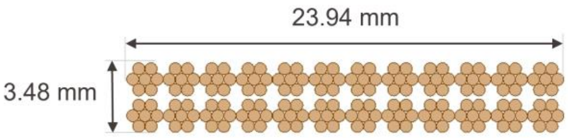
Quench analysis: 0D estimate

Conductor layout:



Conductor cross-section	94.4 mm^2
Cable	64.7 mm^2 (68.5%)
Copper	32.3 mm^2 (34.2%)
Noncopper	32.3 mm^2 (34.2%)
Impregnation	18.7 mm^2 (11.8%)
Insulation	11.1 mm^2 (19.8%)

Strand diameter	0.7 mm
Copper-noncopper ratio	1
RRR	150
Number of strands	24*7 = 168
Total width	24.34 mm
Total height	3.88 mm
Insulation thickness	0.2 mm

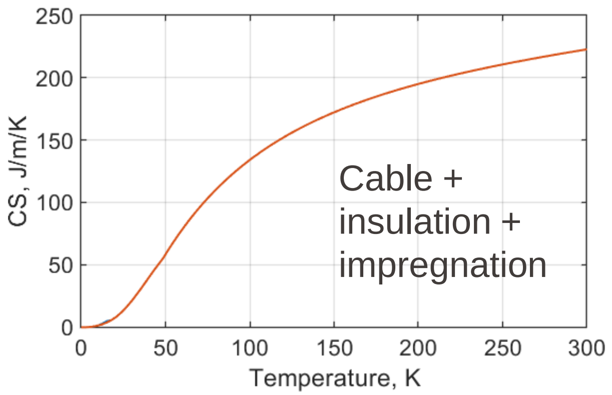
Operating current	18 kA
J eng	182 A/mm^2
J cu	533 A/mm^2
Inductance	0.13 H
Stored energy	21.1 MJ
Discharge voltage (max)	1 kV
Time constant τ	2.34 s
Delay time t_d	16 ms

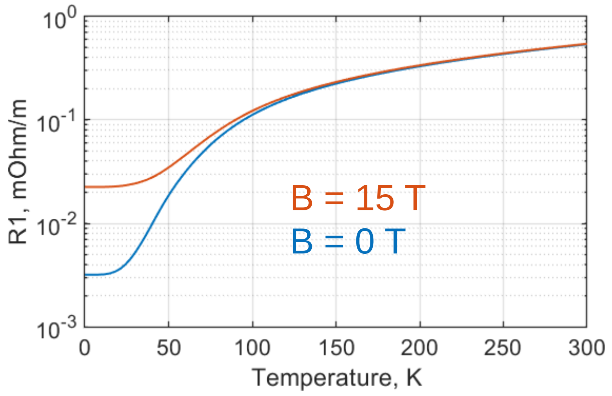
Quench analysis: 0D estimate

Adiabatic analysis:

$C(T)S\frac{\partial T}{\partial t} = I^2 R_1(T,B)$ [W/m]

- Conductor cross-section isothermal
- Current flow in copper
- Size of normal zone to reach 100 mV at 18 kA: 1.7 m (0 T), 0.2 m (15 T)
- $T(t=0)$ = 8 K:
  T_{max} = 397 K at B = 0 T constant
  T_{max} = 1090 K at B = 15 T constant
  T_{max} = 1060 K for B = k x I
- I = 17 kA, V = 1.5 kV, tau = 1.47 s:
  T_{max} = 100 K at B = 0 T constant
  T_{max} = 262 K at B = 15 T constant
  T_{max} = 243 K for B = k x I

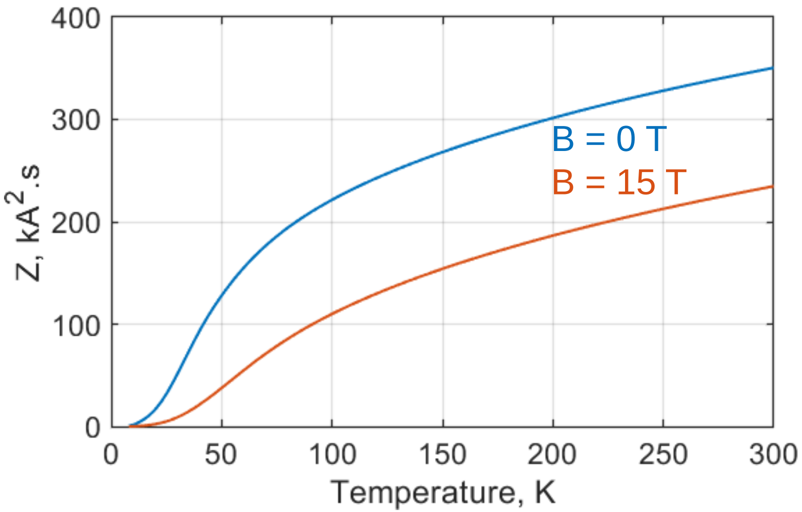




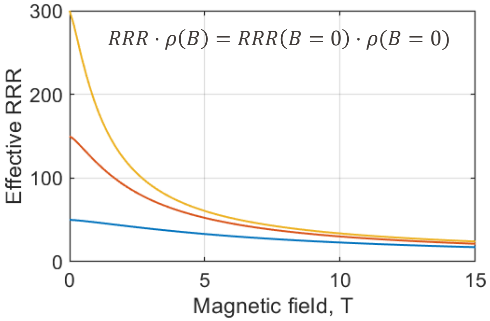
Quench analysis: 0D estimate

Constant B:

- $Z(T) = \int_{T_0}^{T} \frac{C(x)S}{R_1(x,B)} dx$
- Quench integral:
  $\int I^2 dt = I^2(t_d + \tau/2) \approx EI/V = LI^3/2V$
  = 384 kA^2.s at 18 kA, 1.0 kV
  = 218 kA^2.s at 17 kA, 1.5 kV



- Cross-check the actual effect of magnetoresistance?
- 3-D model to be prepared to quantify impact of thermal conductivity in transverse and longitudinal directions, though strong impact on Tmax is not expected

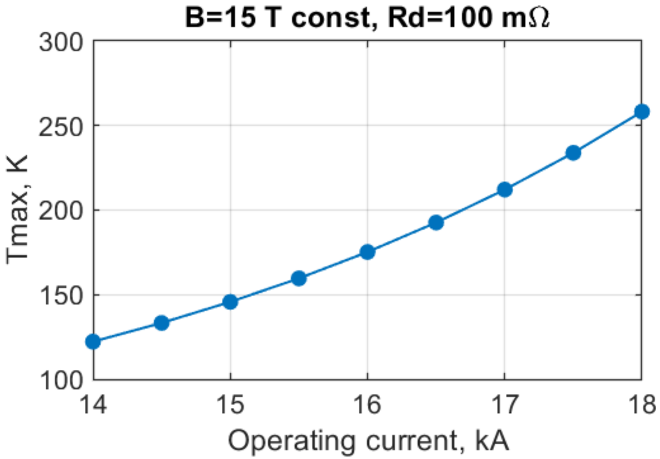


RRR ~ 20

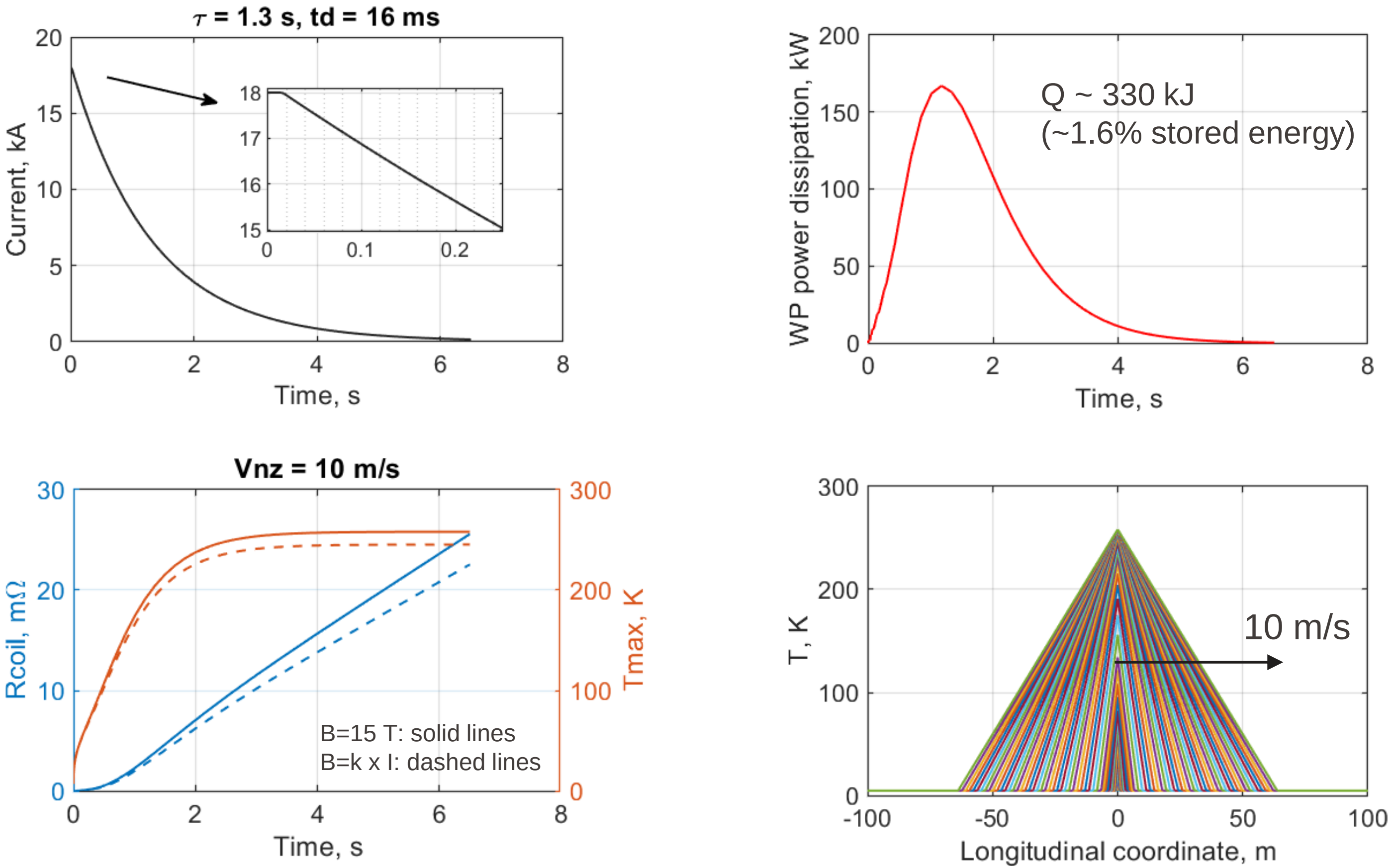
Quench analysis: 0D estimate

Rd, mΩ	**100**	
τ, s	1.3	
I, kA	18.0	17.0
E, MJ	21.1	18.8
V, kV	1.8	1.7
Tmax*, K	258	212

* @ B = 15 T constant



Quench analysis: 0D estimate



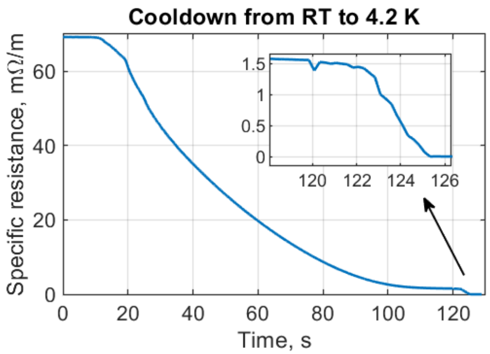
Quench analysis: 0D estimate

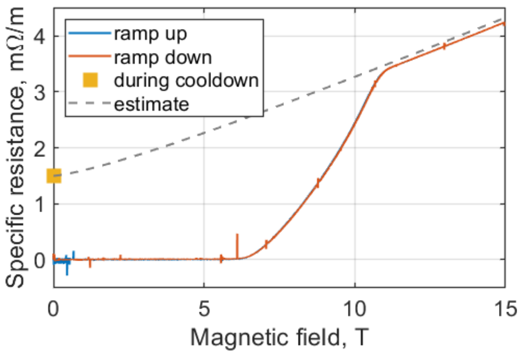
Neglected terms so far:

- Thermal conductivity in longitudinal and transverse direction → lower Tmax
- AC loss heating due to Bdot, thus faster current decay → lower Tmax
- Higher resistance due to Rcoil, thus faster current decay → lower Tmax
- Impact of iron on coil inductance during quench? ~20% higher L at low B?

Quench analysis: Copper RRR

- OD 0.7 mm, cnc ~1.2, Scu 0.21 mm^2, RRR Likely 50-100, but best effort
- Resistance estimate for RRR = 50:
  ~80 mΩ/m at 293 K → ~1.5 mΩ/m at 4 – 20 K → ~4.3 mΩ/m at 4 K, 15 T
- Measurements on **non-reacted** 0.5 m-long sample
- Impact of heat-treatment…





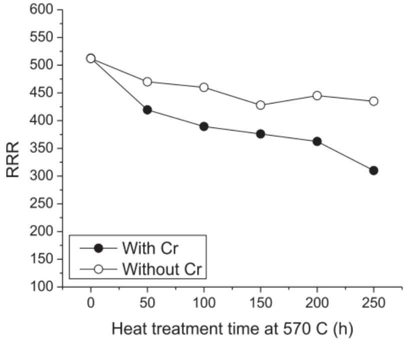
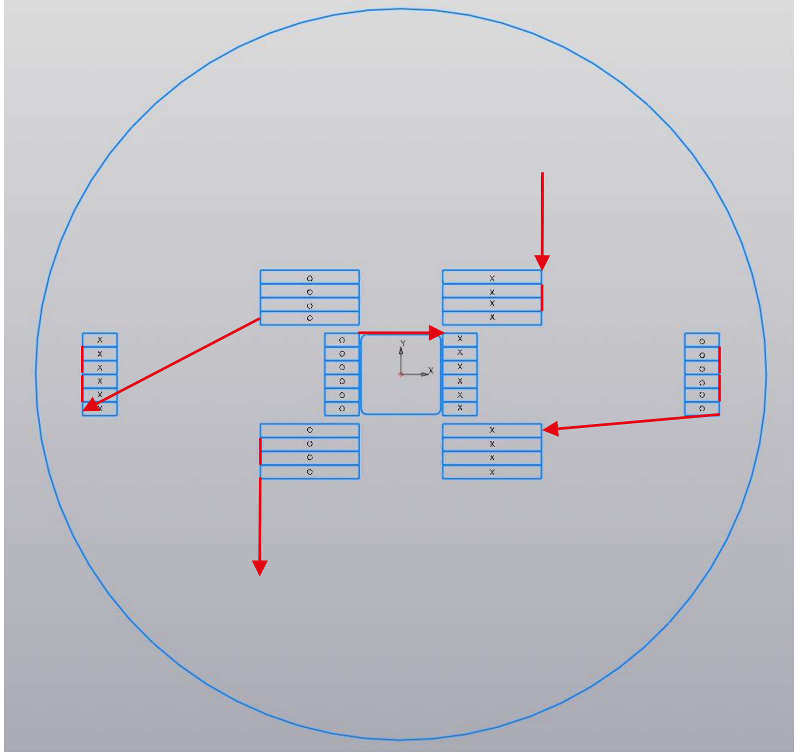


Figure 6. RRR of the JASTEC strand as function of heat treatment time at 570 °C (first step) for samples with and without plated Cr.

https://iopscience.iop.org/article/10.1088/1361-6668/aa67ab

Quench analysis: towards 3D model



Coil splicing layout?

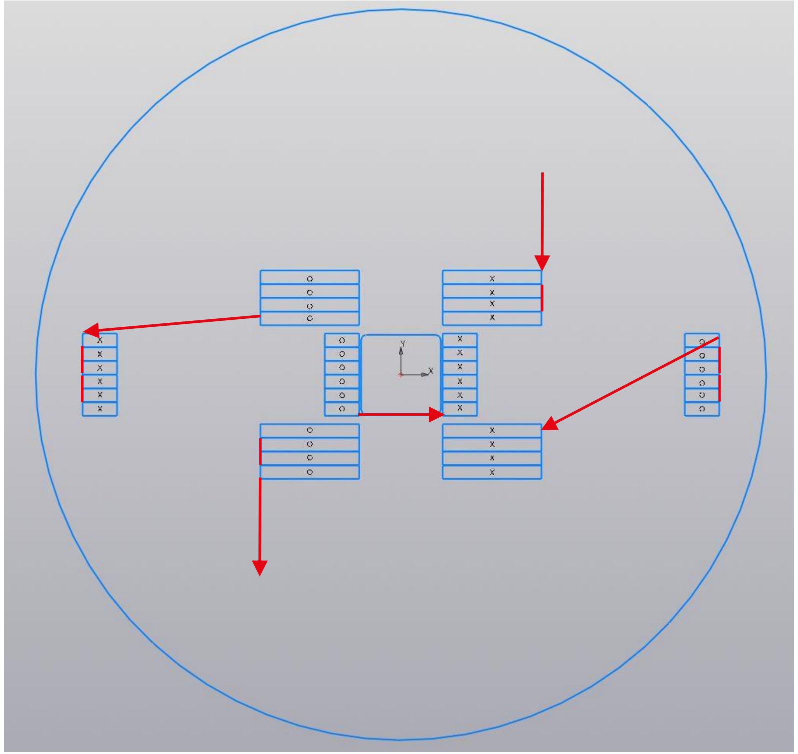
Cooling interface?

EDIP01 QD parameters

25 / 06 /24

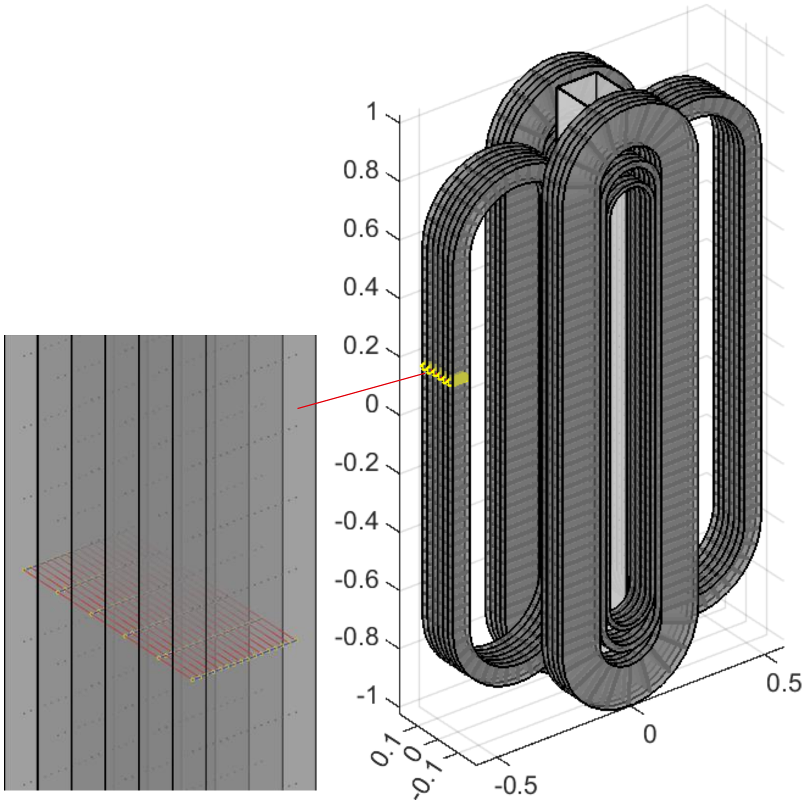
0.099609	{V threshold LF Cable}	[Volt]
0.099609	{V threshold HF Cable}	[Volt]
0.120117	V threshold Current leads Warm Side [Volt]	[Volt]
0.009766	V threshold Current leads Cold Side	[Volt]
0.049805	V threshold Bus Bar Jumper	[Volt]
10	UTV Threshold	[Volt]
800	Req Sampling Freq	(Hz)
800	Applied Sampling Freq	(Hz)
40	Req Total Validation Time	(ms)
39.75	Applied Total Validation Time	(ms)
11	ASOT thr (1 - 100)	#
14	Raw Validation Time	(ms)
1	Fir 16 On ?	0 Off; 1 On.
1	LPF Filter On ?	0 Off; 1 On.
35	Ft LPF	(Hz)
16	FIR delay	(ms)
10	LPF Delay	(ms)
0.21582	a0	0 <= a0 <= 1
60	Pre Trigger	(sec)
10	Post Trigger	(sec)
1000000	Init Time	(uSec)
1000000	Pulse duration	(uSec)
2	Current State	0 Init; 1 Autocal; 2 Reading; 3 Quench; 4 Post Trigger; 5 End
1250	Requested T Sampling	(uSec)
1250	Real T Sampling	(uSec)

+ few ms to open circuit breakers



Setting up 3-D quench model:

- Geometry import
- Matrix of mutual inductances
- Magnetic field incl. iron (by Xabier)
- Current sharing, Tcs distribution
- Heat equation



Geometry:

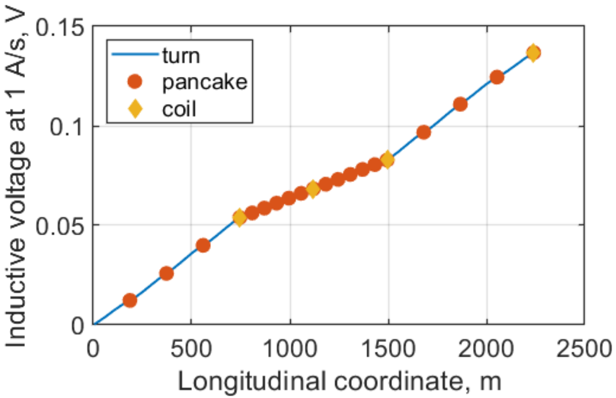
- 20 pancakes (4 per vertical, 6 per side coils)
- 560 turns (46 per vert. pancake, 16 per side pancake)
- 100 nodes per turn

→ 56’000 nodes to evaluate heat equation

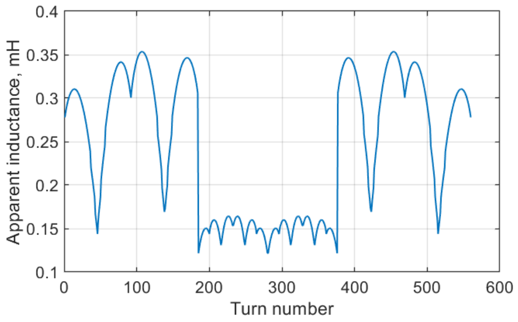
	1	2	3	4
1	43.7290	0.0297	0.0297	10.1622
2	0.0297	15.5806	-1.2102	0.0297
3	0.0297	-1.2102	15.5806	0.0297
4	10.1622	0.0297	0.0297	43.7290

Inductance:

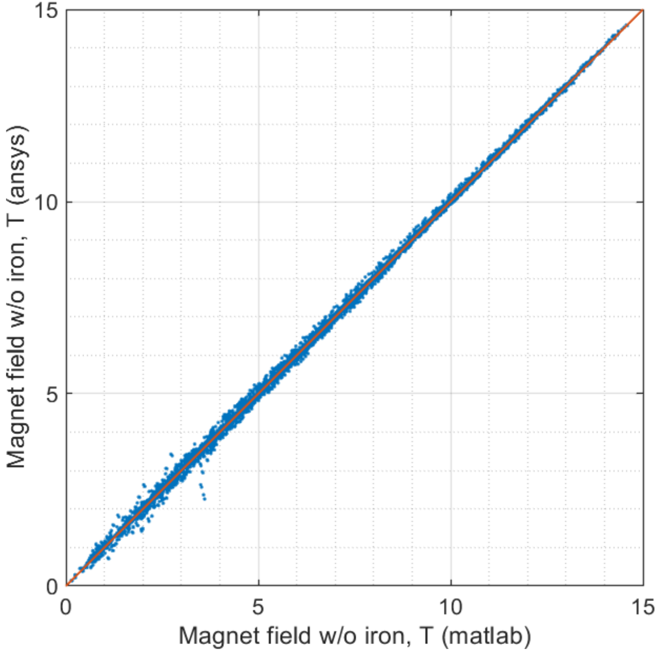
- Magnet: 137 mH
- Coil: 4 x 4 matrix
- Pancake: 20 x 20 matrix
- Turn: 560 x 560 matrix
  (Average value = 0.44 µH, max value = 9.93 µH, min value = -0.21 µH)

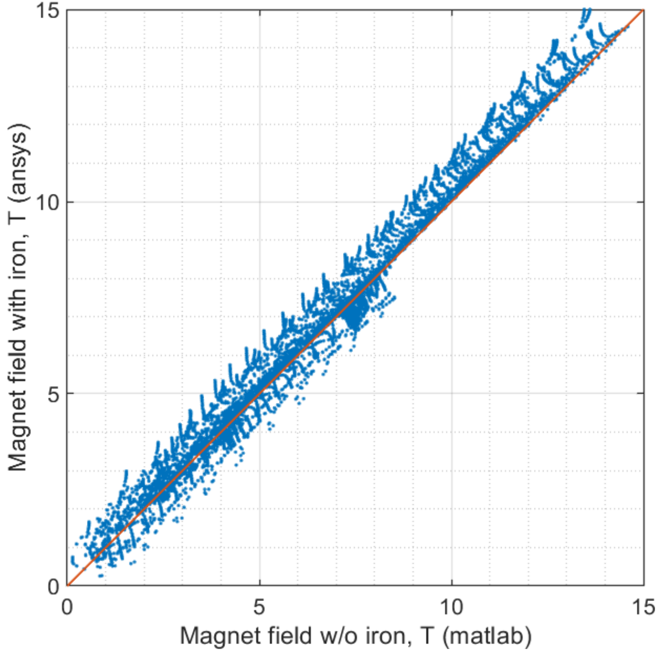


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	3.5317	2.7587	2.2960	1.9329	0.0110	-0.0109	-0.0273	-0.0393	-0.0479	-0.0540	-0.0540	-0.0479	-0.0393	-0.0273	-0.0109	0.0110	0.6208	0.5538	0.4962	0.4464
2	2.7587	3.5317	2.7587	2.2960	0.0400	0.0110	-0.0109	-0.0273	-0.0393	-0.0479	-0.0479	-0.0393	-0.0273	-0.0109	0.0110	0.0400	0.6990	0.6208	0.5538	0.4962
3	2.2960	2.7587	3.5317	2.7587	0.0784	0.0400	0.0110	-0.0109	-0.0273	-0.0393	-0.0393	-0.0273	-0.0109	0.0110	0.0400	0.0784	0.7910	0.6990	0.6208	0.5538
4	1.9329	2.2960	2.7587	3.5317	0.1293	0.0784	0.0400	0.0110	-0.0109	-0.0273	-0.0273	-0.0109	0.0110	0.0400	0.0784	0.1293	0.8997	0.7910	0.6990	0.6208
5	0.0110	0.0400	0.0784	0.1293	0.7086	0.4841	0.3838	0.3160	0.2664	0.2282	-0.0275	-0.0301	-0.0324	-0.0342	-0.0353	-0.0357	-0.0273	-0.0393	-0.0479	-0.0540
6	-0.0109	0.0110	0.0400	0.0784	0.4841	0.7086	0.4841	0.3838	0.3160	0.2664	-0.0301	-0.0324	-0.0342	-0.0353	-0.0357	-0.0353	-0.0109	-0.0273	-0.0393	-0.0479
7	-0.0273	-0.0109	0.0110	0.0400	0.3838	0.4841	0.7086	0.4841	0.3838	0.3160	-0.0324	-0.0342	-0.0353	-0.0357	-0.0353	-0.0342	0.0110	-0.0109	-0.0273	-0.0393
8	-0.0393	-0.0273	-0.0109	0.0110	0.3160	0.3838	0.4841	0.7086	0.4841	0.3838	-0.0342	-0.0353	-0.0357	-0.0353	-0.0342	-0.0324	0.0400	0.0110	-0.0109	-0.0273
9	-0.0479	-0.0393	-0.0273	-0.0109	0.2664	0.3160	0.3838	0.4841	0.7086	0.4841	-0.0353	-0.0357	-0.0353	-0.0342	-0.0324	-0.0301	0.0784	0.0400	0.0110	-0.0109
10	-0.0540	-0.0479	-0.0393	-0.0273	0.2282	0.2664	0.3160	0.3838	0.4841	0.7086	-0.0357	-0.0353	-0.0342	-0.0324	-0.0301	-0.0275	0.1293	0.0784	0.0400	0.0110
11	-0.0540	-0.0479	-0.0393	-0.0273	-0.0275	-0.0301	-0.0324	-0.0342	-0.0353	-0.0357	0.7086	0.4841	0.3838	0.3160	0.2664	0.2282	0.1293	0.0784	0.0400	0.0110
12	-0.0479	-0.0393	-0.0273	-0.0109	-0.0301	-0.0324	-0.0342	-0.0353	-0.0357	-0.0353	0.4841	0.7086	0.4841	0.3838	0.3160	0.2664	0.0784	0.0400	0.0110	-0.0109
13	-0.0393	-0.0273	-0.0109	0.0110	-0.0324	-0.0342	-0.0353	-0.0357	-0.0353	-0.0342	0.3838	0.4841	0.7086	0.4841	0.3838	0.3160	0.0400	0.0110	-0.0109	-0.0273
14	-0.0273	-0.0109	0.0110	0.0400	-0.0342	-0.0353	-0.0357	-0.0353	-0.0342	-0.0324	0.3160	0.3838	0.4841	0.7086	0.4841	0.3838	0.0110	-0.0109	-0.0273	-0.0393
15	-0.0109	0.0110	0.0400	0.0784	-0.0353	-0.0357	-0.0353	-0.0342	-0.0324	-0.0301	0.2664	0.3160	0.3838	0.4841	0.7086	0.4841	-0.0109	-0.0273	-0.0393	-0.0479
16	0.0110	0.0400	0.0784	0.1293	-0.0357	-0.0353	-0.0342	-0.0324	-0.0301	-0.0275	0.2282	0.2664	0.3160	0.3838	0.4841	0.7086	-0.0273	-0.0393	-0.0479	-0.0540
17	0.6208	0.6990	0.7910	0.8997	-0.0273	-0.0109	0.0110	0.0400	0.0784	0.1293	0.1293	0.0784	0.0400	0.0110	-0.0109	-0.0273	3.5317	2.7587	2.2960	1.9329
18	0.5538	0.6208	0.6990	0.7910	-0.0393	-0.0273	-0.0109	0.0110	0.0400	0.0784	0.0784	0.0400	0.0110	-0.0109	-0.0273	-0.0393	2.7587	3.5317	2.7587	2.2960
19	0.4962	0.5538	0.6208	0.6990	-0.0479	-0.0393	-0.0273	-0.0109	0.0110	0.0400	0.0400	0.0110	-0.0109	-0.0273	-0.0393	-0.0479	2.2960	2.7587	3.5317	2.7587
20	0.4464	0.4962	0.5538	0.6208	-0.0540	-0.0479	-0.0393	-0.0273	-0.0109	0.0110	0.0110	-0.0109	-0.0273	-0.0393	-0.0479	-0.0540	1.9329	2.2960	2.7587	3.5317

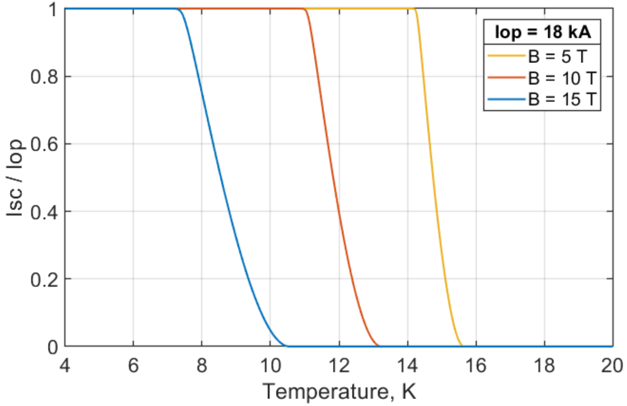


Magnetic field within the coil winding (over 56’000 nodes)





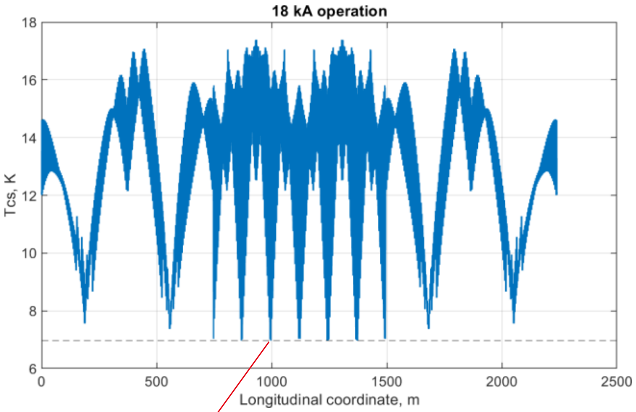
Current sharing at 18 kA operation

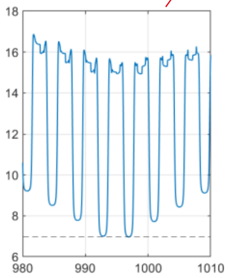


$$\eta_{st}\frac{I_i - I_{sc}}{A_{st}} = E_0\left(\frac{I_{sc}}{I_c}\right)^n \qquad I_{st} = I_i - I_{sc}$$

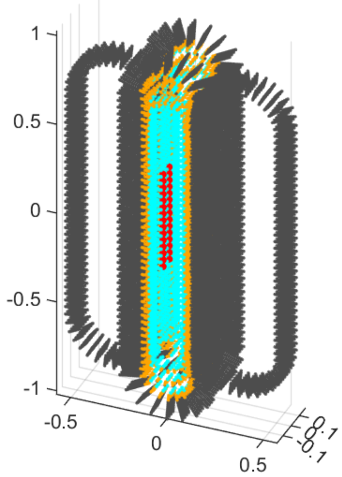
Intra-strand resistance neglected

Tcs distribution along conductor length





min Tcs = 6.97 K



Tcs<11 K

Tcs<9 K

Tcs<7 K

Heat equation:

$$C\frac{\partial T}{\partial t} = q_{joule} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + q_{trans} - q_{cooling} + q_{external}\ [\mathrm{W/m^3}]$$

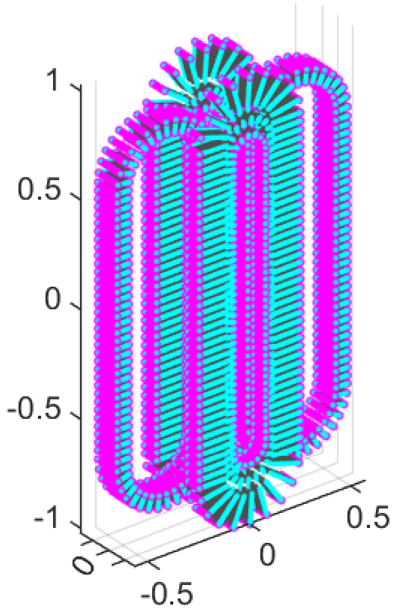
Connectivity matrices for nodes in the same cross-section

```
for i=1:Nl
    Ti=T(i,:);
    h1=h_face(Ti);
    h2=h_side(Ti);
    q_trans(i,:)=sum((C_face.*(h1+h1')/2+C_side.*(h2+h2')/2).*(Ti'-Ti),1);
end

qface(coolingface)=h_face(T(coolingface)).*(T(coolingface)-4.2);
qside(coolingside)=h_side(T(coolingside)).*(T(coolingside)-4.2);
q_cooling=qface+qside;

if t>=heater_t(1) && t<=heater_t(2) && ~quench
    q_heater(heater_pos)=P; %W/m
end
```

Conductor face and conductor side cooled by helium (through 0.2 mm G10)

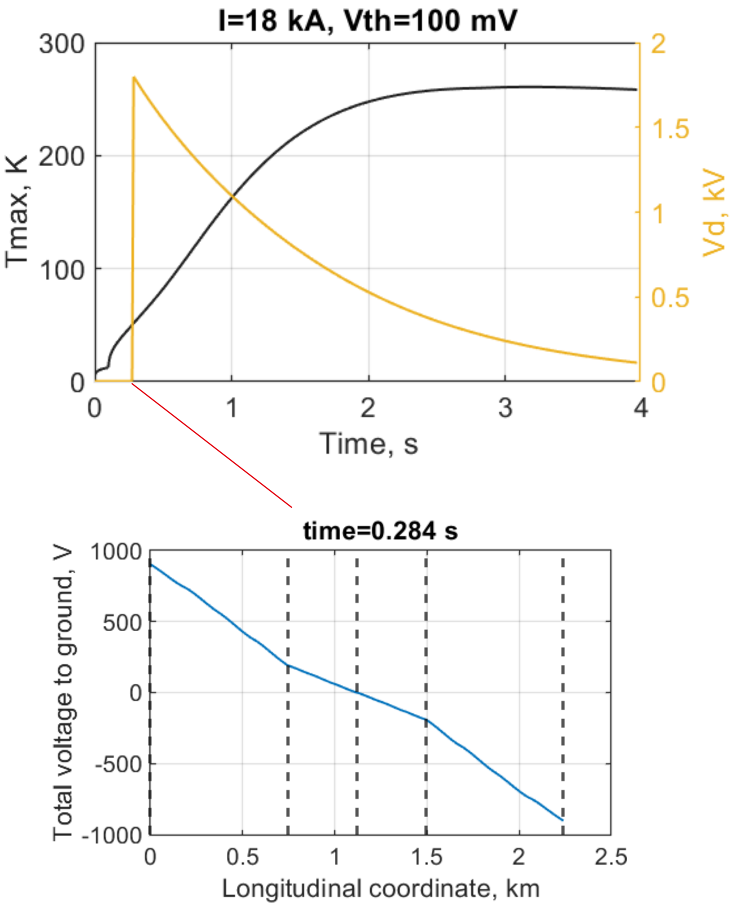


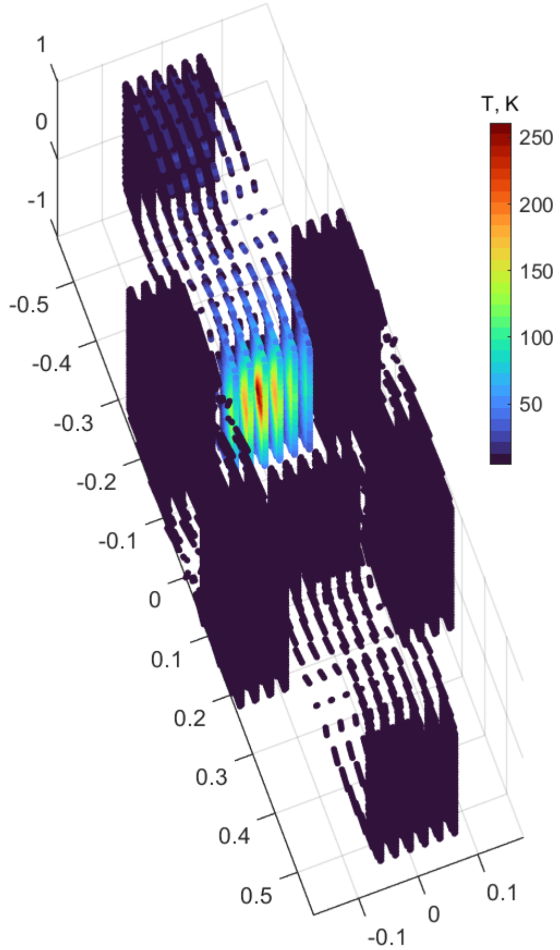
Current discharge once 'quench is detected' (td = 0.1 s):

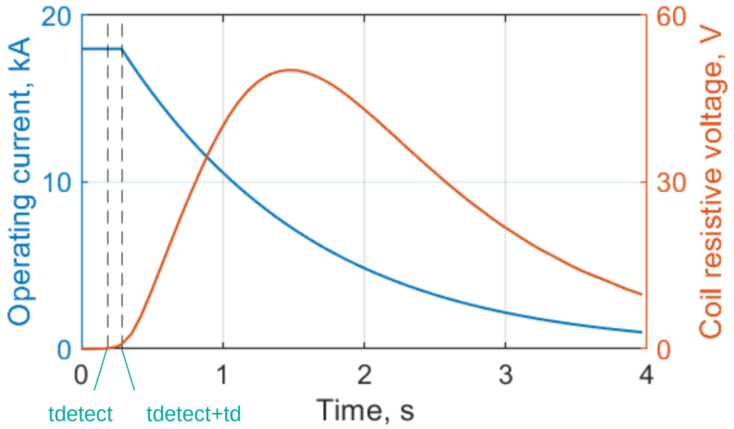
$$L\frac{\partial I}{\partial t} = -V_{coil} - IR_d$$

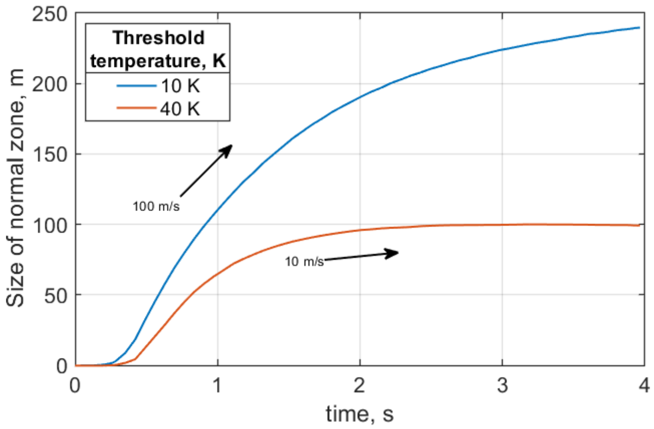
(mutual inductance used to calculate distribution of voltage to ground)

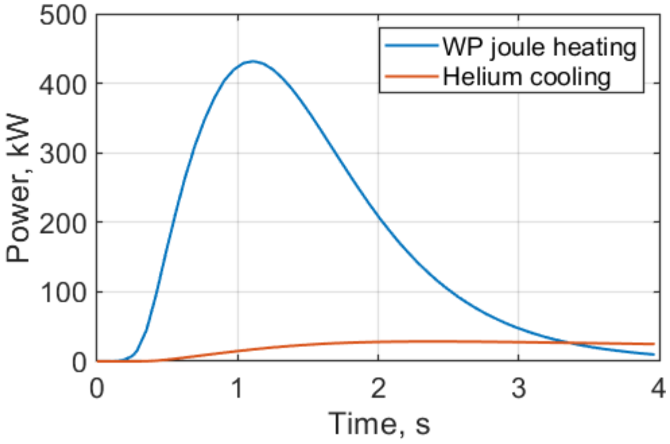
External energy of 1.7 J deposited over 12 cm (3 nodes) within 0.1 s (power ~140 W/m)



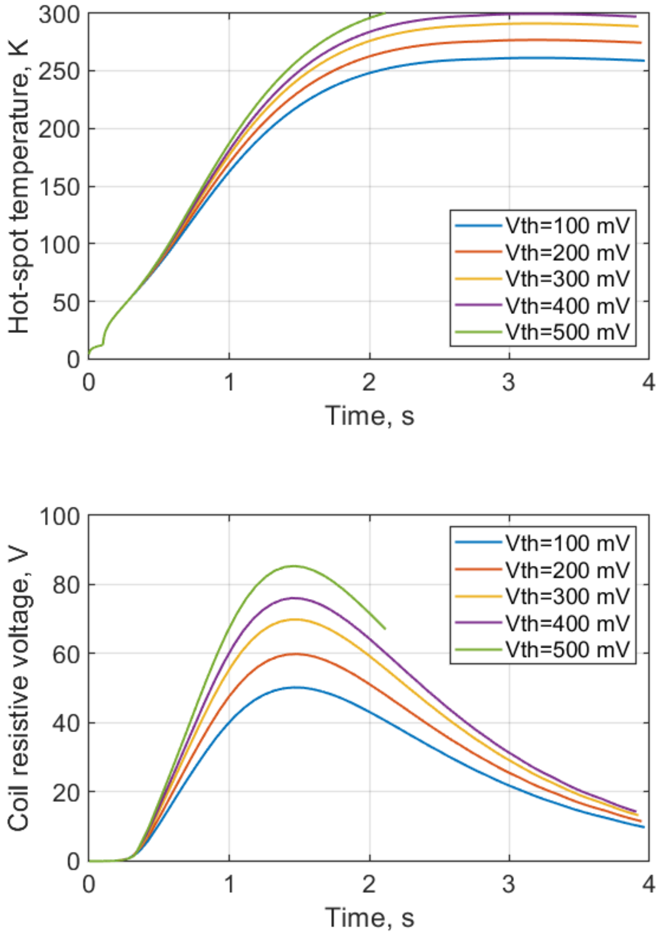


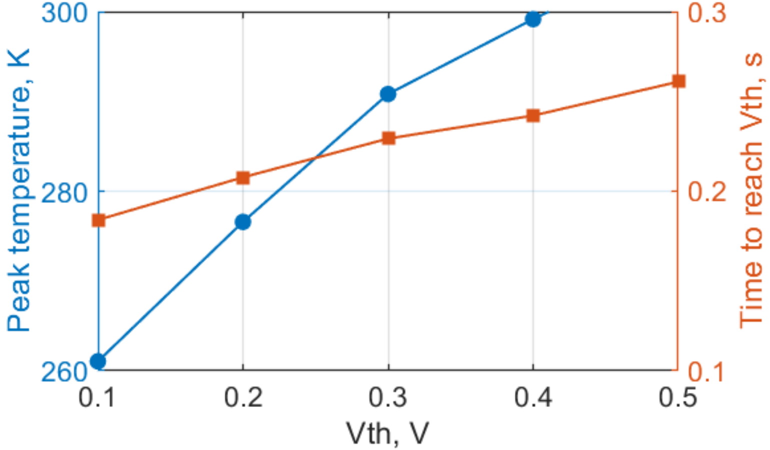






- ~98% stored energy released in Rdump, ~660 kJ in the coil winding, i.e. losing ~250 liters of helium (latent heat 2.6 kJ/liter)
- Heat removal rate by helium up to ~30 kW
- NZPV strongly depends on temperature threshold, up to ~100 m/s for the 10 K front


Hot-spot temperature, K
Time, s
Vth=100 mV
Vth=200 mV
Vth=300 mV
Vth=400 mV
Vth=500 mV
Coil resistive voltage, V
Time, s
Vth=100 mV
Vth=200 mV
Vth=300 mV
Vth=400 mV
Vth=500 mV


Peak temperature, K
Time to reach Vth, s
Vth, V