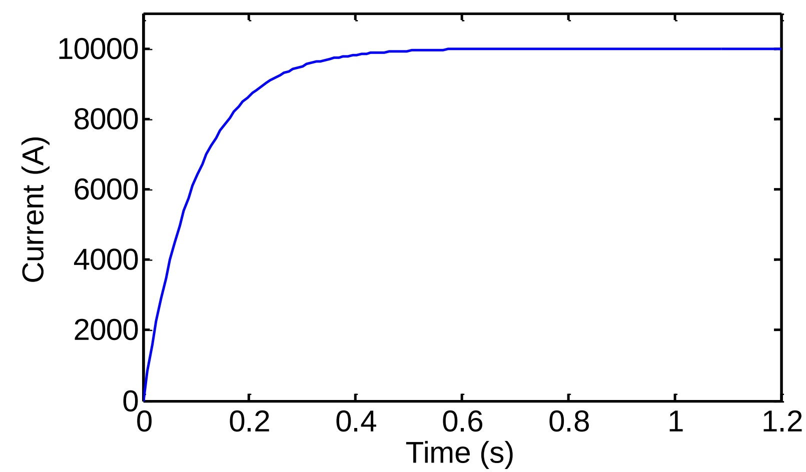
Current transposition effect : 2nd try

2D simulations in transient with supercond. described by power law

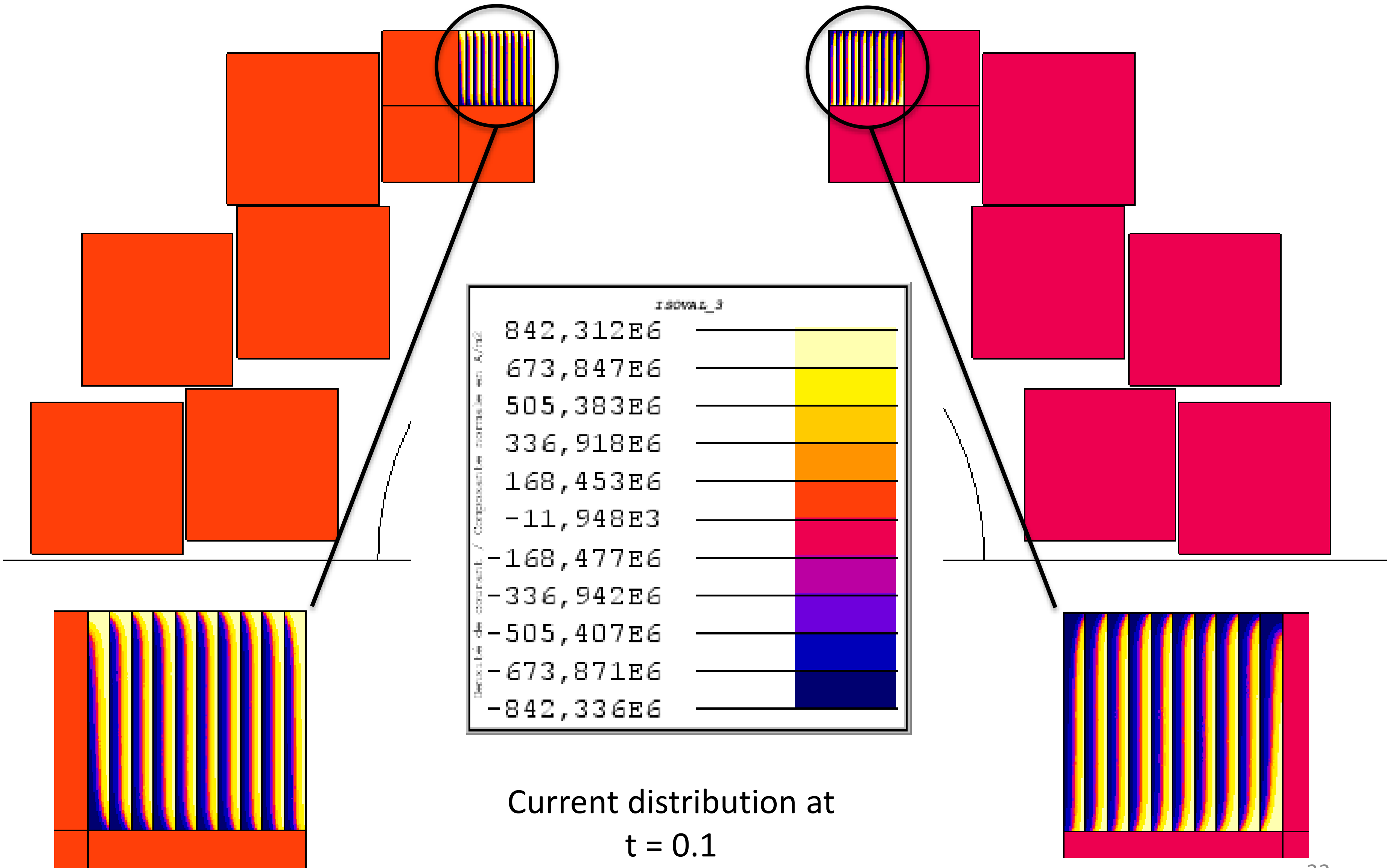
Flux software





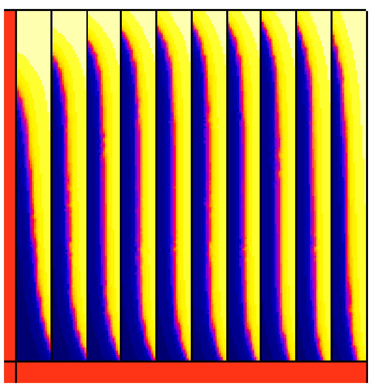
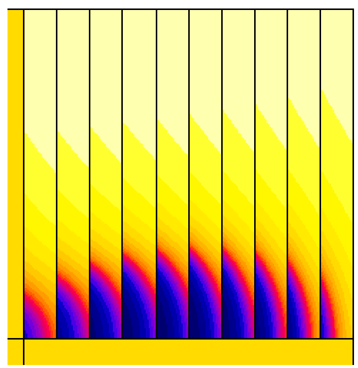
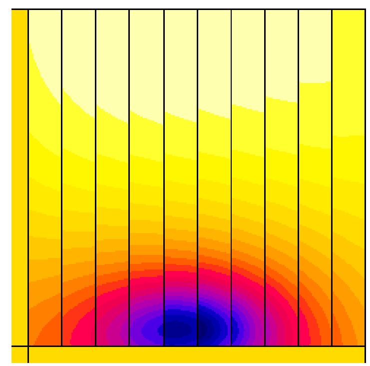
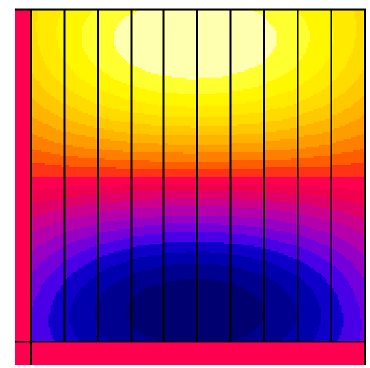


Current transposition effect : upper blocks



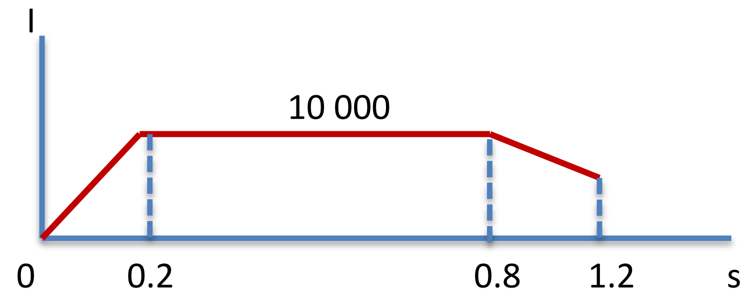
Current distribution at
t = 0.1

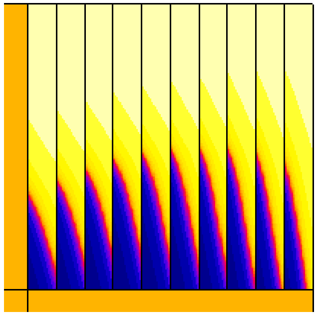
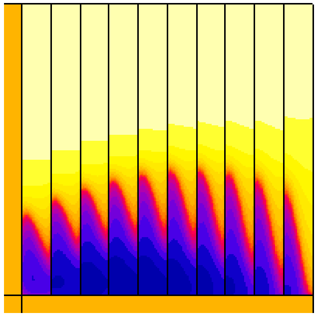
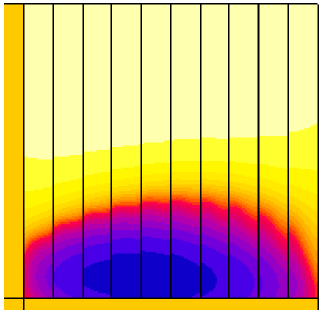
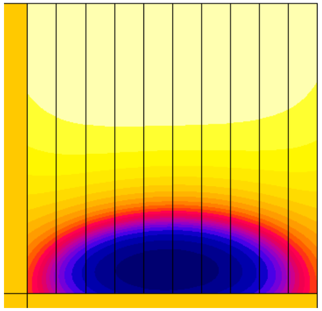
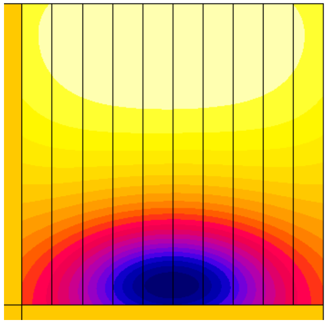
Transposition effect on current density

t = 0.15	t = 0.3	t=0.6	t=1.2
I = 7700 A	I = 9500 A	I = 9975 A	I = 10 000 A
THD = 4.961 660 A/mm^2  -647	THD = 4.836 578 A/mm^2  -396	THD = 1.46 466 A/mm^2  147	THD = 0.49 403 A/mm^2  396

Transposition effect on current density

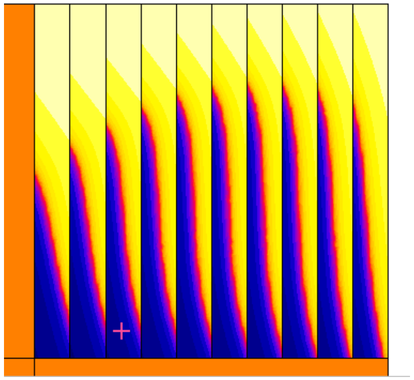
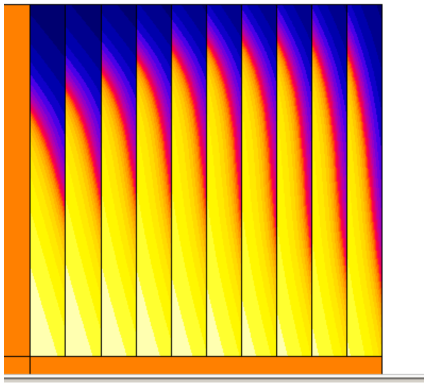
Current density homogenization
on plateau



t = 0.2	t = 0.205	t=0.23	t=0.4	t=0.8
I = 10 000 A	I = 10 000 A	I = 10 000 A	I = 10 000 A	I = 10 000 A
936 A/mm^2  - 936	883 A/mm^2  - 714	797 A/mm^2  -574	640 A/mm^2  - 297	512 A/mm^2  76

Transposition effect on current density

Cycling :

t = 0.1	t = 1.2
I = 5000 A	I = 5000 A
916 A/mm²  - 861	745 A/mm²  - 761

Limitations to this work

- The power law considered has constant Jc = 700 A/mm², and n values = 20
  Beside, the timeframe is not practical (J is during a time at 120 % Jc)
- Conventional $E=Ec(J/Jc)^n$ leads to a paradox : uniform J in steady state !
- Flux2D good current-conserving formulation is not implemented in 3D
- Tapes are considered uniform SC 0.5mm thick, instead of thin-film multi-layers
- Tapes are considered isolated (high R interface) , it may not be ideal.
  if it is not the case, non-uniformity damping wil be much longer.

➡ In order to continue, we need some experimental data !

Some experiments on single tapes are to be done in June (small bore) :
test power law models

We applied for magnet time at LNCMI-Grenoble in 280 mm cold bore to perform tests of stack cable in field varying spatially and temporally

Conclusion

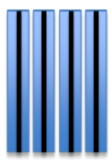
A wide range of studies must be conducted, from magnet to cable, back and forth

- Mechanical stress calculations, at the magnet and cable scale
- Quench modelling and protection development : effect on the range of Iop
- Twisting effect on field distribution and field orientation in the coil heads

Some conclusions can be drawn :

- An insert reaching the requirement can be made with Je = 400 A/mm^2, knowing that the lower value for perfect cos-theta is 340 A/mm^2.

- Twisted stack cable offers impressive advantages, the key issue is current distribution : increase the resistance between tapes may be a solution, some solutions can be found on the magnet side (ramping the insert first?)



- We can at least consider continuously twisted stack :
  Current density in the tapes reaches 620 A/mm^2 but the surface is not lost