

Magnetic Designs for Higher Margin

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Approach to Improve Performance

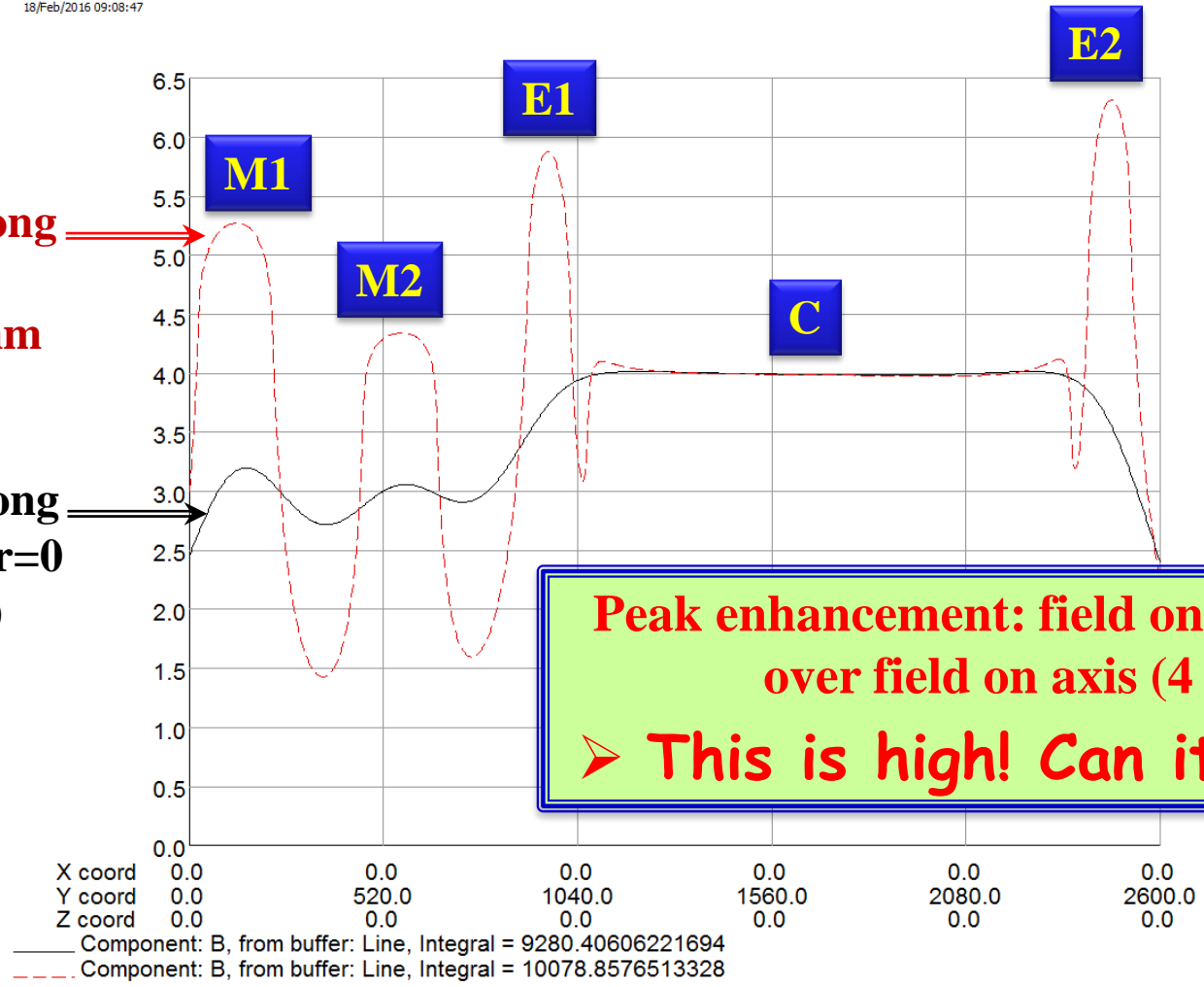
- **Increase margin. However, by making minimum necessary changes in the overall design concept.**
- **Only adjust E1, C and E2. No change in M1 and M2.**
- **Starting suggestion: Increase margin by putting more layers of conductor (less current to produce the same field).**
- **However, investigations of the existing design gave a possibility of a better alternate way to proceed.**

Axial and Peak Fields in Mice Spectrometer Solenoid

18/Feb/2016 09:08:47

**Field along
the line
r=258 mm
(coil id)**

**Field along
the line r=0
(axis)**



UNITS	
Length	mm
Magn Flux Density	T
Magn Field	A m ⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m ⁻¹
Elec Flux Density	C m ⁻²
Elec Field	V m ⁻¹
Conductivity	S m ⁻¹
Current Density	A mm ⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
5 conductors	

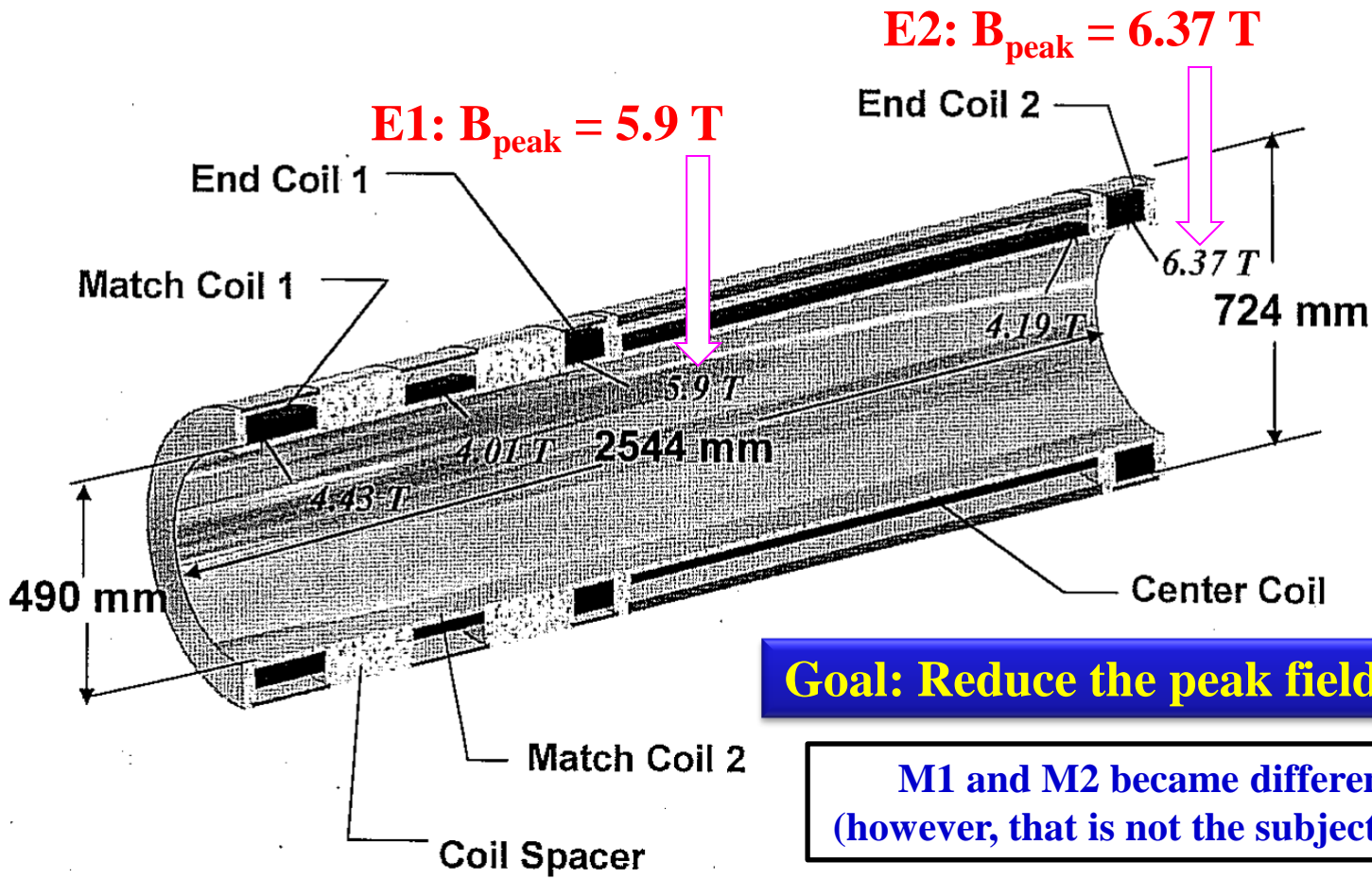
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE (nodal) 1001	Cartesian
x=258.0	y=0.0 to 2600.0 z=0.0

Peak enhancement: field on conductor (6.3 T)
 over field on axis (4 T) > 55%.
 ➤ This is high! Can it be reduced?

Original Design

Tracker Solenoid Peak Field



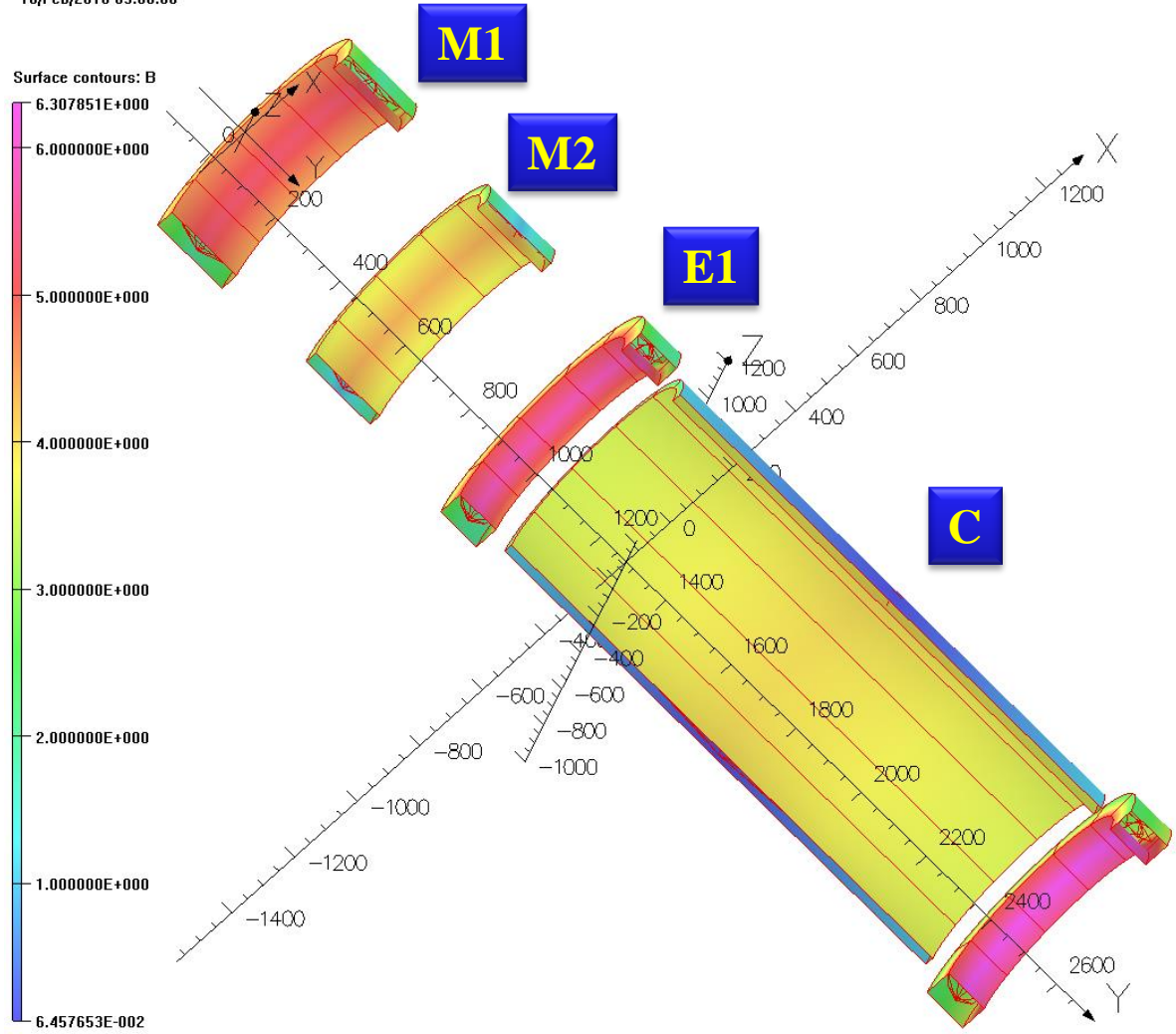
Goal: Reduce the peak fields in E1 and E2

M1 and M2 became different in 2008 design
(however, that is not the subject of the present task)

Cutaway View Showing Field on the surface of all coils (inside view)

18/Feb/2016 09:00:00

6.3T



UNITS	
Length	mm
Magn Flux Density	T
Magn Field	A m ⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m ⁻¹
Elec Flux Density	C m ⁻²
Elec Field	V m ⁻¹
Conductivity	S m ⁻¹
Current Density	A mm ⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
5 conductors	

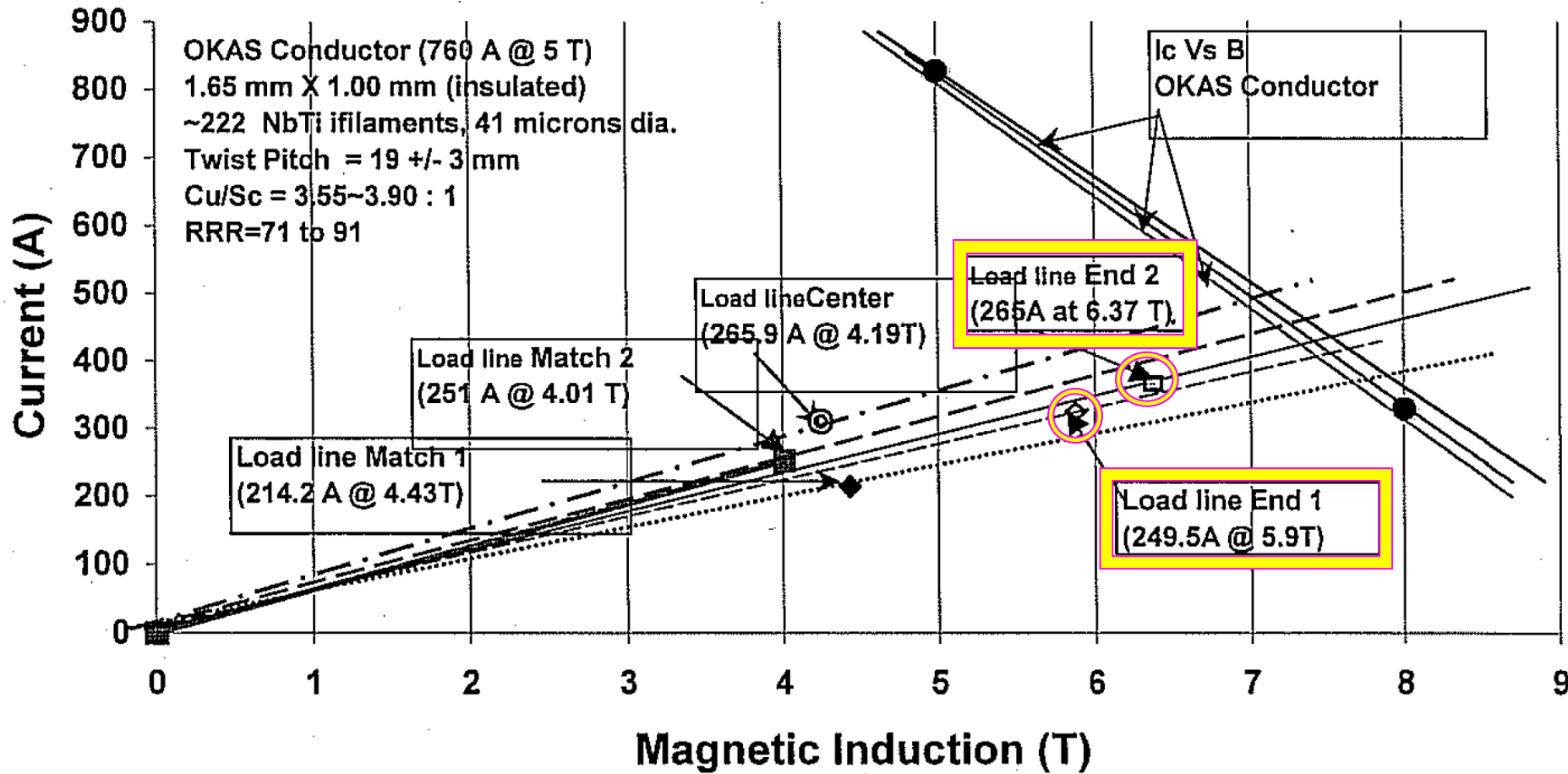
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS		
Line LINE (nodal) 1001	Cartesian	
x=258.0	y=0.0 to 2600.0	z=0.0

Opera

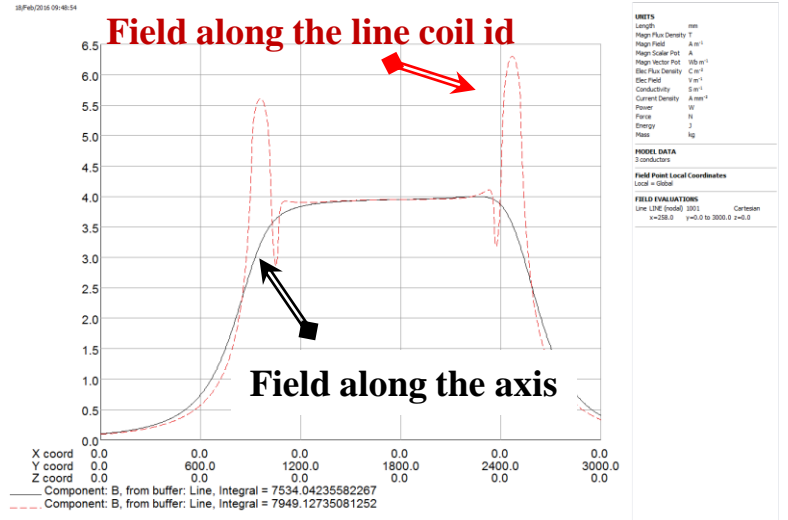
Task : Small Changes in the Design to Increase Margin of "E1" and "E2"

Design Tracker Magnet Load Lines and I_c Versus B for OKAS Superconductor

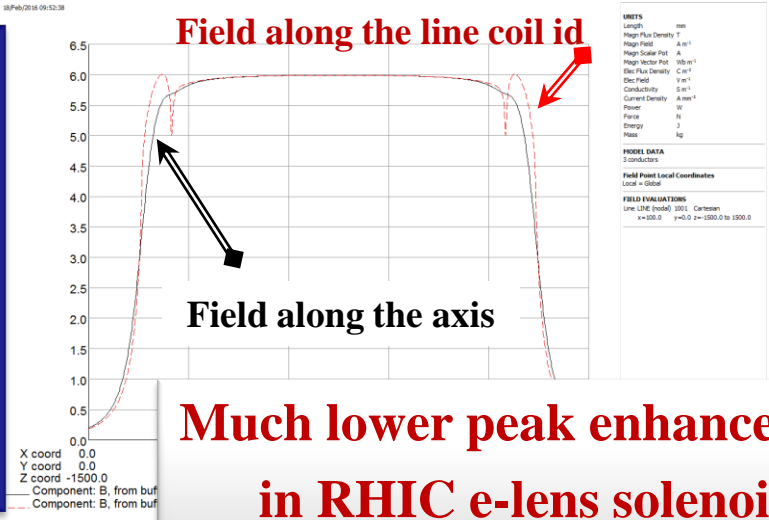


Mice Solenoid Coils E1, C and E2 and RHIC e-lens Solenoid (Main & Trim)

MICE Spectrometer Solenoid

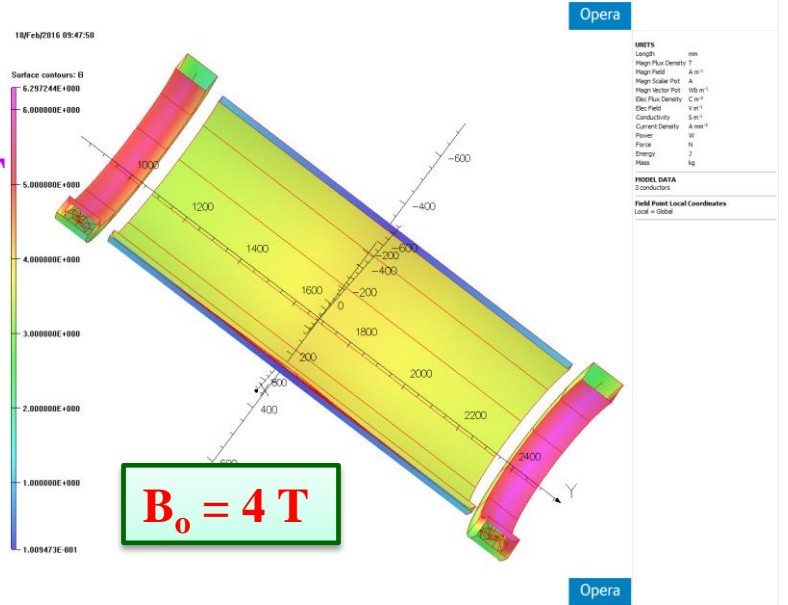


RHIC e-lens Solenoid

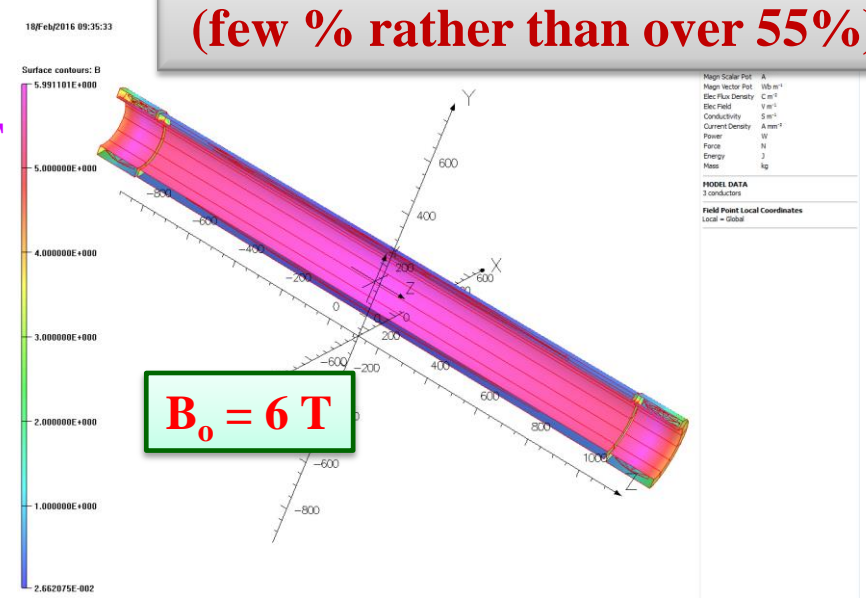


**Much lower peak enhancement
in RHIC e-lens solenoid
(few % rather than over 55%)**

6.3T



6.0T



Comparison between the designs of MICE and RHIC e-lens Solenoids

MICE Spectrometer Solenoid

$B_0 = 4 \text{ T}$

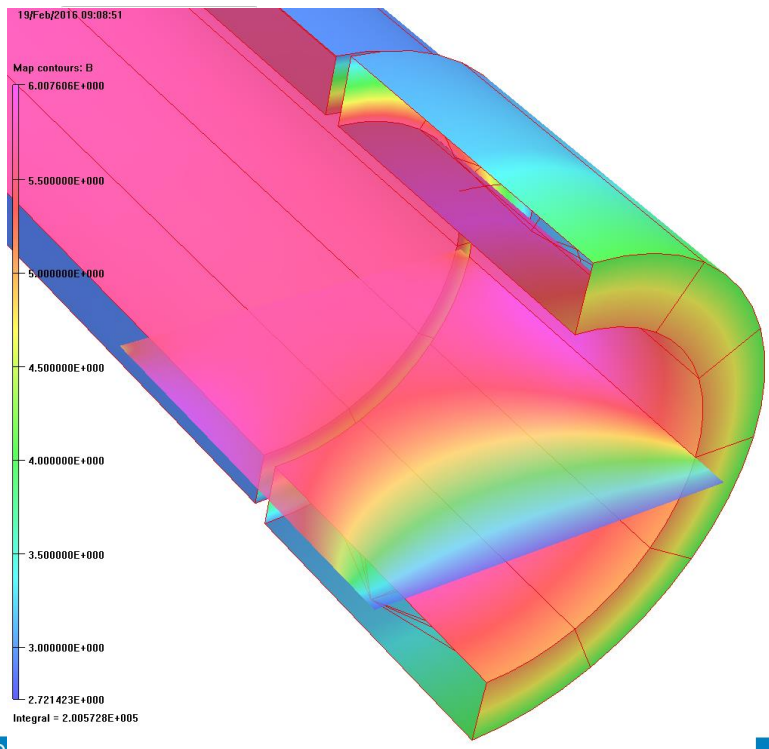
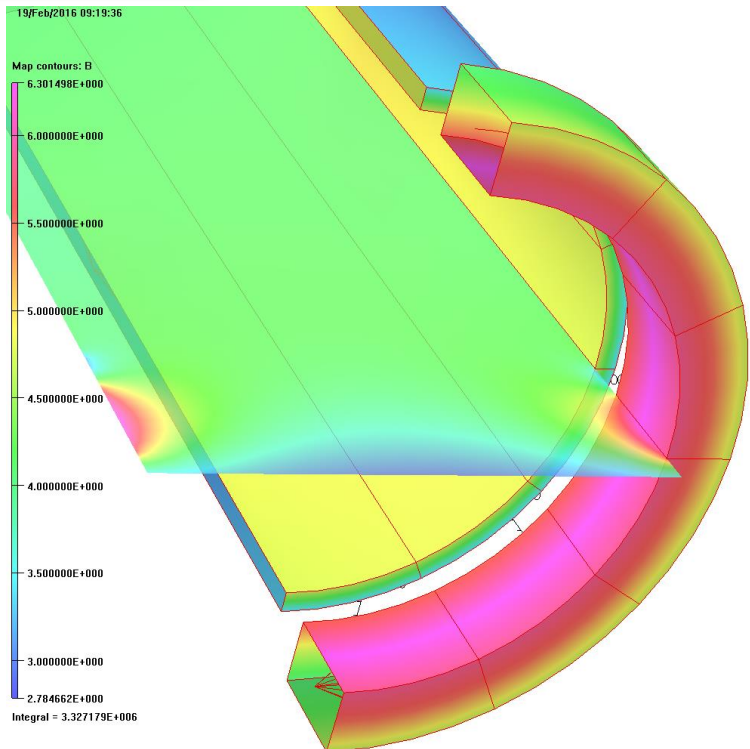
$B_{pk} = 6.3 \text{ T}$

Compare the end coil

RHIC e-lens Solenoid

$B_0 = 6 \text{ T}$

$B_{pk} = 6.0 \text{ T}$



UNITS	
Length	mm
Magn Flux Density	T
Magn Field	A m ⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Vb m ⁻¹
Elec Flux Density	C m ⁻²
Elec Field	V m ⁻¹
Conductivity	S m ⁻¹
Current Density	A mm ⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
3 conductors	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Cartesian	CARTESIAN 100x100 Cartesian (nodal)
x=	-100.0 to 100.0
y=	0.0 to 1200.0
z=	1000.0 to 1200.0
Line	LINE (nodal) 1001 Cartesian
x=	0.0
y=	0.0
z=	1200.0 to 1200.0

**Note: A major difference in the aspect ratio (length vs width)
Unfavorable aspect ratio increases peak field and stresses**

Optimization of New Design (Design 2)

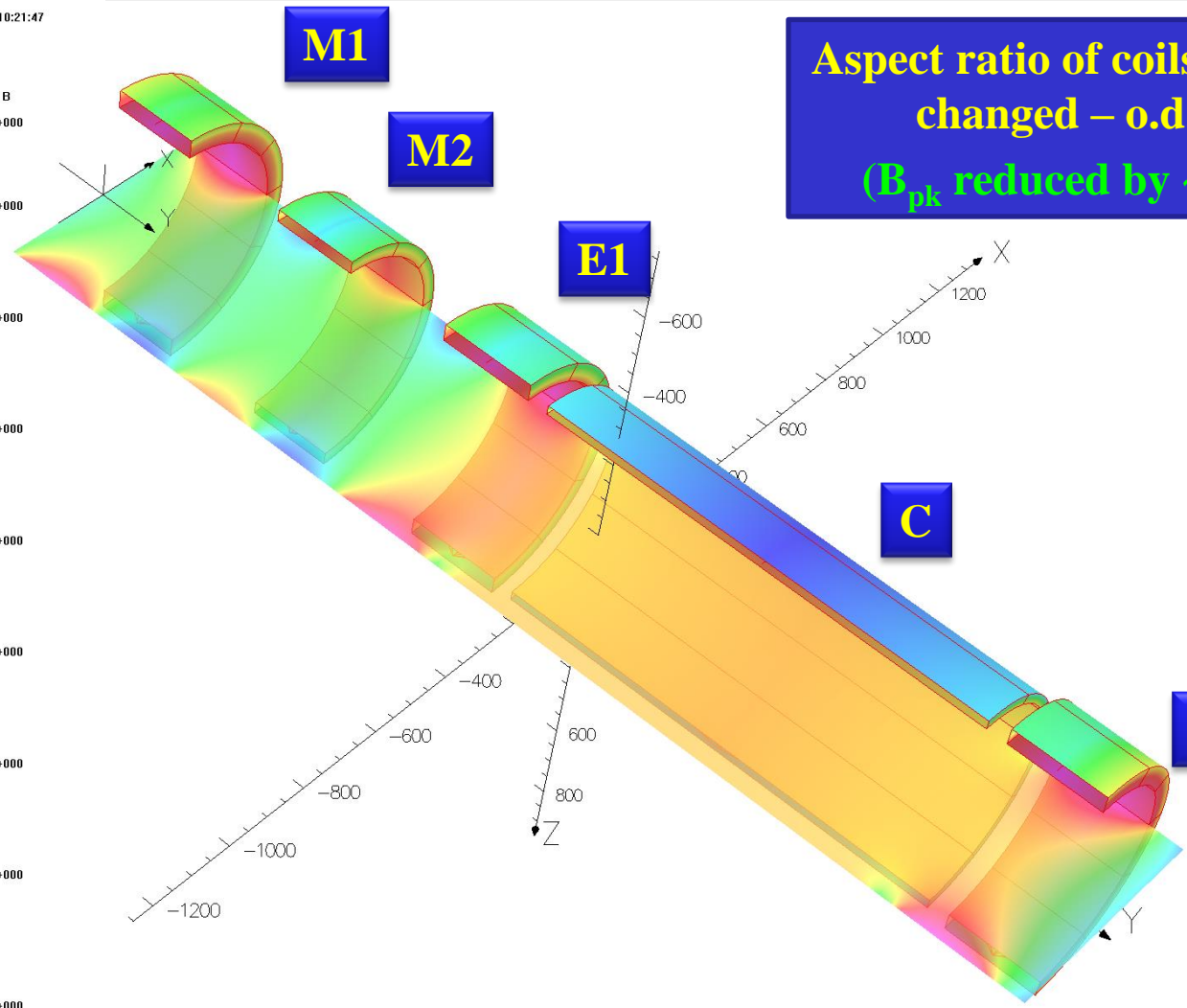
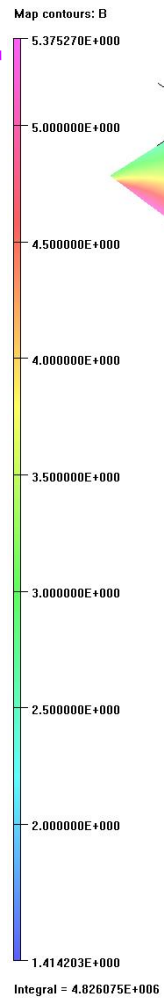
Guiding Principles:

- No change in the overall length of “E1” + “C” + “E2”
- No change the starting or end position of E1 and E2
- Change the aspect ratio of “E1” and “E2” by increasing their length (length of “C” reduces to satisfy the above restrictions).
- Several cases were examined. The chosen design has length of E1 and E2 increased by a factor of two. Width (number of layers) is adjusted to maintain the required field quality. Currents in C, E1 and E2 are also slightly tweaked. These can be adjusted more to further improve the field quality – both in the design and also to accommodate construction errors.

Reduced Peak Field Design of MICE Solenoid (Design 2)

23/Feb/2016 10:21:47

5.37 T



**Aspect ratio of coils E1, E2 and C
changed – o.d. reduced
(B_{pk} reduced by ~24% of B_0)**

MODEL DATA
5 conductors

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Line	LINE (nodal)	1001	Cartesian
	x=0.0	y=1075.0 to 2335.0	z=0.0
Cartesian	CARTESIAN (nodal)	100x100	Cartesian
	x=-258.0 to 258.0	y=0.0 to 2600.0	z=0.0

$B_0 = 4 T$

Opera

Reduction in Peak Fields (Original and Revised Designs)

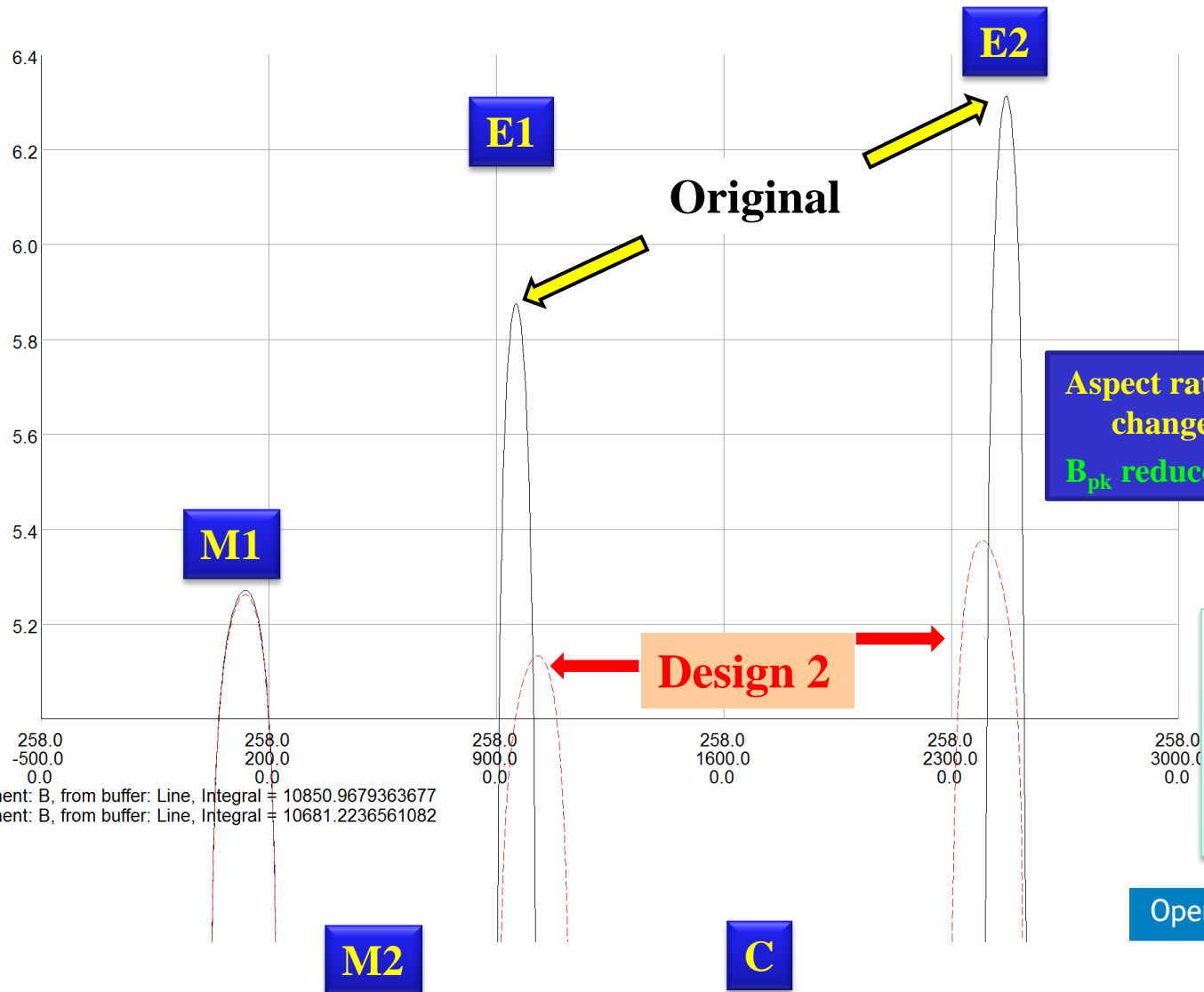
25/Mar/2016 09:54:25

UNITS	
Length	mm
Magn Flux Density	T
Magn Field	A m ⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m ⁻¹
Elec Flux Density	C m ⁻²
Elec Field	V m ⁻¹
Conductivity	S m ⁻¹
Current Density	A mm ⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
5 conductors	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE (modal) 1001	
Cartesian	
x=258.0 y=-500.0 to 3000.0 z=0.0	



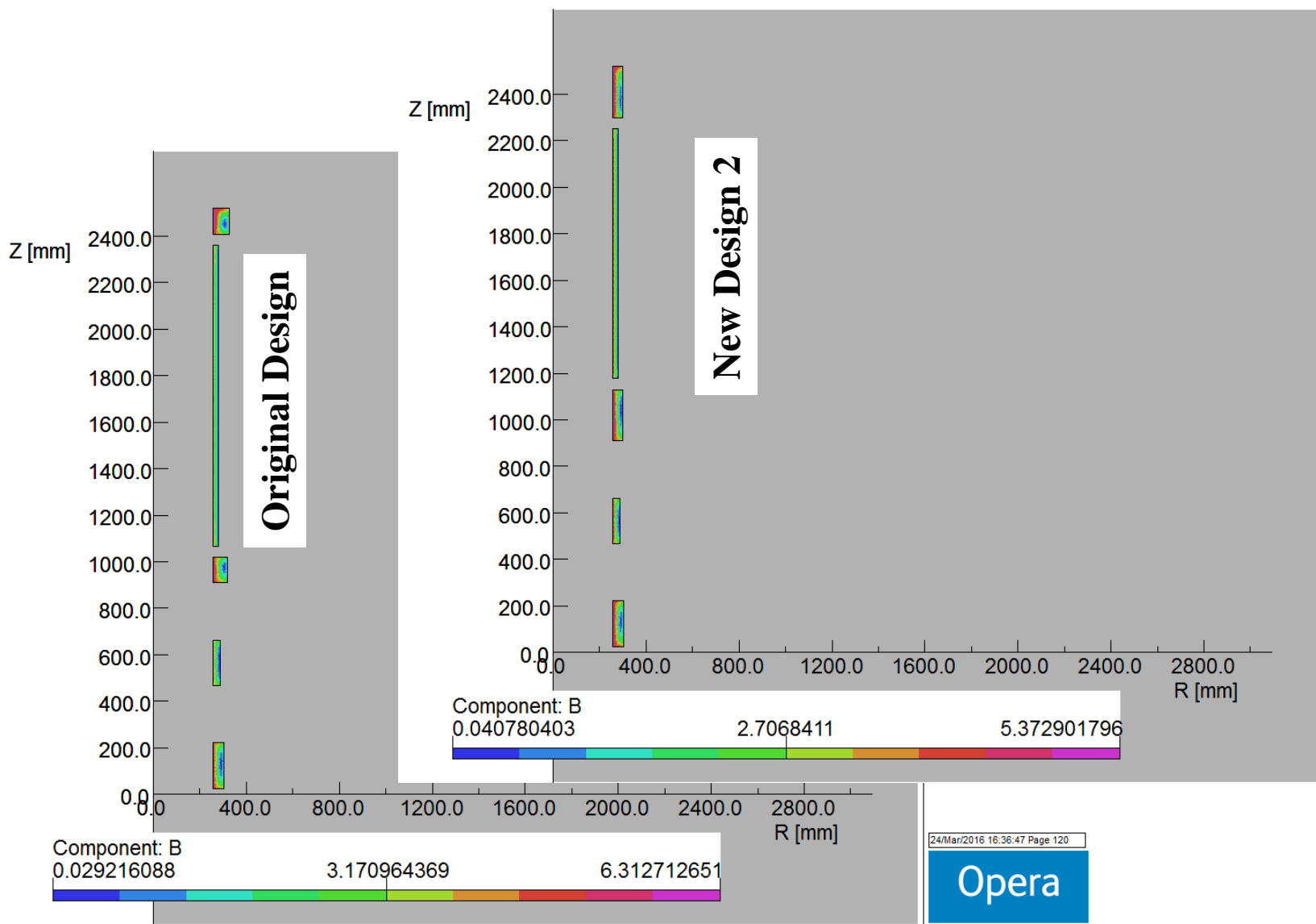
Aspect ratio of coils E1, E2 and C changed – coil o.d. reduced
 B_{pk} reduced by 12% & 24% of B_o

With a lower J_e in E2, margin gained by over 25% of B_o

X coord 258.0 258.0
Y coord -500.0 200.0
Z coord 0.0 0.0
—— Component: B, from buffer: Line, Integral = 10850.9679363677
- - - Component: B, from buffer: Line, Integral = 10681.2236561082

Opera

Reduction in Peak Field on the Conductor to Increase Margin (1)



UNITS

Length	: mm
Flux density	: T
Field strength	: A m ⁻¹
Potential	: Wb m ⁻¹
Conductivity	: S m ⁻¹
Source density	: A mm ⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

MODEL DATA

O:\opera\mice\MICE-N
D2.st

Quadratic elements
Axi-symmetry
Modified R²vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
60990 elements
122641 nodes
22 regions

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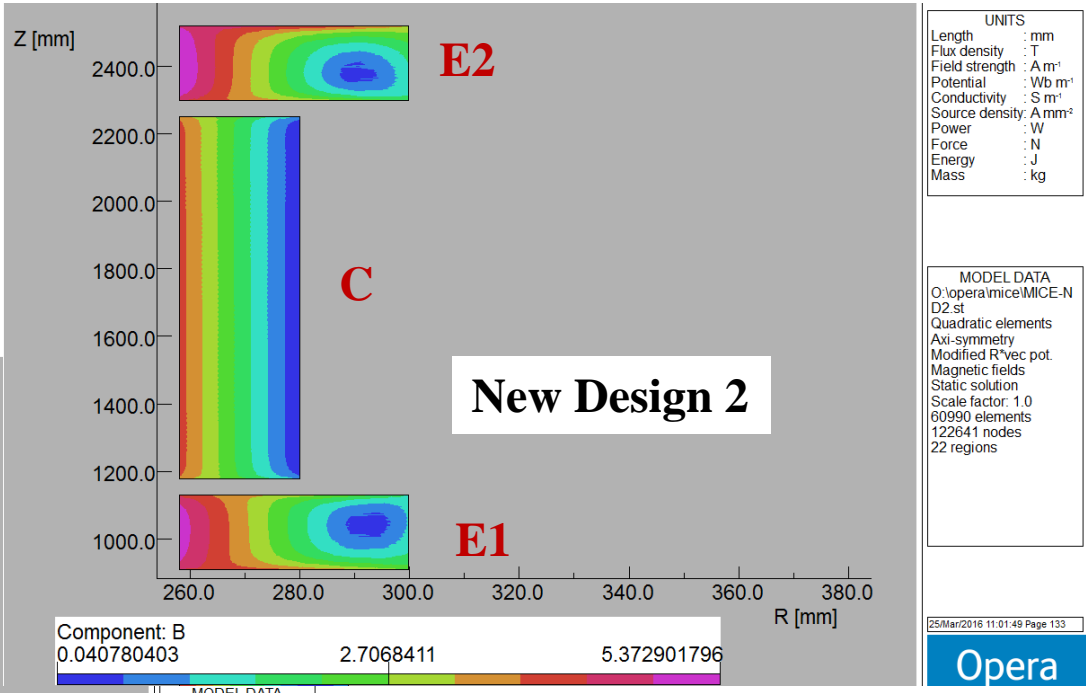
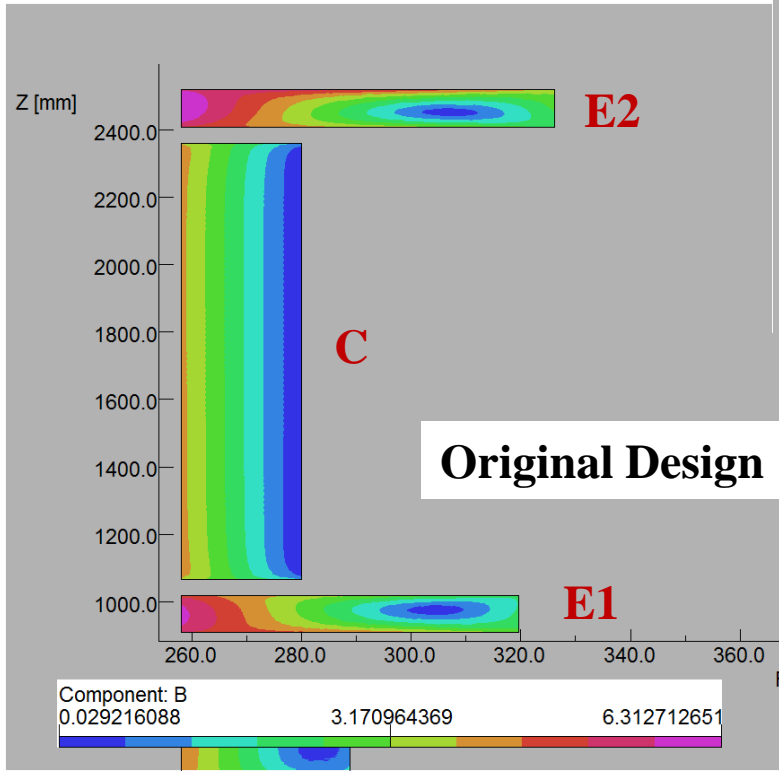


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Reduction in Peak Field on the Conductor to Increase Margin (2)

Scale changed to better view the difference (no longer 1:1 aspect ratio)



UNITS

Length	: mm
Flux density	: T
Field strength	: A m ⁻¹
Potential	: Wb m ⁻¹
Conductivity	: S m ⁻¹
Source density	: A mm ⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

MODEL DATA

O:\opera\mice\MICE-N
D2.st
Quadratic elements
Axi-symmetry
Modified R ² vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
60990 elements
122641 nodes
22 regions

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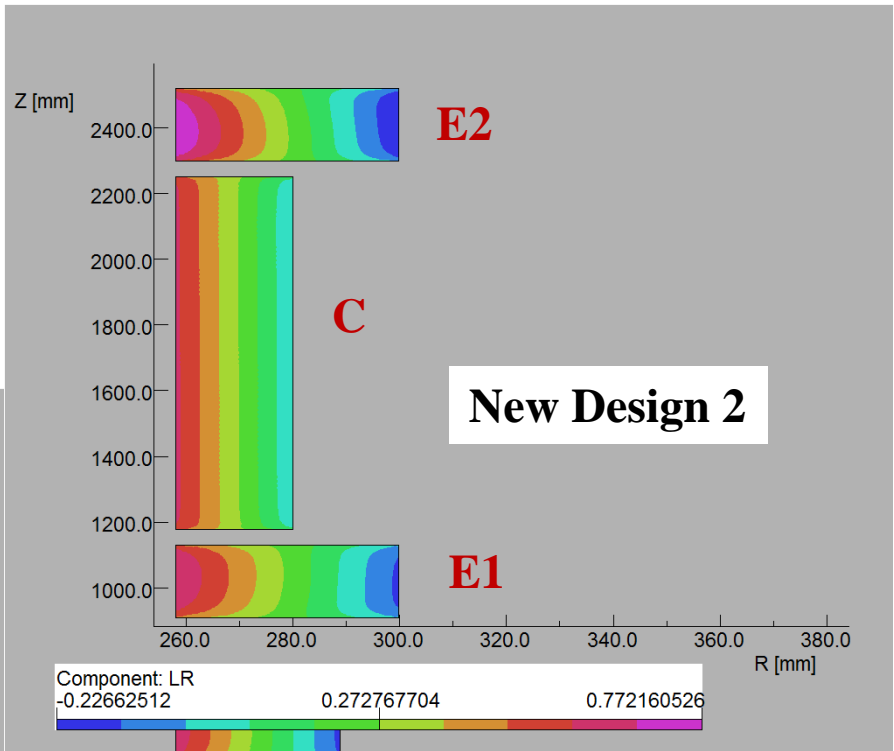
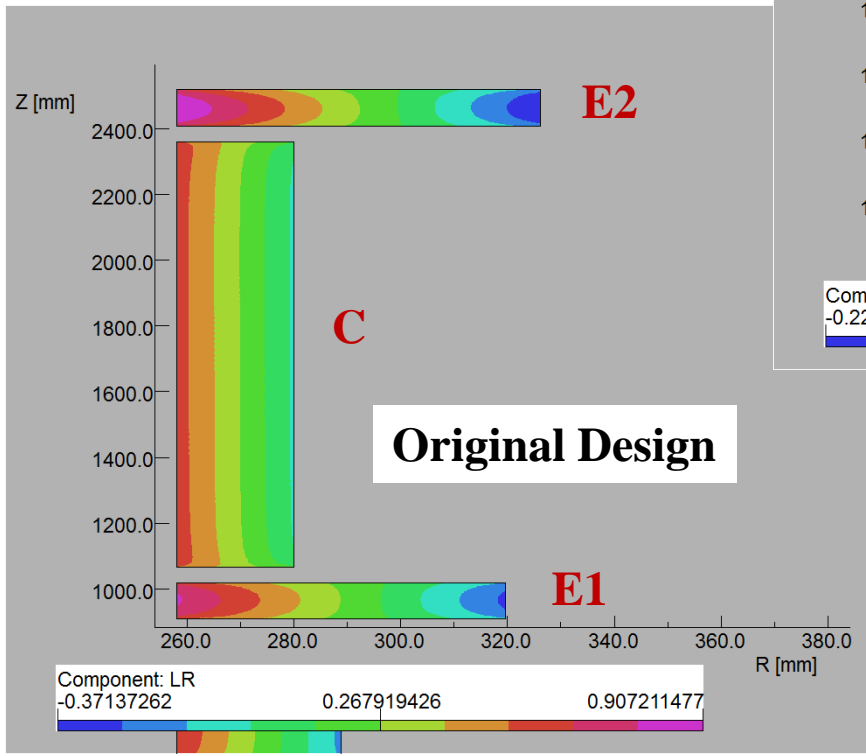
Opera

- Reduction in field would also reduce Lorentz forces, both axial and radial
- Reduction in radial width should further reduce radial stress accumulation

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Opera

Radial Lorentz Force Density on the Conductor at Full Field (4 T)



UNITS

Length	: mm
Flux density	: T
Field strength	: A m ⁻¹
Potential	: Wb m ⁻¹
Conductivity	: S m ⁻¹
Source density	: A mm ⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

MODEL DATA

O:\opera\mice\MICE-N
D2.st

Quadratic elements
Axi-symmetry
Modified R²vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
60930 elements
122641 nodes
22 regions

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Opera

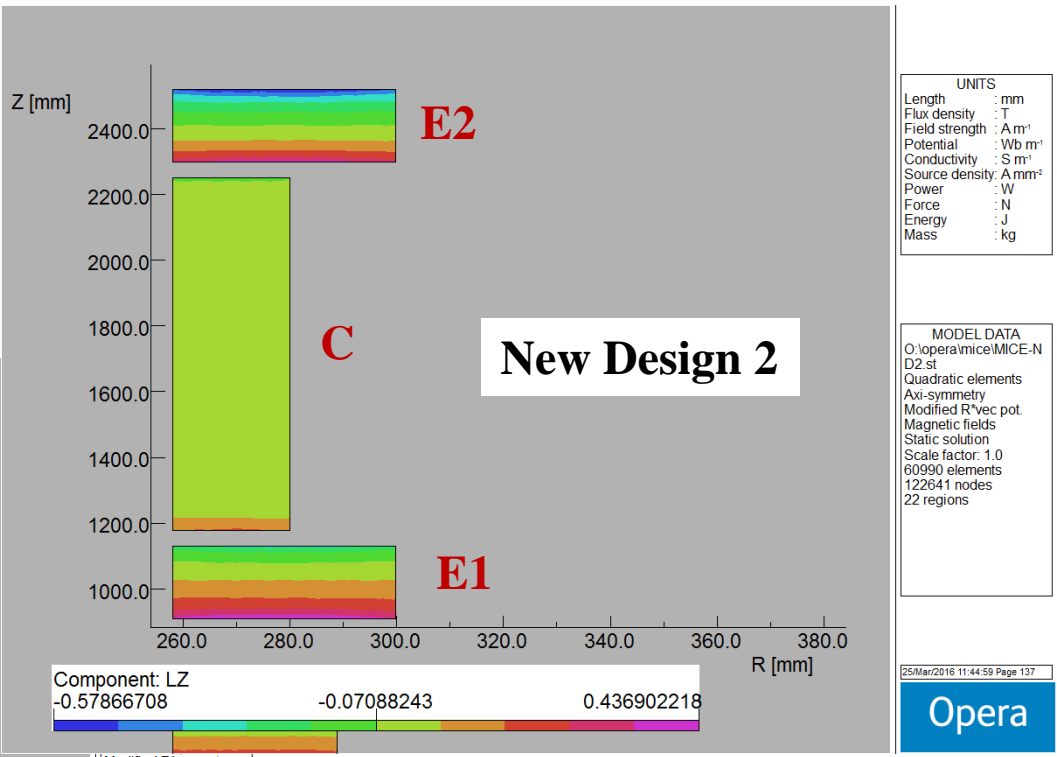
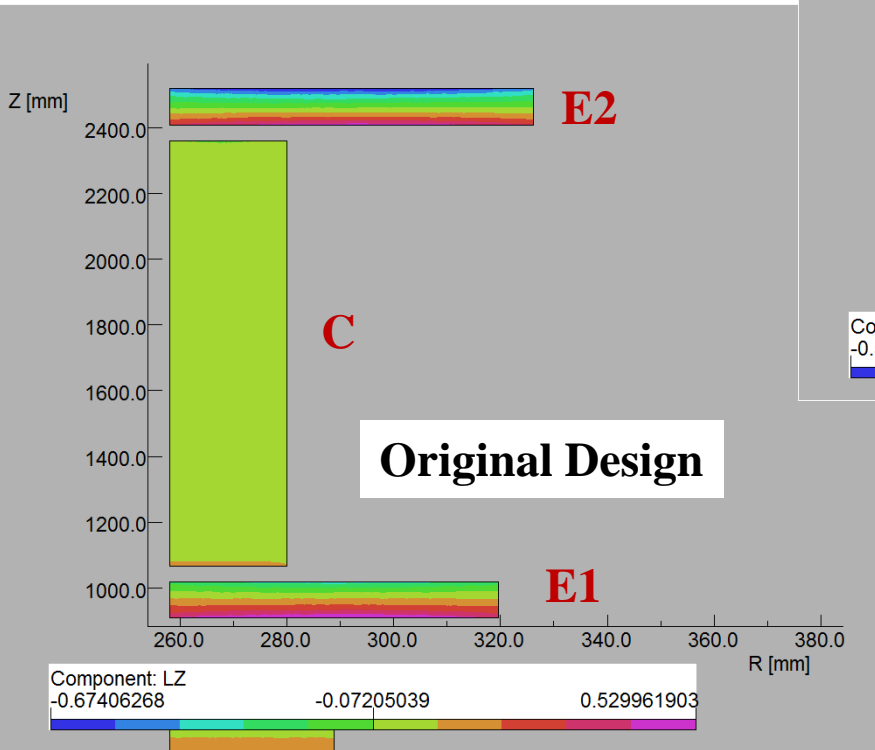
- **Peak Lorentz force density reduced**
- **Reduction in radial width makes accumulated radial stress ~2/3**

Quadratic elements
Axi-symmetry
Mod
Mag
Stat
Sca
618
124
22 r

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Opera

Axial Lorentz Force Density on the Conductor at Full Field (4 T)



UNITS

Length	: mm
Flux density	: T
Field strength	: Am ⁻¹
Potential	: Wb m ⁻¹
Conductivity	: S m ⁻¹
Source density	: Amm ⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

MODEL DATA

O:\opera\mice\MICE-N
D2.st

Quadratic elements
Axi-symmetry
Modified R²vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
60930 elements
122641 nodes
22 regions

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Opera

Modified R²vec pot.
Magnetic fields
Static solution
Scale factor: 1.0
61862 elements
124385 nodes
22 regions

• Peak Lorentz force density reduced

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Opera

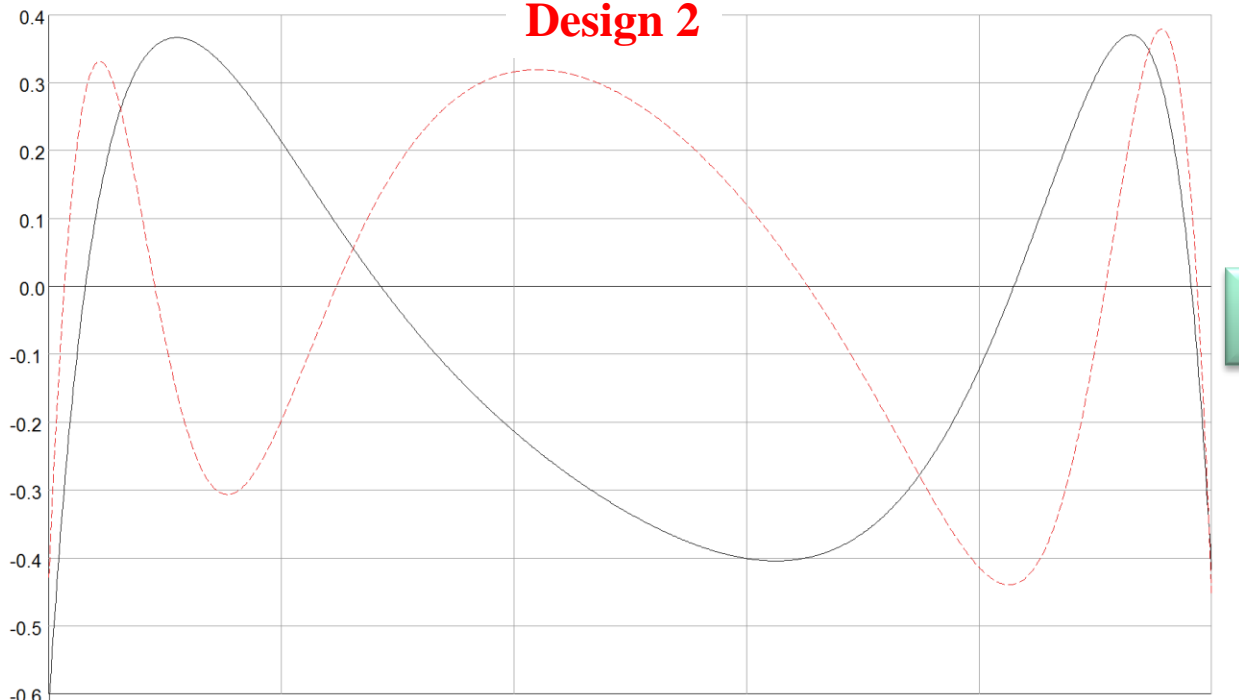
Relative Field Errors in Percentage (Original and Design 2)

Relative field error on axis (in %)

25/Mar/2016 10:09:59

Original

Design 2



X coord 0.0 1070.0 1324.0 1578.0 1832.0 2086.0 2340.0
 Y coord 1070.0 1324.0 1578.0 1832.0 2086.0 2340.0
 Z coord 0.0 0.0 0.0 0.0 0.0 0.0

— Component: (B-4)/4*100, from buffer: Line, Integral = -82.5953990171183
 - - - Component: (B-4)/4*100, from buffer: Line, Integral = 25.4082825115574

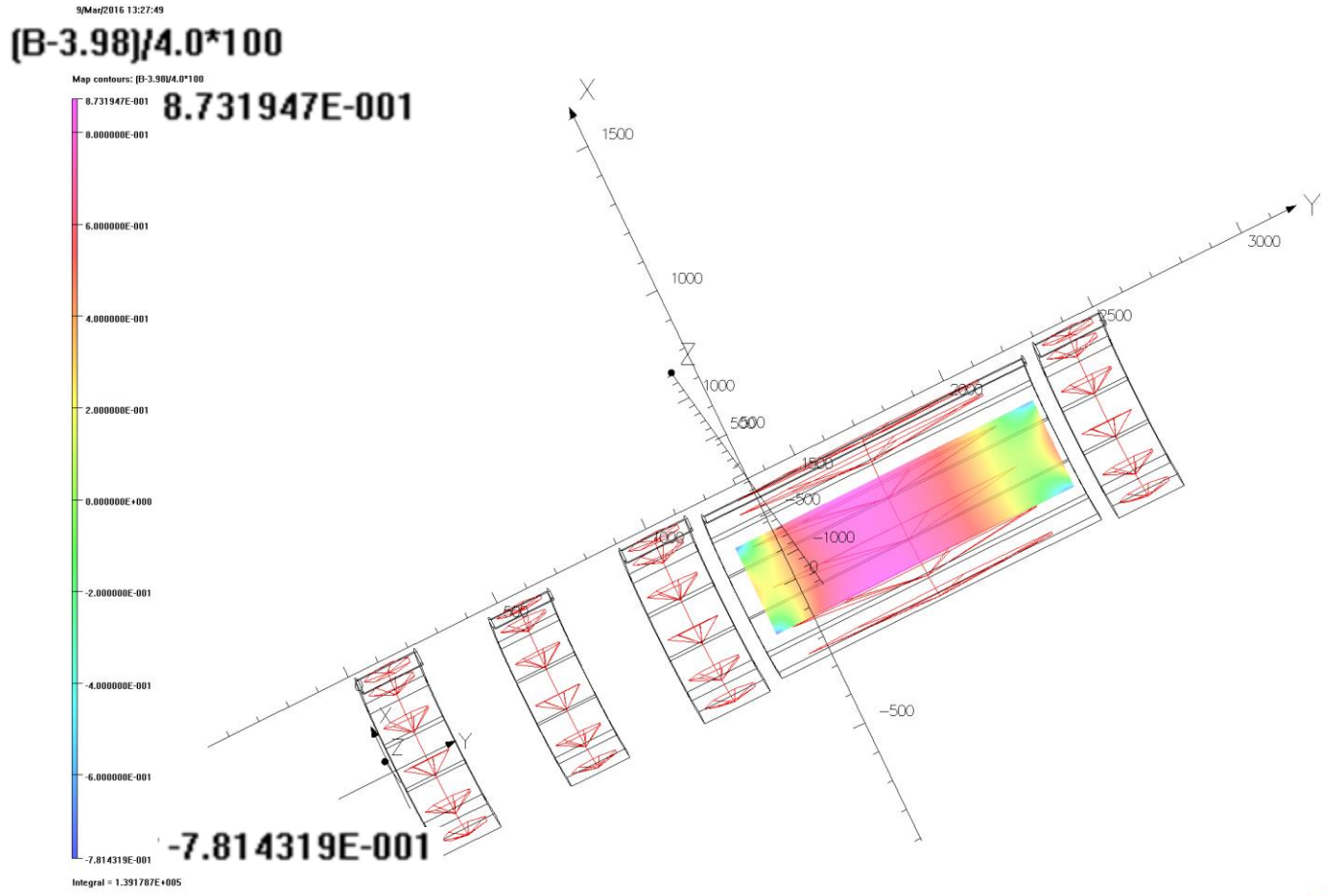
UNITS	
Length	mm
Magn Flux Density T	A/m ²
Magn Field	A/m ²
Magn Scalar Pot	A
Magn Vector Pot	Wb/m ²
Elec Flux Density	C/m ²
Elec Field	V/m ²
Conductivity	S/m ²
Current Density	A/m ²
Power	W
Force	N
Energy	J
Mass	kg
MODEL DATA	
5 conductors	
Field Point Local Coordinates	
Local = Global	
FIELD EVALUATIONS	
Line LH6 (node) 1001 Cartesian	
x=0.0 y=1070.0 to 2340.0 z=0.0	

Specified: < +/- 1%

Opera

Relative Field Errors in Percentage (Design 2)

Relative field error in 300 mm diameter 1000 mm patch (in %)



UNITS	
Length	mm
Magn Flux Density T	A m ⁻¹
Magn Field	A m ⁻¹
Magn Scalar Pot	A
Magn Vector Pot	Wb m ⁻¹
Elec Flux Density	C m ⁻²
Elec Field	V m ⁻¹
Conductivity	S m ⁻¹
Current Density	A mm ⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
3 conductor	

Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS			
Line	LINE (nodes)	1001	Cartesian
	x=0.0	y=1070.0 to 2340.0	z=0.0
	Cartesian CARTESIAN (nodes)	1004/100	Cartesian
	x=-150.0 to 150.0	y=1220.0 to 2220.0	z=0.0

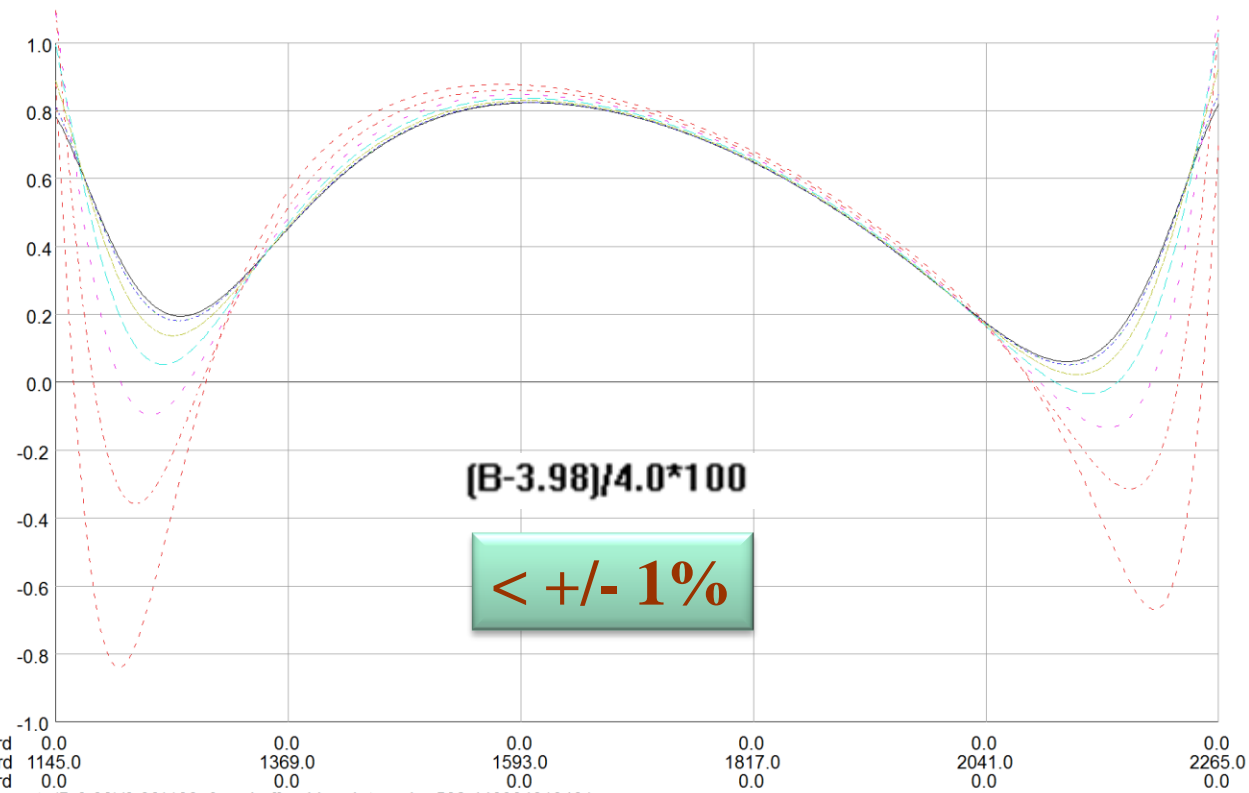
< +/- 1%

Opera

Relative Field Errors in Percentage (Design 2)

Relative field error in 0 to 300 mm diameter in L > 1000 mm

25Mar2016 13:38:21



- Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 562.446984813401
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 375.04588308004
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 560.703151889918
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 560.703151889918
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 554.370191027065
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 540.067377241922
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 511.898492570813
- - - Component: (B-3.98)/3.98*100, from buffer: Line, Integral = 461.031550483072

UNITS	
Length	mm
Magn Flux Density T	A m ⁻¹
Magn Field	A
Magn Scalar Pot	A
Magn Vector Pot	Wb m ⁻¹
Elec Flux Density	C m ⁻²
Elec Field	V m ⁻¹
Conductivity	S m ⁻¹
Current Density	A mm ⁻²
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA	
5 conductor	
Field Point Local Coordinates	
Local = Global	

FIELD EVALUATIONS	
Line LINE (model) 1001	Cartesian
x=125.0	y=1145.0 to 2265.0 z=0.0

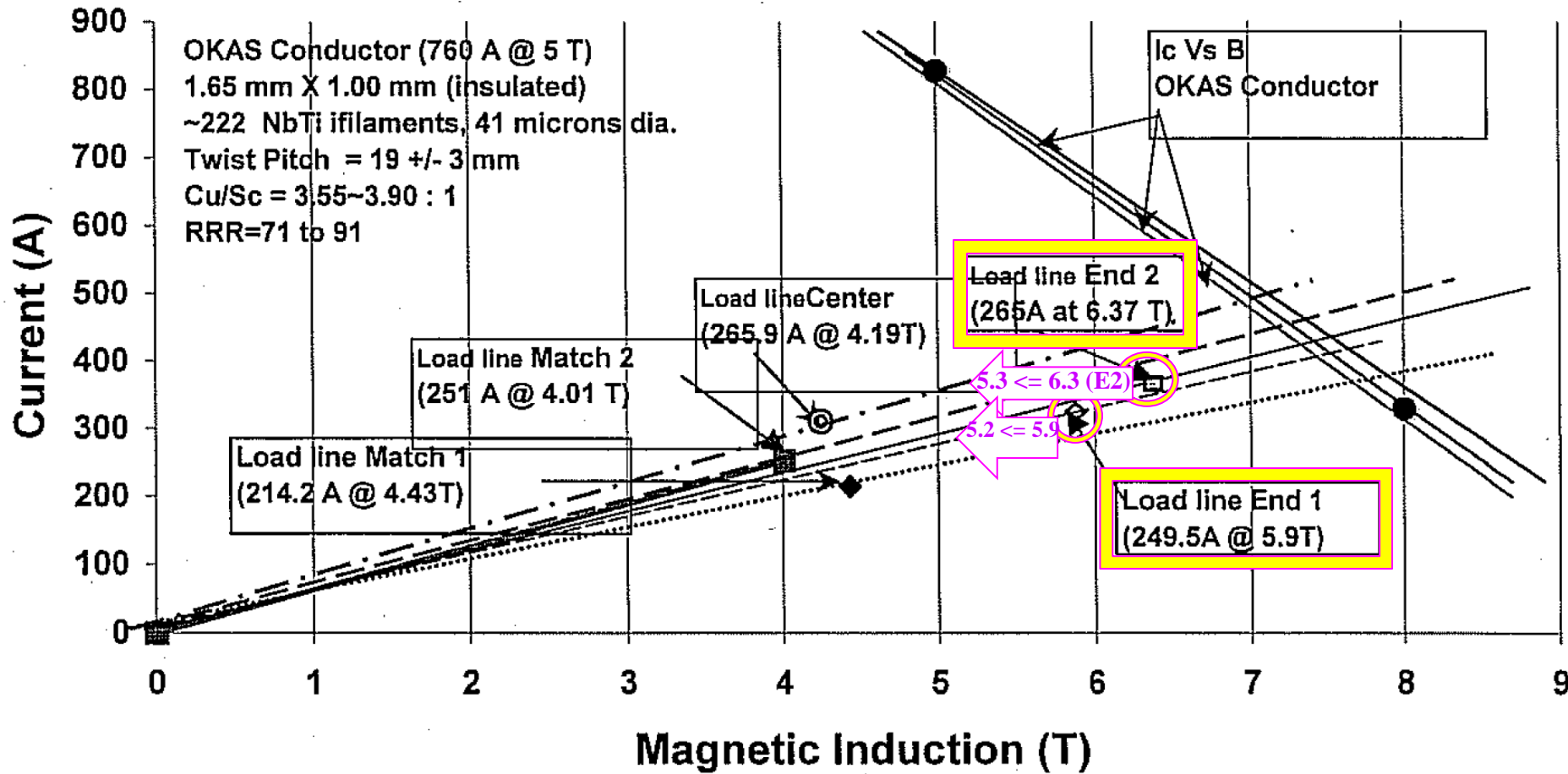
Opera

Major Parameters of Original Design and New Design

Coil E1	Original	New Design 2	Coil E2	Original	New Design 2
Coil Thickness (mm)	61.6	41.8	Coil Thickness (mm)	68.2	41.8
Coil Length (mm)	110	220	Coil Length (mm)	110	220
Number of Layers	56	38	Number of Layers	62	38
No. of turns per layer	66	132	No. of turns per layer	66	132
Total number of turns	3696	5016	Total number of turns	4092	5016
Coil C	Original	New Design 2			
Coil Thickness (mm)	22	22			
Coil Length (mm)	1294	1074			
Number of Layers	20	20			
No. of turns per layer	784	652		Original	New Design 2
Total number of turns	15680	13040	Total # of turns in E1+C+E2	23468	23072

New Design has Significantly reduced Peak Fields and Increased Margin

Design Tracker Magnet Load Lines and I_c Versus B for OKAS Superconductor



Other Possible Approaches

- Remove/reduce space between E1, C and E2 or combine these coils in different ways
- Those techniques may further reduce peak fields

SUMMARY

- **Significant reduction in peak field and hence significant increase in margin can be obtained by changing the aspect ratio of E1 and E2 (and also C).**
- **Overall length and field quality is maintained.**
- **This is not the final design (for example field quality can still be improved by slightly adjusting currents in E1, C and E2) but it provides a reasonable reference design to increase margin.**
- **Reduction in peak field also reduces Lorentz stresses on the coil.**