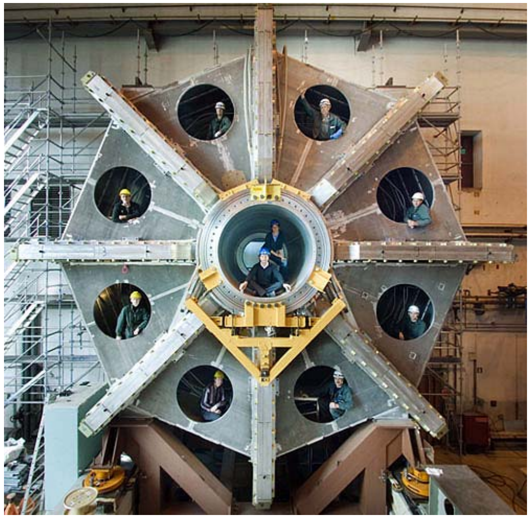
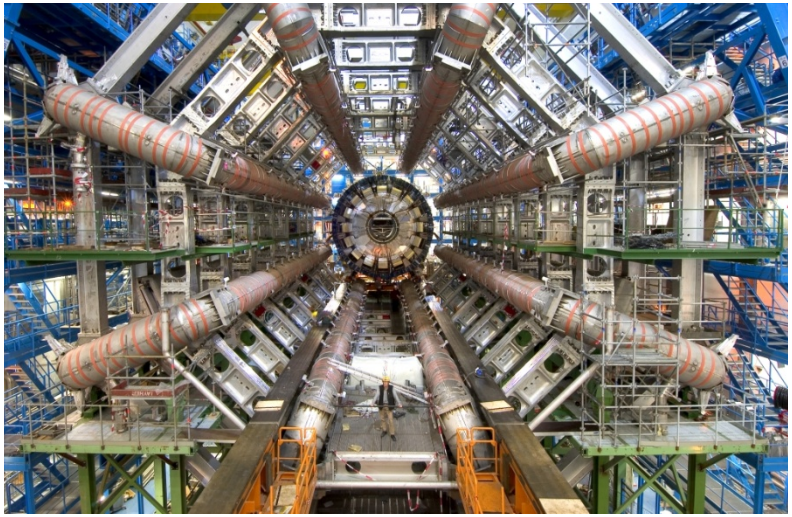
Simulation of the fast dump process of the ATLAS toroids





Gabriella Rolando

Technical Student @ ATLAS Magnet team

Outline

- Introduction

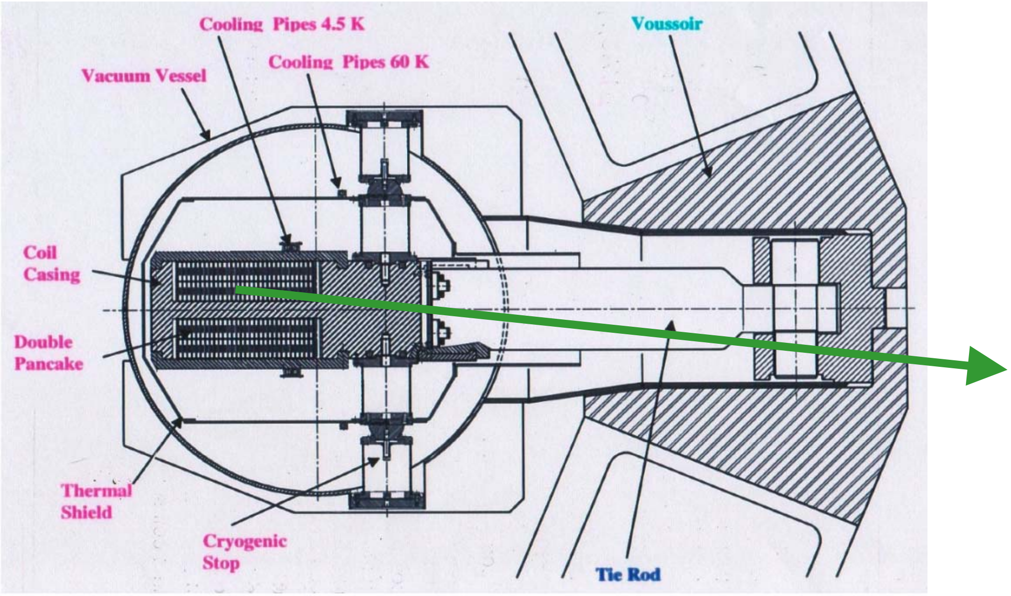
- Fast dump of the Barrel Toroid (stand alone)
- BT energy distribution

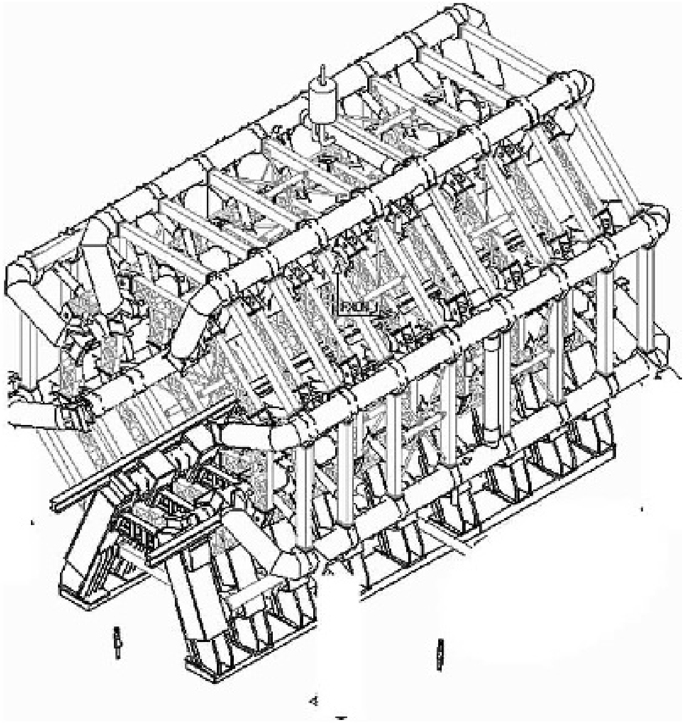
- Fast dump of End Cap Toroid A (stand alone)
- ECTA energy distribution

- Fast dump of the entire ATLAS toroids system (ABC)
- ABC energy distribution

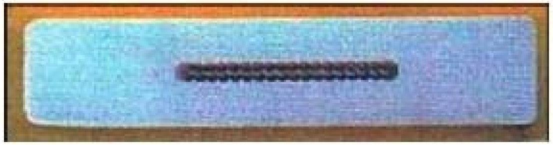
The Barrel Toroid

- 8 racetrack coils 25 x 5 m
- operating current = 20.5 kA
- stored energy = 1080 MJ
- peak field = 3.85 T
- operating temperature = 4.6 K

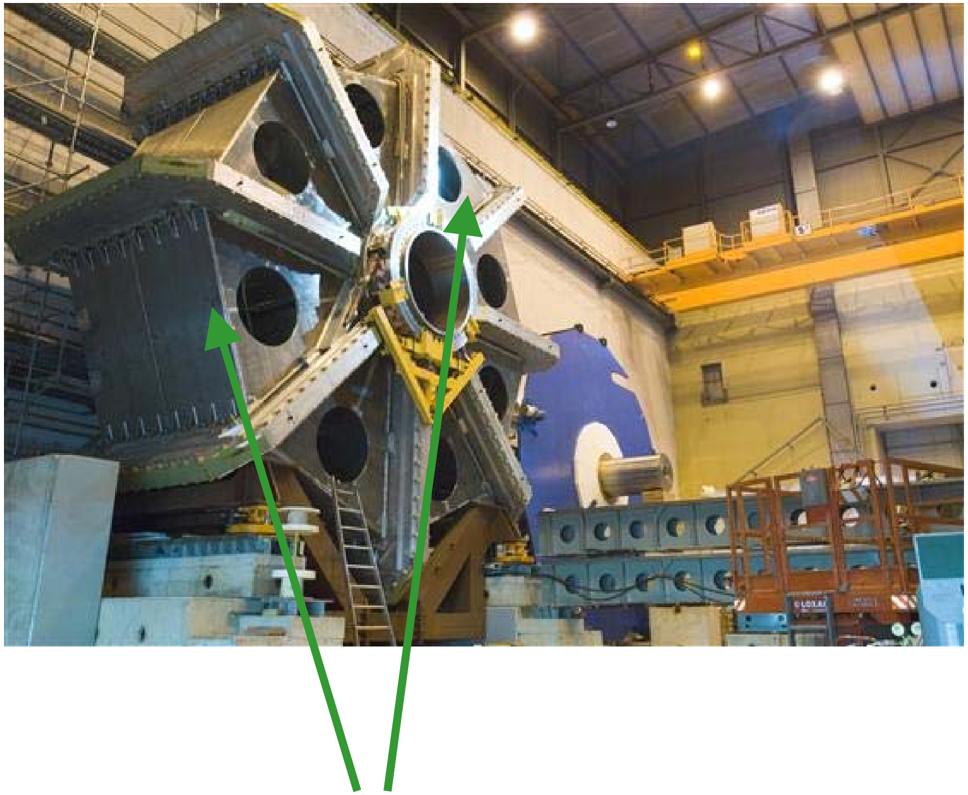




BT conductor

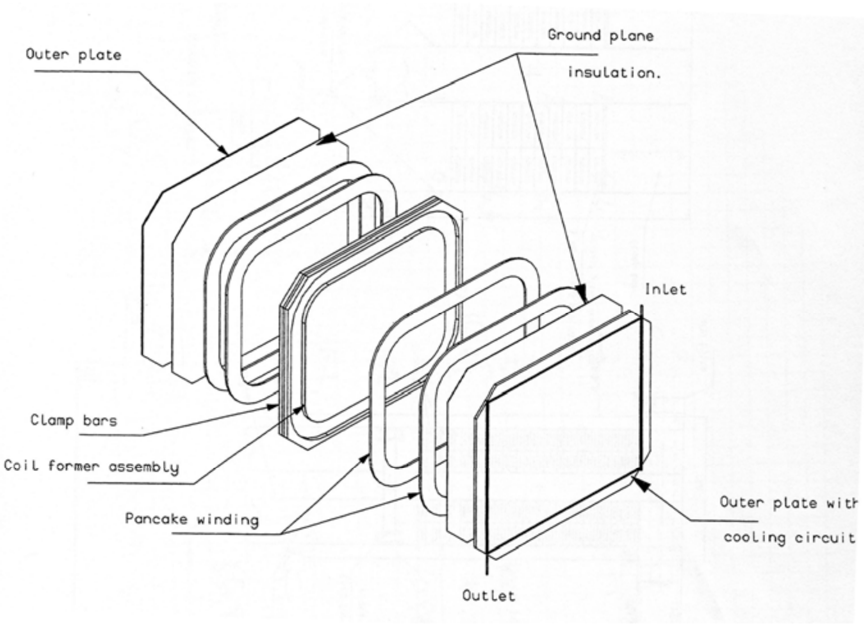


The End Cap Toroids

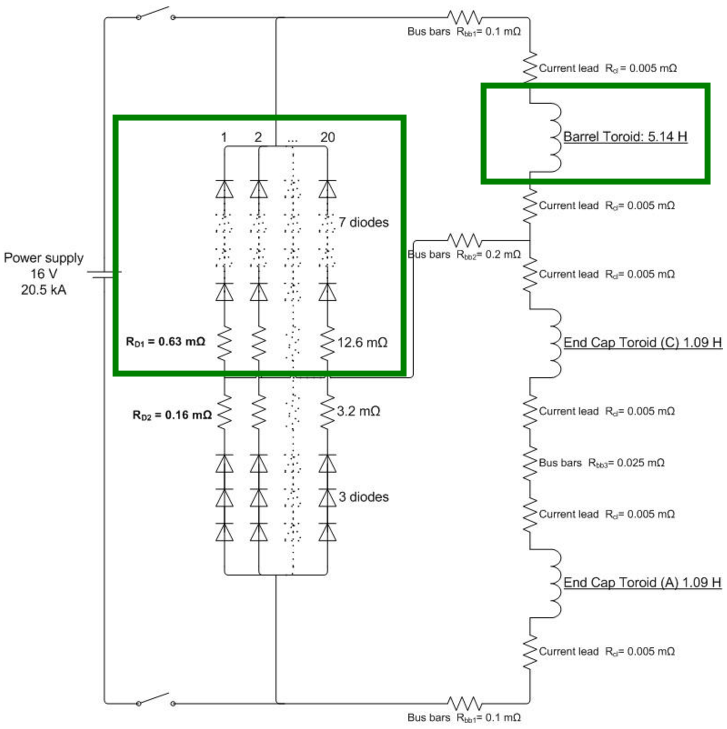


Keystone boxes

- 8 racetrack coils 4.5 x 4 m
- operating current = 20.5 kA
- stored energy = 229 MJ
- peak field = 4.1 T
- operating temperature = 4.6 K



BT: electric model

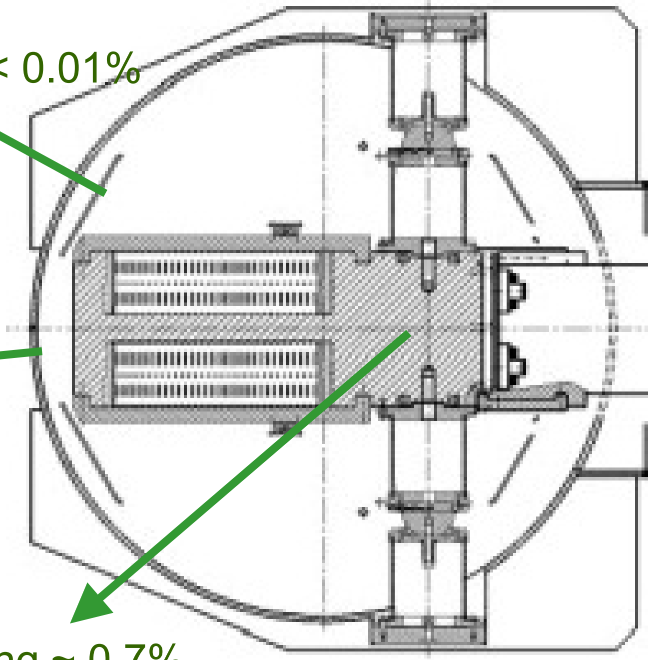


$$E = \int_0^\infty \left(M\frac{dI}{dt}\right)^2 \cdot \frac{1}{R}\, dt$$

M	mutual inductance
R	element resistance

$$L \cdot \frac{dI}{dt} + I \cdot (R + R_{coils}) + V_D = 0$$

L	BT self inductance
R	cable & dump unit resistors resistance
R_{coils}	BT total resistance
V_D	voltage drop across the diodes



Thermal shield < 0.01%

Vacuum vessel < 0.01%

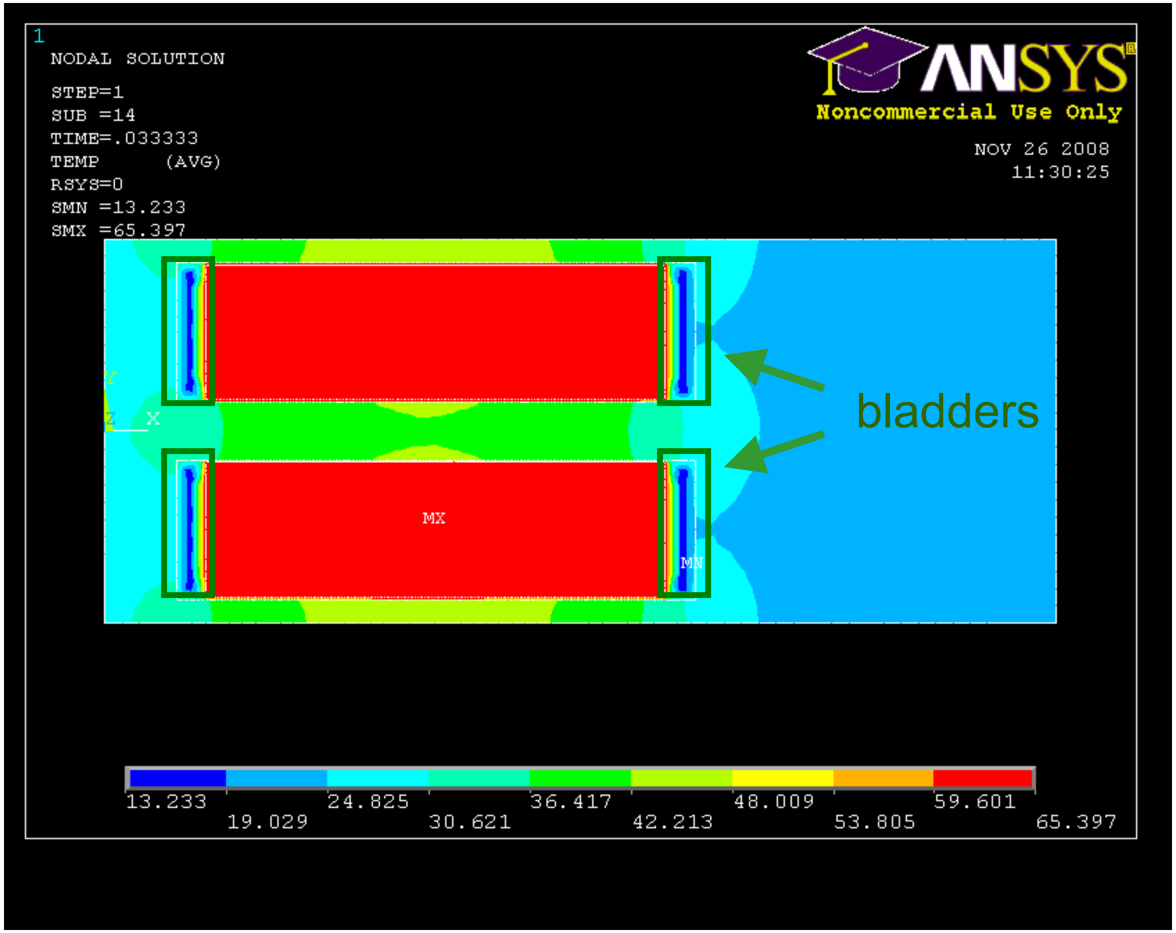
Casing ~ 0.7%

BT: thermal model

$$Q = k \cdot \frac{A}{l} \cdot \Delta T$$

Q	thermal energy
k	thermal conductivity
A	heat exchange surface
l	heat diffusion length
ΔT	temperature difference

After ~ 2 min



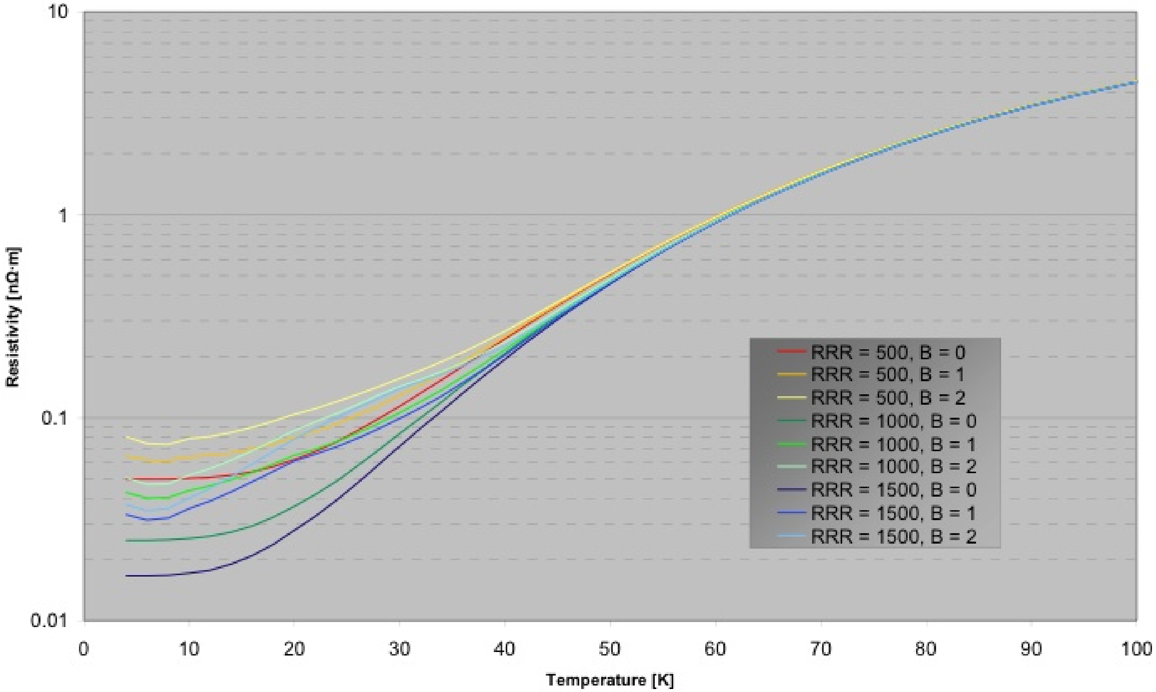
```
1
NODAL SOLUTION

STEP=1
SUB =14
TIME=.033333
TEMP      (AVG)
RSYS=0
SMN =13.233
SMX =65.397
```

BT: Al resistivity

The main factors that determine the Al resistivity are:

- purity grade of the material
- temperature
- magnetic field

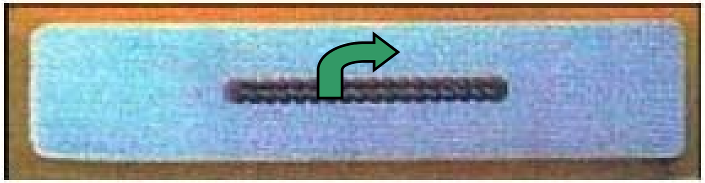


Average *B* ~ 1.8 T

BT: energy release due to the current redistribution

Current diffusion time constant

$\tau \sim$ few s



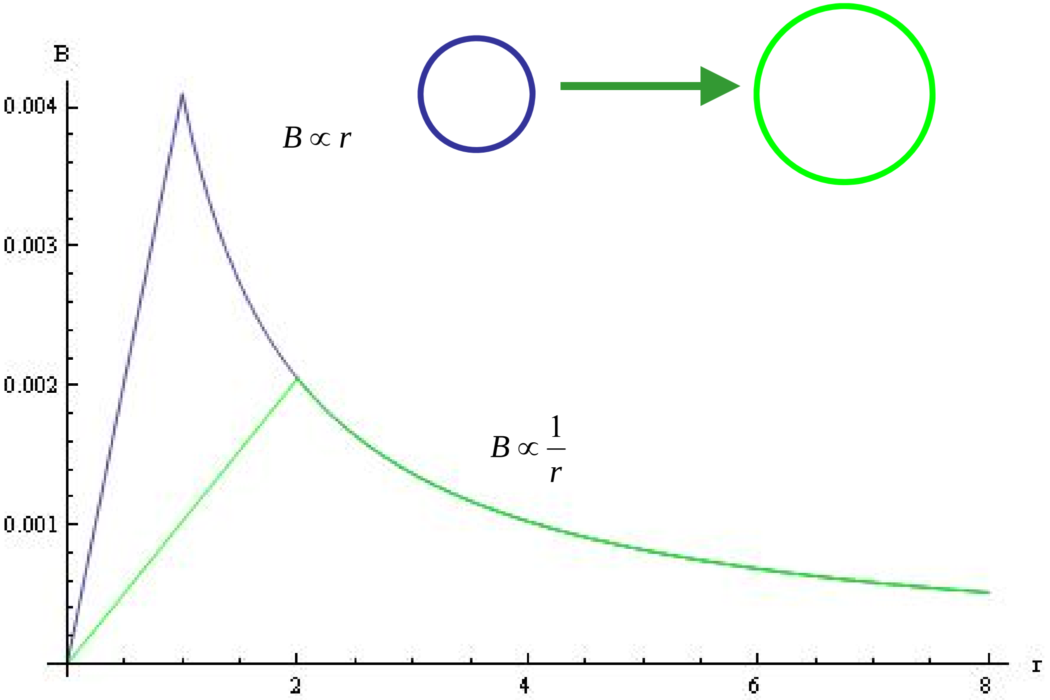
An accurate treatment of the problem implies the solution of

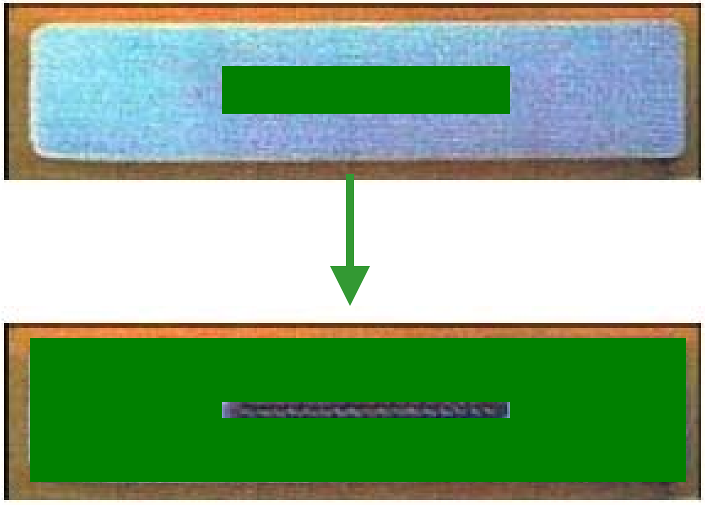
Maxwell's equations

heat conduction and
diffusion equations

A alternative way has been followed that looks at the changing magnetic field energy density between the beginning and end of the process.

BT: energy release due to the current redistribution





To calculate the energy release:

- *B* field energy density
- conductor length (~ 60 km)

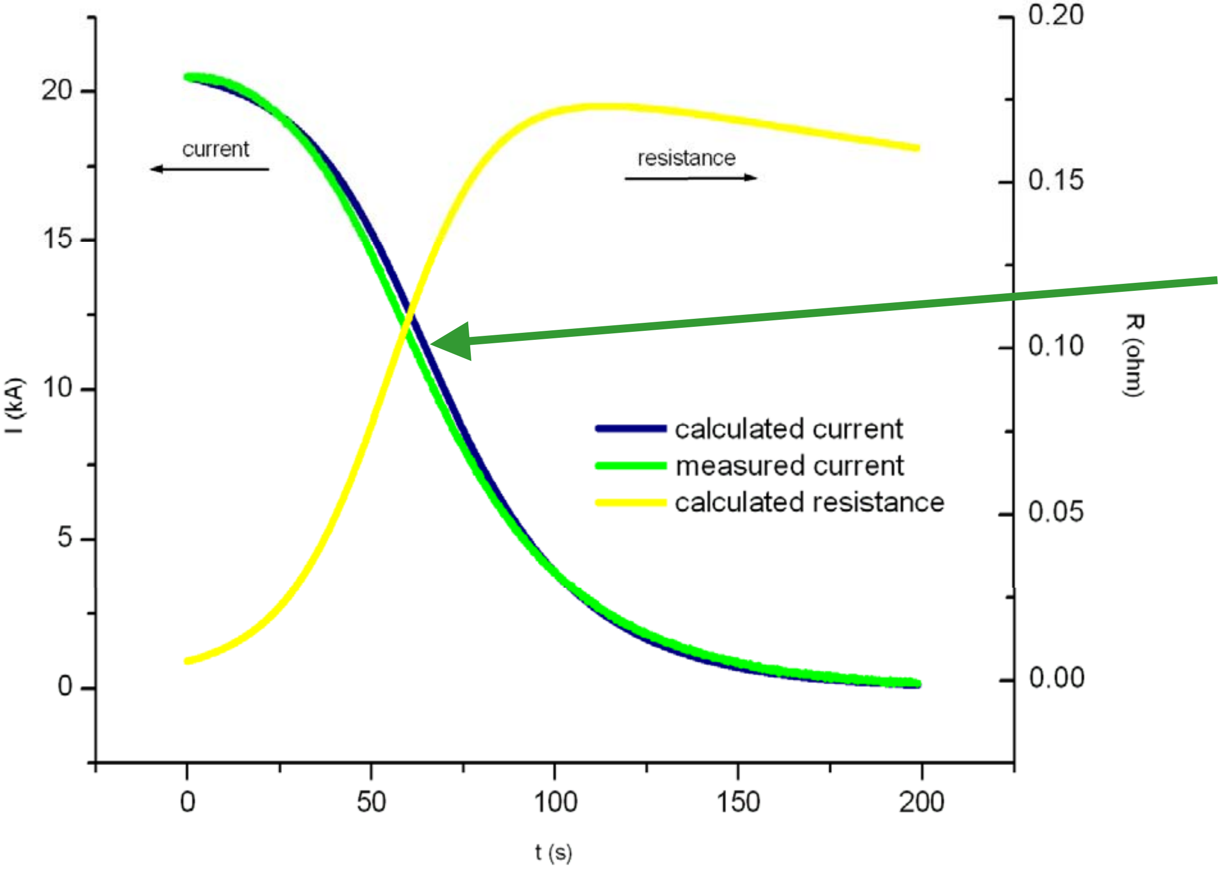
→ E ~ 10 MJ → T_{initial} ~ 21K

BT: simulation of a fast dump

Using *Mathematica*

1. **Resistance of double pancakes**
2. **Current**
3. **Energy dissipation in coils**
4. **Energy transfer from coils to casing**
5. **Temperature increase**

Electric analysis



- Discharge time ~ 180 s

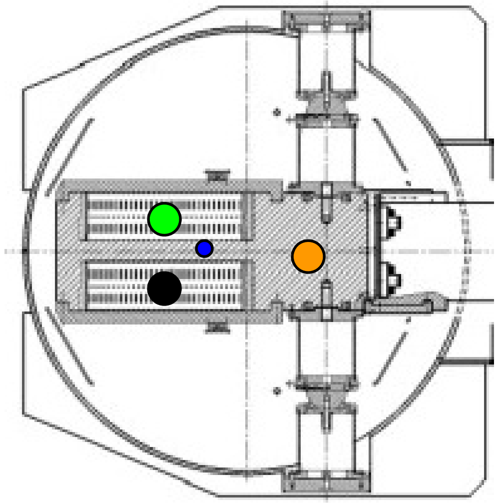
- ΔI max ~ 7%

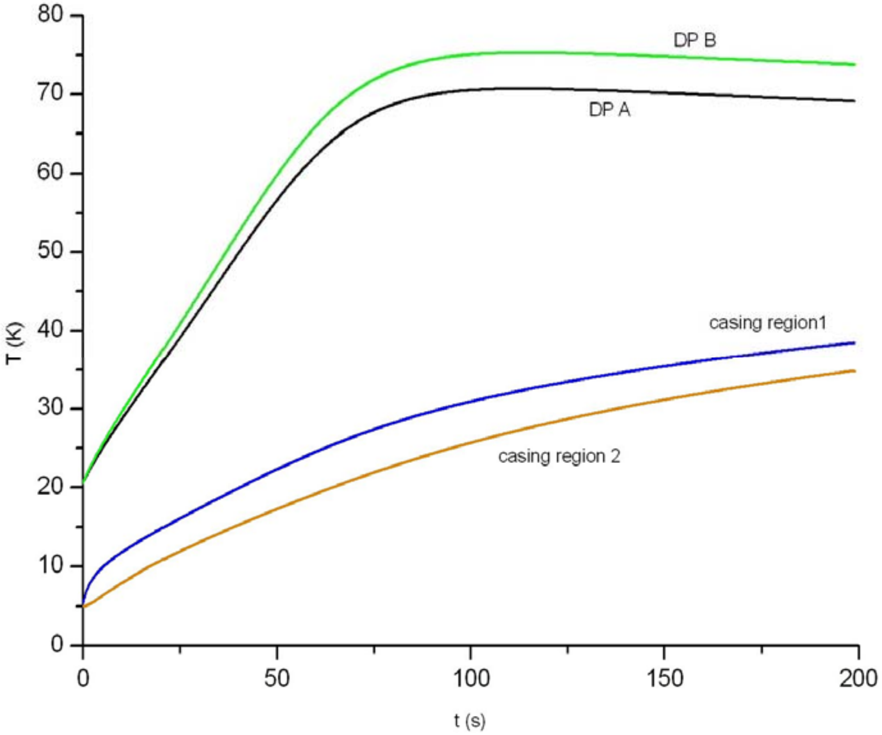
  (t ~ 60 s)

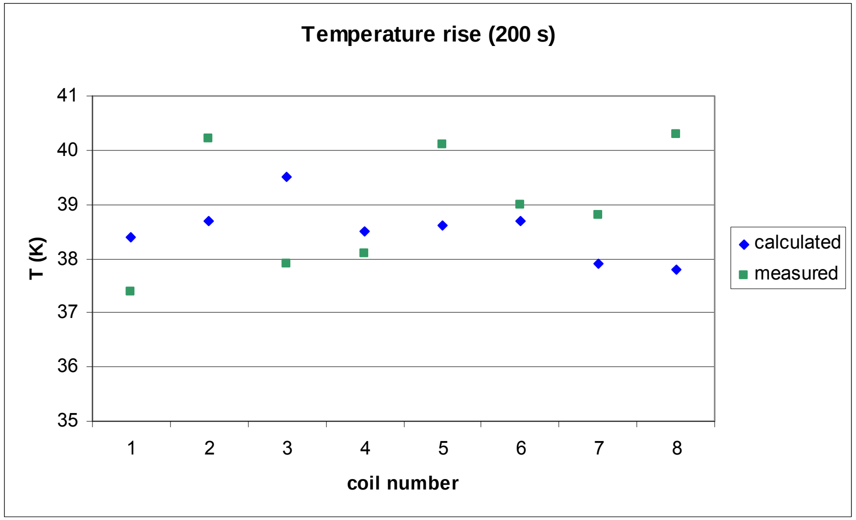
- BT resistance

  $R_{max} < 0.20\ \Omega$

Thermal analysis /1







Temperatures after 200 s from the beginning of the dump

Average difference 3%

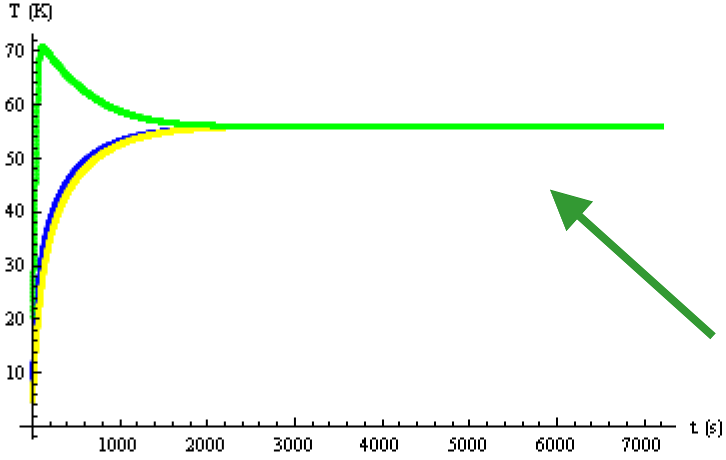
Thermal analysis /2

At the end of the dump the temperature of the coils can be estimated on the base of the energy dissipation in the double pancakes.

$$V_{active} = V_{total} - L \cdot \frac{dI}{dt}$$

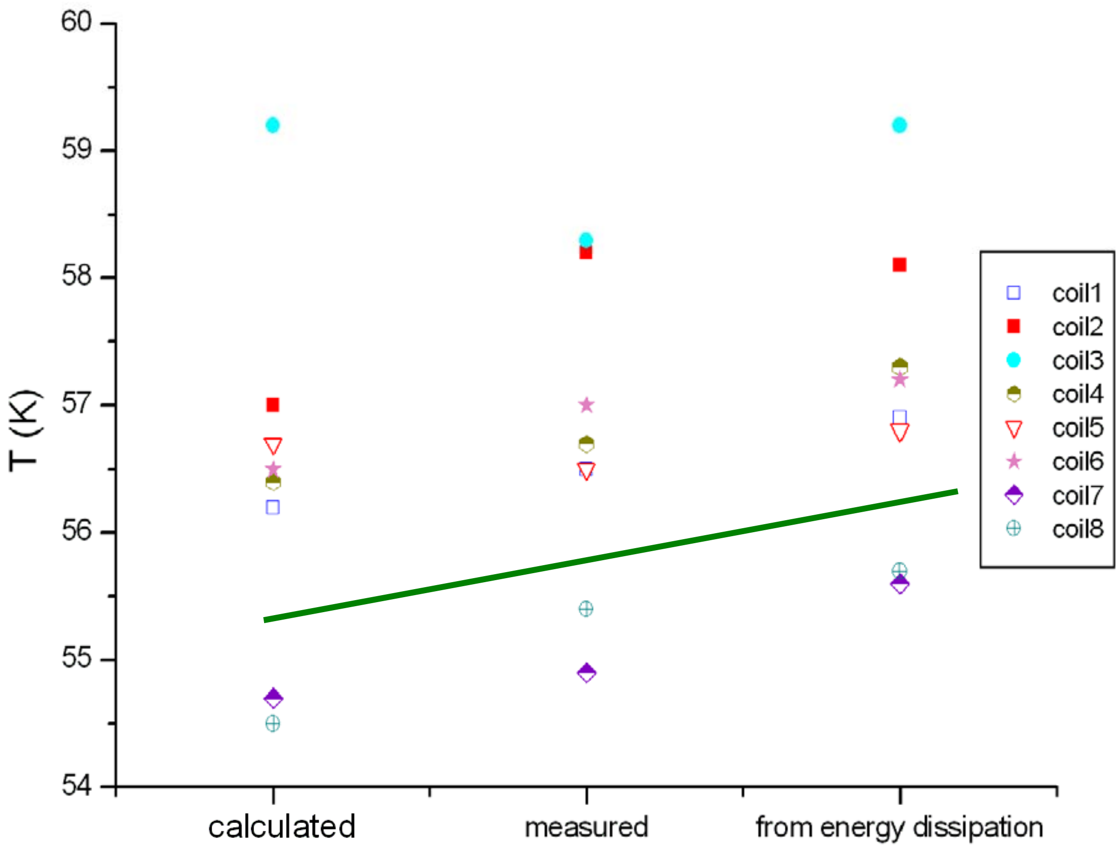
$$E_i = \int_0^{\infty} (V_{DPAi} + V_{DPBi}) \cdot I dt$$

$$H_i(T) = \frac{E_i}{m} \longrightarrow T$$



$V_{active} = V_{DPi}$	resistive voltage across double pancake
V_{total}	total voltage across double pancake
L	DP inductance
dI/dt	current derivative
E_i	coil energy dissipation
H_i	coil enthalpy
m	coil mass

Thermal analysis /2



Average difference

$T_{\text{calculated}} - T_{\text{measured}} = 1\%$

$T_{\text{calcualted}} - T_{\text{voltage}} = 1\%$

In general:

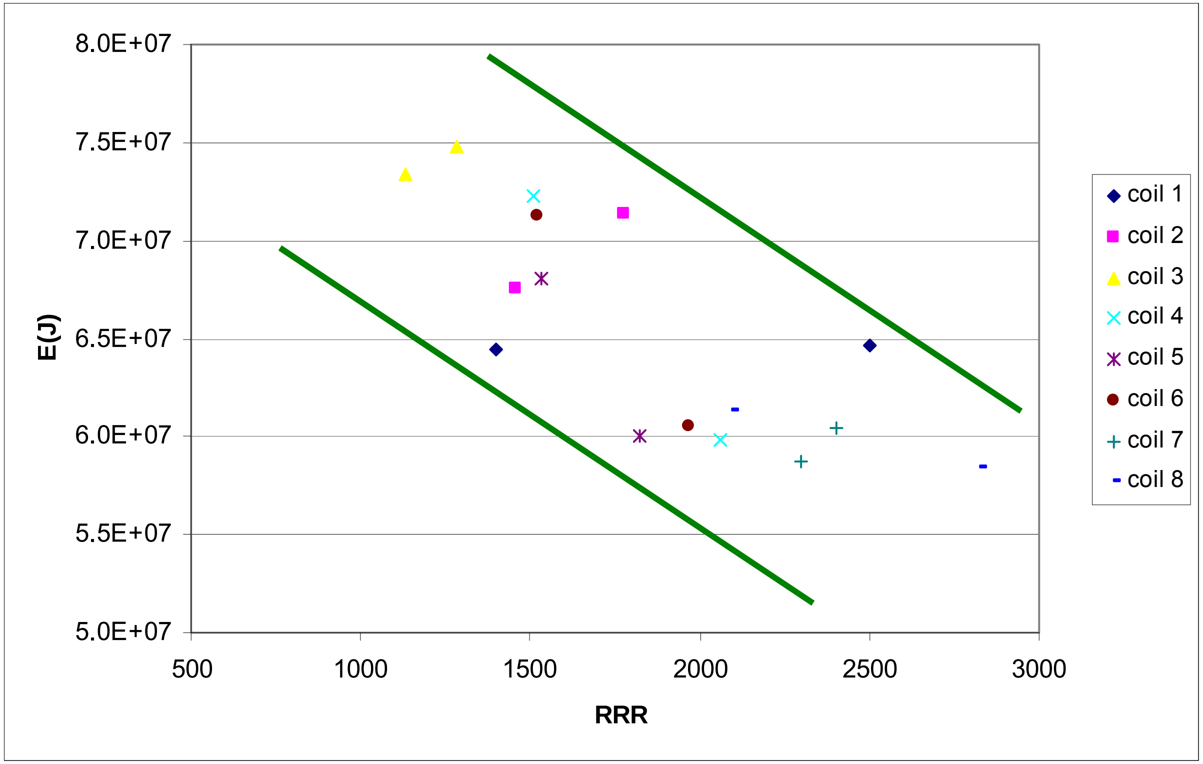
- T_{measured} affected by re-start of He flow

- $T_{\text{calculated}}$ influenced by correctness of RRR values

Energy dissipation

Energy dissipated in a coil $E_{coil} = \int I \cdot V_{active} dt$

Energy dissipated in BT $E = \sum_{i=1}^{16} E_{DPi} = 1047 MJ$



Average coil dissipation

131 MJ

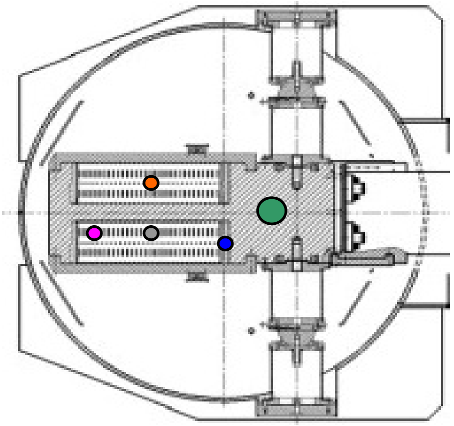
Energy distribution

$$E_{dump} = -\int I \cdot V_{tot} = 32.5MJ$$

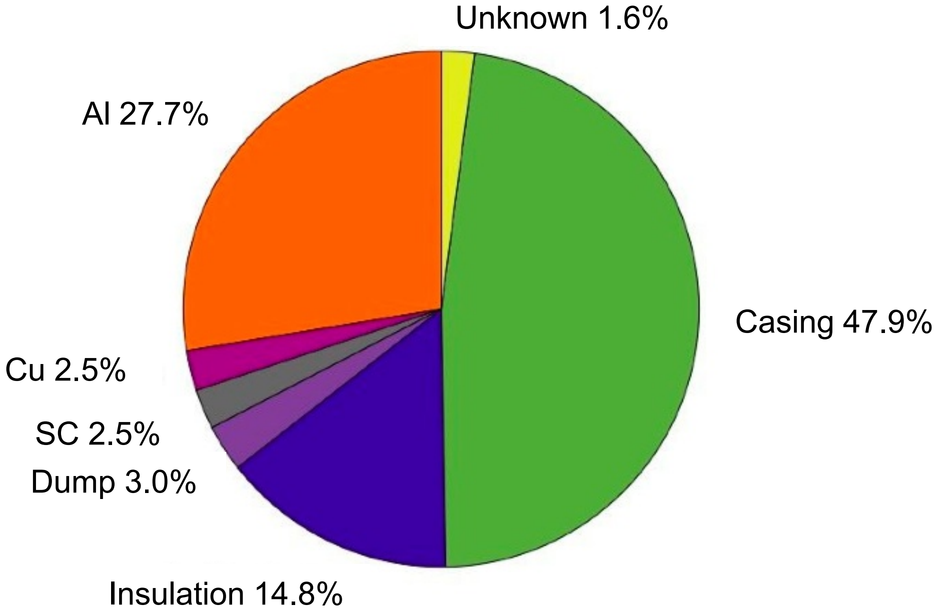
$$E_{coils} = \sum_{i=1}^{16} E_{DPi} = 1047MJ$$

$$\boxed{E_{\exp} = 1079.5MJ}$$

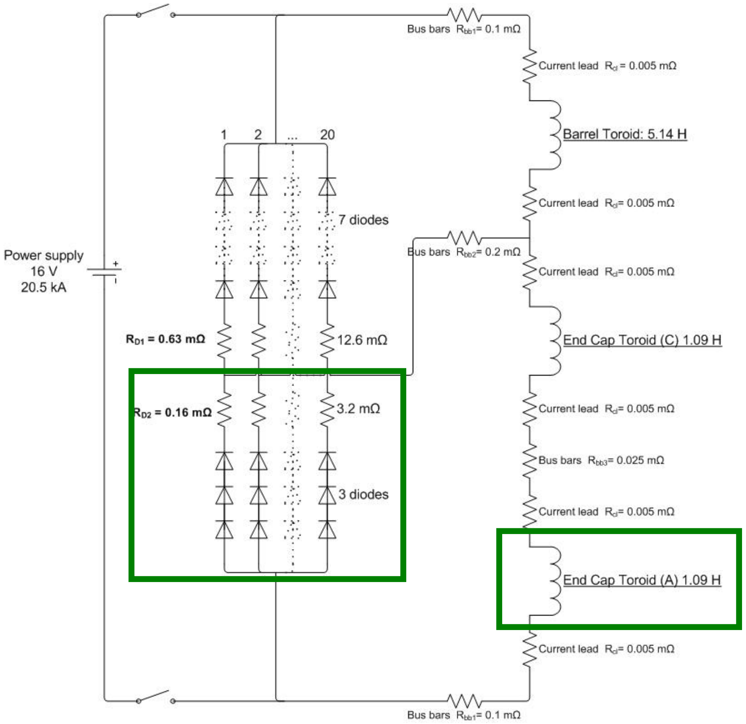
$$\boxed{E_{th} = \frac{1}{2} LI^2 = 1080MJ}$$



Energy distribution in BT coils (dump from 20.5 kA)



ECT: electric model

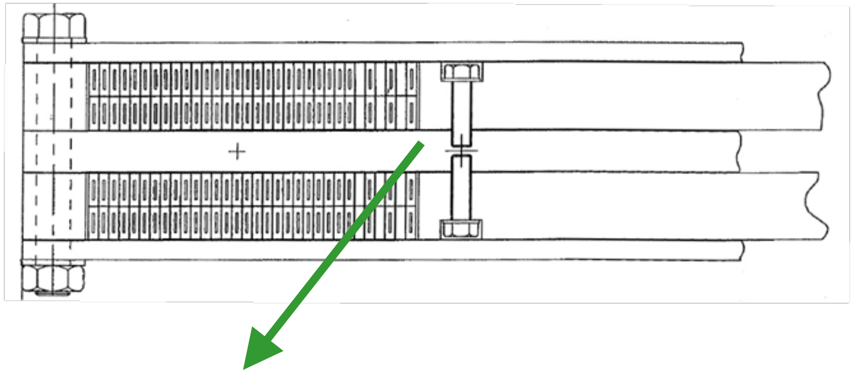


$$L \cdot \frac{dI}{dt} + I \cdot (R + R_{coils}) + V_D = 0$$

L	ECT A self inductance
R	cable & dump unit resistors resistance
R_{coils}	ECT A total resistance
V_D	voltage drop across the diodes

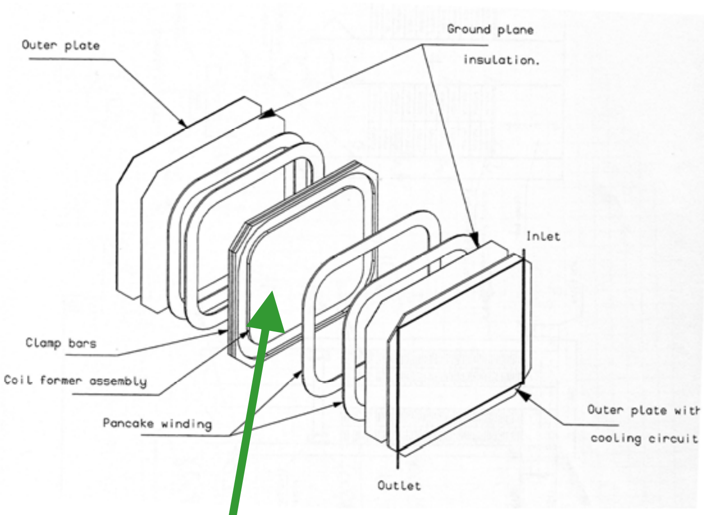
$$E = \int_0^\infty \left(M \frac{dI}{dt}\right)^2 \cdot \frac{1}{R} dt$$

M	mutual inductance
R	element resistance



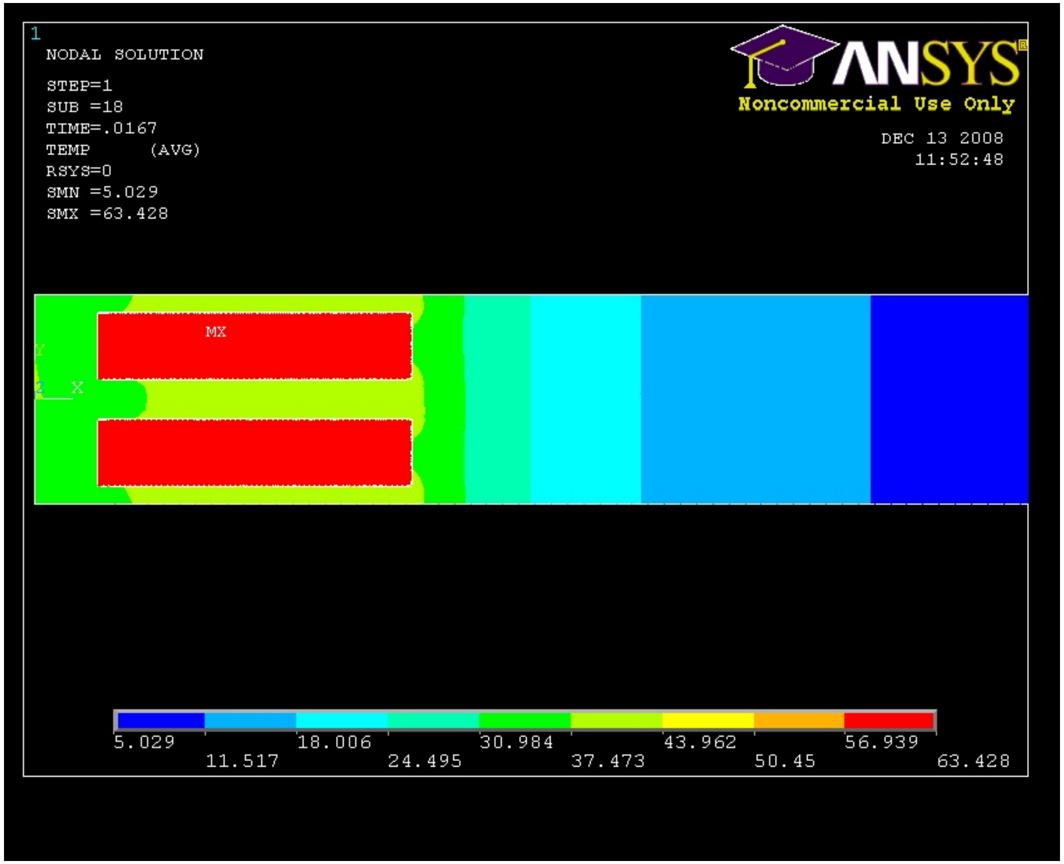
Casing ~ 0.7%

ECT: thermal model



Al alloy central plate

After ~1 min



```
1
NODAL SOLUTION

STEP=1
SUB =18
TIME=.0167
TEMP       (AVG)
RSYS=0
SMN =5.029
SMX =63.428
```

ECT: Al resistivity & initial conditions

Average magnetic field on ECT conductor

↓

$B = 2$ T

Energy release to the conductor:

- *B* field energy density
- conductor length (~ 13 km)

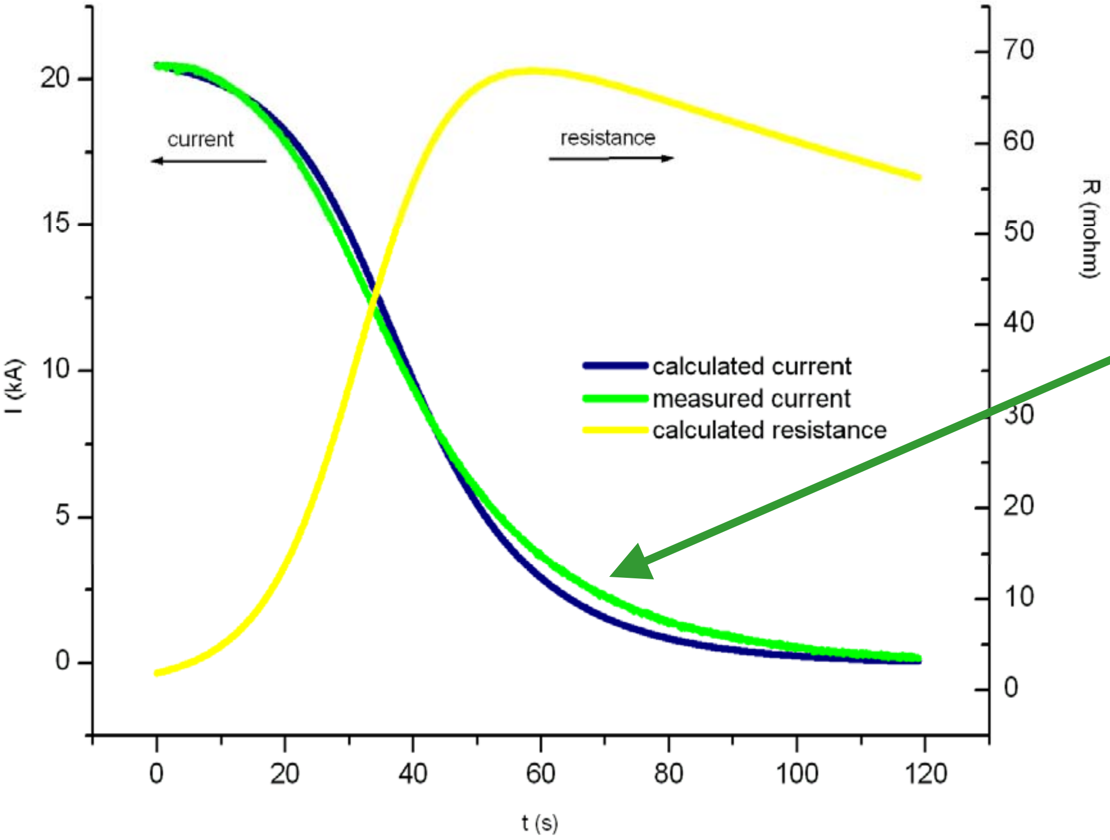
↓

E ~ 1.3 MJ

↓

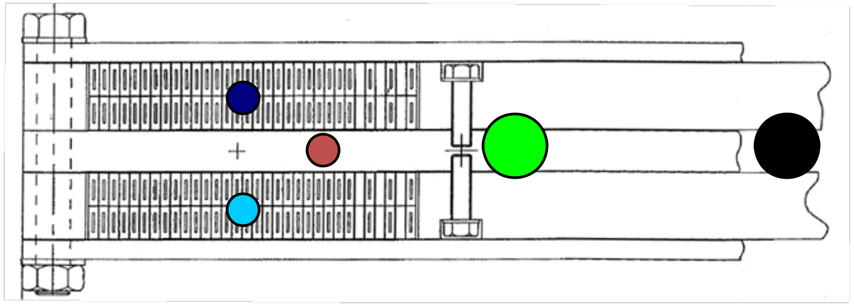
$T_{\text{initial}} \sim 19$ K

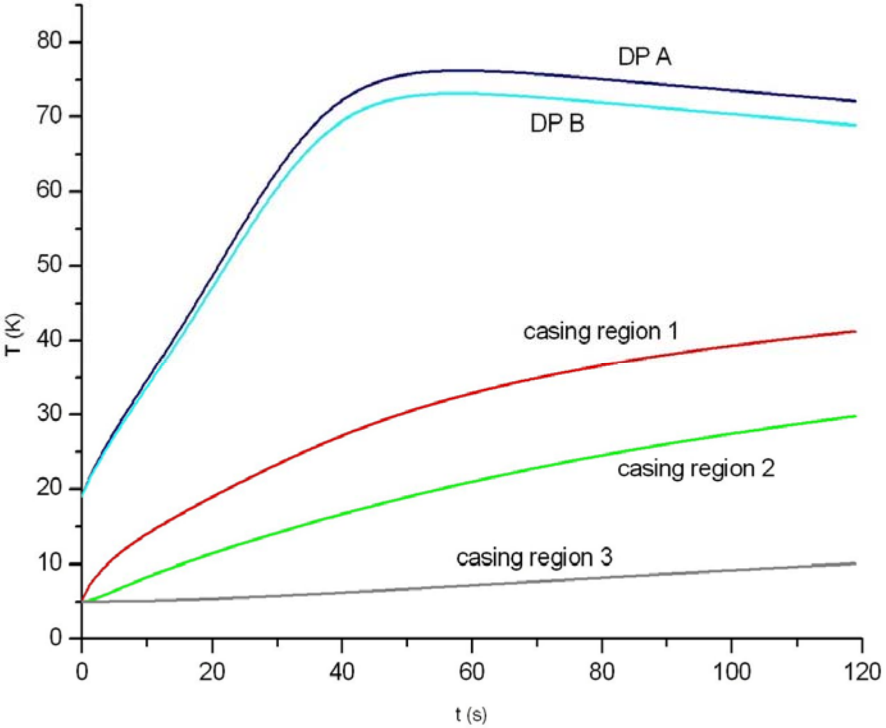
Electric analysis

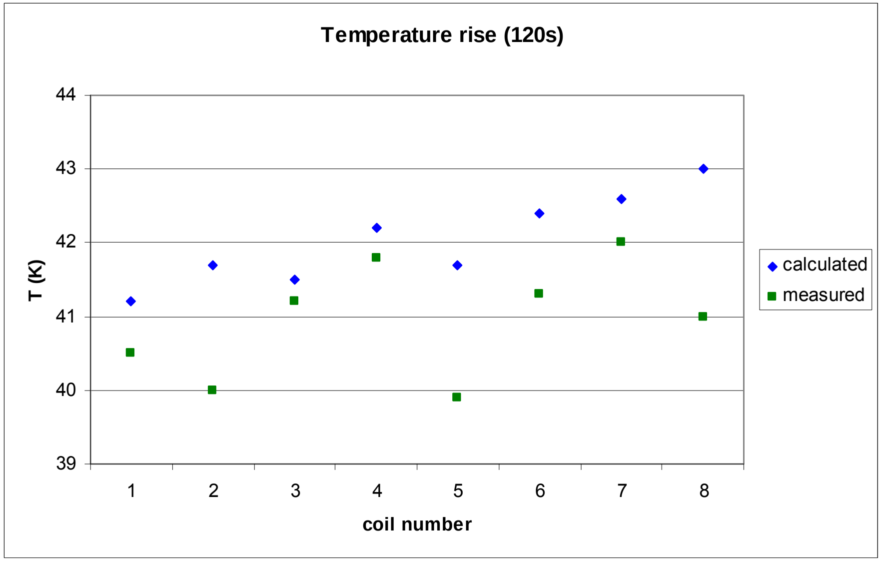


- Discharge time ~ 90 s
- ΔI max ~ 26% (t ~ 63 s)
- higher difference due to keystone boxes
- ECT A resistance $R_{max} < 70\ \text{m}\Omega$

Thermal analysis /1



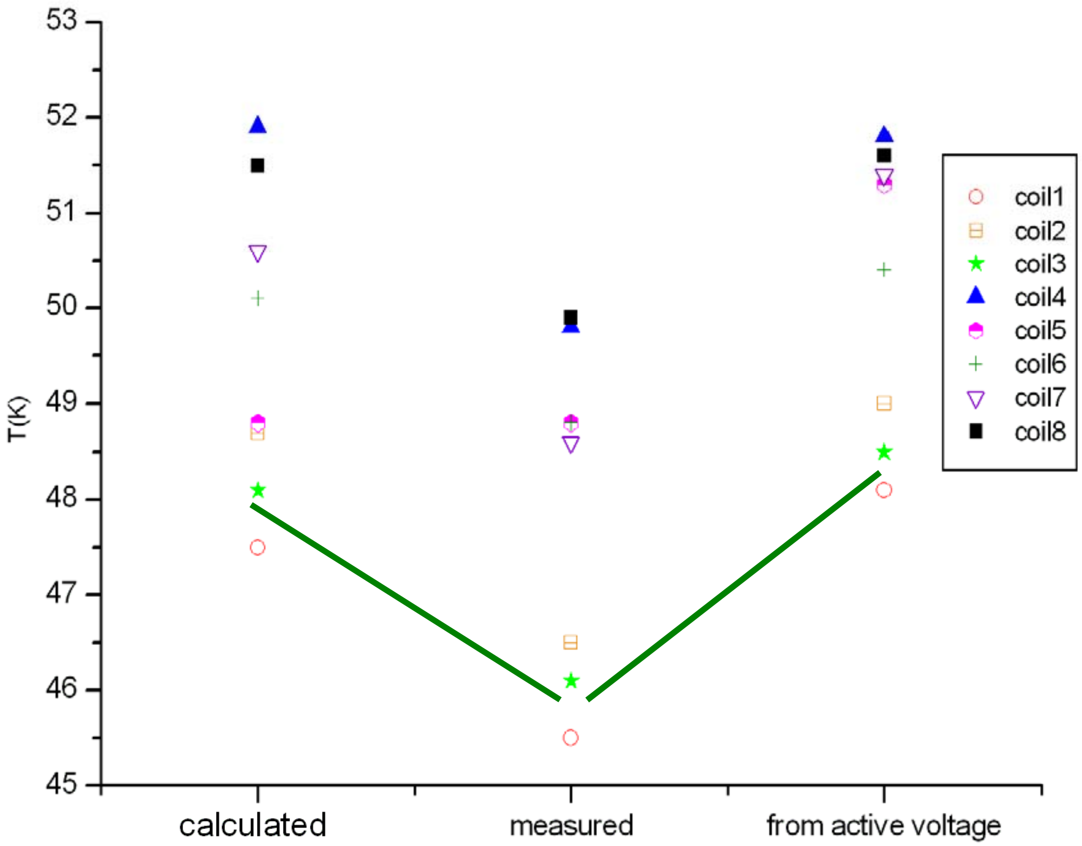




Temperatures after 120 s from the beginning of the dump

Average difference 3%

Thermal analysis /2



Average difference

$T_{calculated} - T_{measured} = 3.5\%$

$T_{calculated} - T_{voltage} = 1.3\%$

In general:

- $T_{measured}$ influenced by keystone boxes
- $T_{measured}$ affected by re-start of He flow
- $T_{calculated}$ influenced by correctness of RRR values

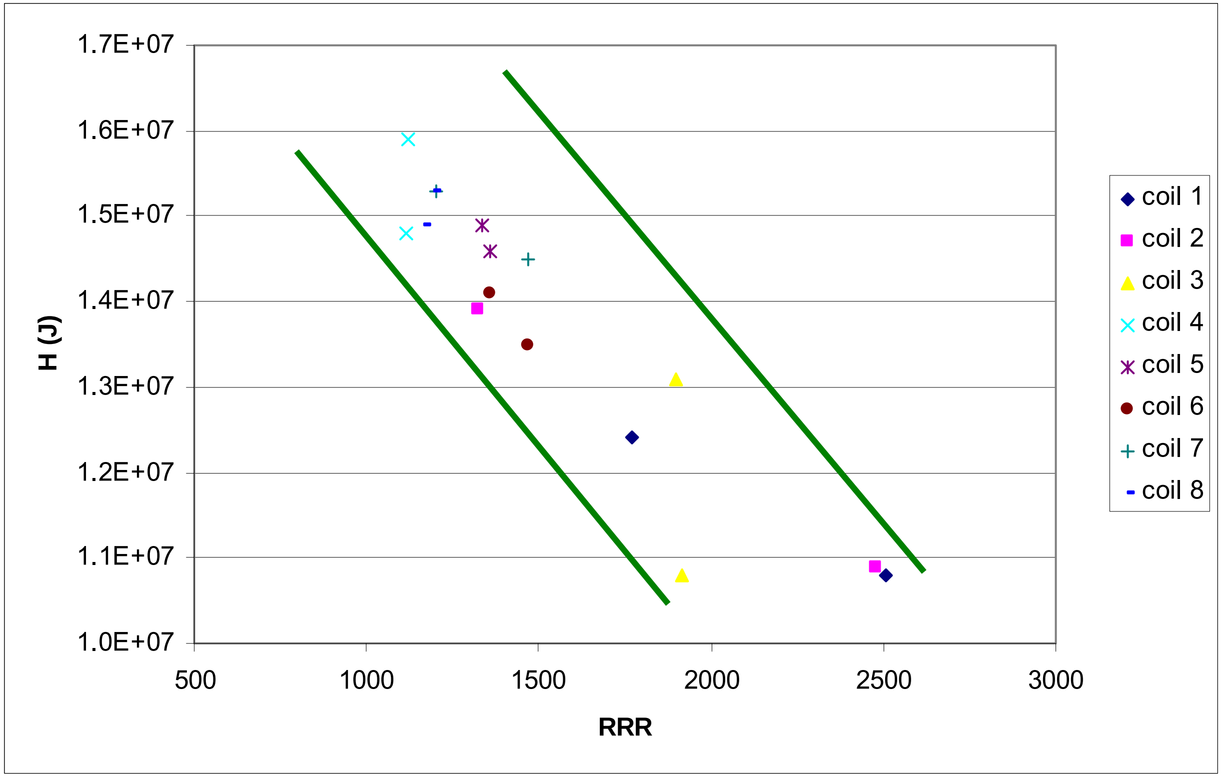
Energy dissipation

Energy dissipated in ECT A

$$E = \sum_{i=1}^{16} E_{DPi} = 219.7MJ$$

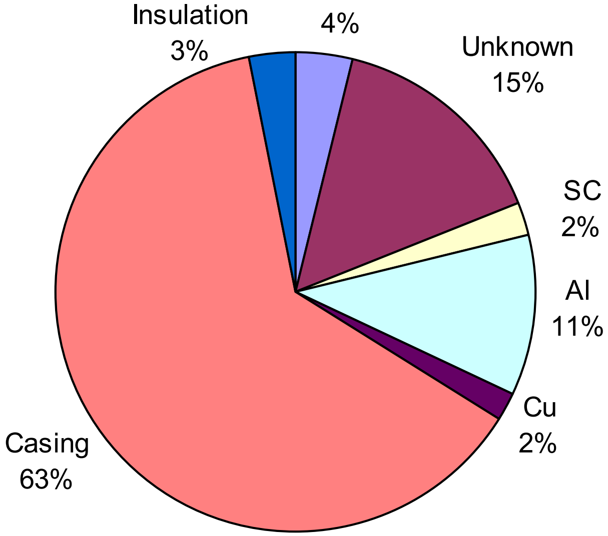
Average coil dissipation

27.5 MJ



Energy distribution

Energy distribution in ECT A coils (dump from 20.5 kA)

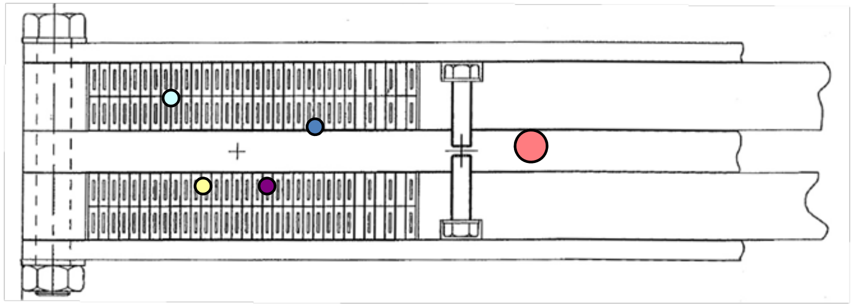


$$E_{coils} = \sum_{i=1}^{16} E_{DPi} = 219.7MJ$$

$$E_{dump} = -\int I \cdot V_{tot} = 8.8MJ$$

$$\boxed{E_{\exp} = 228.5MJ}$$

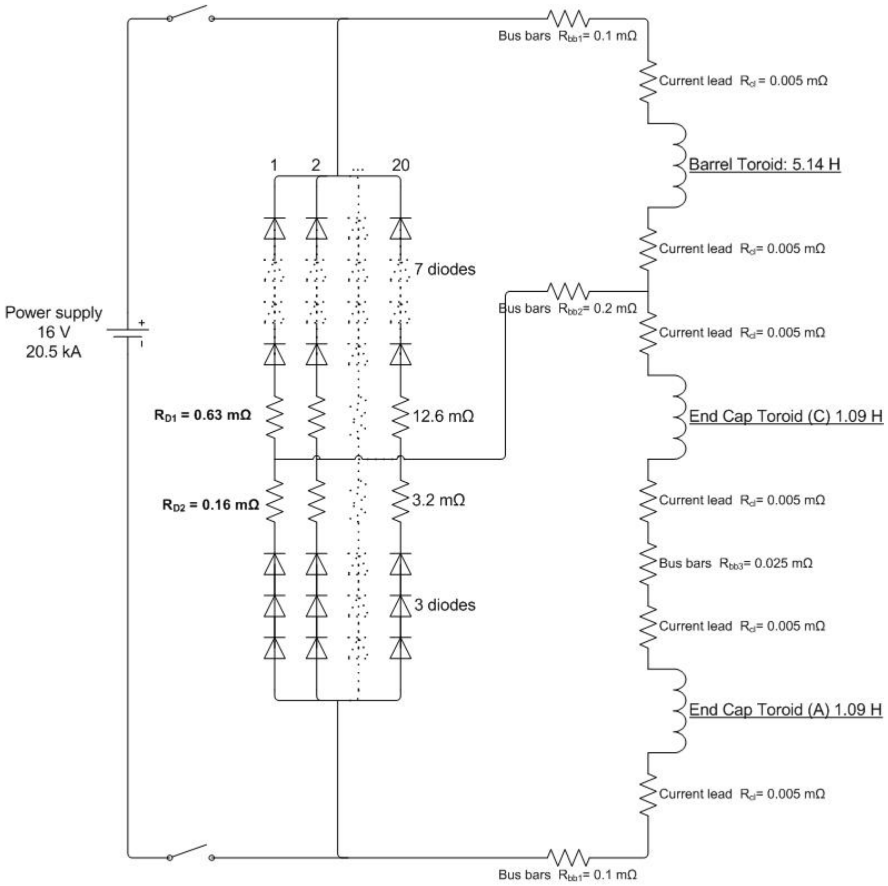
$$\boxed{E_{th} = \frac{1}{2} LI^2 = 229MJ}$$



Missing energy ~ 15%

E keystone boxes ~ 11.4% → Missing energy ~3.8%

ABC: electric model



Current equations

$$\begin{cases} I_{Bi+1} = \dfrac{b\cdot(1+\frac{d}{c})\cdot I_{Bi}+e\cdot I_{Ei}}{a+\frac{d}{c}\cdot(a+c)} \\ I_{Ei+1} = \dfrac{a+c}{c}\cdot I_{Bi+1} - \dfrac{b}{c}\cdot I_{Bi} \\ I_R = I_B - I_E \end{cases}$$

with

$$a = R_{bb1} + 2\cdot R_{cl} + \sum_{n=1}^{16} R_{BTn} + R_{D1} + \frac{L_B}{\Delta t}$$

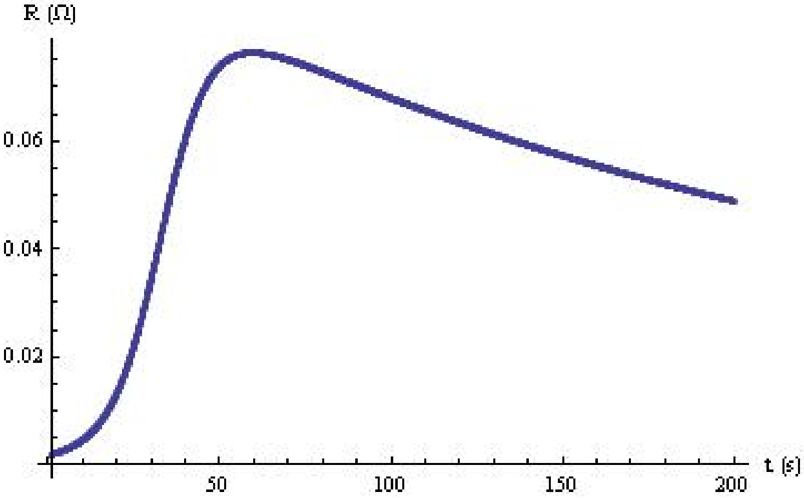
$$b = \frac{L_B}{\Delta t}$$

$$c = R_{bb2}$$

$$d = \sum_{n=1}^{16} R_{ECTCn} + 4\cdot R_{cl} + \sum_{n=1}^{16} R_{ECTAn} + R_{bb1} + R_{bb3} + R_{D2} + 2\cdot\frac{L_E}{\Delta t}$$

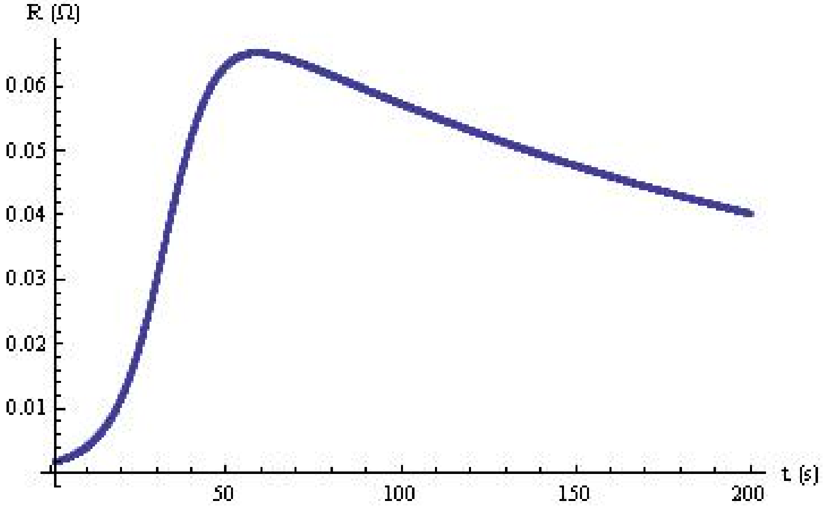
$$e = 2\cdot\frac{L_E}{\Delta t}$$

ECT: electric analysis



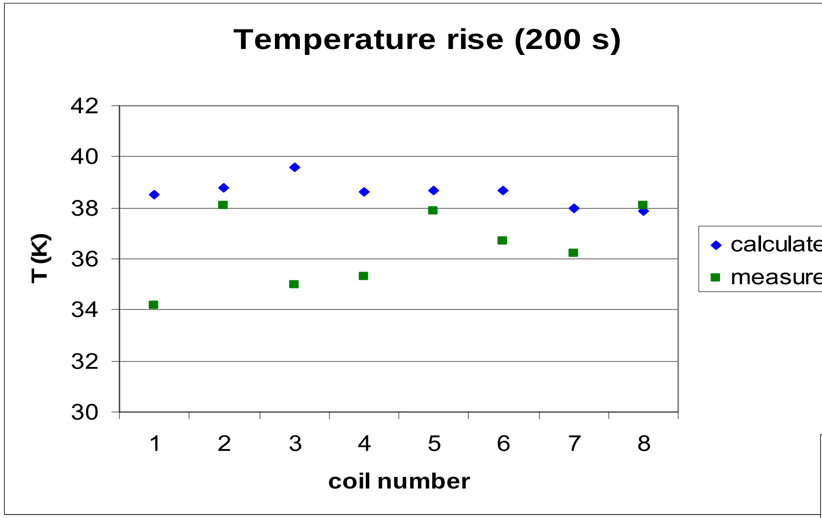
ECT A resistance

ECT C resistance



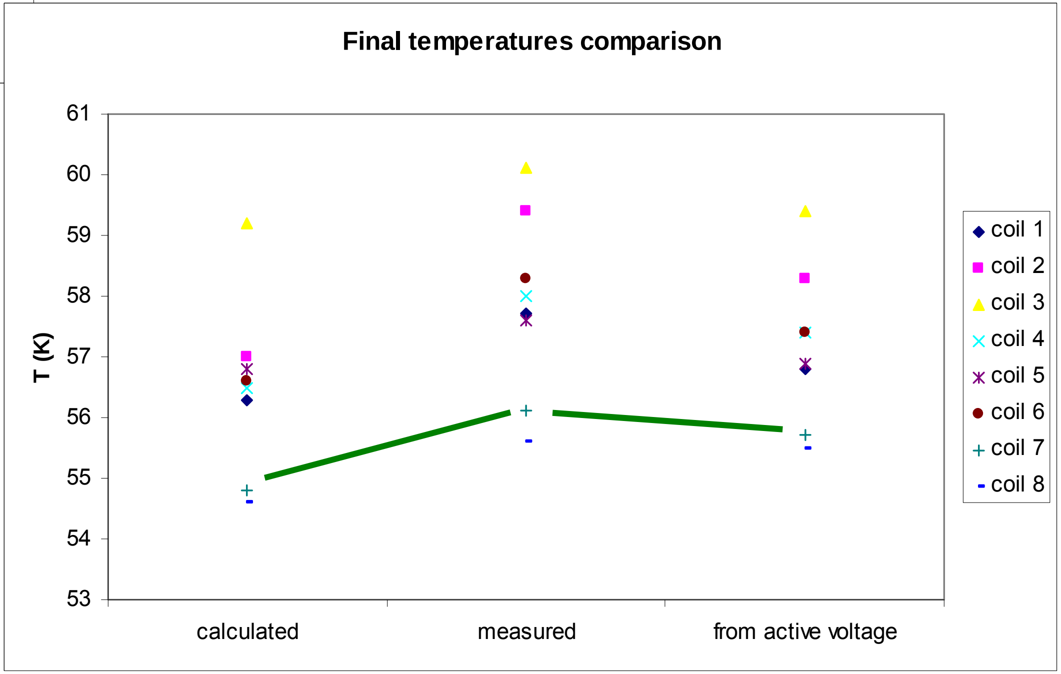
- $R_{\text{ECTA max}} \sim 75\ \text{m}\Omega$
- $R_{\text{ECTA max}}$ in ABC configuration $\sim 10\ \text{m}\Omega$ higher
- $R_{\text{ECTC max}} < 70\ \text{m}\Omega$
- $R_{\text{ECTA max}} > R_{\text{ECTC max}}$ because of the lower average RRR of the double pancakes

BT: thermal analysis



Temperature comparison after 200 s from the beginning of the dump

Average difference 6% (↑)

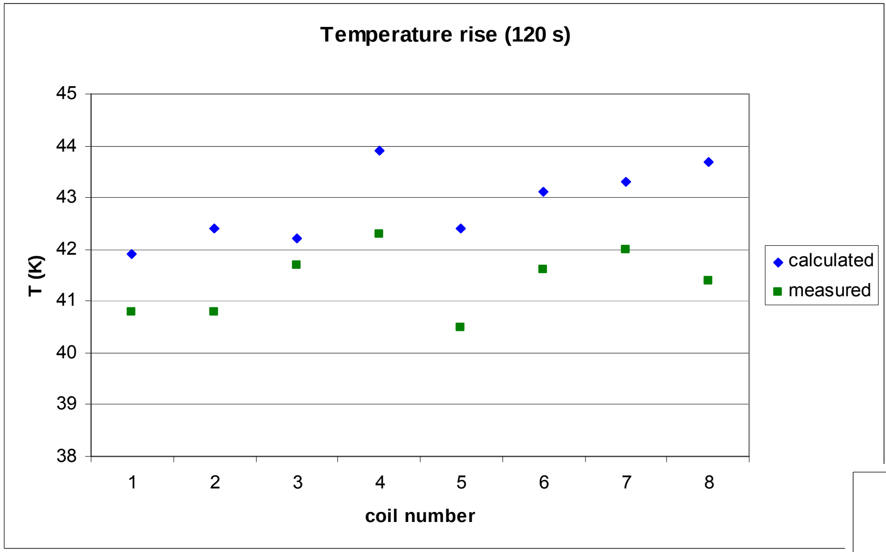


Average difference

$T_{calculated} - T_{measured}$ = 2% (↑)

$T_{calcualted} - T_{voltage}$ = 1% (=)

ECT A: thermal analysis



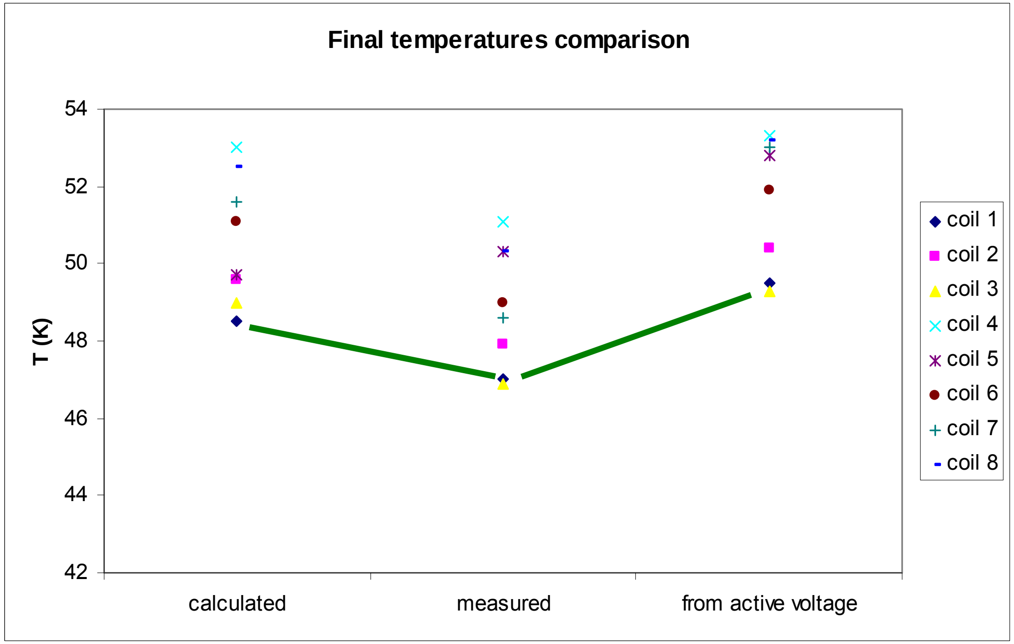
Average difference

$T_{calculated} - T_{measured}$ = 4% (=)

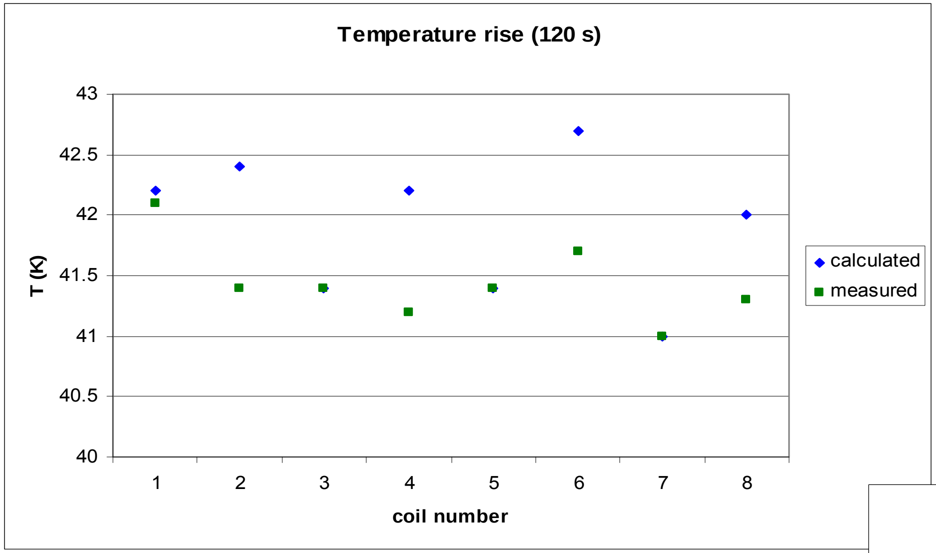
$T_{calculated} - T_{voltage}$ = 2% (↑)

Temperature comparison after 120 s from the beginning of the dump

Average difference 3.6% (=)



ECT C: thermal analysis



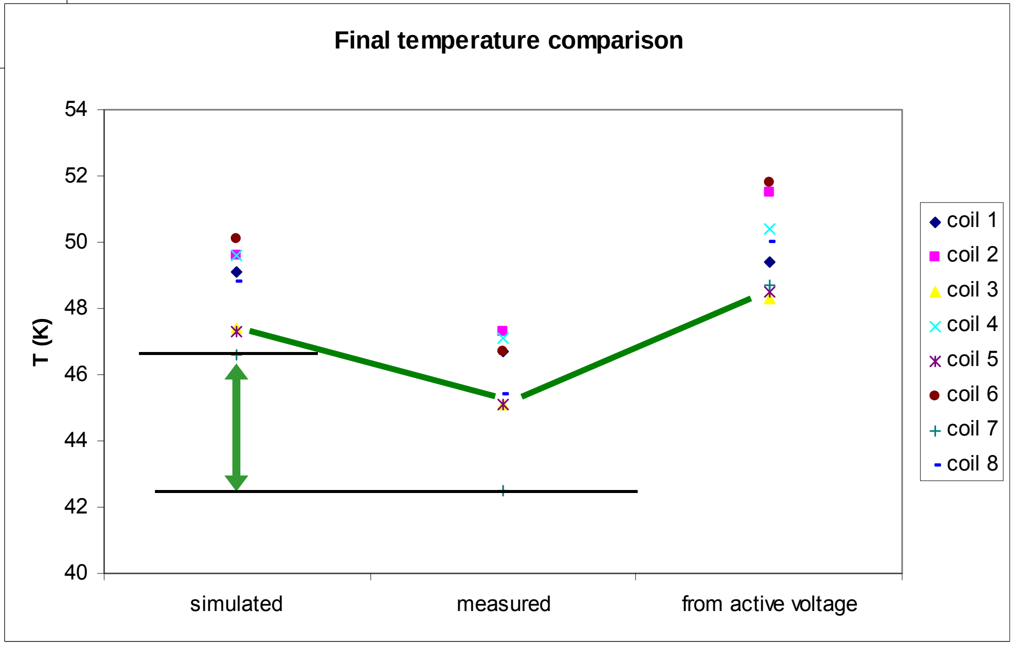
Temperature comparison after 120 s from the beginning of the dump

Average difference 1%

Average difference

$$T_{calculated} - T_{measured} = 6\%$$

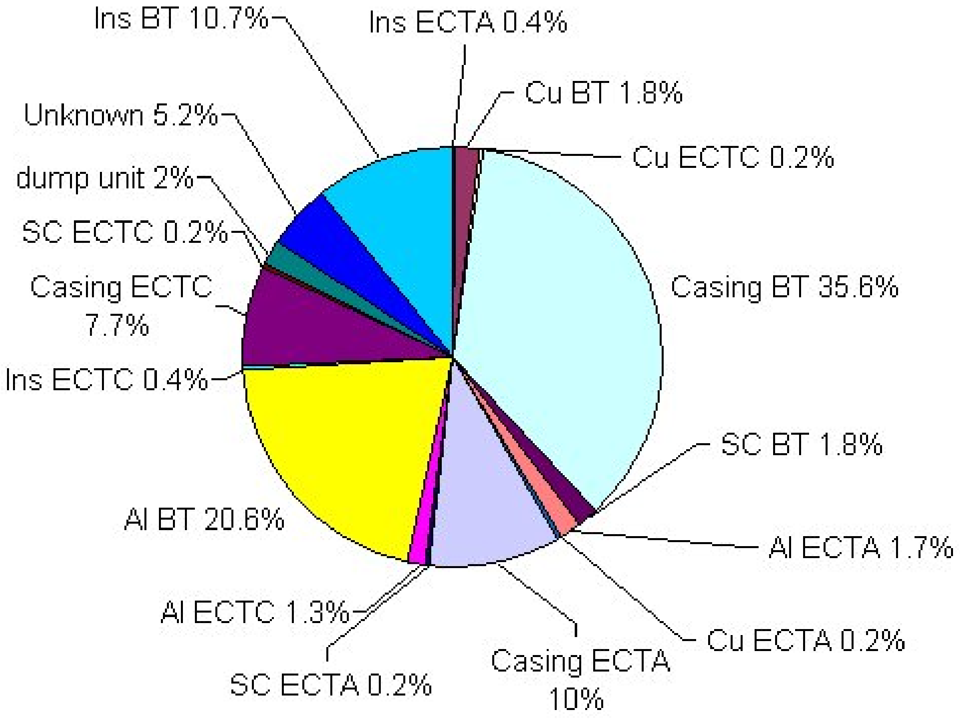
$$T_{calculated} - T_{voltage} = 2.5\%$$



Energy distribution

Energy distribution in the coils

(dump from 20.5 kA)



$$E_{th} = \frac{1}{2}(L_{BT} + 2 \cdot L_{ECT} + 4 \cdot M)I^2 = 1571.7 MJ$$

- casings > 50%
- BT Al stabilizer ~ 20 %
- BT insulation ~10%
- remaining elements each < 2%
- 5% initial energy missing

↓

Keystone boxes contribution

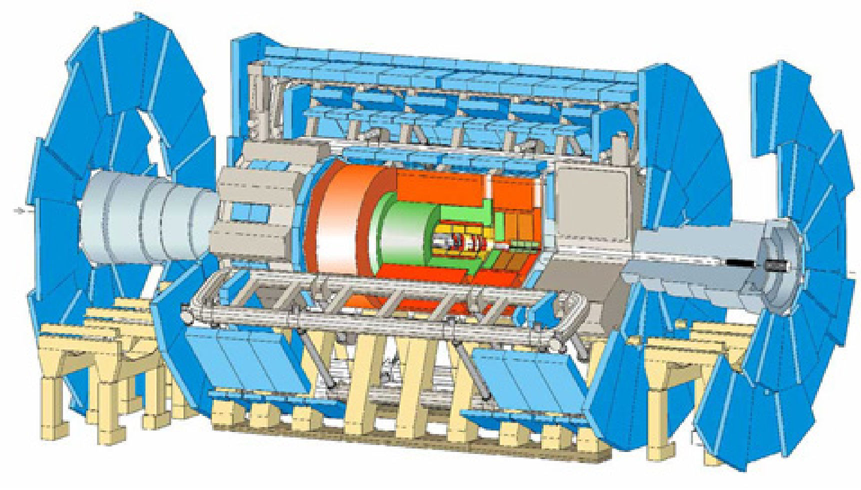
$E_{\text{keystone boxes}} = 3.8\%$

↓

Missing energy reduces to 1.2%

Conclusions

- Simulation of the fast dump of the single toroids from the electrical and thermal point of view
- Results have been validated through the comparison with experimental data



- The simulation is able to describe behavior of the system with a quite good level of accuracy (~ 5%)
- The models of the single magnets have been unified to simulate the fast dump of the complete ATLAS toroid system
- The energy distribution inside the coils has been determined: while the BT coils constitute an adiabatic system, the energy balance of the ECTs is influenced by the keystone boxes