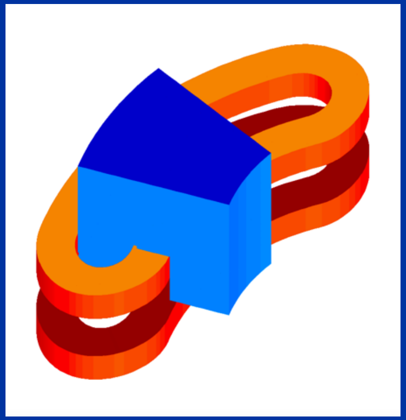
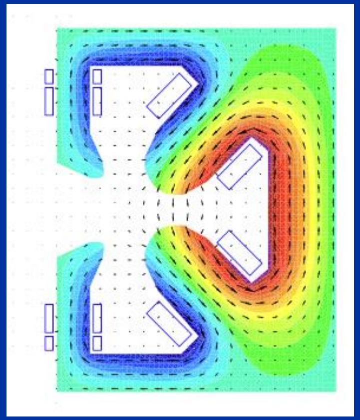
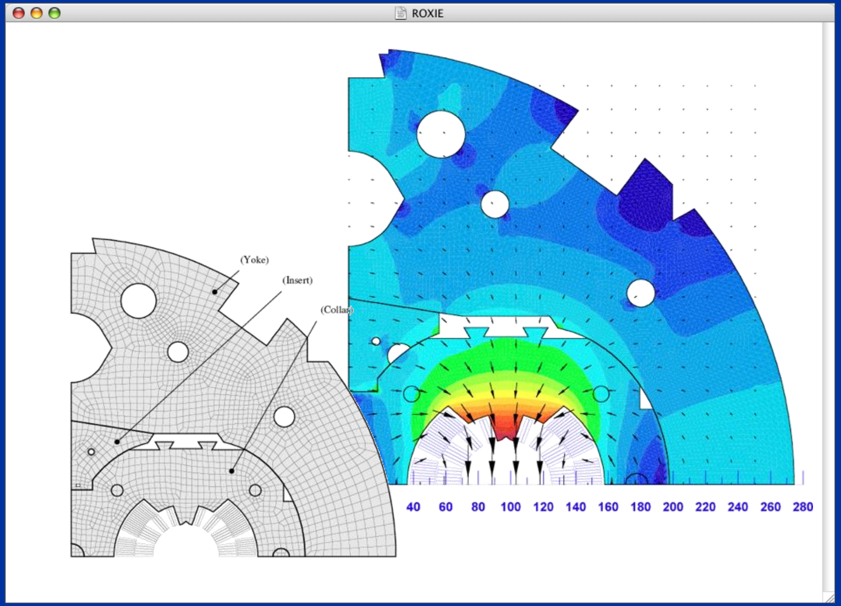
ROXIE 23 Launch Event

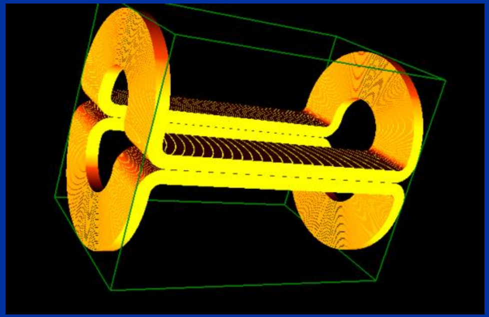


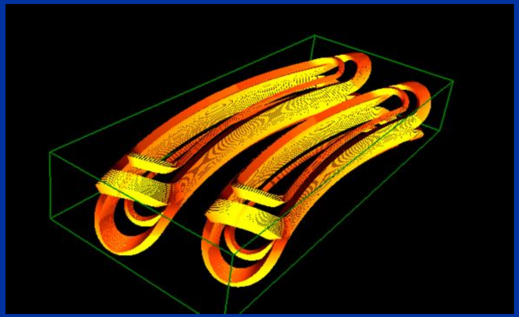


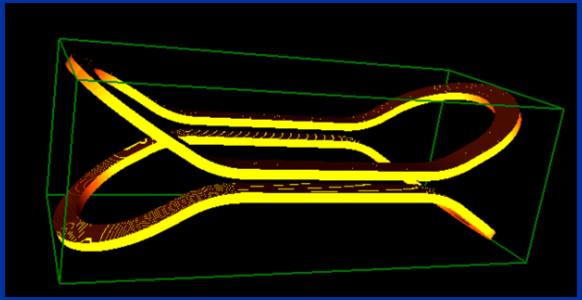
Conceptual Coil Design
Shape Optimization
Persistent Current Calculation
Quench Simulation
Coil-Head Optimization
End-Spacer Design
Inverse Field Computation
Data-Driven Modeling
Product-Cycle Engineering

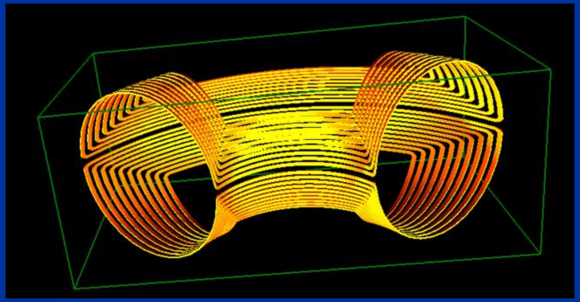


Improved Pre-Processor
CCT Coil Generator
Search-Coil Design
Strongly Curved Magnets
Python Interface
Maxwell Stresses









Aix-en-Provence, 11.09.2023, 14:00 – 16:30

ROXIE Features

Automatic generation of coil and yoke geometries

- Feature-based design

Field computation especially suited for magnet design (BEM-FEM)

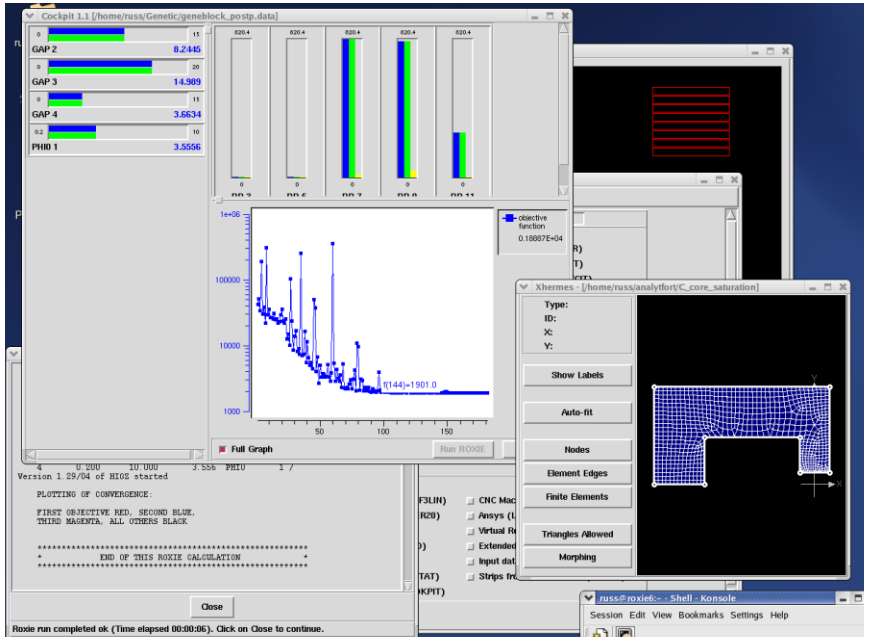
- No meshing of the coil, no artificial boundary conditions
- Higher order quadrilateral meshes, parametric mesh generator, morphing
- Modeling of superconductor magnetization
- Permanent magnets
- Quench simulation of long accelerator magnets (2.5 D)

Mathematical optimization techniques

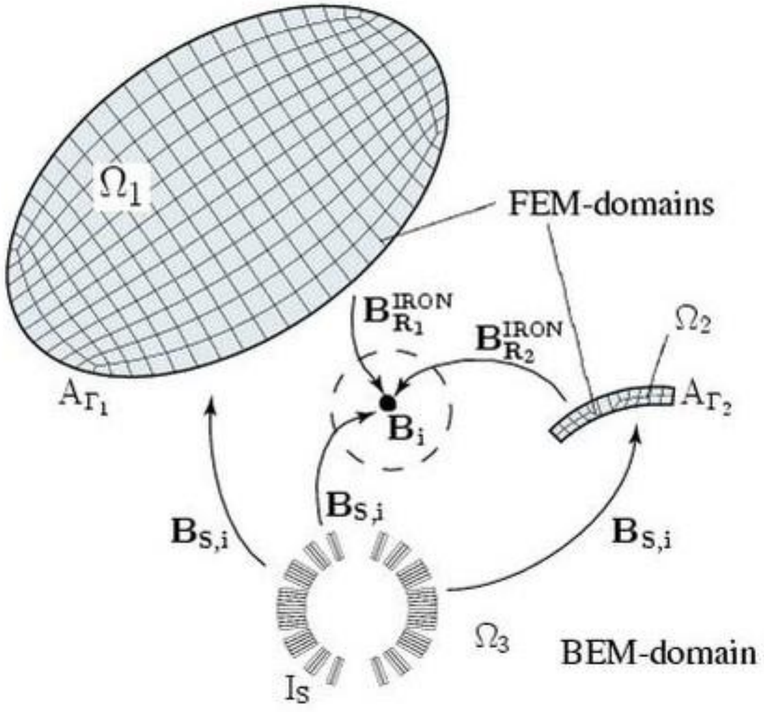
- Genetic optimization, Pareto optimization, Search algorithms

Simulation of magnetic measurements

CAD/CAM interfaces



BEM-FEM Coupling



BEM

$$\{Q\} = -[G]^{-1}[H]\{A\} + [G]^{-1}\{A_s\}$$

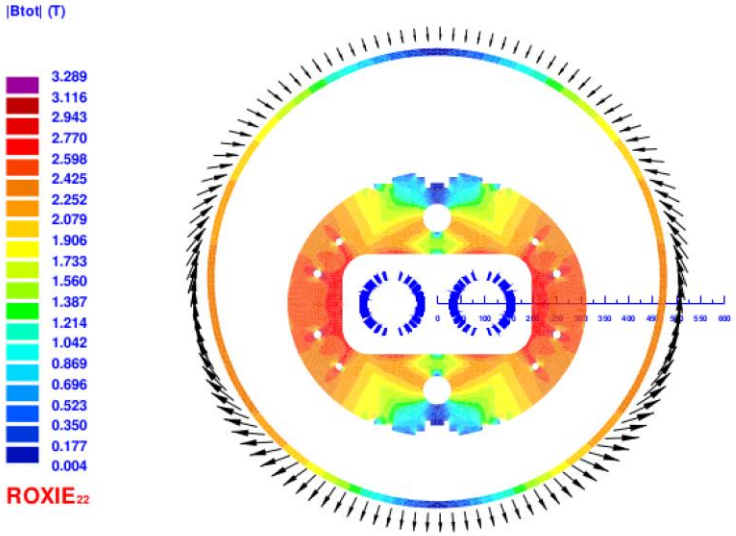
FEM

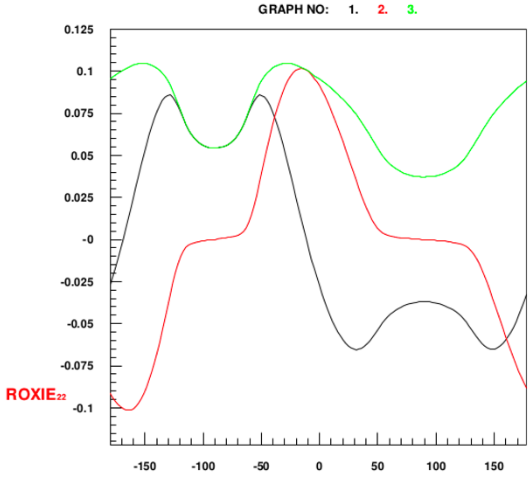
$$[K]\{A\} - [T]\{Q\} = \{F(\mathbf{M})\}$$

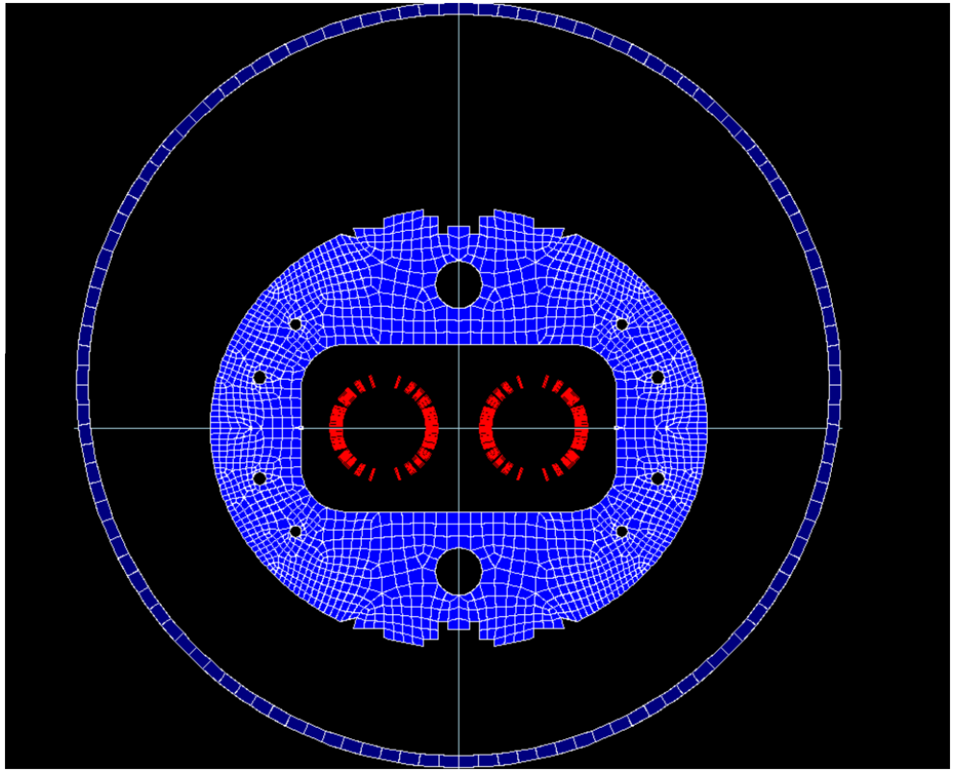
$$\left([K] + [T][G]^{-1}[H]\right)\{A\} = \{F(\mathbf{M})\} + [T][G]^{-1}\{A_s\}$$

$$[\overline{K}]\{A\} = \{\overline{F}(A_s, \mathbf{M})\}$$

HL-LHC Model D2

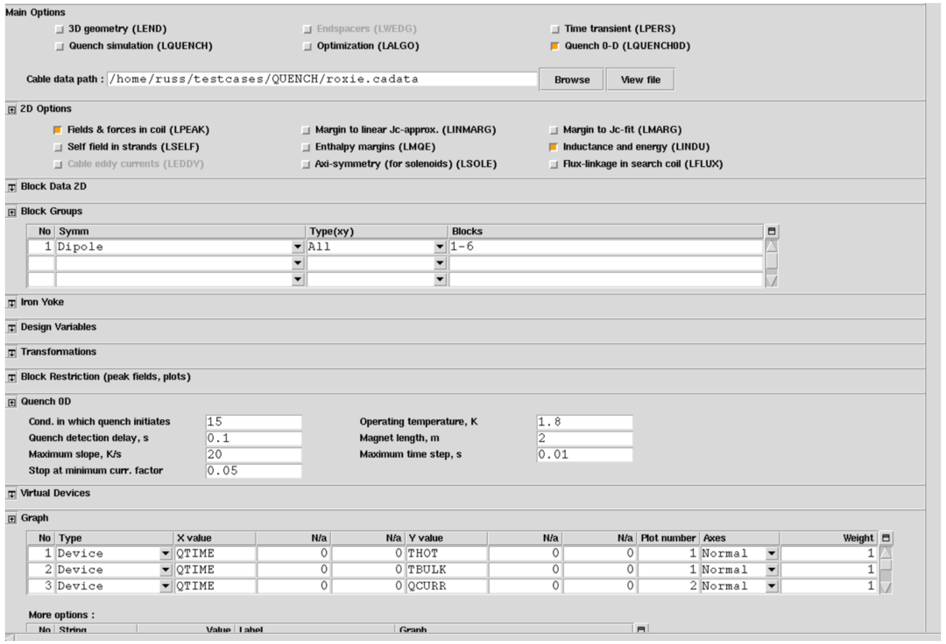


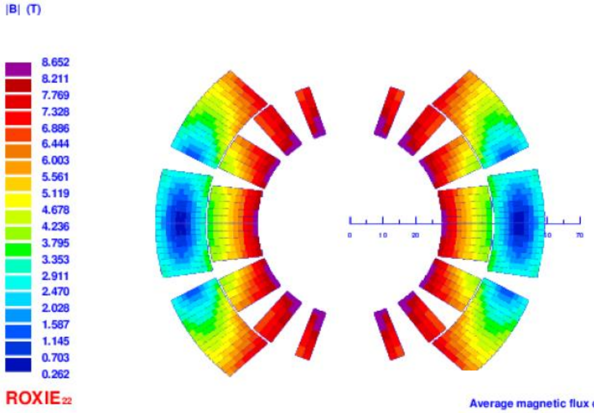


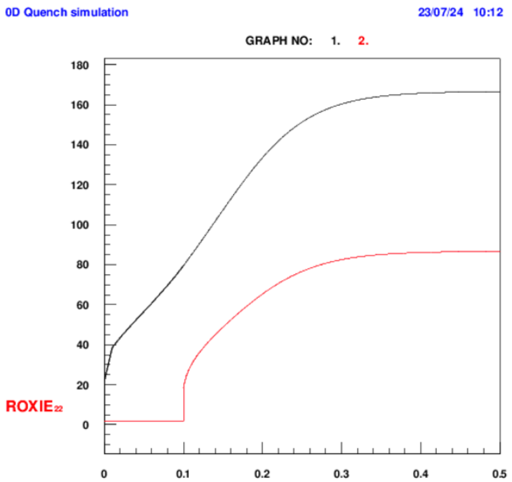


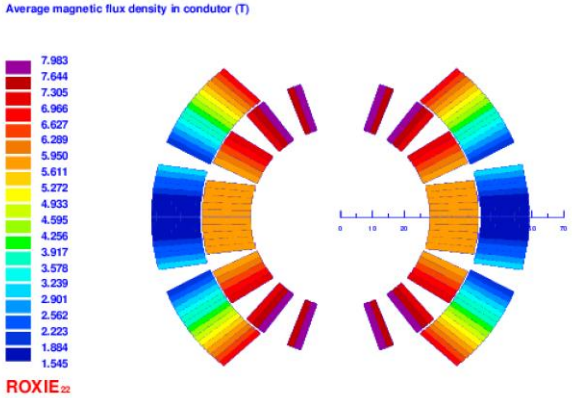
New ROIXE23 Features

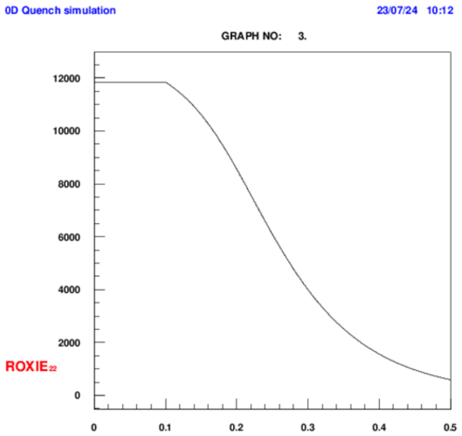
Adiabatic Quench Simulation



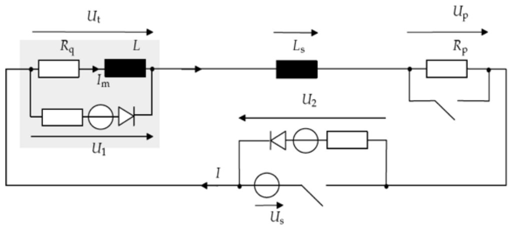
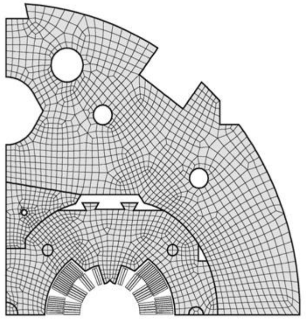
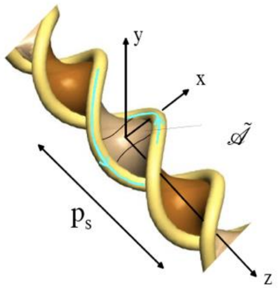
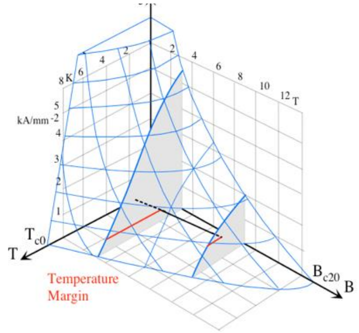




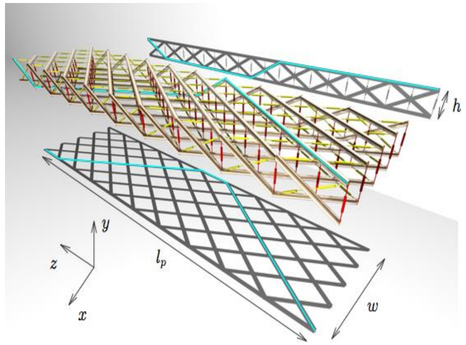
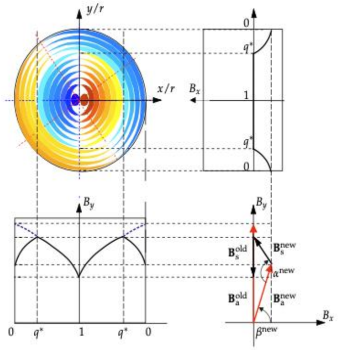
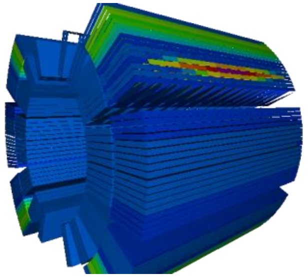




Multiphysics Quench Simulation (2.5 D)

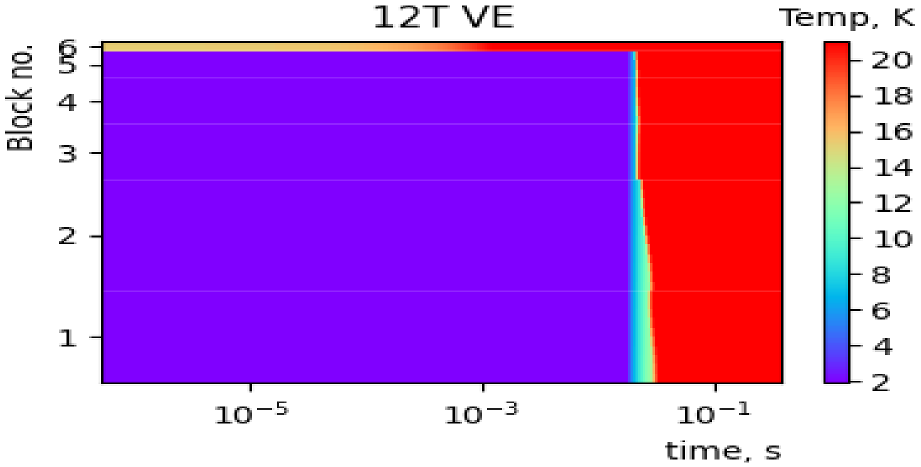





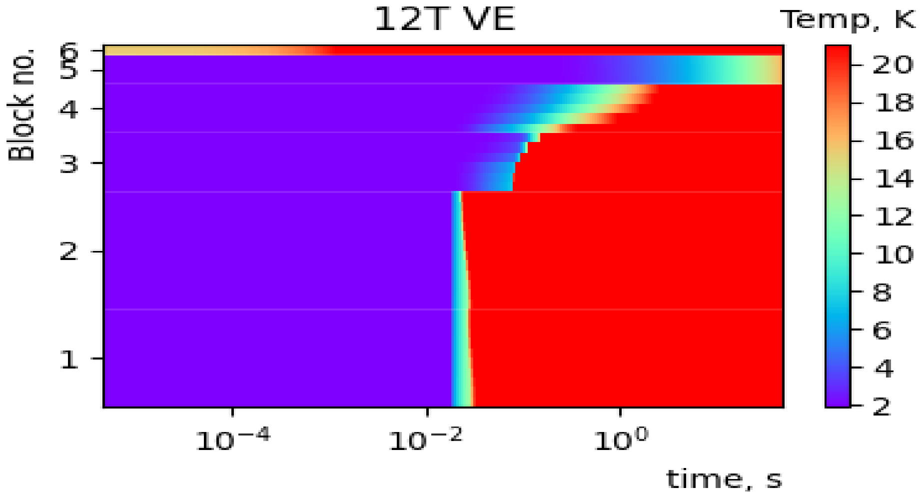
Quench Simulation

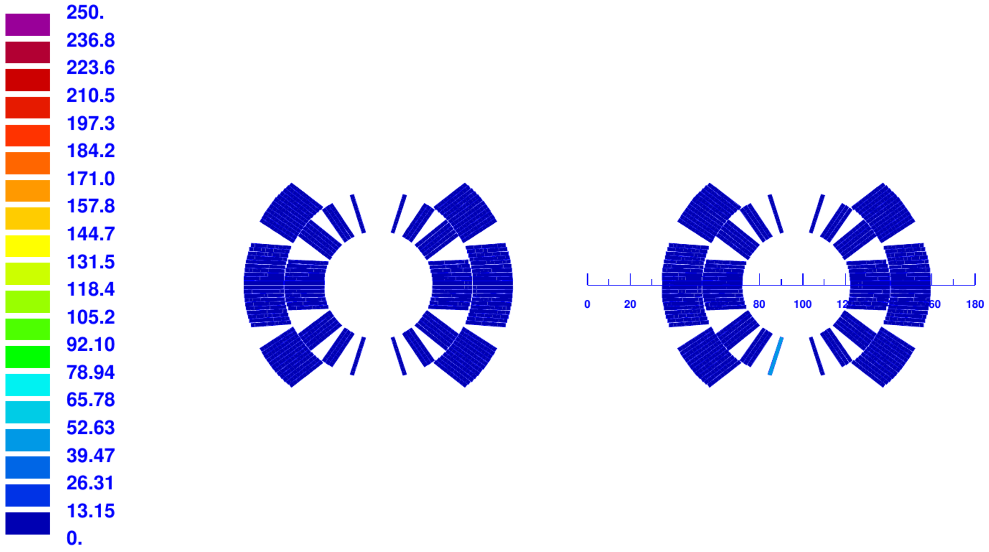
Issue: Empirical parameters: RRR, Ra/Rc, IFCC effective res., heat conductivity, heat capacity.

Multiphysics Quench Simulation (2.5 D)

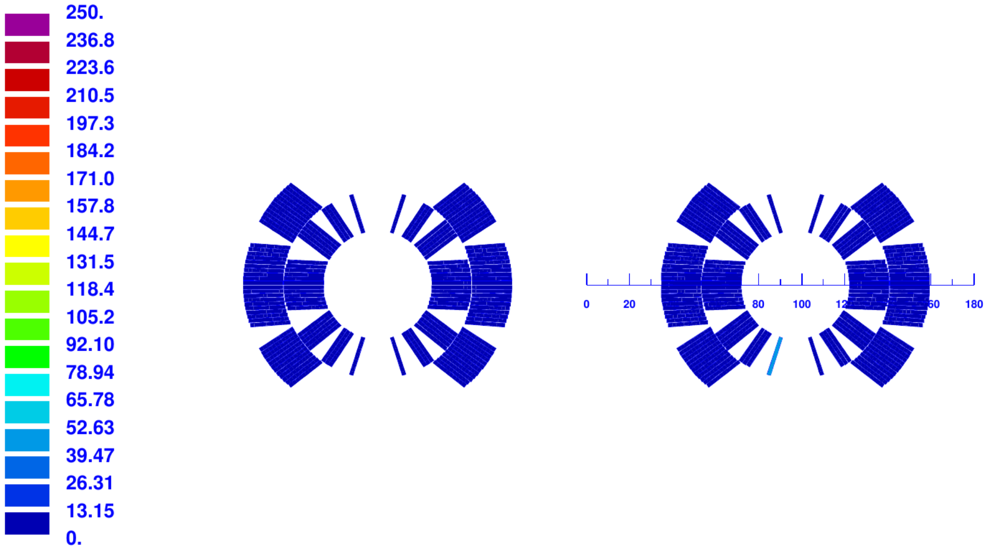




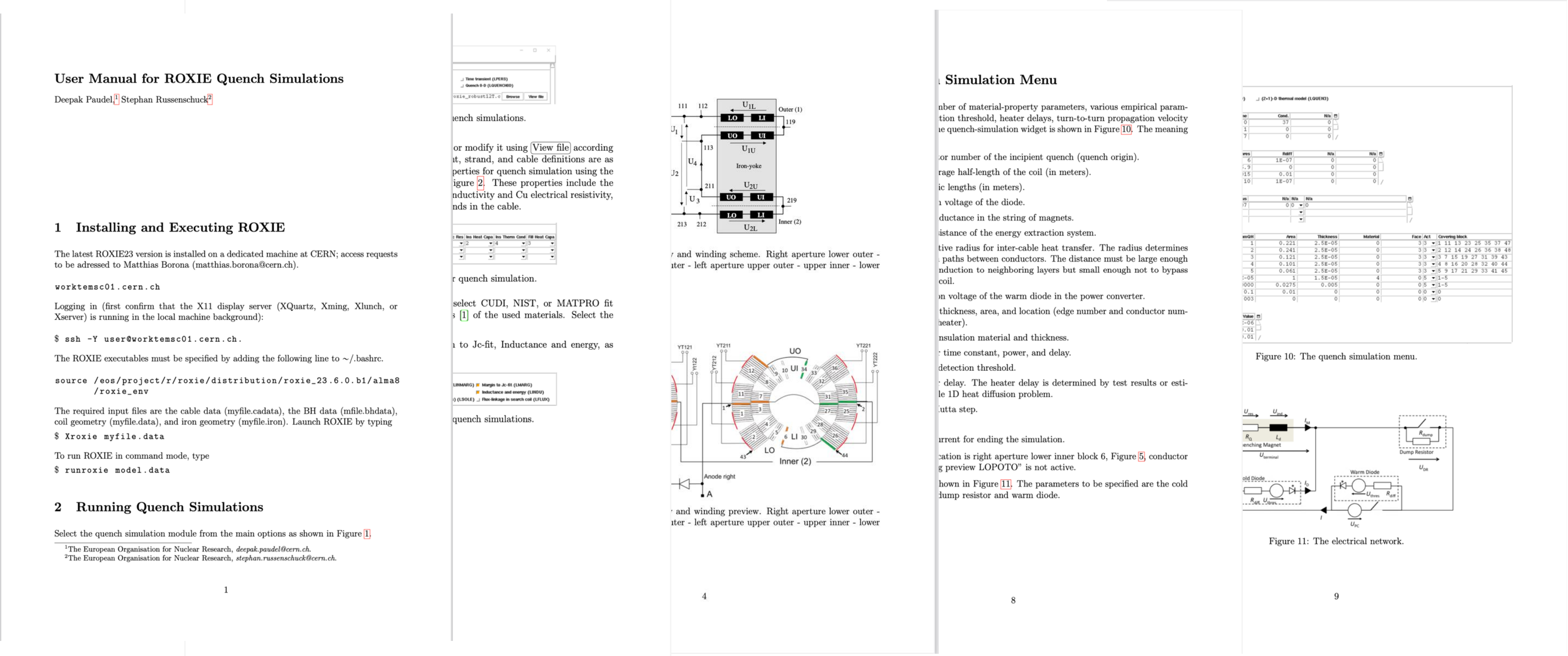
T (K)
Time (s) : 0.02037



T (K)
Time (s) : 0.0223



User Manual for Quench Simulation



User Manual for ROXIE Quench Simulations

Deepak Paudel,[1] Stephan Russenschuck[2]

1 Installing and Executing ROXIE

The latest ROXIE23 version is installed on a dedicated machine at CERN; access requests to be adressed to Matthias Borona (matthias.borona@cern.ch).

```
worktemsc01.cern.ch
```

Logging in (first confirm that the X11 display server (XQuartz, Xming, Xlunch, or Xserver) is running in the local machine background):

```
$ ssh -Y user@worktemsc01.cern.ch.
```

The ROXIE executables must be specified by adding the following line to ~/.bashrc.

```
source /eos/project/r/roxie/distribution/roxie_23.6.0.b1/alma8
        /roxie_env
```

The required input files are the cable data (myfile.cadata), the BH data (mfile.bhdata), coil geometry (myfile.data), and iron geometry (myfile.iron). Launch ROXIE by typing

```
$ Xroxie myfile.data
```

To run ROXIE in command mode, type

```
$ runroxie model.data
```

2 Running Quench Simulations

Select the quench simulation module from the main options as shown in Figure 1.

[1]The European Organisation for Nuclear Research, deepak.paudel@cern.ch.
[2]The European Organisation for Nuclear Research, stephan.russenschuck@cern.ch.

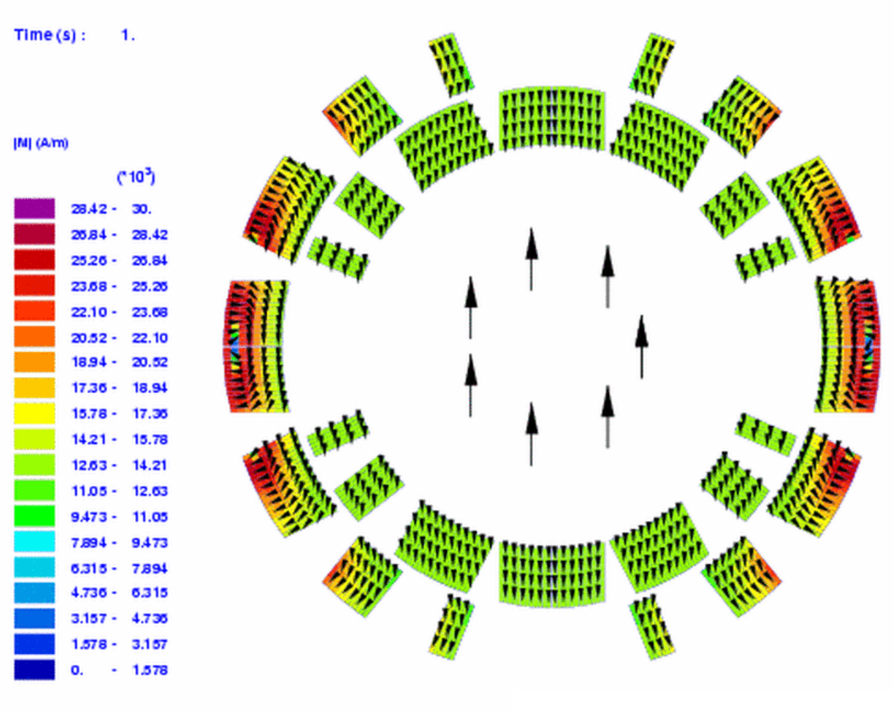
1

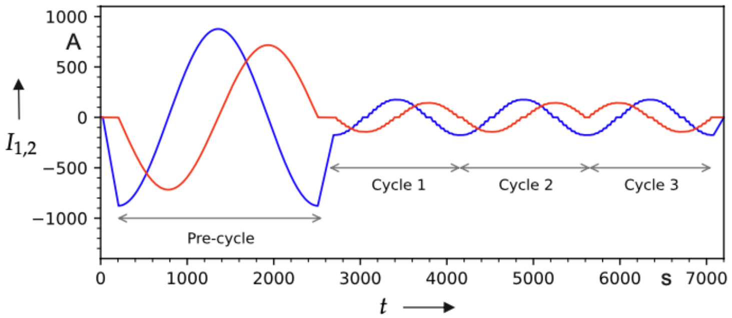
Simulation Menu

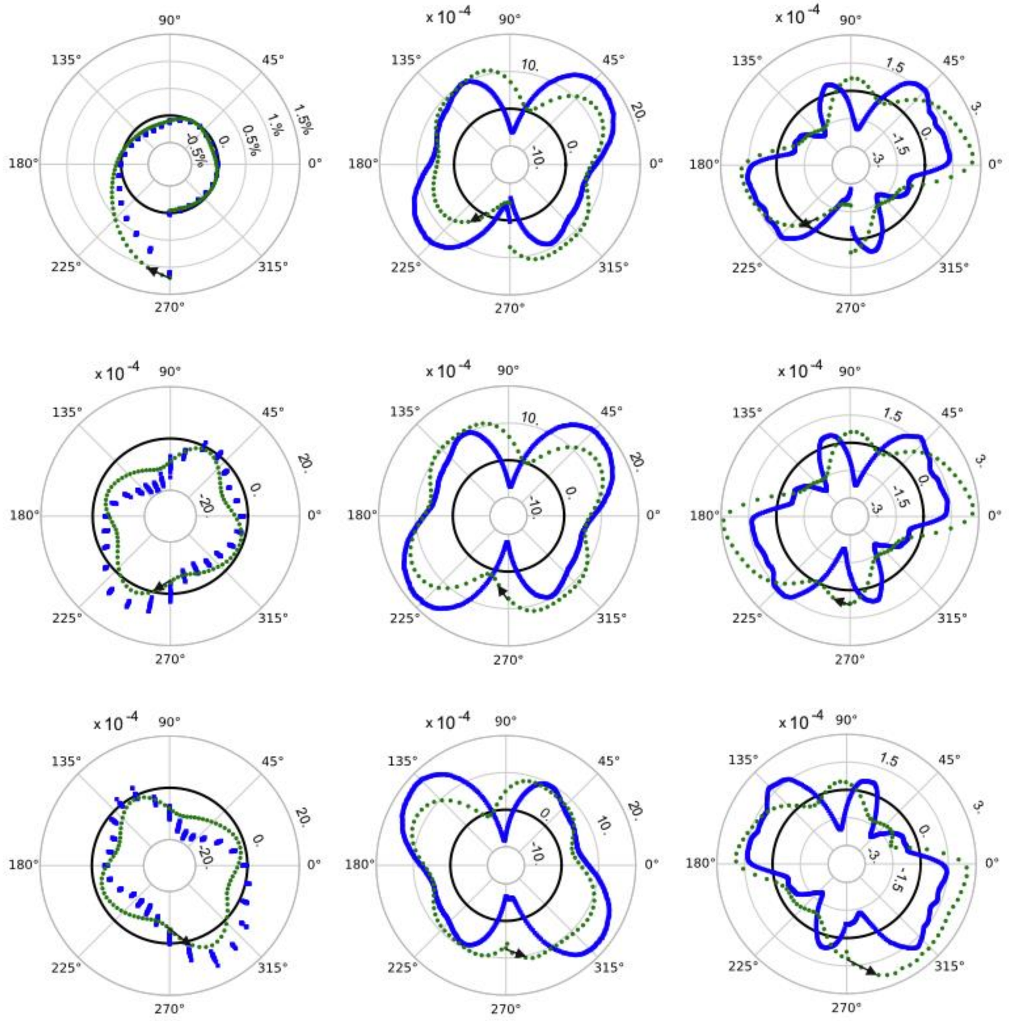
Figure 10: The quench simulation menu.

Figure 11: The electrical network.

Validation of the Vector-Hysteresis Model

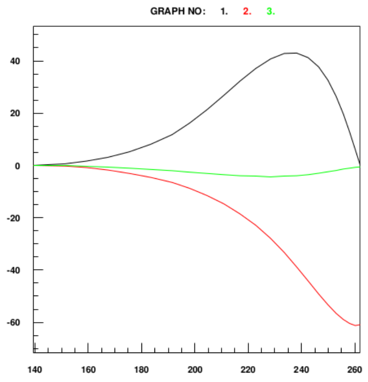


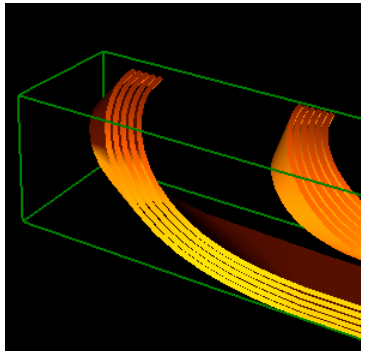




12T Robust End Optimization (winding trials)

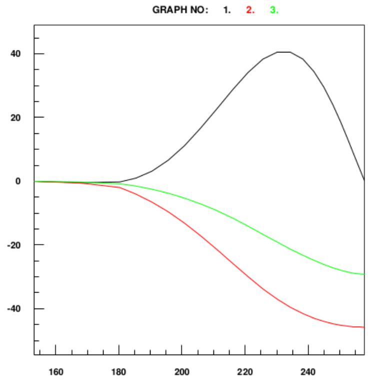
Unconstraint optimization

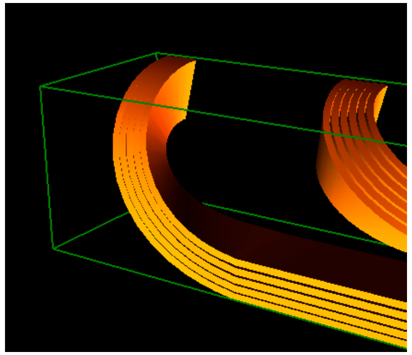




Xs	String
50.0018	BETA
2.6776	BOVERA
4.0176	HORDER

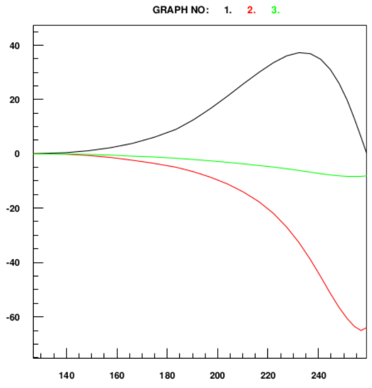
More upright, less k_n

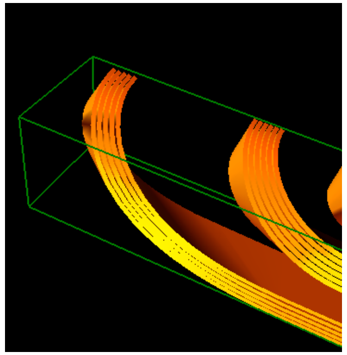




Xs	String
74.9413	BETA
2.0020	BOVERA
3.8366	HORDER

Compromise

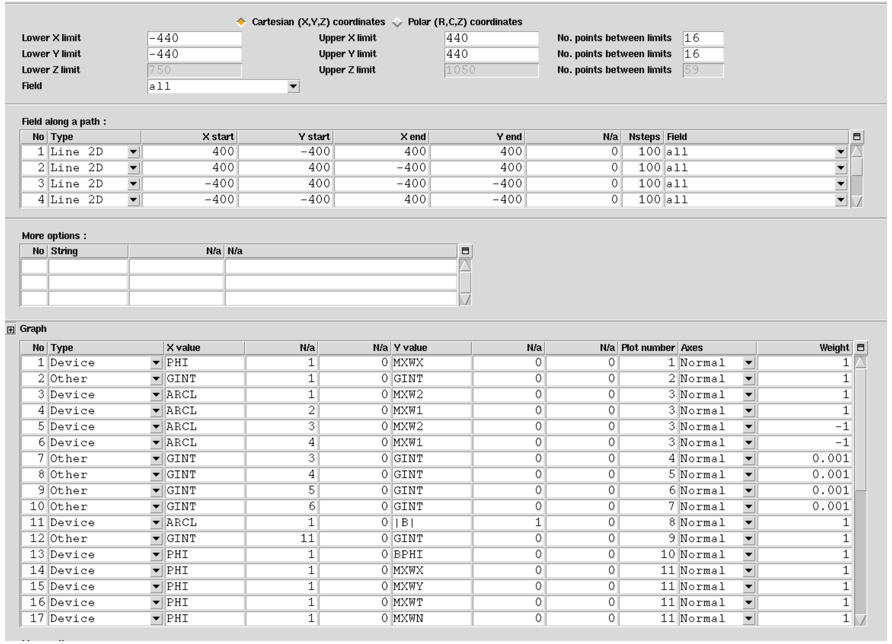




Xs	String	Act	B
60	BETA	3	1
3	BOVERA	3	1
4	HORDER	3	1

Black = Torsion
Green = Geodesic
Red = Normal

Maxwell Stress Tensor on Circle and Line Elements



Cartesian (X,Y,Z) coordinates   Polar (R,C,Z) coordinates

Lower X limit	-440	Upper X limit	440	No. points between limits	16
Lower Y limit	-440	Upper Y limit	440	No. points between limits	16
Lower Z limit	750	Upper Z limit	1050	No. points between limits	59
Field	all				

Field along a path :

No	Type	X start	Y start	X end	Y end	N/a	Nsteps	Field
1	Line 2D	400	-400	400	400	0	100	all
2	Line 2D	400	400	-400	400	0	100	all
3	Line 2D	-400	400	-400	-400	0	100	all
4	Line 2D	-400	-400	400	-400	0	100	all

More options :

No	String	N/a	N/a

Graph

No	Type	X value	N/a	N/a	Y value	N/a	N/a	Plot number	Axes	Weight
1	Device	PHI	1	0	MXWX	0	0	1	Normal	1
2	Other	GINT	1	0	GINT	0	0	2	Normal	1
3	Device	ARCL	1	0	MXW2	0	0	3	Normal	1
4	Device	ARCL	2	0	MXW1	0	0	3	Normal	1
5	Device	ARCL	3	0	MXW2	0	0	3	Normal	-1
6	Device	ARCL	4	0	MXW1	0	0	3	Normal	-1
7	Other	GINT	3	0	GINT	0	0	4	Normal	0.001
8	Other	GINT	4	0	GINT	0	0	5	Normal	0.001
9	Other	GINT	5	0	GINT	0	0	6	Normal	0.001
10	Other	GINT	6	0	GINT	0	0	7	Normal	0.001
11	Device	ARCL	1	0	|B|	1	0	8	Normal	1
12	Other	GINT	11	0	GINT	0	0	9	Normal	1
13	Device	PHI	1	0	BPHI	0	0	10	Normal	1
14	Device	PHI	1	0	MXWX	0	0	11	Normal	1
15	Device	PHI	1	0	MXWY	0	0	11	Normal	1
16	Device	PHI	1	0	MXWT	0	0	11	Normal	1
17	Device	PHI	1	0	MXWN	0	0	11	Normal	1

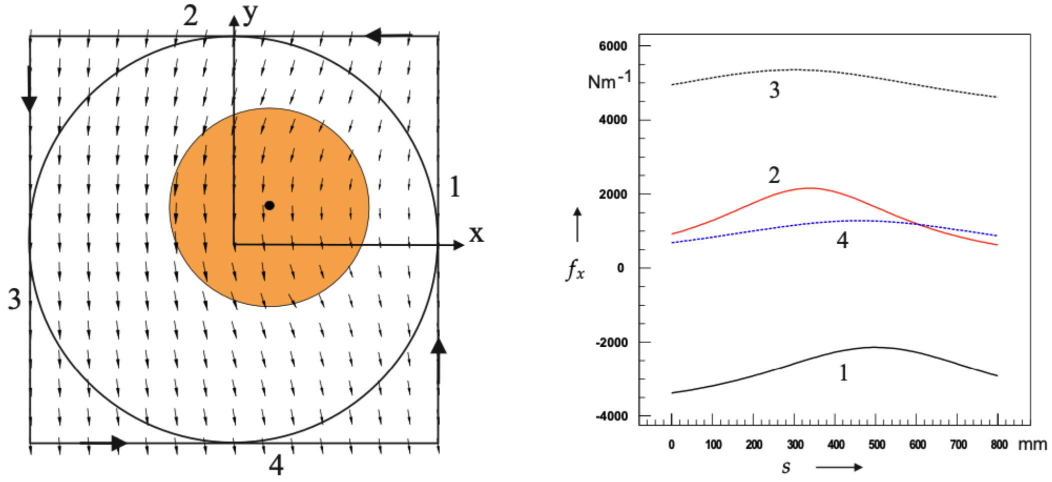
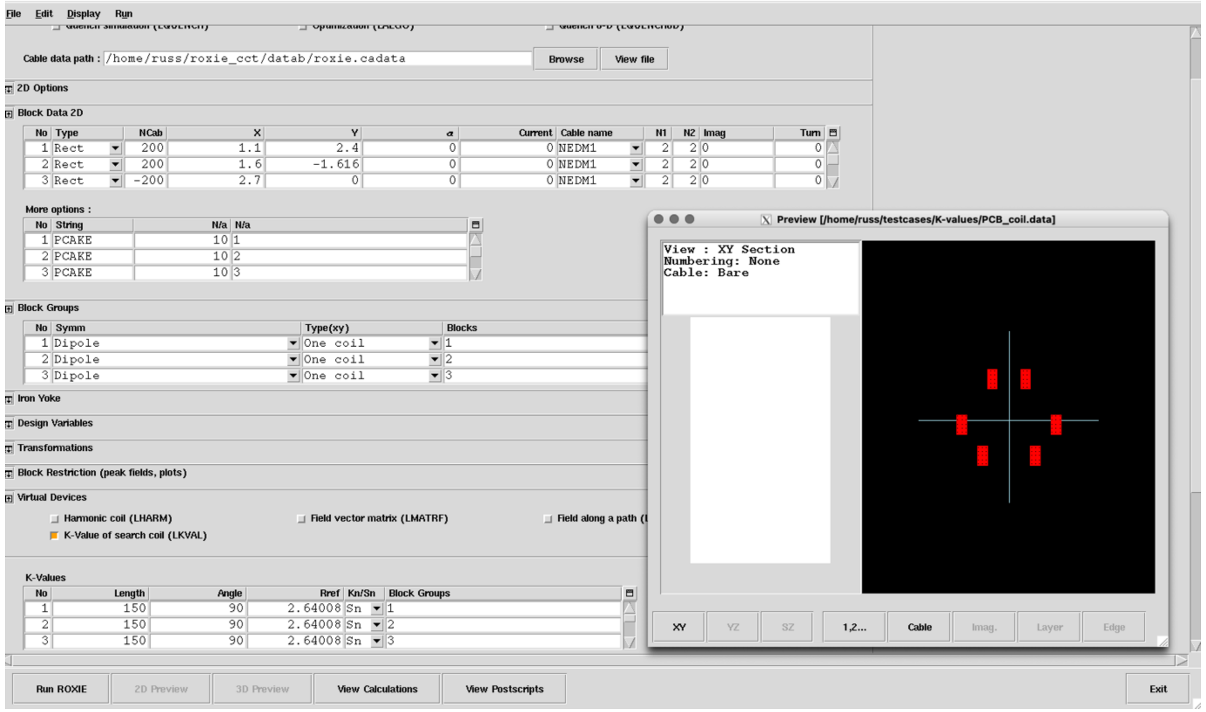
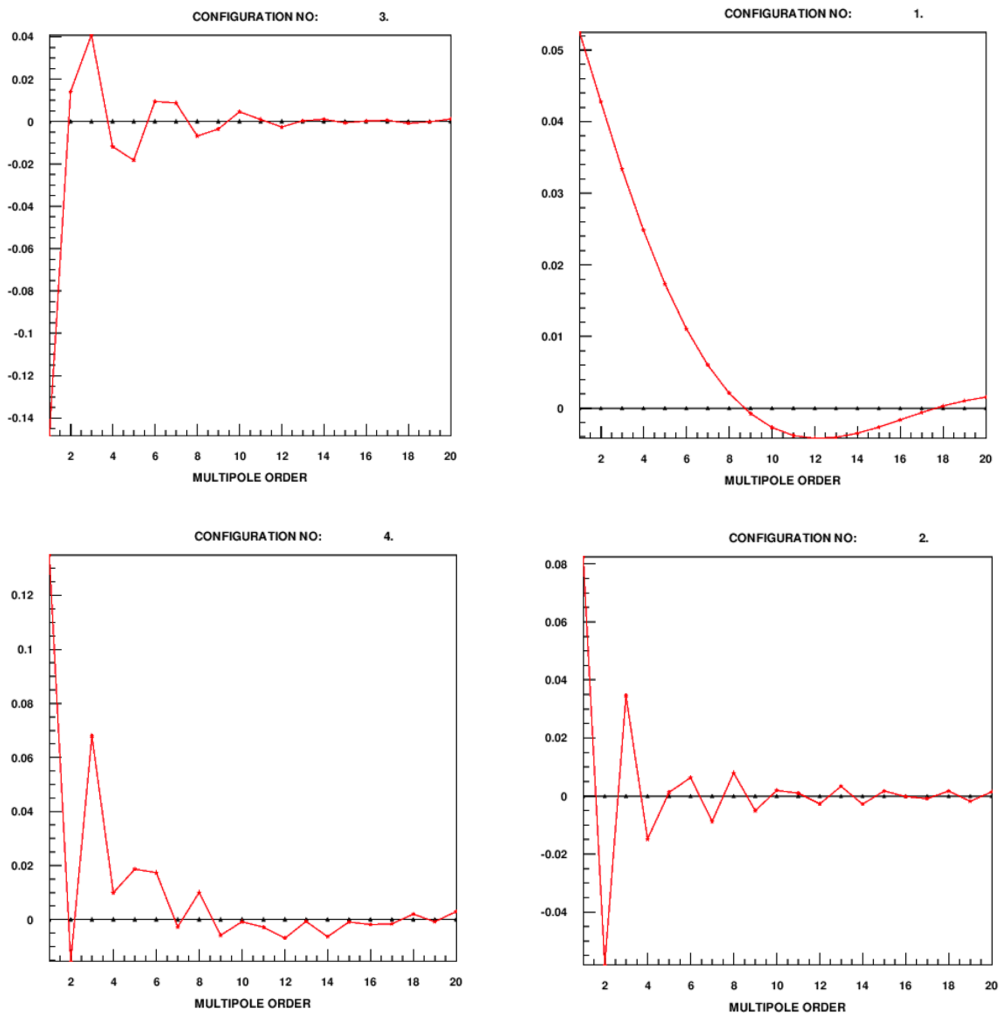


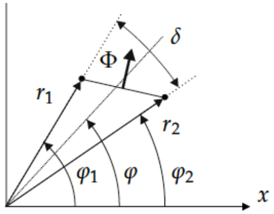
Fig. 4.14: Left: Round conductor of $r = 200$ mm, carrying 40000 A in a 0.1 T dipole field. The total force in the x-direction is 4 kN per meter length of the conductor. Right: Component f_x of the force density per meter length, along the four sides of the de-centered rectangle. Integration over the arc length s and summing up yields -2107 + 1176. + 4075 + 856 = 4000 N, as expected.

S_n-Value of Search Coil





$$U = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$
$$= \sum_{n=1}^{\infty} K_n^{\tan} \frac{n\omega\ell}{r_0^{n-1}} \Big[-B_n(r_0)\cos(n\omega t + n\Theta) + A_n(r_0)\sin(n\omega t + n\Theta) \Big] .$$

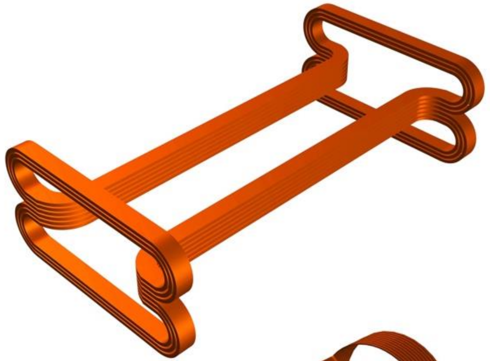


New Coil Macros

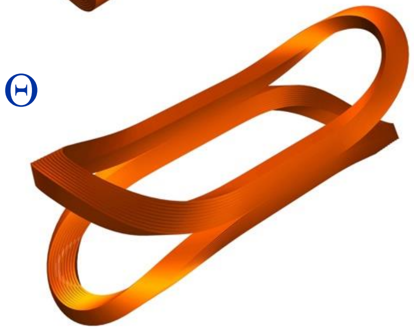
Bedstead

Cradl

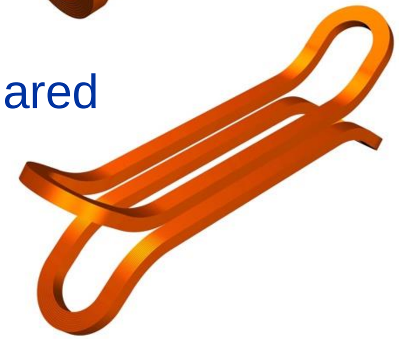
Cranked sattel



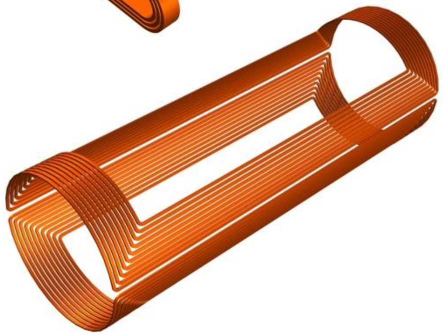
Cos Θ



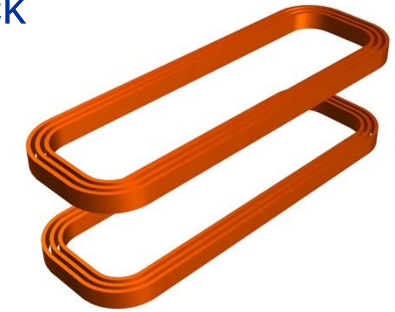
Flared



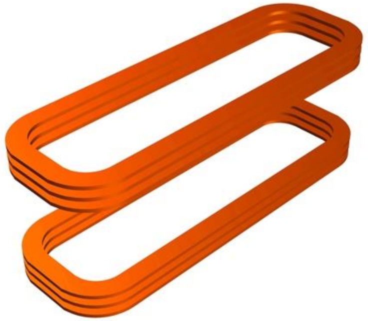
Flex PCB



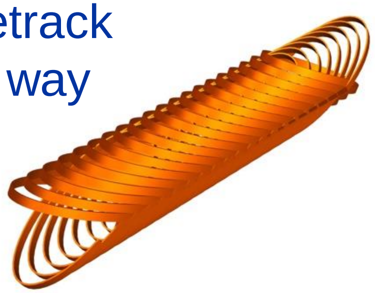
Racetrack
soft way



Racetrack
hard way

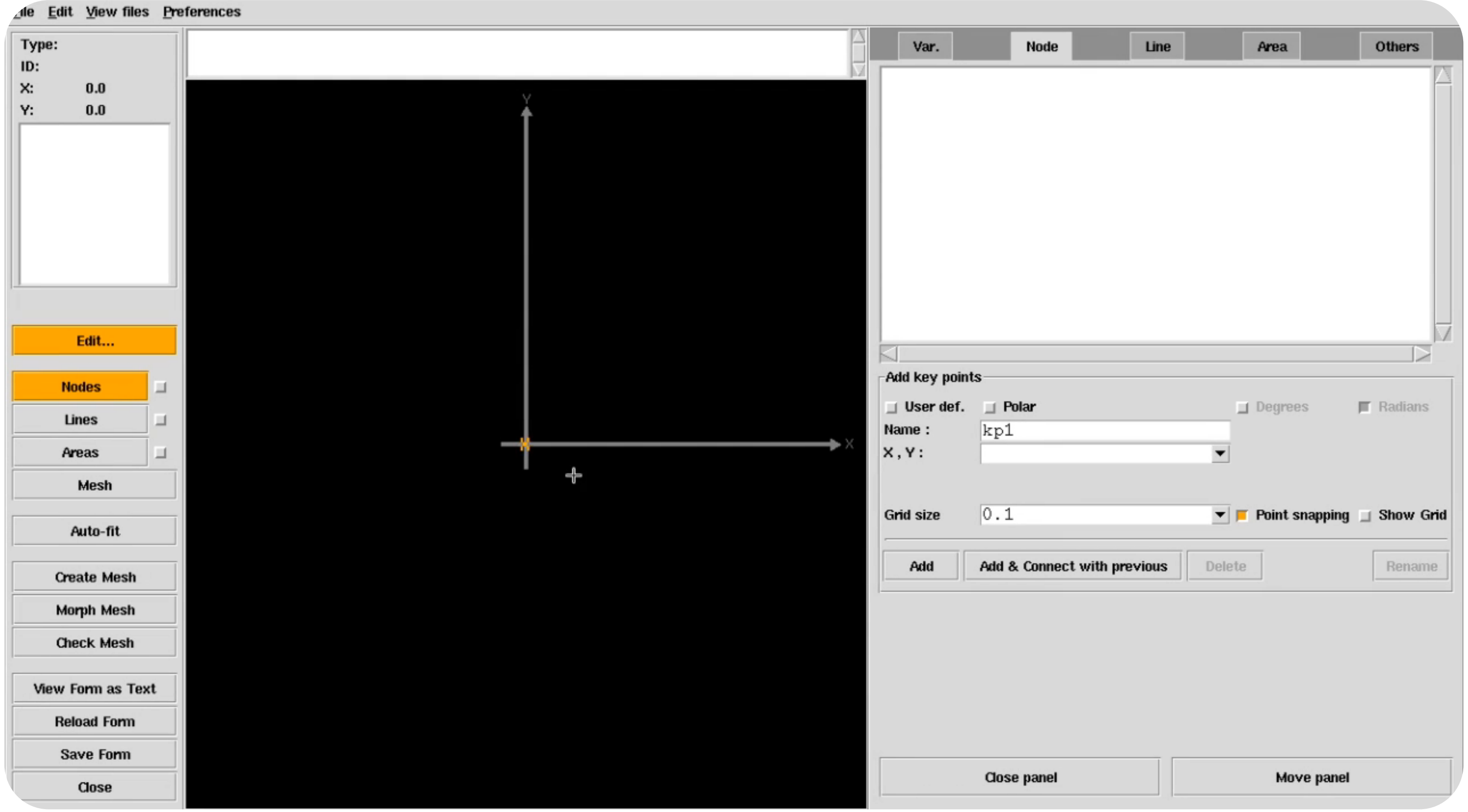


CCT

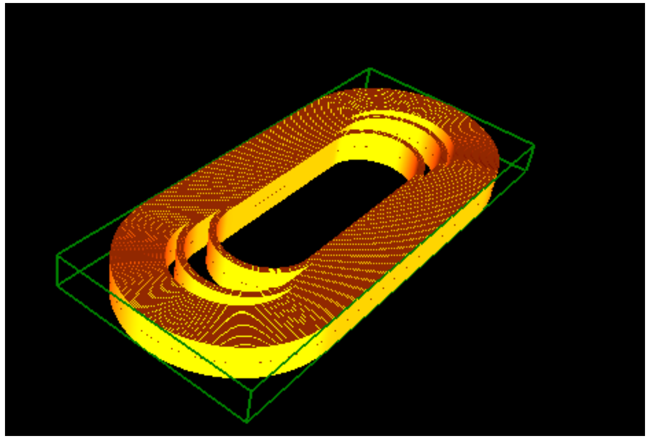


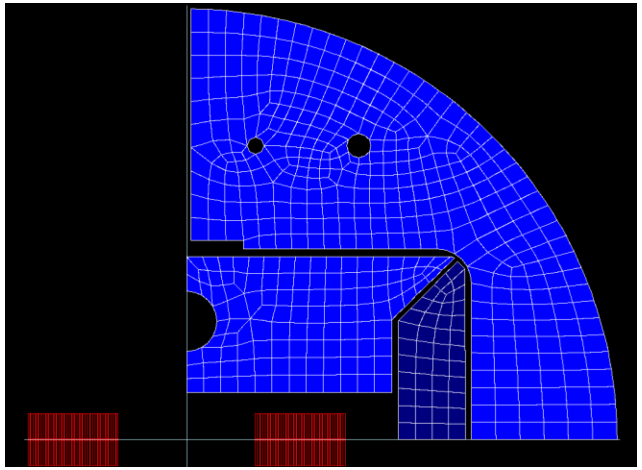
Pre-Processor and Mesh Generator

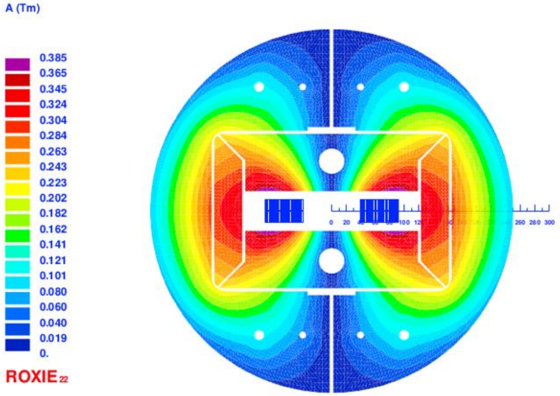
- Add point and connect
- Snap to grid
- Auto save
- Undo
- Delete kp (and dependent
- lines and areas)

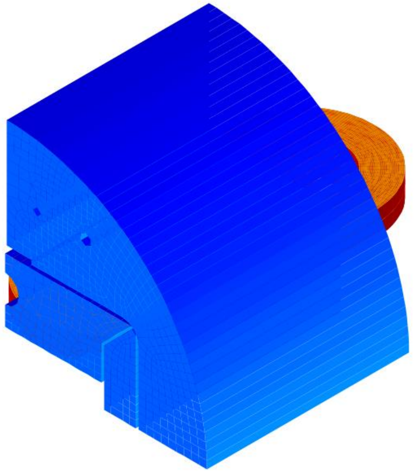


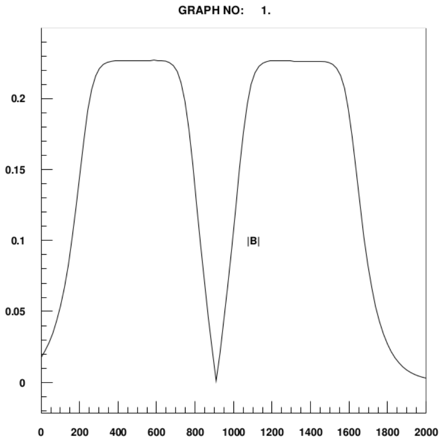
Improved Extrusion Modes

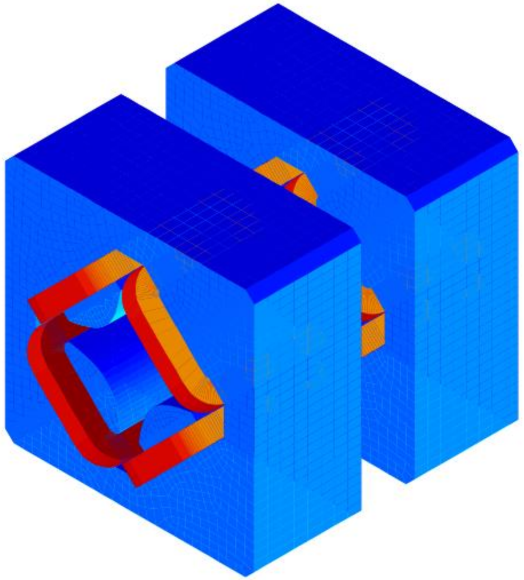


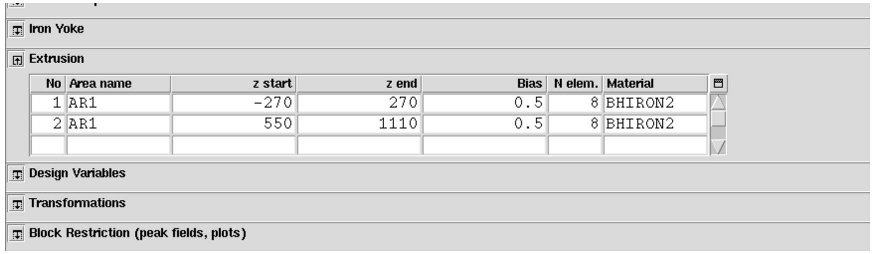












Iron Yoke

Extrusion

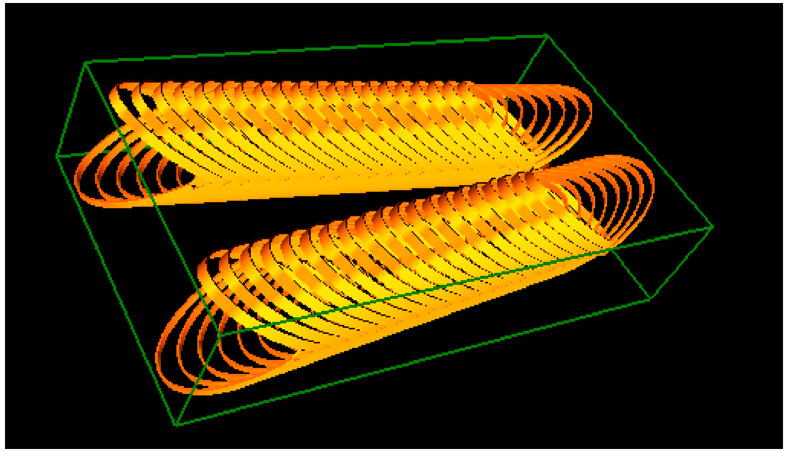
No	Area name	z start	z end	Bias	N elem.	Material
1	AR1	-270	270	0.5	8	BHIRON2
2	AR1	550	1110	0.5	8	BHIRON2

Design Variables

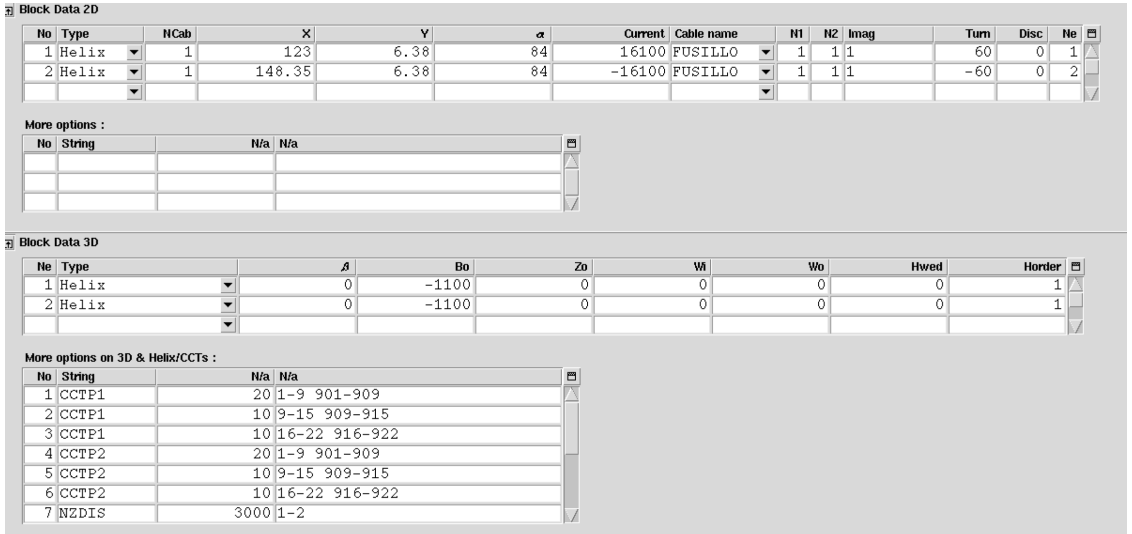
Transformations

Block Restriction (peak fields, plots)

CCT Magnets



Transformations



Block Data 2D

No	Type	NCab	X	Y	α	Current	Cable name	N1	N2	Imag	Turn	Disc	Ne
1	Helix	1	123	6.38	84	16100	FUSILLO	1	1	1	60	0	1
2	Helix	1	148.35	6.38	84	-16100	FUSILLO	1	1	1	-60	0	2

More options :

No	String	N/a	N/a

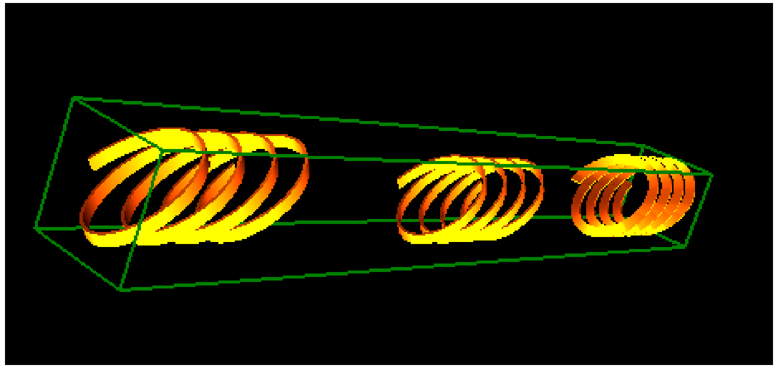
Block Data 3D

Ne	Type	β	Bo	Zo	Wi	Wo	Hwed	Horder
1	Helix	0	-1100	0	0	0	0	1
2	Helix	0	-1100	0	0	0	0	1

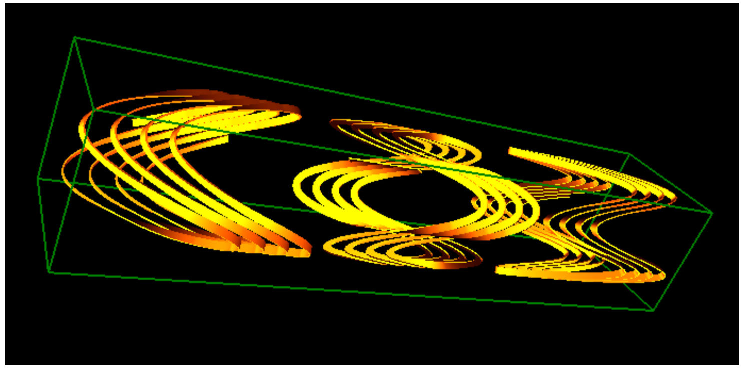
More options on 3D & Helix/CCTs :

No	String	N/a	N/a
1	CCTP1	20	1-9 901-909
2	CCTP1	10	9-15 909-915
3	CCTP1	10	16-22 916-922
4	CCTP2	20	1-9 901-909
5	CCTP2	10	9-15 909-915
6	CCTP2	10	16-22 916-922
7	NZDIS	3000	1-2

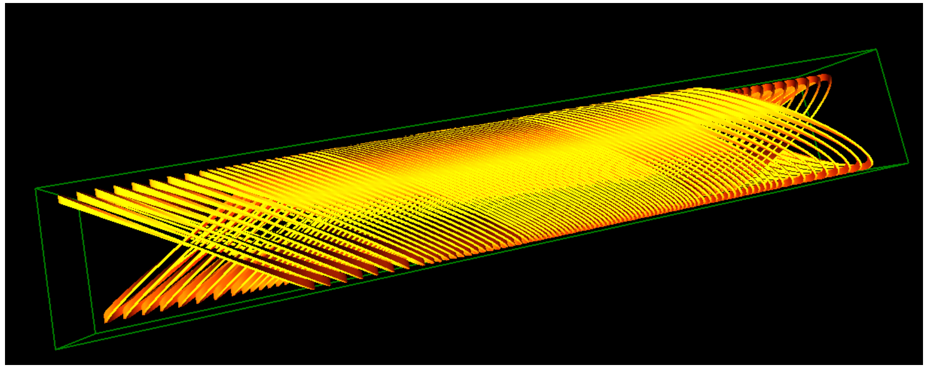
Frenet and Darboux frames,
ID/OD alignment



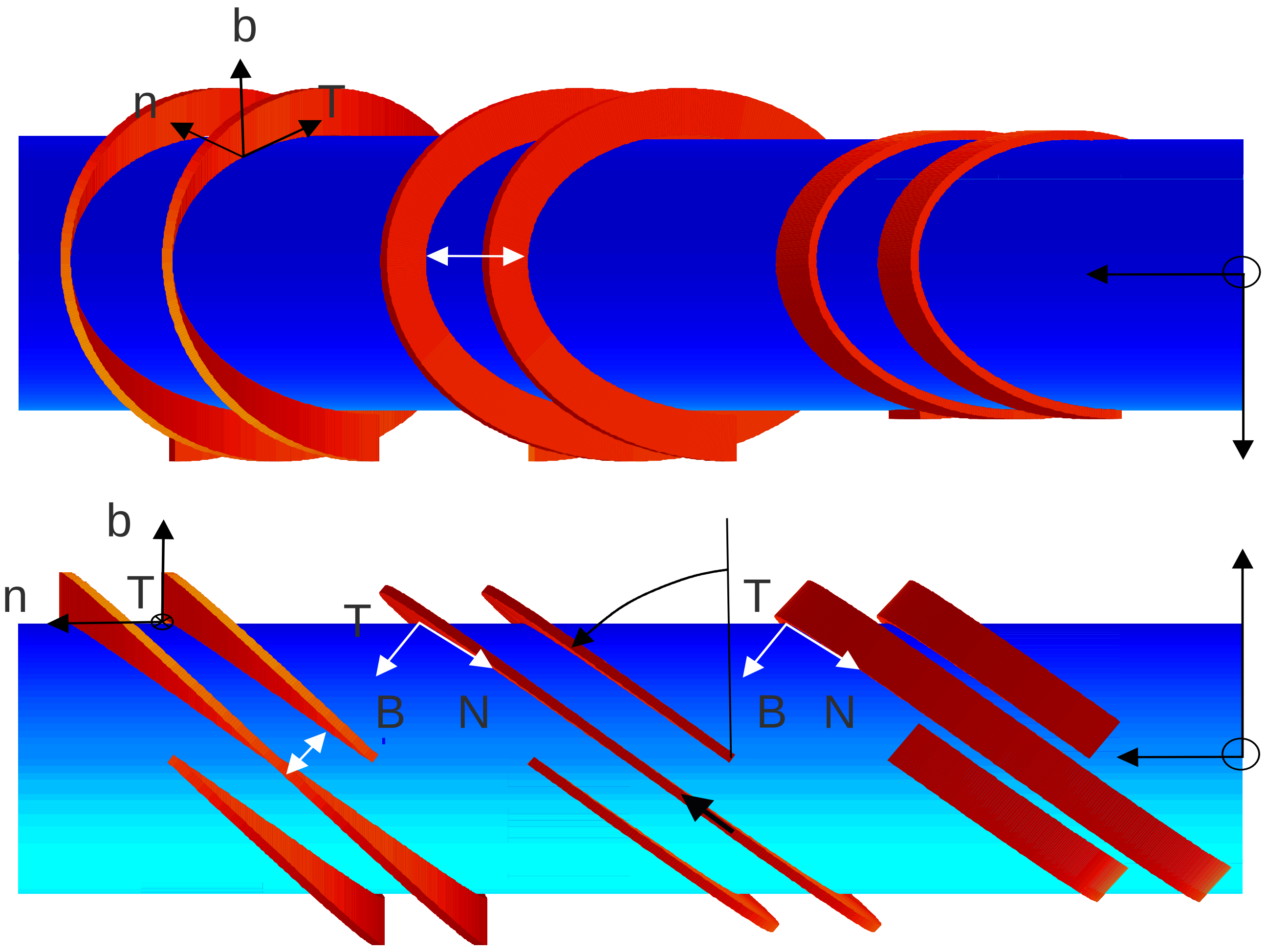
Higher-order multipoles



Pitch variation at the ends



CCT Coil Types

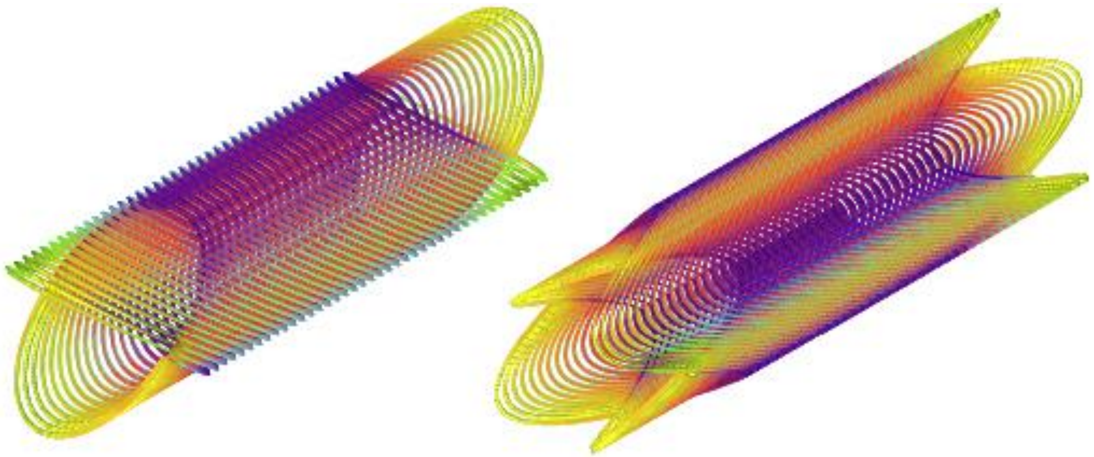


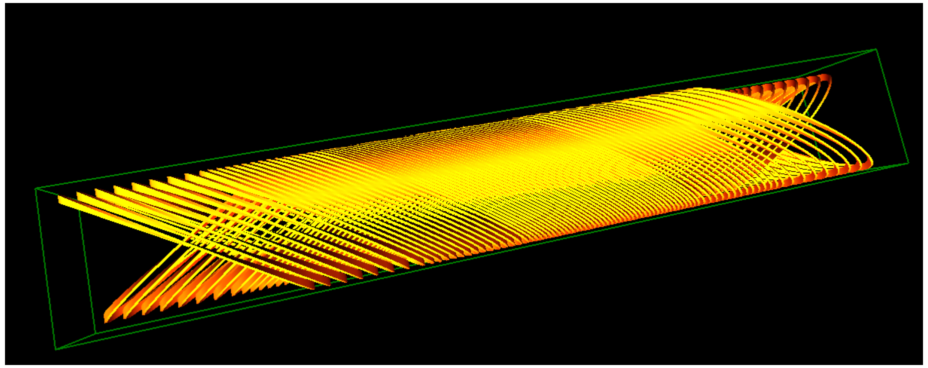
Darboux frame

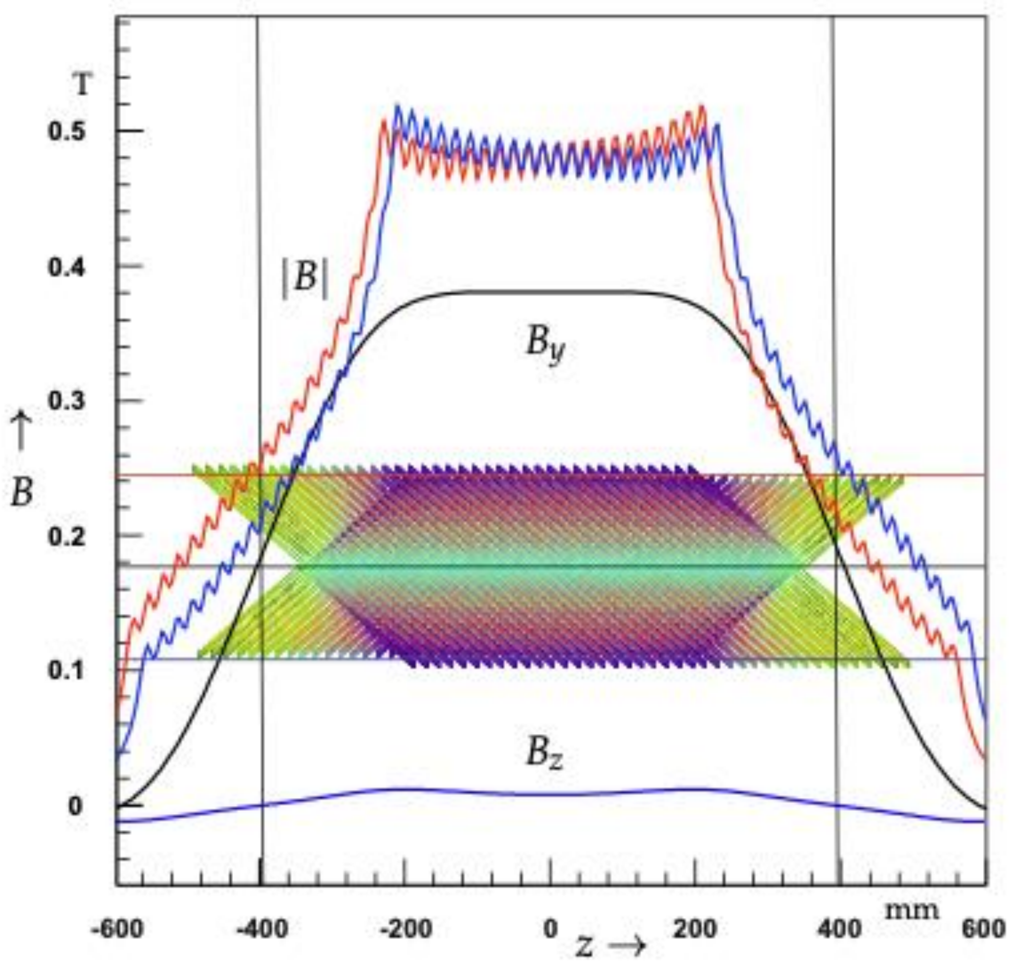
Frenet frame
hard way

Frenet frame
soft way

CCT Magnet Design (Issues)

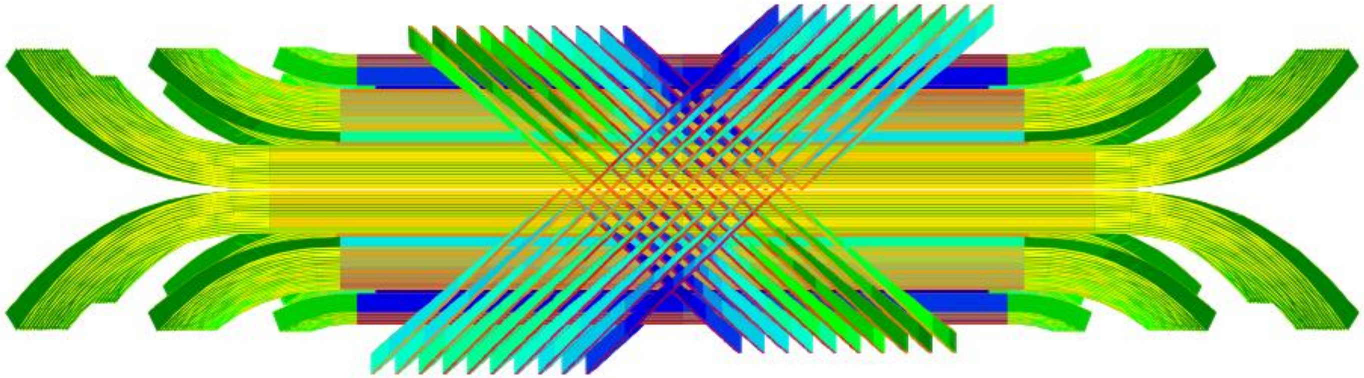


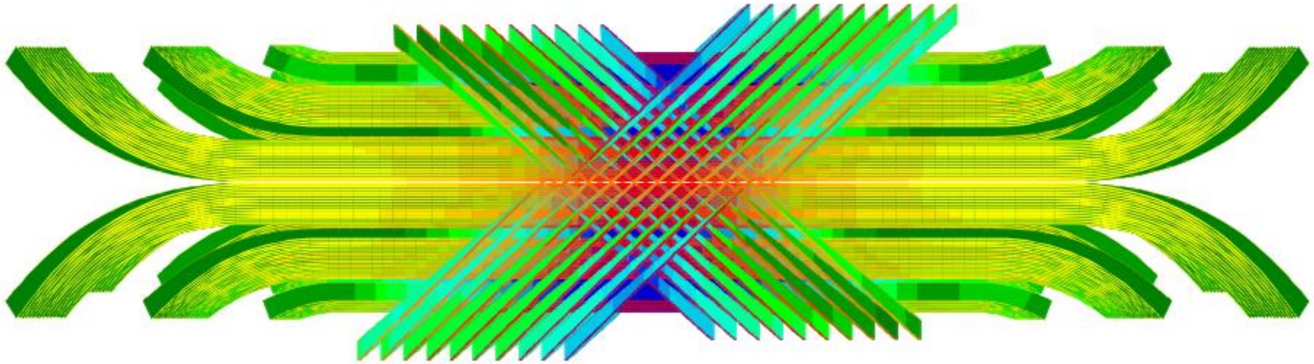




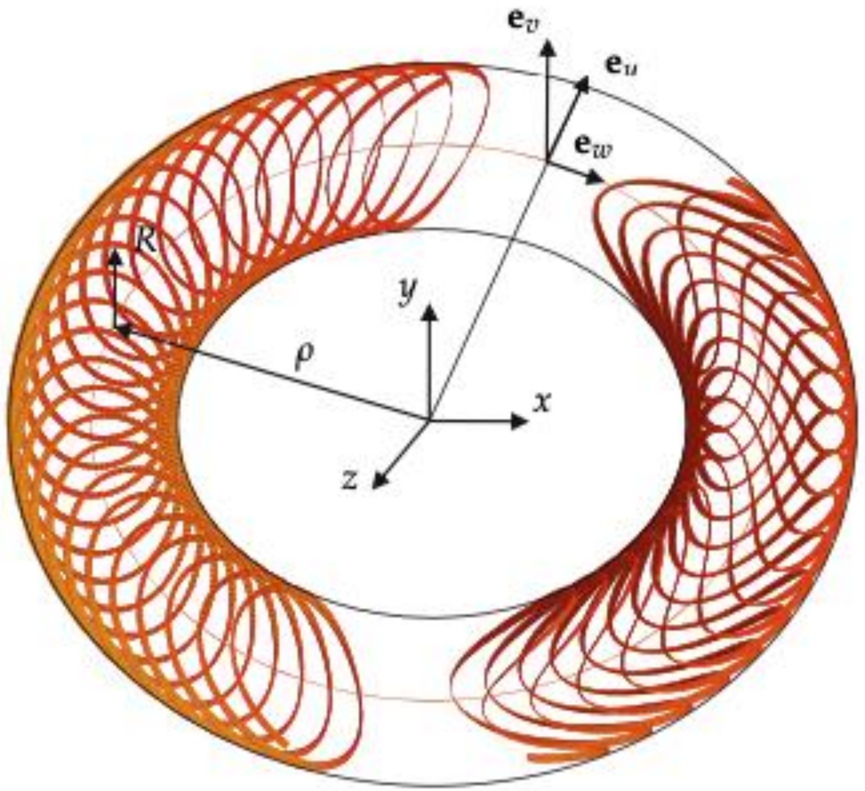
Dynamic Memory Allocation

- 30 elements in straight section
- 25 elements in coil heads
- 28 blocks in cos Θ
- 304 Conductors
- 1500 elements in CCT coils





Curved Magnets



$$\mathbf{e}_u = \cos\left(\frac{\sigma}{\rho}\right)\mathbf{e}_x + \sin\left(\frac{\sigma}{\rho}\right)\mathbf{e}_z\,,$$

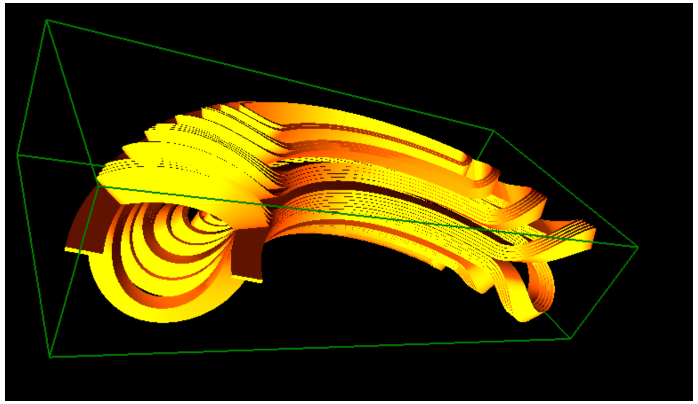
$$\mathbf{e}_v = \mathbf{e}_y\,,$$

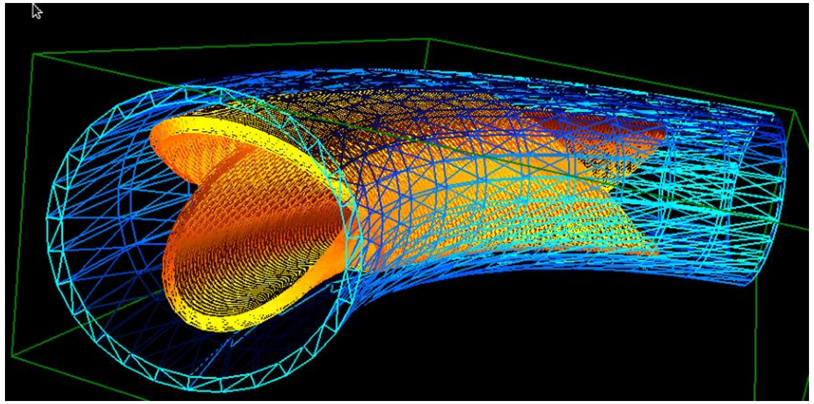
$$\mathbf{e}_w = -\sin\left(\frac{\sigma}{\rho}\right)\mathbf{e}_x + \cos\left(\frac{\sigma}{\rho}\right)\mathbf{e}_z\,.$$

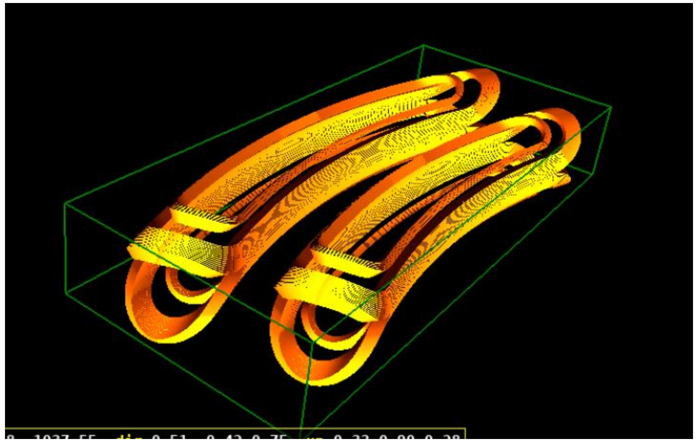
$$\begin{aligned}\mathbf{r}(\varphi) &= \mathbf{o}(\sigma(\varphi)) + R\cos(\varphi)\,\mathbf{e}_u + R\sin(\varphi)\,\mathbf{e}_v \\ &= \cos\left(\frac{\sigma(\varphi)}{\rho}\right)(\rho + R\cos(\varphi))\,\mathbf{e}_x + R\sin(\varphi)\,\mathbf{e}_y \\ &\quad + \sin\left(\frac{\sigma(\varphi)}{\rho}\right)(\rho + R\cos(\varphi))\,\mathbf{e}_z\,.\end{aligned}$$

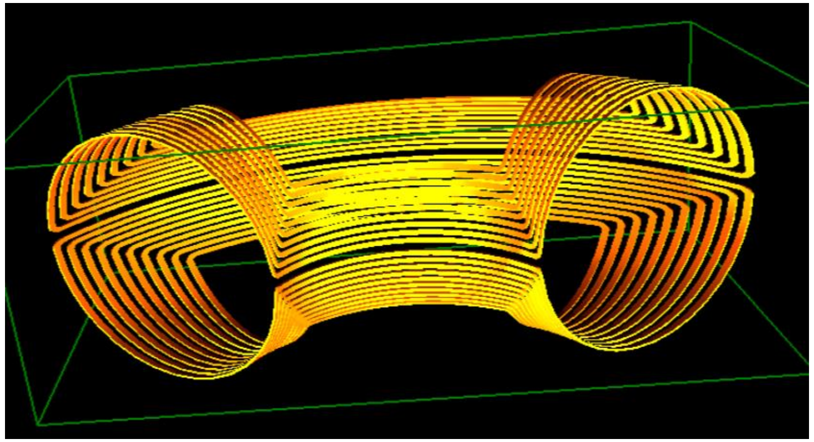
$$\sigma(\varphi) = R\tan(\alpha)\sin(n\varphi) + q\varphi$$

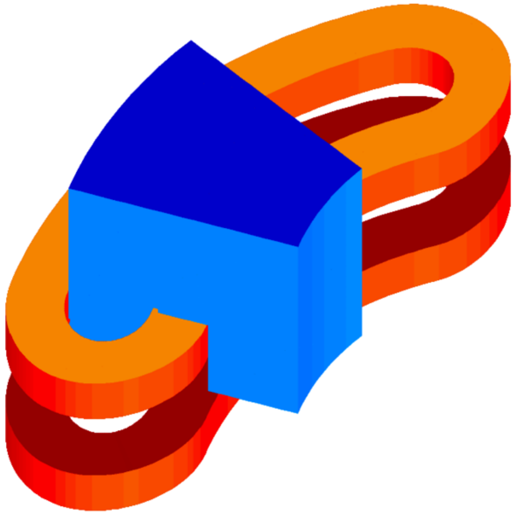
Curved Magnets II

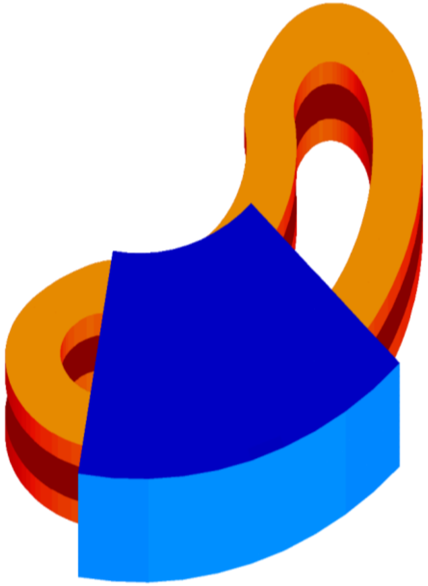










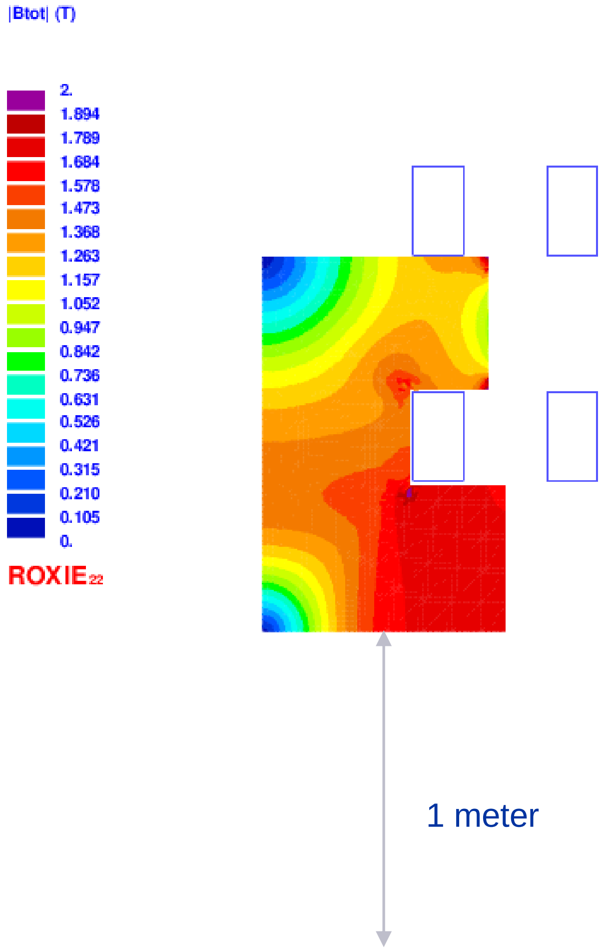


Extracting the Legendre Polynomials

$$
\begin{aligned}
\mathbf{B}_\tau \quad = \quad & \sum_{m=0,n=0}^{\infty} \mathcal{A}_{n,m} \left(-\frac{\mu_0 \cos(n\sigma)\cos(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sinh(\tau)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) + \kappa^{\frac{1}{2}}_{\tau,\sigma} \frac{\partial}{\partial \tau} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) \right] \right) \\
& + \mathcal{B}_{n,m} \left(-\frac{\mu_0 \sin(n\sigma)\cos(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sinh(\tau)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) + \kappa^{\frac{1}{2}}_{\tau,\sigma} \frac{\partial}{\partial \tau} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) \right] \right) \\
& + \mathcal{C}_{n,m} \left(-\frac{\mu_0 \cos(n\sigma)\sin(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sinh(\tau)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) + \kappa^{\frac{1}{2}}_{\tau,\sigma} \frac{\partial}{\partial \tau} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) \right] \right) \\
& + \mathcal{D}_{n,m} \left(-\frac{\mu_0 \sin(n\sigma)\sin(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sinh(\tau)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) + \kappa^{\frac{1}{2}}_{\tau,\sigma} \frac{\partial}{\partial \tau} Q^m_{n-\frac{1}{2}}(\cosh(\tau)) \right] \right) \\
=: \quad & \sum_{m=0,n=0}^{\infty} \left[\mathcal{A}_{n,m} \cdot c^{\mathcal{A}}_{\tau,n,m}(\tau,\sigma,\phi) + \mathcal{B}_{n,m} \cdot c^{\mathcal{B}}_{\tau,n,m}(\tau,\sigma,\phi) \right. \\
& \left. + \, \mathcal{C}_{n,m} \cdot c^{\mathcal{C}}_{\tau,n,m}(\tau,\sigma,\phi) + \mathcal{D}_{n,m} \cdot c^{\mathcal{D}}_{\tau,n,m}(\tau,\sigma,\phi) \right]
\end{aligned}
$$

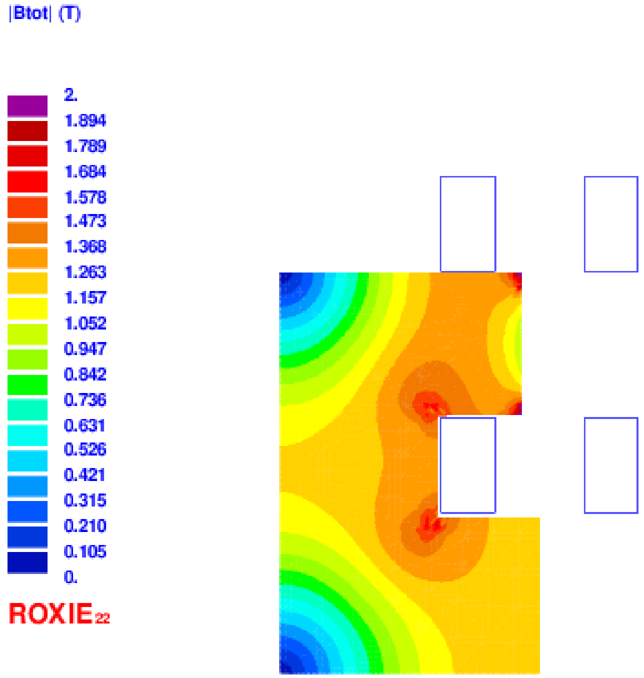
$$
\begin{aligned}
\mathbf{B}_\sigma \quad = \quad & \sum_{m=0,n=0}^{\infty} \mathcal{A}_{n,m} \left(-\frac{\mu_0 Q^m_{n-\frac{1}{2}}(\cosh(\tau))\cos(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sin(\sigma)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} \cos(n\sigma) - \kappa^{\frac{1}{2}}_{\tau,\sigma} n \sin(n\sigma) \right] \right) \\
& + \mathcal{B}_{n,m} \left(-\frac{\mu_0 Q^m_{n-\frac{1}{2}}(\cosh(\tau))\cos(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sin(\sigma)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} \sin(n\sigma) + \kappa^{\frac{1}{2}}_{\tau,\sigma} n \cos(n\sigma) \right] \right) \\
& + \mathcal{C}_{n,m} \left(-\frac{\mu_0 Q^m_{n-\frac{1}{2}}(\cosh(\tau))\sin(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sin(\sigma)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} \cos(n\sigma) - \kappa^{\frac{1}{2}}_{\tau,\sigma} n \sin(n\sigma) \right] \right) \\
& + \mathcal{D}_{n,m} \left(-\frac{\mu_0 Q^m_{n-\frac{1}{2}}(\cosh(\tau))\sin(m\phi)\kappa_{\tau,\sigma}}{a Q^m_{n-\frac{1}{2}}(\cosh(\tau_0))} \left[\frac{\sin(\sigma)}{2\kappa^{\frac{1}{2}}_{\tau,\sigma}} \sin(n\sigma) + \kappa^{\frac{1}{2}}_{\tau,\sigma} n \cos(n\sigma) \right] \right) \\
=: \quad & \sum_{m=0,n=0}^{\infty} \left[\mathcal{A}_{n,m} \cdot c^{\mathcal{A}}_{\sigma,n,m}(\tau,\sigma,\phi) + \mathcal{B}_{n,m} \cdot c^{\mathcal{B}}_{\sigma,n,m}(\tau,\sigma,\phi) \right. \\
& \left. + \mathcal{C}_{n,m} \cdot c^{\mathcal{C}}_{\sigma,n,m}(\tau,\sigma,\phi) + \mathcal{D}_{n,m} \cdot c^{\mathcal{D}}_{\sigma,n,m}(\tau,\sigma,\phi) \right]
\end{aligned}
$$

Curved Magnet Study (Rotational Symmetric)

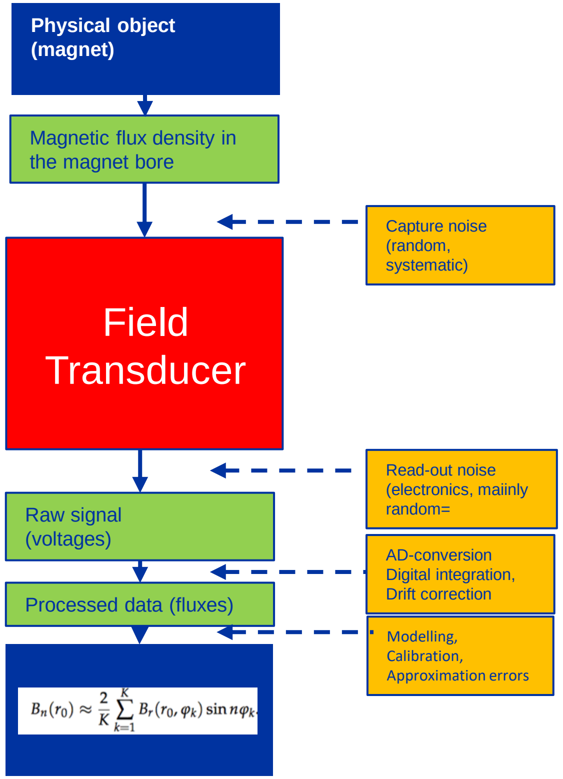



```
MAIN FIELD (T) ....................................     0.924326
MAGNET STRENGTH (T/(m^(n-1)) ......................       0.9243

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     -0.13532  b 3:     -0.15851
b 4:      0.00002  b 5:      0.01623  b 6:      0.00443
b 7:      0.00846  b 8:      0.00396  b 9:      0.00173
b10:     -0.00179  b11:     -0.00437  b12:     -0.00483
b13:     -0.00337  b14:     -0.00051  b15:      0.00277
b16:      0.00471  b17:      0.00473  b18:      0.00262
b19:     -0.00058  b20:     -0.00350  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:      0.00000  a 3:      0.00000
a 4:     -0.00000  a 5:     -0.00000  a 6:     -0.00000
a 7:     -0.00000  a 8:     -0.00000  a 9:      0.00000
a10:     -0.00000  a11:      0.00000  a12:     -0.00000
a13:     -0.00000  a14:      0.00000  a15:     -0.00000
a16:     -0.00000  a17:      0.00000  a18:     -0.00000
a19:     -0.00000  a20:      0.00000  a

SURFACE OF ALL FEM-ELEMENTS (MM**2) ...............  460541.9852
```

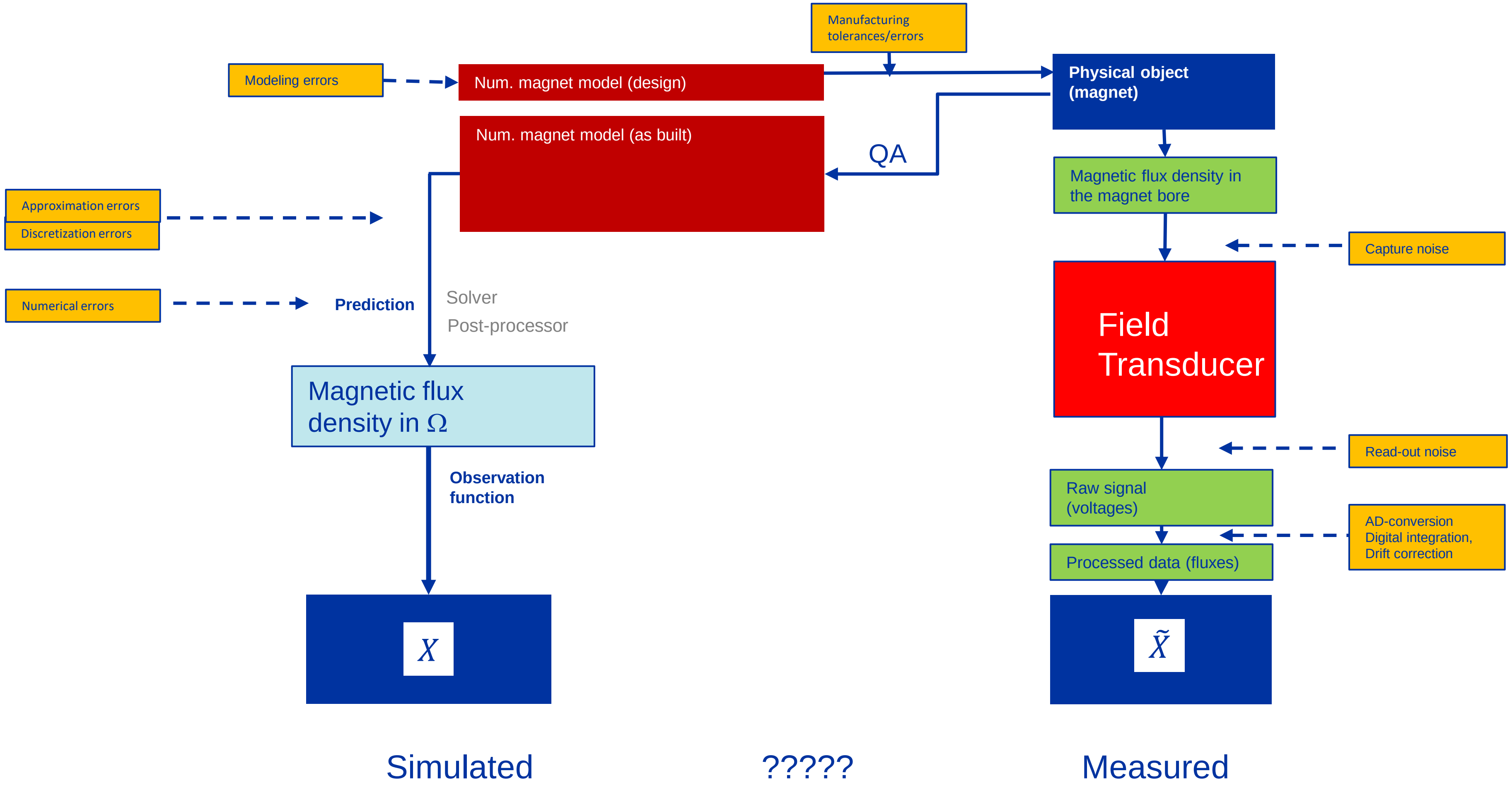
```
TURNING ANGLE OF HARMONIC COIL (DEG) ...............      90.0000
MEASUREMENT TYPE ......................... ALL FIELD CONTRIBUTIONS
ERROR OF HARMONIC ANALYSIS OF Br ..................   0.1003E-03
SUM (Br(p) - SUM (An cos(np) + Bn sin(np))

MAIN FIELD (T) ....................................     0.972557
MAGNET STRENGTH (T/(m^(n-1)) ......................       0.9726

NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     -0.23264  b 3:     -0.10184
b 4:      0.02140  b 5:      0.00746  b 6:      0.00376
b 7:      0.00804  b 8:      0.00366  b 9:      0.00201
b10:     -0.00176  b11:     -0.00436  b12:     -0.00459
b13:     -0.00321  b14:     -0.00052  b15:      0.00268
b16:      0.00455  b17:      0.00454  b18:      0.00251
b19:     -0.00055  b20:     -0.00337  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:     -0.00000  a 2:      0.00000  a 3:     -0.00000
a 4:      0.00000  a 5:     -0.00000  a 6:     -0.00000
```



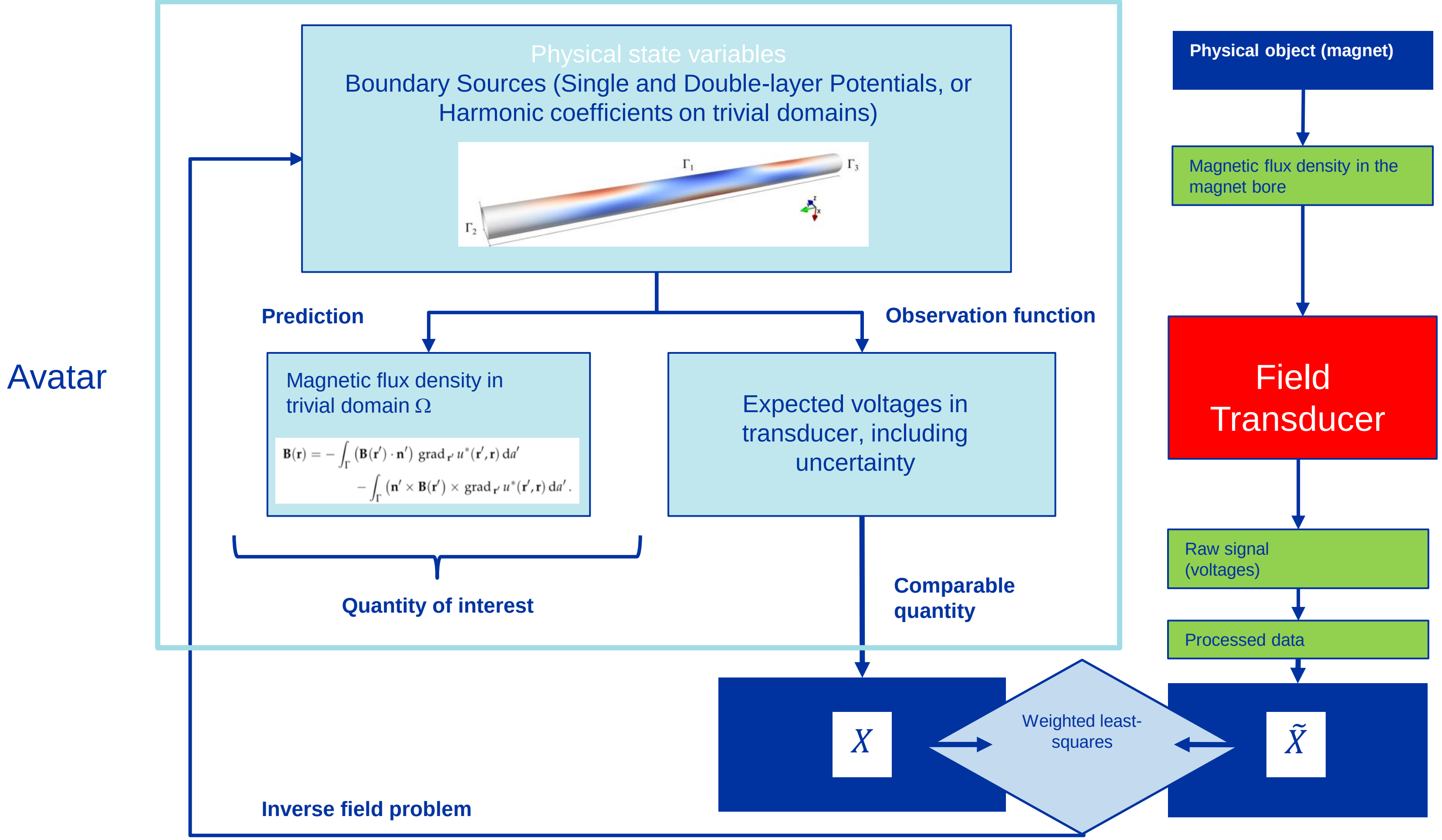
The Avatar and Twin (classical black-box measurement)



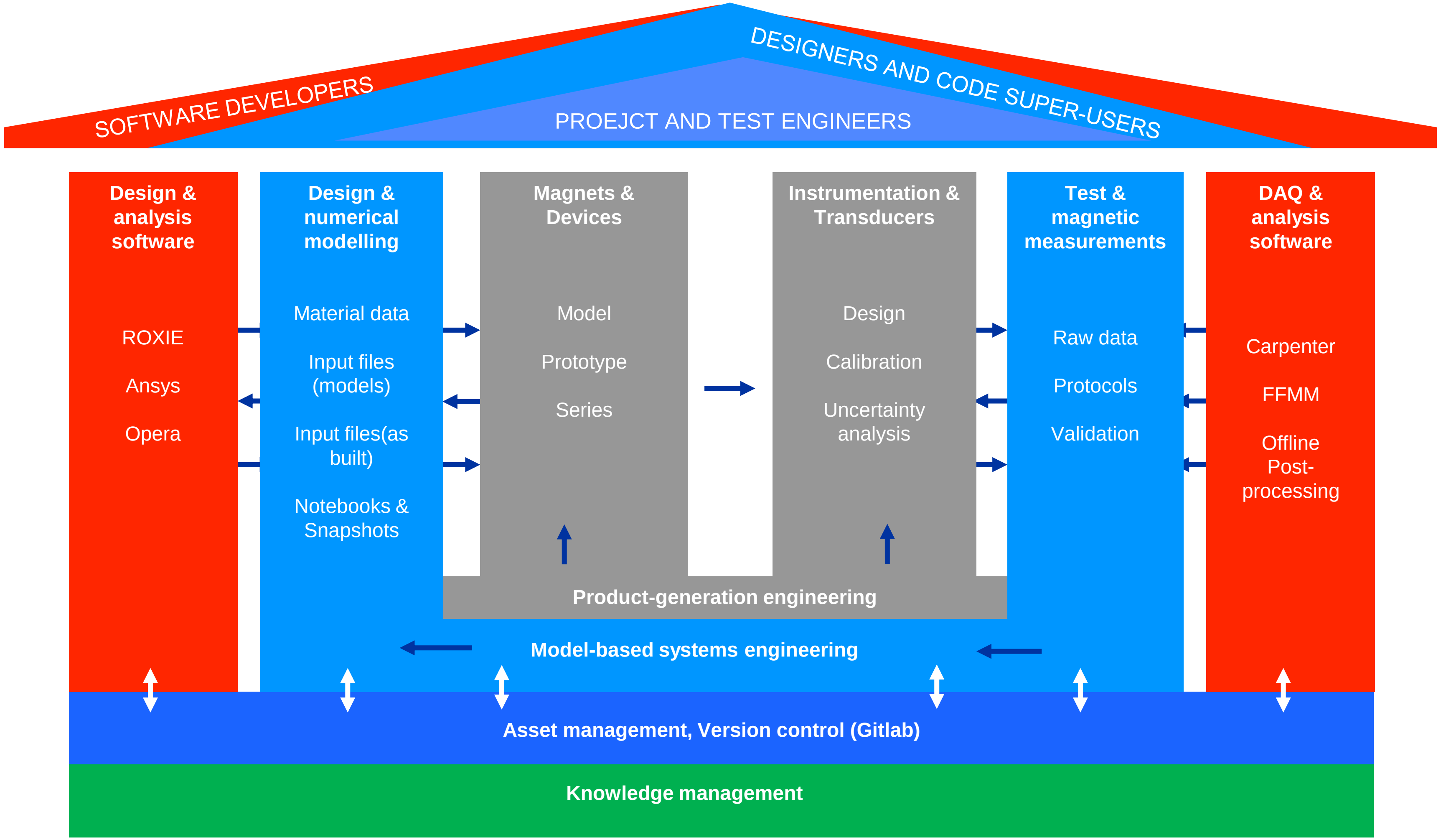
The Avatar and Twin (tracing of manufacturing tolerances and errors)



The Avatar and Twin (generalized field description)



Data-Driven Systems and Product-Cycle Engineering



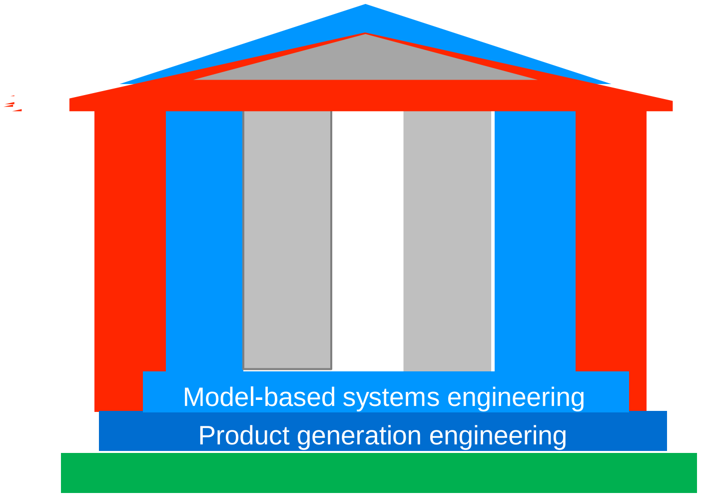
Prerequisites for Model-Based Systems Engineering

Collaborative efforts are required to establish MBSE

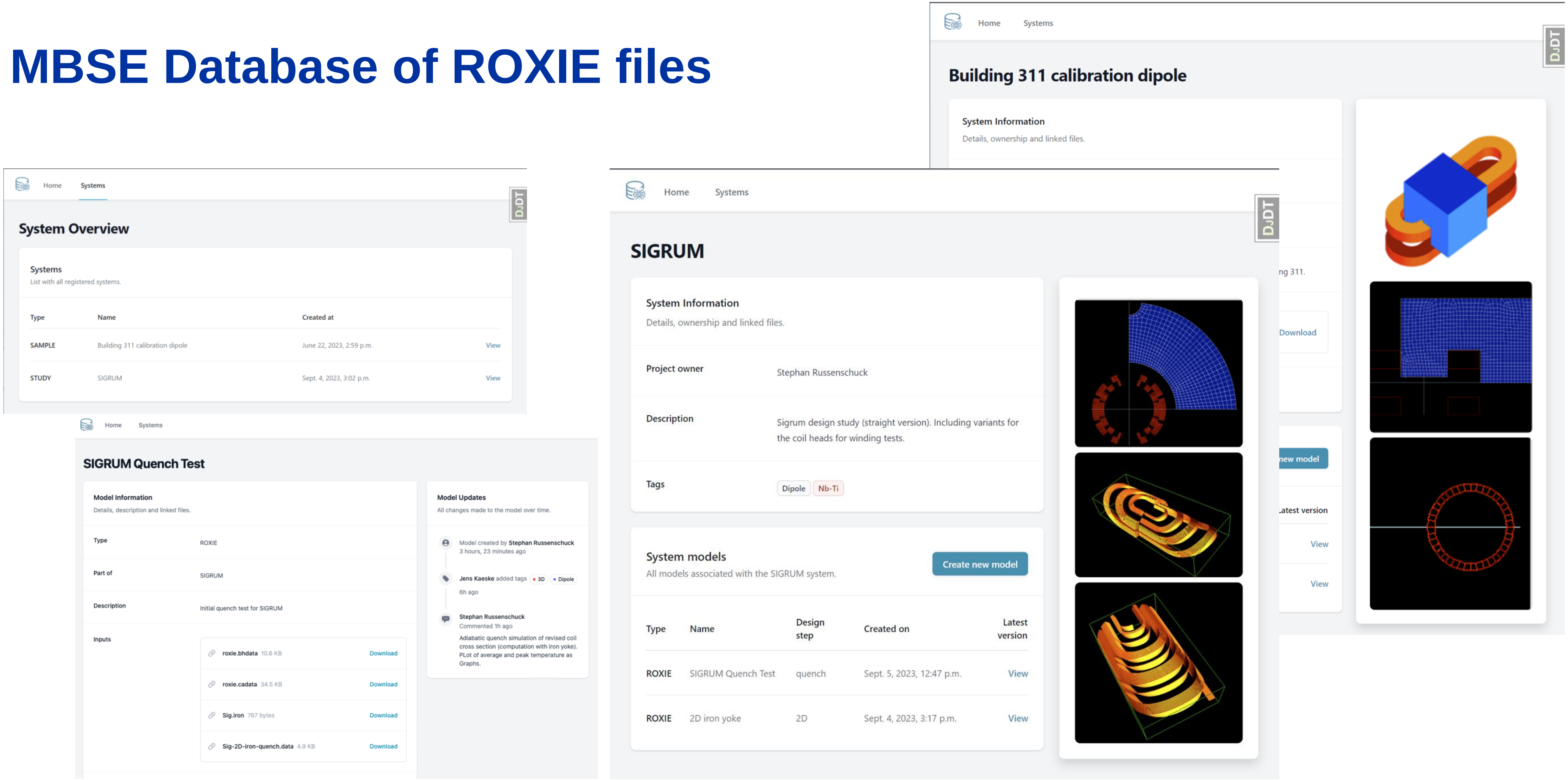
Ownership
Co-authorship of a paper is not enough
Released and traceable data

Accessibly
Files and software exec is not enough
MBSE with extended interfaces
Virtual machines via Docker
Gitlab repositories

Sustainability
A ppt presentation or paper is not enough
Product cycle engineering
Jupiter notebooks



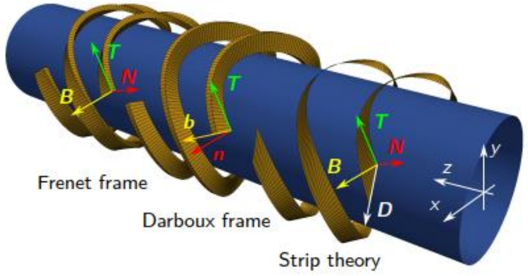
MBSE Database of ROXIE files

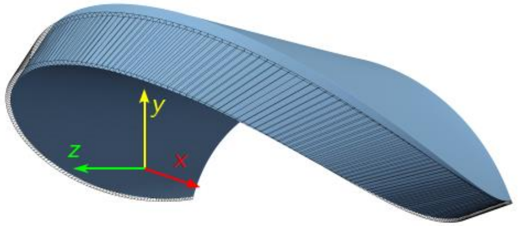


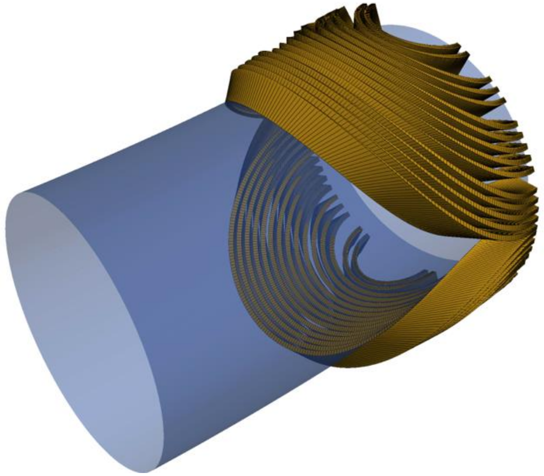
Example: Differential-geometry-based coil design

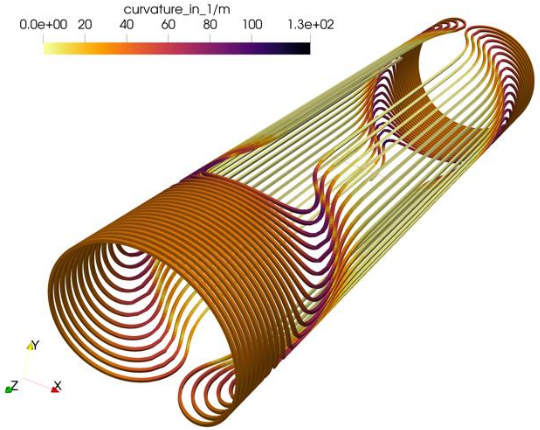
ROXIE Python API

- **Structured access To Roxie data files**
  - Modify blocks, flags, plots, etc
  - Combine files
- **Structured output**
  - XML output of run information, results and plots
  - Associated parser for data access
- **Interface to execute Roxie from code**
  - On local machine
  - Via Docker



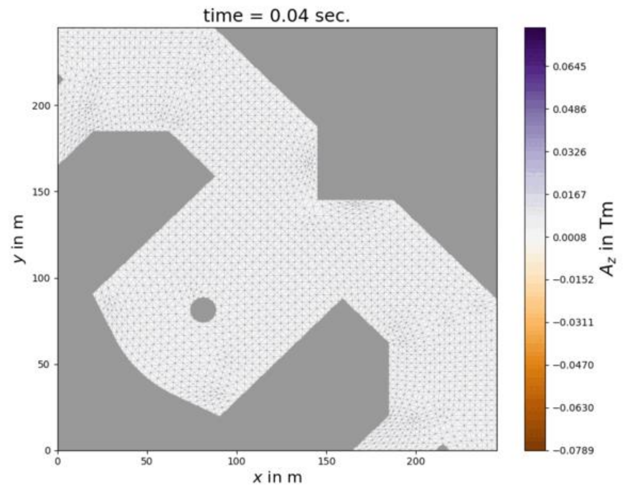


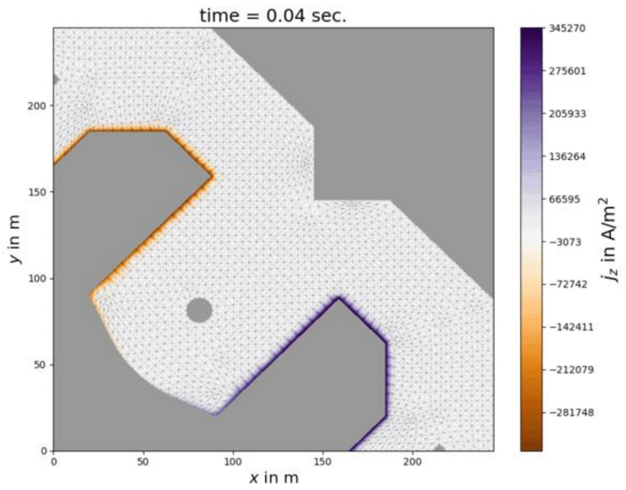


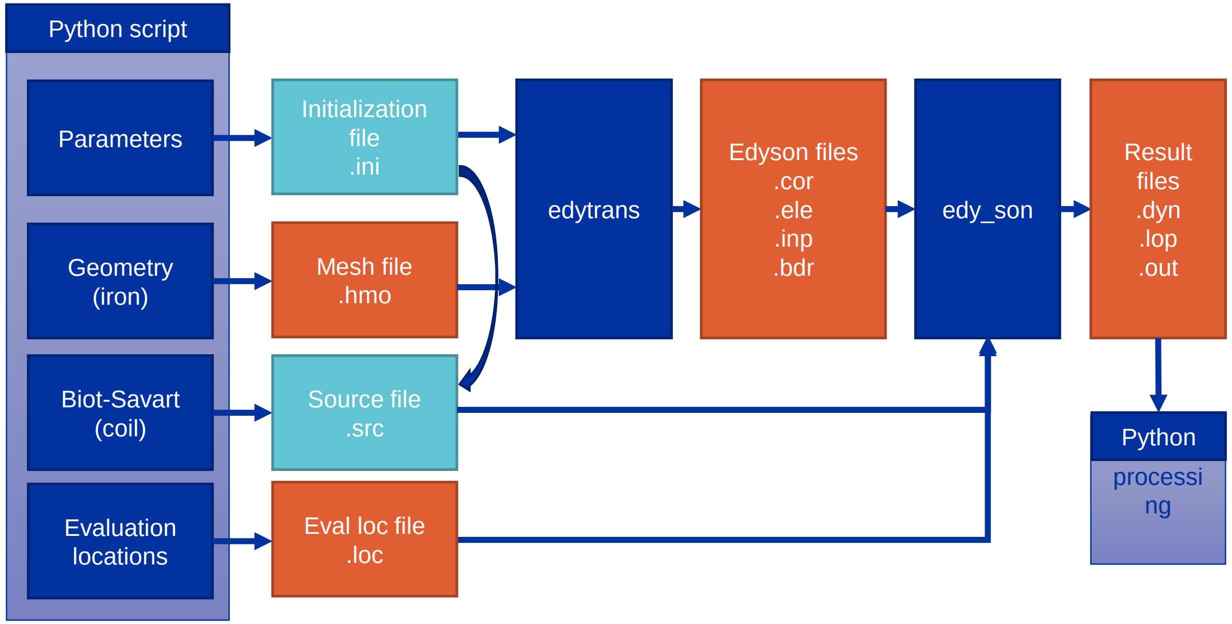


Eddy current solver

- Eddy current computation in yoke and endplates (2D and 3D)
- Skin effect in conductors in 2D
- Skin effect in pancake coils in 3D
- Post processing
- Visualization
  - Python (2D)
  - Vtk (3D)

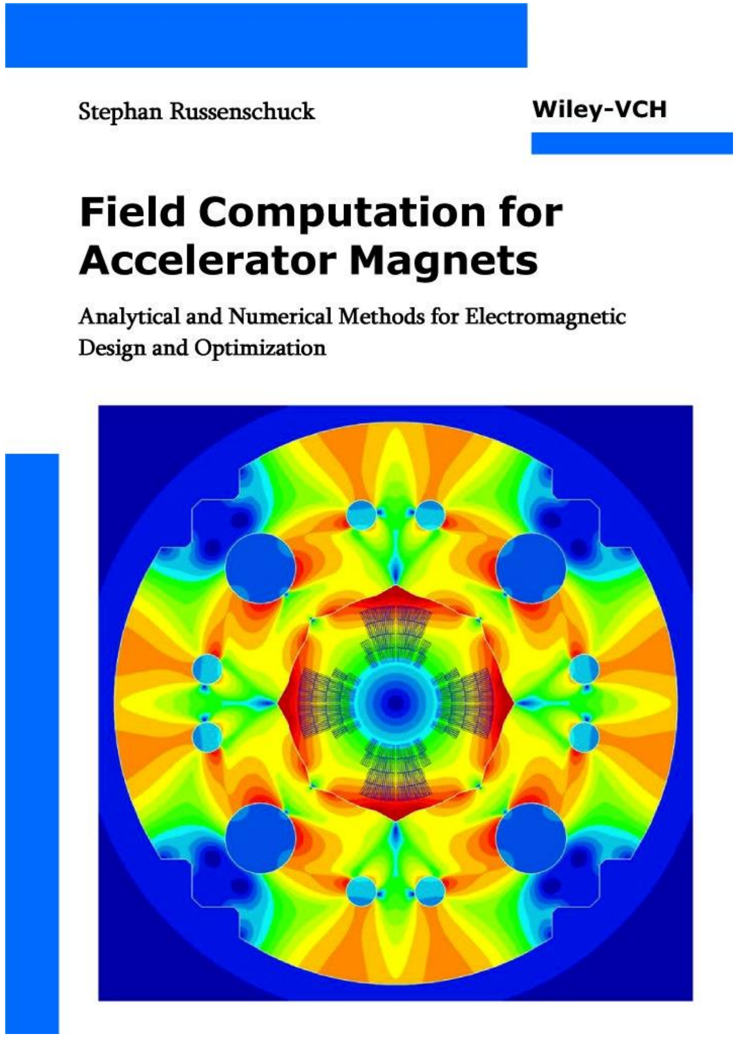






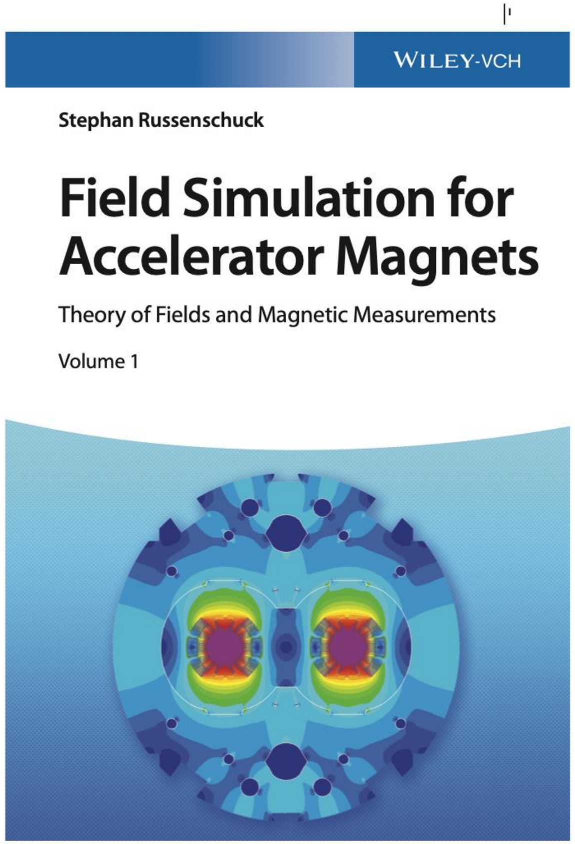
Field Computation for Accelerator Magnets

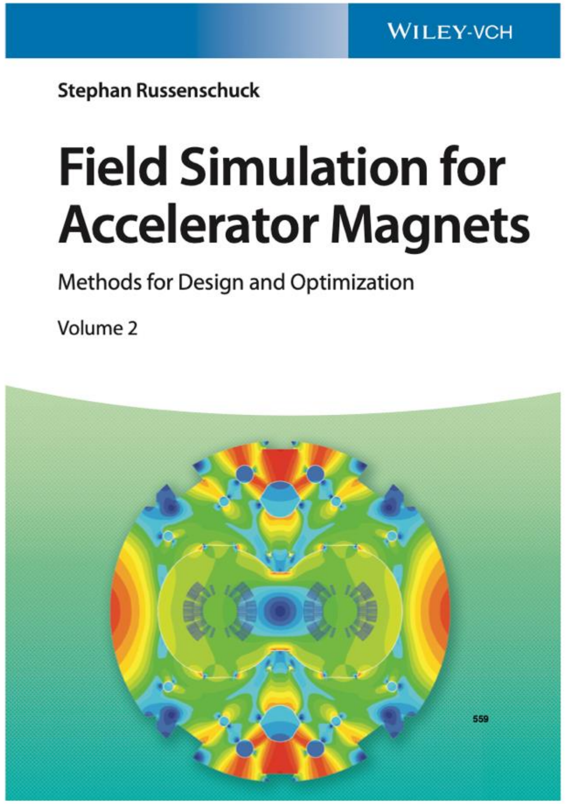
- Linear algebra
- Vector analysis
- Harmonic fields
- Green’s functions and the method of images
- Complex analysis
- Differential geometry
- Numerical field computation
- Hysteresis modeling
- Coupled (thermo, magnetic, electric) systems
- Mathematical optimization



New Edition, Autumn 2024

- **Field harmonics**
  - Toroidal harmonics
  - Pseudo-multipoles
- **Coil Magnetometers**
- **Stretched-Wire Measurements**
- **Synchrotron Radiation**
- **Faraday Paradoxes**
- **Iron-dominated magnets**
  - Wigglers and Undulators
- **Coil-dominated magnets**
  - CCT Magnets
  - Strongly curved magnets





Things for/from the Wishlist

- Hypermesh (External mesh generator)
- Quench computation (validation and user documentation)
- Curved coils & iron & harmonics
- Fast transient analysis with eddy currents
- Iron remanence calculation for very low field magnets (FCC-ee collider and booster)
- Simple optics to ROXIE, “beam-based magnet optimization”.
- Anisotropic BH (packing factor possibly in pre-defined direction, and grain-oriented steel).