cern.ch/STEAM

ProteCCT

(Protection of **C**anted-**C**osine-**T**heta-type Magnets**)**

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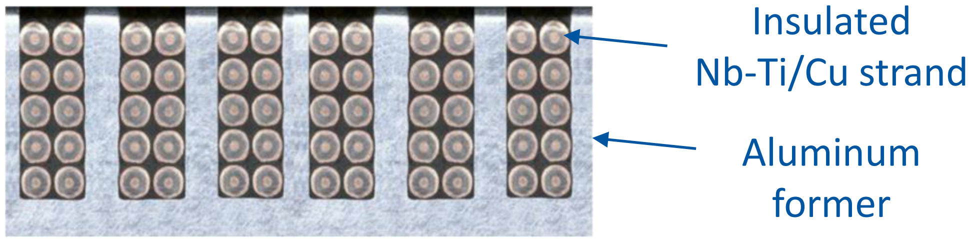
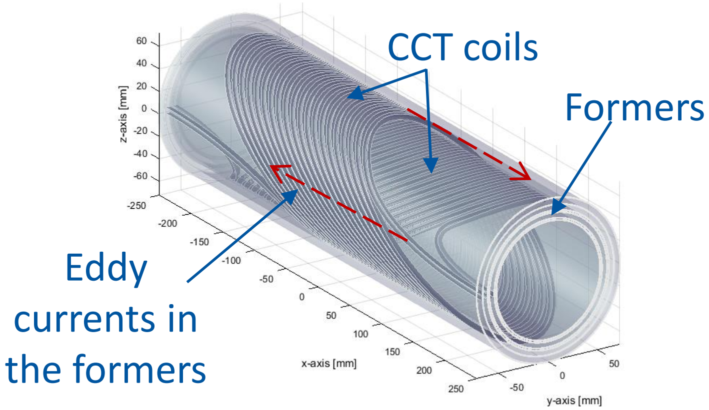
Overview

- Motivation
- Thermal aspects
- Internal circuit / Co-simulation
- User interface
- Complexities + correction factors:
  - Oversimplified model of eddy currents in the formers → Correction factor fLoopFactor
  - Additional helium present between the (non-bonded) formers and outer cylinder → Correction factor addedHeCpFrac
- Simulation vs. experimental observations
- Running the model
- Demonstration
- Summary

Motivation



Canted-Cosine-Theta (CCT) magnets: superconducting strand inside slots in conductive former [1]



Eddy currents in formers surrounding CCT coils during discharge
(Field, courtesy J. van Nugteren)

Why STEAM-ProteCCT?

- Canted Cosine Theta Magnets: Concentric superconducting coils held in place by conductive aluminum formers

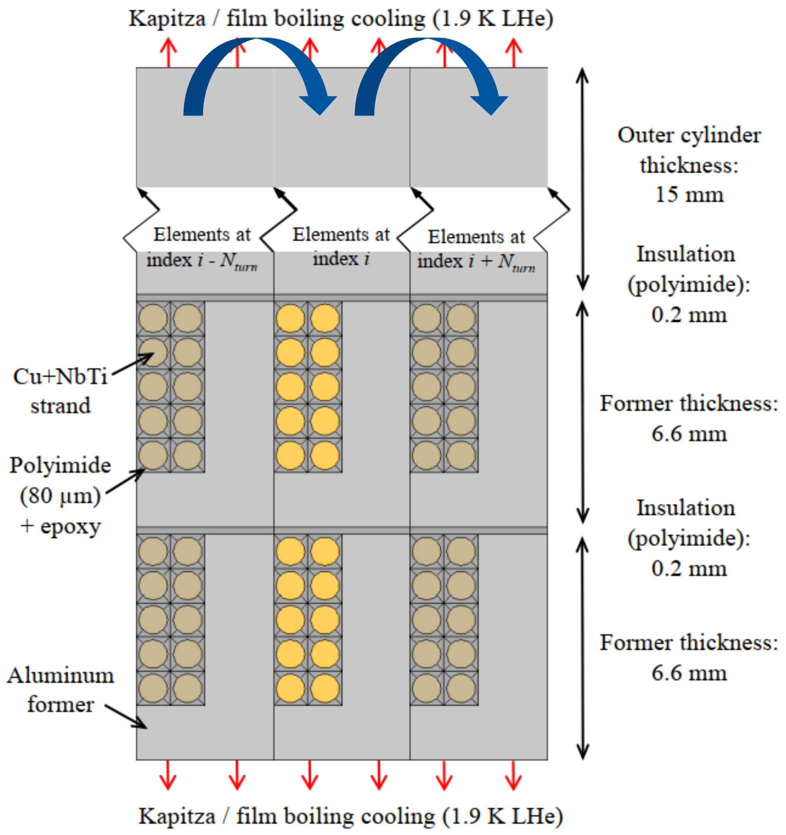
- Quench protection of MCBRD Twin Aperture Orbit Correctors for HL-LHC upgrade and other future CCT-type magnets
  - Magnet is discharged over energy extractor
  - Eddy currents in the conductive formers → Heating in formers → Fast development of normal zone throughout superconducting coils (Quench-back)
  - Complex three-dimensional geometry

→ Quench simulation with STEAM-ProteCCT

[1] G. Kirby et al. IEEE Trans. on Appl. Supercond. 28, p. 4002205 (2018)

Thermal aspects

Turn-to-turn periodic boundary condition



Thermal layout [1]

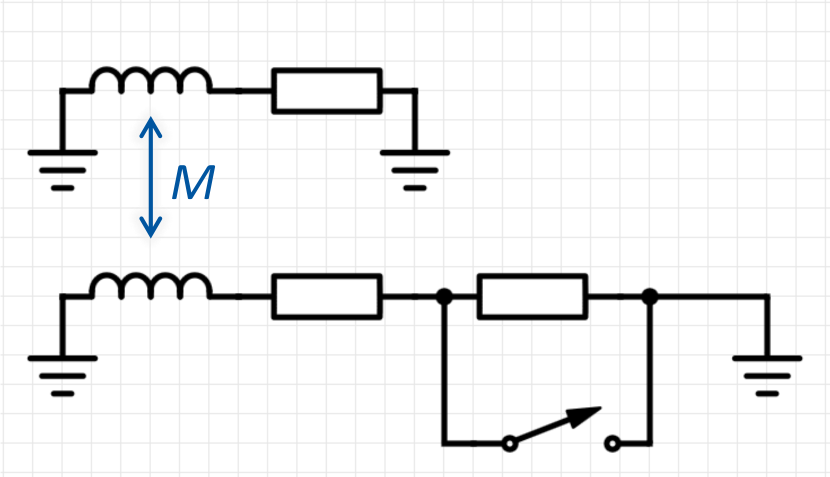
Three-dimensional thermal propagation in simplified geometry [2]

- Longitudinal heat propagation along length of strands, insulation, and formers
- Transverse heat propagation
  - Individual thermal elements for strands, insulation, formers, former insulation
  - Heat flow to the bath: 1.9 K: Kapitza + film boiling cooling, 4.5 K: Nucleate + film boiling
  - Periodic boundary conditions: Simulation of single turn per former to simulate entire magnet
- Non-linear magnetic-field- and temperature-dependent properties taken from STEAM library and LEDET material database

[2] M. Mentink et al. IEEE Trans. on Appl. Supercond. 28, p. 4004806 (2018)

Internal circuit / Co-simulation

Formers + outer cylinder: Inductively coupled to main circuit (typically: 4x4 matrix)



Main circuit with CCT coils: Inductance, internal resistance, crowbar and dump resistor

Representation of internal circuit

- Circuit types:
  - Internal circuit: Inductance of CCT coils, internal resistance, crowbar, dump resistor + switch
  - External circuit: ProteCCT takes external current waveform (co-simulation)
  - Both cases: Main circuit (CCT coils) inductively coupled to formers and outer cylinder

- Adaptive time-stepping (constraints on maximum *dT/dt*, maximum *dI/dt* in formers, user-specified *dt*)

User interface

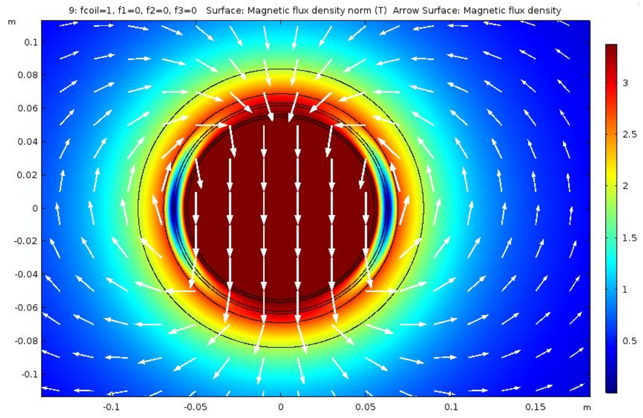
	A	B	C	D	E	G
1	**ProteCCT v1.0**					
2						
3	magnetIdentifier	"MCBRDp1_1.43Ohm				*Magnet identifier. Here " should be placed in front of the name.*
4						
5	**Magnet properties**					
6	totalConductorLength	4480				*Total strand length in [m], for both inner and outer former.*
7	numTurnsPerStrandTotal	365				*Total number of windings on a single former.*
8	CuFraction	0.661016949				*Copper fraction of the Nb-Ti/Cu conductor.*
9	RRRStrand	230				*RRR of the copper. Note that the considered reference temperature is 295 K. The literature reference curve is NIST, which includes temperature- and*
10	BMaxAtNominal	3.1				*Peak field on conductor at nominal current in [T].*
11	BMinAtNominal	1.86				*Lowest field on conductor at nominal current in [T].*
12	INominal	400				*Nominal current in [A], used as reference for calculating magnetic field profile over the conductor.*
13	fieldPeriodicity	2				*Field periodicity (2 for a dipole, 4 for a quadrupole, etc).*
14	magneticLength	1.92				*Magnetic Length in [m].*
15	thFormerInsul	3.50E-04				*Insulation thickness between formers in [m]. This insulation is considered a mixture of polyimide and epoxy, and the ratio between the two is given by*
16	wStrandSlot	1.00E-03				*Size of the strand slot in [m]*
17	DStrand	8.25E-04				*Strand diameter in [m]*
18	numRowStrands	2				*The number of rows of strands*
19	numColumnStrands	5				*The number of columns of strands*
20	IcFactor	1.00				*Ic multiplier, to allow for heat-treatment-induced degradation of Ic*
21	polyimideToEpoxyRatio	0.5				*Ratio of polyimide to G10 in insulation. For thermal purposes, the two materials are assumed in series*
22	windingOrder	[6 16 1 11 7 17 2 12 8 18 3 13 9 19 4 14 10 20 5 15]				*Gives the electrical ordering of the turns. Note that the indexing in the simulation takes 1 as the bottom-left of the inner former, 2 as the bottom-right*
23						
24	**Former related properties**					
25	M	5.05E-01	5.62E-04	5.93E-04	5.17E-04	*Inductance matrix in units of [H/m]. Must have dimensions (Numformers+2 *Numformers+2)*
26		5.62E-04	7.17E-07	6.53E-07	5.41E-07	
27		5.93E-04	6.53E-07	7.17E-07	5.99E-07	
28		5.17E-04	5.41E-07	5.99E-07	6.76E-07	
29						
30	innerRadiusFormers	5.50E-02	6.20E-02			*Inner radius of the formers in [m]*
31	formerThicknessUnderneathCoil	1.60E-03				*Thickness of the former underneath the slot holding the strands in [m]*
32	innerRadiusOuterCylinder	6.90E-02				*Inner radius of the outer cylinder in [m]*
33	thicknessOuterCylinder	1.50E-02				*thickness of the outer cylinder in [m]*
34	RRRFormer	8.0				*RRR of the former, assuming aluminum. Note that the considered reference temperature is 295 K.*
35	RRROuterCylinder	8.0				*RRR of the outer cylinder, assuming aluminum. Note that the considered reference temperature is 295 K.*
36						
37	**Extra stuff**					
38	coolingToHeliumBath	1				*Determines whether inner surface of inner former and outer surface of outer support cylinder are in contact with the helium bath*
39	tMaxStopCondition	10				*Maximum evaluation time in [s] after which simulation is stopped*
40	tempMaxStopCondition	350				*Maximum allowed hotspot temperature in [K] after which simulation is stopped*
41	IOpFractionStopCondition	0.01				*Once the operating current drops below IOpFractionStopCondition * the initial current, the simulation is stopped*
42						
43	**Sweepable parameters (this means that you may put more than one value and the simulation will run for these multiple values)**					
44	fLoopLength	2.0				*The simulation model assumes cos-theta current distribution in the formers, but the reality is more complicated with spiralling current. This empirical*
45	TOp	1.9				*Bath temperature in [K]*
46	IOpInitial	400				*Initial operating current in [A]*
47	RCrowbar	5.50E-02				*Crowbar resistance in Ohm*
48	RDumpPreconstant	1.428				*Constants describing the dump resistance. R(I)=RdumpPreconstant*(abs(I)^RdumpPower)*
49	RDumpPower	0				*Constants describing the dump resistance. R(I)=RdumpPreconstant*(abs(I)^RdumpPower)*
50	addedHeCpFrac	0.006				*Extra helium heat capacity that is added to the formers. This number is the fraction of the former volume that is assigned to be helium, assuming a ba*
51	addedHeCoolingFrac	0				*Fraction of regular cooling to the helium bath that the other formers besides the inner-most former sees*
52	tSwitchDelay	1.00E-02				*Time required to open the switch after protection triggering in [s]*
53	coolingToHeliumBath	1				*For (0), cooling to the bath is not considered. For (1), the inner surface of the inner former and the outer surface of the outer support cylinder are in*
54						
55	**Solver configuration options**					
56	fracCurrentChangeMax	0.025				*Maximum dI/I for a given iteration (applies to both the coil and the formers). This parameter is used for adaptive time stepping*
57	resultsAtTimeStep	2.00E-03				*The simulation time step in [s] at which the simulation notifies the user of the current variable state. The solver is forced to calculate this time step.*
58	deltaTMaxAllowed	0.1				*Maximum change in temperature in [K] between subsequent solver iterations. This parameter is used for adaptive time-stepping*
59	minTimeStep	1.00E-06				*Absolute minimum time step size in [s]*
60	turnLengthElements	50				*Amount of elements for given turn.*
61						
62	**Graphics options**					
63	withPlots	1				*If withPlots is set to 1 then for every timeStep, the voltage-to-ground distribution is plotted*
64	plotPauseTime	0.1				*if withPlots is set to 1, then some pause time is needed to render the graphs. Furthermore, for convenience, the user might add more*
65						
66	**postProcessing**					
67	withVoltageEvaluation	1				*If this option is set to 1, then for selected turns (see voltageToGroundOutputSelection), the voltage-to-ground of that turn is calculated and include*
68	voltageToGroundOutputSelection	[6 10 14 20]				*Selected turns for voltage-to-ground-evaluation (see above option). Here the indexes consider the winding order.*
69						
70	**Options used for co-simulation**					
71	externalWaveform	0				*Option to use either internal circuit (0) or externally supplied current waveform (1)*
72	saveStateAtEnd	0				*Saves the workspace at the end of the simulation, 0 = no save, 1 = save to 'workspace, t0 = %last time interval%.mat'*
73	restoreStateAtStart	0				*Loads the workspace at the start of the simulation, 0 = no load, 1 = load from 'workspace, t0 = %first time interval%.mat'*
74	silentRun	0				*If this option is enabled then output during the simulation is minimal.*

Model input: Excel file

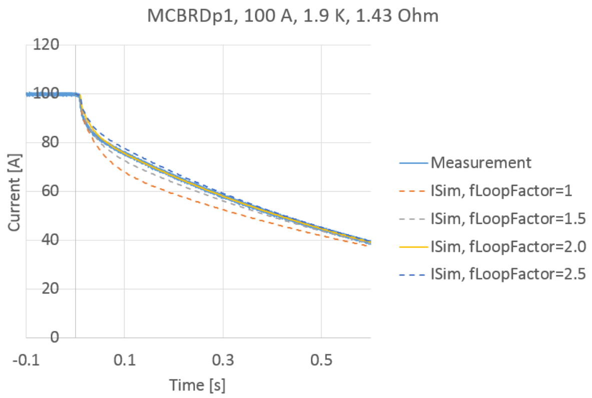
- ProteCCT user manual [3]
- All user input is taken from a single Excel file (inspired by LEDET user interface)
- Co-simulation: Tool exchanges information through text-files
- For the most part, easy-to-understand parameters (Conductor RRR, Operating current, etc.)

[3] M. Mentink, "STEAM-ProteCCT User manual", EDMS nr. 2160020, (2019)

Complexity & correction factor #1: *fLoopFactor*



Coupling-matrix calculated in Comsol, assuming simplified 2D geometry with cos-ϑ current distribution



Determination of fLoopFactor by matching to experimentally observed low-current discharge (no quench-back)

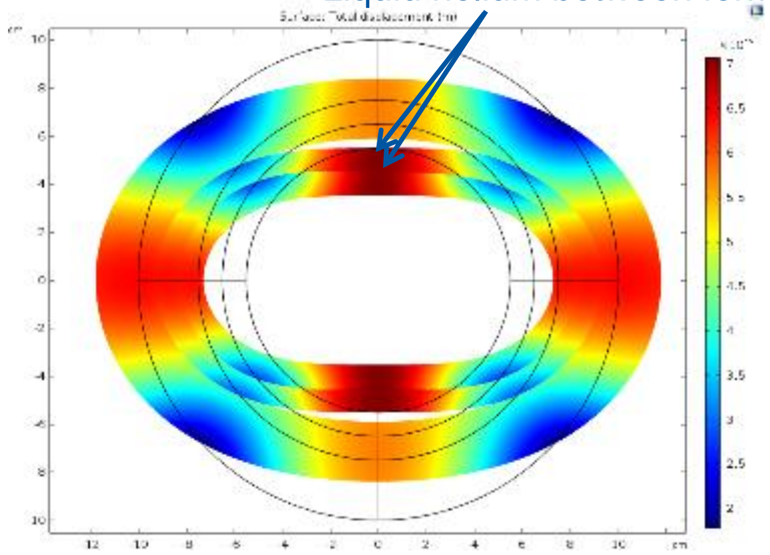
- Coupling matrix: Calculated in Comsol, assuming simplified 2D geometry with cos-θ current distribution in the coils, formers, and outer cylinder [3]
- Assumption: Eddy current flows axially through formers
- Reality: Eddy current model is oversimplified (and uncertainty in former material parameters)

→ Empirical correction factor *fLoopFactor* (= 2.0), to modify eddy current path length, determined by matching simulations to experimental observations

[3] M. Mentink, “STEAM-ProteCCT User manual”, EDMS nr. 2160020, (2019)

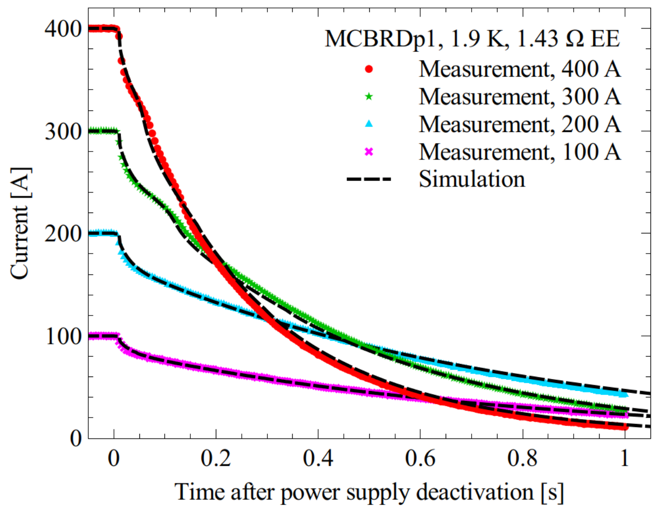
Complexity & correction factor #2: *addedHeCpFrac*

- CCT magnets: Formers are sliding with respect to each-other when powered → Gaps are present, which fill with liquid helium
- Heat capacity of liquid helium has to be overcome before quench back can occur
- To account for liquid helium: Global correction factor *addedHeCpFrac* → Additional heat capacity in formers (~0.6% of volume)
- Determination of correction factor by matching quench back onset t_{QB} at I_0 = 400 A, 1.9 K, 1.43 Ω → Used as a global parameter

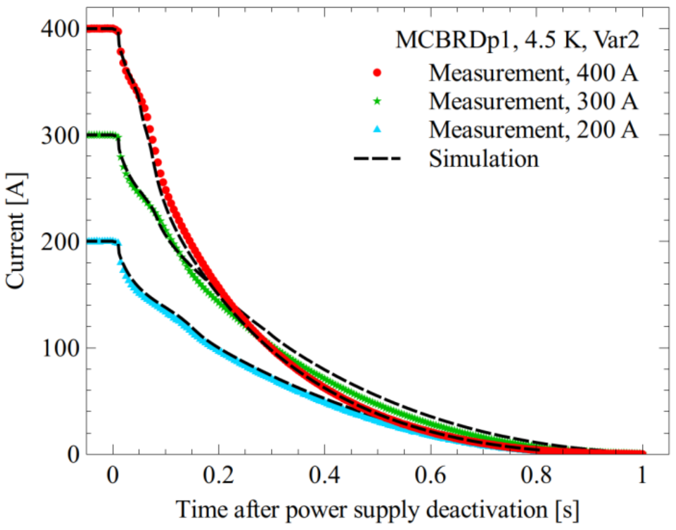


Sliding and deformation of formers during powering (Courtesy Martin Novak)

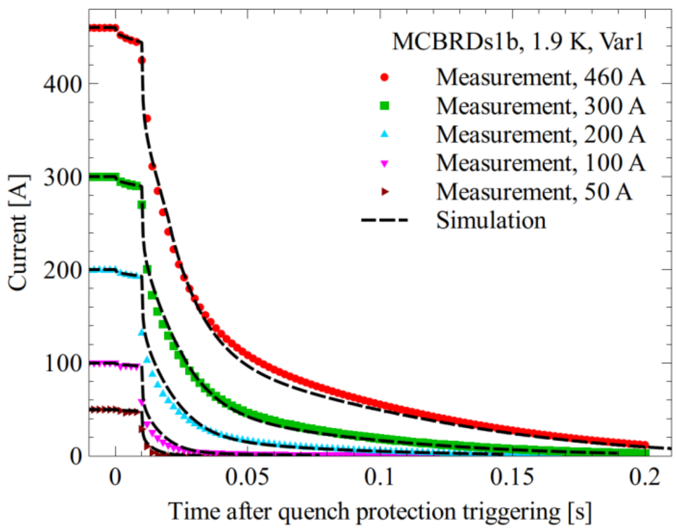
Simulation vs. Experimental observation



MCBRDp1 prototype, discharge over 1.43 Ω dump resistor



MCBRDp1 prototype, discharge over Metrosil varistor

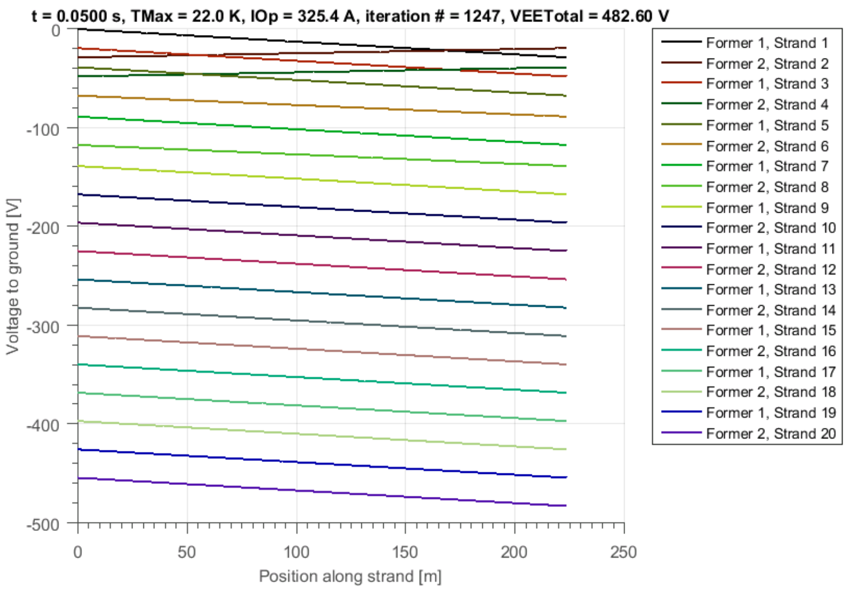


MCBRDs1b short model, discharge over Metrosil varistor

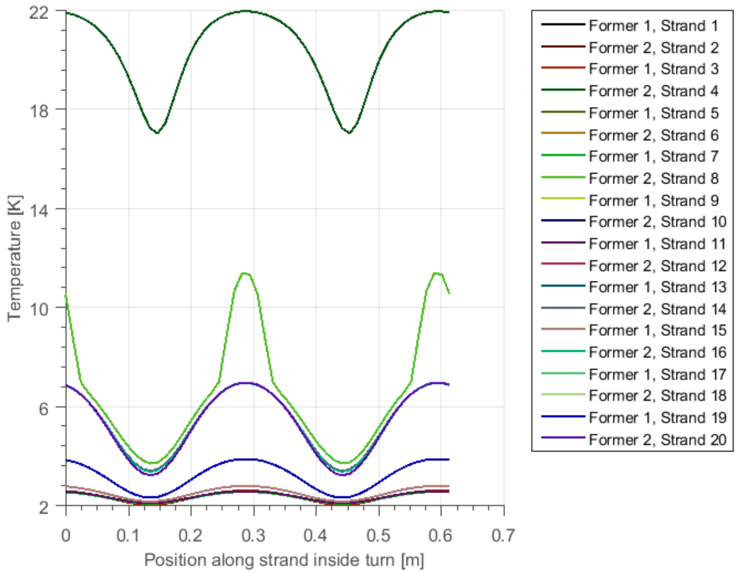
Comparison between simulation and experimental (MCBRD prototype apertures and short models):

- High degree of consistency between simulations and experimental observations
- Checked for: Different magnetic lengths, former material types, operating temperatures, varying dump resistors + Metrosil varistors, operating currents
- Two fixed global correction parameters *fLoopFactor* and *addedHeCpFrac* for all cases
- Measurement data: Courtesy F. Mangiarotti

Running the simulation



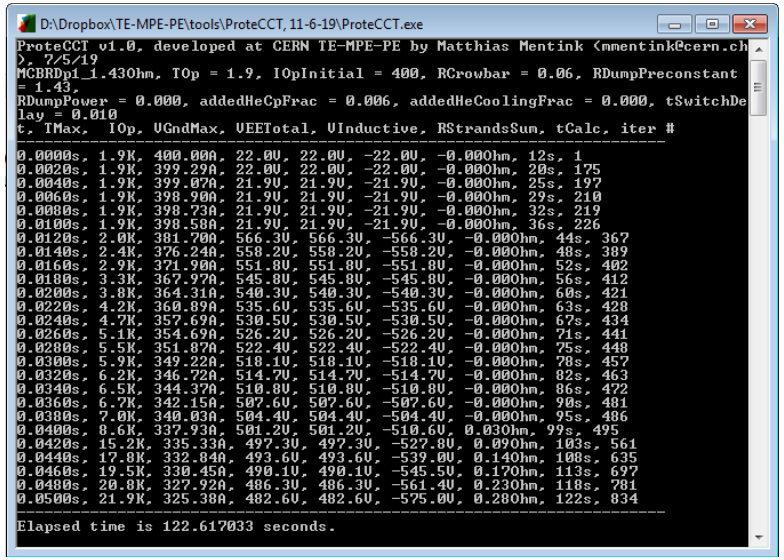
Voltage-to-ground calculation
(During simulation, t = 50 ms)



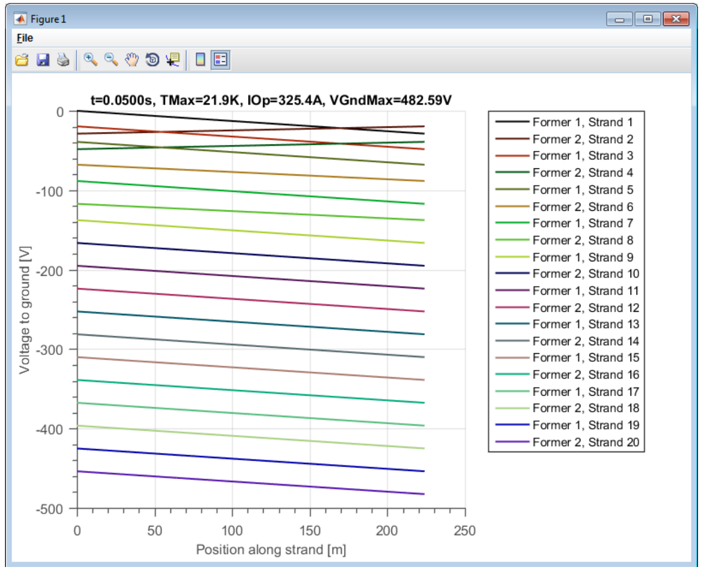
Strand temperature development
(During simulation, t = 50 ms)

- Fast: Typically no more than few minutes to run
- Free-to-use standalone executable, no license required (Does require MCR installation)
- During simulation: Optional plotting of voltage-to-ground and strand temperature for each time-step
- Simulation output written to excel file: Time-dependent Current, hot-spot temperature, voltage-to-ground of selected turns, etc

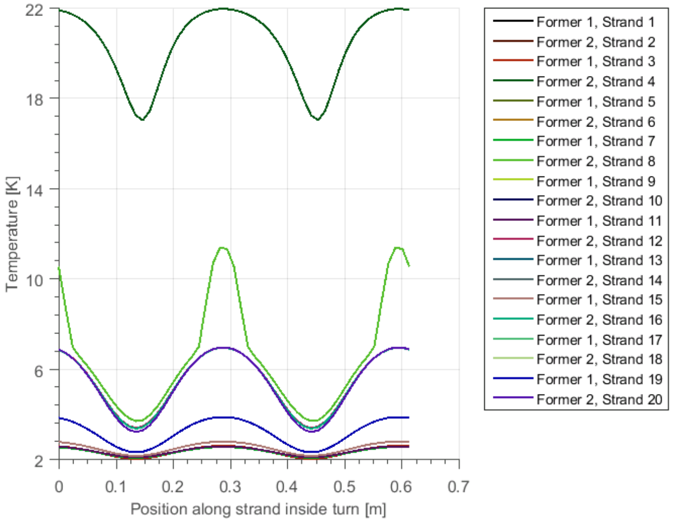
Demo: MCBRDp1



Command prompt output



Voltage distribution in magnet during simulation, t = 50 ms



Strand temperature development during simulation, t = 50 ms

ProteCCT is found on STEAM website: *cern.ch/steam*

- Manual: EDMS Nr. 216002 (link of STEAM website)
- Simulation tool available of steam website
- Running requires installation of Matlab runtime (see *Matlab runtime.txt*)

Summary

ProteCCT

- Simulation tool for evaluating discharge of CCT-type magnets (With quench-back from conductive formers)
- Very fast, standalone executable
- User-interface: Input from Excel, output to Excel (plus optional plotting during execution)
- Available on STEAM website (cern.ch/steam)
- Compatible with co-simulation, which allows for more exotic circuits
- Free to use, but please reference to ProteCCT manual when used for publications / presentations