Studies on Pulsed Wire Discharges

Experimental and Numerical Investigations on Exploding X5CrNi18-10 Wires

Presentation
Master Thesis

Max Bigelmayr

Rostock 31. July 2019

Pulsed Wire Discharge (PWD) Experiments & Exploding Wire Method (EWM)

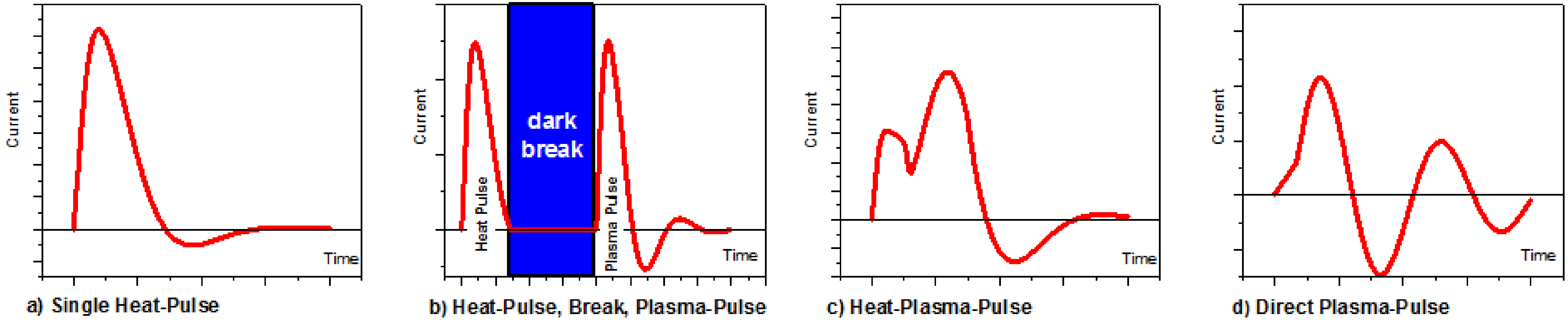
- first discharge of capacitors through metal wires by Edward Nairne 1774

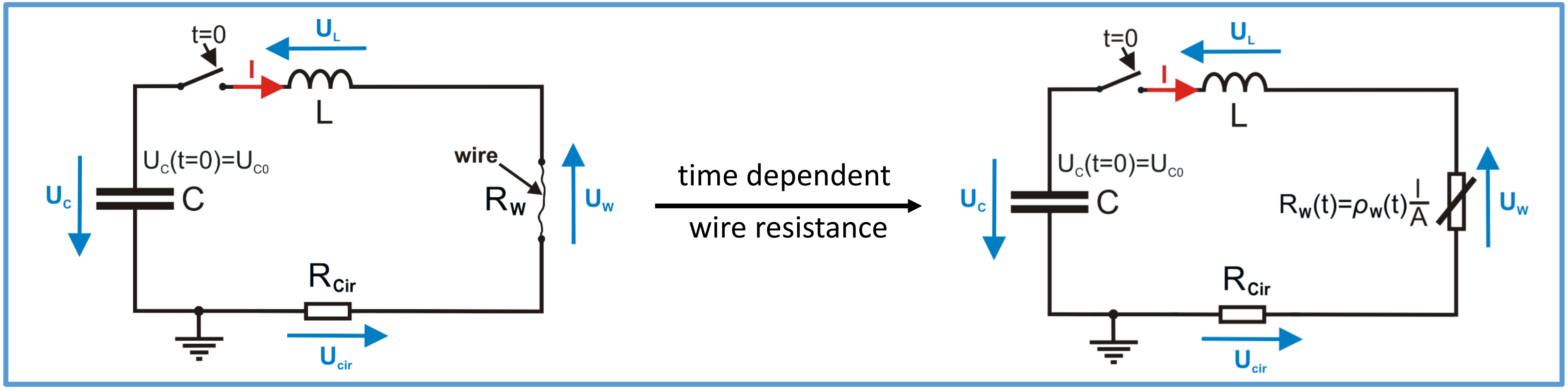
Practical Application:

- high intensity light source
- production method for metal nanoparticles
- method for sheet metal forming (using shock waves)

Advantage: - energy may be adjusted very accurately
- no legal restraints
- new capacitor technology allows small setups

Current Pulse Shape of Exploding Wires





Goal of the Master Thesis:

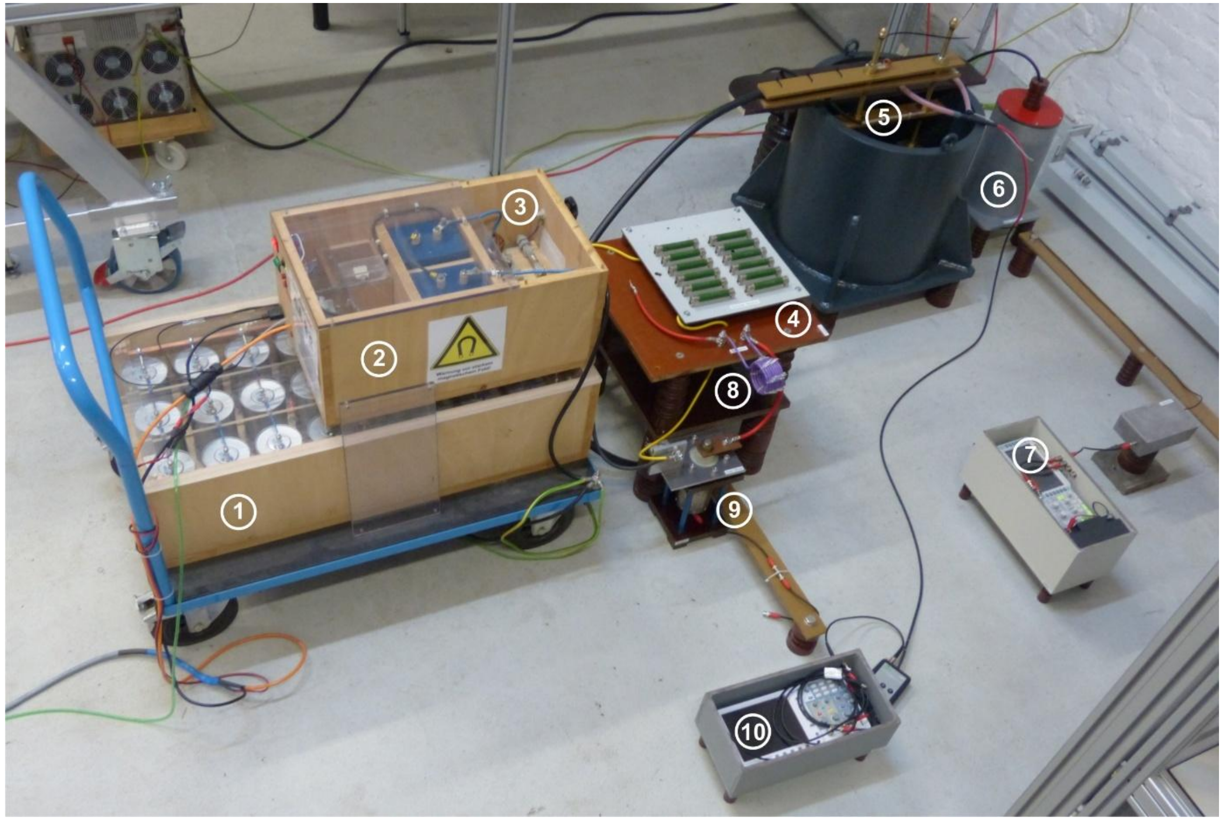
Experimental investigations of exploding wires (alloy X5CrNi18-10)

- **Statistical proof of repeatability**
- **Capacitor voltage variations**
- **Wire diameter and wire length variations**

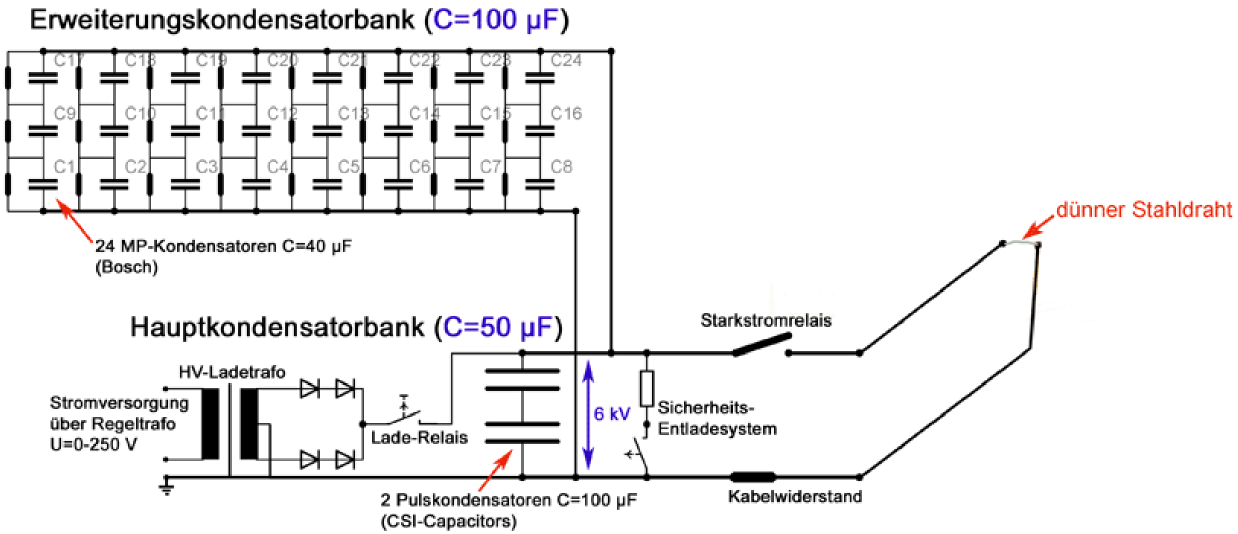
Design of a simulation model

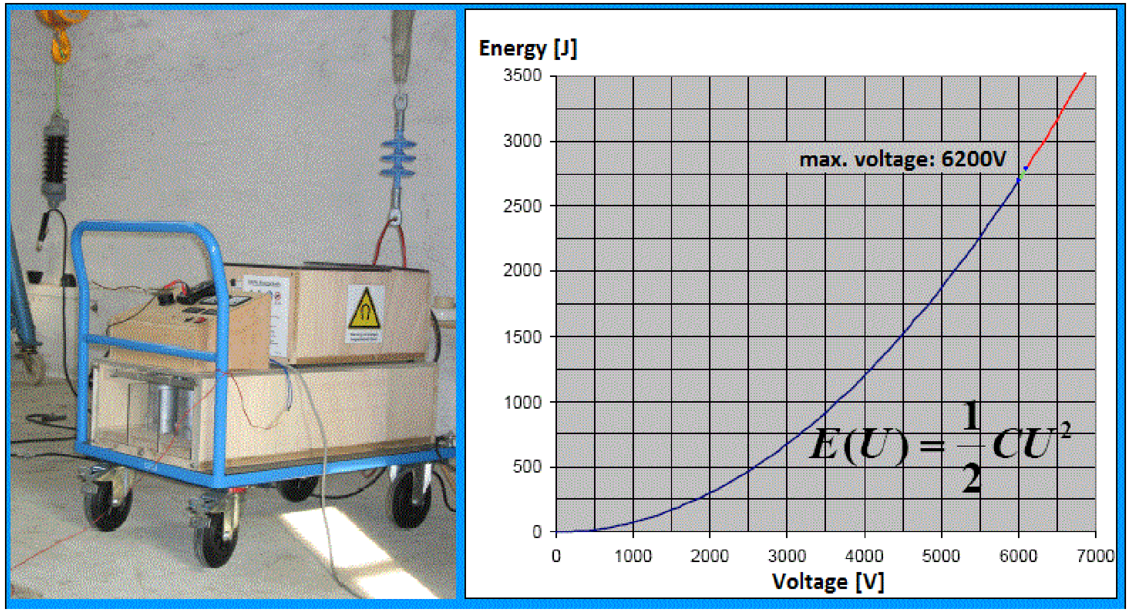
- **Derivation of a coupled differential equation system**
- **Software implementation**
- **first simulation results**

Experimental Setup

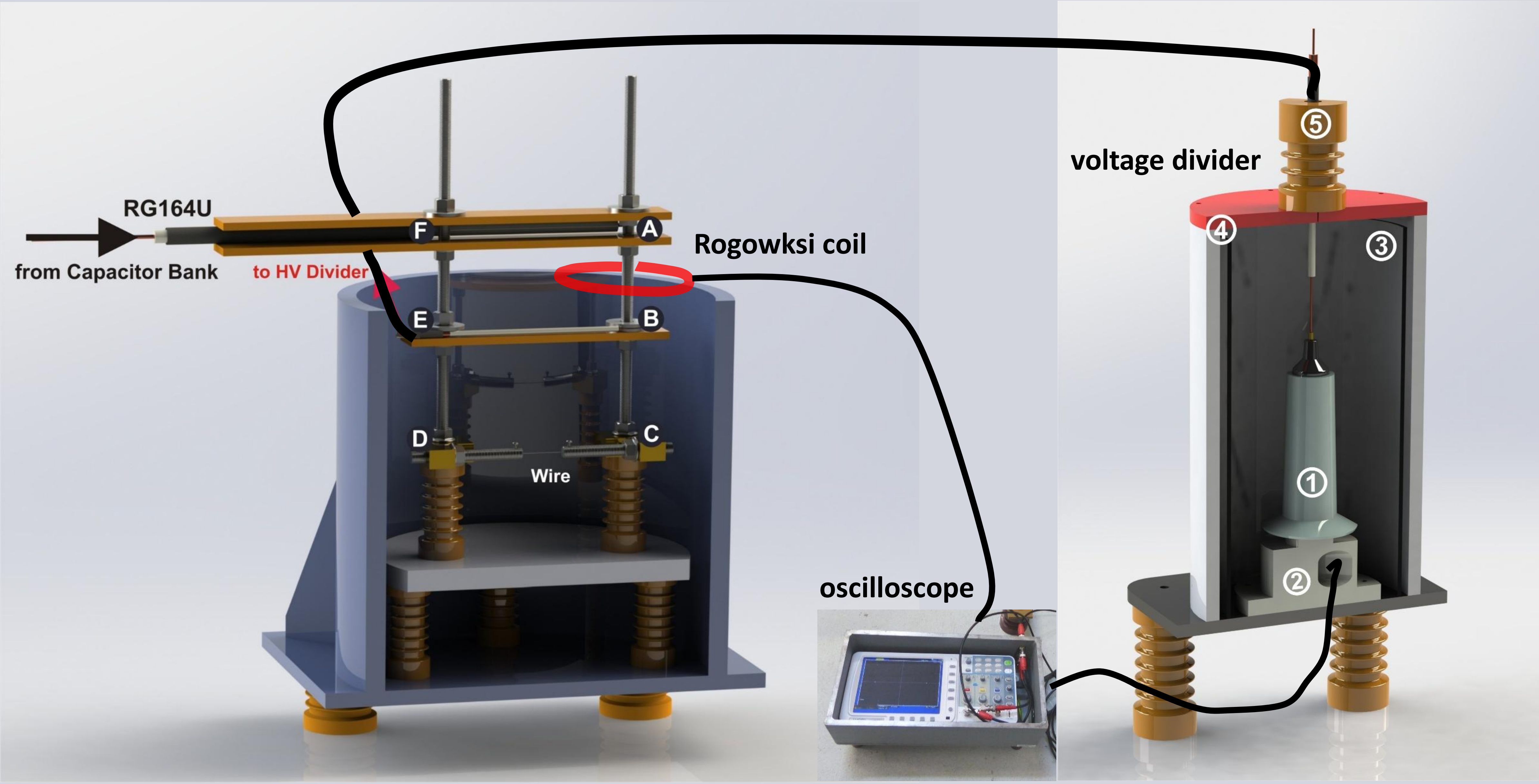


① *capacitor bank KB2,* ② *capacitor Bank KB1,* ③ *high current switch,* ④ *safety dischargesystem 1,* ⑤ *discharge chamber with metal wire,* ⑥ *high voltage divider,* ⑦ *digital storage oscillosope nr. 2,* ⑧ *variable inductance L*,* ⑨ *coaxial shunt resistor,* ⑩ *digital storage oscillosope nr. 1*

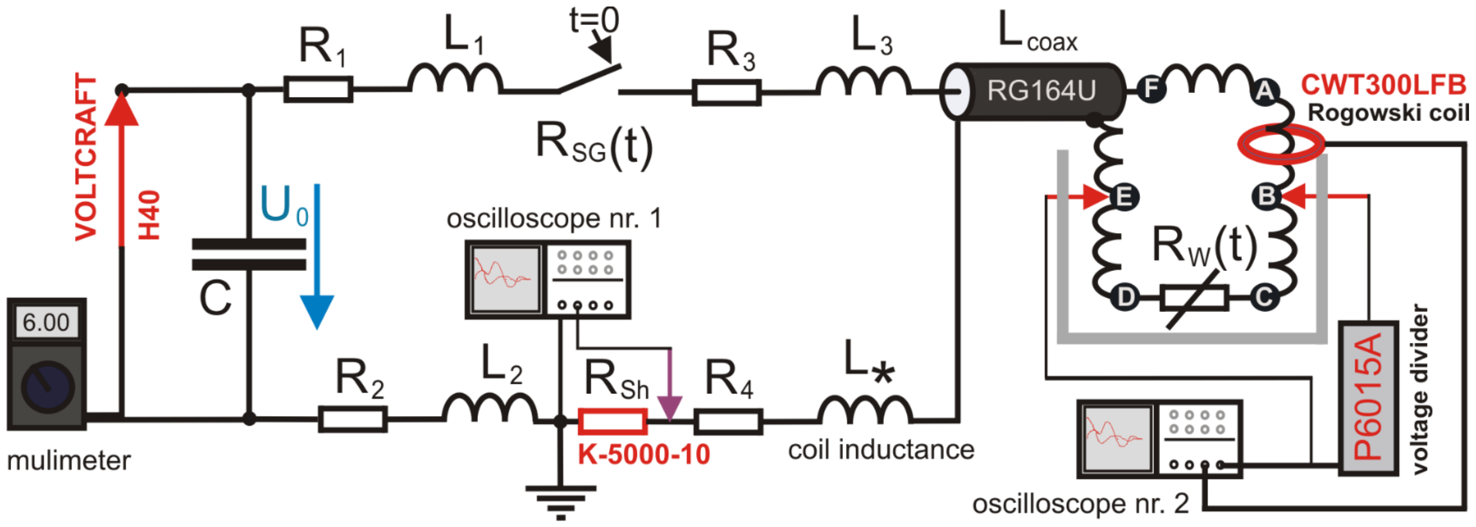


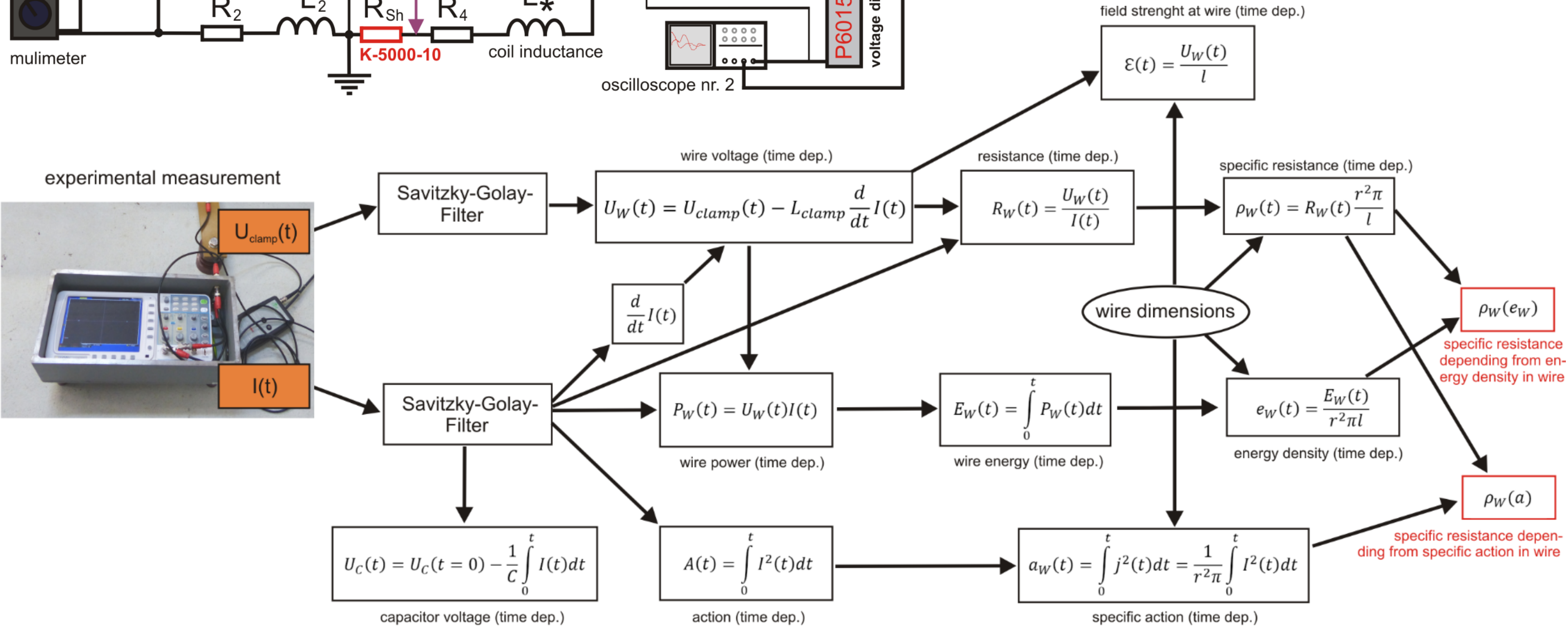


Wire Voltage and Current Measurements



Method of Data Analysis

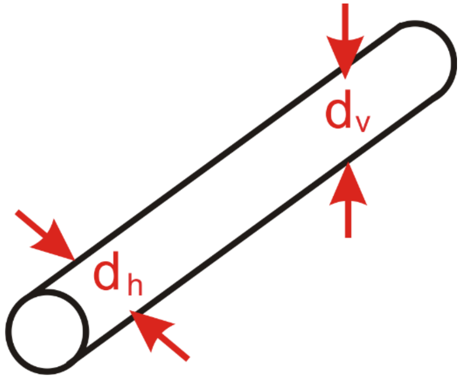


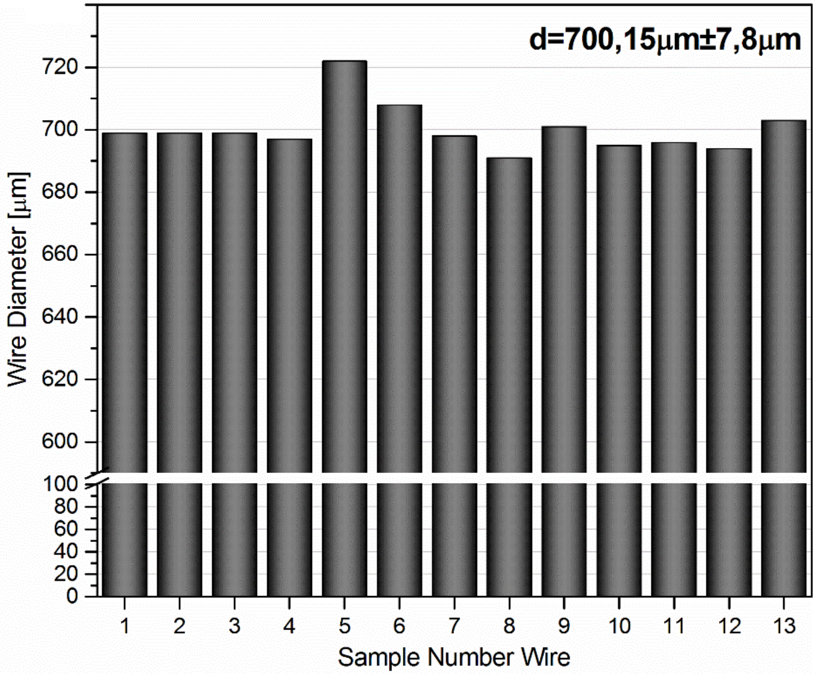


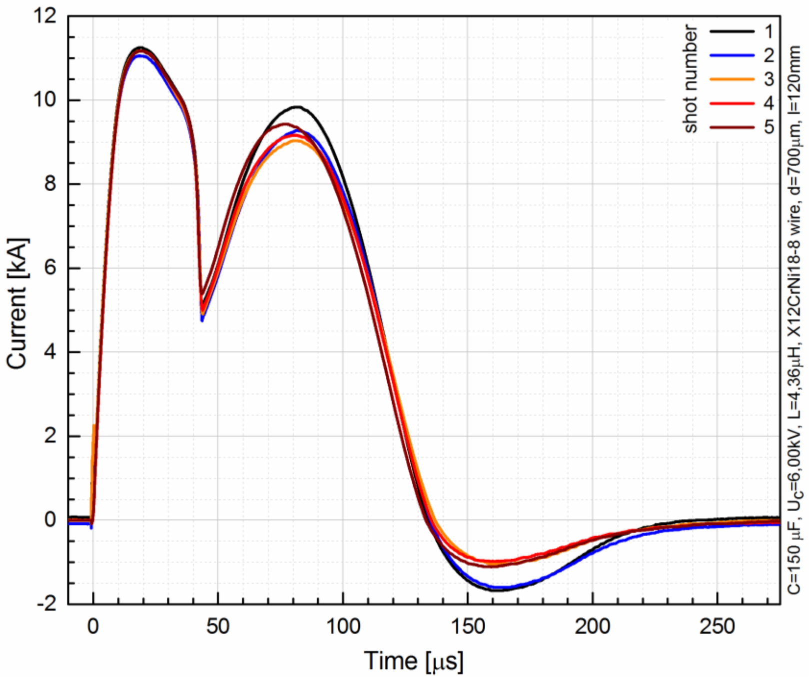
Experimental Investigations of Exploding Wires

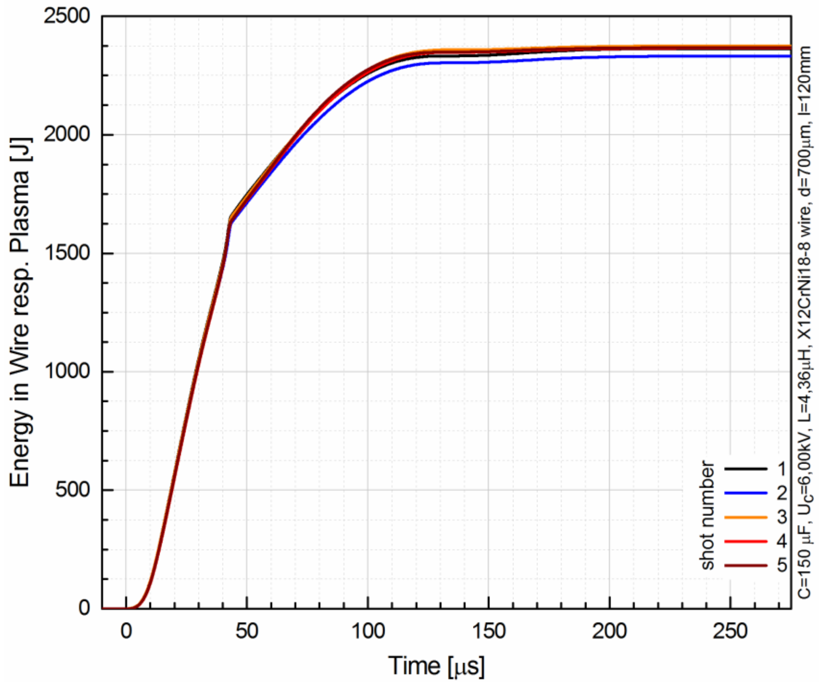
Statistical Proof of Repeatability

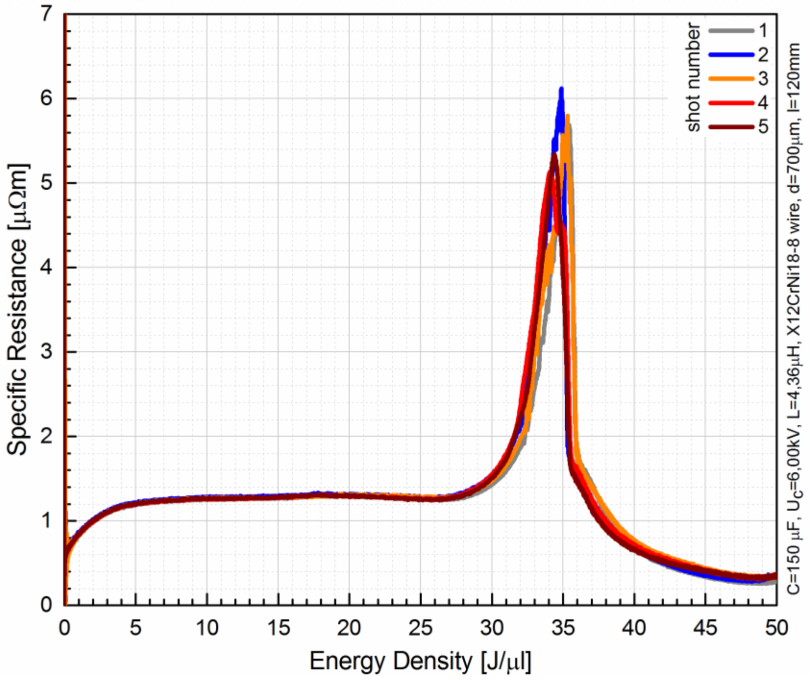
- wire with same length (120mm) and diameter (700µm) was used
- length variations where less then 1mm: dl<|±1mm|
- diameter variations where measured with a micrometer screw in horizontal (d_h) and vertical (d_v) direction



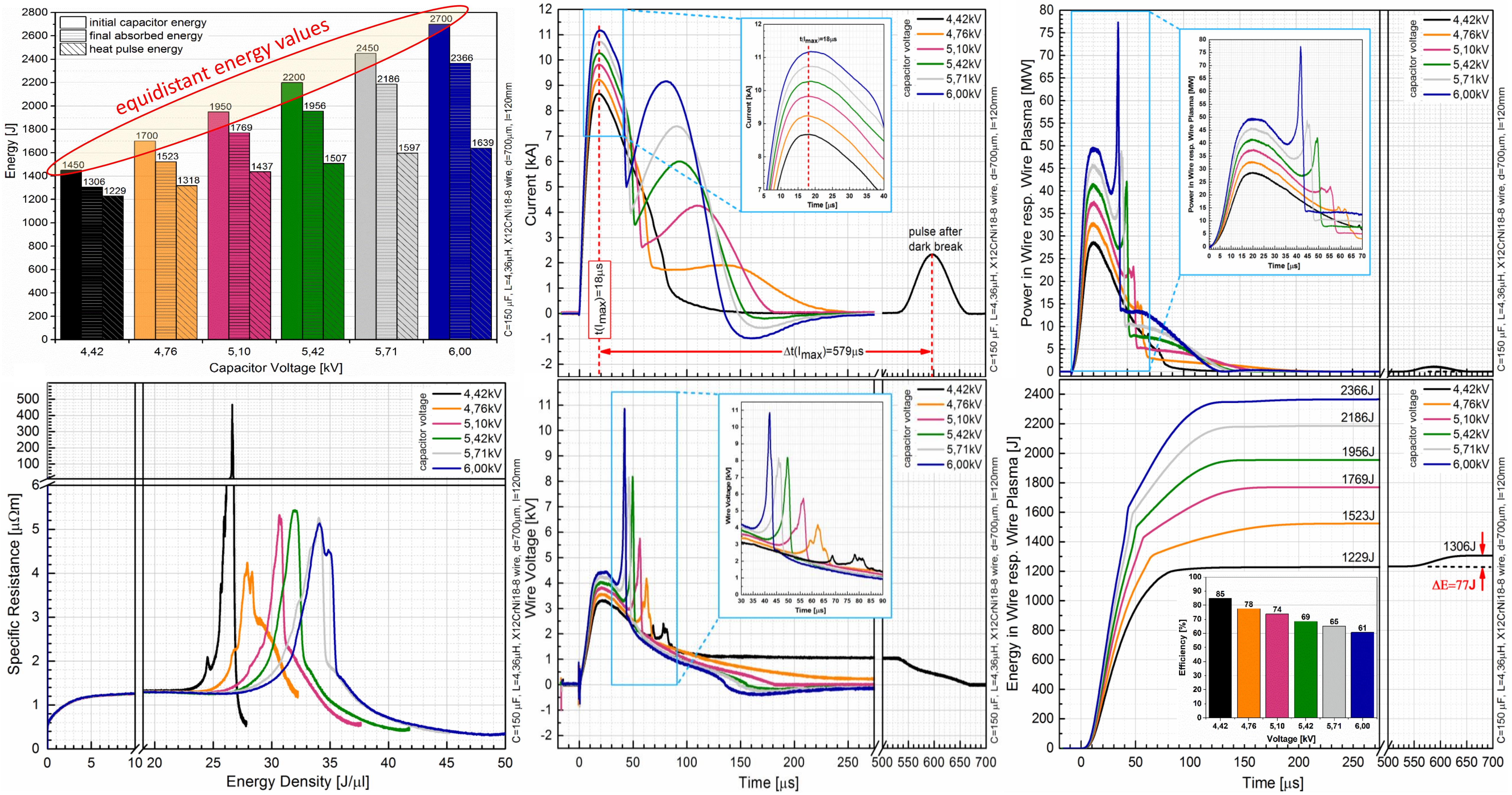






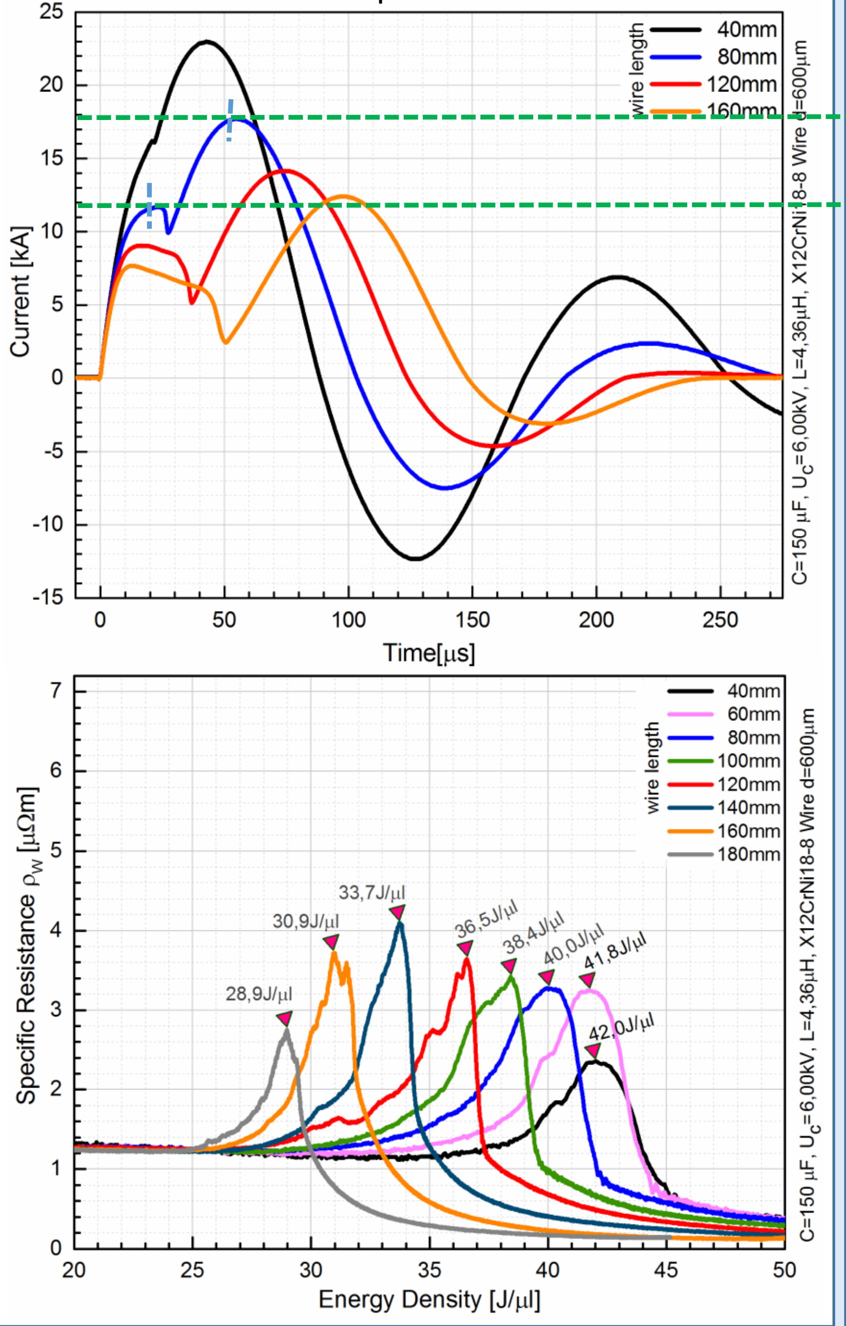


Capacitor Voltage Variations (wires with d=700µm, l=120mm)

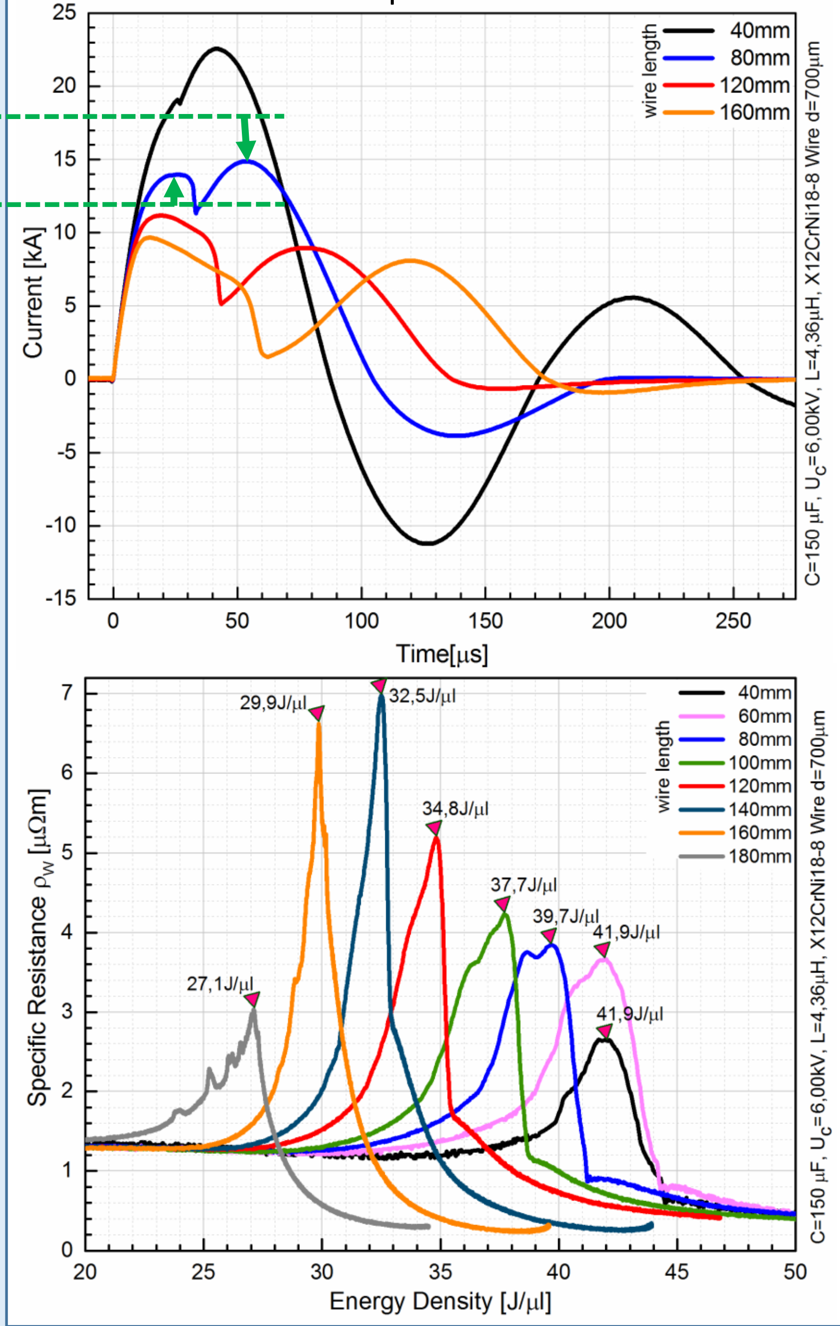


Discharge Current and Resistance Characteristic for different Wire Diameters

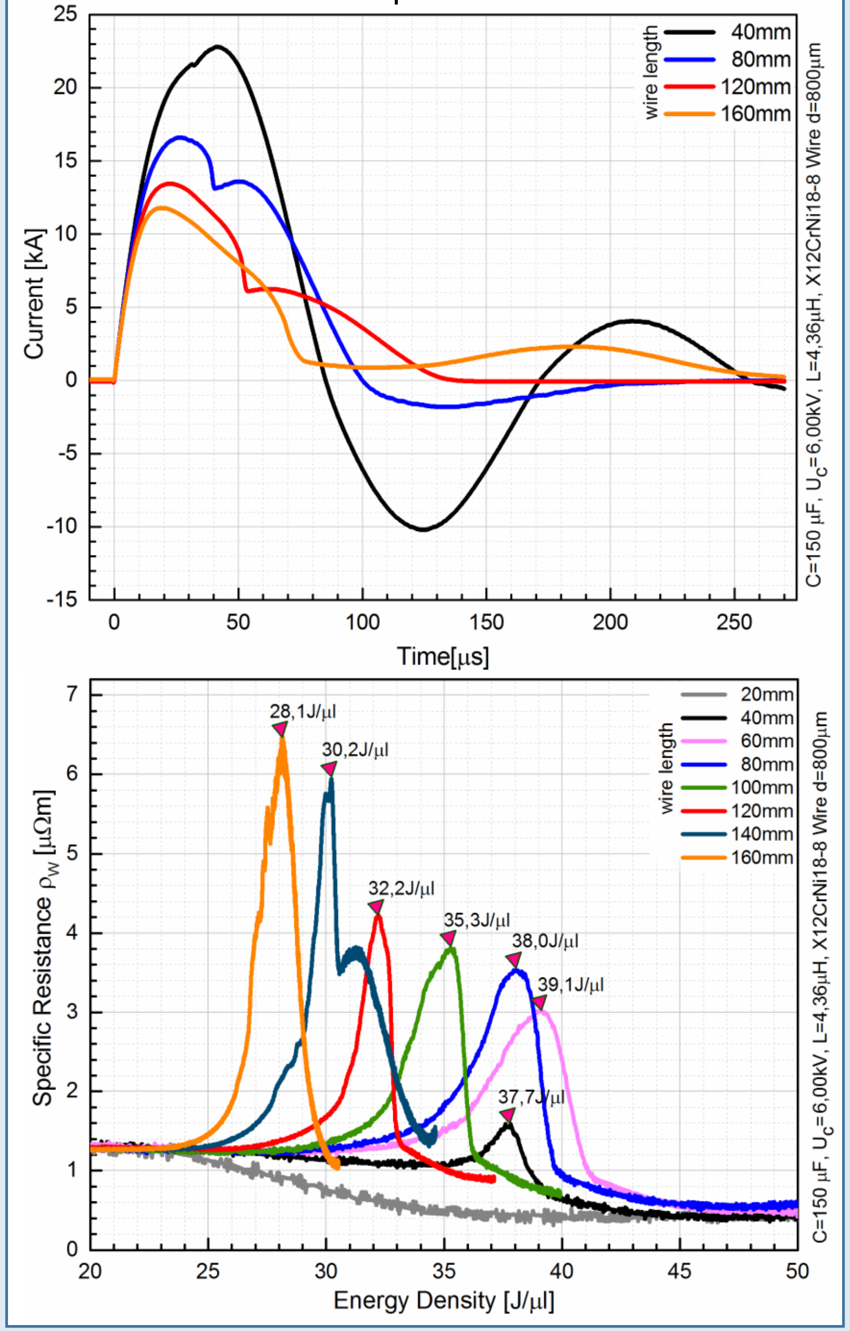
600µm Wires



700µm Wires

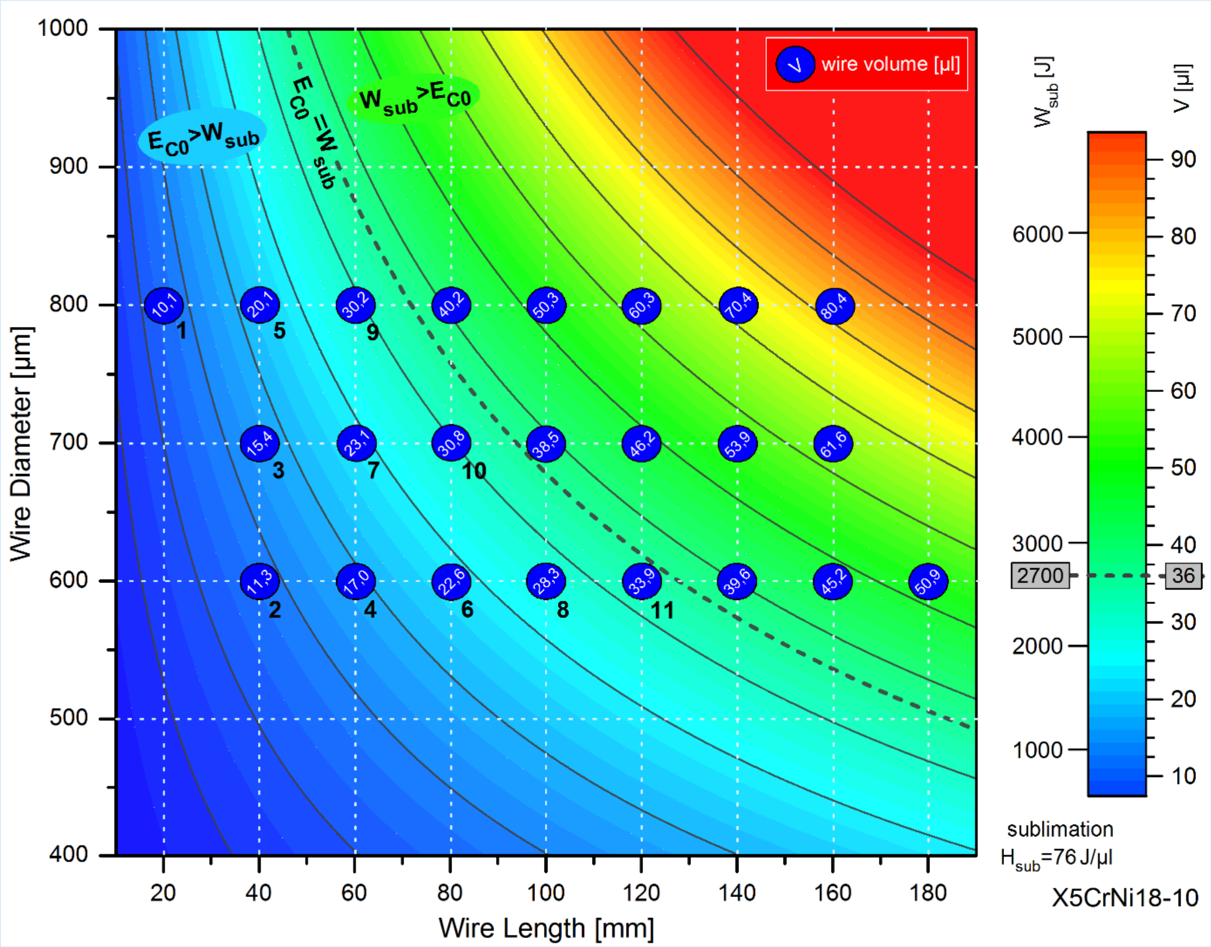


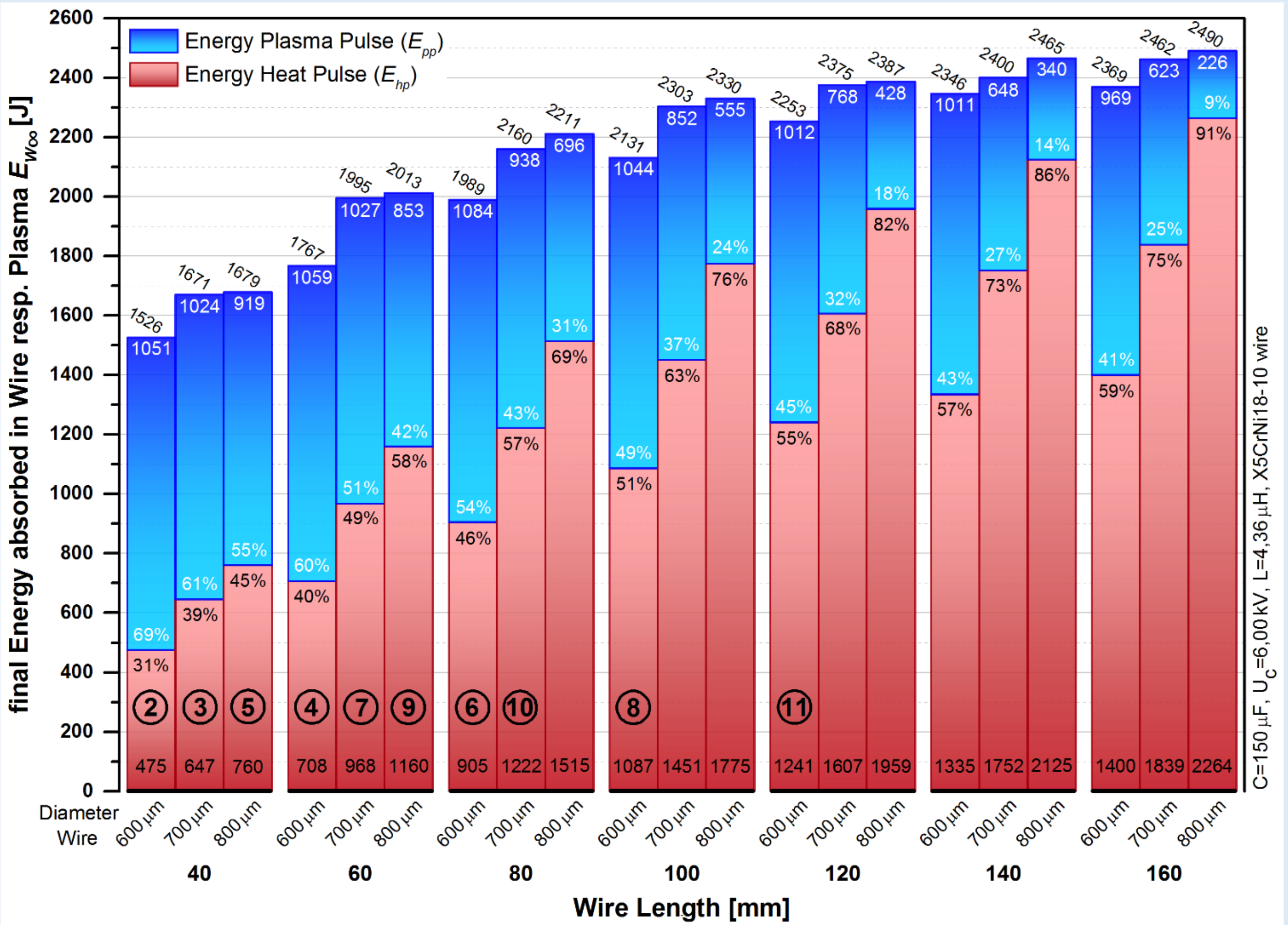
800µm Wires



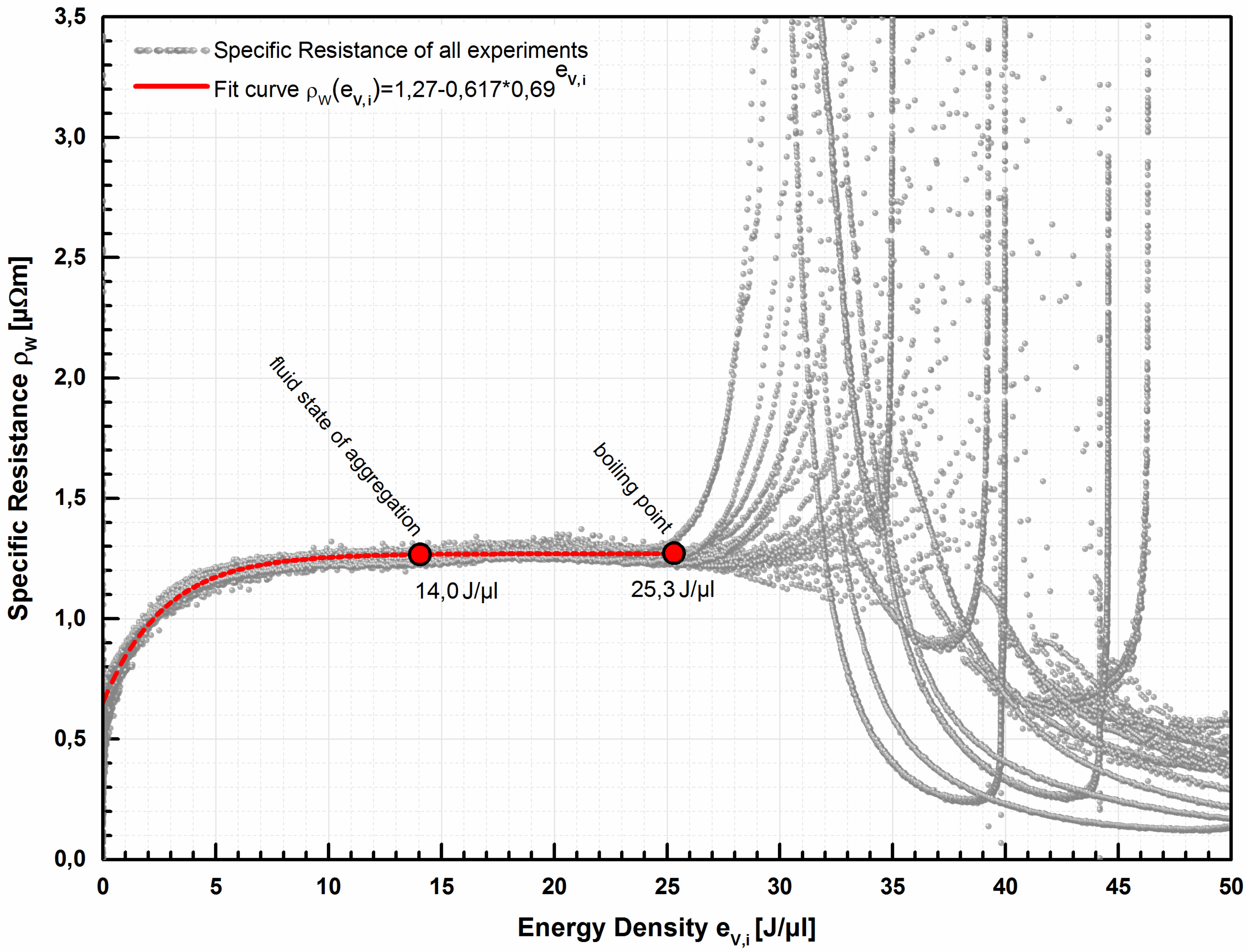
Energy absorbed in the Wire depending on Wire Dimensions

- Energy absorbed in wire may be less or larger than needed energy for total sublimation
- Influence of wire dimensions may be analysed by using wires with different length and diameter





Specific Resistance depending on Energy Density in Wire

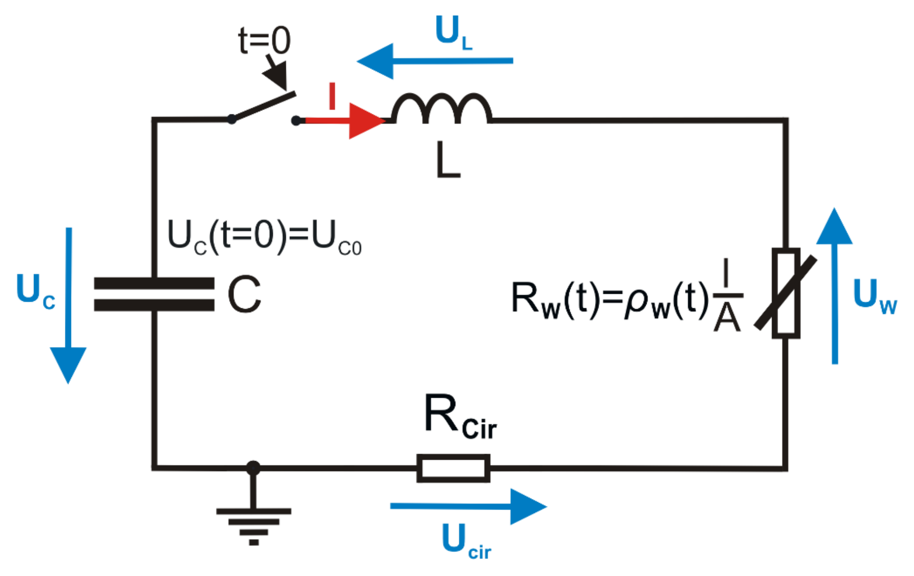


Design of a Simulation Model

$$U_C(t) + U_L(t) + U_{circuit}(t) + U_w(t) = 0 \quad \xrightarrow{\frac{d}{dt}}$$

$$\frac{1}{C}I(t) + L\frac{d^2I(t)}{dt^2} + \frac{dI}{dt}\left(R_{circuit} + R_w(t)\right) + I(t)\frac{dR_w(t)}{dt} = 0$$

$$\Rightarrow \frac{d^2I(t)}{dt^2} = -\frac{1}{L}\left[\frac{1}{C}I(t) + \frac{dR_w(t)}{dt}I(t) + \left(R_{circuit} + R_w(t)\right)\frac{dI}{dt}\right]$$



$$R_w(t) = \rho(t)\frac{l}{S} \quad \Rightarrow \quad \frac{dR_w(t)}{dt} = \frac{d\rho(t)}{dt}\frac{l}{S}$$

Assume the *specific resistance* as a linear function of the (homogenous) *energy density* in the wire:

$$\rho(t) = \rho\left(e(t)\right) = \rho_0 + me(t) \quad \Rightarrow \quad \frac{d\rho(t)}{dt} = m\frac{de(t)}{dt}$$

$$\Rightarrow \frac{d^2I(t)}{dt^2} = -\frac{1}{L}\left[\frac{1}{C}I(t) + m\frac{de(t)}{dt}\frac{l}{S}I(t) + \left(R_{circuit} + (\rho_0 + me(t))\frac{l}{S}\right)\frac{dI}{dt}\right]$$

power in the wire:

$$P_w(t) = I^2(t)\rho(t)\frac{l}{S}$$

volume power density in the wire:

$$\Rightarrow \frac{de(t)}{dt} = \frac{dP_w(t)}{dV} = I^2(t)\rho(t)\frac{l}{SV} = I^2(t)\frac{\rho(t)}{S^2} = \frac{1}{S^2}\left(\rho_0 + me(t)\right)I^2(t)$$

formula letters:

L	= total circuit inductance	[H]
R_W	= wire resistance	[Ω]
ρ	= specific ristance wire	[Ωm]
ρ_0	= initial specific resitance	[Ωm]
m	= slope factor	[l·Ωm/J]
e	= energy density in wire	[J/l]
S	= wire cross section	[m^2]
l	= wire length	[m]
V	= wire volume	[m^3]

Table of Coupled Differential Equation System (ODE)

	Equation Nr.	Boundary Conditions	Differential Equation	Solved Function
Current	**0**	$I(0) = 0$	$\frac{dI(t)}{dt} = s(t)$	$I(t)$
Current-Deviation	**1**	$\frac{dI(0)}{dt} = \frac{U_C(0)}{L}$	$\frac{ds(t)}{dt} = \frac{d^2I(t)}{dt^2} = -\frac{1}{L}\left[\frac{1}{C}I(t) + \frac{ml}{S^3}\big(\rho_0 + me(t)\big)I^3(t) + \left(R_{circuit} + (\rho_0 + me(t))\frac{l}{S}\right)\frac{dI}{dt}\right]$	$s(t) = \frac{dI(t)}{dt}$
Energy Density	**2**	$e(0) = 0$	$\frac{de(t)}{dt} = \frac{1}{S^2}\big(\rho_0 + me(t)\big)I^2(t)$	$e(t)$
Capacitor Voltage	**3**	$U_C(0) = U_0$	$\frac{dU_C(t)}{dt} = -\frac{I(t)}{C}$	$U_C(t)$
Action	**4**	$A(0) = 0$	$\frac{dA(t)}{dt} = I^2(t)$	$A(t)$

capacitor energy

$$E_C(t) = \frac{1}{2}CU_C^2(t)$$

$$E_L(t) = \frac{1}{2}LI^2(t)$$

inductive energy

$$E_W(t) = e(t)r^2 l$$

wire energy

$$\rho(t) = \rho\big(e(t)\big) = \rho_0 + me(t)$$

specific resistance

$$U_W(t) = R_W(t)I(t) = \rho(t)\frac{l}{r^2\pi}I(t)$$

wire voltage

$$P_W(t) = I(t)U_W(t)$$

wire power

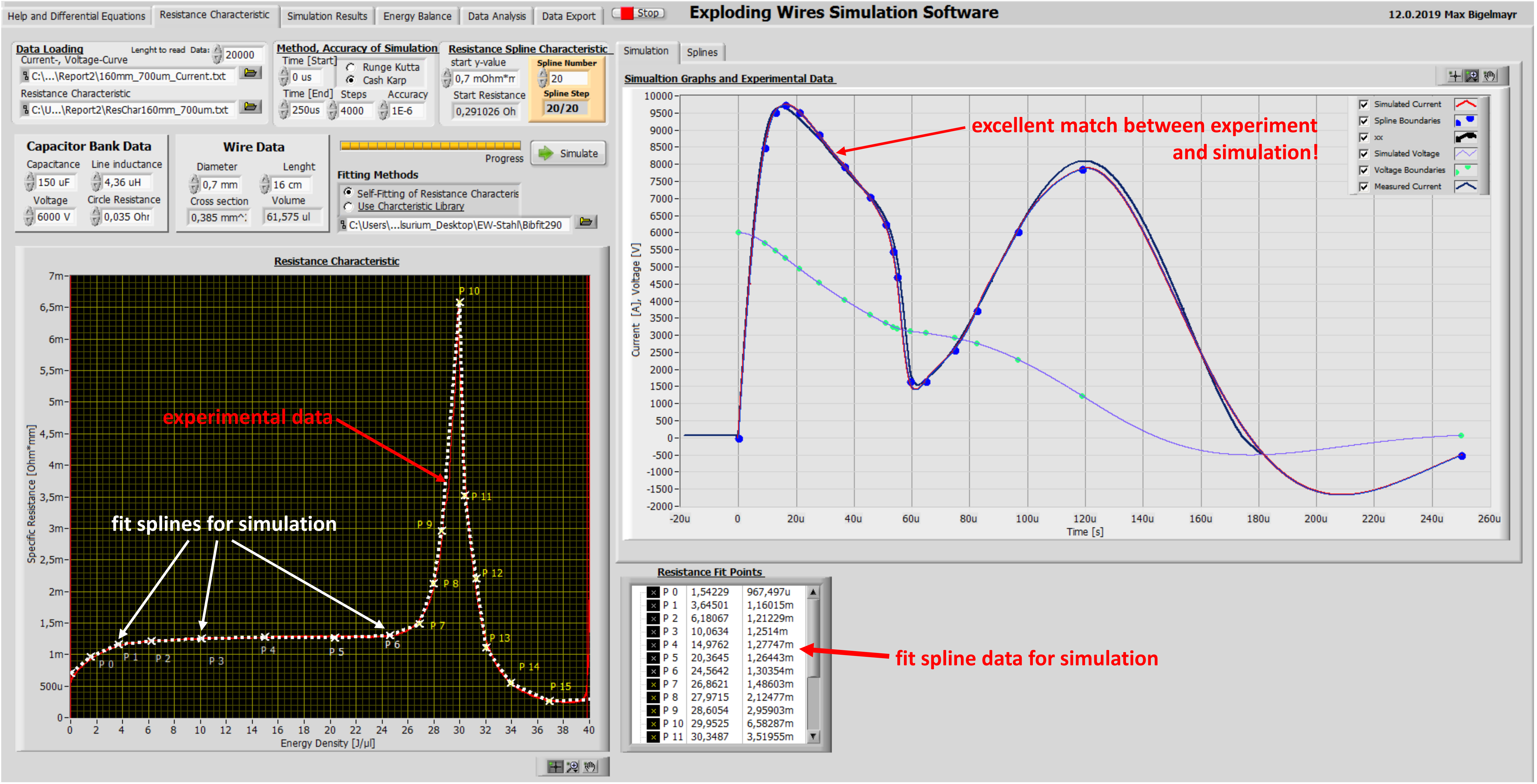
Founded differential equations built a *differential equation system*, which may be solved numerically using *Runge Kutta Algorithms.*

Check, whether method is correct:

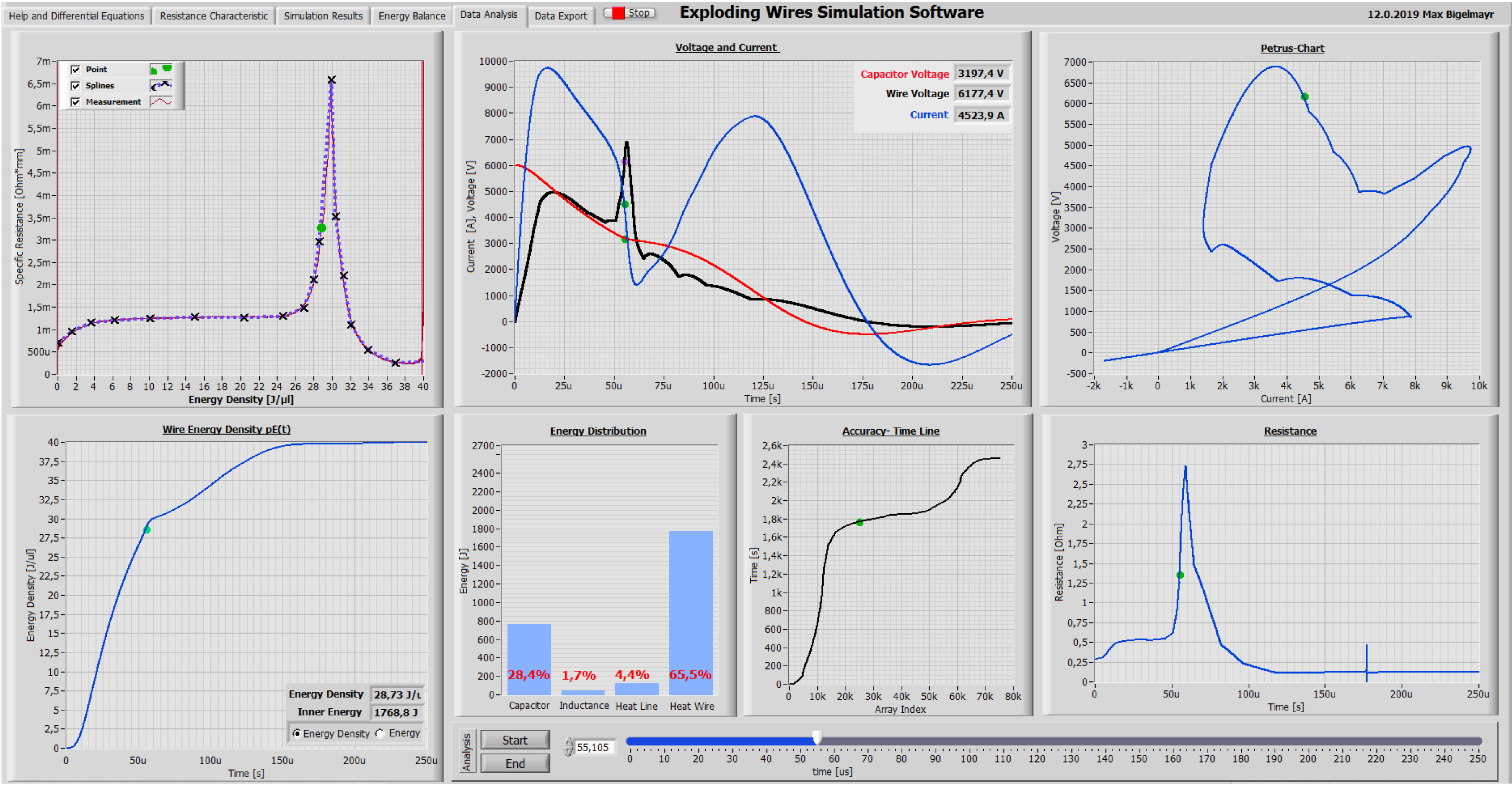
-> ***law of energy conservation***

$$E_{total} = \frac{1}{2}CU_C^2(t) + \frac{1}{2}LI^2(t) + e(t)r^2\pi l + A(t)R_{circuit} = const.$$

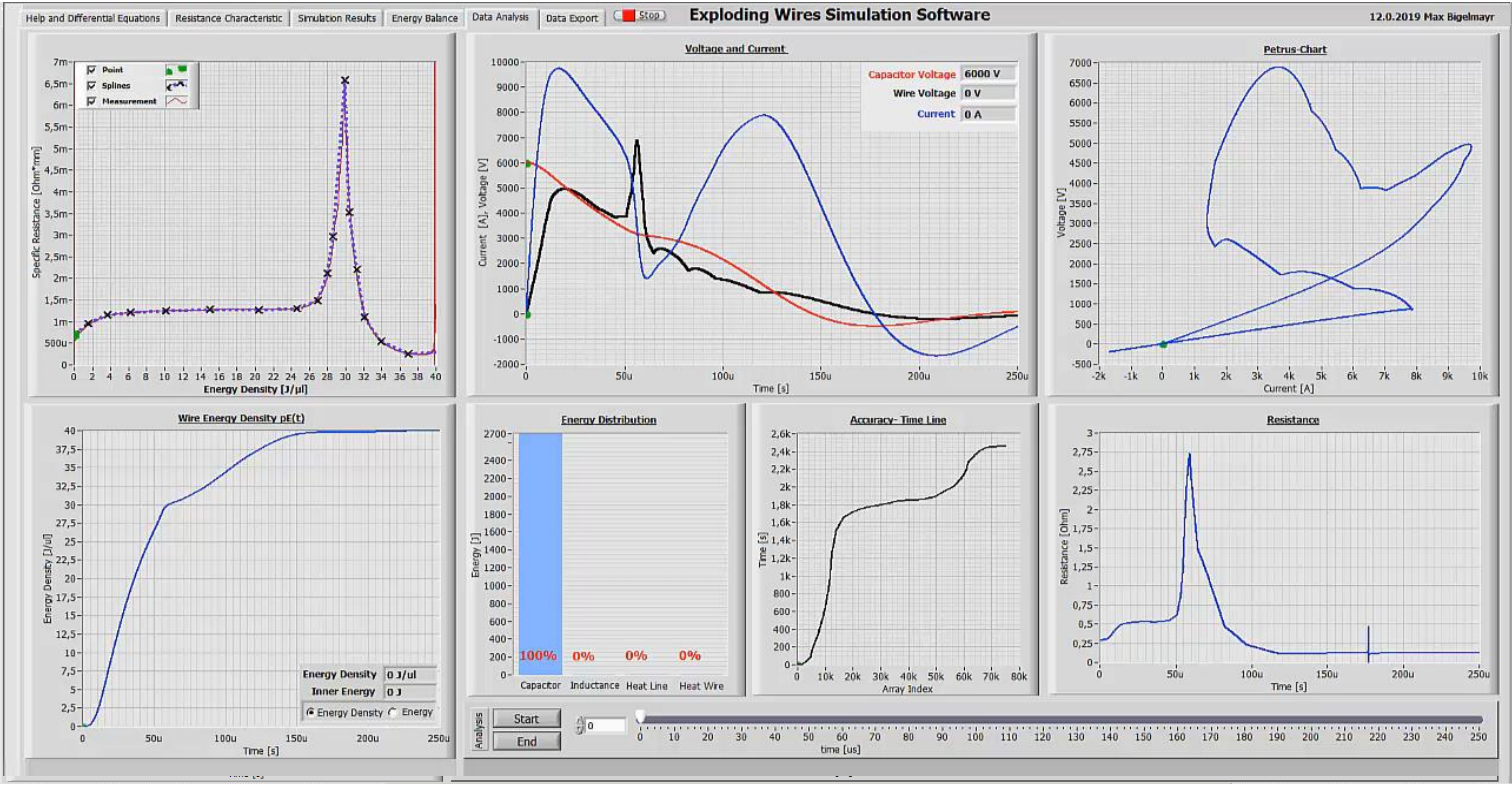
Software Implementation



Simulation Example with 160mm V2A-wire @700µm



Simulation Example with 160mm V2A-wire @700µm



Summary and Conclusion

Experimental investigations of exploding wires

- excellent repeatability of experiments
- discharge behaviour strongly depends on initial capacitor voltage:

  When enlarging the initial capacitor voltage, the absorbed energy in the wire increases, while the efficiency decreases.

- discharge behaviour strongly depends on wire dimensions:

  When enlarging the wire diameter and length, the absorbed energy in the wire increases.

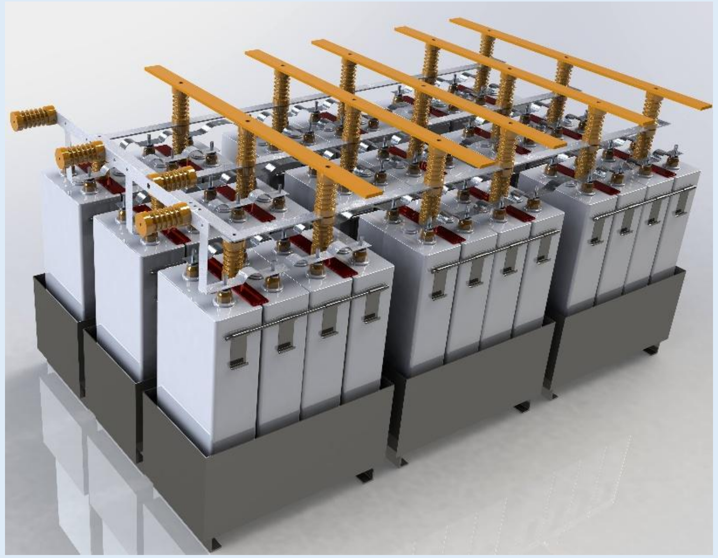
- resistance characteristic may be fitted by a fit function in the interval [0; 25.3J/µl]

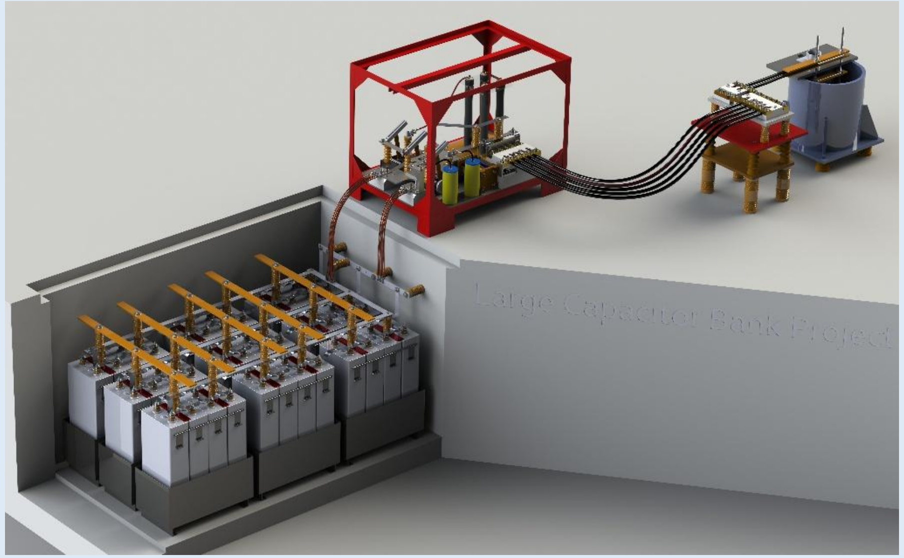
Design of a simulation model

- derivation of a coupled differential equation system (ODE)
- sucessful software implementation
- sucessful simulation of exploding wire experiments with given resistance characteristics
- verification of simulation results by comparison with experimental data
- proof of simulation accuracy by law of energy conservation

Future Experiments and Challenges

- Construction of a large capacitor bank system (40kJ@12kV) is in progress





Experimental investigations for generation of shockwaves under water

- finding of rules how to adjust the resistance characteristic
- use of more complex methods (*magnetohydrodynamic simulations*)

Improvement of the simulation model

Thanks for your attention!