COMSOL CONFERENCE
2018 LAUSANNE

streamer®
keeping the light

FINITE ELEMENT SIMULATION OF IMPULSE ARC DISCHARGE

Alexander Chusov

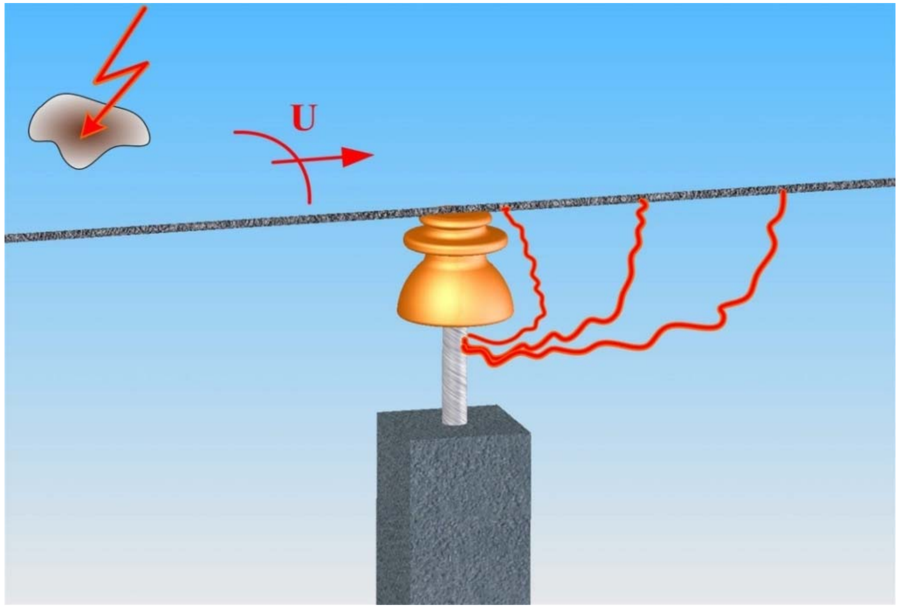
OUTLINE:

- **Problem statement**
- **Description of the physical model**
- **Numerical implementation**
- **Validation**
- **Preliminary results**
- **Conclusions**

Lightning protection of overhead lines

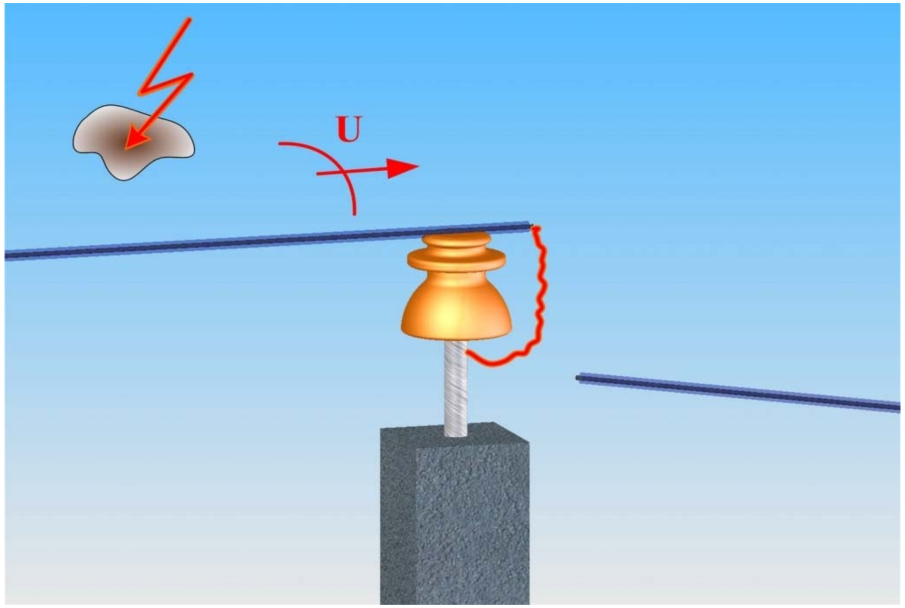
Lightning protection of overhead lines

Lightning protection of overhead lines



A line with bare conductor

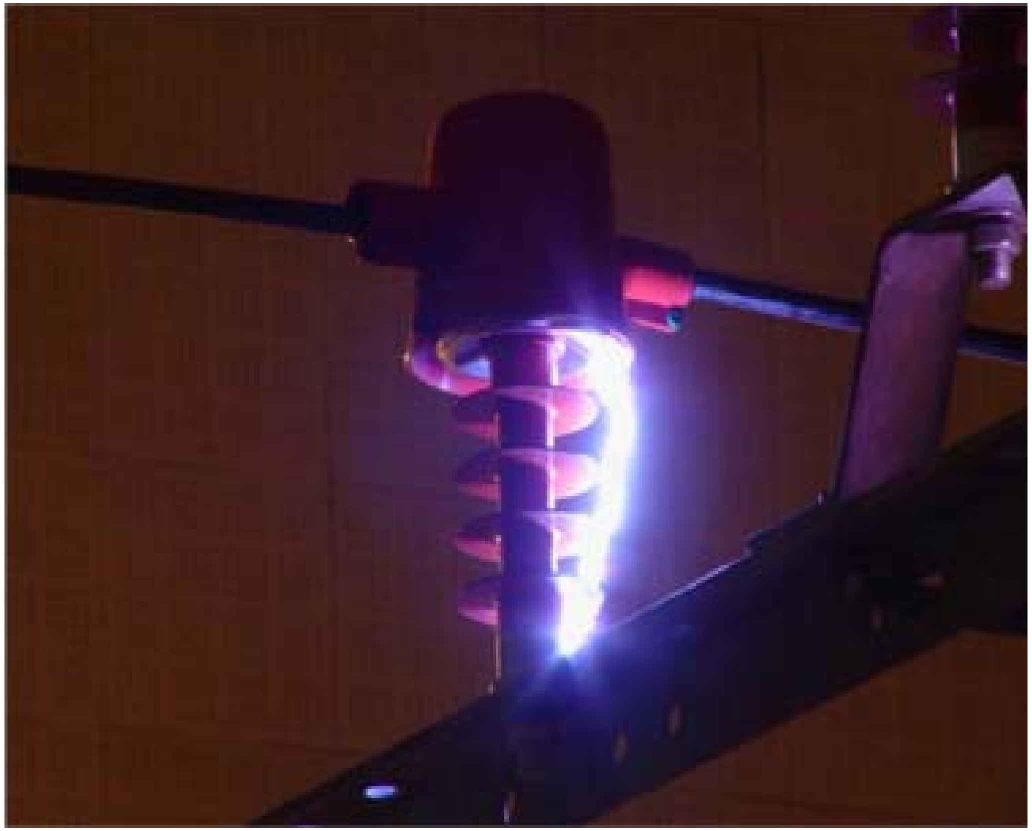
Arc is moving



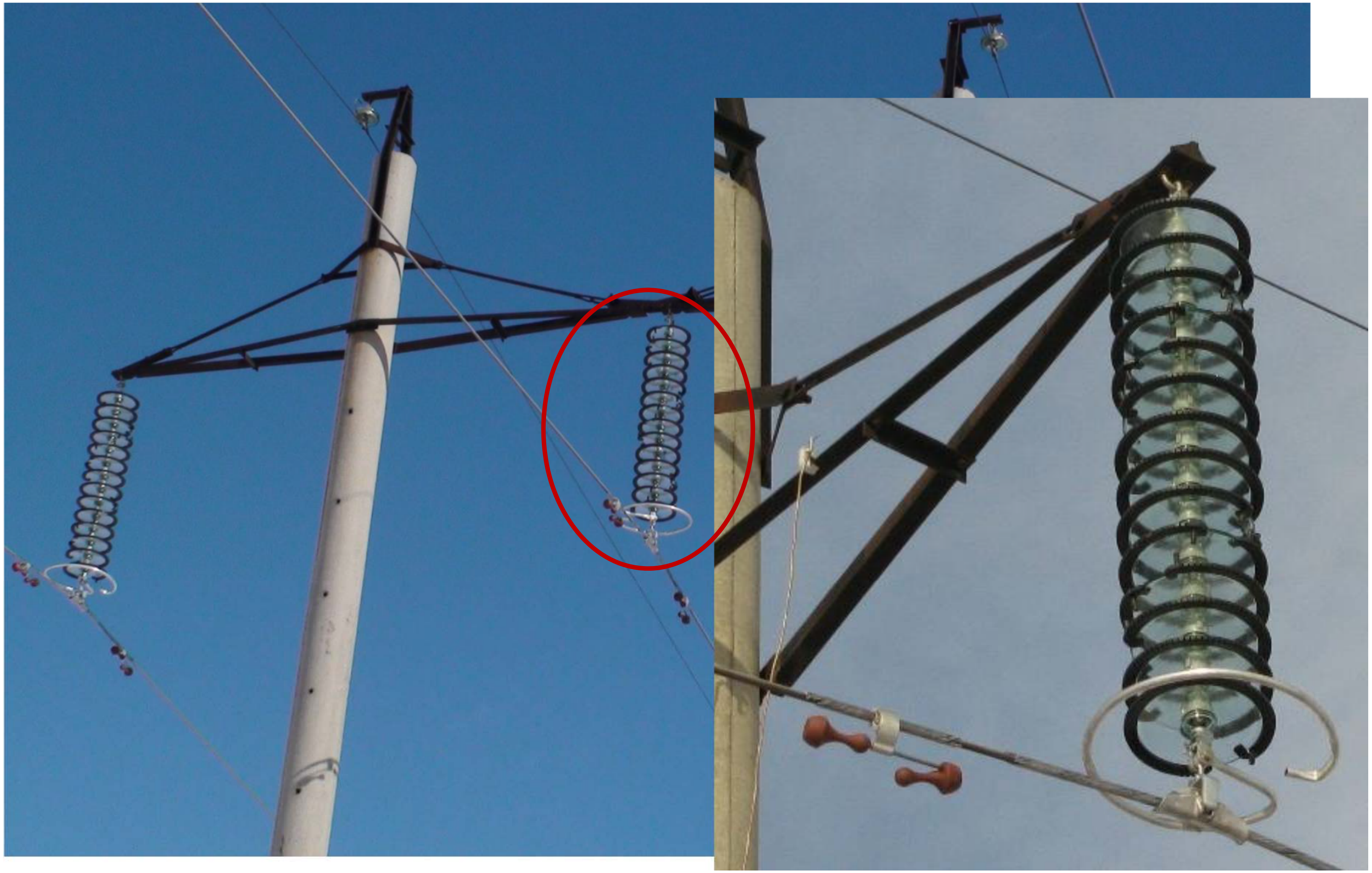
A line with covered conductor

Conductor burn down

Insulator flashover



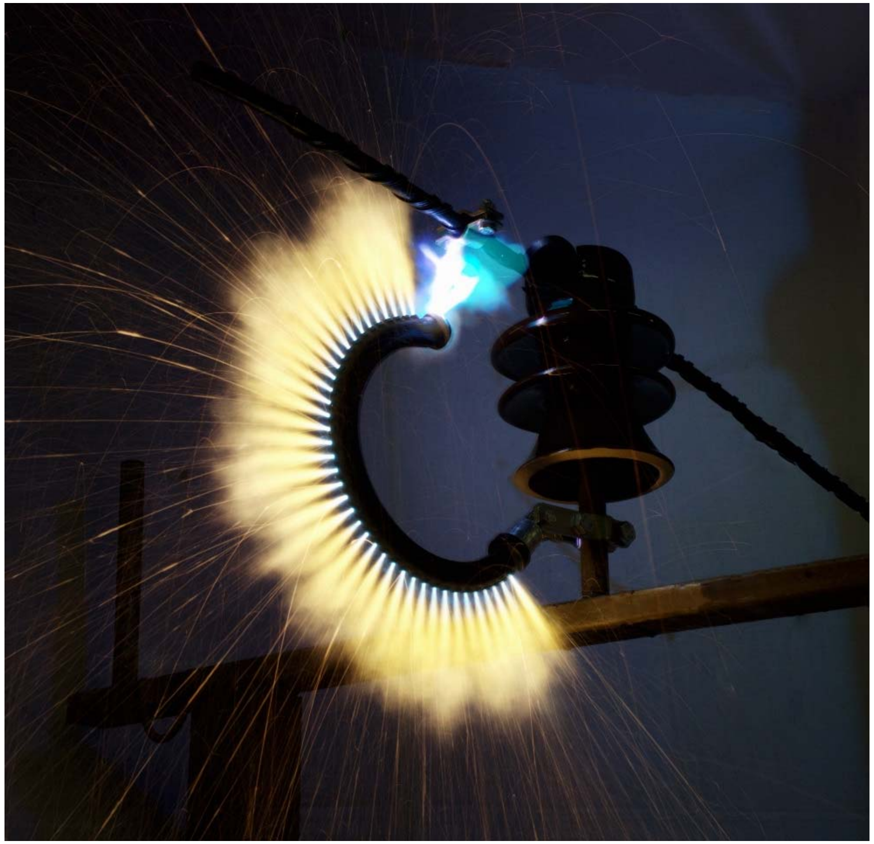
Lightning protection of overhead lines



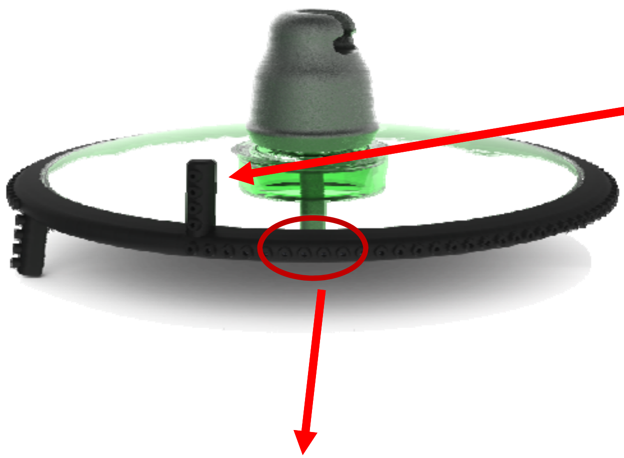
MULTI-CHAMBER ARRESTERS

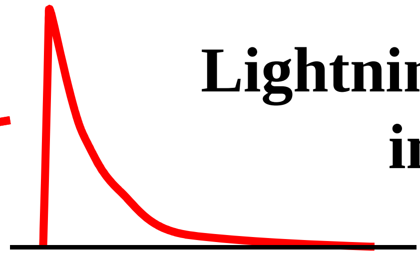
Lightning protection of overhead power lines up to 35 kV

20 kV

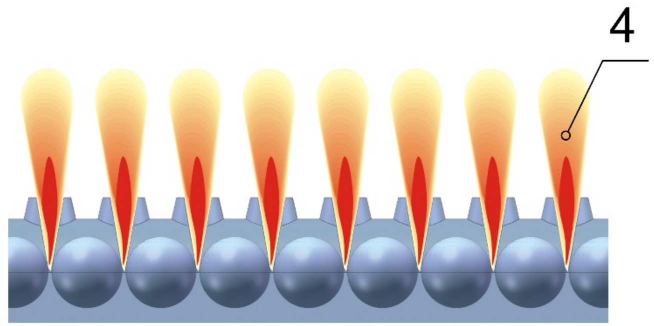


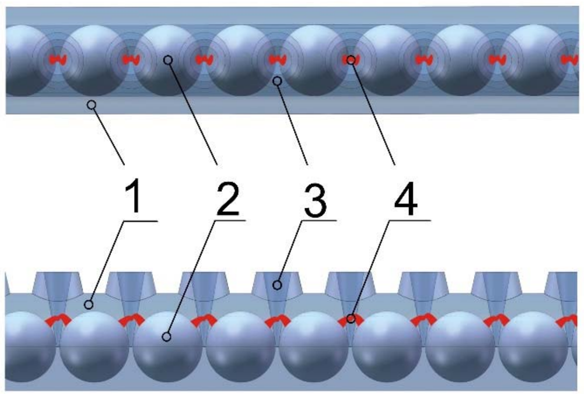
35 kV

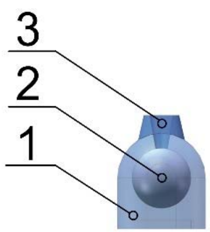


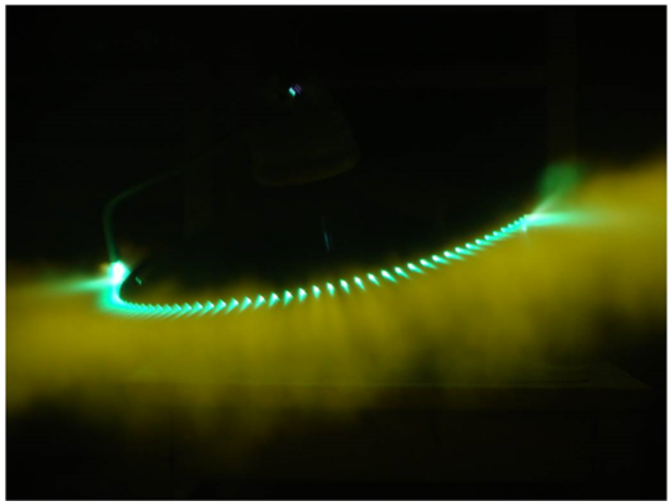


Lightning overvoltage imposed









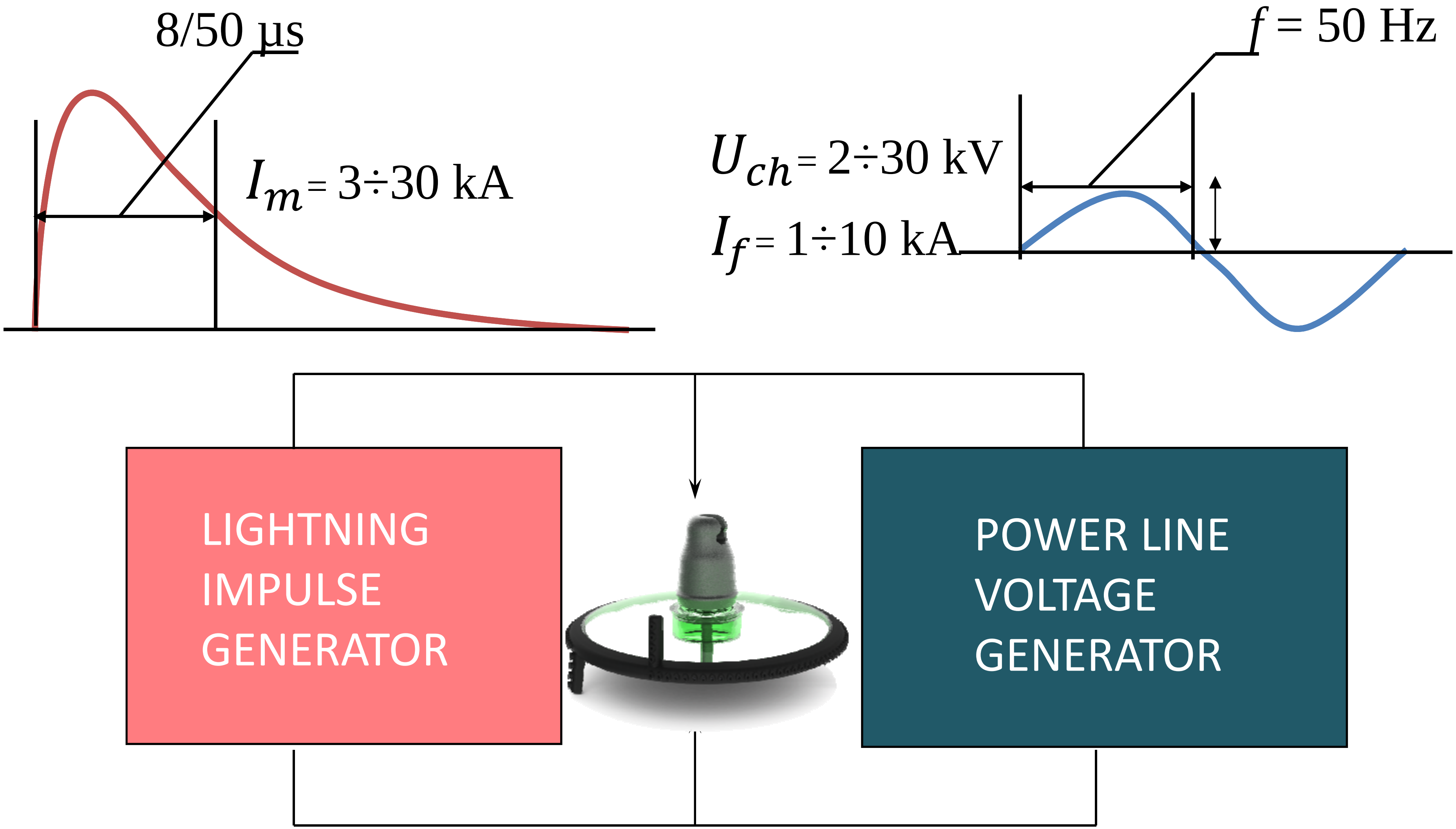
1 – silicone rubber length;

2 – intermediate electrodes;

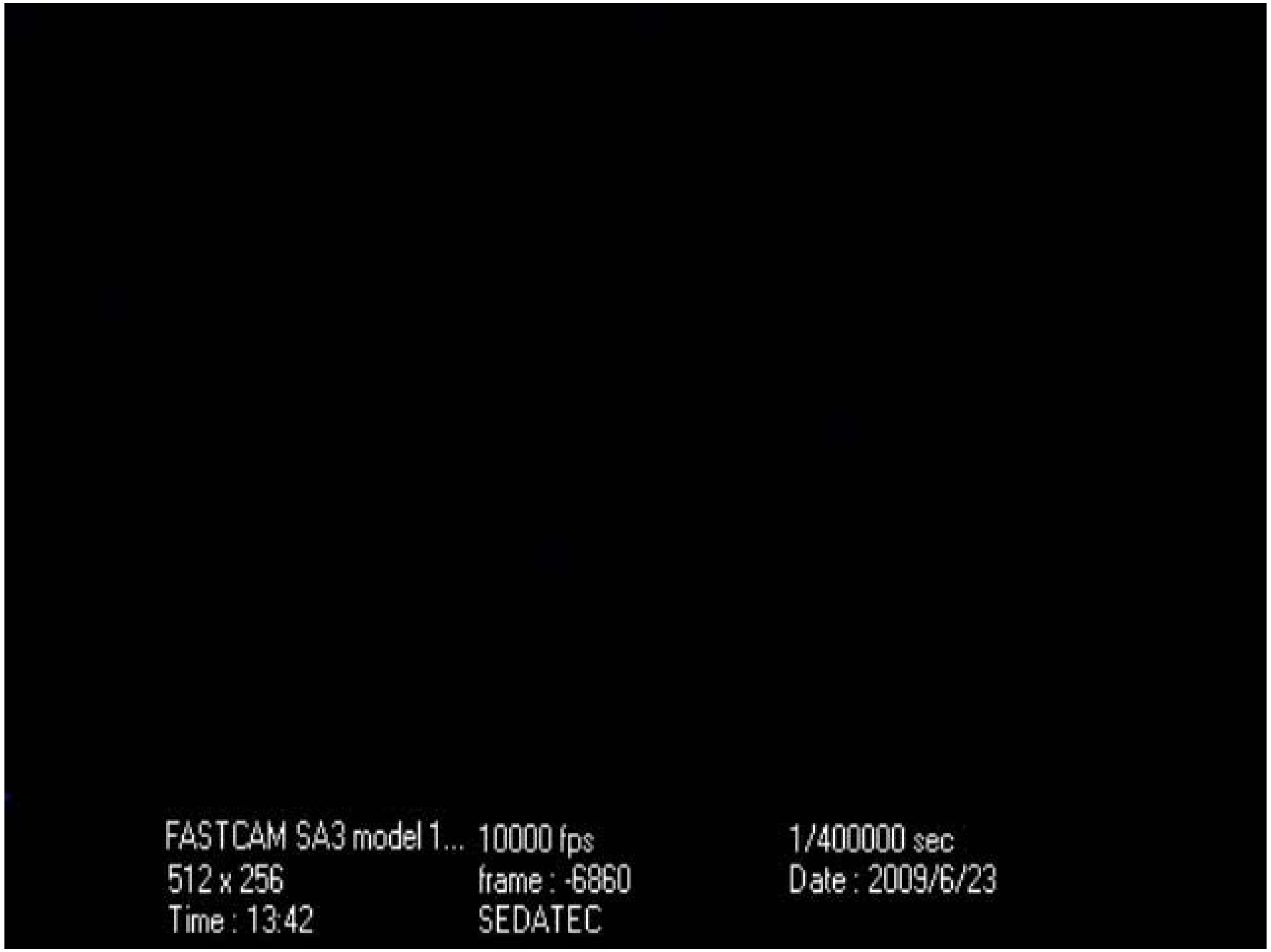
3 – arc quenching chamber;

4 – discharge channel.

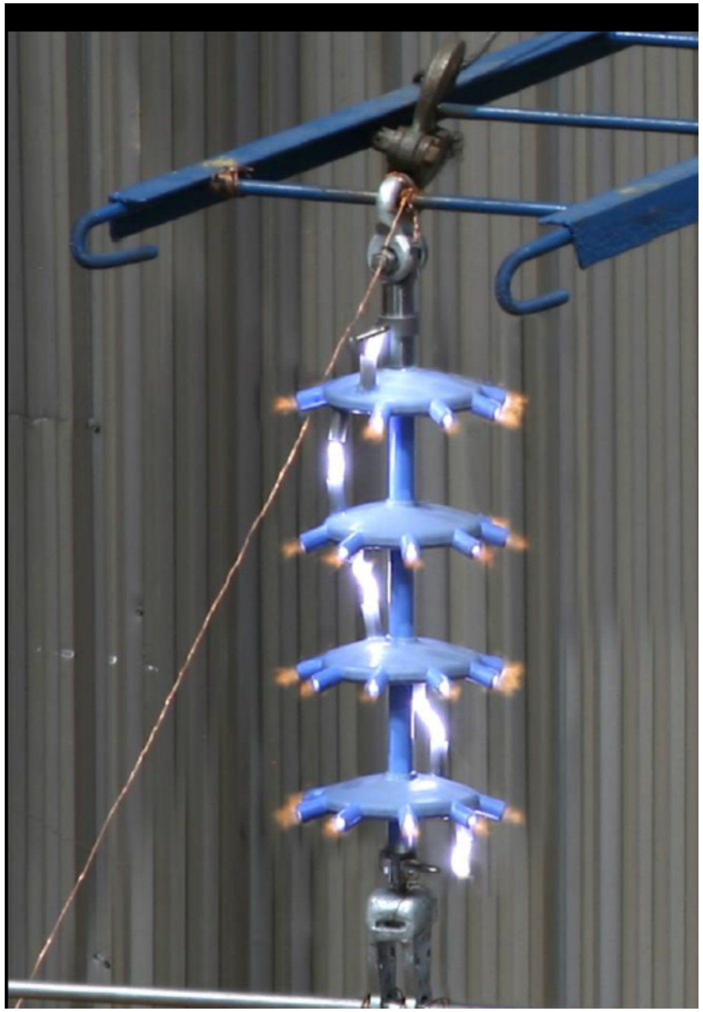
QUENCHING TEST SCHEME

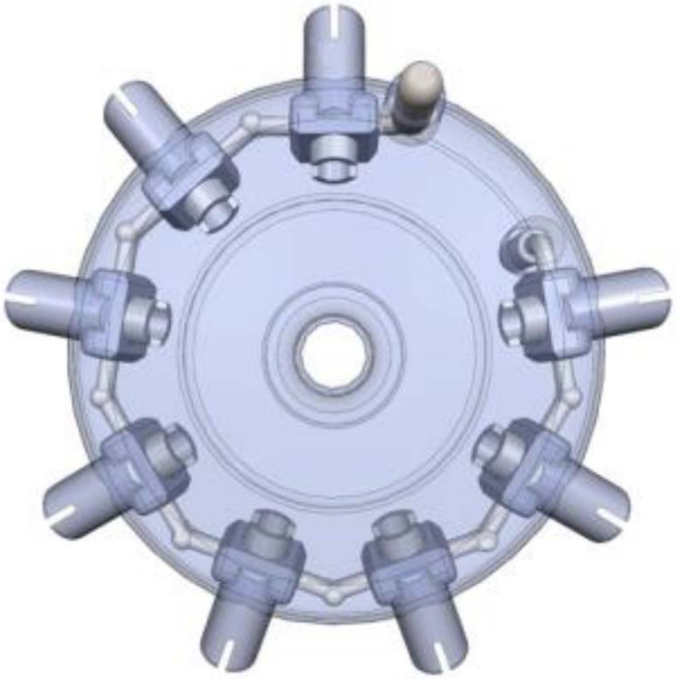


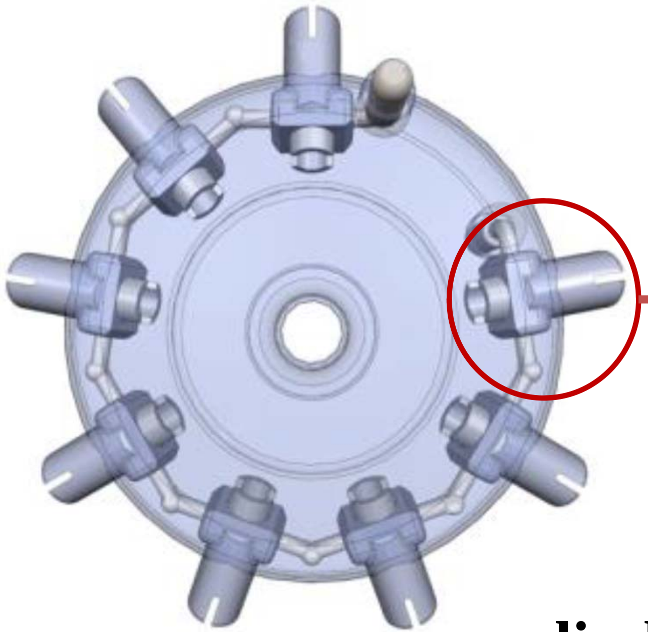
MULTI-CHAMBER ARRESTERS

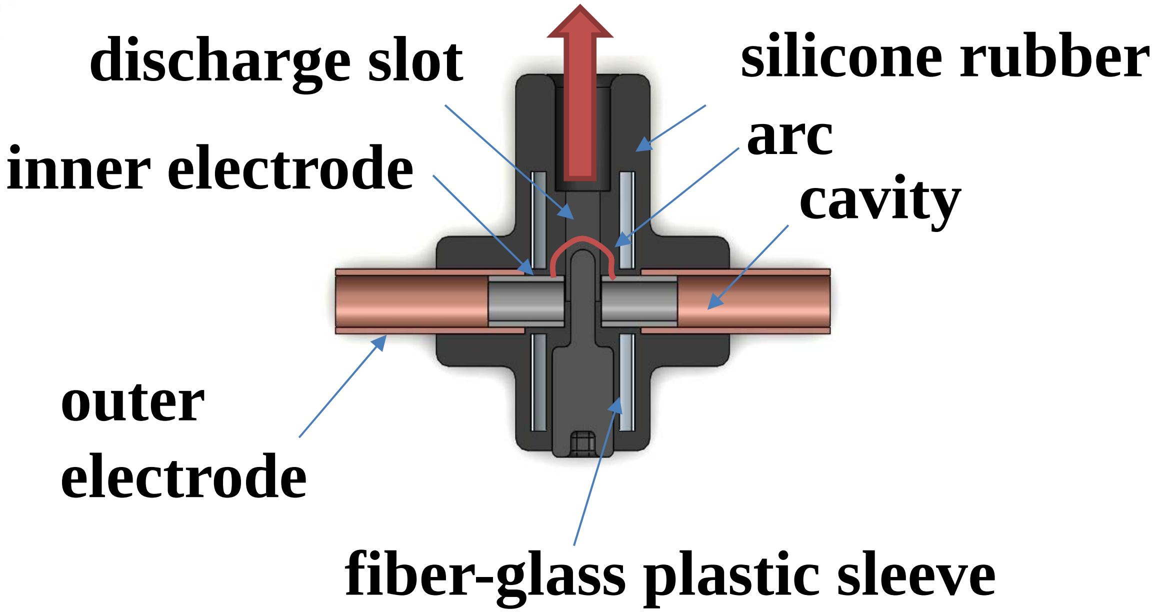


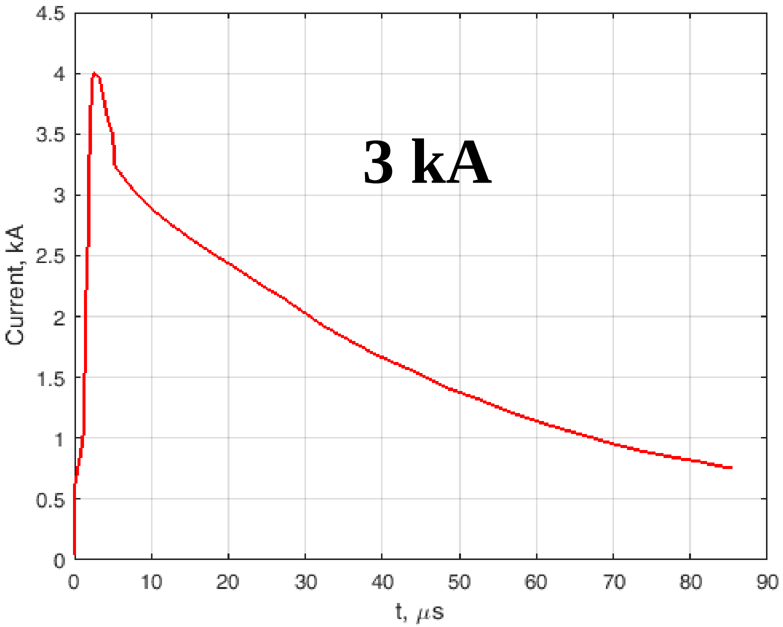
MULTI-CHAMBER ARRESTERS

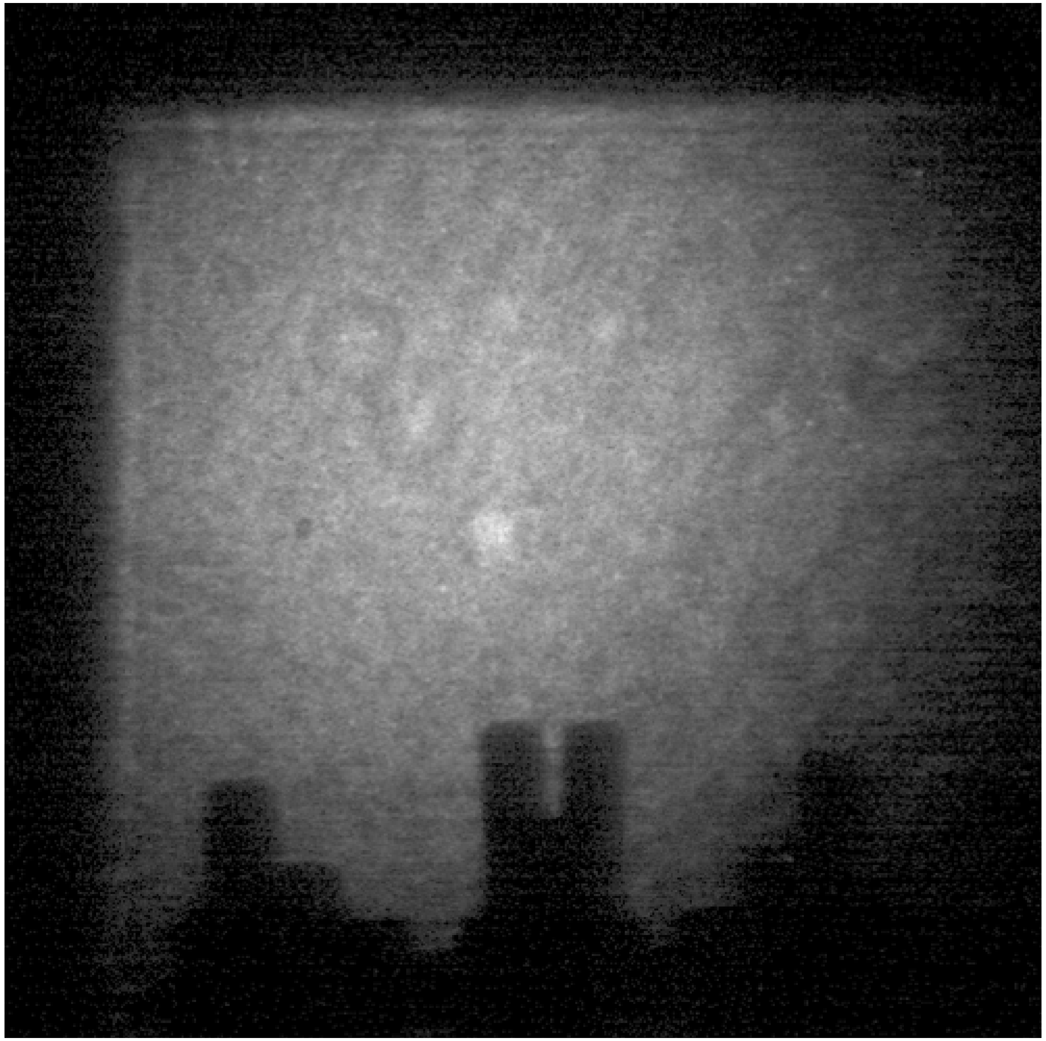


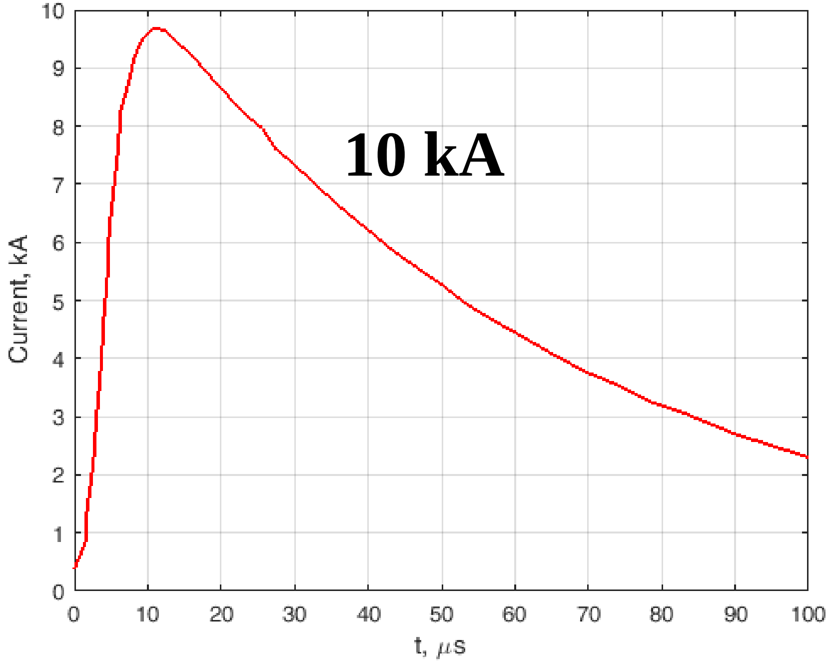


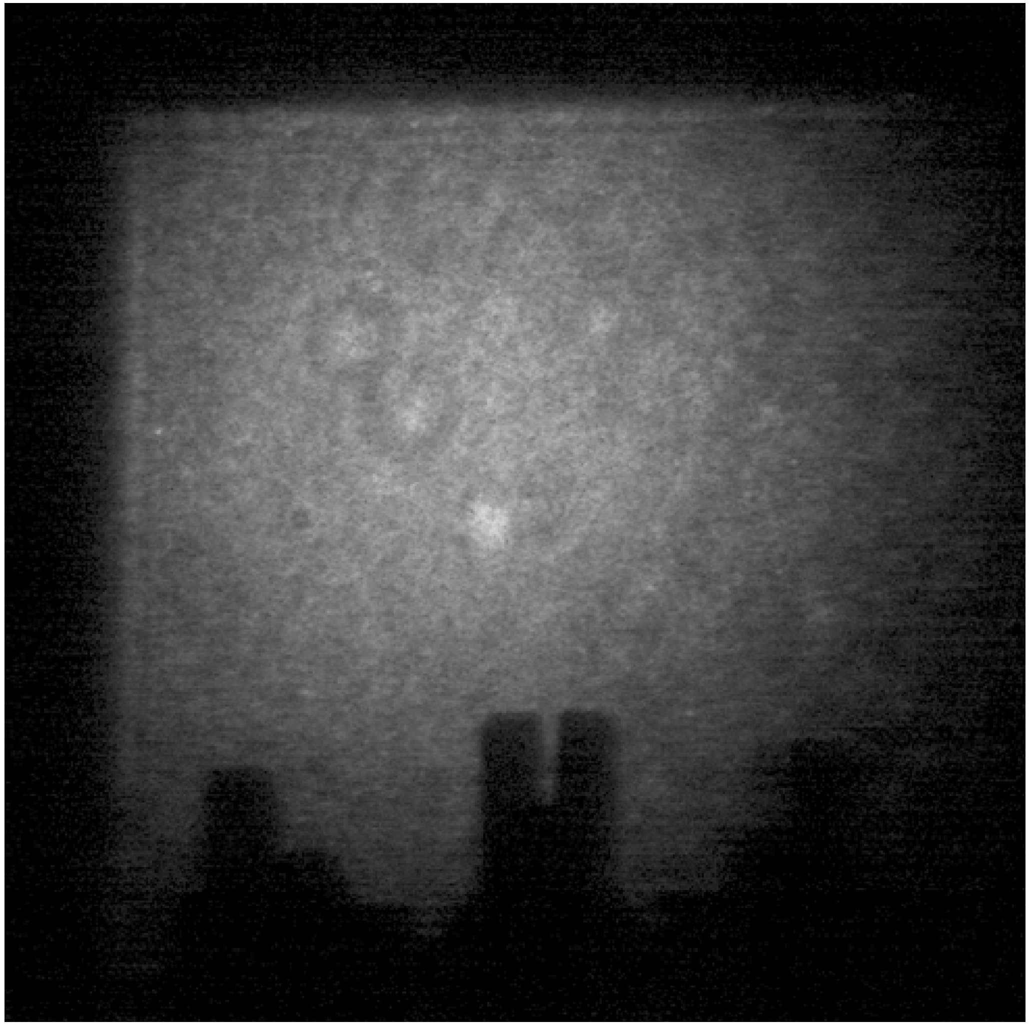


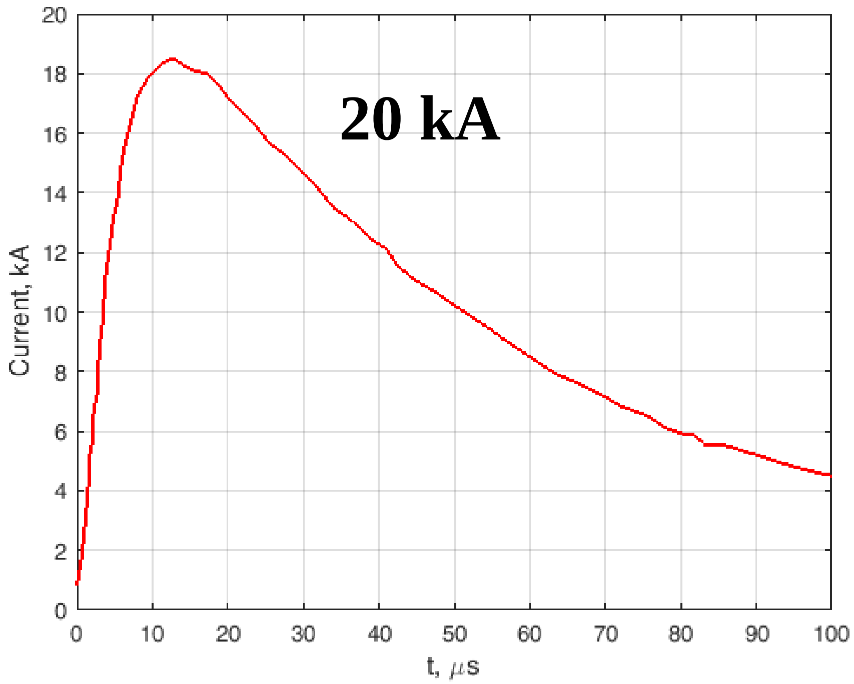

discharge slot
silicone rubber
inner electrode
arc
cavity
outer
electrode
fiber-glass plastic sleeve


3 kA
Current, kA
t, μs
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
10
20
30
40
50
60
70
80
90




10 kA
Current, kA
t, μs
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100




20 kA
Current, kA
t, μs
0
2
4
6
8
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12
14
16
18
20
0
10
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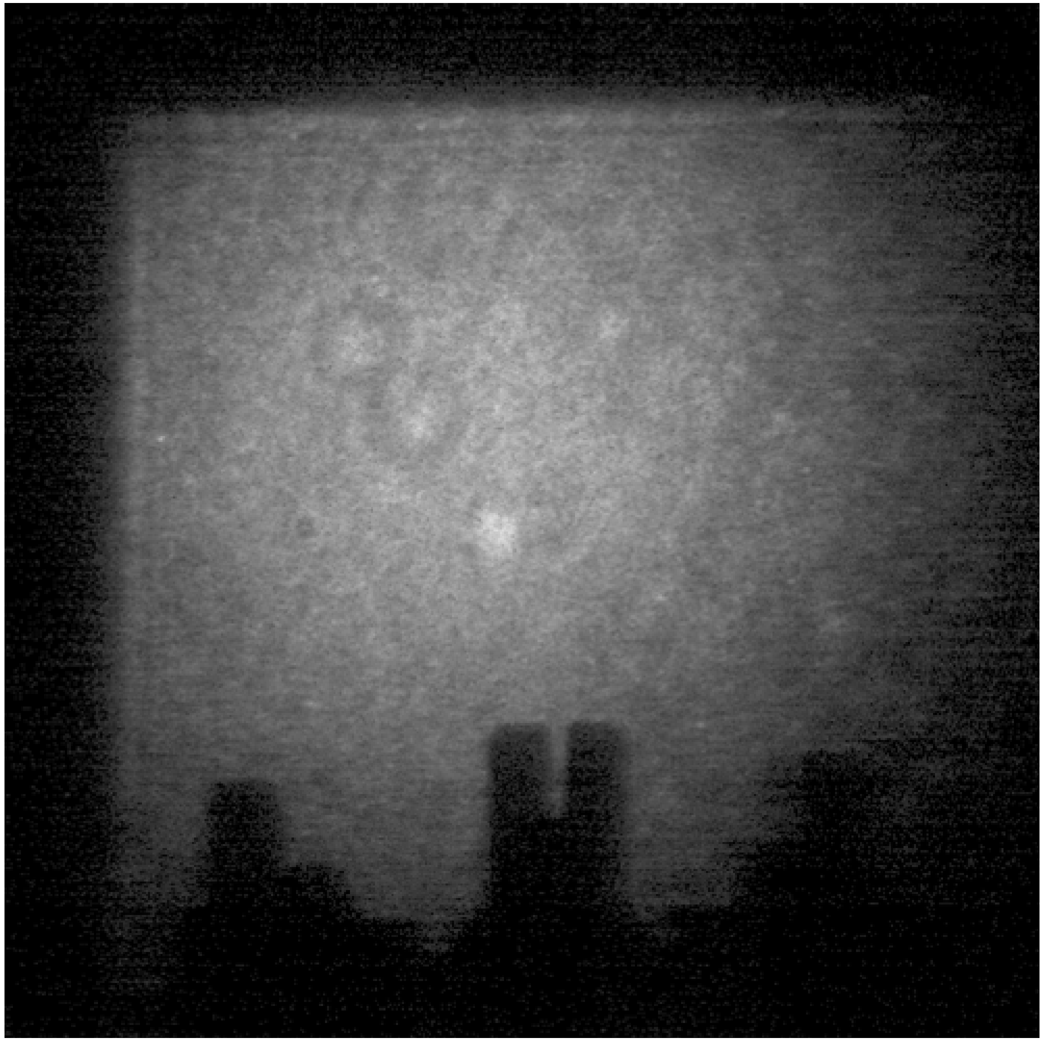
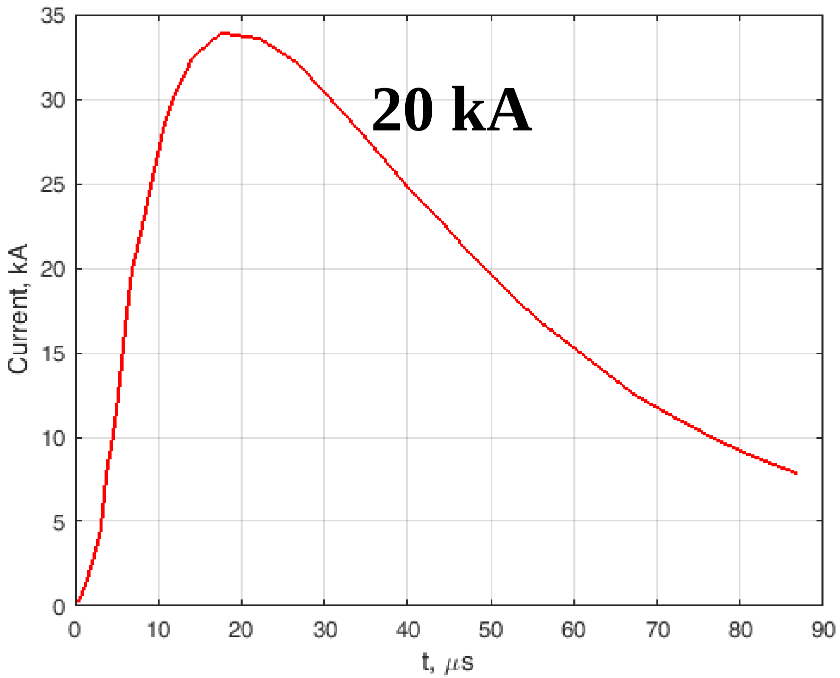
60
70
80
90
100




20 kA
Current, kA
t, µs
35
30
25
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15
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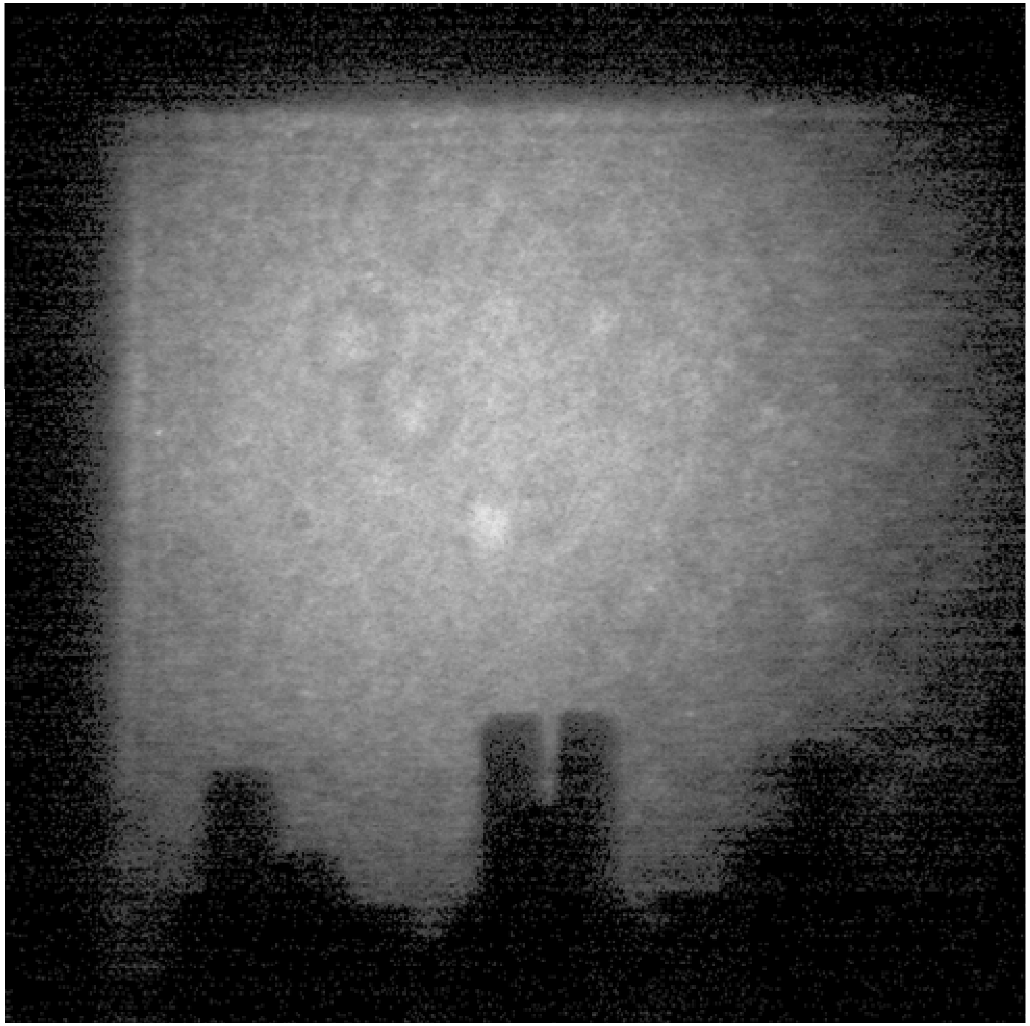
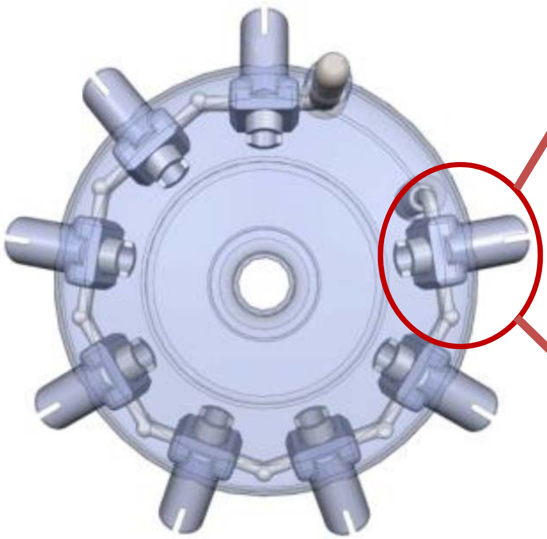
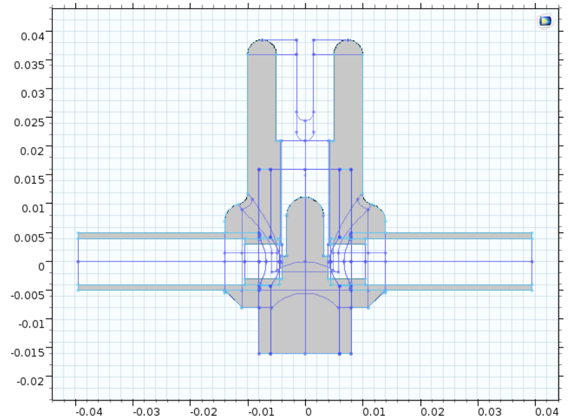
5
0
0
10
20
30
40
50
60
70
80
90



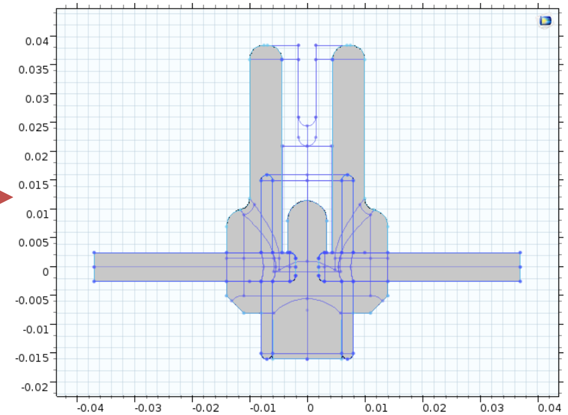


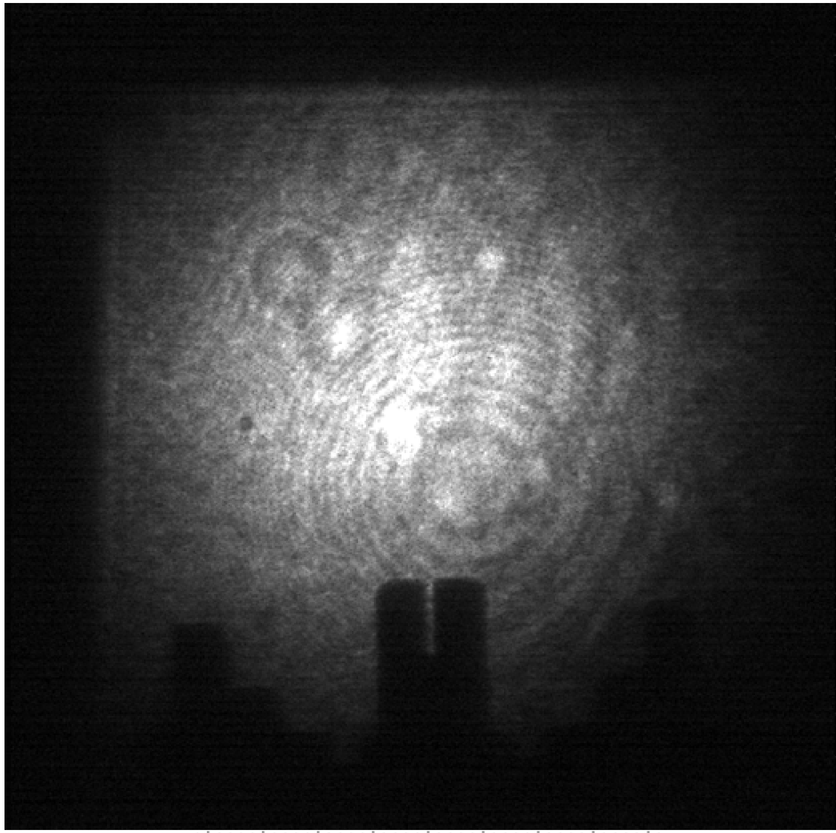
Type #1

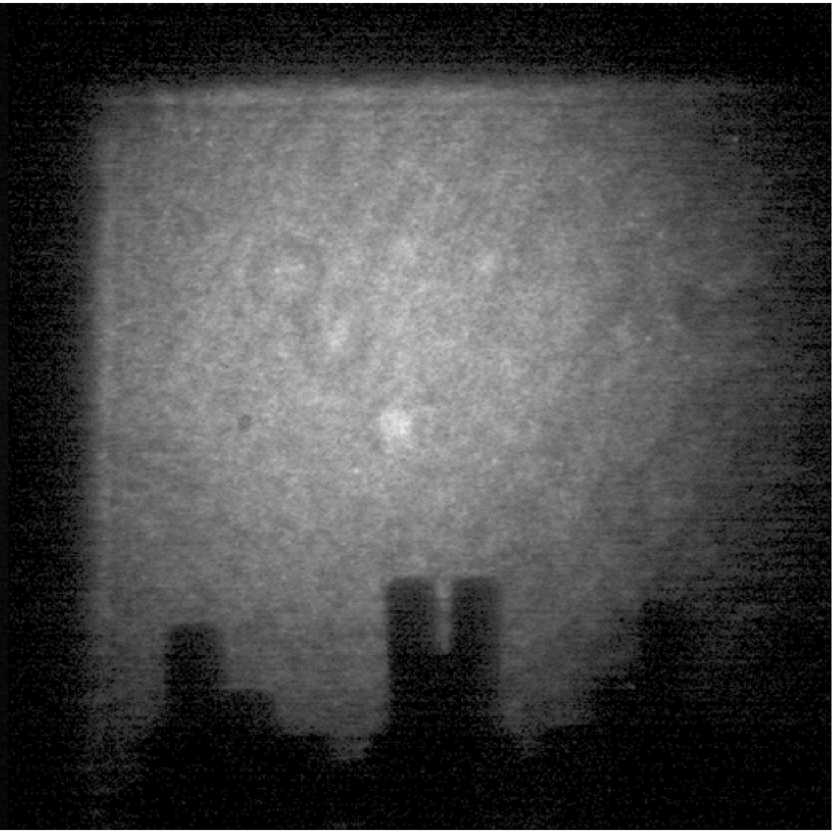


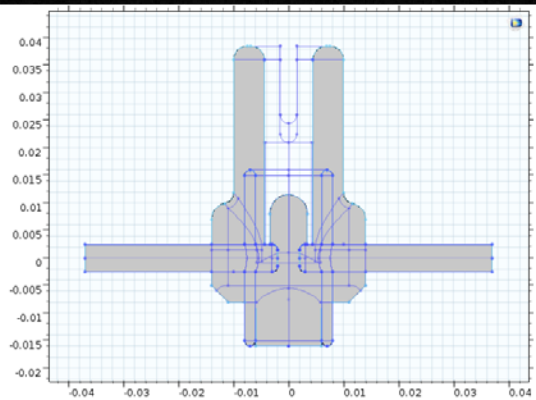
Optimal geometry?

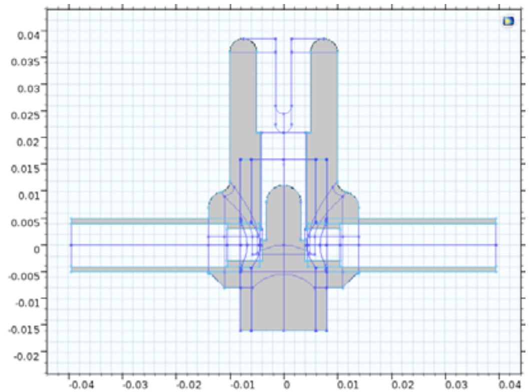
Type #2








0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.04 -0.03 -0.02 -0.01 0 0.01 0.02 0.03 0.04


0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.04 -0.03 -0.02 -0.01 0 0.01 0.02 0.03 0.04

ARC DISCHARGE MODEL

Magnetohydrodynamics equations (MHD)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \{\rho \mathbf{v}\} = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \{\rho \mathbf{v} \otimes \mathbf{v}\} = -\nabla p + \nabla \cdot \mathbf{T} + \mathbf{j} \times \mathbf{B}$$

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot \{\rho H \mathbf{v} - \lambda \nabla T\} = \frac{\partial p}{\partial t} + \nabla \cdot (\mathbf{T} \cdot \mathbf{v}) + \mathbf{j} \cdot \mathbf{E} - \nabla \cdot \mathbf{F}$$

$$\mathbf{j} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$

$$\partial_t \mathbf{B} + \nabla \times \mathbf{E} = 0$$

ARC DISCHARGE MODEL

- **CFD**

High Mach Number Flow, Laminar *(hmnf)*

- **Electrodynamics**

Electric Currents *(ec)*

- **Radiation Transport**

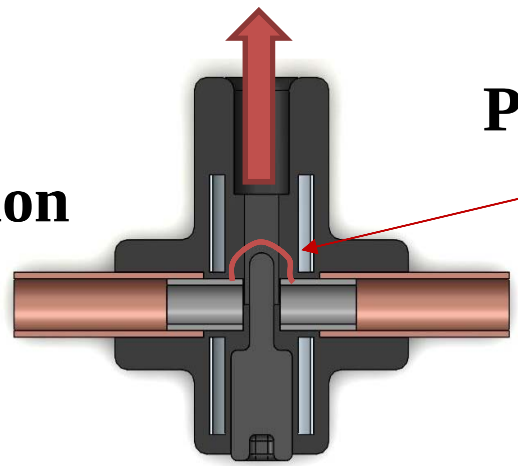
Radiation in Participating Media *(rpm)*

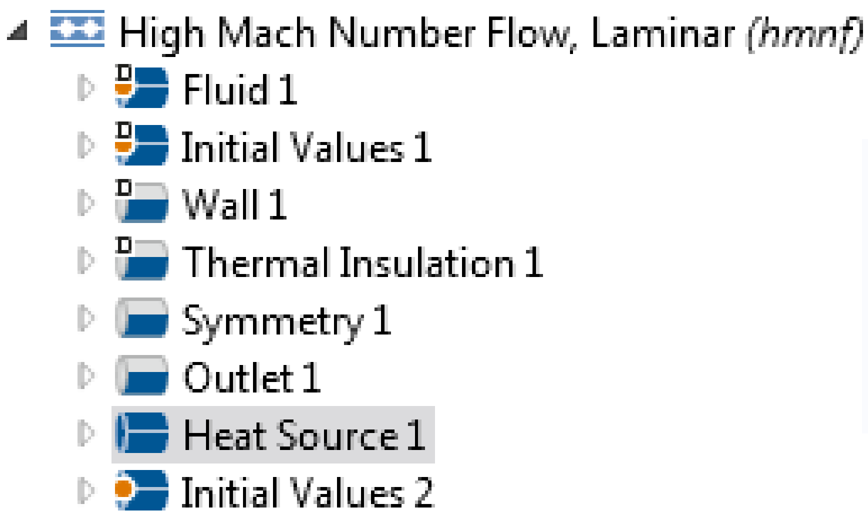
ARC DISCHARGE MODEL

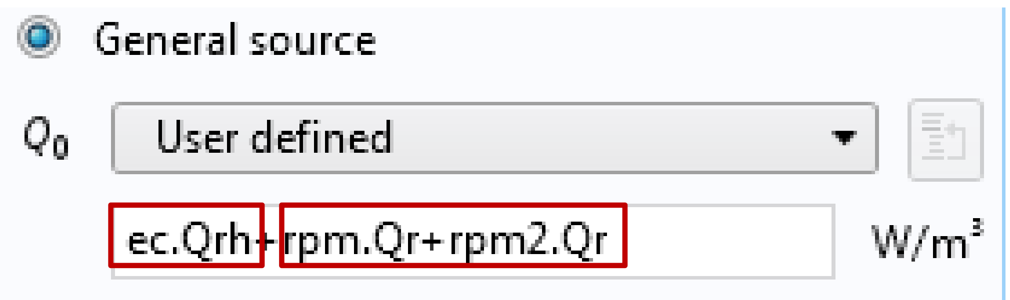
Outlet

Heat source
Joule Heat+Radiation

Preheated channel (~10 kK)







Joule Heat Radiation

ARC DISCHARGE MODEL

- **CFD**

High Mach Number Flow, Laminar *(hmnf)*

- **Electrodynamics**

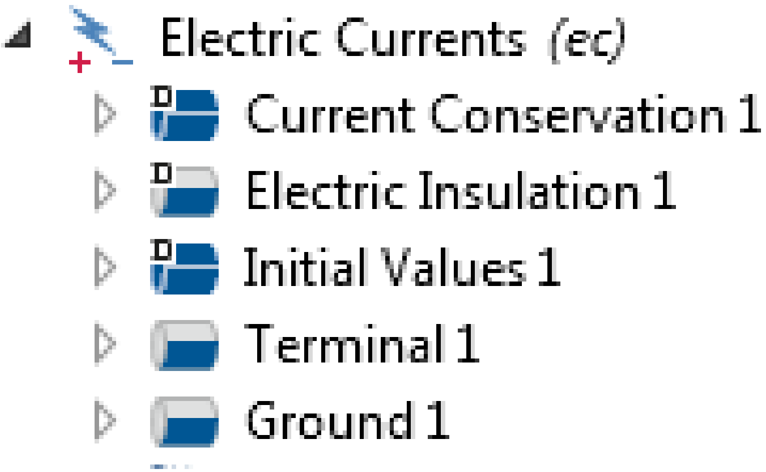
Electric Currents *(ec)*

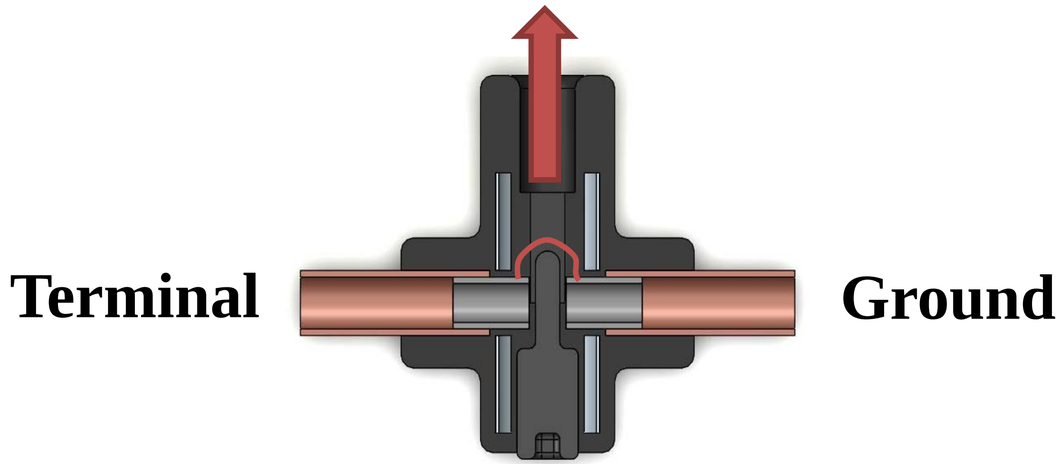
- **Radiation Transport**

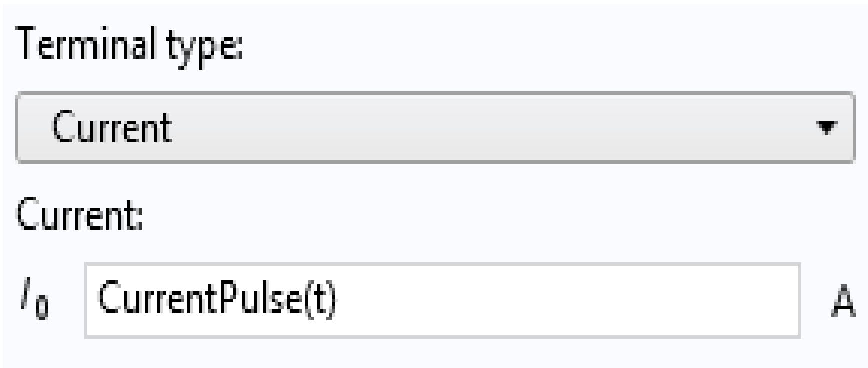
Radiation in Participating Media *(rpm)*

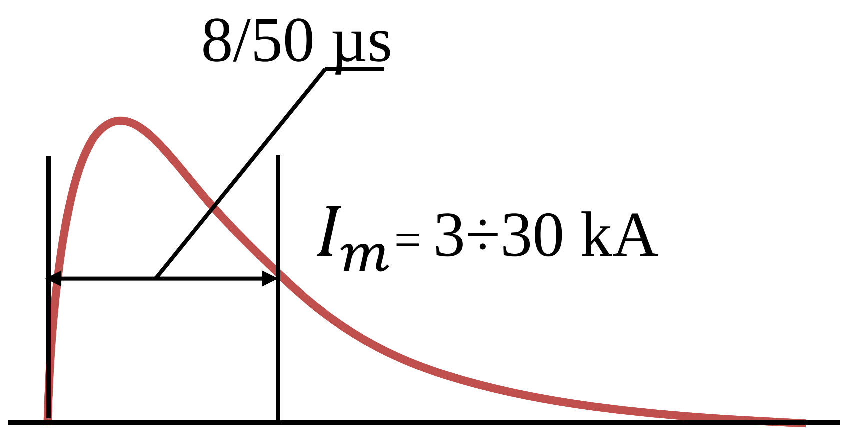
ARC DISCHARGE MODEL

Electrodynamics









ARC DISCHARGE MODEL

- **CFD**

High Mach Number Flow, Laminar *(hmnf)*

- **Electrodynamics**

Electric Currents *(ec)*

- **Radiation Transport**

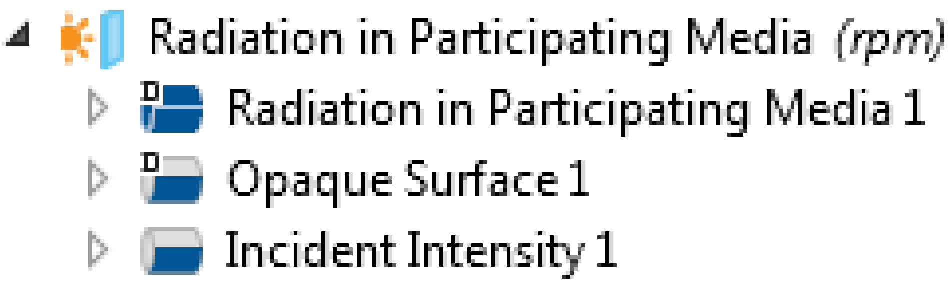
Radiation in Participating Media *(rpm)*

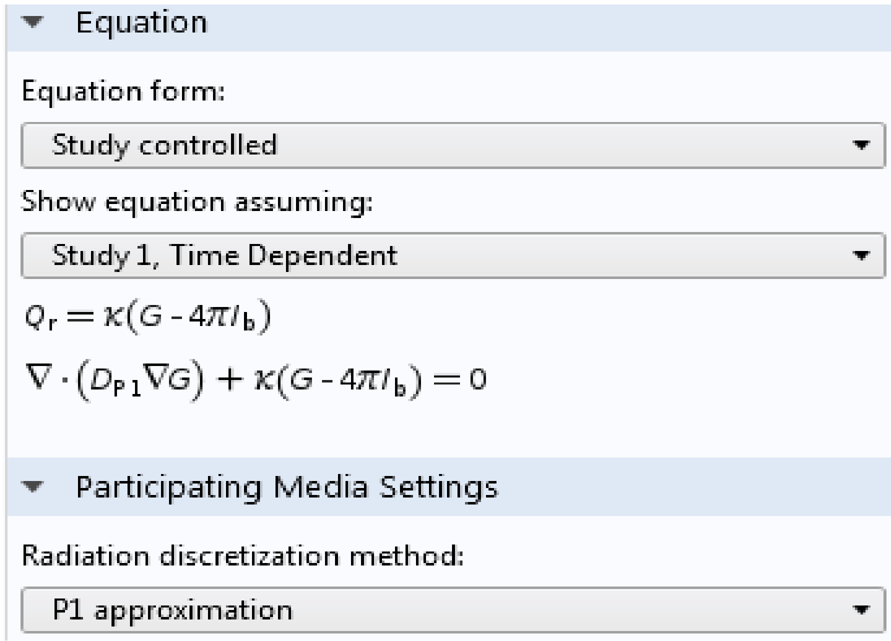
Radiation transport

$$\mathbf{s} \cdot \nabla I_\nu(\mathbf{r}, \mathbf{s}) = \kappa_\nu \left[I_\nu^b(T) - I_\nu(\mathbf{r}, \mathbf{s}) \right]$$

$$I_\nu^b(T) = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/k_B T} - 1} \qquad G_\nu(r, s) = \int_{4\pi} I_\nu(r, s) d\Omega$$

$$\nabla \cdot \left(\frac{1}{\kappa_\nu} \nabla G_\nu \right) = 3\kappa_\nu (G_\nu - 4\pi I_{b\nu})$$





Radiation transport

Two-band model

from zero up to $\lambda = 120$ nm

$$\alpha = 2000\ \mathrm{m}^{-1}$$

from $\lambda = 120$ nm up to $\lambda = 1$ mm

$$\alpha = 50\ \mathrm{m}^{-1}$$

Radiation in Participating Media *(rpm)*

Radiation in Participating Media 2 *(rpm2)*

Absorption

Absorption coefficient:

κ User defined

50 1/m

Absorption

Absorption coefficient:

κ User defined

2000 1/m

ARC DISCHARGE MODEL

Material properties

- High Mach Number Flow, Laminar *(hmnf)*
- Electric Currents *(ec)*
- Radiation in Participating Media *(rpm)*
- Radiation in Participating Media 2 *(rpm2)*

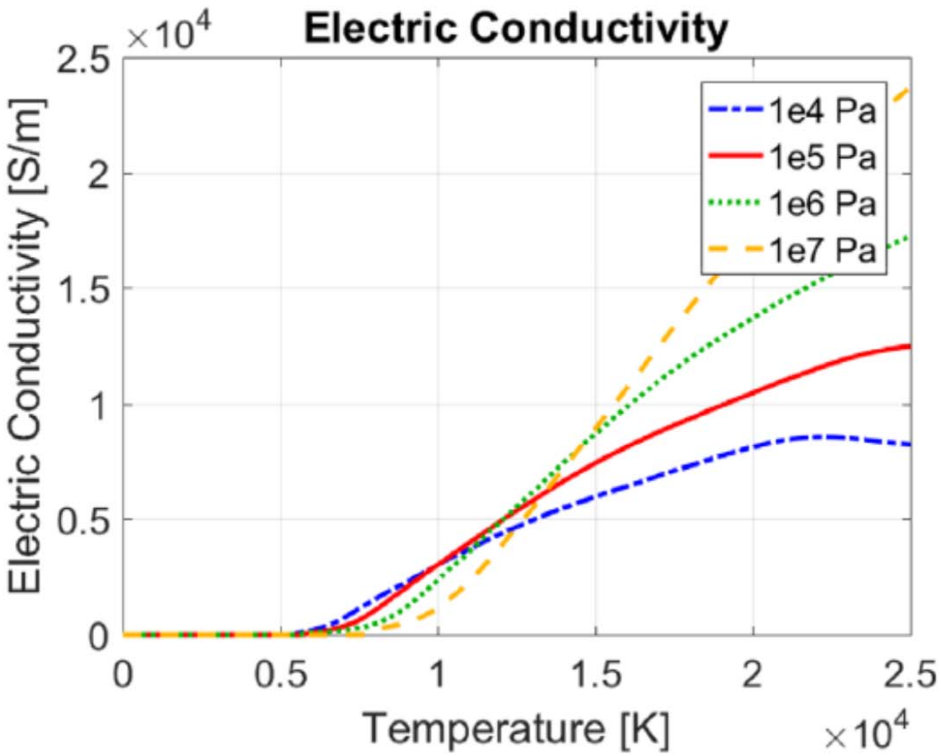
- Materials
  - Air *(mat1)*
    - Basic *(def)*
      - Interpolation 1 *(rho)*
      - Interpolation 2 *(cp)*
      - Interpolation 3 *(mu)*
      - Interpolation 4 *(k)*
      - Interpolation 5 *(sigma)*
    - Radiation heat transfer *(RadiationHeatTransfer)*
      - Interpolation 1 *(Qrad)*
    - Ideal gas *(idealGas)*

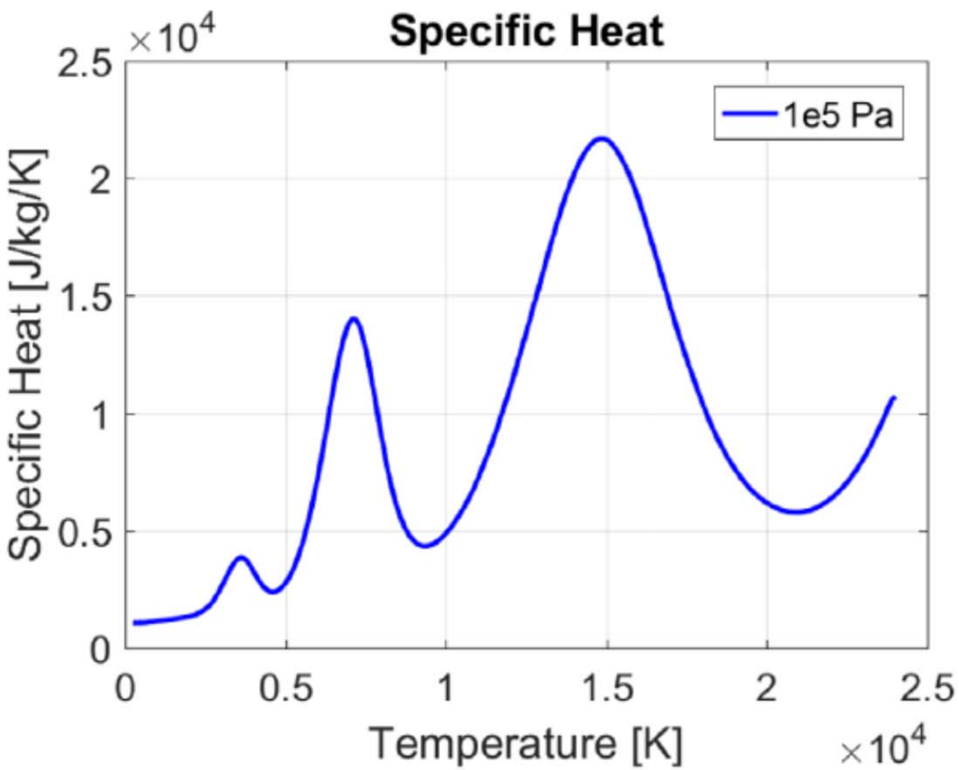
ARC DISCHARGE MODEL

Material properties

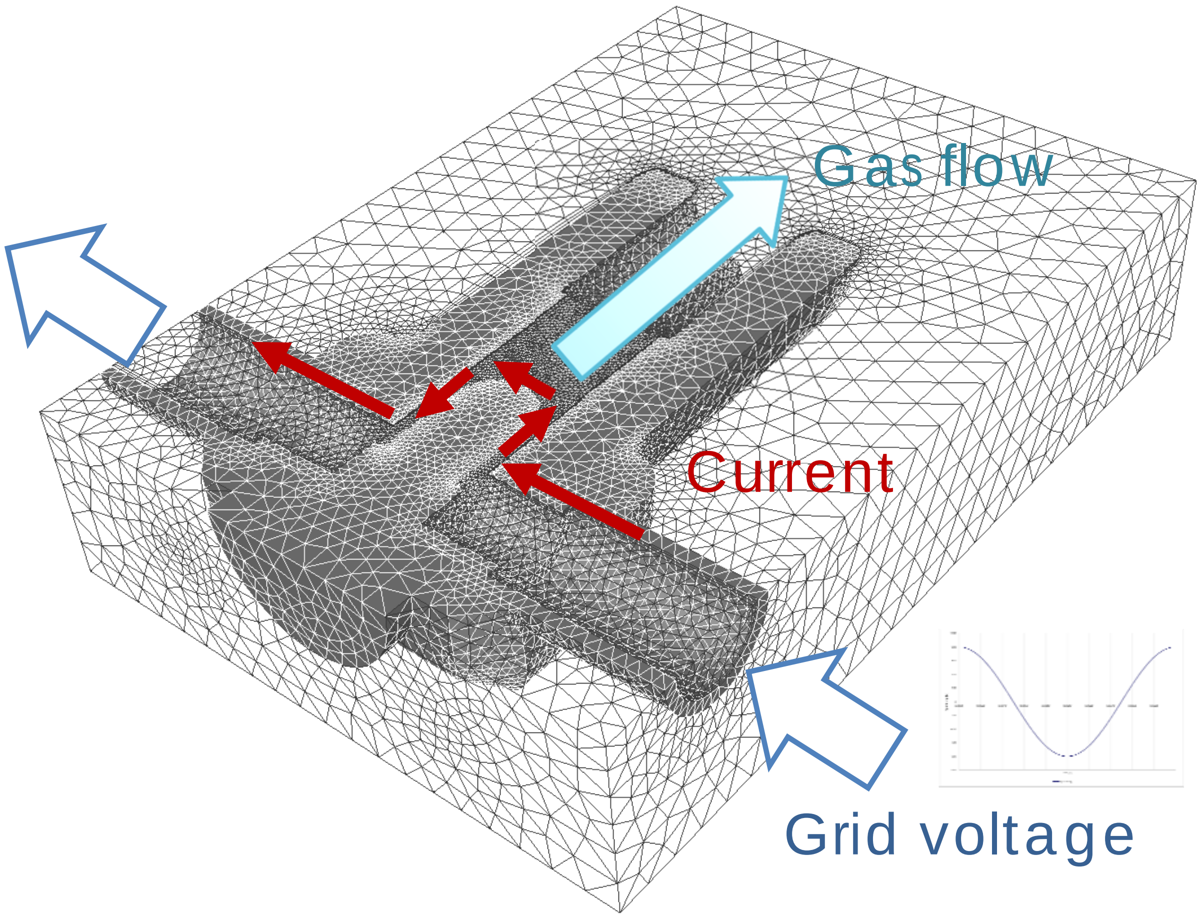
$$\sigma(p, T)$$

$$\rho(p, T)$$





ARC DISCHARGE MODEL

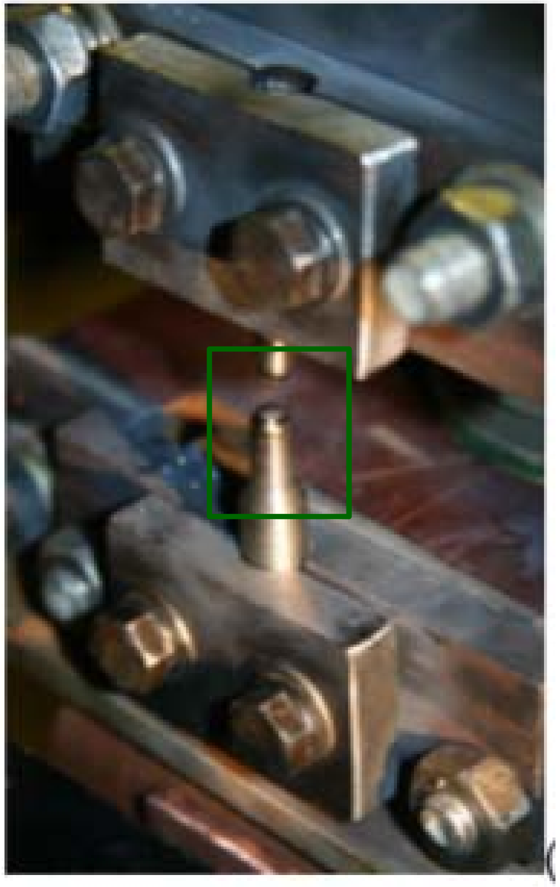


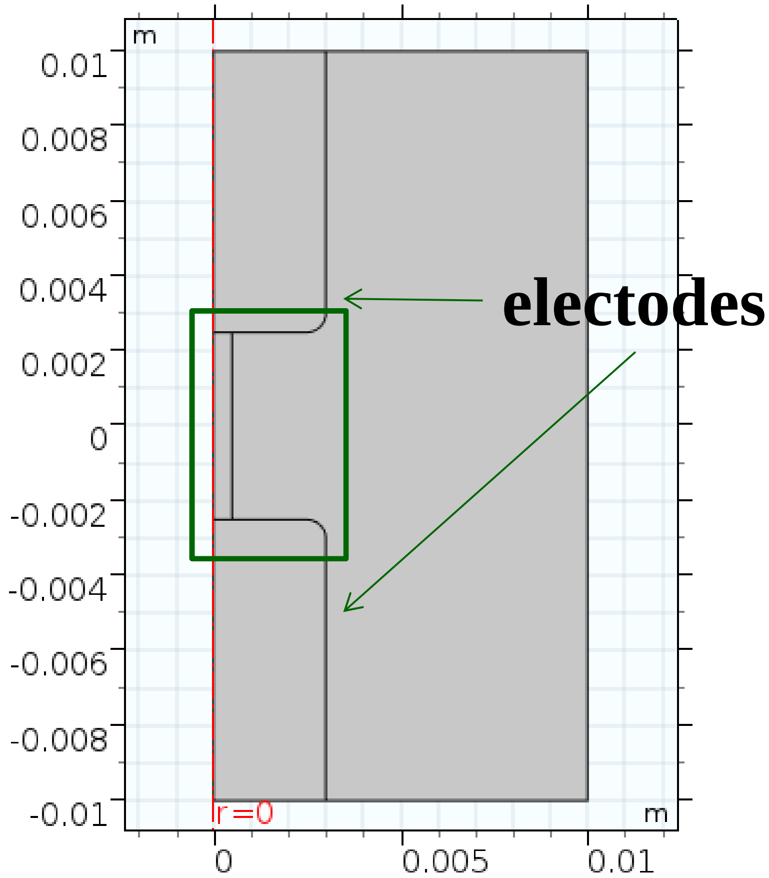
ARC MODEL VALIDATION

Open spark gap

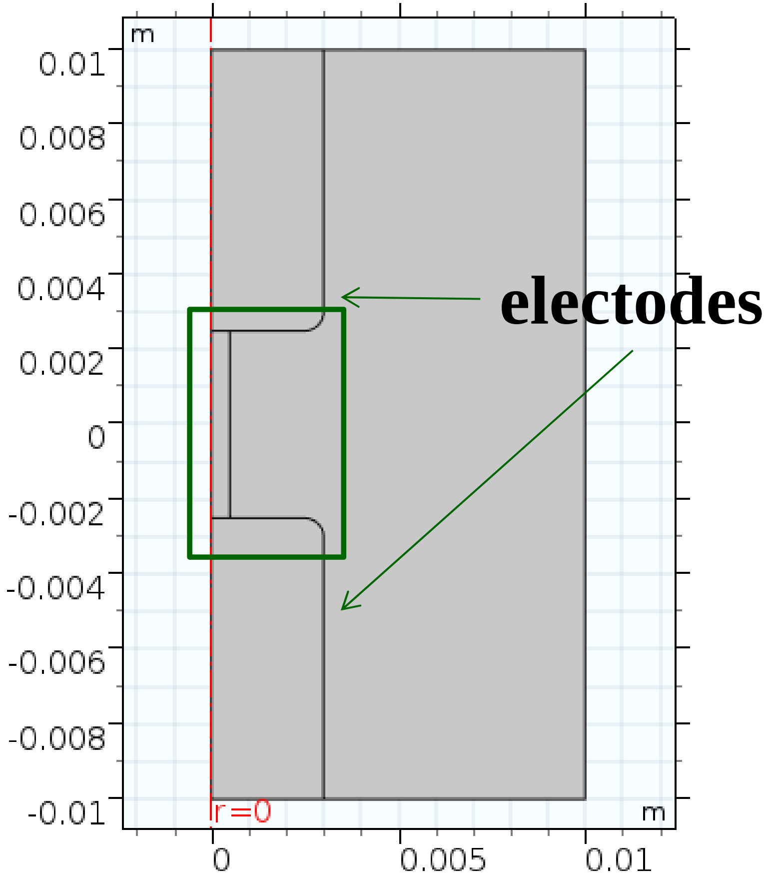
Steel electrodes

ARC MODEL VALIDATION

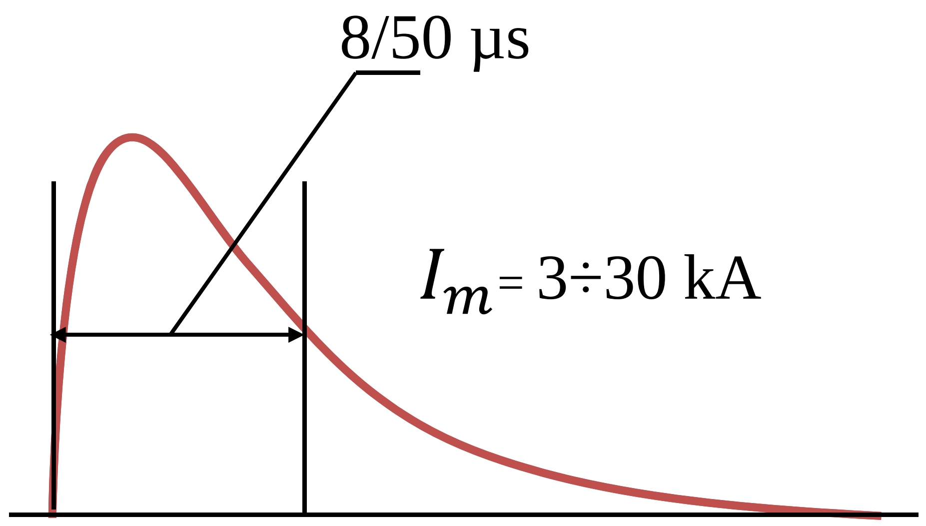




ARC MODEL VALIDATION

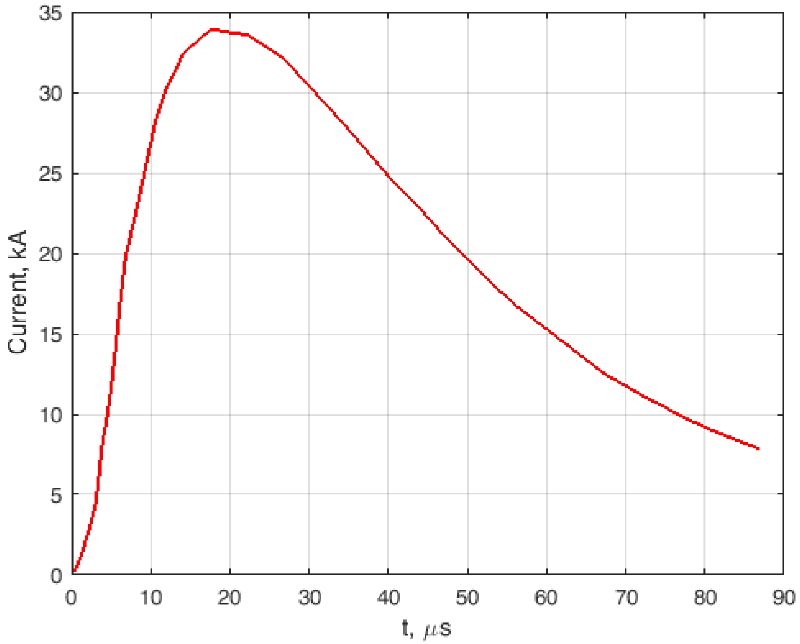


- High Mach Number Flow, Laminar *(hmnf)*
- Electric Currents *(ec)*
- Radiation in Participating Media *(rpm)*
- Radiation in Participating Media 2 *(rpm2)*

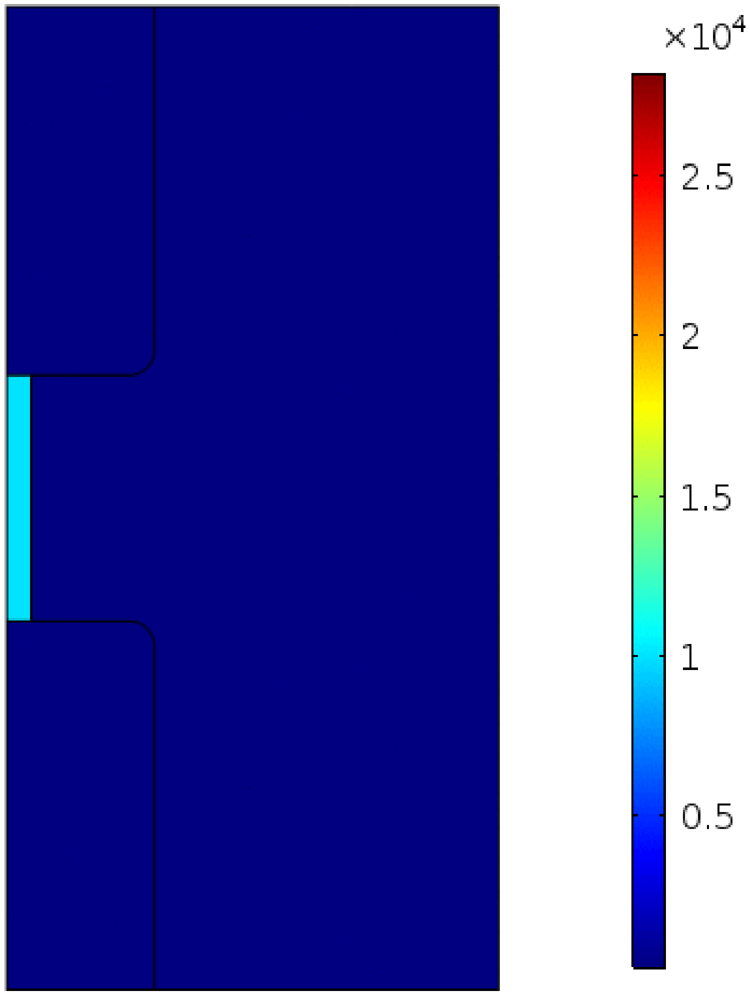


SIMULATION RESULTS

30 kA

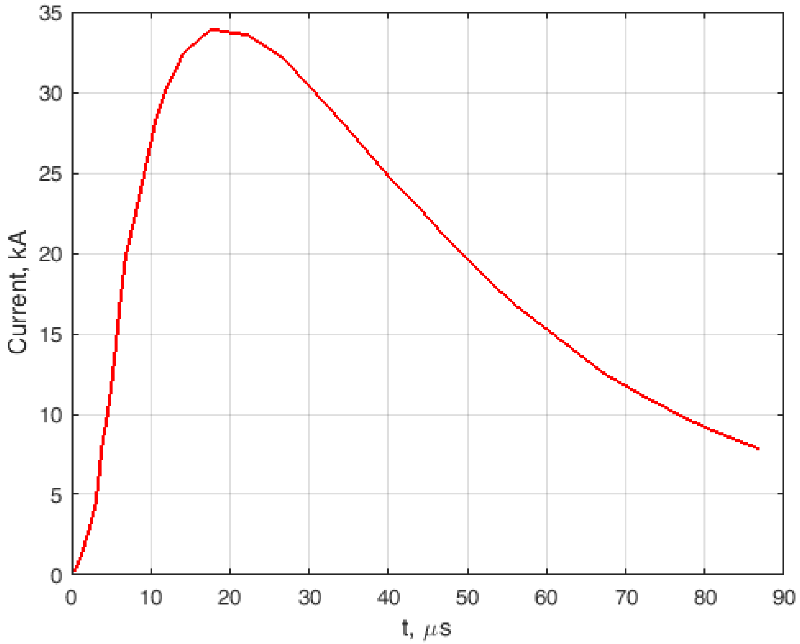


Temperature, K

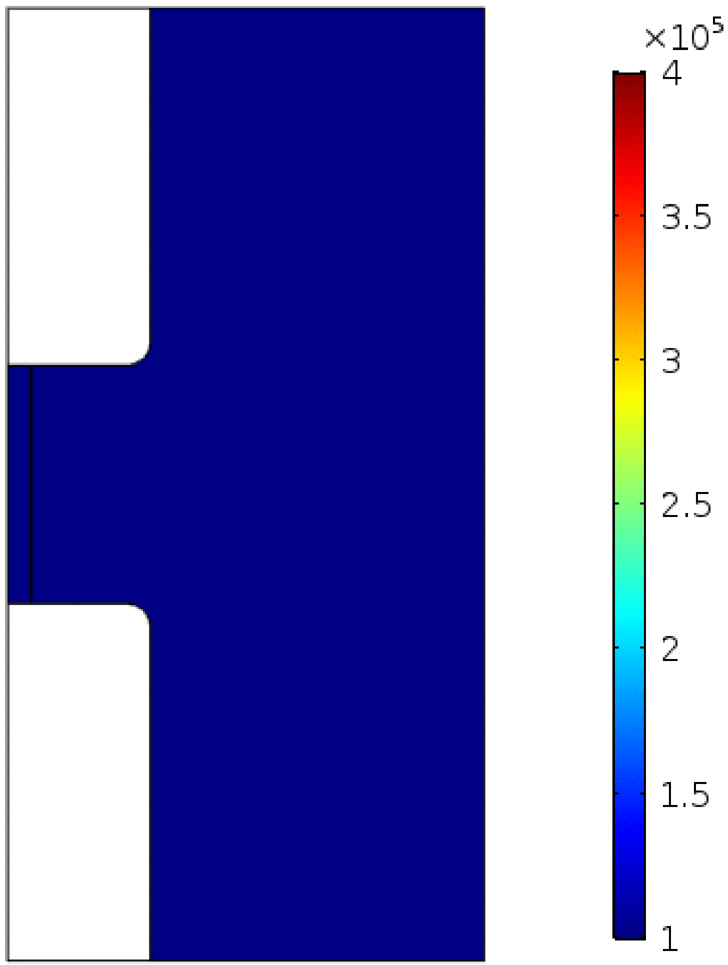


SIMULATION RESULTS

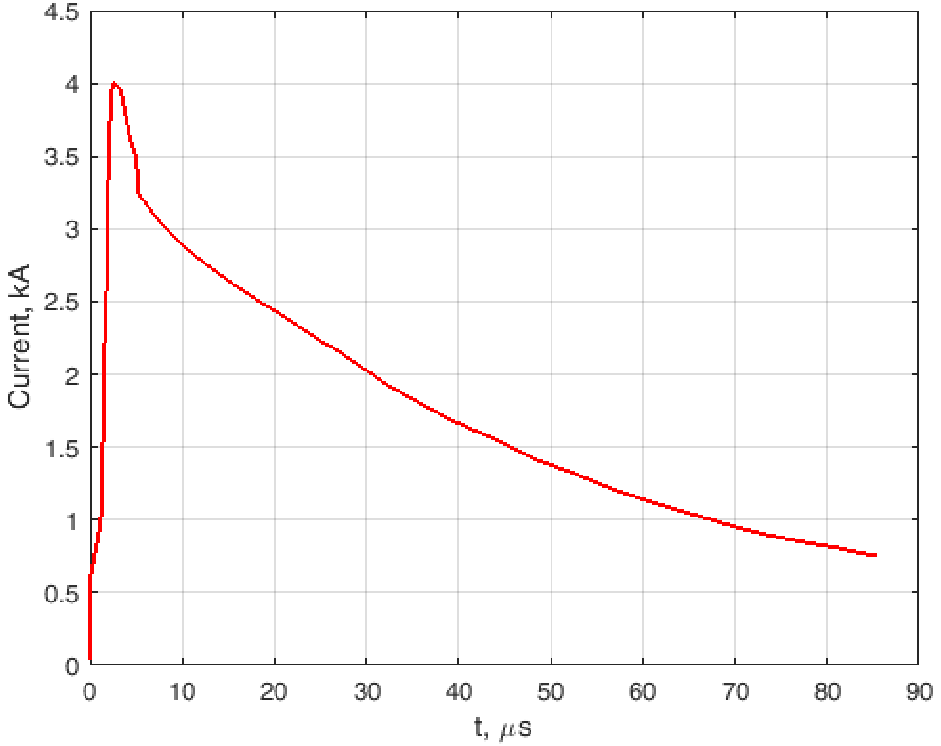
30 kA

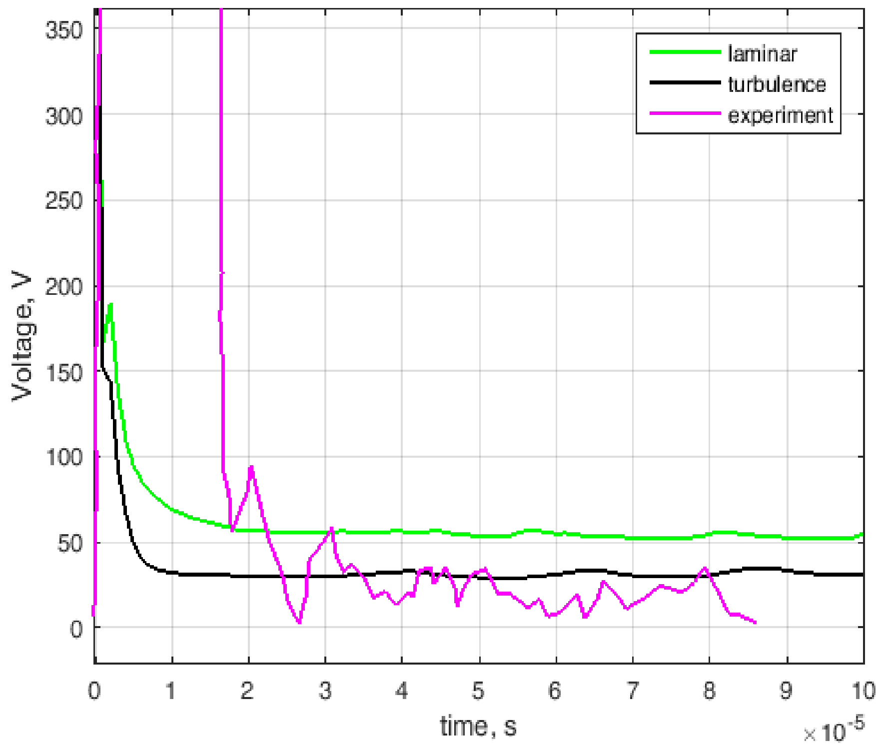


Pressure, Pa



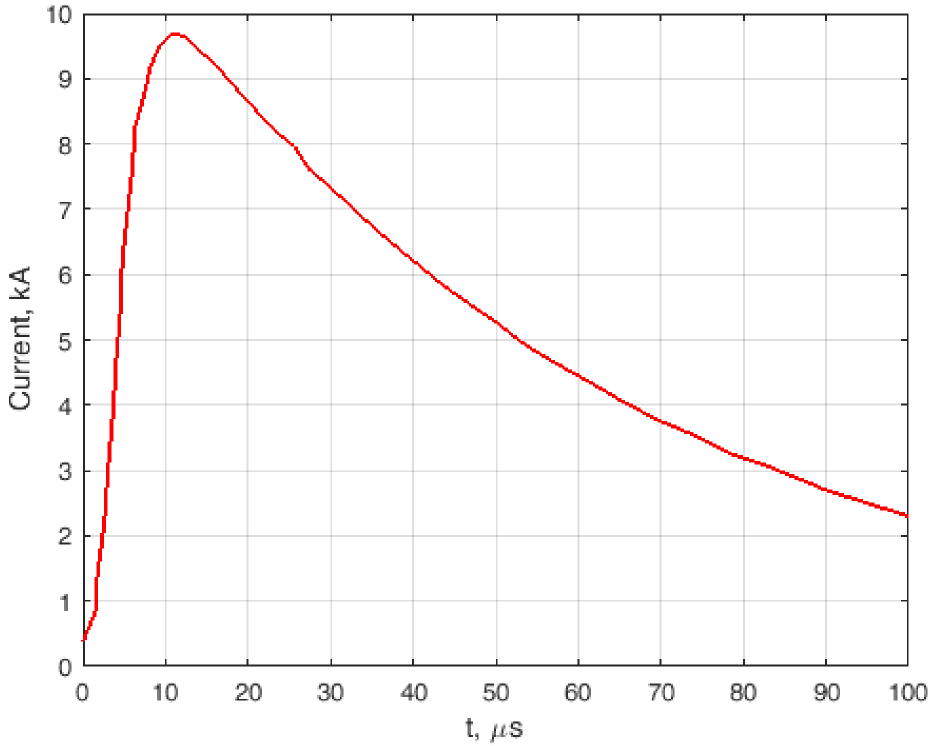
SIMULATION RESULTS

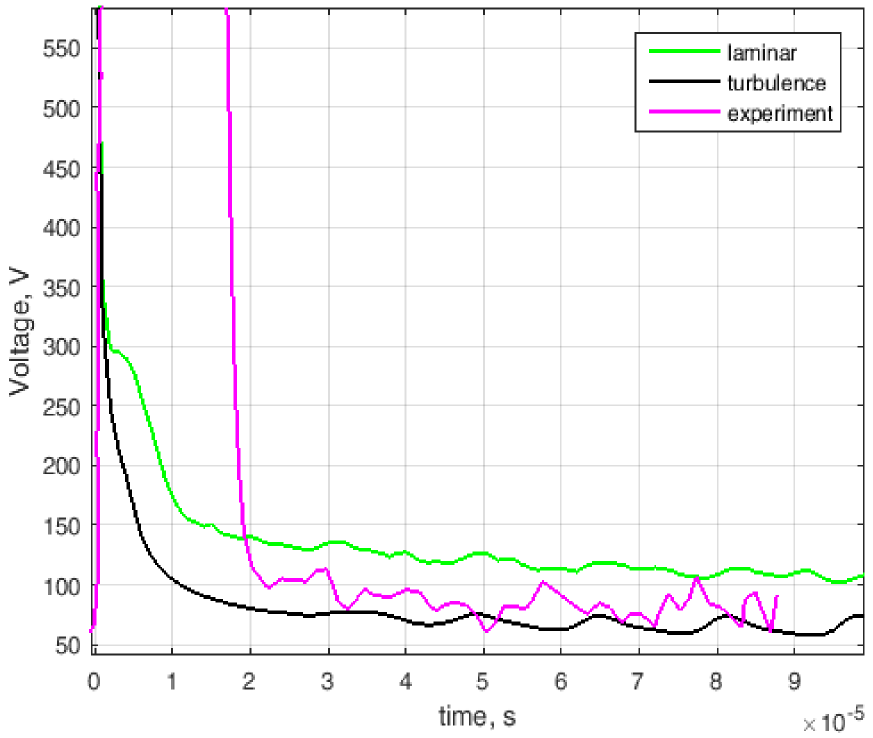




3 kA

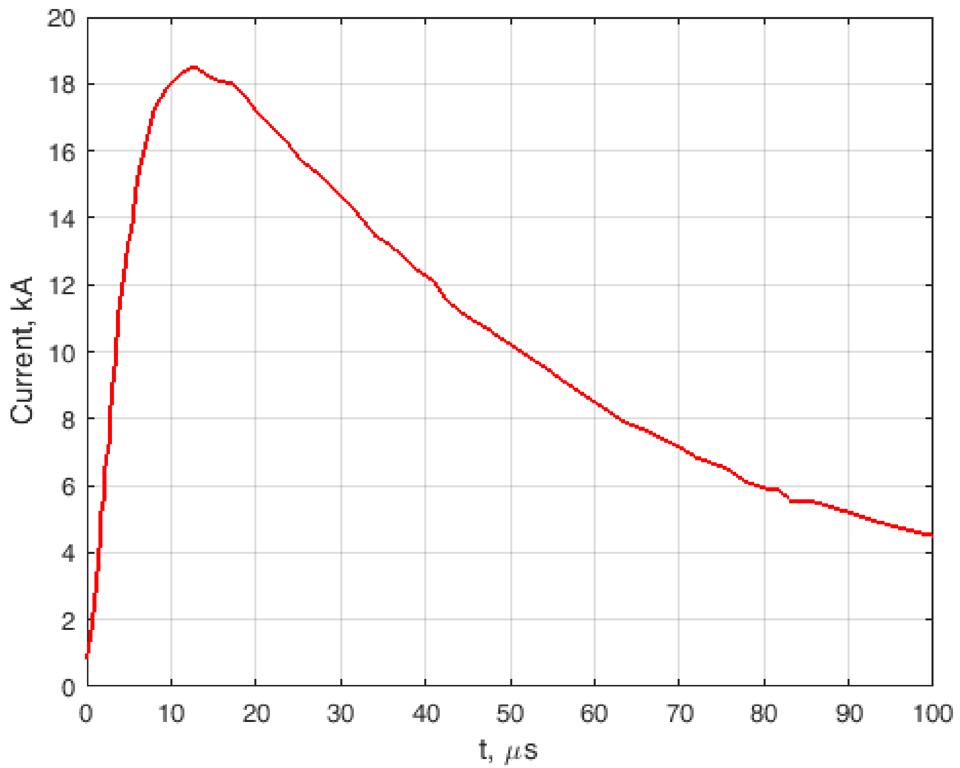
SIMULATION RESULTS

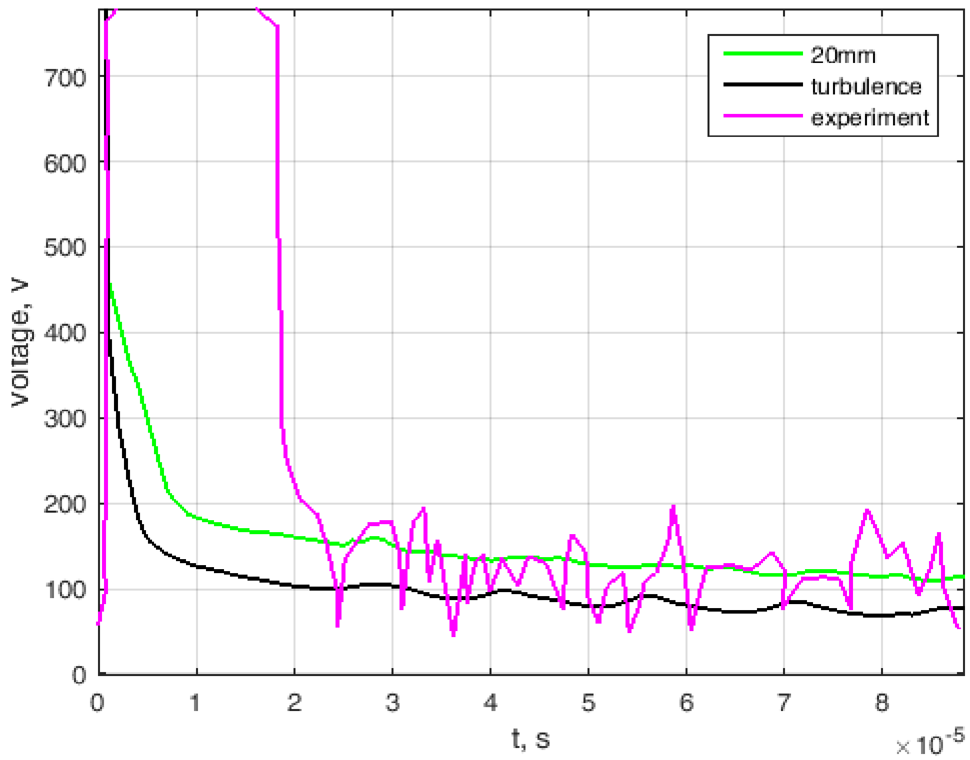




10 kA

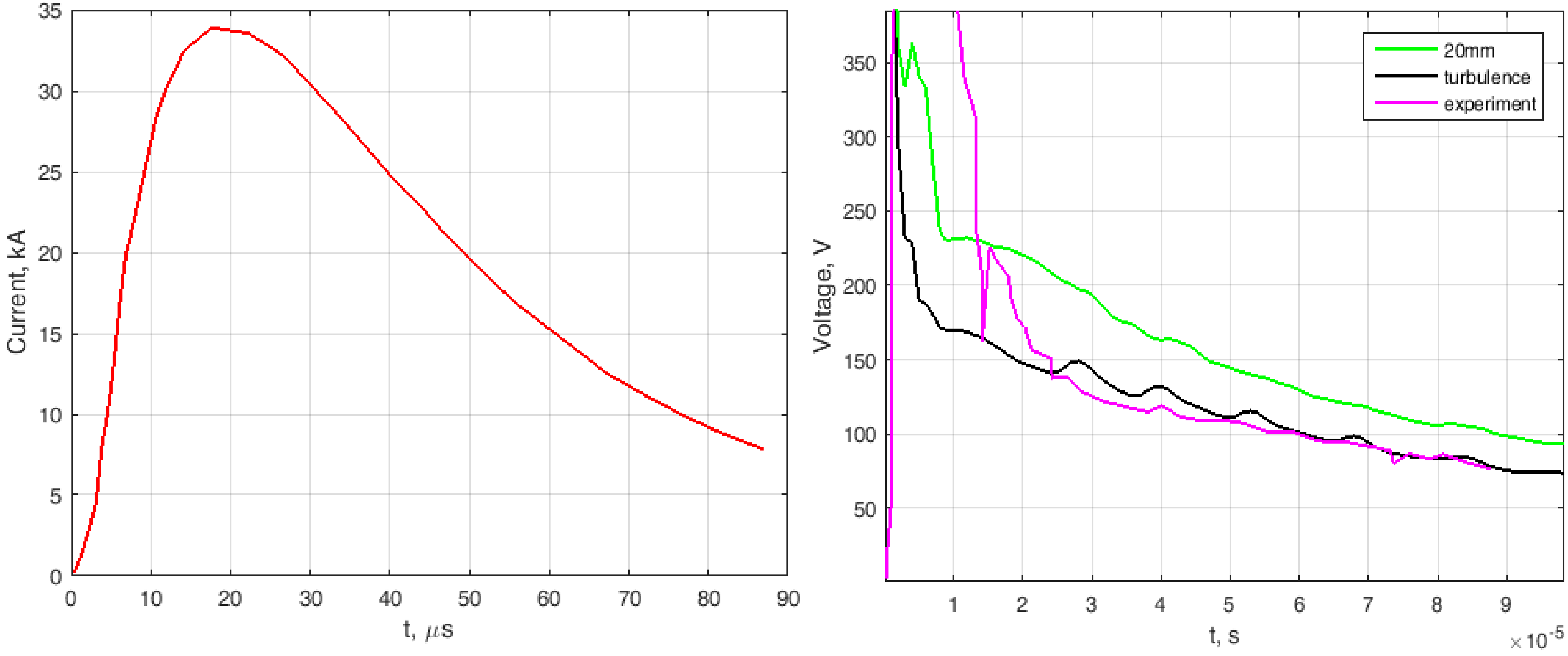
SIMULATION RESULTS





20 kA

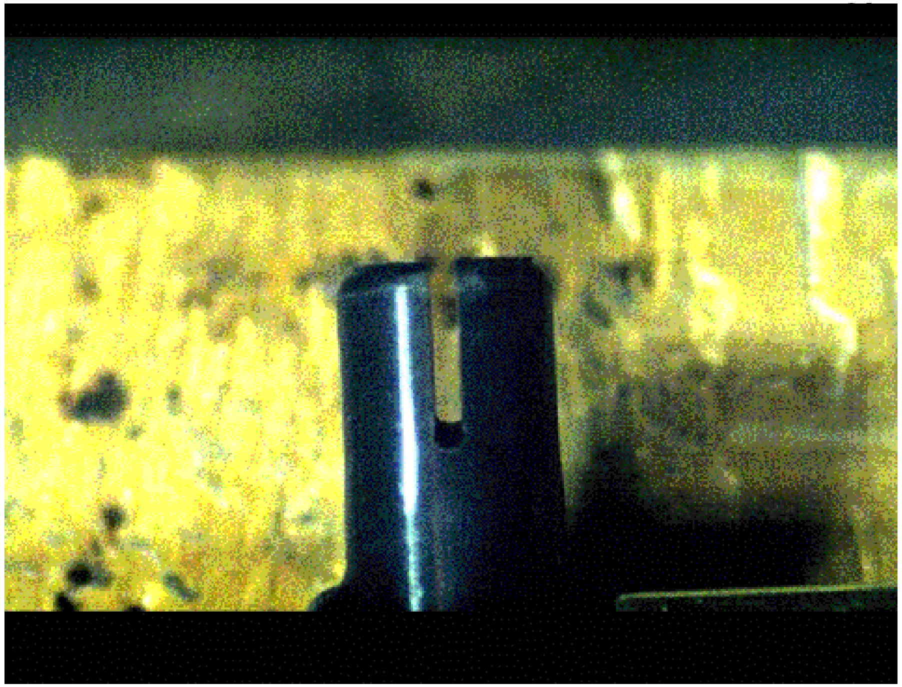
SIMULATION RESULTS

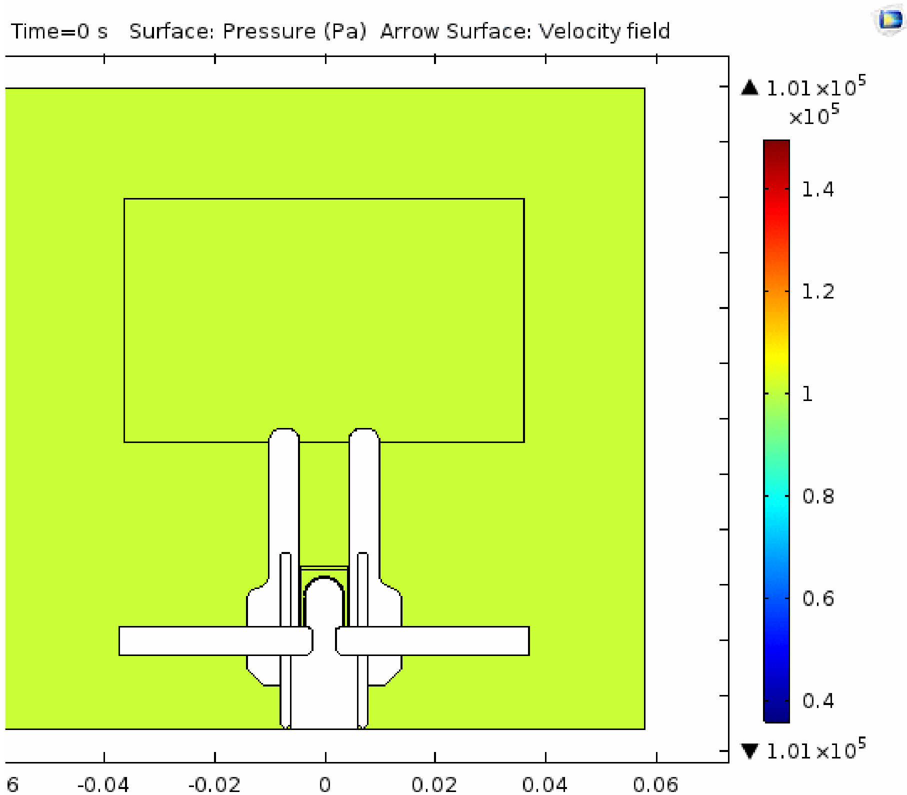


30 kA

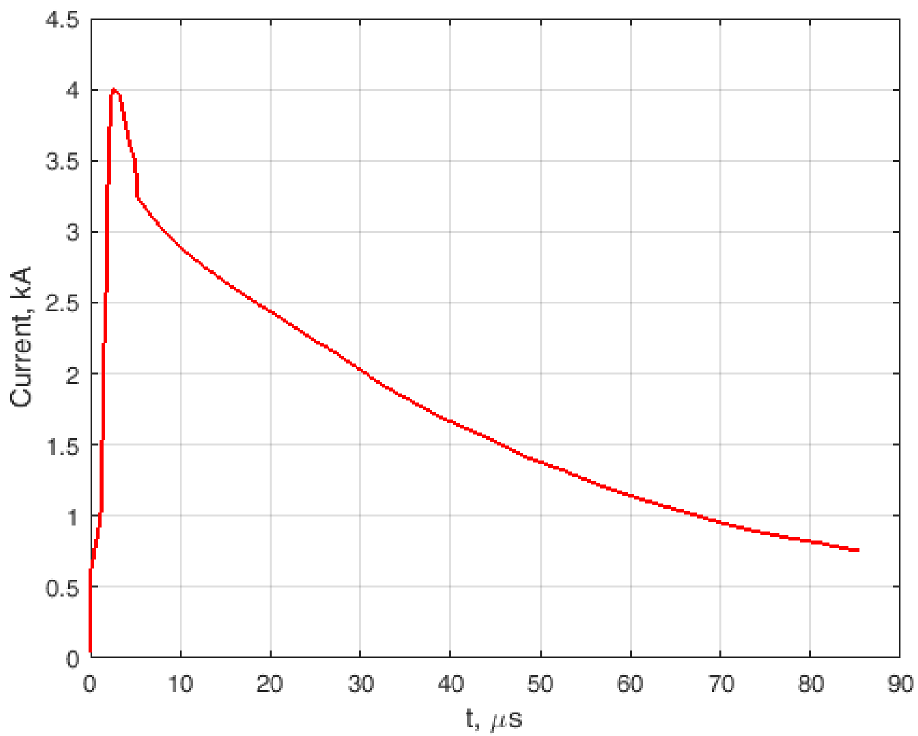
SIMULATION RESULTS

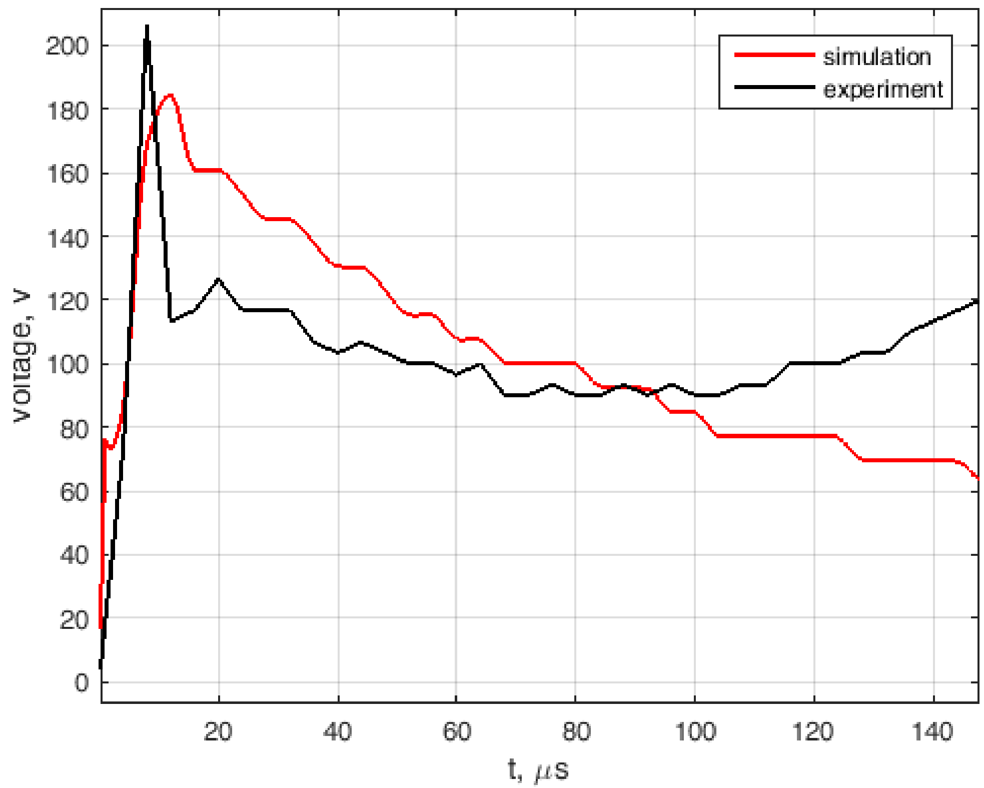
Fast-imaging record of plasma jet





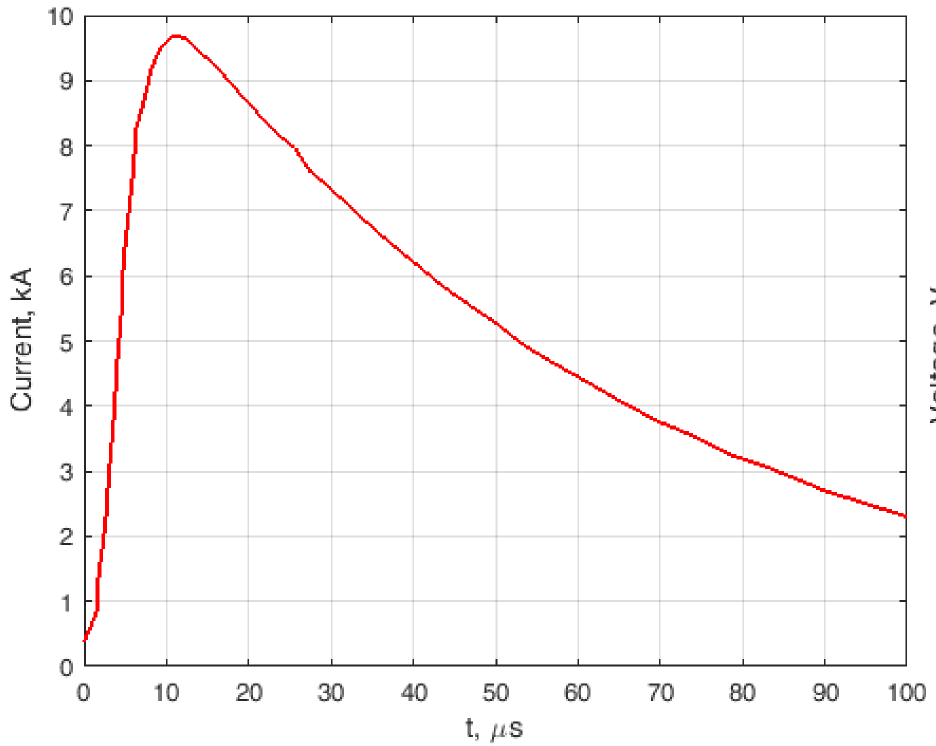
SIMULATION RESULTS

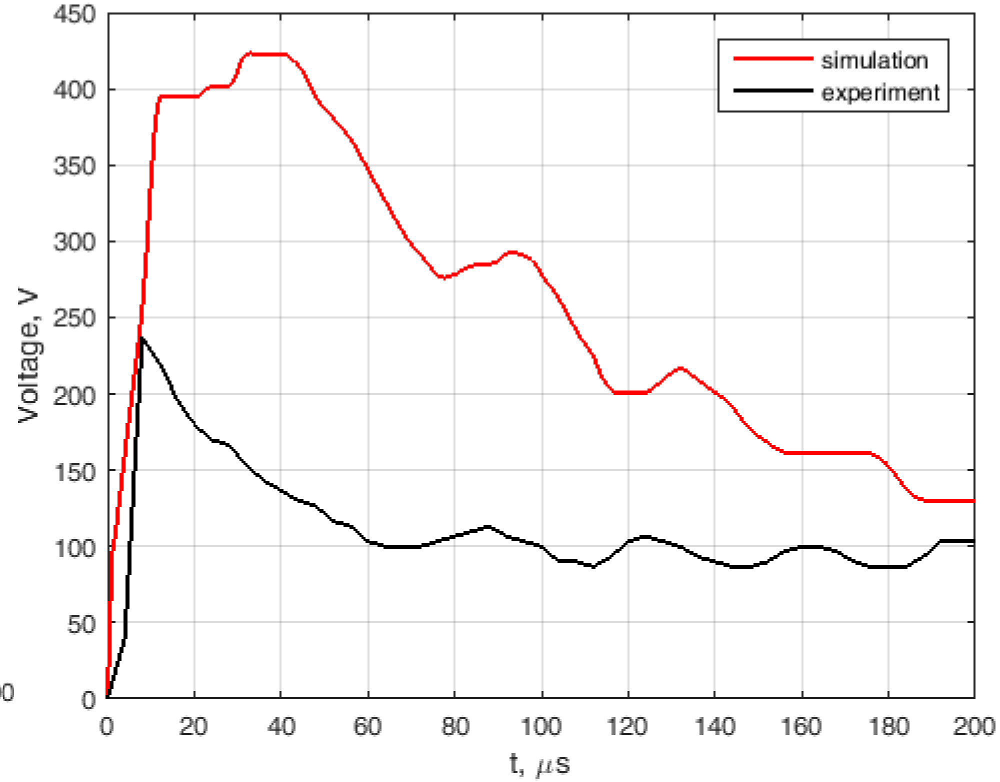




3 kA

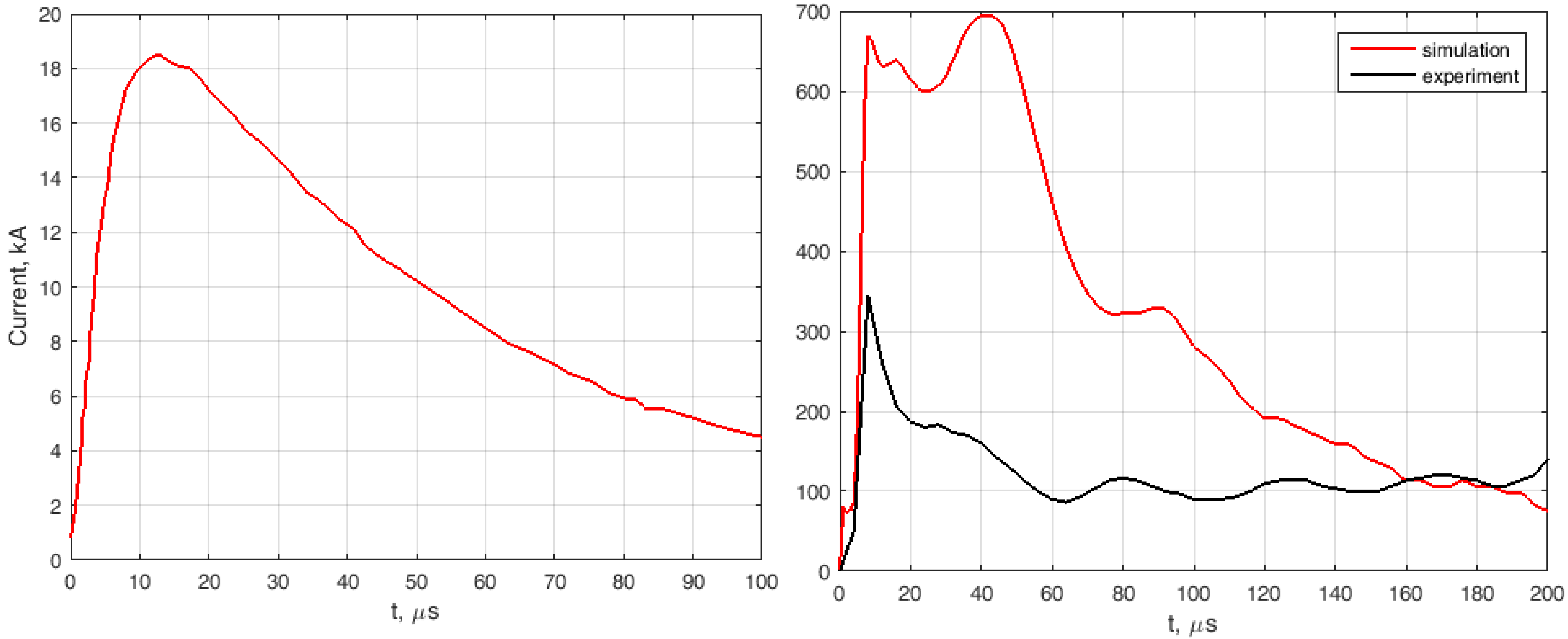
SIMULATION RESULTS





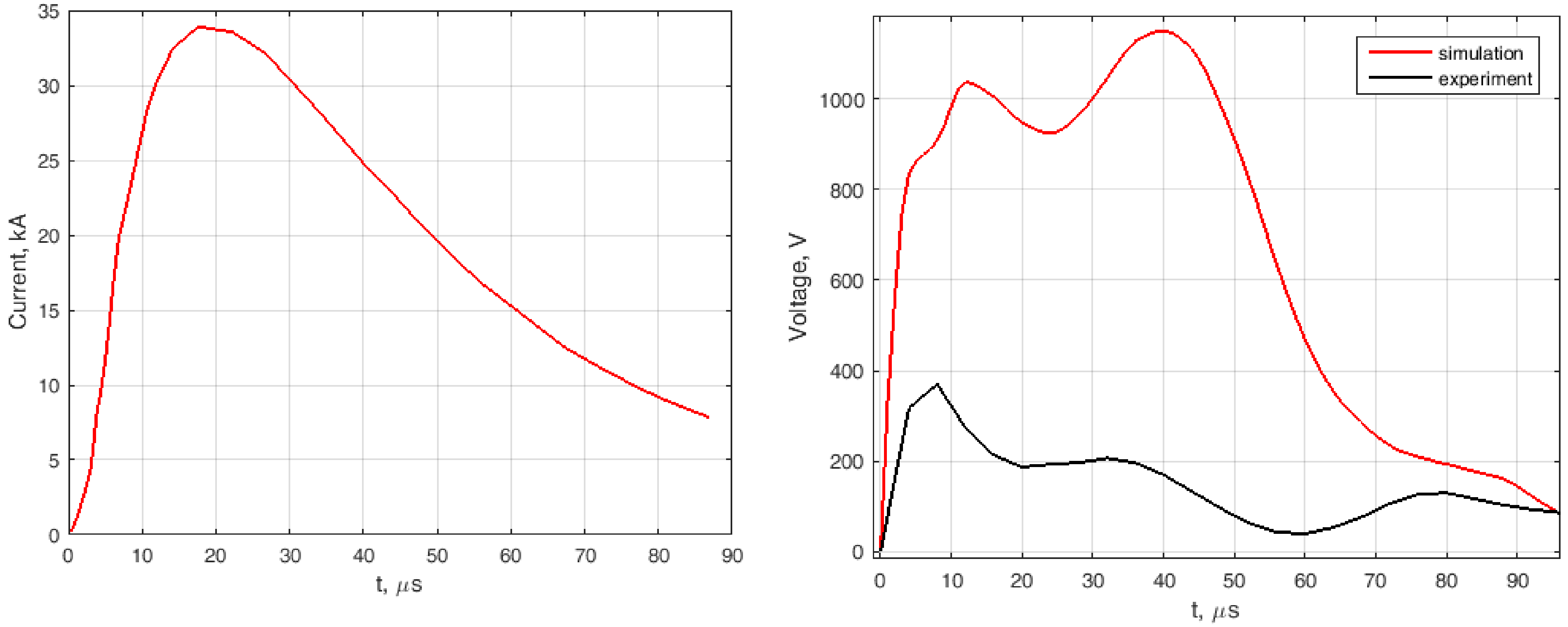
10 kA

SIMULATION RESULTS



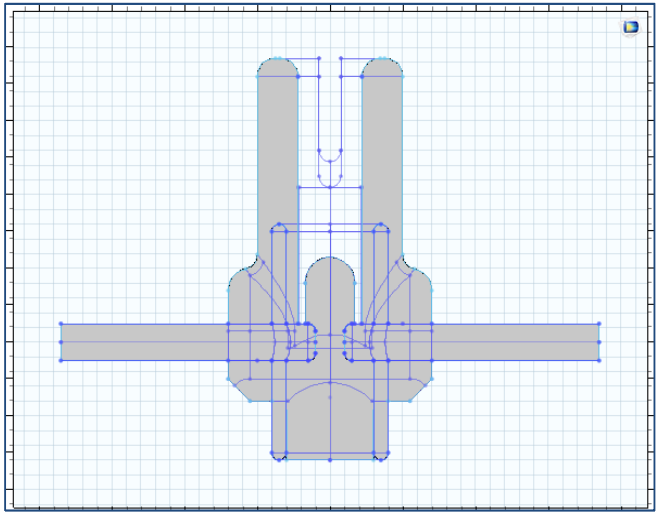
20 kA

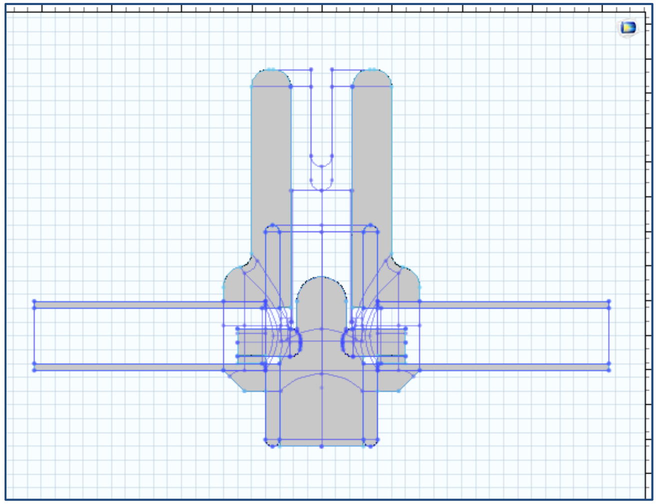
SIMULATION RESULTS

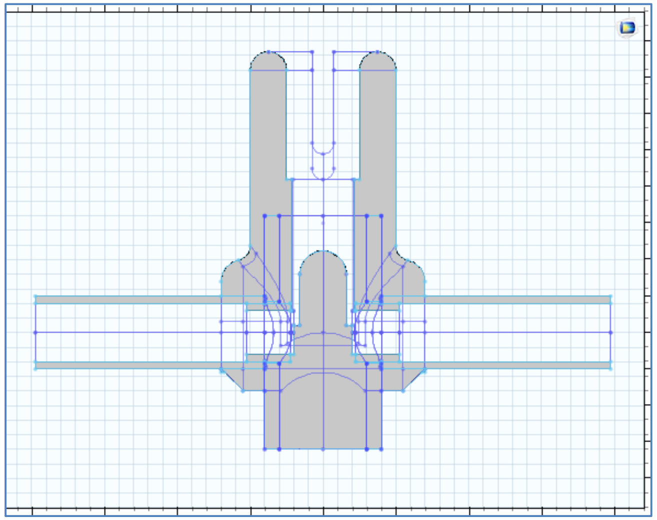


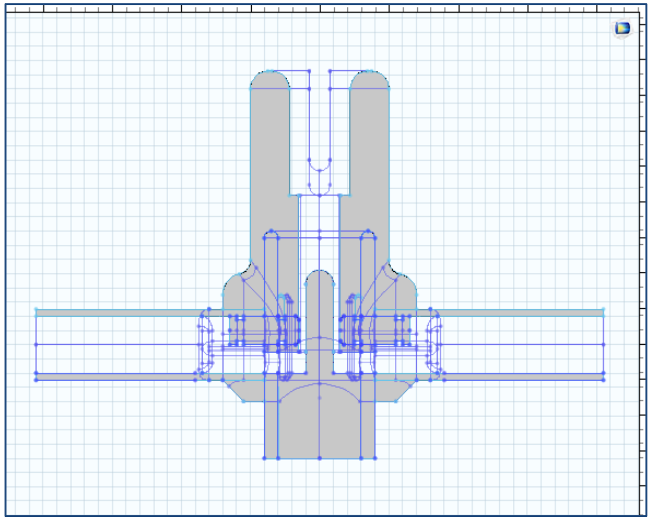
30 kA

SIMULATION RESULTS

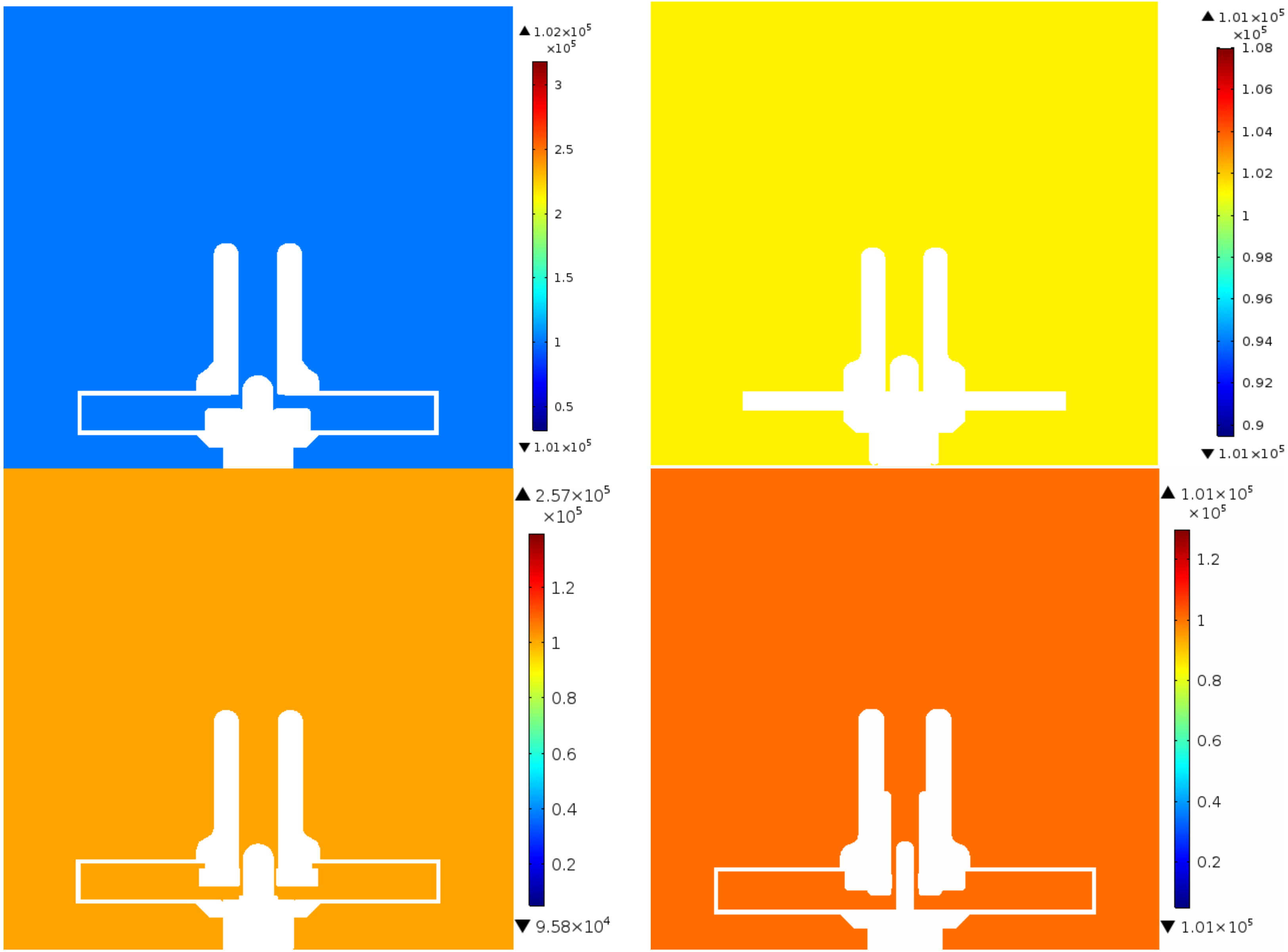




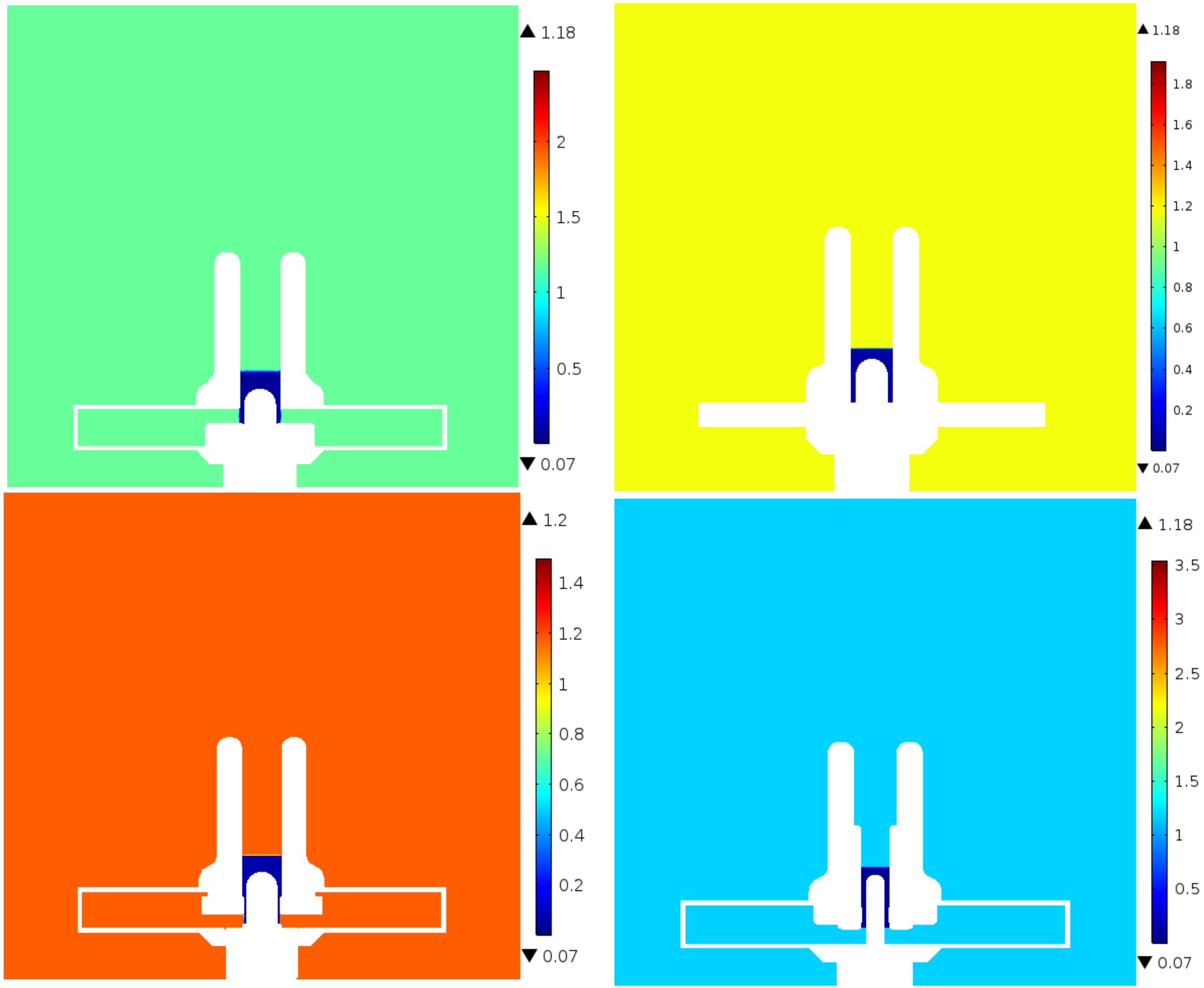




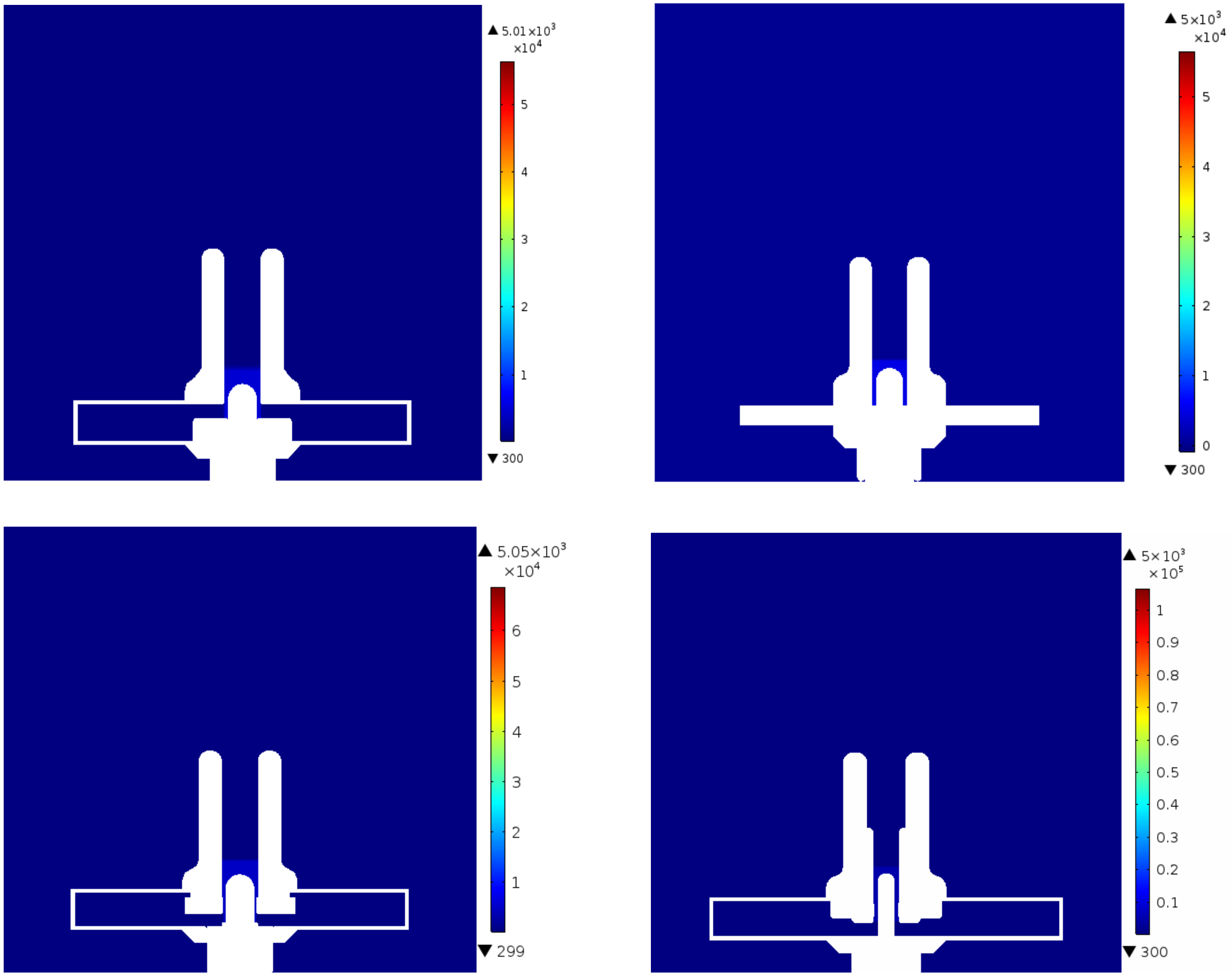
SIMULATION RESULTS:PRESSURE



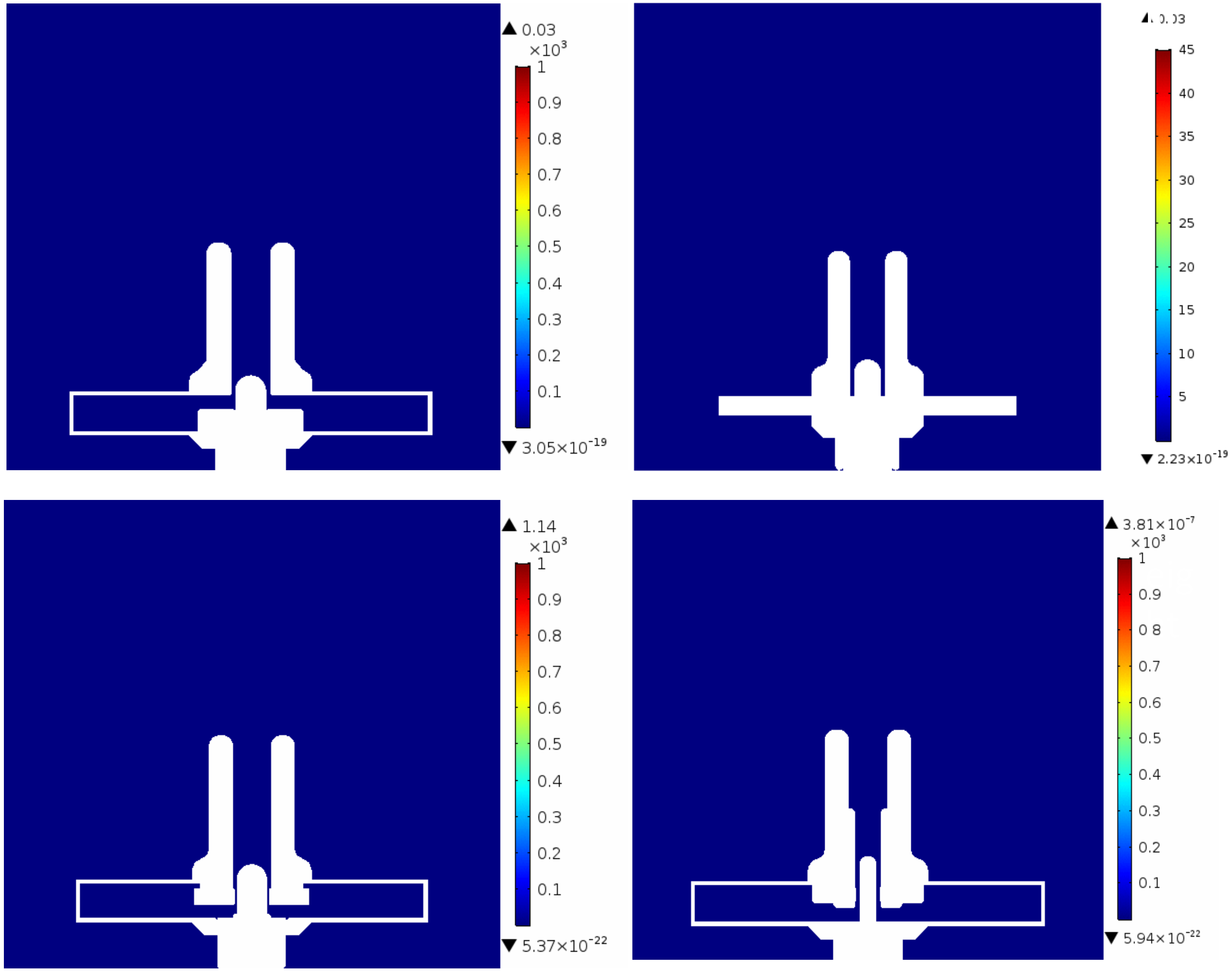
SIMULATION RESULTS:DENSITY



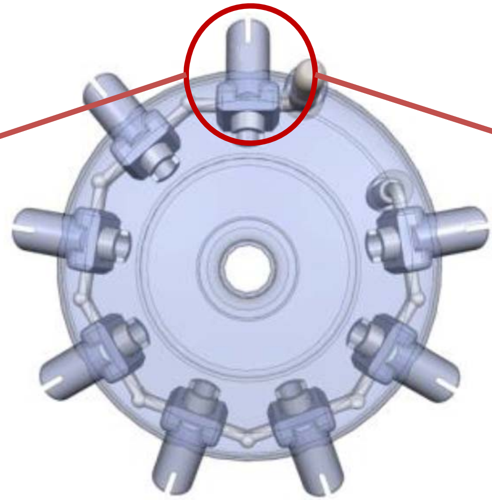
SIMULATION RESULTS:TEMPERATURE



SIMULATION RESULTS:VELOCITY

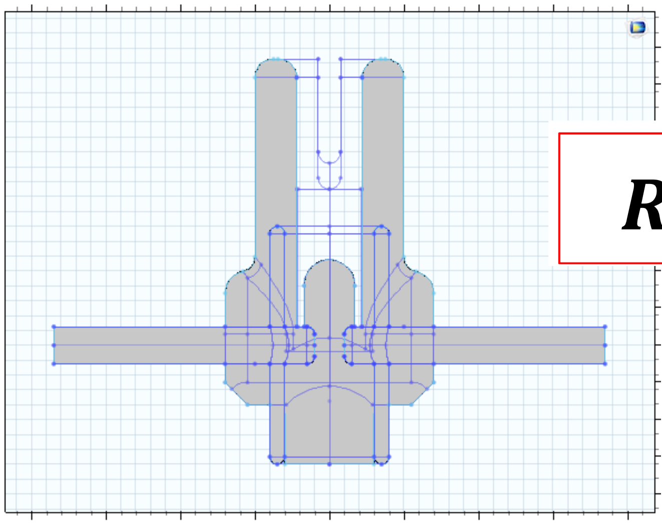


SIMULATION RESULTS

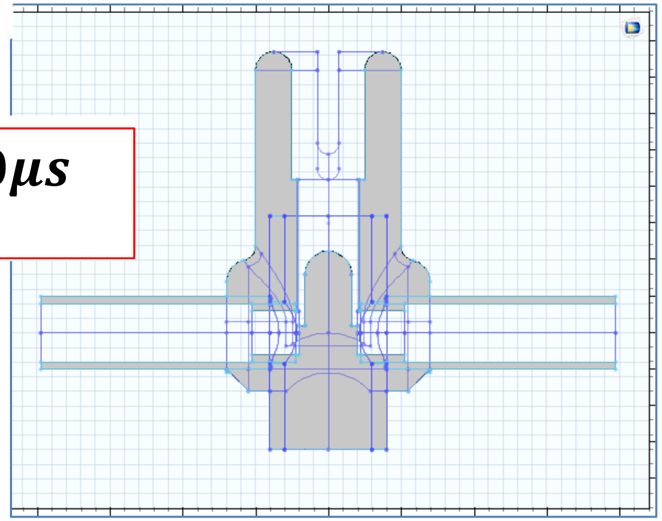


Type #1

Type #2



$$R_1^{t=200\mu s} < R_2^{t=200\mu s}$$



Type #1 is better than Type #2

CONCLUSIONS:

- Conventional approach to thermal plasma modeling based on MHD is applicable for the case of impulse arcs caused by lightning overvoltage to some certain extent

- However current model is lacking some important physics

- It could be electrode erosion, chamber geometry deformation, Lorentz force influence, something else

- Still numerical simulation is considered as a promising tool for development of future lightning protection devices

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Thank you for your attention!