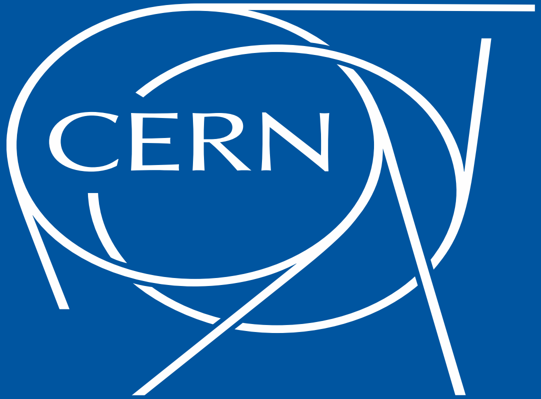
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MT-27 18 Nov 2021

THU-OR4-401-03

Design of a Curved Combined Function Bending Magnet Demonstrator for Hadron Therapy

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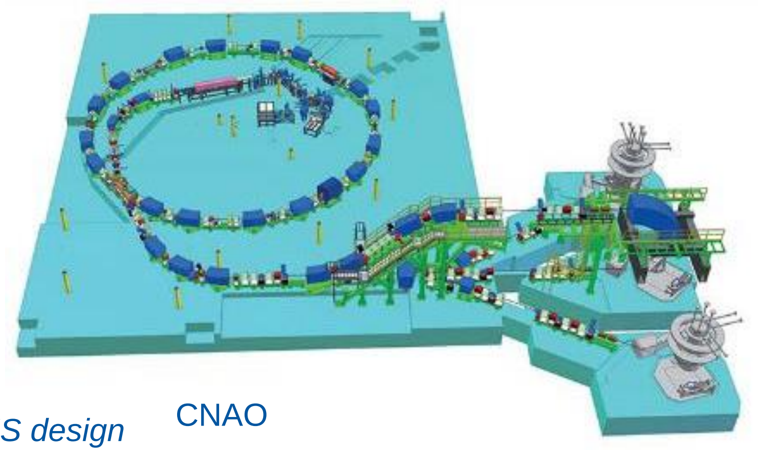
Ch. Kokkinos (FEAC Engineering P.C.)

Acknowledgements:
U. Amaldi (TERA Foundation)
E. Benedetto, M. Cirilli, D. Tommasini, M. Vretenar (CERN)

Introduction

- CNAO & MedAUSTRON intend to upgrade their radiotherapy facilities with a superconducting rotating gantry for heavy ion therapy
- Since spring 2019 regular meetings between CERN, CNAO, INFN and MedAUSTRON on novel ion gantry concepts
- CNAO aims to complete design within the next 3-5 years and to install the gantry within the next 7-10 years

MedAUSTRON



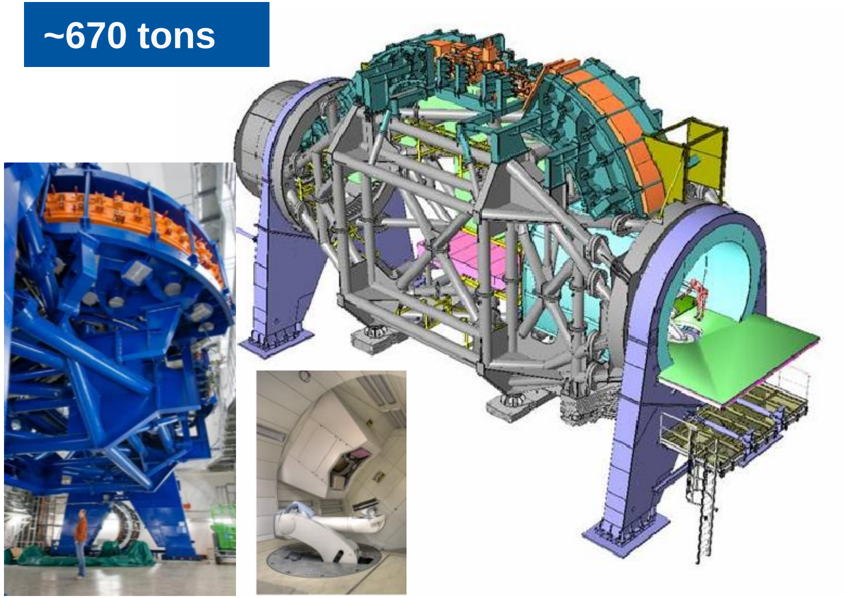
CNAO

Both based on PIMMS design

Rotating Gantries for Carbon Ions

2012

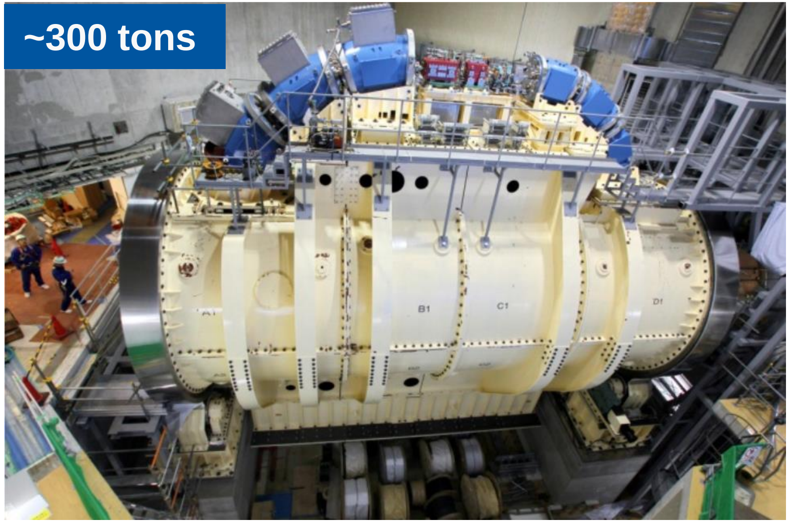
~670 tons



- Heidelberg Ion Beam Therapy Center (HIT)
- Normal conducting magnets
- Beam orbit radius 6.5 m, Length 25 m

2016

~300 tons

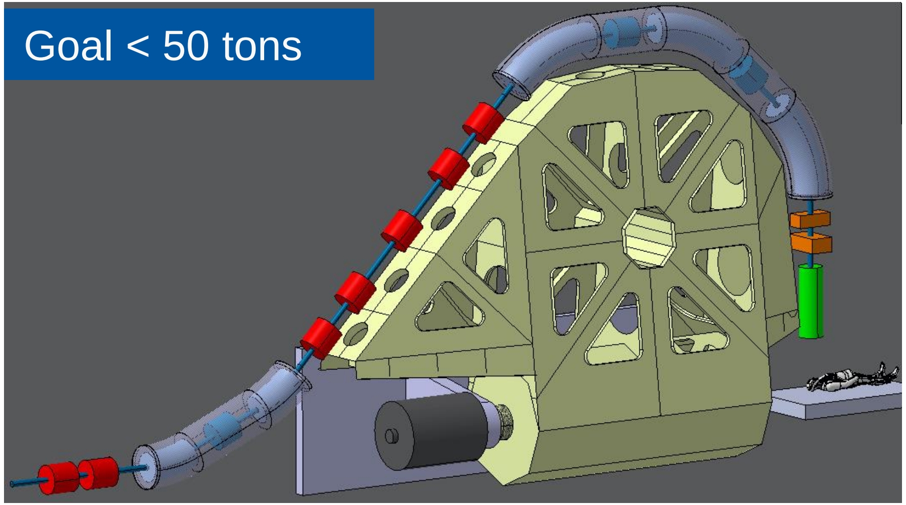


- HIMAC at NIRS made by Toshiba
- Superconducting 2.37 T .. 2.88 T magnets
- Beam orbit radius 5.5 m, Length 13 m

New Compact Gantry for $^{12}C^{6+}$ Therapy

- Reduced complexity of the main magnets for maximum reliability
  - Two cryo-assemblies: 2 x 22.5°, 3 x 45°
  - B_{nom} = 3 T
  - G_{nom} = ~3.5 T/m (Combined function only)
  - dB/dt = 0.10 T/s
  - Aperture = ø70 mm
  - Radius of curvature = 2.207 m(*
  - Field quality < 10^{-3}
- Additional quadrupoles for tuning the optics
  - 3 x Superconducting G_{nom} = 40 T/m
  - 7 x Normal conducting G_{nom} = 25 T/m

L. Gentini (CERN)



- Beam orbit radius 6.37 m,
- Length ~16 m
- Momentum acceptance 1%

*)*For 430 MeV/u beam*

Curved Cos-Theta Combined Function Magnet

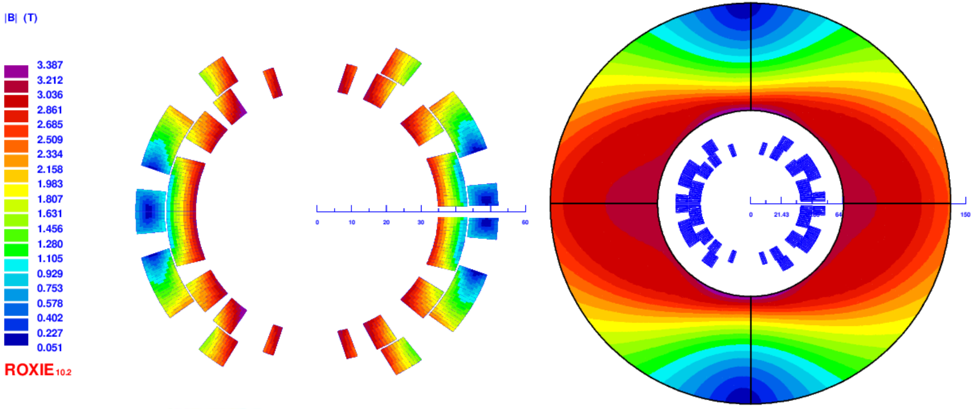
- Long experience from accelerator magnets (LHC, Tevatron, RHIC, etc)
  - Existing tooling and infrastructure, well-established manufacturing methods, trained personnel
- Specific aspects of a gantry magnet:
  - Fabrication of curved cos-theta coils
  - Assembly of curved cold-mass
  - Helium bath for cooling not permitted
  - Extraction of transient losses from conduction cooled coils
  - Field measurement in curved aperture

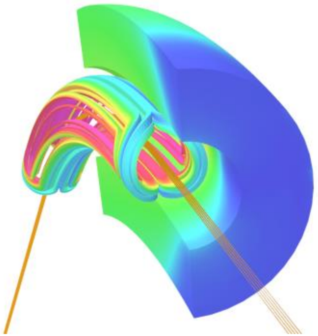
➢ Design, build and test a curved 30 ° demonstrator magnet meeting the gantry specification to validate the concept by 2024
  - First test in He-bath, then ideally with conduction cooling system

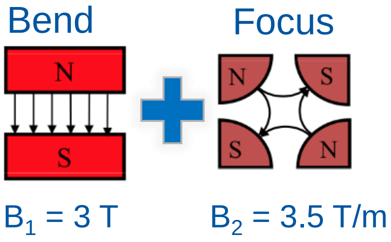
➢ Full scale 45° Prototype magnet
  - Include all lessons learned and target highest reliable performance for the 45° Prototype
  - Optimized for the final gantry specification according to optimal cooling and integration considerations

Combined Function Dipole

Parameter	Value			Unit
Nb-Ti strand diameter	0.48			mm
Filament diameter	6			µm
Cu:Sc ratio	1.75			
No. of strands	34			
Cable width	8.3			mm
Core thickness (stainless steel)	25			µm
B_{nom} (70-430 MeV/u)	1.11 - 3.0			T
G_{nom} (430 MeV/u)	3.5			T/m
I_{nom}	796 – 2144			A
dB/dt	0.10			T/s
Margin at 4.7/6 K	45% / 27%			
Aperture	70			mm
Yoke ID/OD	~130 / 320			mm
Bending angle	22.5°	30°	45°	
Magnetic length	0.87	1.16	1.74	m
Stored energy	23	31	46	kJ
Self inductance	10.1	13.5	20.2	mH
Coil length	1.0	1.3	1.88	m
Total length	1.15	1.45	2.05	m
Approx. mass	560	710	1020	kg
Coil sagitta (R2.207 m)	25.7	42.3	86.5	mm







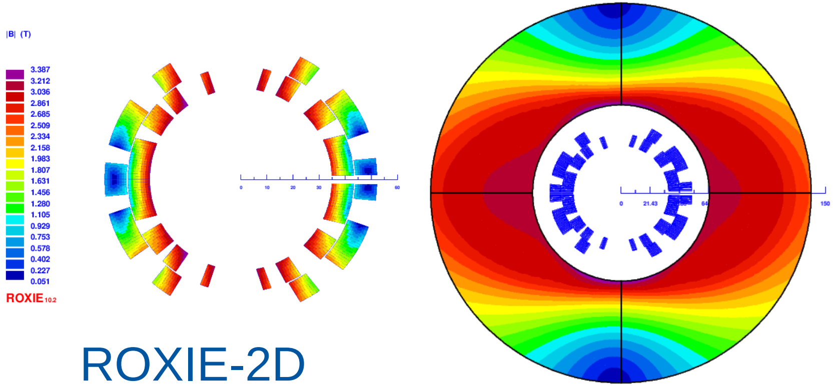
Bend

Focus

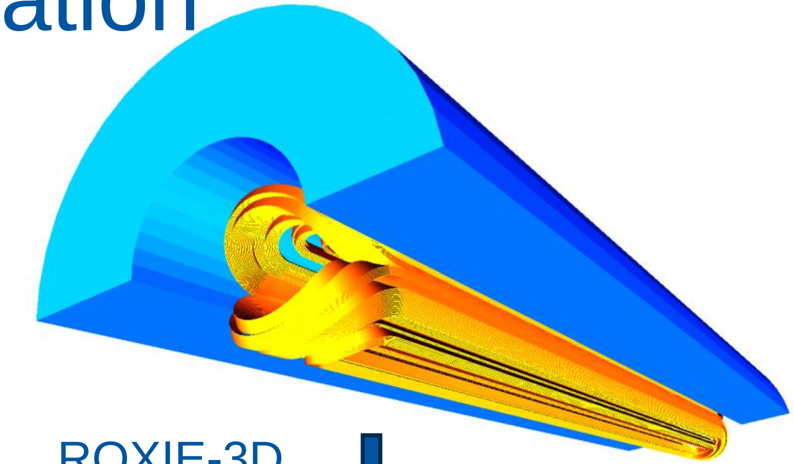
$B_1 = 3$ T

$B_2 = 3.5$ T/m

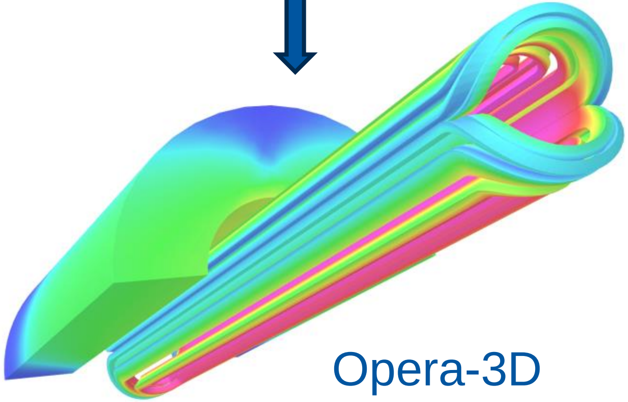
Electro-magnetic Optimization



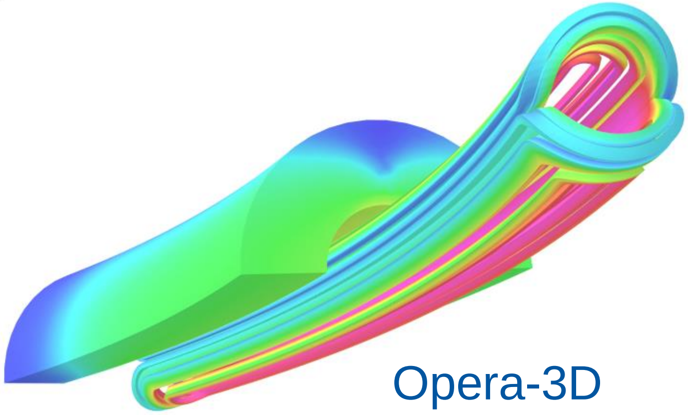
ROXIE-2D



ROXIE-3D

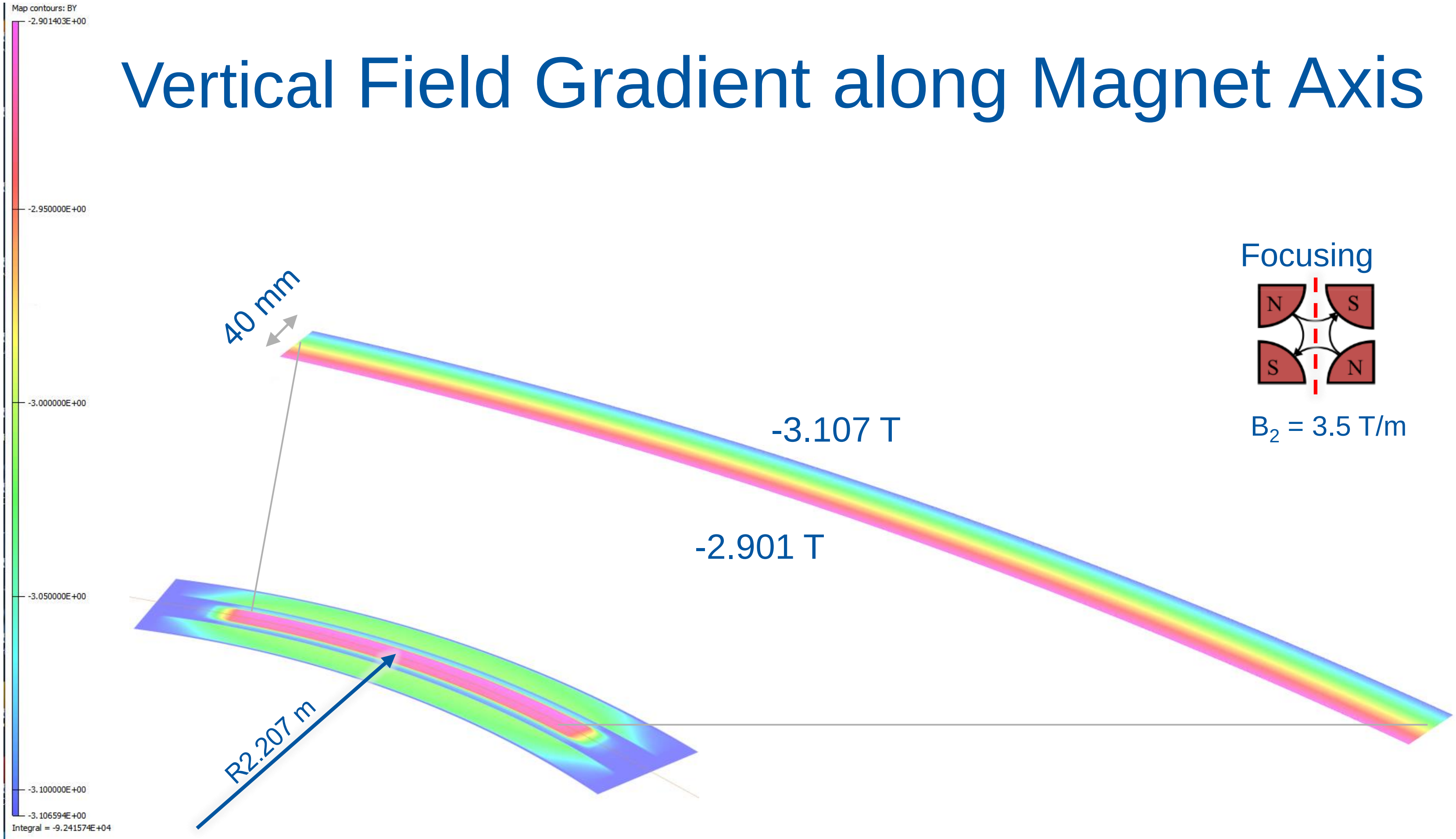


Opera-3D

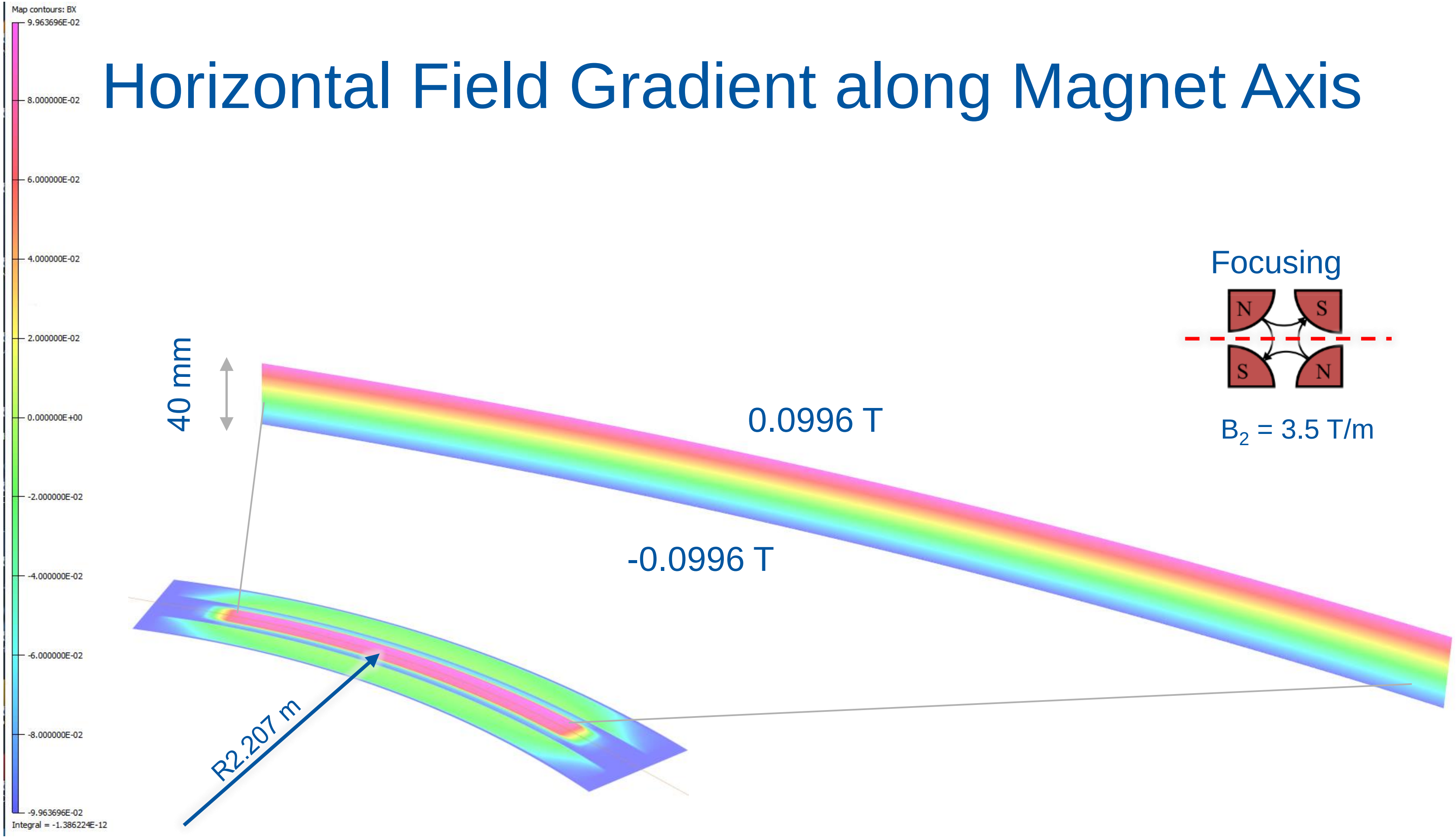


Opera-3D

Vertical Field Gradient along Magnet Axis

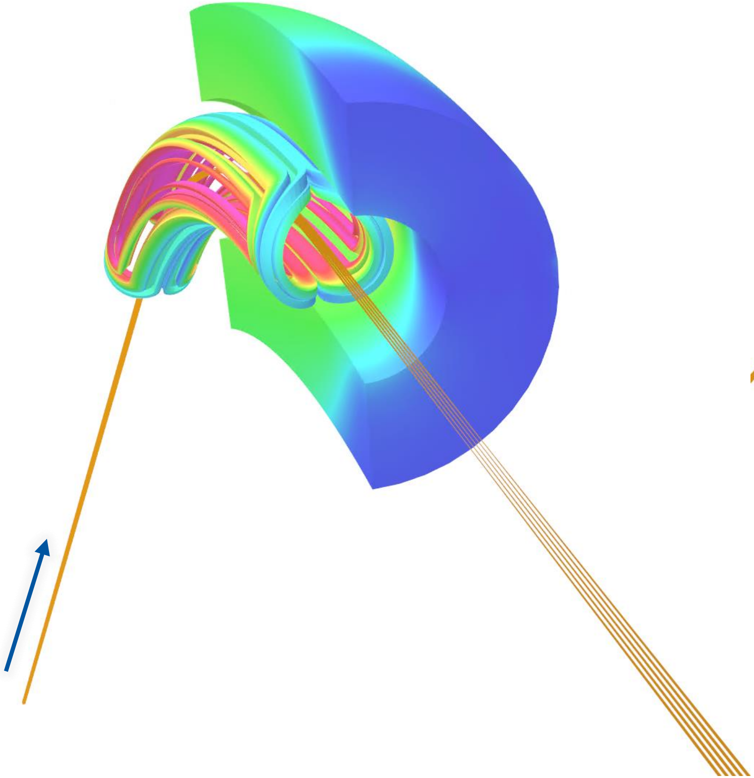


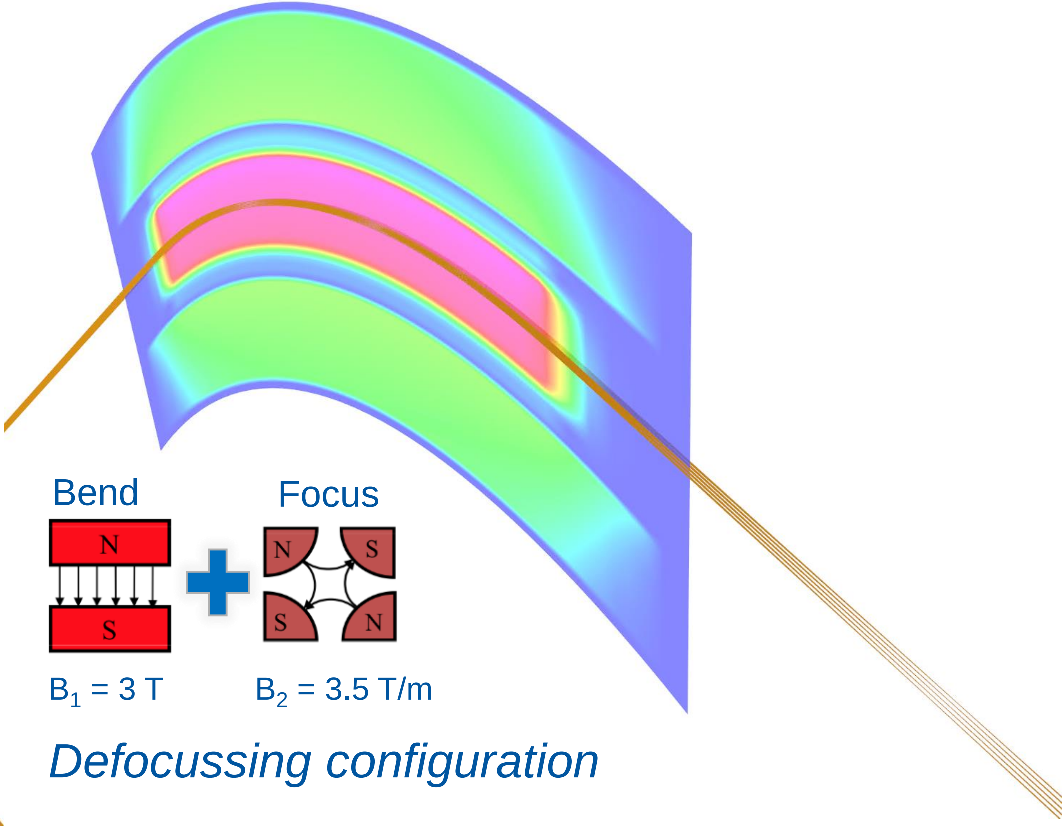
Horizontal Field Gradient along Magnet Axis



$B_2 = 3.5$ T/m

Tracking parallel 5 x 5 mm 430 MeV/u $^{12}C^{6+}$ Beam



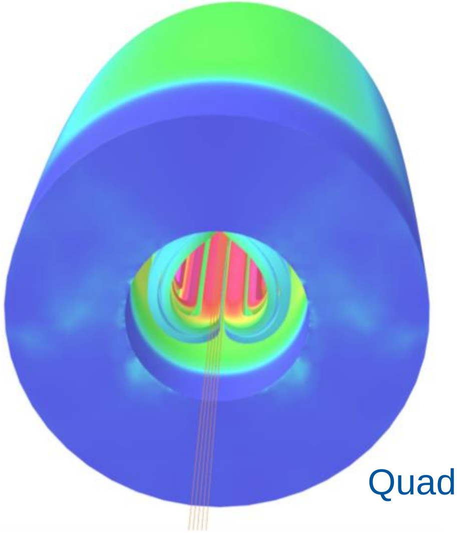


$B_1 = 3$ T

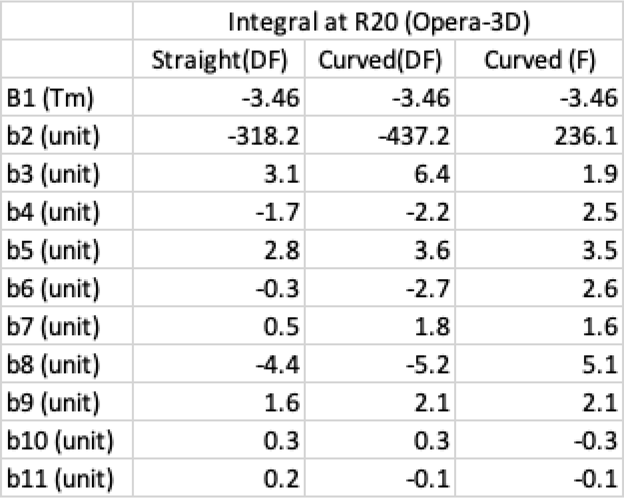
$B_2 = 3.5$ T/m

Defocussing configuration

Defocusing and Focusing Configurations (30° Magnet)



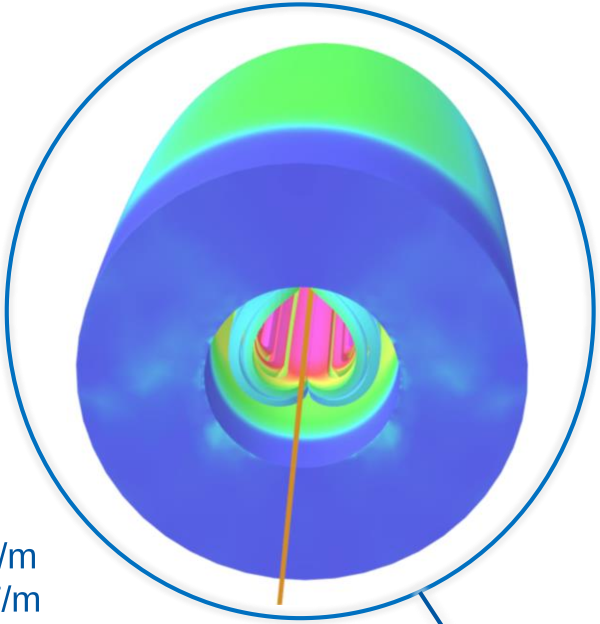
DF



	Integral at R20 (Opera-3D)		
	Straight(DF)	Curved(DF)	Curved (F)
B1 (Tm)	-3.46	-3.46	-3.46
b2 (unit)	-318.2	-437.2	236.1
b3 (unit)	3.1	6.4	1.9
b4 (unit)	-1.7	-2.2	2.5
b5 (unit)	2.8	3.6	3.5
b6 (unit)	-0.3	-2.7	2.6
b7 (unit)	0.5	1.8	1.6
b8 (unit)	-4.4	-5.2	5.1
b9 (unit)	1.6	2.1	2.1
b10 (unit)	0.3	0.3	-0.3
b11 (unit)	0.2	-0.1	-0.1

Quadrupole: 318.2 units = 5.5 T/m m or G = 4.76 T/m
437.2 units = 7.6 T/m m or G = 6.55 T/m
236.1 units = 4.1 T/m m or G = 3.53 T/m
L_{mag} = 1.155 m

Field calculated from line integrals along toroidal/cylindrical surface



F

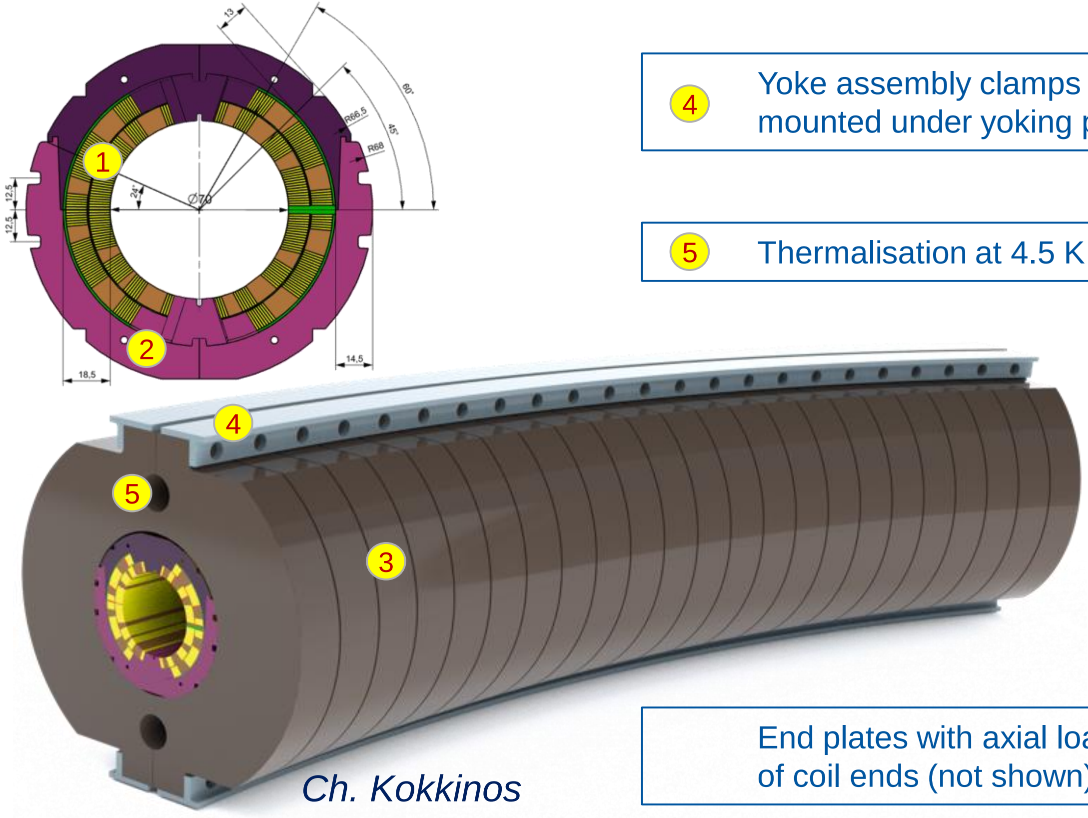
This is the configuration for the gantry

Mechanical Concept

① Epoxy-impregnated 2-layer coils with inter-layer splice, wound with cored 34-strand 8.3 mm Nb-Ti cable with braided glass insulation

② Stiff austenitic steel collars with 0.15..0.2 mm thick spacers on one side to follow the coil curvature

③ Horizontally split laminated iron yoke made of 1-mm-thick Si-steel with b-staged resin coating. Yoke sectors machined out of glued lamination stacks.



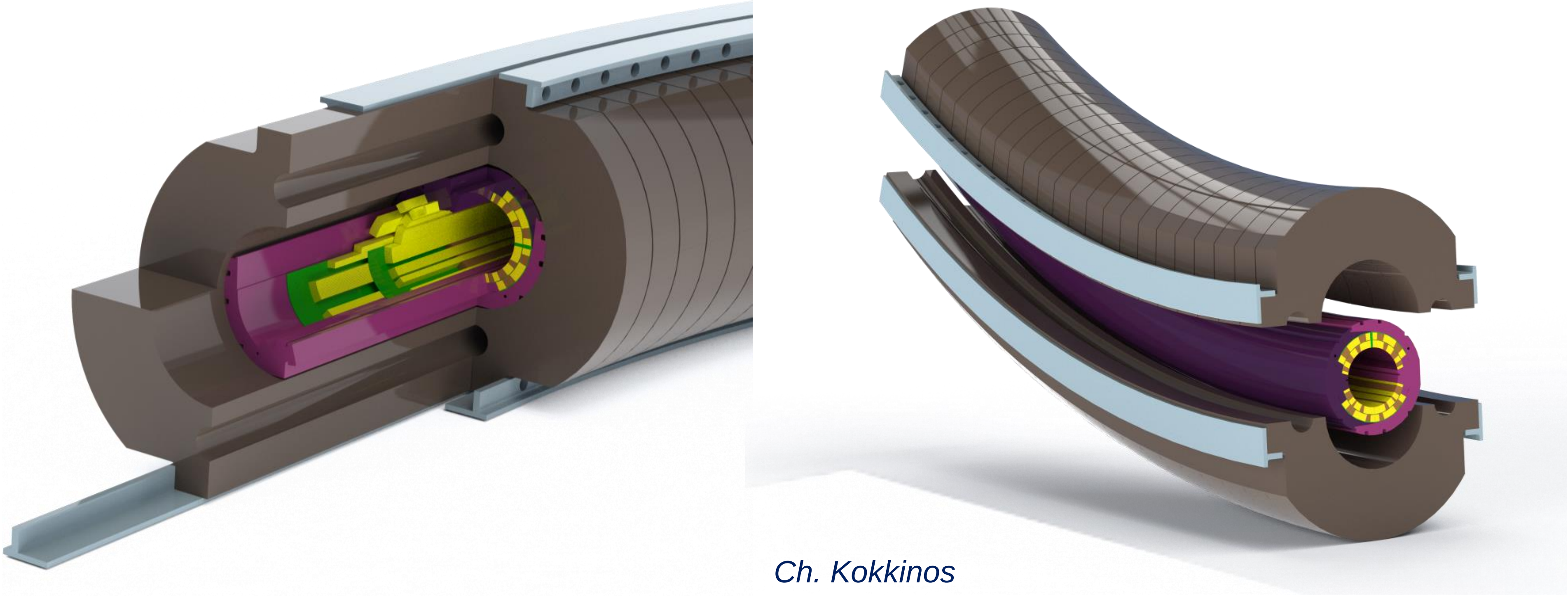
Ch. Kokkinos

④ Yoke assembly clamps mounted under yoking press

⑤ Thermalisation at 4.5 K

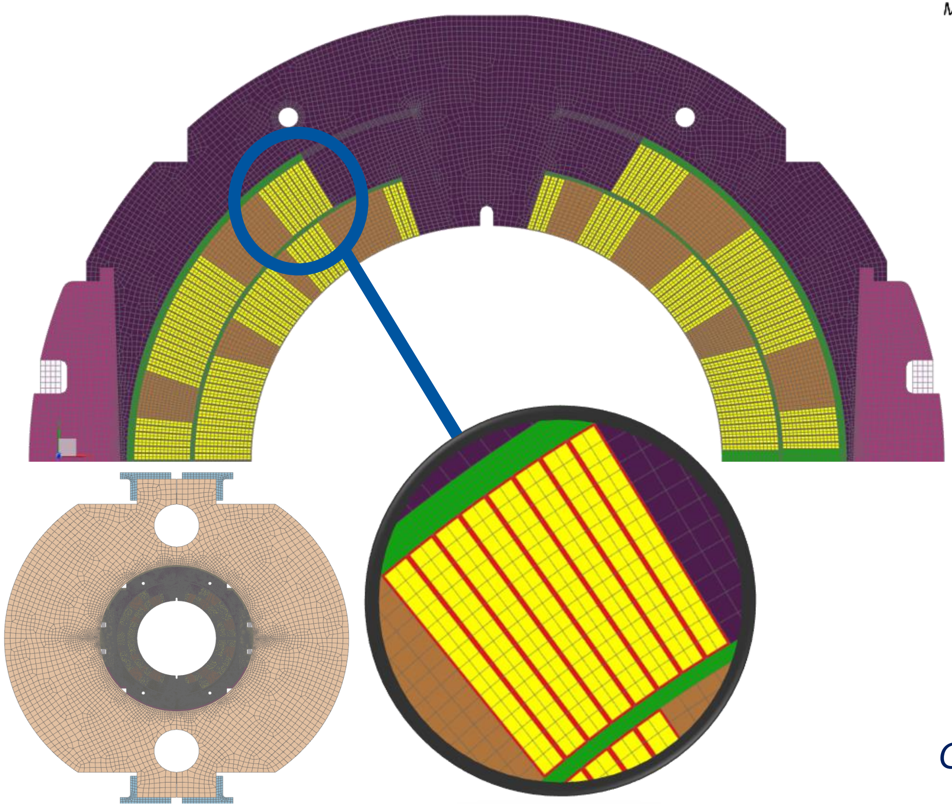
End plates with axial loading of coil ends (not shown)

Magnet assembly

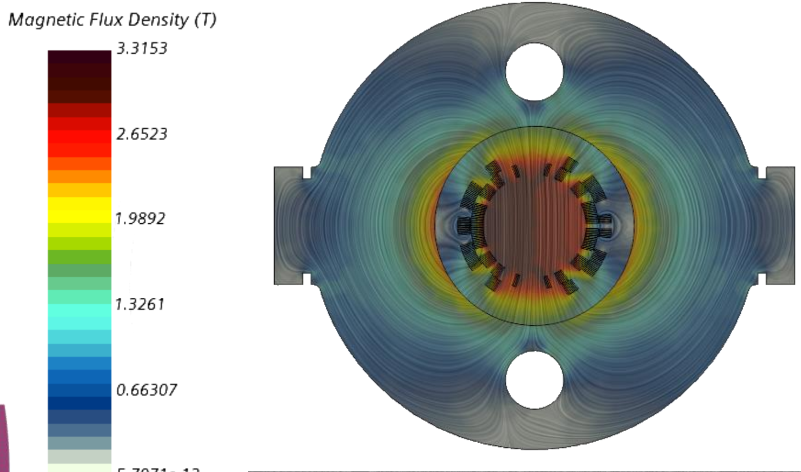


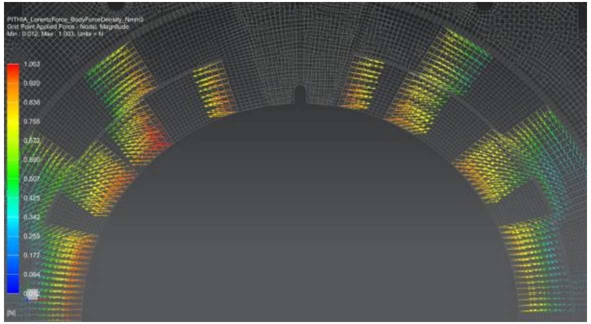
Ch. Kokkinos

FE-model & EM-Forces



Mapping of Lorentz Forces





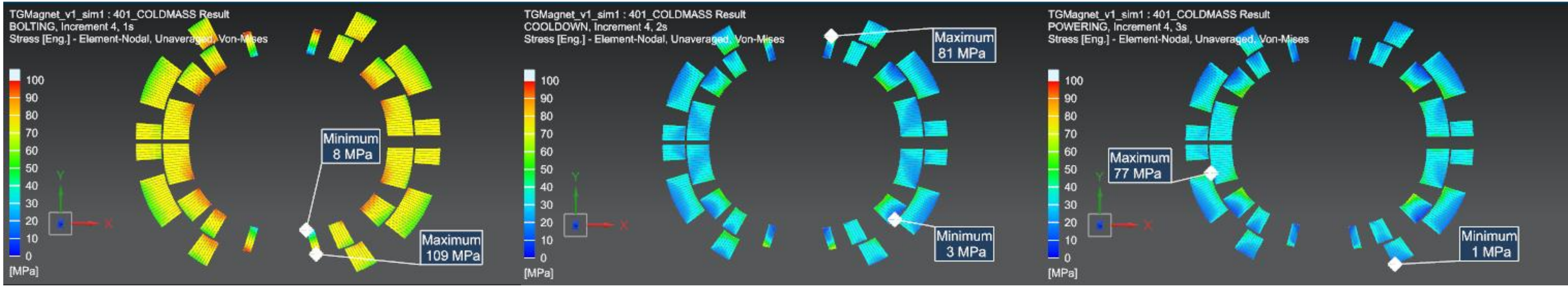
Ch. Kokkinos

Coil Von-Mises stress evolution

LS1:
Yoke Bolting
@ 293K

LS2:
@4.5K

LS3:
3.0 T @4.5K



TGMagnet_v1_sim1 : 401_COLDMASS Result
BOLTING, Increment 4, 1s
Stress [Eng.] - Element-Nodal, Unaveraged, Von-Mises

TGMagnet_v1_sim1 : 401_COLDMASS Result
COOLDOWN, Increment 4, 2s
Stress [Eng.] - Element-Nodal, Unaveraged, Von-Mises

TGMagnet_v1_sim1 : 401_COLDMASS Result
POWERING, Increment 4, 3s
Stress [Eng.] - Element-Nodal, Unaveraged, Von-Mises

Ch. Kokkinos

The optimised FE-model meets the design goals

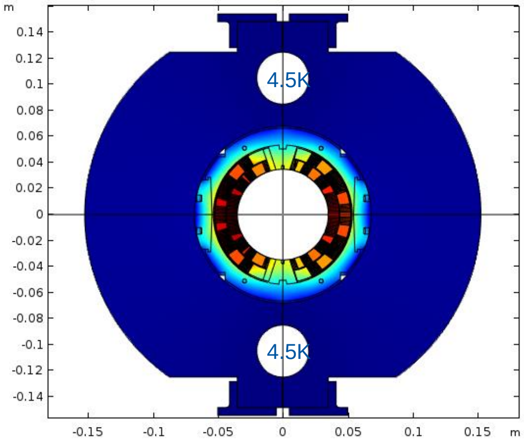
Transient analysis: STEAM-SIGMA/Comsol

- **Goals:**
  - Understand T-gradient between the coils and thermalisation point
  - Verification of the operational margins
  - Estimate the required cooling power

- **Transient losses:**
  - Inter-filament coupling loss (IFCL) and Inter-strand coupling loss (ISCL) and eddy current loss in wedges from transient analysis
  - Persistent current loss (PCL) from ROXIE as constant heat source
  - Conductor effective transverse resistivity ($fRho_{eff}$) between filamens used as variable for scaling the losses

- **FE-model:**
  - Conservative thermal resistance at collar-yoke interface based on contact pressure from structural analysis
  - Detailed non-linear material properties
  - Perfect 4.5 K heat sink applied on yoke holes

- **“Reference case (0..3 T)”** and **“Expected operational case (1..3 T)”** were analysed in addition to a highly pessimistic **“Worst case (0..3 T)”** scenario

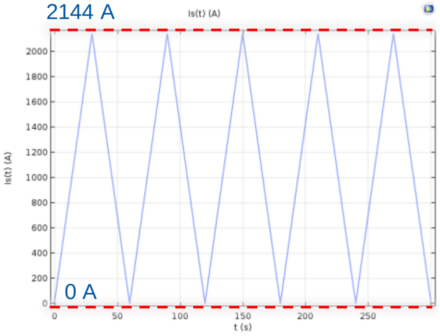


V. Ferrentino

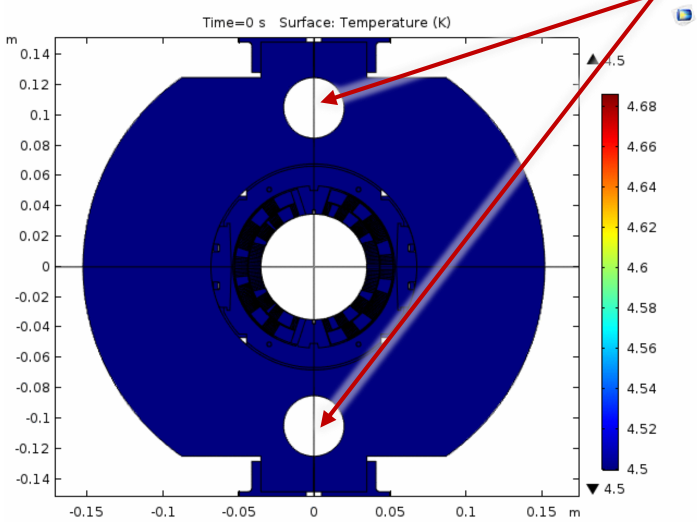
Transient analysis: Reference case (0 .. 3 T)

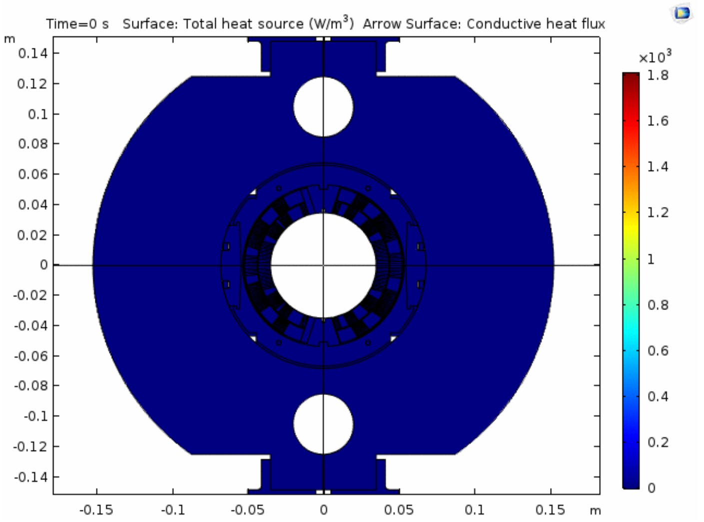
- Quasi-steady state reached after one cycle of 60 s
- T_{max} = 4.69 K

V. Ferrentino



Perfect heat sink a 4.5 K



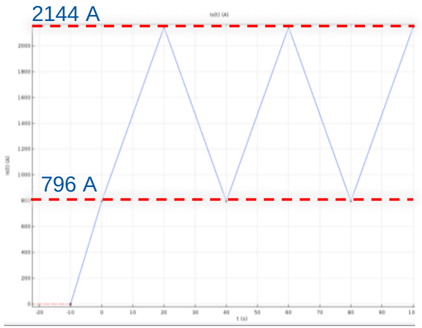


Case	**Field range (T)**	**dB/dt (T/s)**	**Cycle (s)**	**$fRho_{eff}$**	**PCL (J/m)**	**IFCL (J/m)**	**ISCL (J/m)**	**Wedges (J/m)**	**L_{AVG} (W/m)**	**dT_{max} (mK)**
Reference	0 .. 3	0.1	60	1	26.4	8.5	0.5	9.0	0.74	190

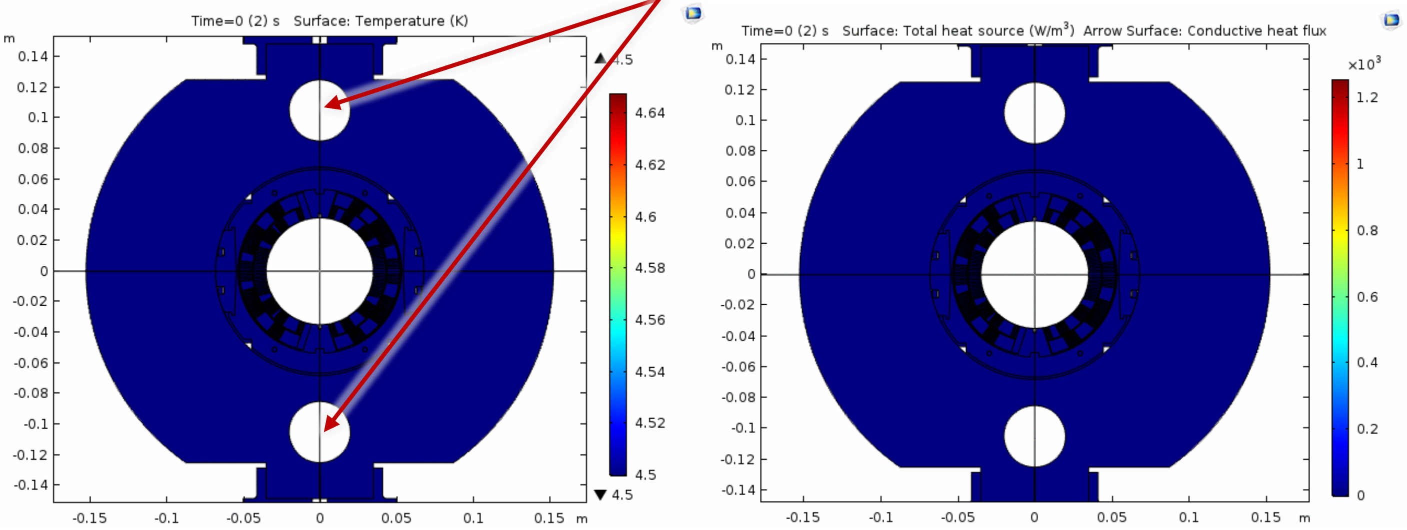
Transient analysis: Operational case (1 .. 3 T)

V. Ferrentino

- Quasi-steady state reached after two cycles of 40 s
- T_{max} = 4.65 K



Perfect heat sink a 4.5 K



Case	Field range (T)	dB/dt (T/s)	Cycle (s)	$fRho_{eff}$	PCL (J/m)	IFCL (J/m)	ISCL (J/m)	Wedges (J/m)	L_{AVG} (W/m)	dT_{max} (mK)
Expected operation	1 .. 3	0.1	40	1	14.1	4.5	0.3	4.7	0.59	150
Reference	0 .. 3	0.1	60	1	26.4	8.5	0.5	9.0	0.74	190

Transient analysis: “Worst” case

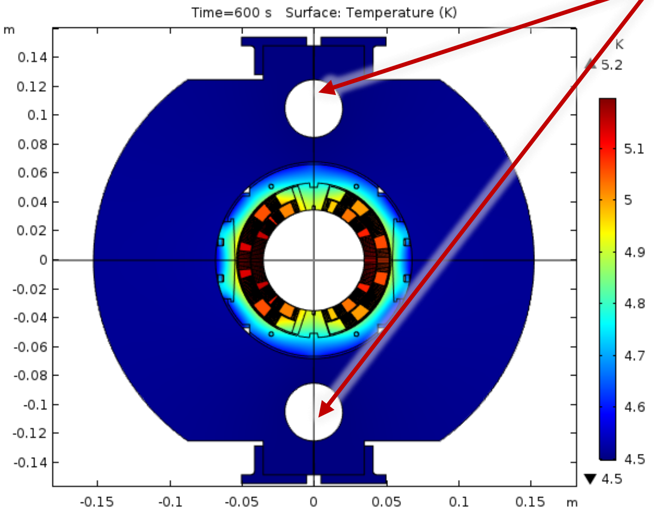
V. Ferrentino

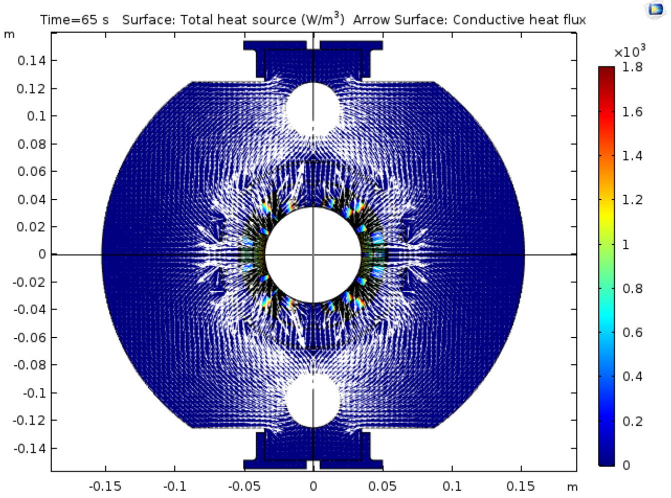
- Thermal conductivity at Coil-Collar / 4
- IFCL x 3
- PCL x 4 *(very pessimistic)*

- Quasi-steady state after **two** cycles of 60 s
- T_{max} = 5.2 K

- G10 wedges instead of Cu make it worse

Perfect heat sink a 4.5 K





Case	Field range (T)	dB/dt (T/s)	Cycle (s)	$fRho_{eff}$	PCL (J/m)	IFCL (J/m)	ISCL (J/m)	Wedges (J/m)	L_{AVG} (W/m)	dT_{max} (mK)
Expected operation	1 .. 3	0.1	40	1	14.1	4.5	0.3	4.7	0.59	150
Reference	0 .. 3	0.1	60	1	26.4	8.5	0.5	9.0	0.74	190
Worst (Cu-wedges)	0 .. 3	0.1	60	0.33	105.6	25.6	0.5	9.0	2.34	700
Worst (G10-wedges)	0 .. 3	0.1	60	0.33	105.6	25.6	0.5	0.0	2.19	800

Total cooling power for transient losses

- Scaling from Discorap(* gives a total of roughly 0.51 W/m per cycle for eddy current (collars, collaring keys, iron) and hysteresis (iron) losses in the cold mass for the conservative power cycle of the reference case

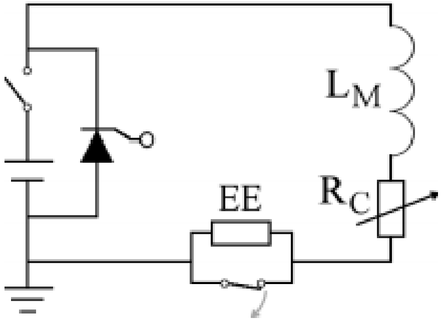
- For the **reference case (0 .. 3 T)** the coil loss is 0.74 W/m and the total loss below 1.25 W/m per 60 s cycle (or below 2.2 W for 45° magnet)

- For the **expected operation (1 .. 3 T)** the coil loss is 0.65 W/m and the total loss below 1 W/m per 40 s cycle (or 1.6 W for 45° magnet)

*)*INFN-13-06/GE 22 th May 2013, TECHNICAL DESIGN REPORT OF THE SUPERCONDUCTING DIPOLE FOR FAIR SIS300*

Quench protection system

- The quench protection analysis has been performed with STEAM – LEDET tool for **3 x 45°magnet in series**
- **Goals:**
  - Peak hot-spot temperature < 300K
  - Peak voltage < 1 kV



- An energy extraction system based on 90 mΩ R_{EE}
  - Quench detection and validation = (5 + 10) ms = 15 ms
  - Energy extraction switch opening = 5 ms
  - **T_{max} < 70 K**
  - **U_{max} < 200 V**

E. Ravaioli & V. Ferrentino

Present Design Status

- **Conceptual design**:
  - **Electro-magnetic design** well understood, design & analysis tools developed
  - **Structural optimization and sensitiviy analysis** were carried out taking into account realistic manufacturing tolerances
  - **Thermal modelling of transient heat losses** completed with very encouraging results
  - **Quench protection** study based on energy extraction completed
  - **Link to beam dynamics** in terms of field quality definition being studied

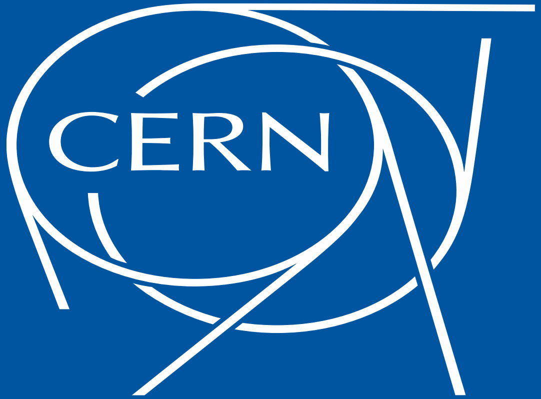
- **Engineering design** (next step):
  - **Final design optimisation** to meet all design requirements
  - **Integration of the cooling features** in the cold mass and associated heat transfer study
  - **Manufacturing design** of magnet components and tooling

Summary

- The proposed combined function magnet, based on the technologies extensively developed for the LHC project, meets the present specification and includes several gantry-specific features that would be validated by a demonstrator magnet
- Conservative parameters chosen to ensure comfortable operational margins and to maximise the reliability of the magnets
- Transient losses to be extracted from the cold mass by the cryogenics are less than 2 W/m
- 3 x 45° magnets in series can be protected with simple energy extraction

- The goal is to test the demonstrator magnet in He-bath by 2023-2024
- Construction and test as a complete system including the features for conduction cooling based on cryocoolers possibly at a later stage depending on the available resources

- The lessons from the 30° demonstrator magnet will be implemented in the design of the 45° prototype magnet targeting the final gantry specification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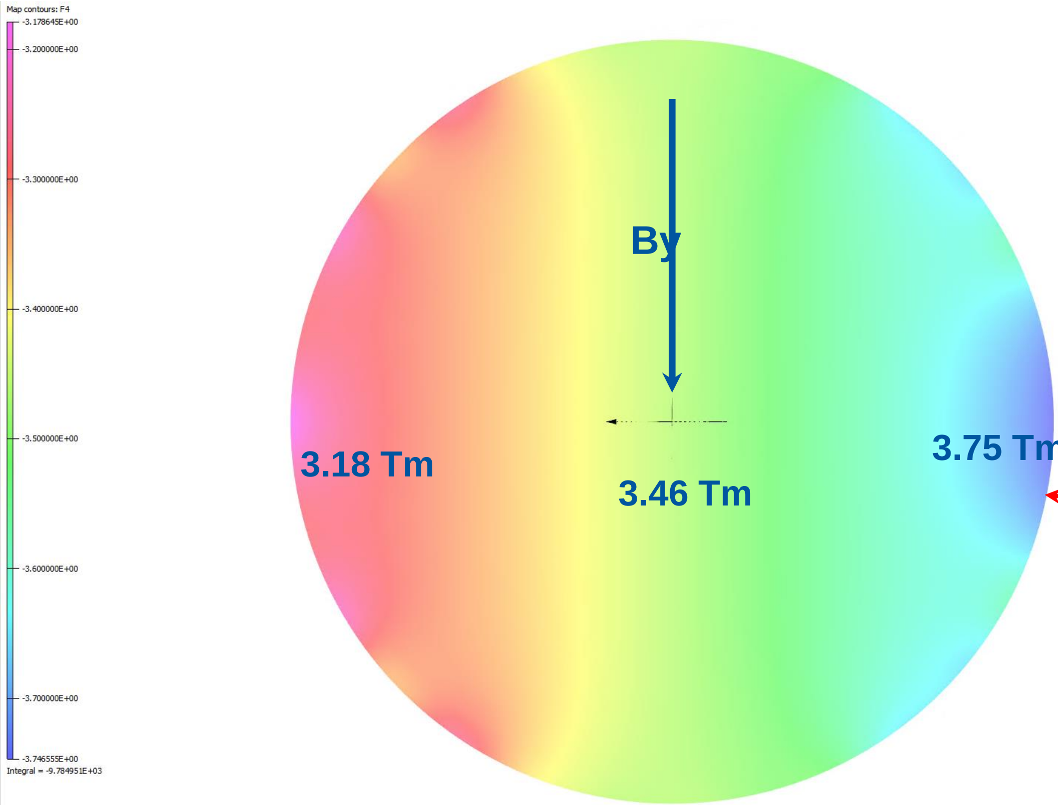
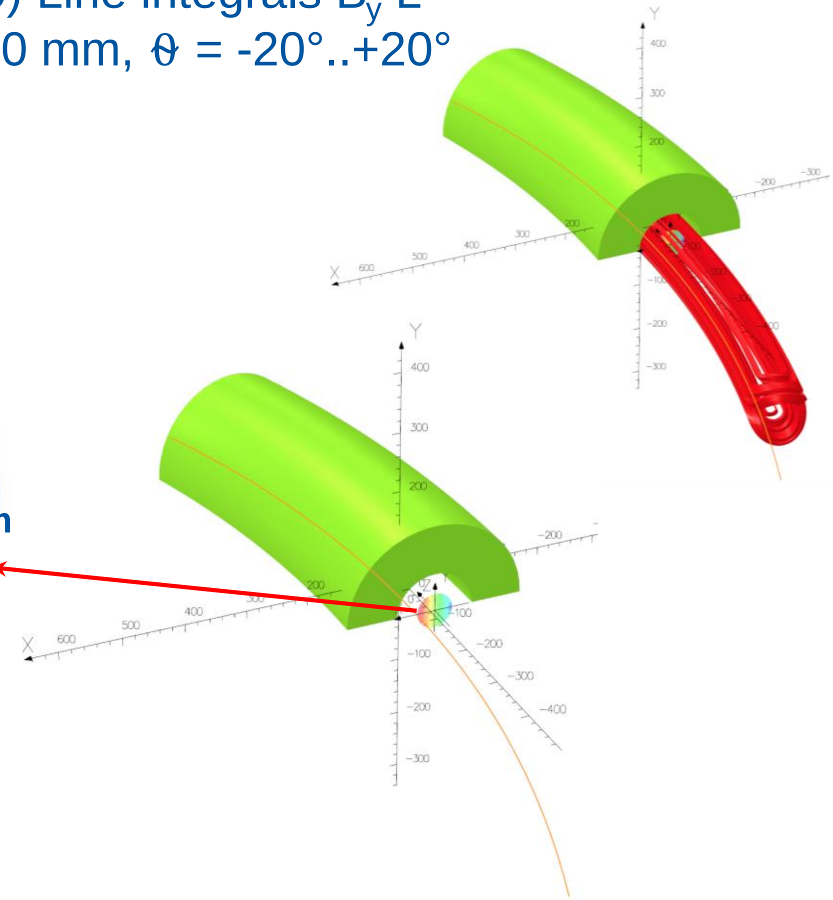
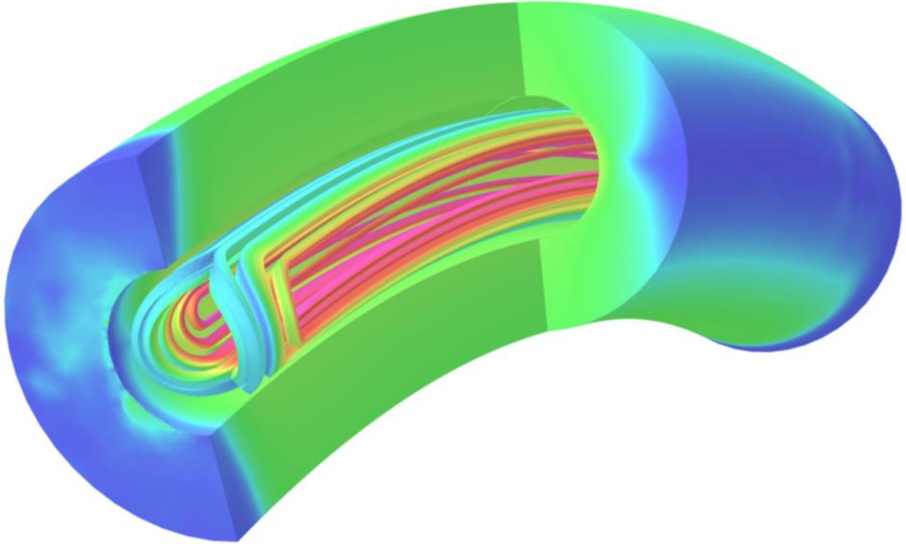
Complementary slides

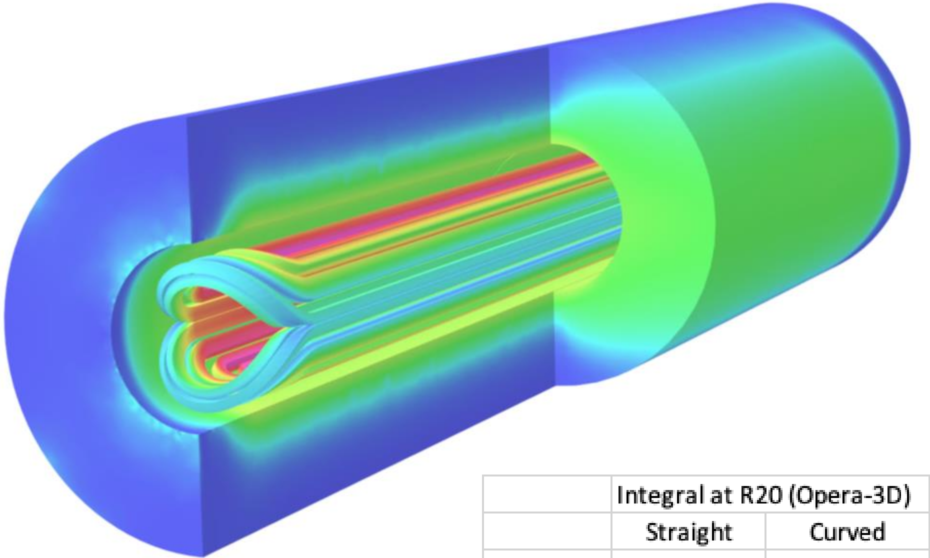
Summary of 2700 (15 x 180) Line integrals B_y L within a toroidal sector R < 30 mm, ϑ = -20°..+20°





“Pure Dipole”

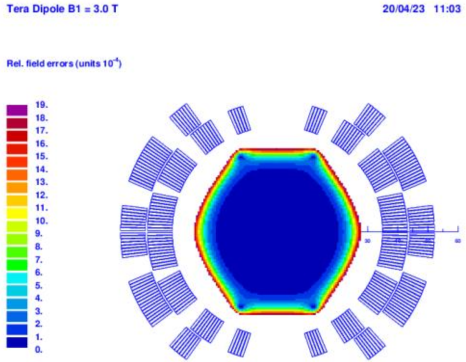




Perfect agreement of L_{mag} = 1.22 m and B1 = 3.66 Tm

Curvature gives -100.9 units of b2 (G = 1.85 T/m) and about 0.5 units of b3

Field calculated from line integrals along toroidal/cylindrical surface

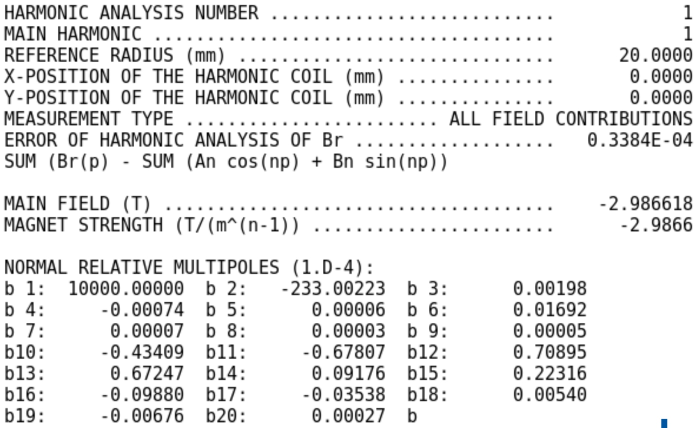


	Integral at R20 (Opera-3D)	
	Straight	Curved
B1 (Tm)	-3.66	-3.66
b2 (unit)	0.00	-100.86
b3 (unit)	-12.64	-13.18
b4 (unit)	0.00	0.52
b5 (unit)	-2.34	-2.55
b6 (unit)	0.00	-0.01
b7 (unit)	0.33	0.48
b8 (unit)	0.00	-0.01
b9 (unit)	-0.16	0.40
b10 (unit)	0.00	-0.03
b11 (unit)	0.66	1.06

Low Current MBCFD Main Design Features

- 8-way ribbon made with LHC wire #4 (1.53x0.85 metal, 60 µm PVA)
- Wires in the cable connected in series on the end plate
- Nominal current 584 A
- Single layer epoxy impregnated coil
- B_{nom} = 3 T
- G_{nom} = 2 T/m (in focussing configuration)
- Margin at 4.5 K / 6 K = 40 % / 18 %
- Inductance 144 mH/m (10 X 2-layer design)
- Collared coil and laminated yoke (similar to 2-layer design)

Low current MBCFD



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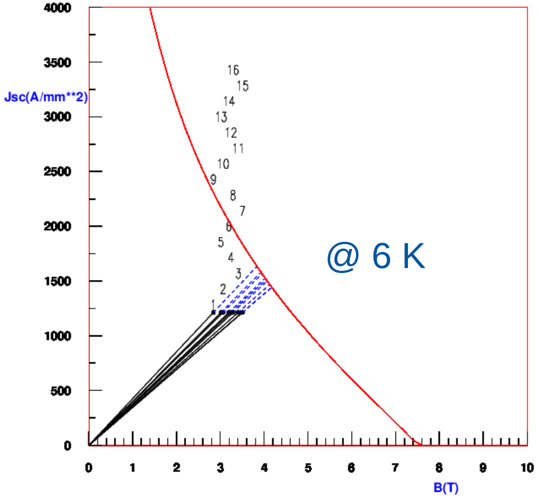
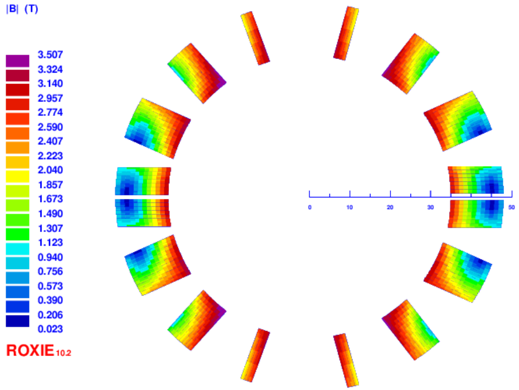
HARMONIC ANALYSIS NUMBER ...........................          1
MAIN HARMONIC ......................................          1
REFERENCE RADIUS (mm) ..............................    20.0000
X-POSITION OF THE HARMONIC COIL (mm) ...............     0.0000
Y-POSITION OF THE HARMONIC COIL (mm) ...............     0.0000
MEASUREMENT TYPE ....................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ...................   0.3384E-04
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

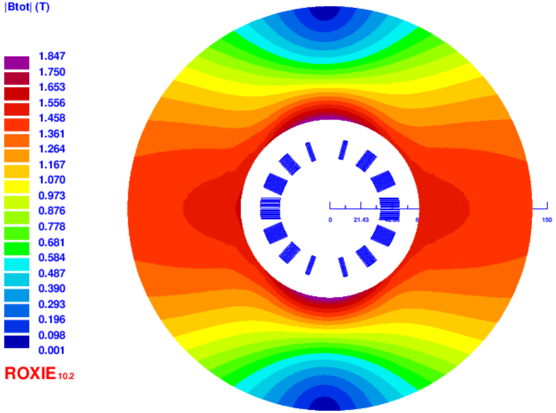
MAIN FIELD (T) .....................................   -2.986618
MAGNET STRENGTH (T/(m^(n-1)) .......................     -2.9866

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:   -233.00223  b 3:      0.00198
b 4:      -0.00074  b 5:      0.00006  b 6:      0.01692
b 7:       0.00007  b 8:      0.00003  b 9:      0.00005
b10:      -0.43409  b11:     -0.67807  b12:      0.70895
b13:       0.67247  b14:      0.09176  b15:      0.22316
b16:      -0.09880  b17:     -0.03538  b18:      0.00540
b19:      -0.00676  b20:      0.00027  b
```



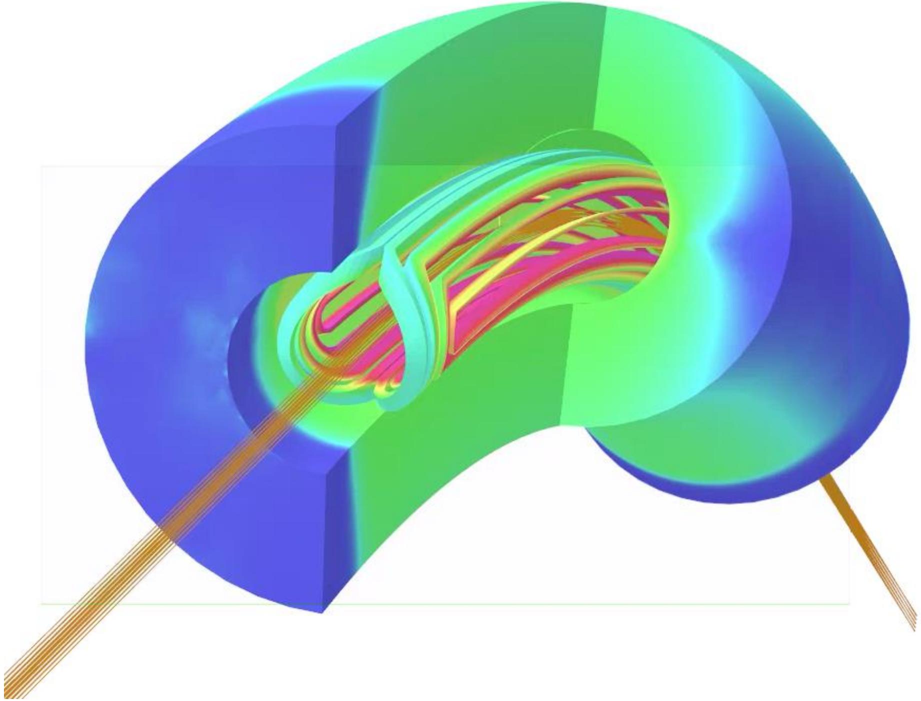
@ 6 K



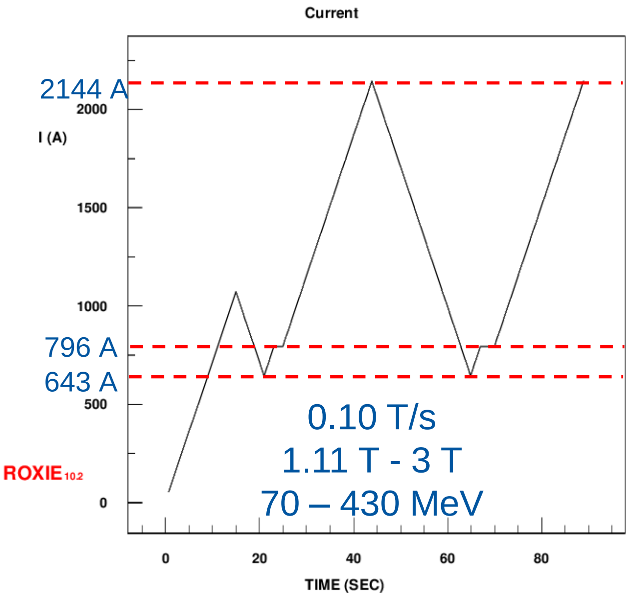


Low current MBCFD (30° Design)

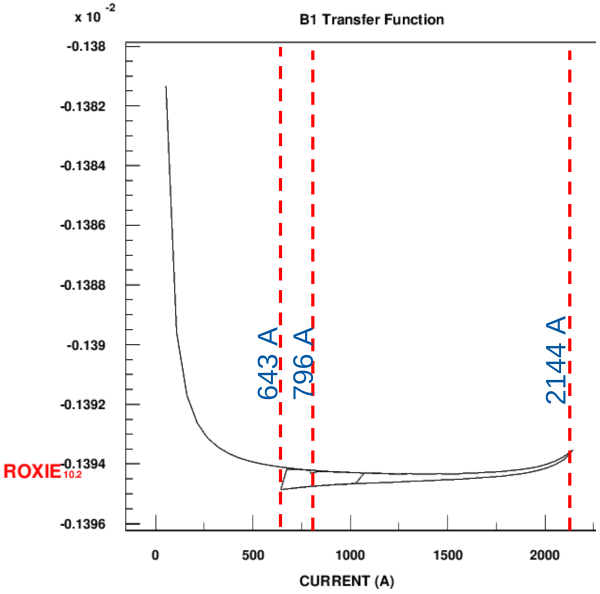
	Curved (F)
B1 (Tm)	3.45
b2 (unit)	134.1
b3 (unit)	-7.4
b4 (unit)	0.4
b5 (unit)	7.5
b6 (unit)	0.8
b7 (unit)	0.6
b8 (unit)	0.5
b9 (unit)	-0.7
b10 (unit)	-0.2
b11 (unit)	0.0
B2(T/m m)	2.32
Lmag(m)	1.154
G(T/m)	2.01

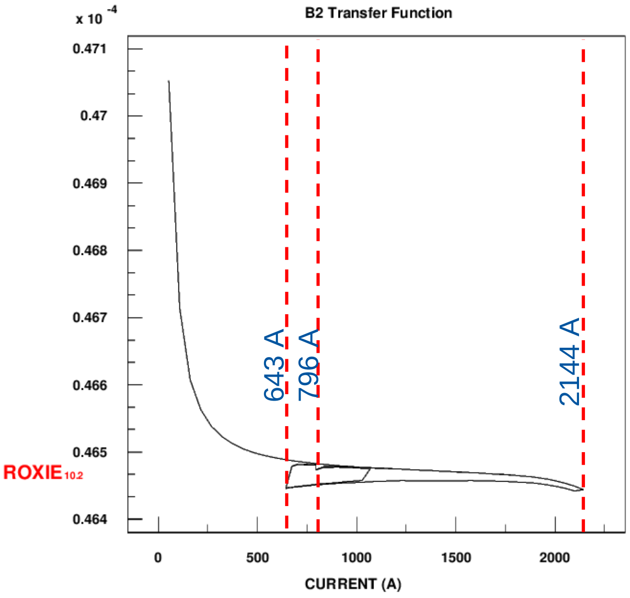


Transient Effects: TF of Main Components



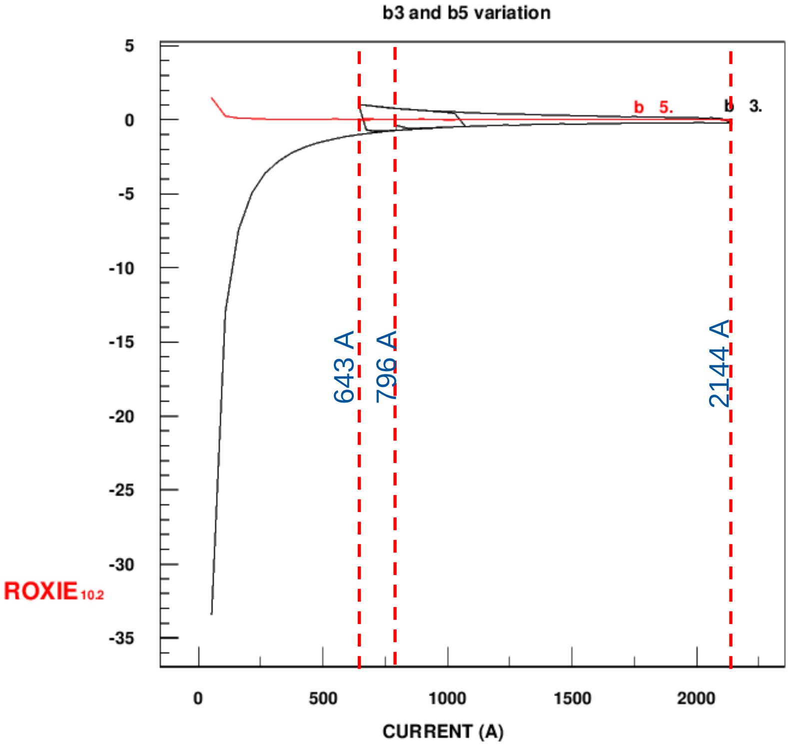
0.10 T/s
1.11 T - 3 T
70 – 430 MeV





I_{reset} of 640 A reduces transient coil losses by about 40 % wrt 0-current.

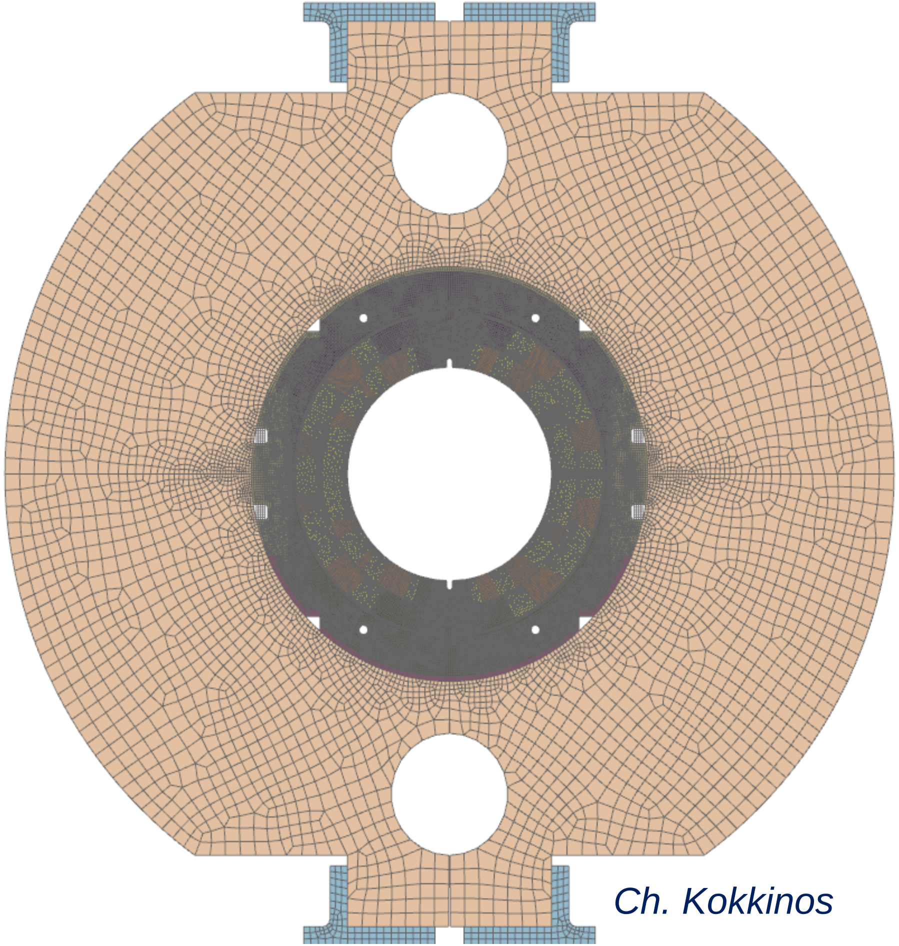
Transient Effects : b3 & b5



Structural Analysis

Design goals:

- Static and mechanically rigid structure
- Coil stress <150 MPa at all times
- No unloading at the poles
- Smooth stress gradients in coils
- Maximal contact area on collar-yoke interface for minimal thermal resistance
- Minimal distortion of circular coil shape
- Assembly parameters achievable with practical tolerances on parts and sub-assemblies
- Easy integration of cooling system



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`	Material	Mechanical Properties						Thermal Properties (Tref =293K, Top=4.5K)				EM Properties (Tref =293K) (magn.length1.15m)			
		E [GPa]		Prxy		Stress limit [MPa]		k @ 4.5K	Cp @ 4.5K	a		Electrical Conductivity @ 4.5 K	Electrical Relative permittivity	Magnetic Relative Permeability	density
		@ 300K	@ 4.5K	@ 300K	@ 4.5K	@ 300K	@ 4.5K	[W/m*K]	[J/kg*K]	K^{-1} (293K -> 4.5K)	mm/m	S/m			Kg/m3
Outer Shell Collars Poles Keys	Austenitic Steel 316LN	191	210.1	0.28	0.28	350	1050	0.32	22190	$9.70537e^{-6}$	2.8	1.827*e6	1	1.02	1
Yoke	Silicone Steel	204	224.4	0.28	0.28	230	720	35 (@293K)	0.40	$6.93241e^{-6}$	2	1.12*e7	1	BH-Curve (EBG1200-100A)	
Insulation	G10	25	27.5	0.2	0.2	150	150	0.079	5300	$8.66551e^{-6}$	2.5	10	1	1	
Wedges	Copper	100	110	0.3	0.3	250	250	715 (RRR=100)	1080	$1.16811e^{-5}$	3.37	3.11*e9	1	1	
Coil	NbTi	15	20	0.3	0.3	150	150	0.123	5740	$1.7e^{-5}$	4.9	$58e^{6}$ (perfect conductor)	1	1	

Ref: CERN, FCC, NbTi from MCXB/MCQX

Ref: Sigma

Ref: CERN FCC, NbTi from MCXB/MCQX

Ref: Sigma, SIEMENS

Ref: CERN

NOTES:

- Electrical permittivity (ε), is a measure of the electric polarizability of a dielectric. A material with high permittivity polarizes more in response to an applied electric field than a material with low permittivity, thereby storing more energy in the material.
- Relative permittivity εr is the ratio of the absolute permittivity ε and the vacuum permittivity ε0 [εr = ε/ε0].

- Electrical resistivity ρ [Ω·m] and its inverse, electrical conductivity, is a fundamental property of a material that quantifies how strongly it resists or conducts electric current. A low resistivity indicates a material that readily allows electric current. Electrical conductivity σ [S/m] represents a material's ability to conduct electric current.

- Magnetic Permeability (μ) [H/m]: the measure of the resistance of a material against the formation of a magnetic field. Hence, it is the degree of magnetization that a material obtains in response to an applied magnetic field.
- Magnetic constant or the permeability of free space μ_0, is a measure of the amount of resistance encountered when forming a magnetic field in vacuum. $\mu_0 = 4\pi \times 10^{-7}$ H/m ≈ 12.57×10^{-7} H/m.
- Relative permeability, denoted by the symbol μr is the ratio of the permeability of a specific medium to the permeability of free space μ0: μr = μ / μ0

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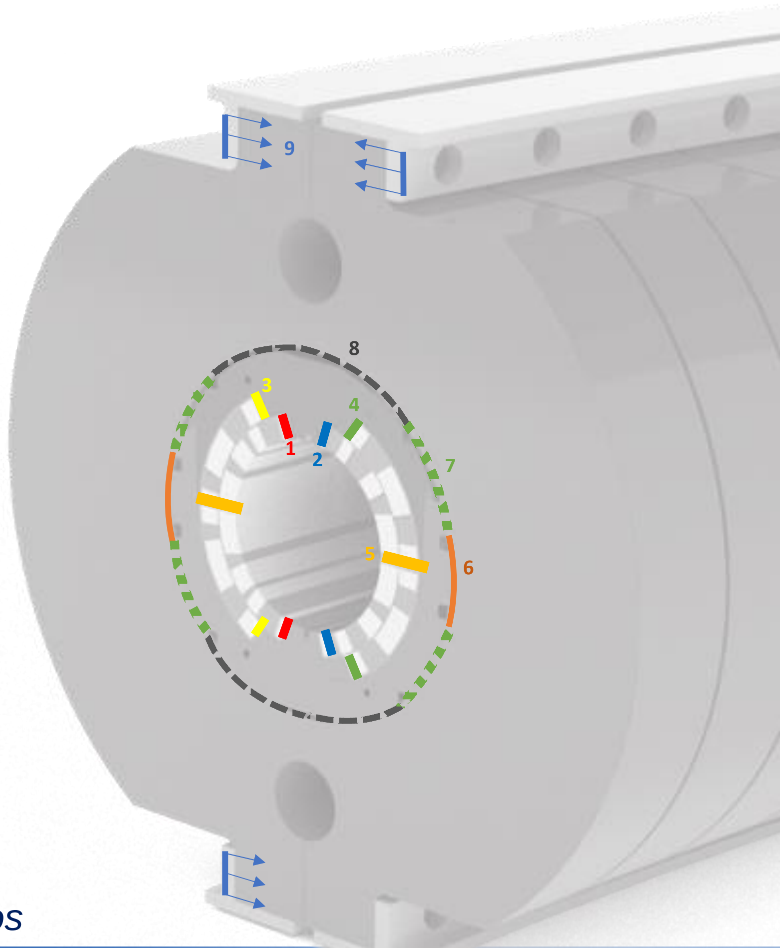
Assembly Parameters

Assembly parameters used for the results presented below:

Shimming Interface	Shim #	Direction	Interference [mm]
Coil Pole Shim – Inner Layer - LEFT	1	Azimuthal	0.00
Coil Pole Shim – Inner Layer - RIGHT	2	Azimuthal	0.00
Coil Pole Shim – Outer Layer - LEFT	3	Azimuthal	0.00
Coil Pole Shim – Outer Layer - RIGHT	4	Azimuthal	0.00
Coil Midplane	5	Vertical	0.04 (total)
Collar – Yoke [± (0˚ - 20˚)]	6	Radial	0.1
Collar Yoke [± (20˚ - 45˚)]	7	Radial	0.06
Collar Yoke [± (45˚ - 90˚)]	8	Radial	0.05
Bolt Preload	9	Vertical	0.4 (per side)



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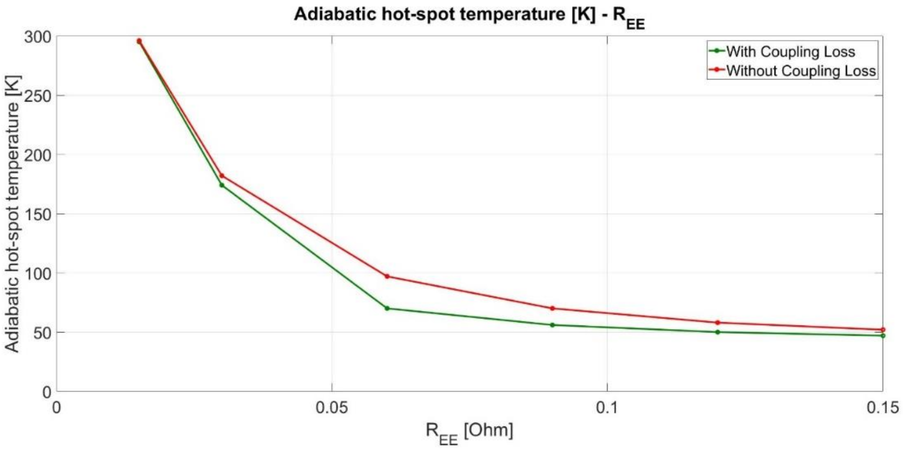
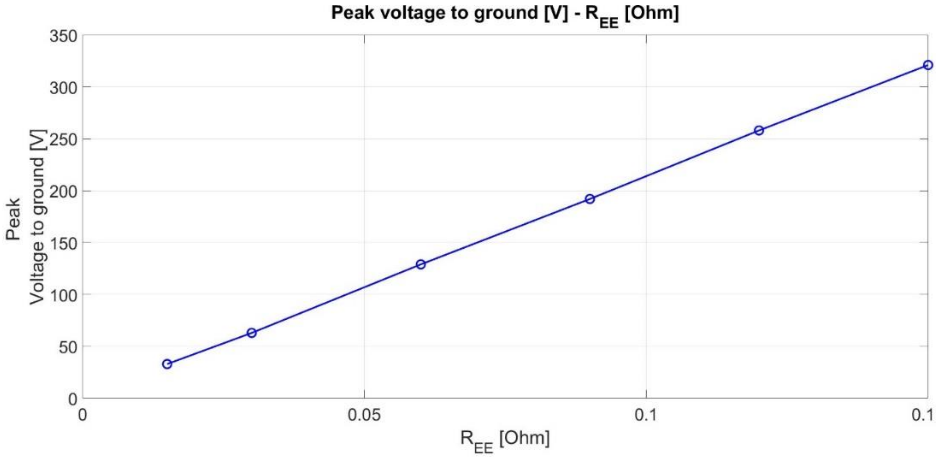
Quench protection: EE-Resistance

- R_{EE} = 90mΩ comfortably meets the goals
- T_{max} = 70 K
- U_{max} = 200 V





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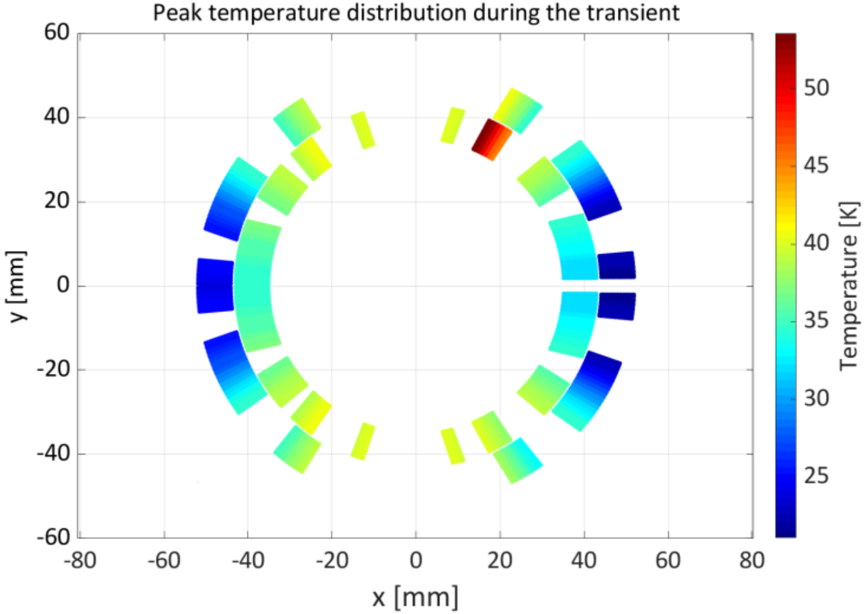
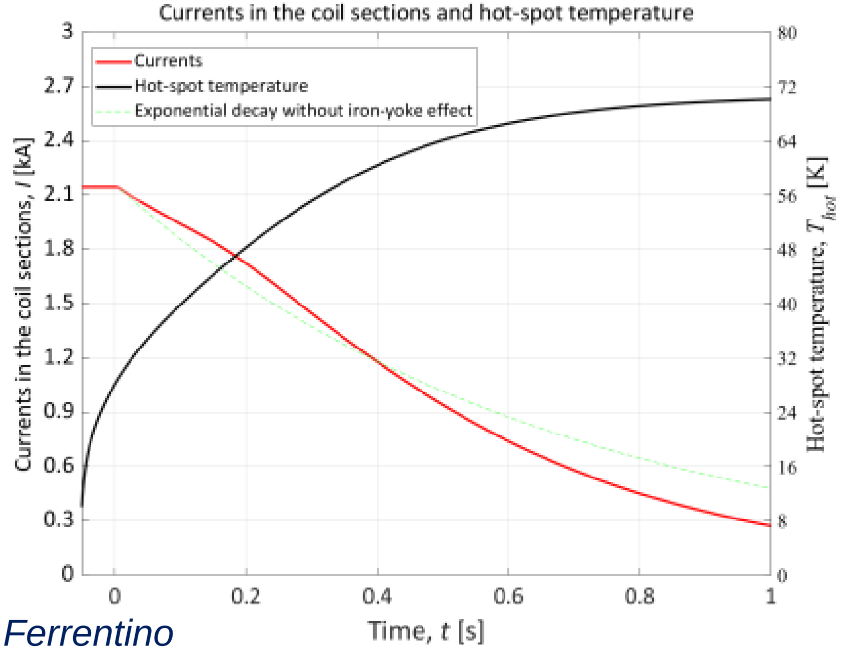
Quench protection: Hot-spot temperature

- $R_{EE} = 90\ m\Omega$
- $T_{max} < 75$ K (without IFCL, conservative)





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