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Thermal-Electrical Study of an Ultra-fast Disconnect Switch with a Piezoelectric Actuator

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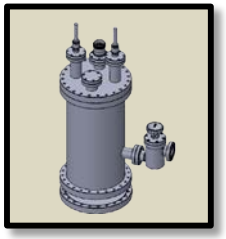
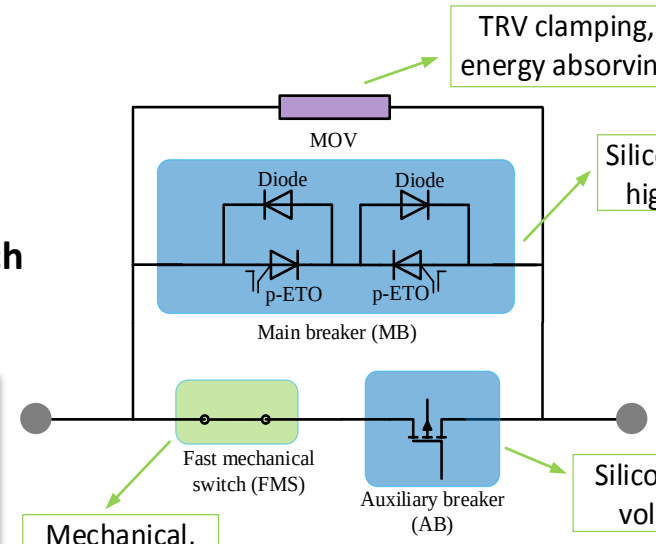
Need for a High Speed Mechanical Disconnect Switch

- **Hybrid circuit breakers**
  - Low conduction losses by **bypassing the semiconductors**
  - Only as fast as the mechanical switch
  - No arcing in the mechanical switch

200A, 15 kV mechanical disconnect switch Open in < 1ms





15 kV, 200 A, SiC p-ETO, bi-directional

200 (400) A, MOSFET Rds(on) < 1mOhm Vbr = 100

Figure by FREEDM Systems Center

Need for a High Speed Mechanical Disconnect Switch

- The conduction losses drop:
  - From **4 kW** to **1.8 kW** by using SiC ETOs instead of Si IGBTs
  - From **1.8 kW** to **900 W** by using advanced symmectric GTOs
  - From **900 W** to **10 W** by adding a mechanical switch

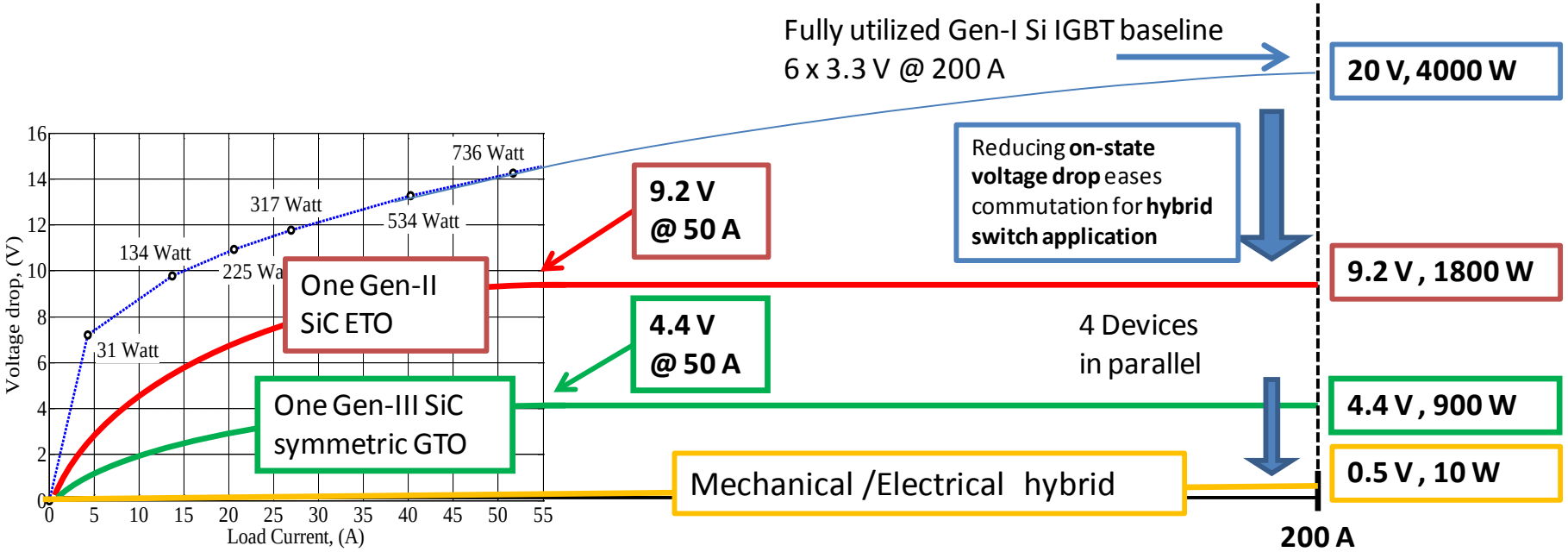
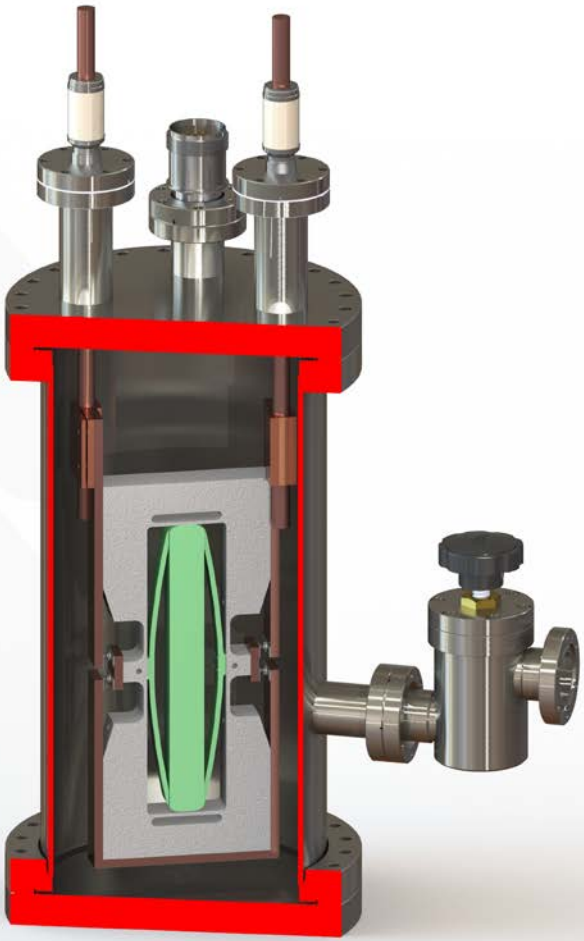


Figure by FREEDM Systems Center

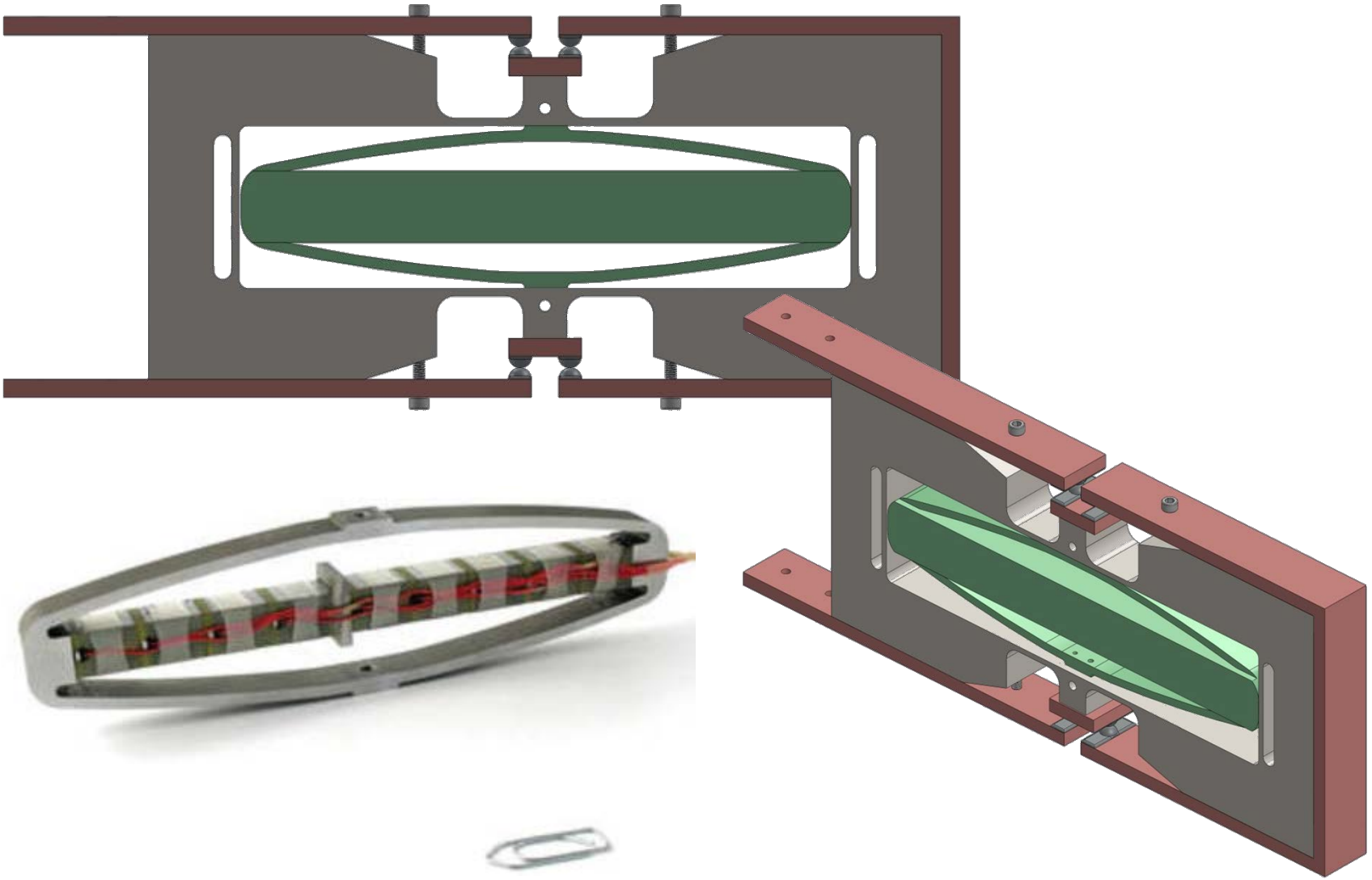
Design of the Switch

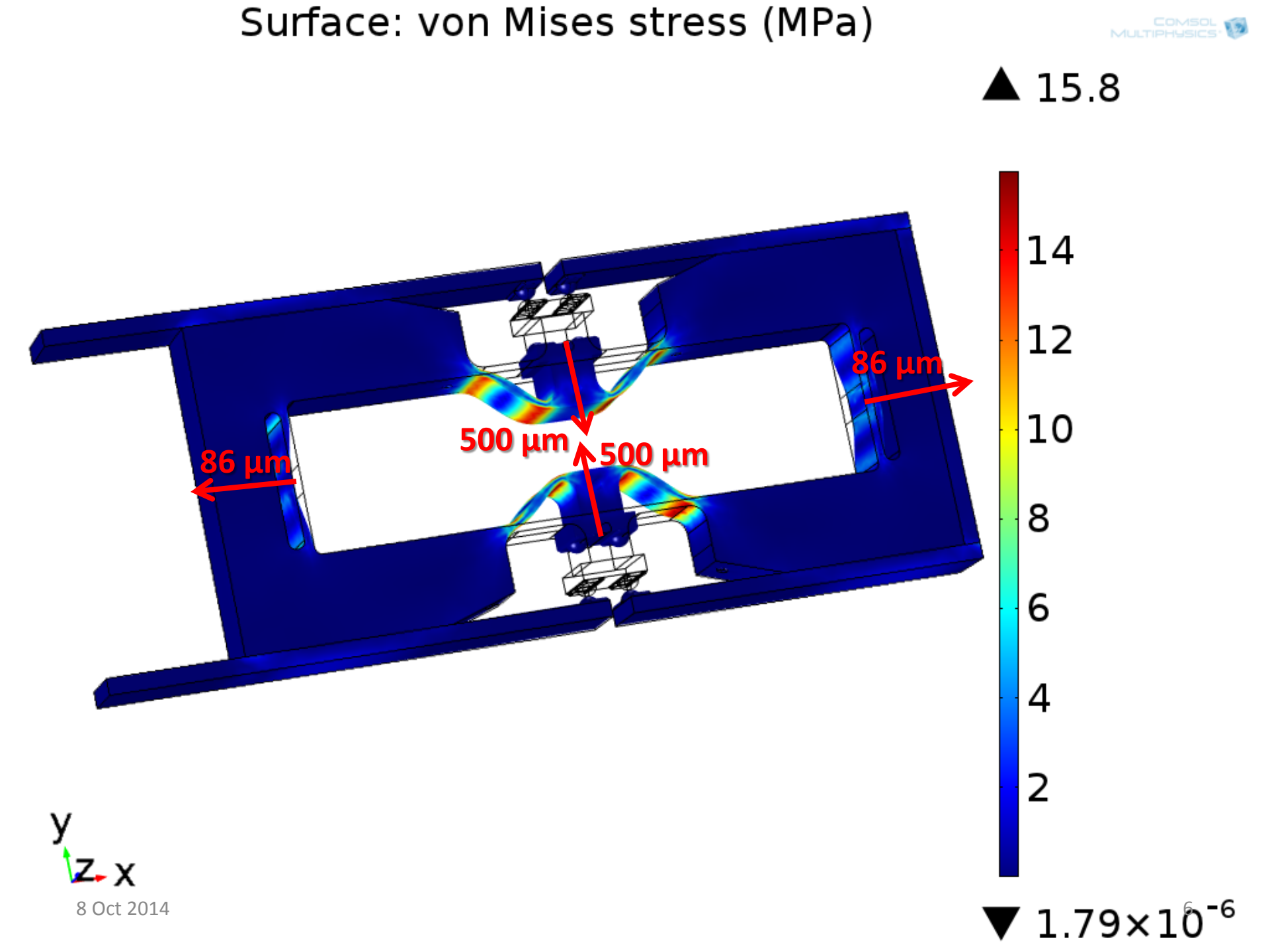


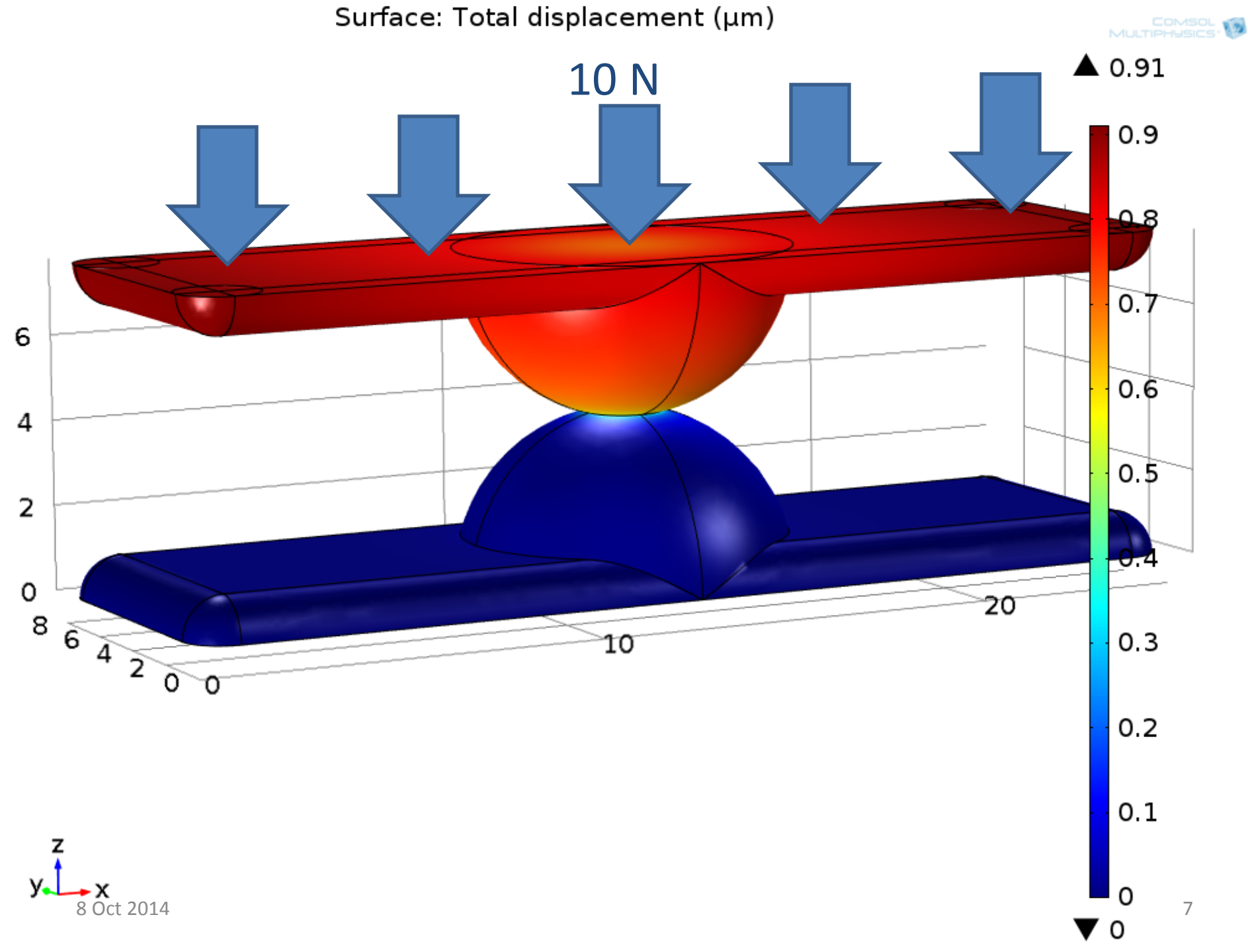
Patents pending

- 15 kV_{RMS}, 200 A
- Opening in < 1 ms
- Losses in on-state: < 5 W

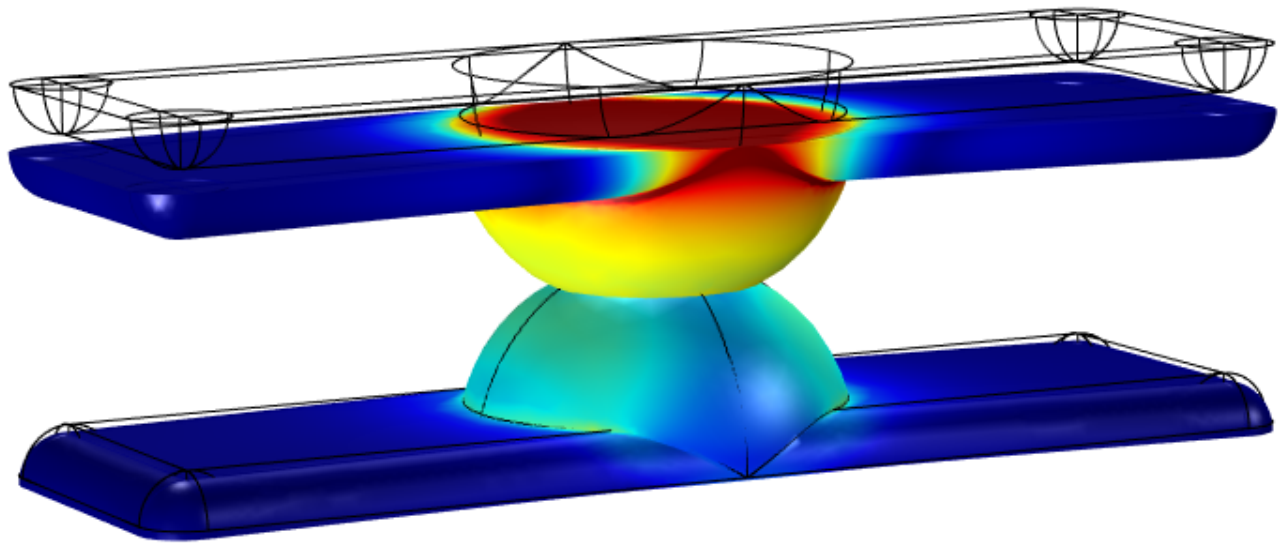
Actuator and Frame




Surface: von Mises stress (MPa)
▲ 15.8
14
12
10
8
6
4
2
▼ 1.79×10-6
86 µm
500 µm
500 µm
86 µm
y
z
x


Surface: Total displacement (µm)
10 N
▲ 0.91
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
▼ 0
6
4
2
0
8
6
4
2
0
0
10
20
z
y
x

Surface: von Mises stress (MPa)



▲ 130

3

2.5

2

1.5

1

0.5

▼ 2.8×10^8

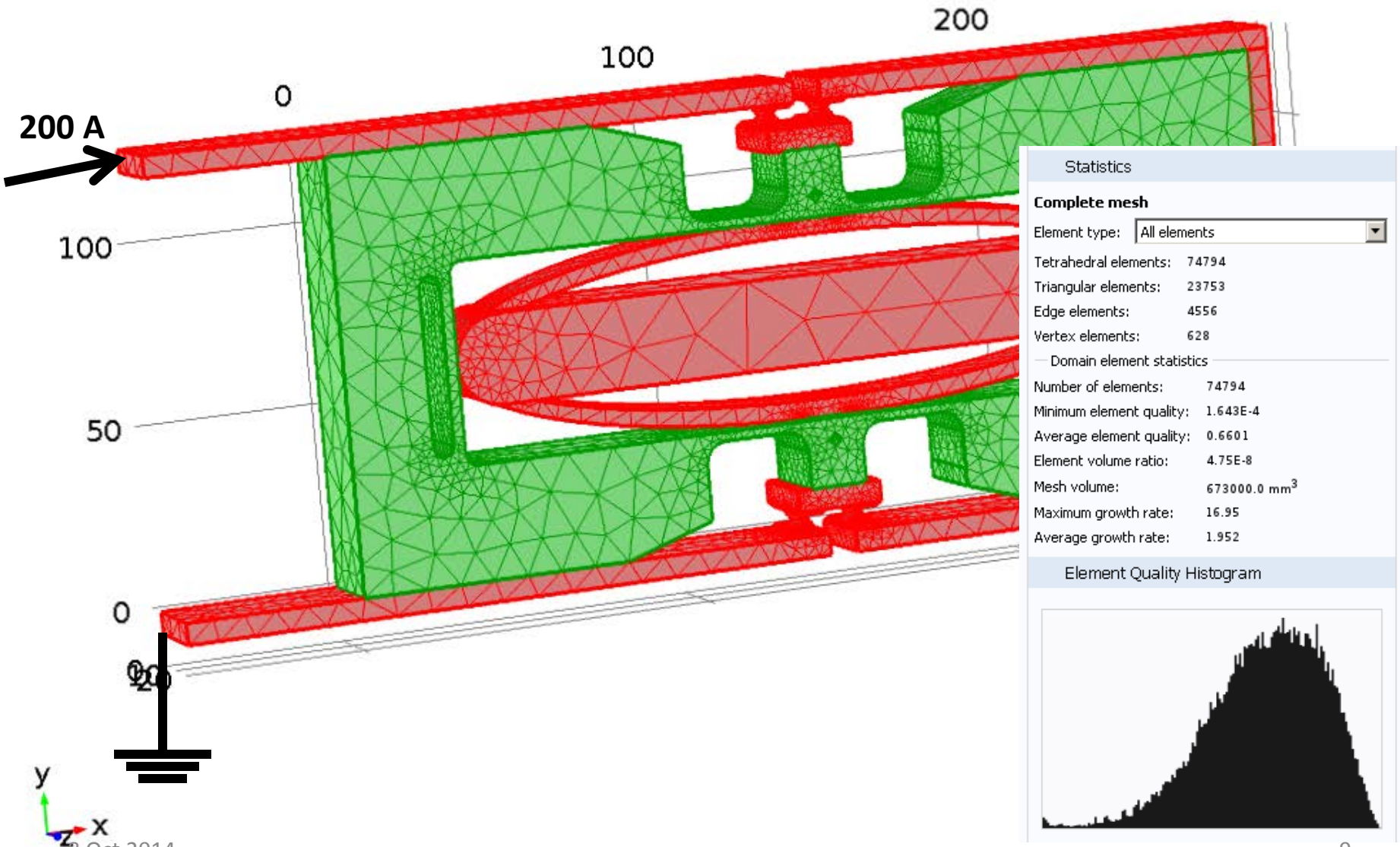
5

z
y x

8 Oct 2014

Mesh

- Terminated with ground at the end of the “current path”



Statistics

Complete mesh

Element type: All elements

Tetrahedral elements:	74794
Triangular elements:	23753
Edge elements:	4556
Vertex elements:	628

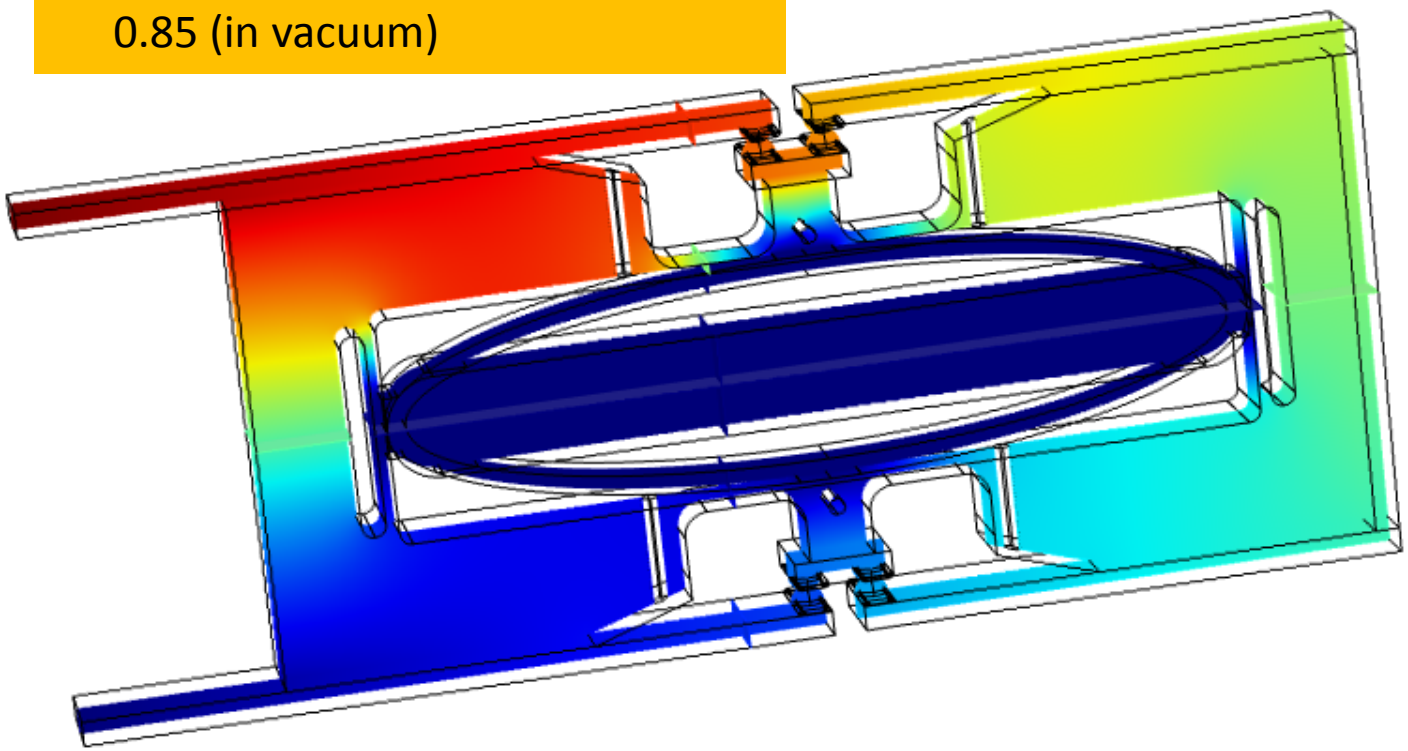
Domain element statistics

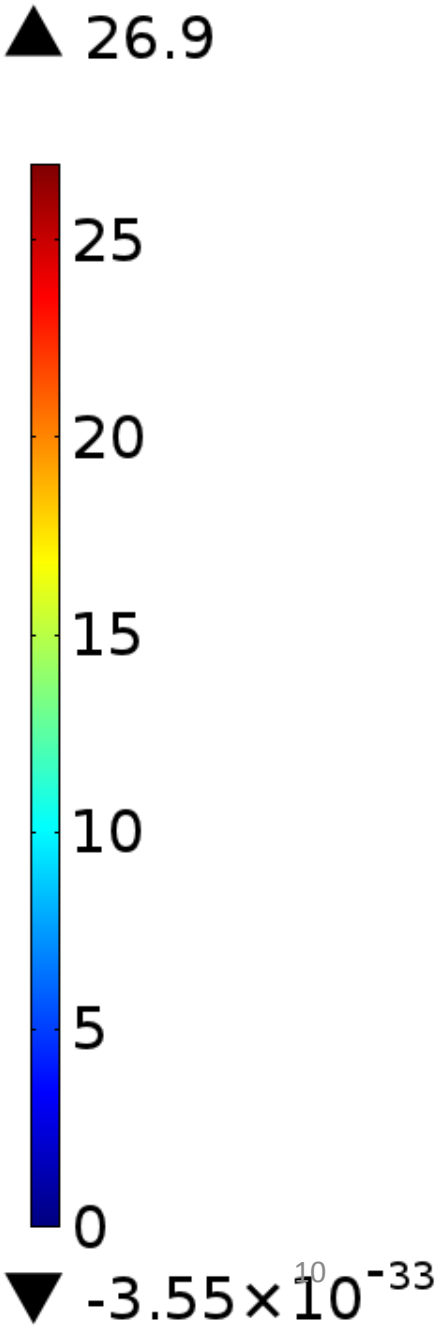
Number of elements:	74794
Minimum element quality:	1.643E-4
Average element quality:	0.6601
Element volume ratio:	4.75E-8
Mesh volume:	673000.0 mm^3
Maximum growth rate:	16.95
Average growth rate:	1.952

Element Quality Histogram

Time=0 s Multislice: Electric potential (mV)

- Current 200 A
- Contact resistance for solder joints and contact tabs (thin resistive layer)
- Surface to ambient emissivity 0.85 (in vacuum)

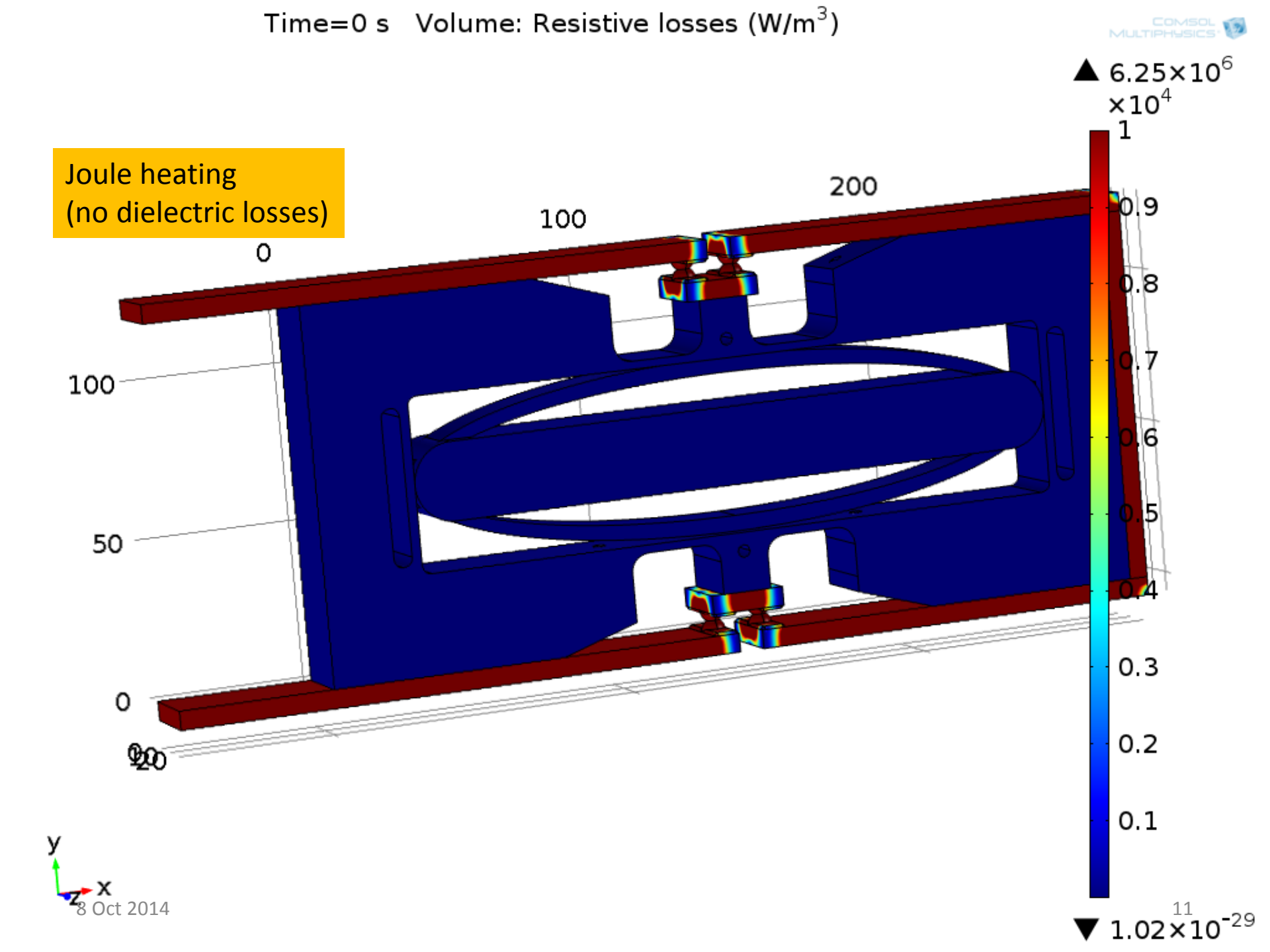


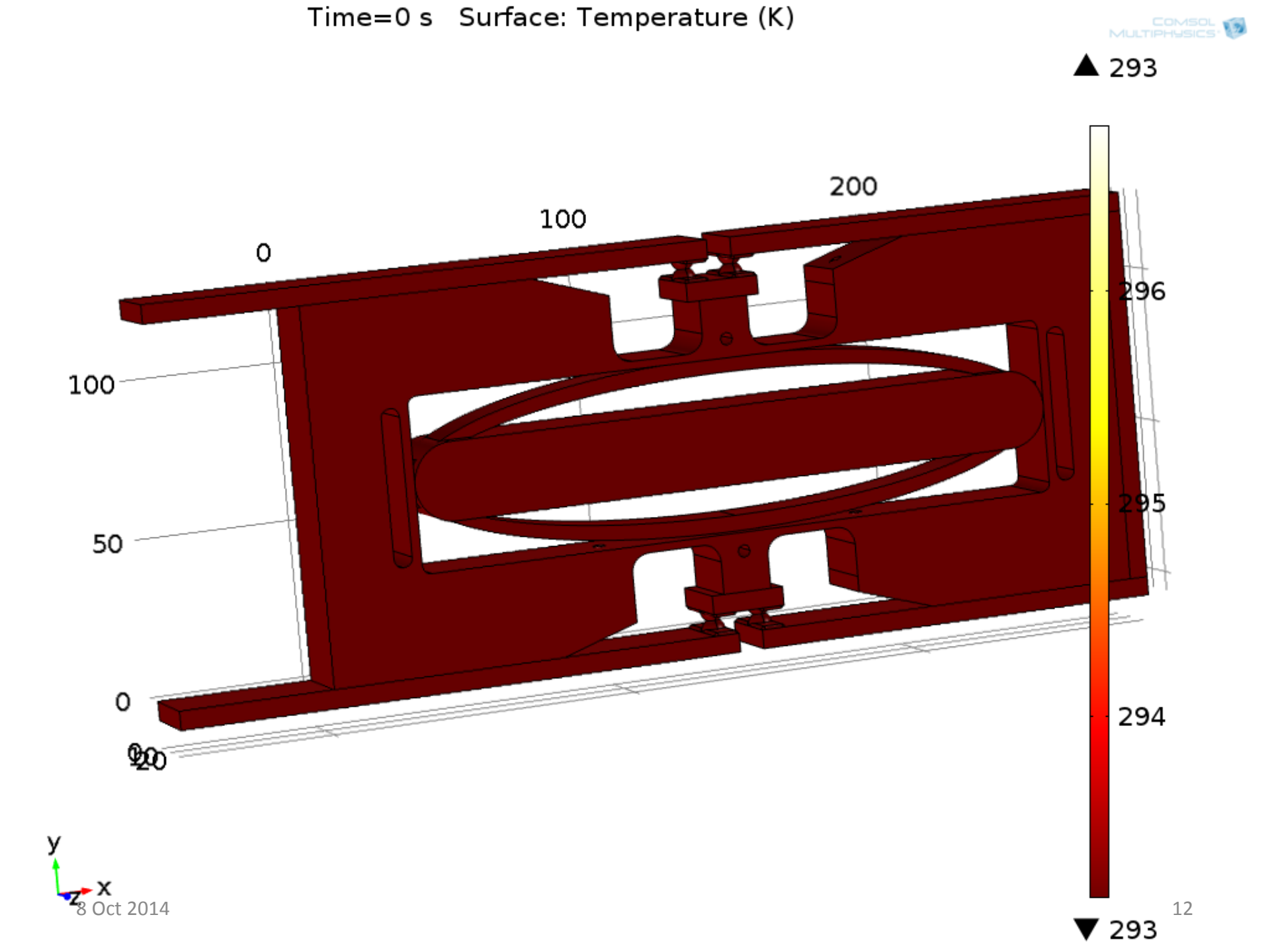


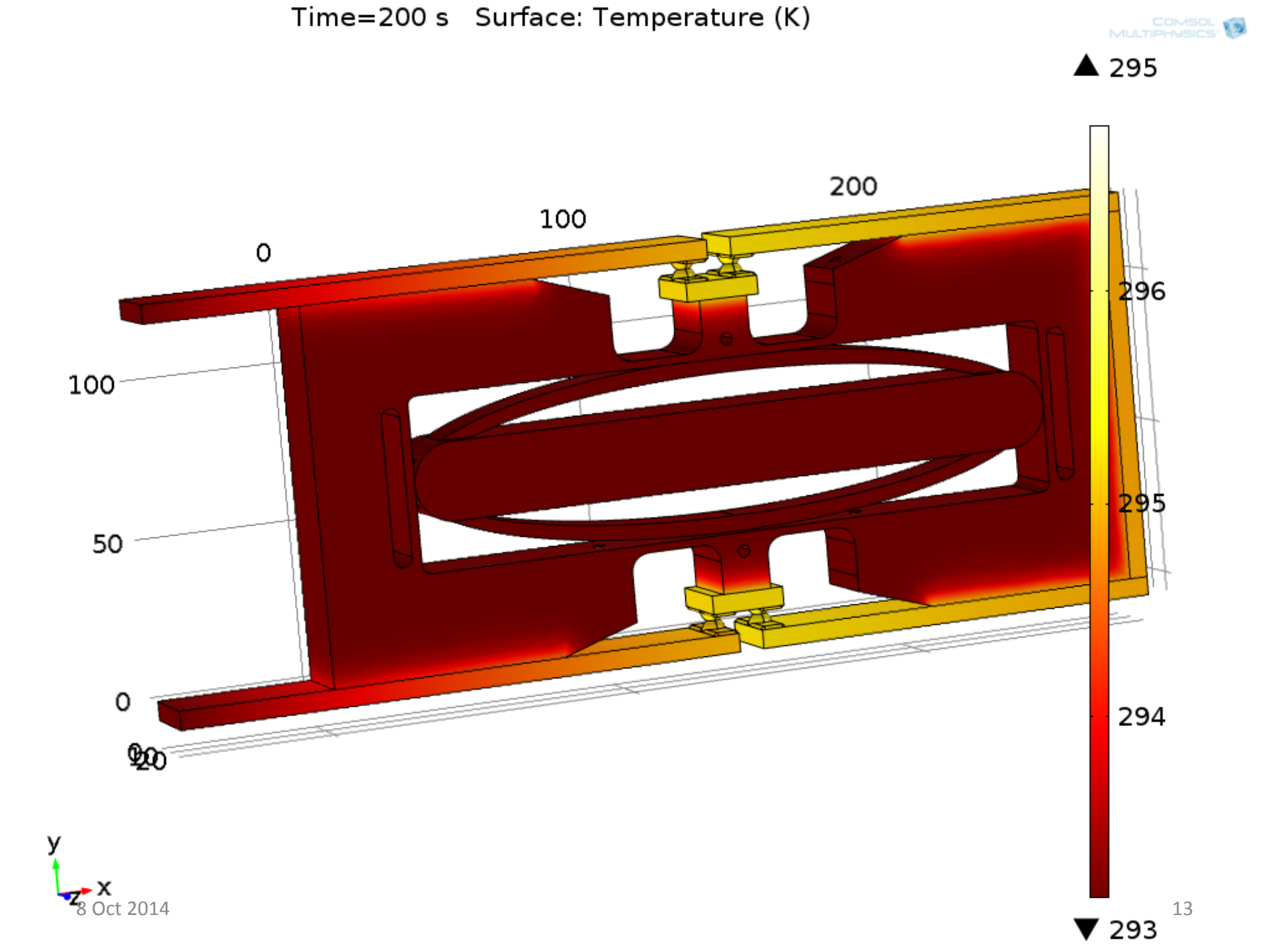
$$R = \frac{26.6\ \text{mV}}{200\ \text{A}} = 133\ \mu\Omega$$

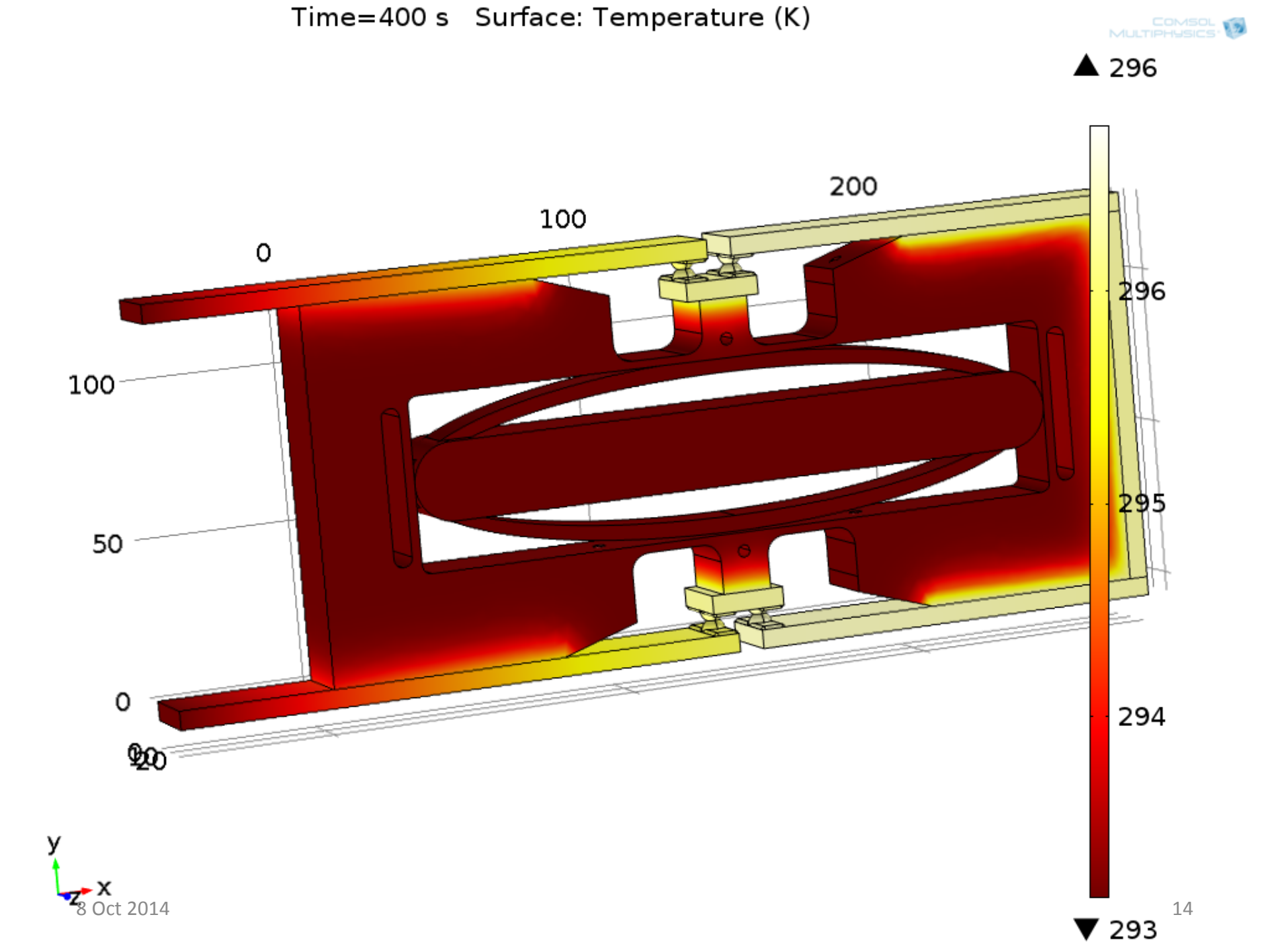
$$P_{tot} = 5.32\ \text{W}$$

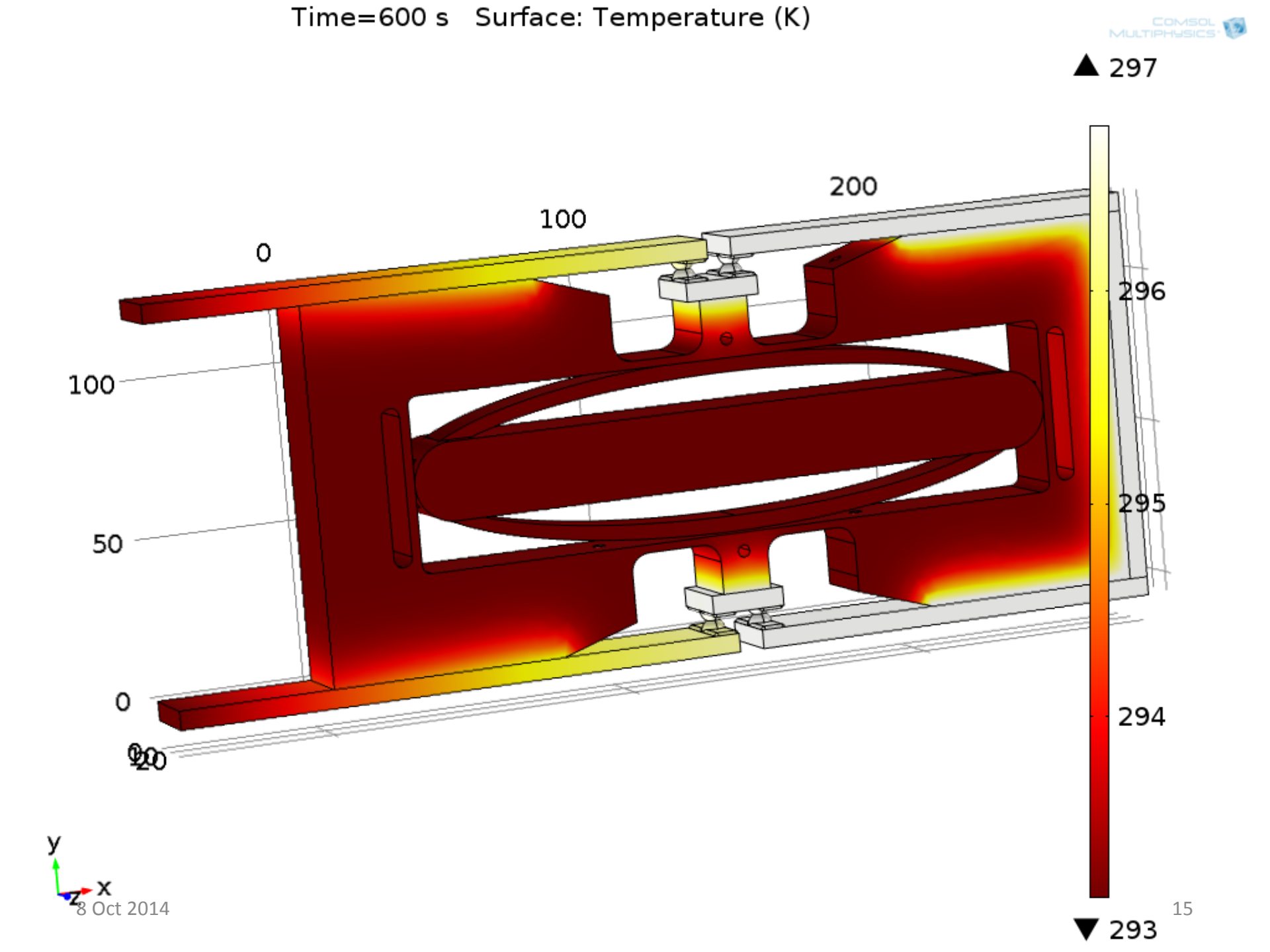
Measured: ~7 W

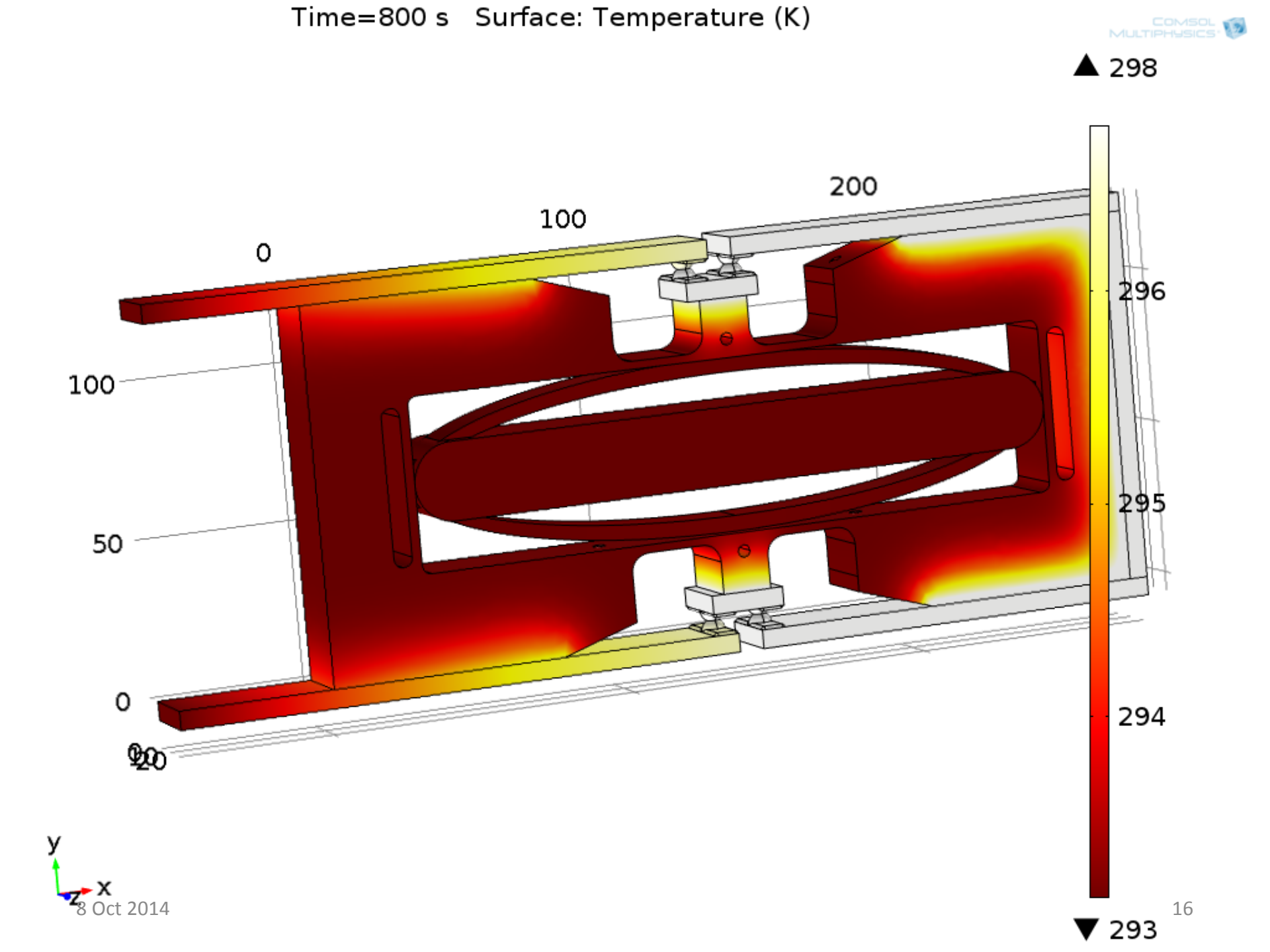

Time=0 s Volume: Resistive losses (W/m3)
Joule heating
(no dielectric losses)
▲ 6.25×10^6
×10^4
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
▼ 1.02×10^-29
0
100
200
0
50
100
y
x
z

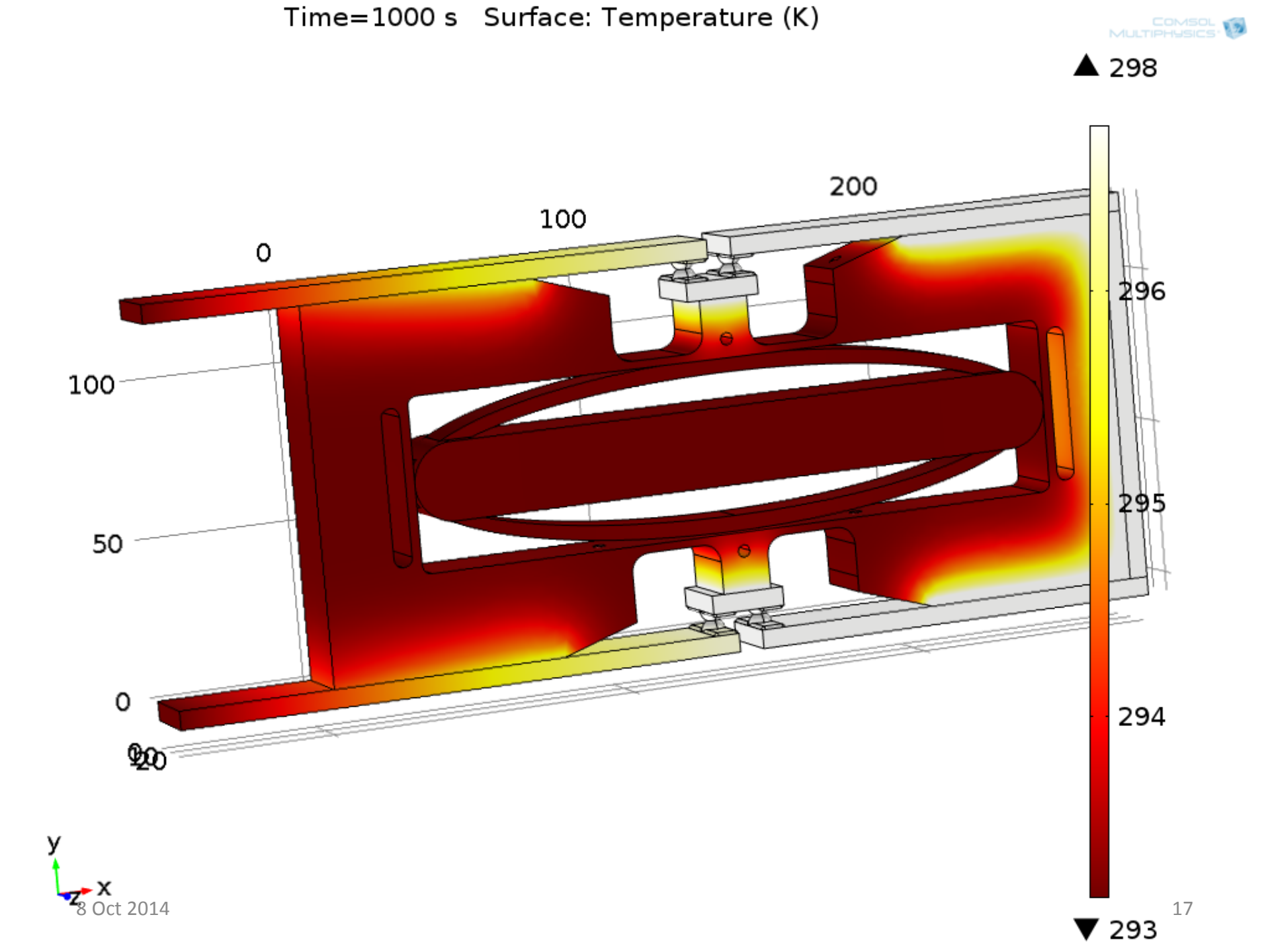

Time=0 s Surface: Temperature (K)
293
296
295
294
293
0
100
200
100
50
0
y
x
z

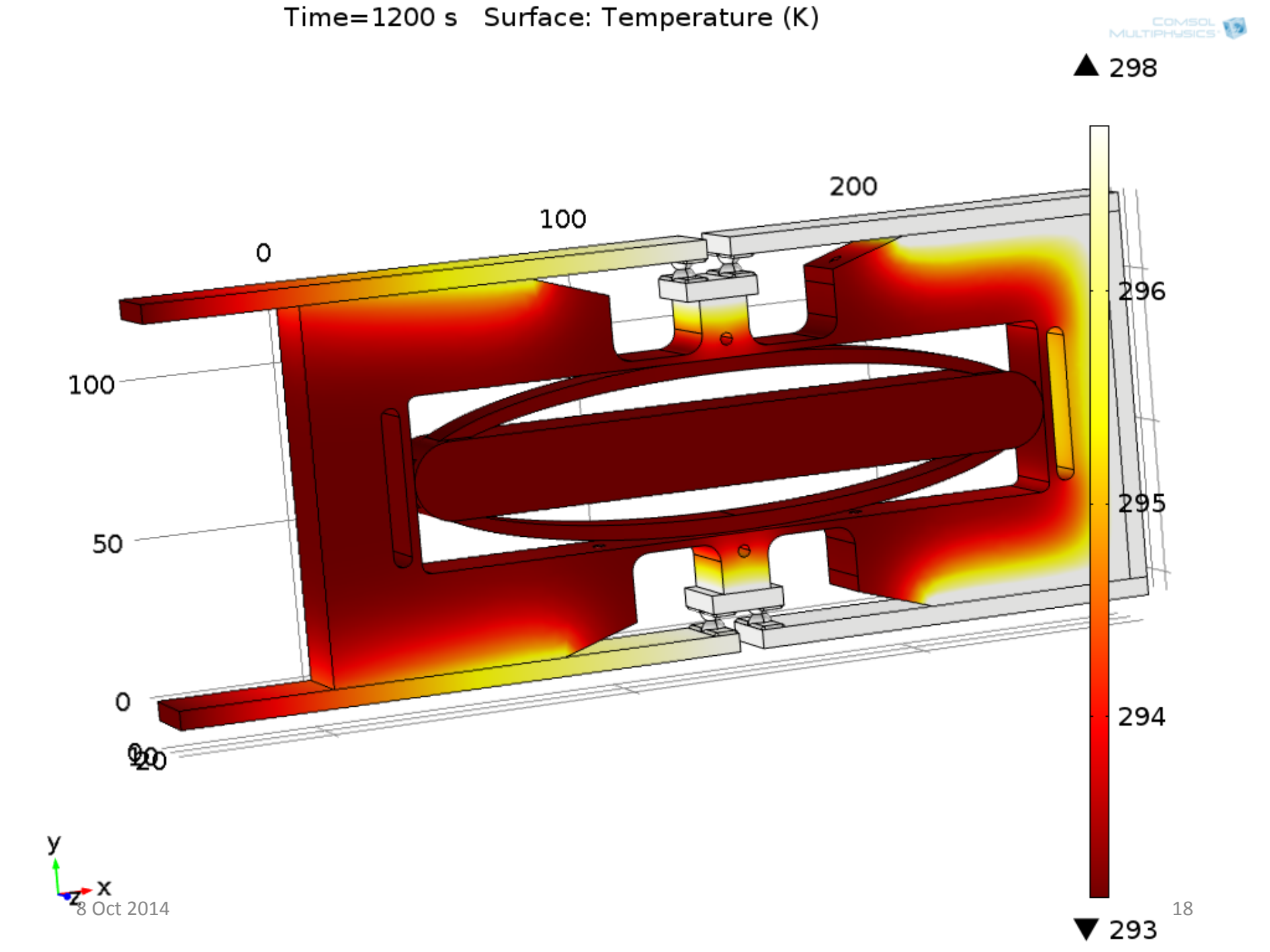

Time=200 s Surface: Temperature (K)
▲ 295
296
295
294
▼ 293
0
100
200
100
50
0
y
x
z


Time=400 s Surface: Temperature (K)
▲ 296
296
295
294
▼ 293
0
100
200
100
50
0
y
x
z

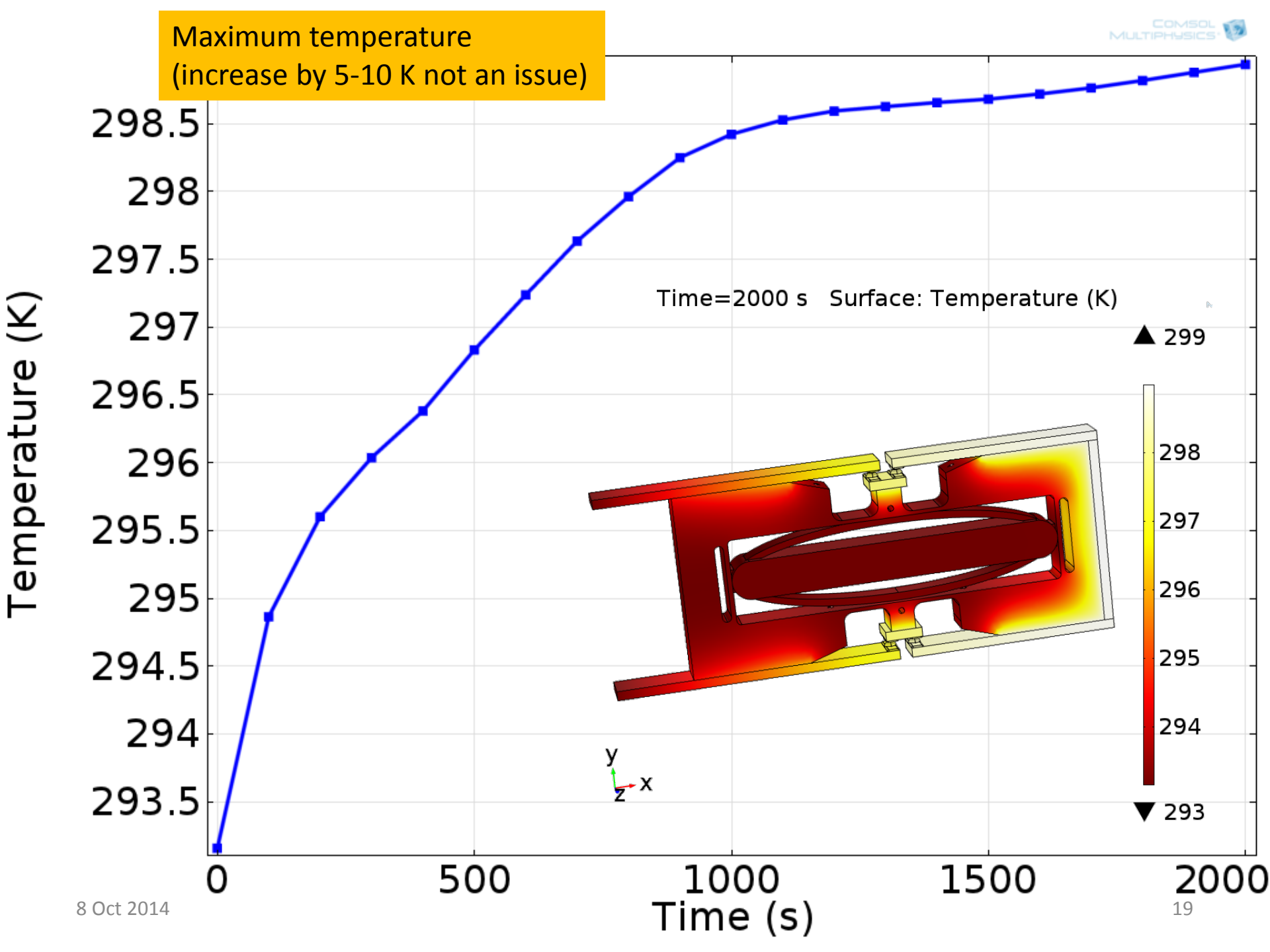

Time=600 s Surface: Temperature (K)
▲ 297
296
295
294
▼ 293
0
100
200
100
50
0
y
x
z

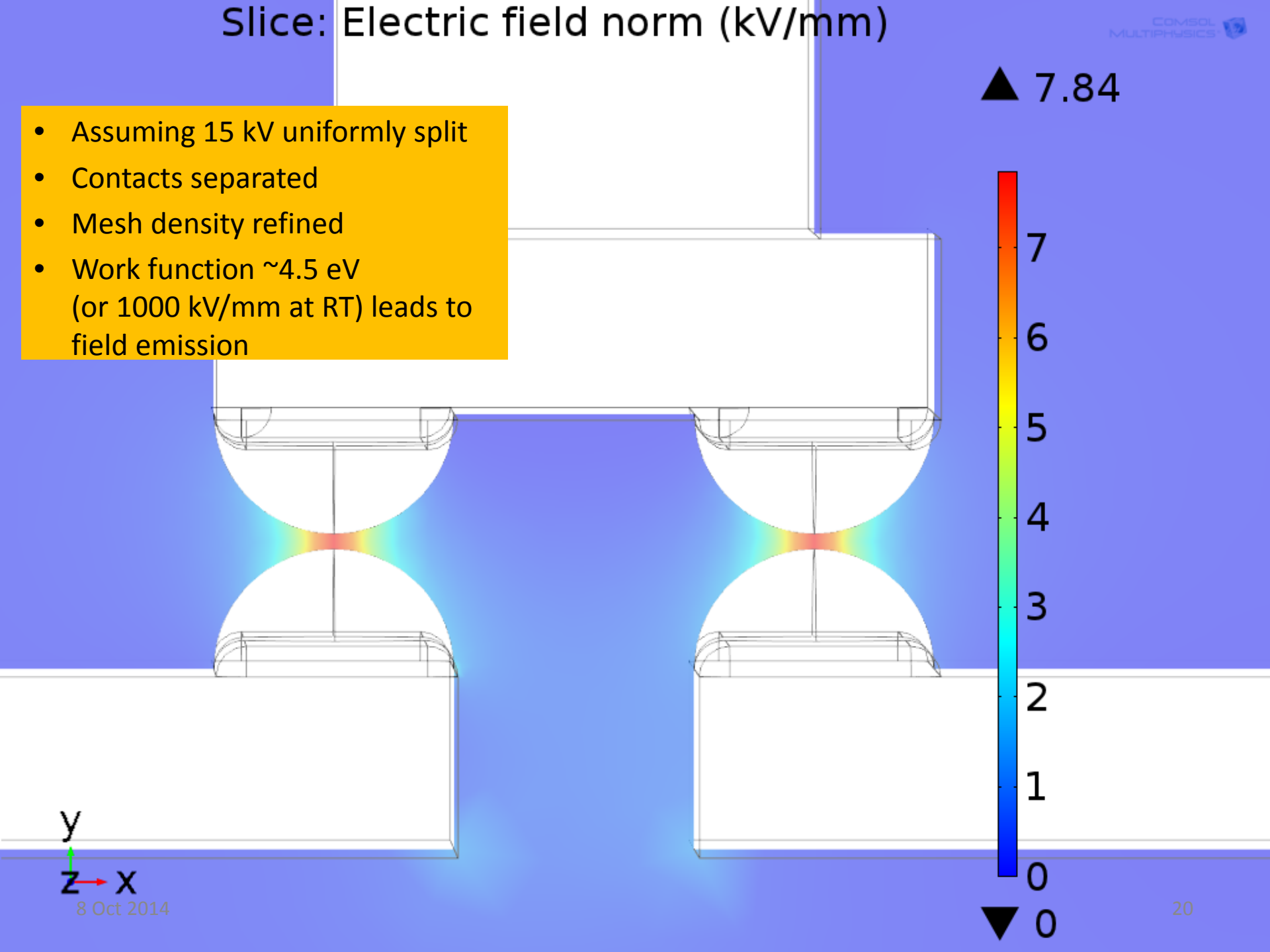

Time=800 s Surface: Temperature (K)
▲ 298
296
295
294
▼ 293
0
100
200
100
50
0
y
x
z


Time=1000 s Surface: Temperature (K)
298
296
295
294
293
0
100
200
100
50
0
y
x
z


Time=1200 s Surface: Temperature (K)
▲ 298
296
295
294
▼ 293
0
100
200
100
50
0
y
x
z

Maximum temperature
(increase by 5-10 K not an issue)





- Assuming 15 kV uniformly split
- Contacts separated
- Mesh density refined
- Work function ~4.5 eV (or 1000 kV/mm at RT) leads to field emission

Conclusion

- **Finite element analysis proved to be useful for**
  - Design of insulator frame (narrow regions)
  - Dimensions of conductors
  - Material selection (especially contact tabs)

- **Next steps**
  - Implement dynamic model (contact bouncing?)
  - Implement more accurate, multiphysical contact model
  - Validate model by measuring strain and temperature increase
  - Finish demonstrator unit

Acknowledgment

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