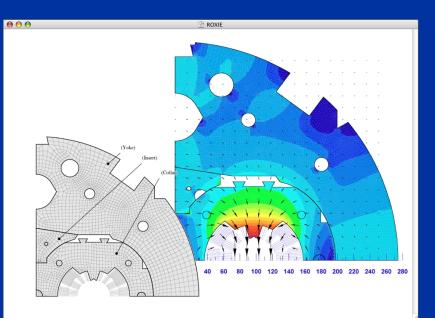
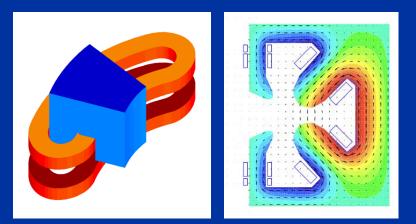


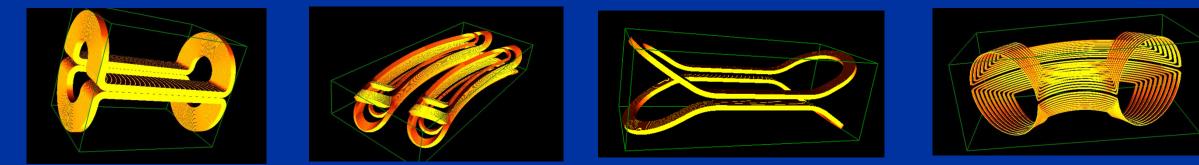
ROXIE 23 Launch Event

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)

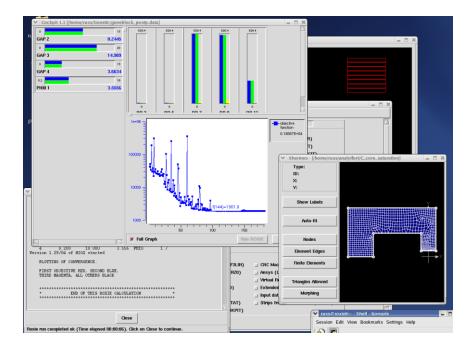
- No meshing of the coil, no artificial boundary conditions
- Higher order quadrilateral meshes, parametric mesh generator, morphing
- Modeling of superconductor magnetization
- Permanent magnets
- Quench simulation of long accelerator magnets (2.5 D)

Mathematical optimization techniques

• Genetic optimization, Pareto optimization, Search algorithms

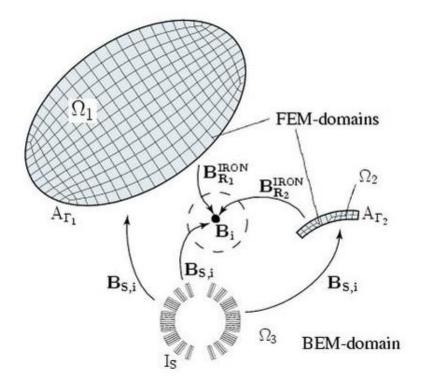
Simulation of magnetic measurements

CAD/CAM interfaces





BEM-FEM Coupling



BEM

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

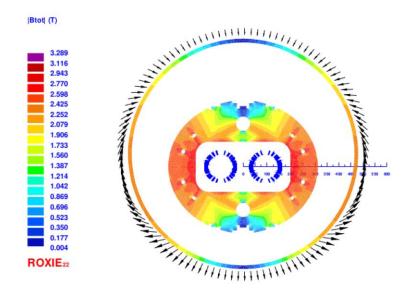
FEM

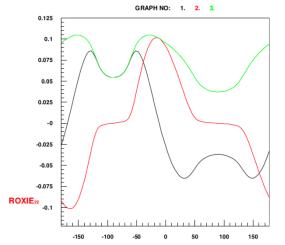
$$[K]{A} - [T]{Q} = {F(\mathbf{M})}$$

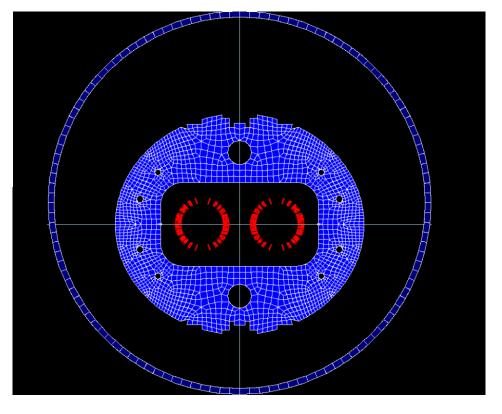
$$([K] + [T][G]^{-1}[H]) \{A\} = \{F(\mathbf{M})\} + [T][G]^{-1}\{A_s\}$$
$$[\overline{K}]\{A\} = \{\overline{F}(A_s, \mathbf{M})\}$$



HL-LHC Model D2











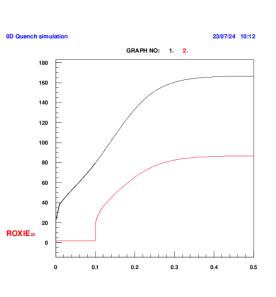
New ROXIE23 Features

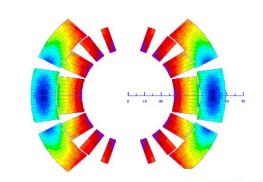
- ➔ Dynamic memory allocation
- ➔ Zonal harmonics for solenoid design
- → K-values of search coils
- Maxwell stress tensors
- ➔ CCT magnets
- ➔ External HMO files (HyperMesh Interface)
- ➔ Wigglers and Undulators
- ➔ Quench simulation update
- ➔ Python interface (post-processing, multiphysics, traceability)
- Material databases



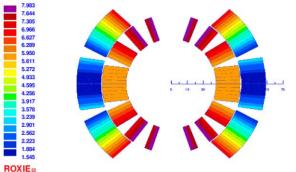
Adiabatic Quench Simulation

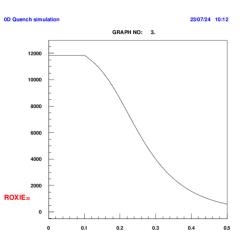
| lain Options | | | | | | | | | | | |
|----------------------------------|-----------------|--------------|------------|------------------|-------------------|----------|------------------|--------------|---|----------|---|
| _ 3D geometry | (LEND) | | 🔟 Endsj | acers (LWED) | i) | 🔟 Time | transient (LPEF | IS) | | | |
| 🔟 Quench simu | lation (LQUEN | CH) | _ Optin | nization (LALG | 0) | 📕 Quen | ch O-D (LQUEN | CHOD) | | | |
| Cable data path : /hc | me/russ/ | testcases | /QUENCH/ro | xie.cadat | 8 | Browse | View file | | | | |
| E 2D Options | | | | | | | | | | | |
| 📕 Fields & force | s in coil (LPE/ | ٩K) | 🔟 Margi | n to linear Jc-a | pprox. (LINMARG) | 🔄 Margi | n to Jc-fit (LMA | RG) | | | |
| Self field in s | trands (LSELF |) | 🔟 Entha | lpy margins (L | MQE) | 📕 Induc | tance and energ | y (LINDU) | | | |
| 🔟 Cable eddy cu | irrents (LEDD) | Y) | ∐ Axi-sy | mmetry (for s | olenoids) (LSOLE) | 🔄 Flux-l | inkage in search | coil (LFLUX) | | | |
| Block Data 2D | | | | | | | | | | | |
| Block Groups | | | | | | | | | | | |
| No Symm | | | Type(x | y) | Blocks | | | | | | |
| 1 Dipole | | | ▼ A11 | | ▼ 1-6 | | | | 4 | | |
| | | | • | | • | | | | | | |
| | | | • | | • | | | | | | |
| r Iron Yoke | | | | | | | | | | | |
| p Design Variables | | | | | | | | | | | |
| Transformations | | | | | | | | | | | |
| Block Restriction (peak | fields, plots) | | | | | | | | | | |
| E Quench 0D | | | | | | | | | | | |
| Cond. in which quench | initiates | 15 | _ | Operating | lemperature, K | 1.8 | _ | | | | |
| Quench detection dela | vy,s | 0.1 | | Magnet len | gth, m | 2 | _ | | | | |
| Maximum slope, K/s | | 20 | | Maximum 1 | ime step, s | 0.01 | | | | | |
| Stop at minimum cu rr | . factor | 0.05 | | | | | | | | | |
| r Virtual Devices | | | | | | | | | | | |
| E Graph | | | | | | | | | | | |
| No Type | Xva | alue | N/a | N/a | Y value | N/a | N/a Plot | number Axes | | Weight E | |
| 1 Device | ▼ QTI | IME | 0 | 0 | THOT | 0 | 0 | 1 Normal | • | 1 | Ζ |
| 2 Device | ▼ QT1 | | 0 | | TBULK | 0 | 0 | 1 Normal | • | 1 | - |
| 3 Device | ▼ QT1 | IME | 0 | 0 | QCURR | 0 | 0 | 2 Normal | • | 1 | 7 |
| More options : | | | | | | | | | | | |
| No String | | Value ahel | | G | anh | | m | | | | |





Average magnetic flux density in condutor (T)







|B| (T)

8.65

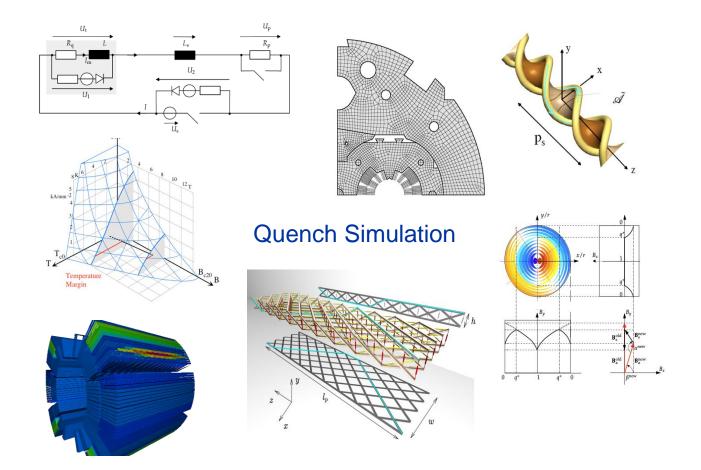
8.211

7.769 7.328 6.886 6.444 6.003 5.561 5.119

5.119 4.678 4.236 3.795 3.353 2.911 2.470 2.028 1.587 1.145 0.703 0.262

ROXIE₂₂

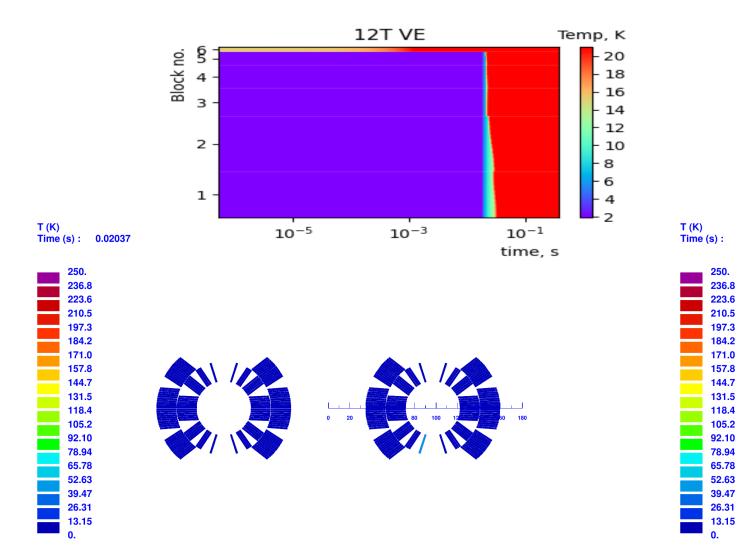
Multiphysics Quench Simulation (2.5 D)

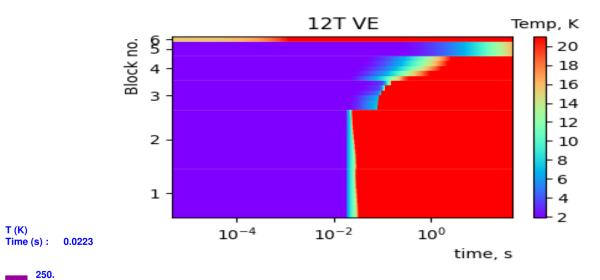


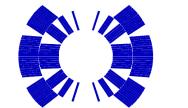
Issue: Empirical parameters: RRR, Ra/Rc, IFCC effective res., heat conductivity, heat capacity.

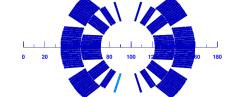


Multiphysics Quench Simulation (2.5 D)











User Manual for Quench Simulation

User Manual for ROXIE Quench Simulations

The latest ROXIE23 version is installed on a dedicated machine at CERN; access requests

Logging in (first confirm that the X11 display server (XQuartz, Xming, Xlunch, or

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

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

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

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

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

Deepak Paudel,¹ Stephan Russenschuck²

worktemsc01.cern.ch

/roxie_env

To run ROXIE in command mode, type

2 Running Quench Simulations

\$ Xroxie myfile.data

\$ runroxie model.data

1 Installing and Executing ROXIE

to be adressed to Matthias Borona (matthias.borona@cern.ch).

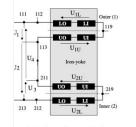
Xserver) is running in the local machine background):

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

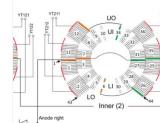


ench simulations.

or modify it using View file according it, strand, and cable definitions are as perties for quench simulation using the igure 2. These properties include the nductivity and Cu electrical resistivity, nds in the cable.



and winding scheme. Right aperture lower outer ıter - left aperture upper outer - upper inner - lower



Simulation Menu

nber of material-property parameters, various empirical paramtion threshold, heater delays, turn-to-turn propagation velocity e quench-simulation widget is shown in Figure 10. The meaning

or number of the incipient quench (quench origin).

rage half-length of the coil (in meters).

ic lengths (in meters). 1 voltage of the diode.

ductance in the string of magnets.

istance of the energy extraction system.

tive radius for inter-cable heat transfer. The radius determines paths between conductors. The distance must be large enough nduction to neighboring layers but small enough not to bypass coil

in voltage of the warm diode in the power converter.

thickness, area, and location (edge number and conductor numneater).

nsulation material and thickness.

time constant, power, and delay.

detection threshold.

delay. The heater delay is determined by test results or estile 1D heat diffusion problem.

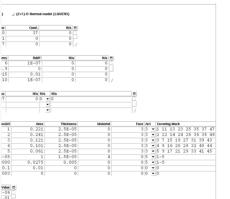
utta step.

irrent for ending the simulation.

8

cation is right aperture lower inner block 6, Figure 5, conductor g preview LOPOTO" is not active.

hown in Figure 11. The parameters to be specified are the cold lump resistor and warm diode.





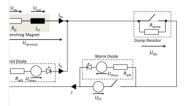


Figure 11: The electrical network.

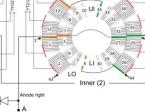


quench simulation.

select CUDI, NIST, or MATPRO fit s [1] of the used materials. Select the to Jc-fit, Inductance and energy, as

ARG) 📕 Margin to Jc-fit (LMARG) Inductance and energy (LINDU)
(LSOLE) _| Flux-linkage in search ceil (LFLUX)

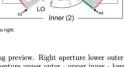
quench simulations.



and winding preview. Right aperture lower outer ıter - left aperture upper outer - upper inner - lower

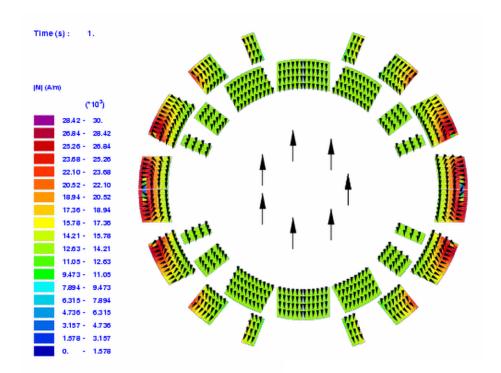
4

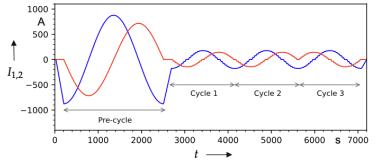


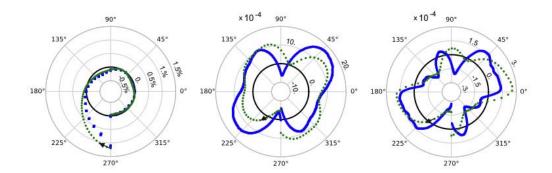


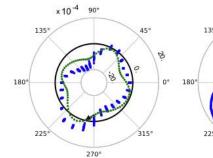


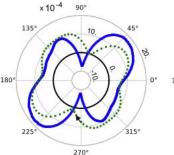
Validation of the Vector-Hysteresis Model



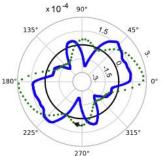


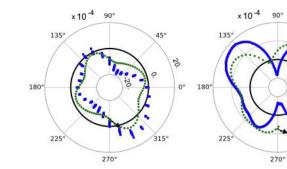


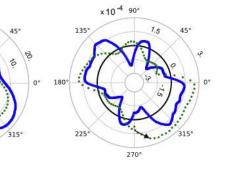




90°

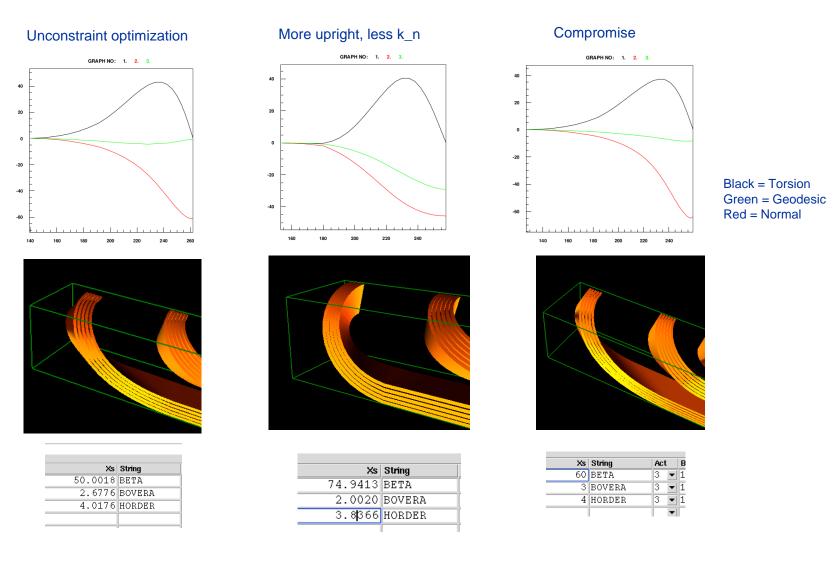








12T Robust End Optimization (winding trials)





Maxwell Stress Tensor on Circle and Line Elements

| wer | ' X limit | - 4 | 440 | Upper : | × limit | 440 | No. points bet | ween limit | s 16 | | |
|---|---|-----|--|---|--|-------|---|------------|--|-----------------------|--------------------------------------|
| wer | ' Y limit | | 440 | Upper ' | Y limit | 440 | No. points bet | ween limit | s 16 | | |
| wer | · Z limit | 7. | 50 | Upper 2 | Z limit | 1050 | No. points bet | ween limit | s 59 | | |
| əld | | a | 11 | • | | | | | | | |
| eld a | dong a path : | | | | | | | | | | |
| | Туре | | X start | Y start | × 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 | | |
| | options : | | | | | | | | | | |
| | opuons : String | | N/a N/a | | | 8 | | | | | |
| | oung | _ | ind ind | | | | | | | | |
| - | | _ | | | | -6 | | | | | |
| | | | | | | | | | | | |
| -i | | | | | | | | | | | |
| Ì | | ĺ | | | | | | | | | |
| aph | | | | | | | | | | | |
| No | Туре | | X value | N/a | N/a Y value | N/a | | Plot numb | | | Weig |
| No 1 | Device | | PHI | 1 | 0 MXWX | | 0 | | 1 Normal | | Weij |
| No 1 | | • | PHI GINT | 1 | 0 MXWX 0 GINT | | 0 0 | | 1 Normal 2 Normal | - | Wei |
| No 1 2 | Device | • | PHI | 1 1 1 | 0 MXWX | | 0 0 | | 1 Normal 2 Normal 3 Normal | | Wei |
| No 1 2 3 | Device Other | • | PHI GINT | 1 1 1 2 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 | | 0 0 0 | | 1 Normal 2 Normal 3 Normal 3 Normal | - | |
| No 1 2 3 4 | Device Other Device | • | PHI GINT ARCL | 1 1 1 | 0 MXWX 0 GINT 0 MXW2 | | 0 0 0 | | 1 Normal 2 Normal 3 Normal | • • | |
| No 1 2 3 4 5 | Device Other Device Device | • | PHI GINT ARCL ARCL | 1 1 1 2 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 0 MXW1 | | 0 0 0 0 0 | | 1 Normal 2 Normal 3 Normal 3 Normal | • • | |
| No 1 2 3 4 5 6 | Device Other Device Device Device | • | PHI GINT ARCL ARCL ARCL | 1 1 2 3 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 | | 0 0 0 0 0 0 | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal | • • • | |
| No 1 2 3 4 5 6 7 | Device Other Device Device Device Device | | PHI GINT ARCL ARCL ARCL ARCL ARCL | 1 1 2 3 4 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 0 MXW1 | | 0 0 0 0 0 0 0 0 0 | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 3 Normal | • • • • | 0.0 |
| No 1 2 3 4 5 6 7 8 | Device Other Device Device Device Device Other | | PHI GINT ARCL ARCL ARCL ARCL GINT GINT GINT GINT GINT GINT GINT GINT | 1 1 2 3 4 3 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 0 MXW1 0 GINT | | | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 3 Normal 4 Normal | ▼ ▼ ▼ ▼ | 0.0 |
| No 1 2 3 4 5 6 7 8 9 | Device Other Device Device Device Device Other Other | | PHI GINT ARCL ARCL ARCL GINT GINT | 1 1 2 3 4 3 4 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 0 MXW1 0 GINT 0 GINT | | | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal | V V V V V | 0.0 |
| No 1 2 3 4 5 6 7 8 9 10 | Device Other Device Device Device Other Other Other | | PHI GINT ARCL ARCL ARCL GINT GINT GINT | 1 1 2 3 4 3 4 5 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW1 0 GINT 0 GINT 0 GINT | | | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal 6 Normal | | 0.0 |
| No 1 2 3 4 5 6 7 8 9 9 10 11 | Device Other Device Device Device Other Other Other Other Other | | PHI GINT ARCL ARCL ARCL GINT GINT GINT GINT ARCL | 1 1 2 3 4 3 4 5 6 1 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW1 0 GINT 0 GINT 0 GINT 0 GINT | | | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal 6 Normal 7 Normal | | 0.0 |
| No 1 2 3 4 5 6 7 8 9 10 11 12 | Device Other Device Device Device Other Other Other Other Device | | PHI GINT ARCL ARCL ARCL GINT GINT GINT GINT GINT GINT GINT | 1 1 2 3 4 3 4 5 6 1 1 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 0 MXW1 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT | | | | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal 6 Normal 8 Normal | | 0.0 |
| No 1 2 3 4 5 6 7 8 9 10 11 12 13 | Device Other Device Device Device Other Other Other Other Device Other Device | | PHI GINT ARCL ARCL ARCL GINT GINT GINT GINT ARCL GINT BRCL GINT PHI | 1 1 2 3 4 3 4 5 6 1 1 1 1 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW1 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT | | | 1 | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal 6 Normal 7 Normal 8 Normal 9 Normal 0 Normal | | 0.0 |
| No 1 2 3 4 5 6 7 8 9 10 11 12 13 14 | Device Other Device Device Device Other Other Other Device Other Device Device Device | | PHI GINT ARCL ARCL ARCL GINT GINT GINT ARCL GINT GINT HI PHI PHI | 1 1 2 3 4 3 4 5 6 1 1 11 1 1 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW2 0 MXW1 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 BPHI 0 BPHI | | | 1 | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal 6 Normal 7 Normal 8 Normal 9 Normal 1 Normal | | 0.00 |
| No 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 | Device Other Device Device Device Other Other Other Other Device Other Device | | PHI GINT ARCL ARCL ARCL GINT GINT GINT GINT ARCL GINT BRCL GINT PHI | 1 1 2 3 4 3 4 5 6 1 1 1 1 | 0 MXWX 0 GINT 0 MXW2 0 MXW1 0 MXW1 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT 0 GINT | | | 1 | 1 Normal 2 Normal 3 Normal 3 Normal 3 Normal 4 Normal 5 Normal 6 Normal 7 Normal 8 Normal 9 Normal 0 Normal | | Weig 0.00 0.00 0.00 0.00 |

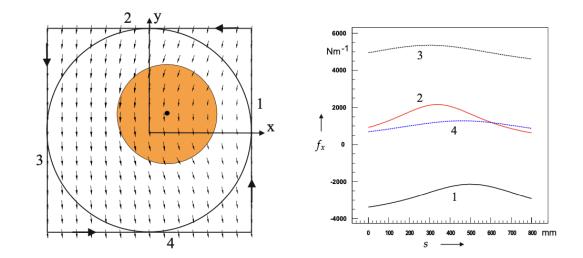


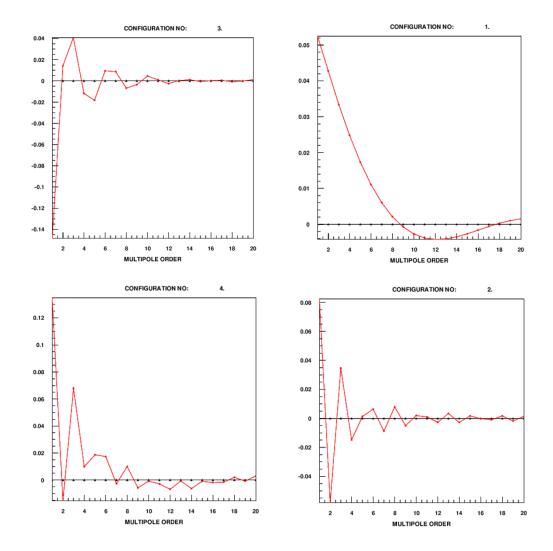
Fig. 4.14: Left: Round conductor of r = 200 mm, carrying 40000 A in a 0.1 T dipole field. The total force in the *x*-direction is 4 kN per meter length of the conductor. Right: Component f_x of the force density per meter length, along the four sides of the de-centered rectangle. Integration over the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



S_n-Value of Search Coil

| | 11 | | | _ | | | | | | | | | |
|-----------------|-----------------|----------------|---------------------------------|------------|------------------|-------------|----|--------------|---------------|-----------------|-------------------|-------------|------|
| ole data path : | /home/ru | iss/roxie_cct/ | datab/roxie.cadat | a | Browse | View fi | le | | | | | | |
| Options | | | | | | | | | | | | | |
| k Data 2D | | | | | | | | | | | | | |
| No Type | NCab | | Y | α | Current Cable na | | N1 | N2 Imag | Turn | | | | |
| 1 Rect | ▼ 200 | | 2.4 | 0 | 0 NEDM1 | • | 2 | | 0 | | | | |
| 2 Rect | ▼ 200 | | -1.616 | 0 | 0 NEDM1 | - | 2 | 2 0 | 0 | | | | |
| 3 Rect | -200 | 2.7 | 0 | 0 | 0 NEDM1 | • | 2 | 2 0 | 0 | 1 | | | |
| ore options : | | | | | | | | | D Paula III | | | | |
| No String | | N/a N/a | | | | | | | A Preview [/h | iome/russ/testc | ases/K-values/PCE | _coll.dataj | |
| 1 PCAKE | | 10 1 | | A | | | v | iew : XY Se | ction | | _ | | |
| 2 PCAKE | | 10 2 | | | | | N | umbering: N | one | | | | |
| 3 PCAKE | | 10 3 | | N. | | | C. | able: Bare | | | | | |
| k Groups | | | | | | - | | | | | | | |
| No Symm | | | Type(xy) | Blocks | | _ | | | | | | | |
| 1 Dipole | | | ▼ One coil | • 1 | | _ | | | | | | | |
| 2 Dipole | | | One coil | ▼ 2 | | _ | | | | | | | |
| 3 Dipole | | | ▼ One coil | ▼ 3 | | | | | | | | | |
| Yoke | | | | | | | | | | | | | |
| ign Variables | | | | | | | | | | | | ي الم | |
| sformations | | | | | | | | | | | | | |
| k Restriction | (peak fields, p | lots) | | | | | | | | | | | |
| al Devices | | | | | | | | | | | | | |
| 🔄 Harmoni | ic coil (LHAR) | 1) | 🔄 Field vector matrix | (LMATRF) | 🔄 Field alon | g a path (l | | | | | | | |
| 📕 K-Value | of search coi | (LKVAL) | | | | | | | | | | | |
| | | | | | | - | | | | | | | |
| Values | | | | | | | | | | | | | |
| No | Length 150 | Angle 90 | Rref Kn/Sn Bi 2.64008 Sn ▼ 1 | JCK Groups | | | | | | | | | |
| 2 | 150 | 90 | 2.64008 Sn • 2 | | | -8 | | | 07 | 10 | Cabla | | |
| 3 | 150 | 90 | 2.64008 Sn • 3 | | | _ | | XY YZ | SZ | 1,2 | Cable Imag. | Layer | Edge |
| ~ | 100 | 50 | 2.04000 511 • 0 | | | | _ | | | | | _ | - |

 $\varphi_1 \setminus \varphi$



$$U = -\frac{d\Phi}{dt}$$

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

CÉRN

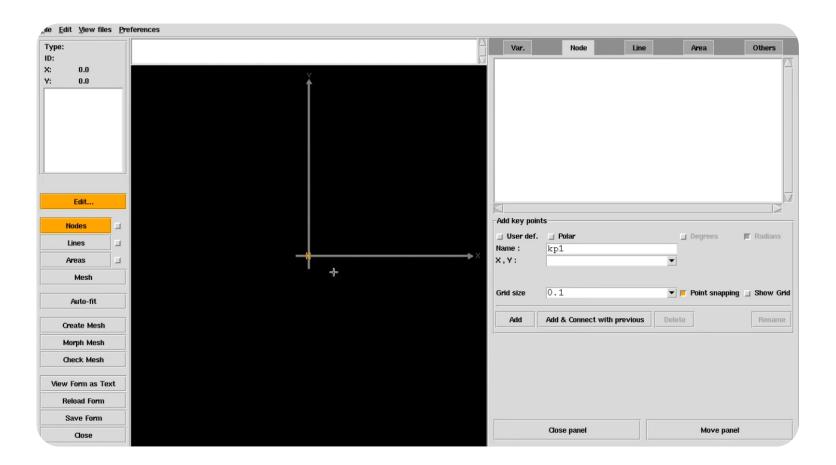
New Coil Macros

Bedstead Cradl Cranked sattel Cos Flared Flex PCB Racetrack Racetrack CCT soft way hard way



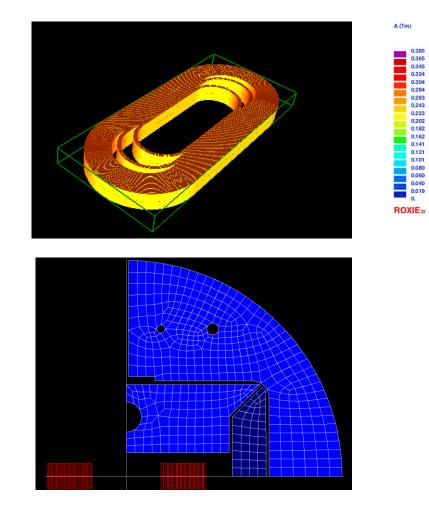
Pre-Processor and Mesh Generator

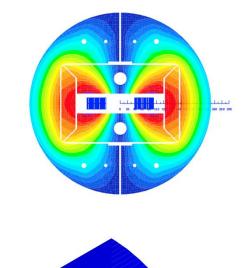
- Add point and connect
- Snap to grid
- Auto save
- Undo
- Delete kp (and dependent
- lines and areas)

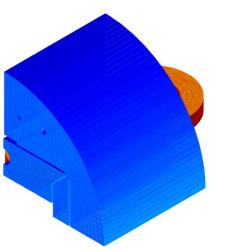


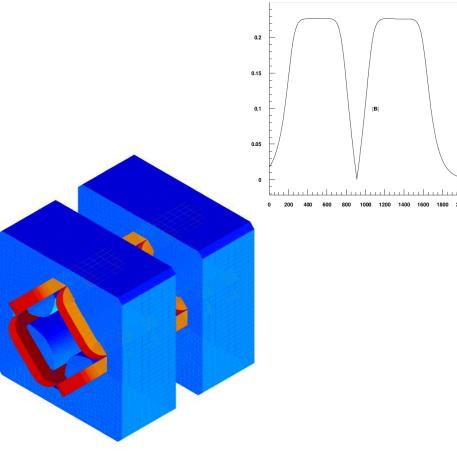


Improved Extrusion Modes









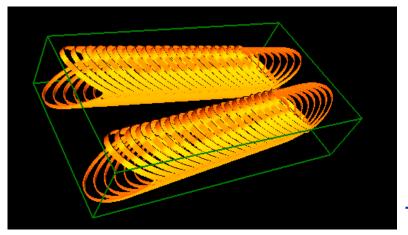
| _ | | - | | | | | | | |
|------------|-------|------------------|------------------|-------|------|---------|----------|-------------------------|--|
| T I | on Y | oke | | | | | | | |
| Ē. | xtrus | sion | | | | | | | |
| | No | Area name | z start | z end | Bias | N elem. | Material | 8 | |
| | 1 | AR1 | -270 | 270 | 0.5 | 8 | BHIRON2 | | |
| | 2 | AR1 | 550 | 1110 | 0.5 | 8 | BHIRON2 | | |
| | | | | | | | | $\overline{\mathbf{A}}$ | |
| T (| esigi | n Variables | | | | | | | |
| T T | rans | formations | | | | | | | |
| ŢΕ | llock | Restriction (pea | k fields, plots) | | | | | | |



GRAPH NO: 1.

2000

CCT Magnets



Transformations

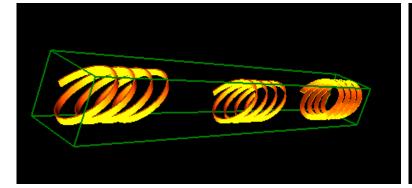
| | Туре | | NCab | | X | | Y | a | | Current | Cable name | | N1 | N2 Im | ag | Turn | Disc | Ne | 1 |
|---------|----------------------|---|------|----------|------|---------------|------|------------------|----------------|---------|------------|---|----|-------|------|------|------|-------|---|
| 1 | Helix | - | 1 | | 123 | | 6.38 | 84 | | 16100 | FUSILLO | - | 1 | 11 | | 60 | 0 | 1 |] |
| 2 | Helix | - | 1 | 14 | 8.35 | | 6.38 | 84 | | -16100 | FUSILLO | • | 1 | 11 | | -60 | 0 | 2 | 2 |
| | | • | | | | | | | | | | • | | | | | | | 1 |
| | | | | | | | | | | | | | | | | | | | |
| | options : | | | | | | | | | | | | | | | | | | |
| No | String | | | N/a | N/a | | | | | | | | | | | | | | |
| | | | | | | | | | IA. | | | | | | | | | | |
| | | | | | | | | | _ (=) | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| ock I | Data 3D | | | | | | | | | | | | | | | | | | |
| | Data 3D Type | | | | | A | | Во | Zo | | w | | W | 0 | Hwed | | Hord | ler 🖻 | 3 |
| Ne | | | | v | | A 0 | -1: | Bo 100 | | | Wi | | | • | Hwed | | Hord | ler E | 9 |
| Ne 1 | Туре | | | | | | | | Zo | | | | | | | | Hord | er E | |
| Ne 1 | Type Helix | | | V | | 0 | | 100 | Zo 0 | | 0 | | | | 0 | | Hord | 1 | 9 |

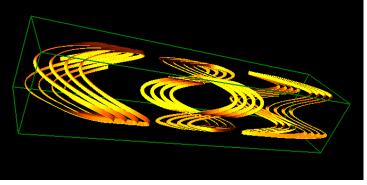
| No | String | N/a | N/a |
|----|--------|------|---------------|
| 1 | CCTP1 | 20 | 1-9 901-909 |
| 2 | CCTP1 | 10 | 9-15 909-915 |
| 3 | CCTP1 | 10 | 16-22 916-922 |
| 4 | CCTP2 | 20 | 1-9 901-909 |
| 5 | CCTP2 | 10 | 9-15 909-915 |
| 6 | CCTP2 | 10 | 16-22 916-922 |
| 7 | NZDIS | 3000 | 1-2 |

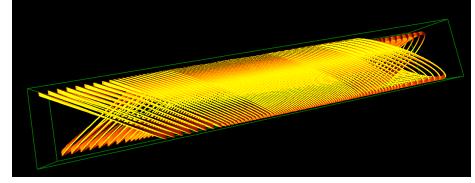
Frenet and Darboux frames, ID/OD alignment

Higher-order multipoles

Pitch variation at the ends

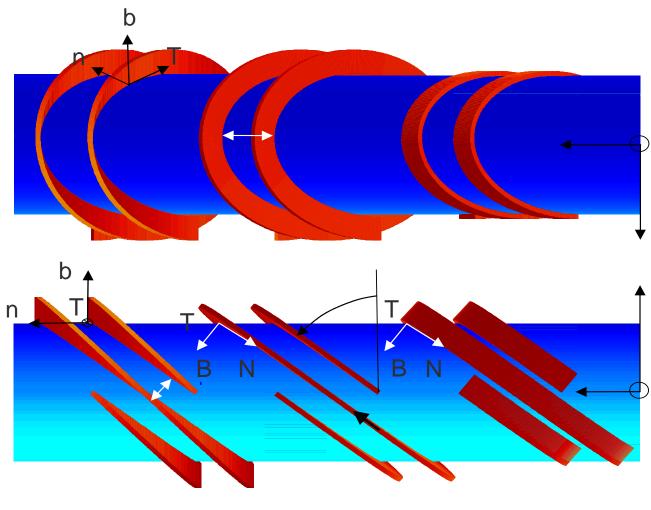








CCT Coil Types



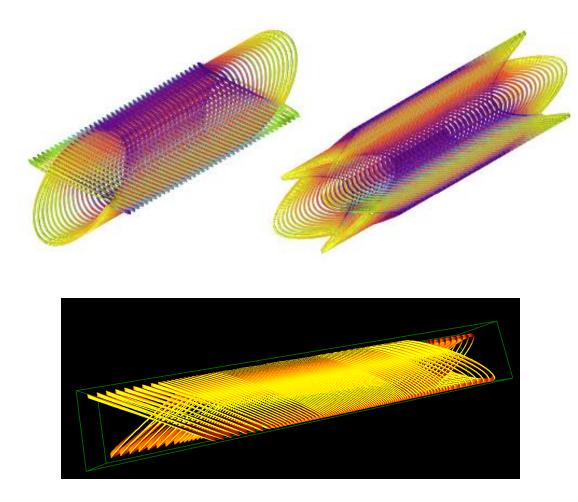
Darboux frame

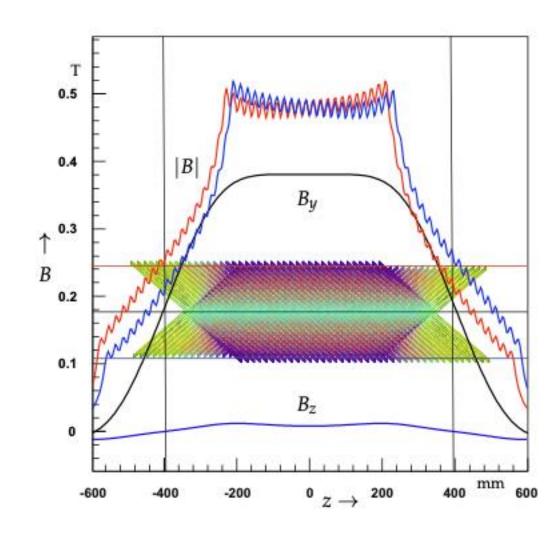
Frenet frame hard way

Frenet frame soft way



CCT Magnet Design (Issues)

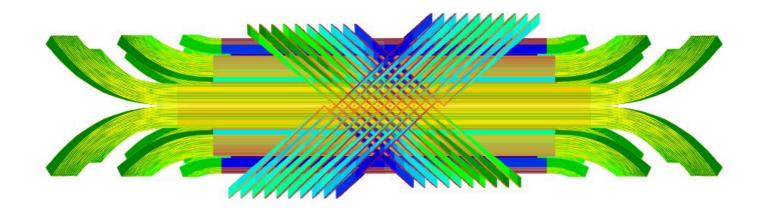


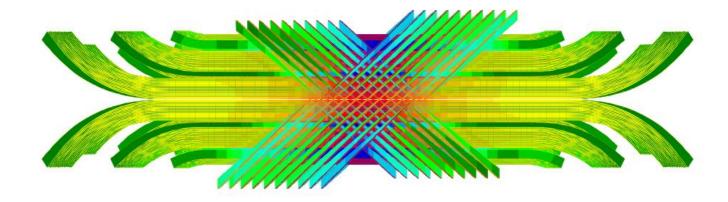




Dynamic Memory Allocation

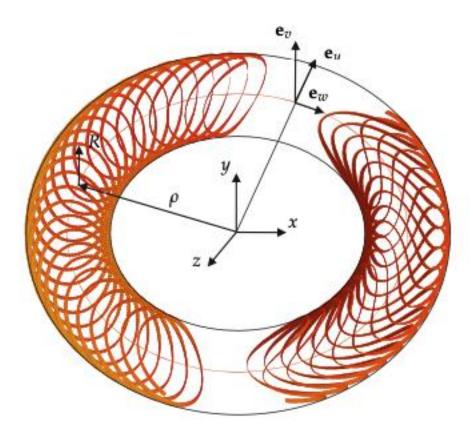
- 30 elements in straight section
- 25 elements in coil heads
- 28 blocks in $\cos \Theta$
- 304 Conductors
- 1500 elements in CCT coils







Curved Magnets



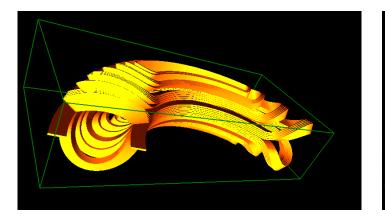
$$\begin{aligned} \mathbf{e}_{u} &= \cos\left(\frac{\sigma}{\rho}\right)\mathbf{e}_{x} + \sin\left(\frac{\sigma}{\rho}\right)\mathbf{e}_{z}, \\ \mathbf{e}_{v} &= \mathbf{e}_{y}, \\ \mathbf{e}_{w} &= -\sin\left(\frac{\sigma}{\rho}\right)\mathbf{e}_{x} + \cos\left(\frac{\sigma}{\rho}\right)\mathbf{e}_{z}. \end{aligned}$$

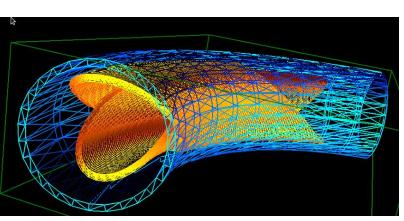
$$\mathbf{r}(\varphi) = \mathbf{o}(\sigma(\varphi)) + R\cos(\varphi) \,\mathbf{e}_u + R\sin(\varphi) \,\mathbf{e}_v$$
$$= \cos\left(\frac{\sigma(\varphi)}{\rho}\right) (\rho + R\cos(\varphi)) \,\mathbf{e}_x + R\sin(\varphi) \,\mathbf{e}_y$$
$$+ \sin\left(\frac{\sigma(\varphi)}{\rho}\right) (\rho + R\cos(\varphi))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

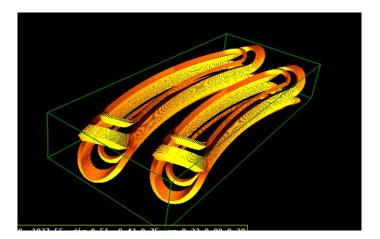
 $\sigma(\varphi) = R \tan(\alpha) \sin(n\varphi) + q\varphi$

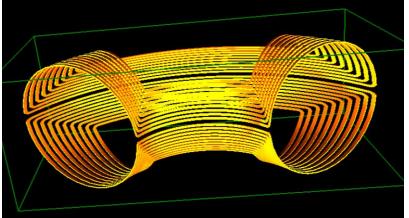


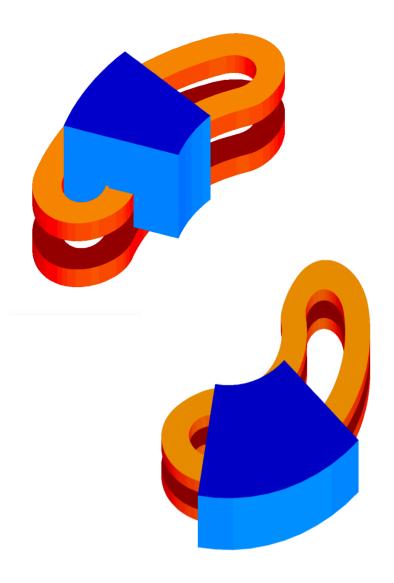
Curved Magnets II













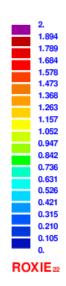
Extracting the Legendre Polynomials

$$\begin{aligned} \mathbf{B}_{\tau} &= \sum_{m=0,n=0}^{\infty} \mathcal{A}_{n,m} \left(-\frac{\mu_{0} \cos(n\sigma) \cos(m\phi)\kappa_{\tau,\sigma}}{aQ_{n-\frac{1}{2}}^{m}(\cosh(\tau))} \left[\frac{\sinh(\tau)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) + \kappa_{\tau,\sigma}^{\frac{1}{2}} \frac{\partial}{\partial\tau} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) \right] \right) \\ &+ \mathcal{B}_{n,m} \left(-\frac{\mu_{0} \sin(n\sigma) \cos(m\phi)\kappa_{\tau,\sigma}}{aQ_{n-\frac{1}{2}}^{m}(\cosh(\tau))} \left[\frac{\sinh(\tau)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) + \kappa_{\tau,\sigma}^{\frac{1}{2}} \frac{\partial}{\partial\tau} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) \right] \right) \\ &+ \mathcal{C}_{n,m} \left(-\frac{\mu_{0} \cos(n\sigma) \sin(m\phi)\kappa_{\tau,\sigma}}{aQ_{n-\frac{1}{2}}^{m}(\cosh(\tau))} \left[\frac{\sinh(\tau)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) + \kappa_{\tau,\sigma}^{\frac{1}{2}} \frac{\partial}{\partial\tau} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) \right] \right) \\ &+ \mathcal{D}_{n,m} \left(-\frac{\mu_{0} \sin(n\sigma) \sin(m\phi)\kappa_{\tau,\sigma}}{aQ_{n-\frac{1}{2}}^{m}(\cosh(\tau))} \left[\frac{\sinh(\tau)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) + \kappa_{\tau,\sigma}^{\frac{1}{2}} \frac{\partial}{\partial\tau} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau)) \right] \right) \\ &=: \sum_{m=0,n=0}^{\infty} \left[\mathcal{A}_{n,m} \cdot c_{\tau,n,m}^{\mathcal{A}}(\tau,\sigma,\phi) + \mathcal{B}_{n,m} \cdot c_{\tau,n,m}^{\mathcal{B}}(\tau,\sigma,\phi) \\ &+ \mathcal{C}_{n,m} \cdot c_{\tau,n,m}^{\mathcal{C}}(\tau,\sigma,\phi) + \mathcal{D}_{n,m} \cdot c_{\tau,n,m}^{\mathcal{D}}(\tau,\sigma,\phi) \right] \end{aligned}$$

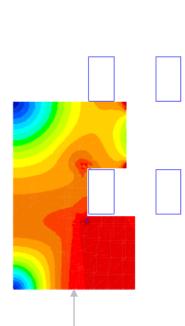
$$\begin{aligned} \mathbf{B}_{\sigma} &= \sum_{m=0,n=0}^{\infty} \mathcal{A}_{n,m} \left(-\frac{\mu_{0} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau))\cos(m\phi)\kappa_{\tau,\sigma}}{a Q_{n-\frac{1}{2}}^{m}(\cosh(\tau_{0}))} \left[\frac{\sin(\sigma)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}}\cos(n\sigma) - \kappa_{\tau,\sigma}^{\frac{1}{2}}n\sin(n\sigma) \right] \right) \\ &+ \mathcal{B}_{n,m} \left(-\frac{\mu_{0} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau))\cos(m\phi)\kappa_{\tau,\sigma}}{a Q_{n-\frac{1}{2}}^{m}(\cosh(\tau_{0}))} \left[\frac{\sin(\sigma)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}}\sin(n\sigma) + \kappa_{\tau,\sigma}^{\frac{1}{2}}n\cos(n\sigma) \right] \right) \\ &+ \mathcal{C}_{n,m} \left(-\frac{\mu_{0} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau))\sin(m\phi)\kappa_{\tau,\sigma}}{a Q_{n-\frac{1}{2}}^{m}(\cosh(\tau_{0}))} \left[\frac{\sin(\sigma)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}}\cos(n\sigma) - \kappa_{\tau,\sigma}^{\frac{1}{2}}n\sin(n\sigma) \right] \right) \\ &+ \mathcal{D}_{n,m} \left(-\frac{\mu_{0} Q_{n-\frac{1}{2}}^{m}(\cosh(\tau))\sin(m\phi)\kappa_{\tau,\sigma}}{a Q_{n-\frac{1}{2}}^{m}(\cosh(\tau_{0}))} \left[\frac{\sin(\sigma)}{2\kappa_{\tau,\sigma}^{\frac{1}{2}}}\sin(n\sigma) + \kappa_{\tau,\sigma}^{\frac{1}{2}}n\cos(n\sigma) \right] \right) \\ &=: \sum_{m=0,n=0}^{\infty} \left[\mathcal{A}_{n,m} \cdot c_{\sigma,n,m}^{\mathcal{A}}(\tau,\sigma,\phi) + \mathcal{B}_{n,m} \cdot c_{\sigma,n,m}^{\mathcal{B}}(\tau,\sigma,\phi) \right] \end{aligned}$$



Curved Magnet Study (Rotational Symmetric)



Btot (T)

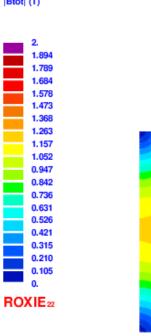


| MAIN FIELD (T) MAGNET STRENGTH (T/(m^(n-1)) | 0.924326 0.9243 |
|---|--|
| NORMAL RELATIVE MULTIPOLES (1.D-4 b 1: 10000.0000 b 2: -0.13 b 4: 0.00002 b 5: 0.03 b 7: 0.00846 b 8: 0.00 b 10: -0.017 b 11: -0.01 b 13: -0.00337 b 14: -0.00 b 16: 0.00471 b 17: 0.00 b 19: -0.00058 b 20: -0.00 | x532 b -0.15851 1623 b 6: 0.00443 3396 b 9: 0.01173 1437 b12: -0.00483 1051 b15: 0.00277 1473 b18: 0.00262 |
| SKEW RELATIVE MULTIPOLES (1.D-4): a 1: 0.00000 a 2: 0.00 a 4: -0.000000 a 5: -0.00 a 7: -0.000000 a 8: -0.00 a 10: -0.000000 a 11: 0.00 a 13: -0.00000 a 14: 0.00 a 16: -0.000000 a 17: 0.00 a 19: -0.000000 a 20: 0.00 | 0000 a 3: 0.0000 0000 a 6: -0.0000 0000 a 9: 0.0000 0000 a12: -0.0000 0000 a12: -0.0000 0000 a18: -0.0000 0000 a18: -0.00000 0000 a |
| SURFACE OF ALL FEM-ELEMENTS (MM** | 2) 460541.9852 |

. . . .

| TURNING ANGLE OF F MEASUREMENT TYPE . ERROR OF HARMONIC SUM (Br(p) - SUM (| ANALYSIS | OF Br | ALL | FIELD CONT | RIBUTIONS |
|---|------------|----------|-------|------------|--------------------|
| MAIN FIELD (T) MAGNET STRENGTH (T | C∕(m^(n-1) |) | | | 0.972557 0.9726 |
| NORMAL RELATIVE MU | LTIPOLES | (1.D-4): | | | |
| b 1: 10000.00000 | | | ь З: | -0.10184 | |
| b 4: 0.02140 | | | | | |
| ь 7: 0.00804 | b 8: | 0.00366 | b 9: | 0.00201 | |
| b10: -0.00176 | b11: | -0.00436 | b12: | -0.00459 | |
| b13: -0.00321 b16: 0.00455 | b14 : | -0.00052 | b15 : | 0.00268 | |
| b16: 0.00455 | b17: | 0.00454 | b18: | 0.00251 | |
| b19: -0.00055 | b20: | -0.00337 | Ъ | | |
| SKEW RELATIVE MULT | TPOLES (1 | D-4): | | | |
| a 1: -0.00000 | a 2: | 0. 00000 | a 3: | -0.00000 | |
| a 4: 0.00000 | | | | | |

1 meter



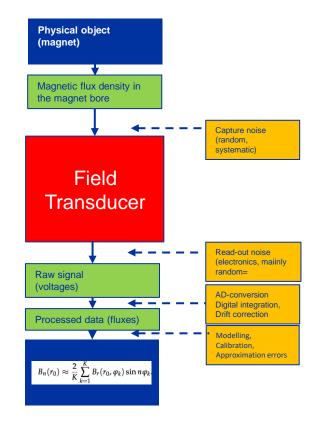
Btot (T)

2.

0.

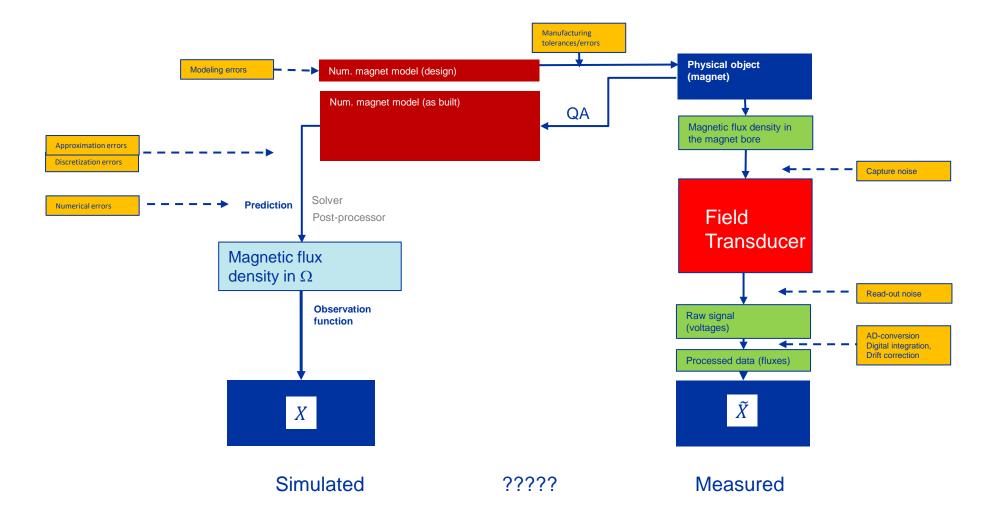


The Avatar and Twin (classical black-box measurement)



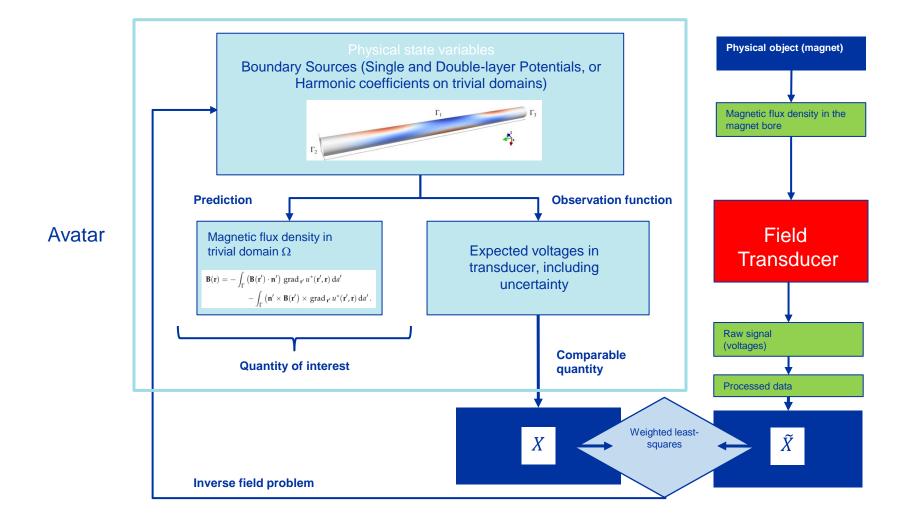


The Avatar and Twin (tracing of manufacturing tolerances and errors)



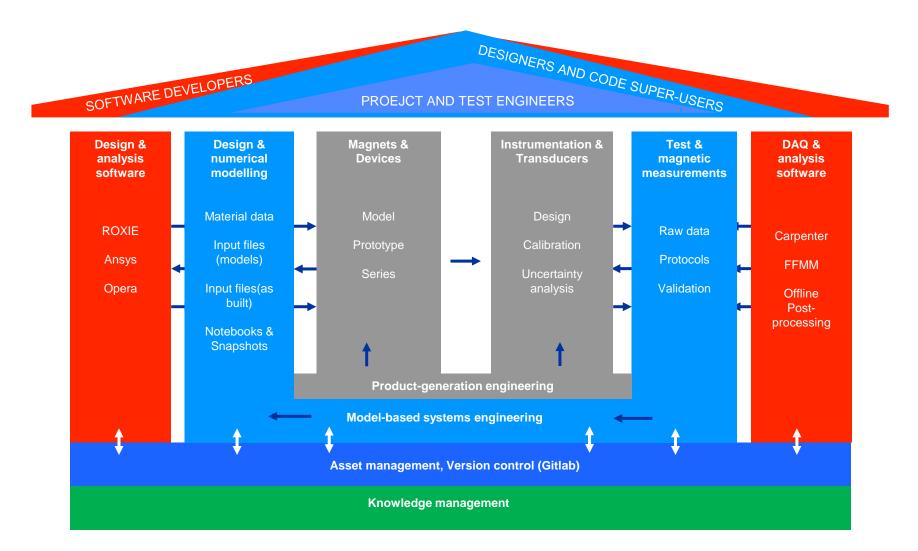


The Avatar and Twin (generalized field description)





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

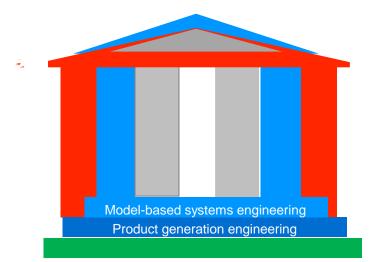
Accessibly

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

| ystem C | Overview | | |
|-------------------|---------------------------------|--------------------------|------|
| Systems | | | |
| List with all reg | istered systems. | | |
| Туре | Name | Created at | |
| | Building 311 calibration dipole | June 22, 2023, 2:59 p.m. | View |
| SAMPLE | | | |

SIGRUM Quench Test

| Model Information Details, description and linked files. | | | Model Updates All changes made to the model over time. | |
|---|--------------------------------|----------|--|-----|
| Туре | ROXIE | | Model created by Stephan Russenschu 3 hours, 23 minutes ago | JC |
| Part of | SIGRUM | | Jens Kaeske added tags • 3D • Dig Objects | olo |
| Description | Initial quench test for SIGRUM | | 6h ago Stephan Russenschuck | |
| Inputs | | Download | Commented th ago Adiabatic quench simulation of revised cross section (computation with iron yo PLot of average and peak temperature Graphs. | oke |
| | Proxie.cadata 34.5 KB | Download | | |
| | Ø Sig.iron 767 bytes | Download | | |
| | Sig-2D-iron-quench.data 4.9 KB | Download | | |

| Home Systems | | | | | TOLO |
|---|--------------------------------------|---|-------------------|--------|-----------|
| RUM | | | | | ng 311. |
| em Information ils, ownership and linked | files. | | | | Download |
| ect owner | Stephan Russen | schuck | | AN PAR | |
| ription | Sigrum design s the coil heads fo | tudy (straight version). Including v or winding tests. | variants for | | |
| | Dipole Nb-Ti | | | | new model |
| tem models | e SIGRUM system. | Create n | ew model | | View |
| • Name | Design step | Created on | Latest version | | View |
| IE SIGRUM Quench Te | est quench | Sept. 5, 2023, 12:47 p.m. | View | | |
| IE 2D iron yoke | 2D | Sept. 4, 2023, 3:17 p.m. | View | | |

Home Systems

System Information

Building 311 calibration dipole

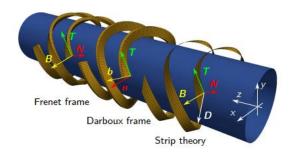


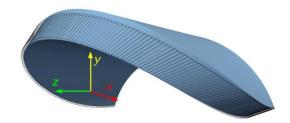
DJDT

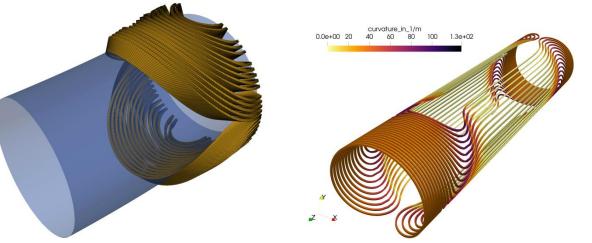
ROXIE Python API

- 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



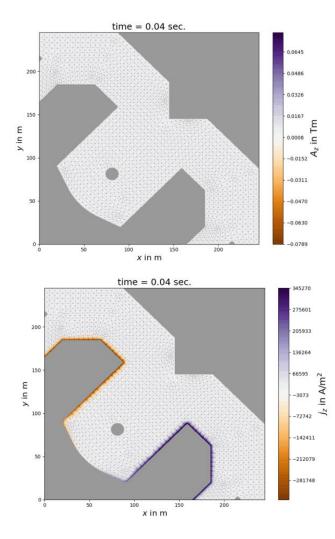




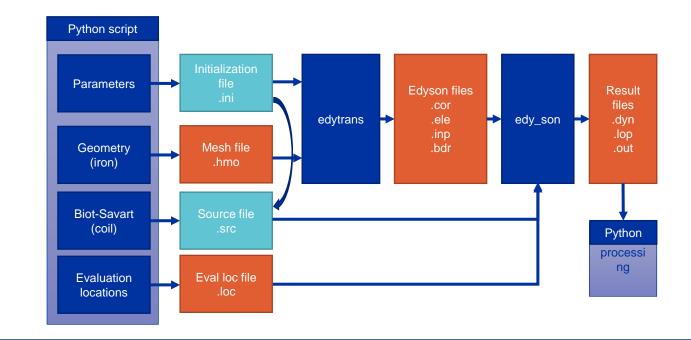




Eddy current solver



- 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

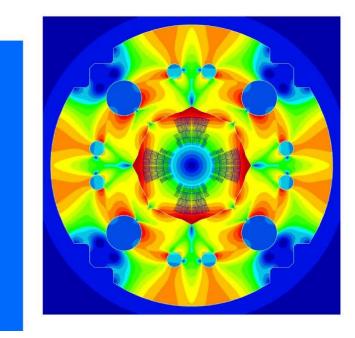
- Linear algebra
- Vector analysis
- Harmonic fields
- Green's functions and the method of images
- Complex analysis
- Differential geometry
- Numerical field computation
- Hysteresis modeling
- Coupled (thermo, magnetic, electric) systems
- Mathematical optimization

Stephan Russenschuck

Wiley-VCH

Field Computation for Accelerator Magnets

Analytical and Numerical Methods for Electromagnetic Design and 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

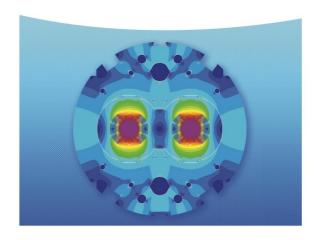
Stephan Russenschuck

Field Simulation for Accelerator Magnets

WILEY-VCH

Theory of Fields and Magnetic Measurements

Volume 1

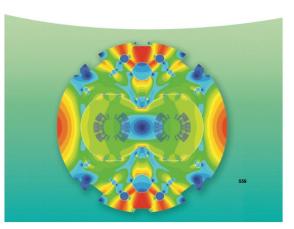




Stephan Russenschuck

Field Simulation for Accelerator Magnets

Methods for Design and Optimization Volume 2





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).

