

Studies on Pulsed Wire Discharges

Experimental and Numerical Investigations
on Exploding X5CrNi18-10 Wires

Presentation
Master Thesis

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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:

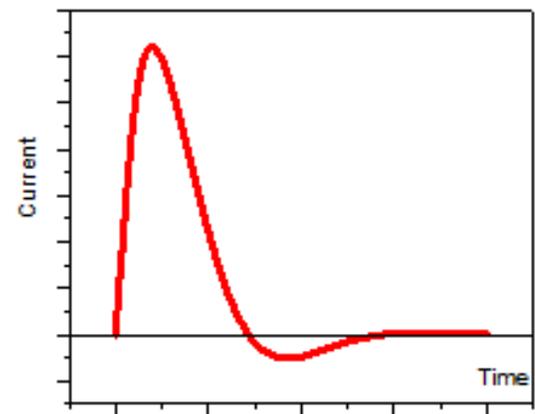
- high intensity light source
- production method for metal nanoparticles
- method for sheet metal forming (using shock waves)

Advantage:

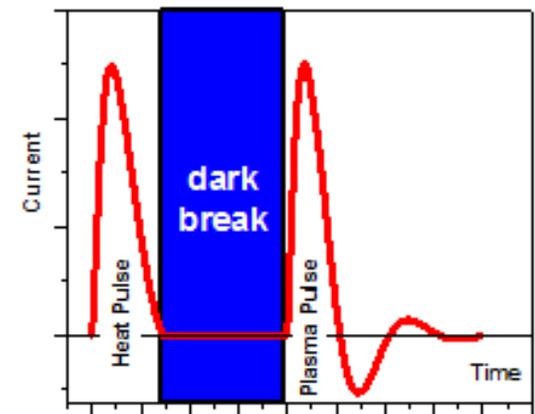
- energy may be adjusted very accurately
- no legal restraints
- new capacitor technology allows small setups



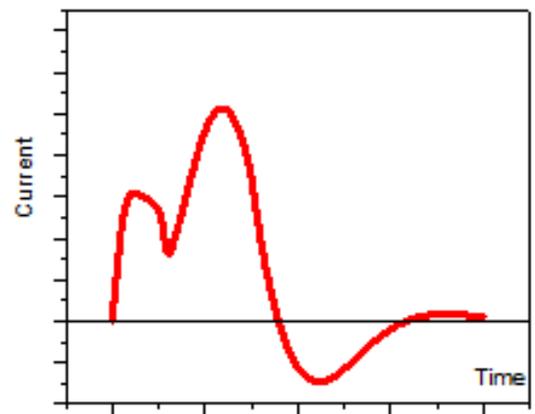
Current Pulse Shape of Exploding Wires



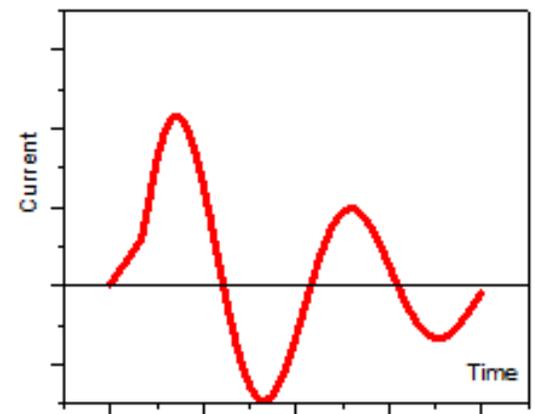
a) Single Heat-Pulse



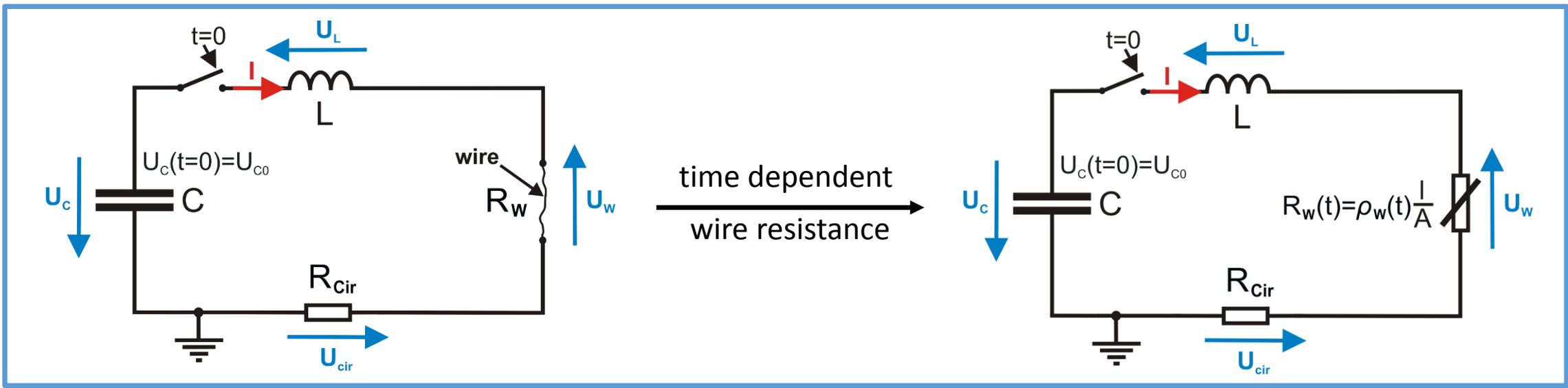
b) Heat-Pulse, Break, Plasma-Pulse



c) Heat-Plasma-Pulse



d) Direct Plasma-Pulse



Goal of the Master Thesis:

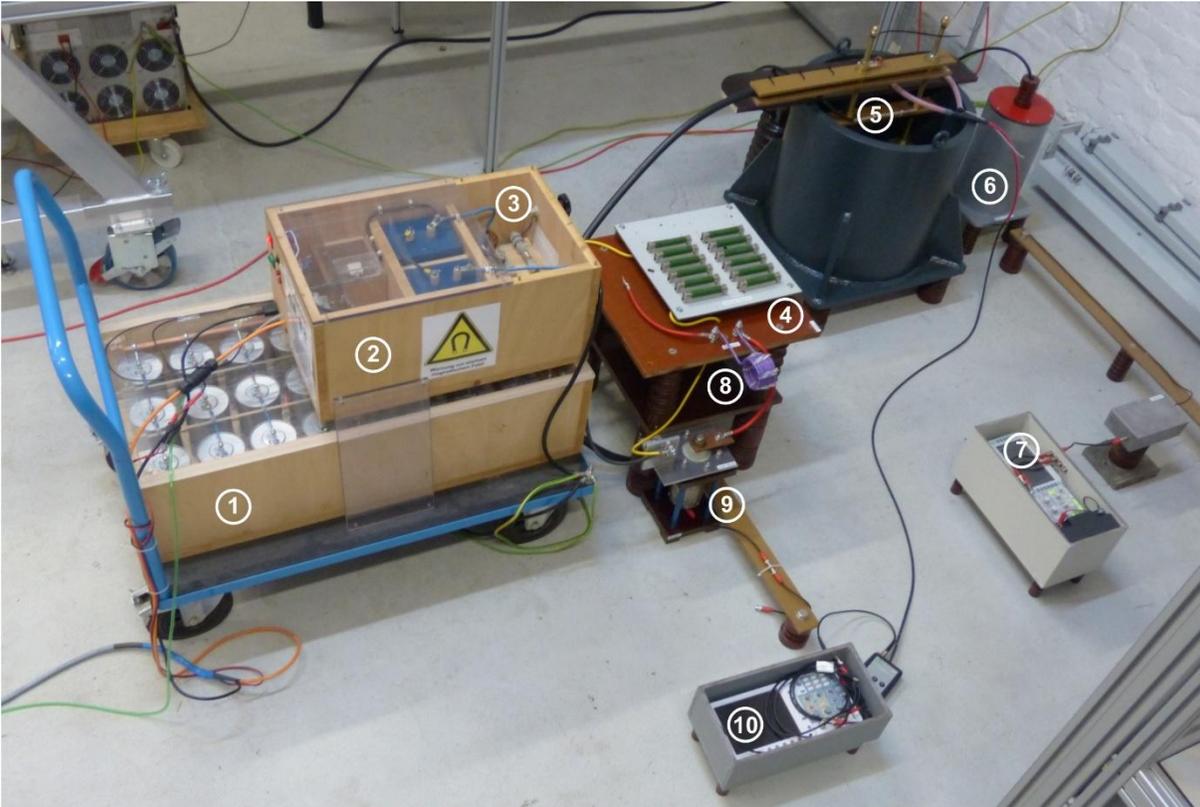
Experimental investigations of exploding wires (alloy X5CrNi18-10)

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

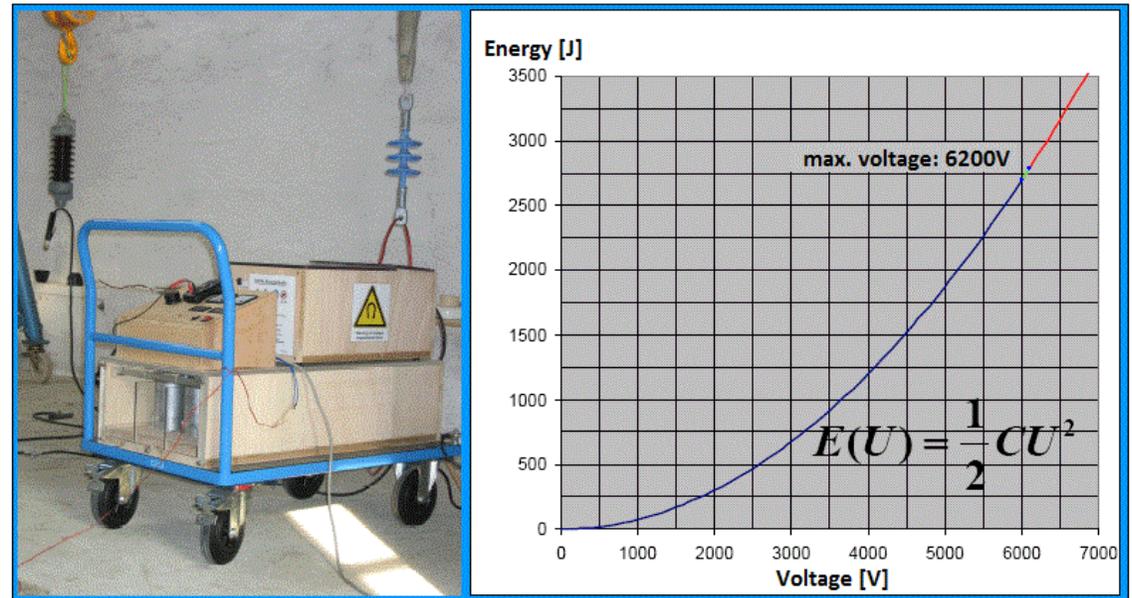
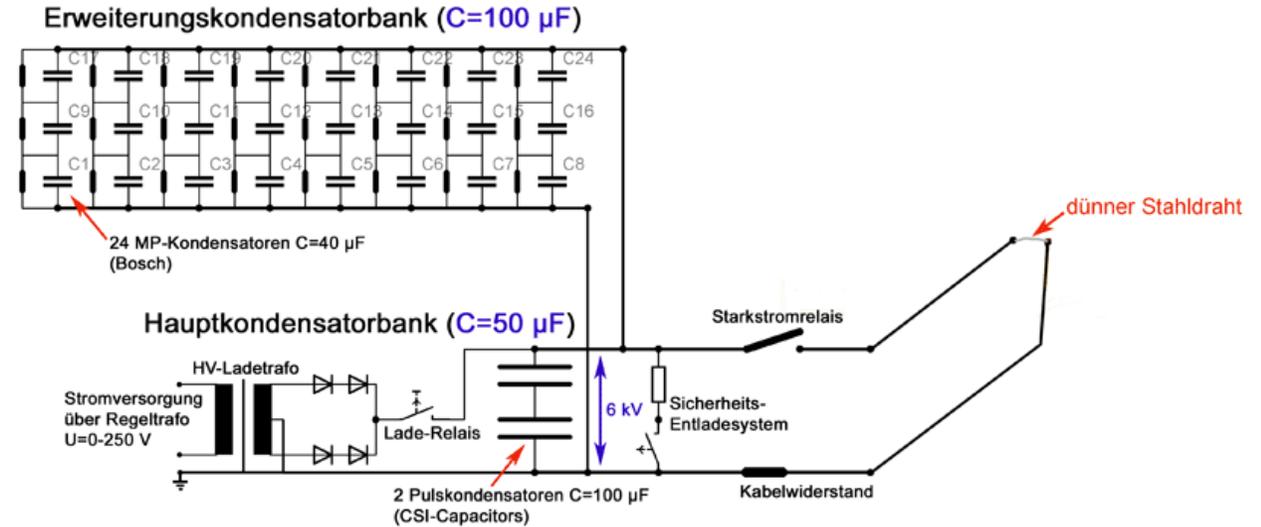
Design of a simulation model

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

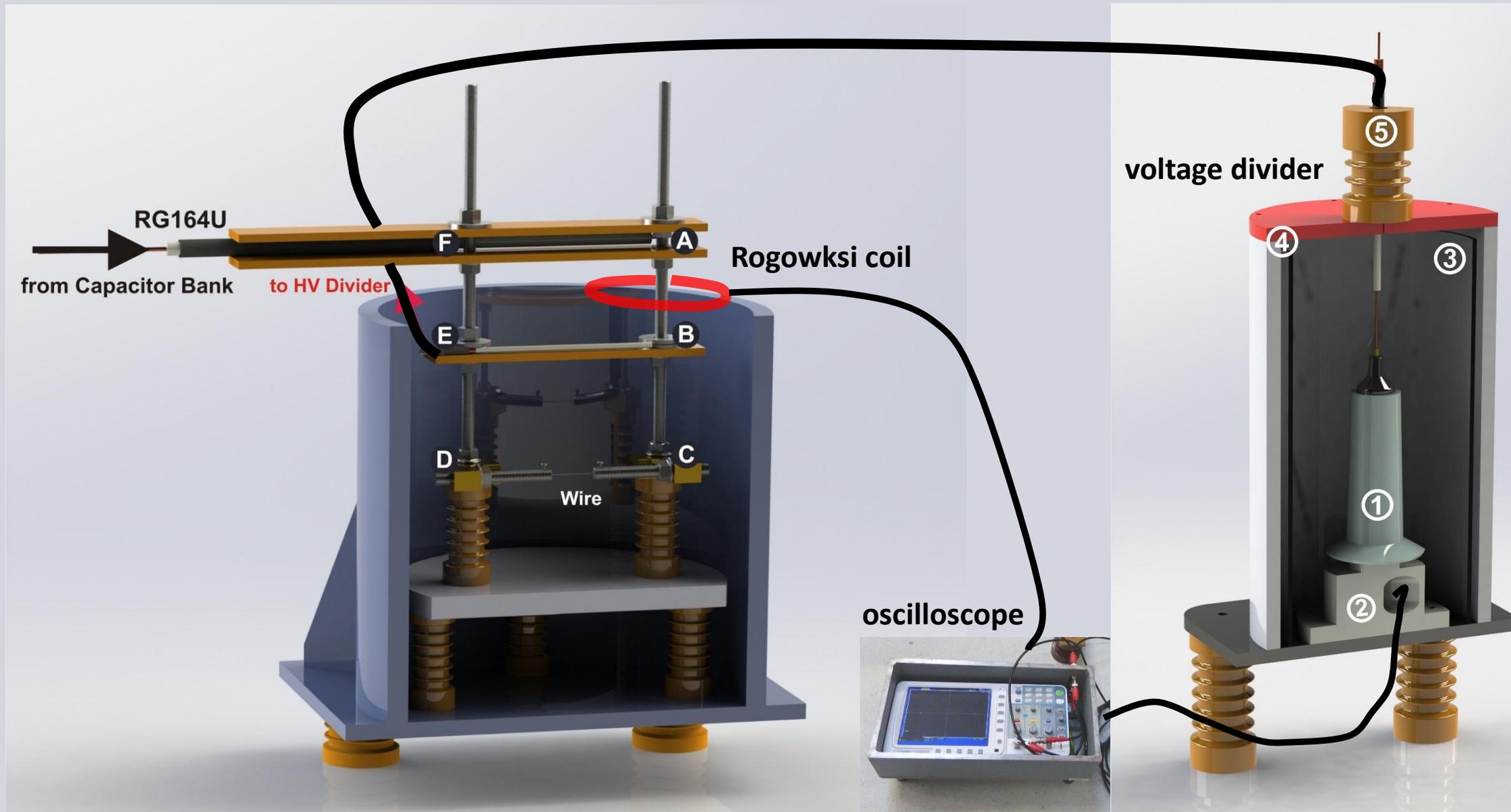
Experimental Setup



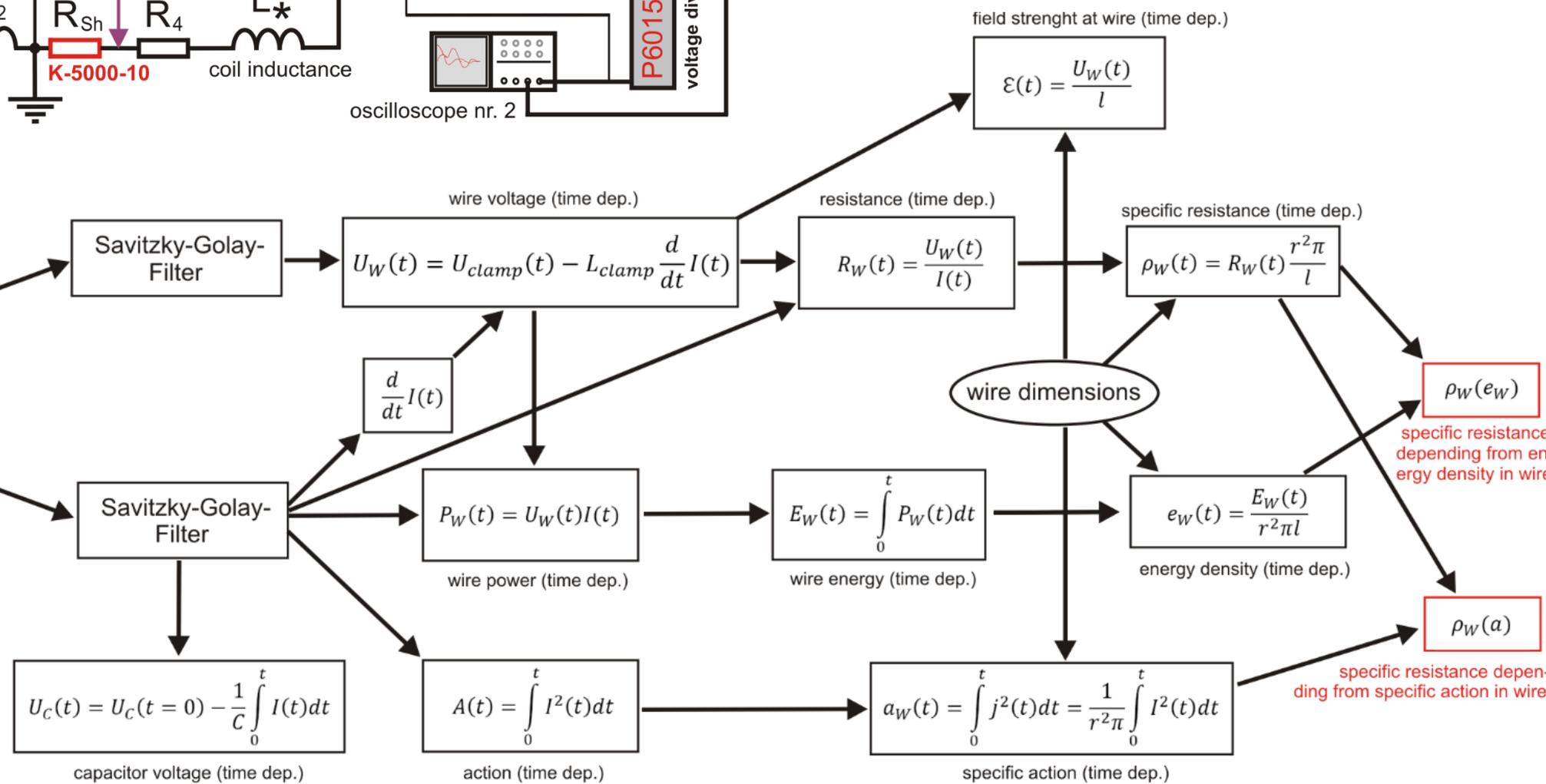
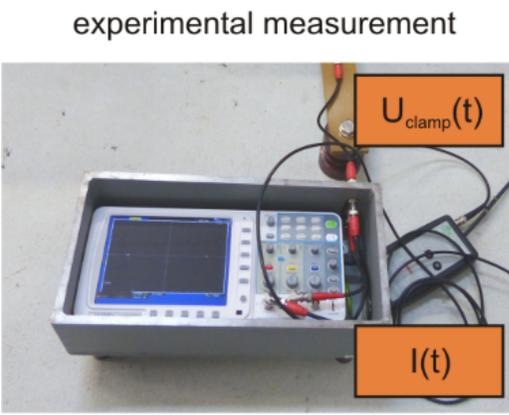
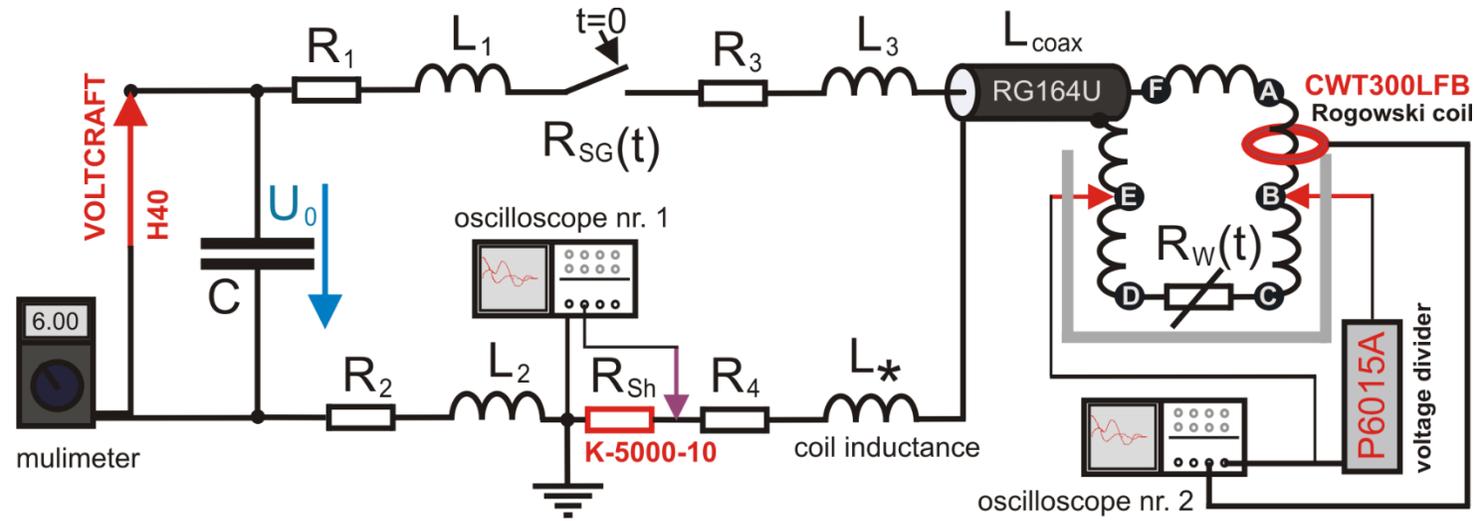
- ① capacitor bank KB2, ② capacitor Bank KB1, ③ high current switch,
 ④ safety dischargesystem 1, ⑤ discharge chamber with metal wire,
 ⑥ high voltage divider, ⑦ digital storage oscillosope nr. 2, ⑧ variable inductance L^* , ⑨ coaxial shunt resistor, ⑩ digital storage oscillosope nr. 1



Wire Voltage and Current Measurements



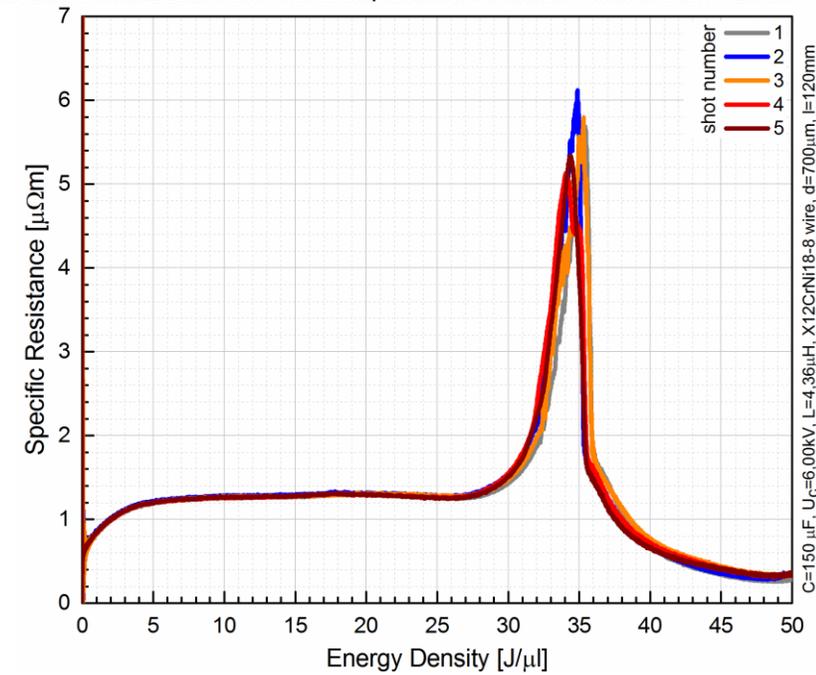
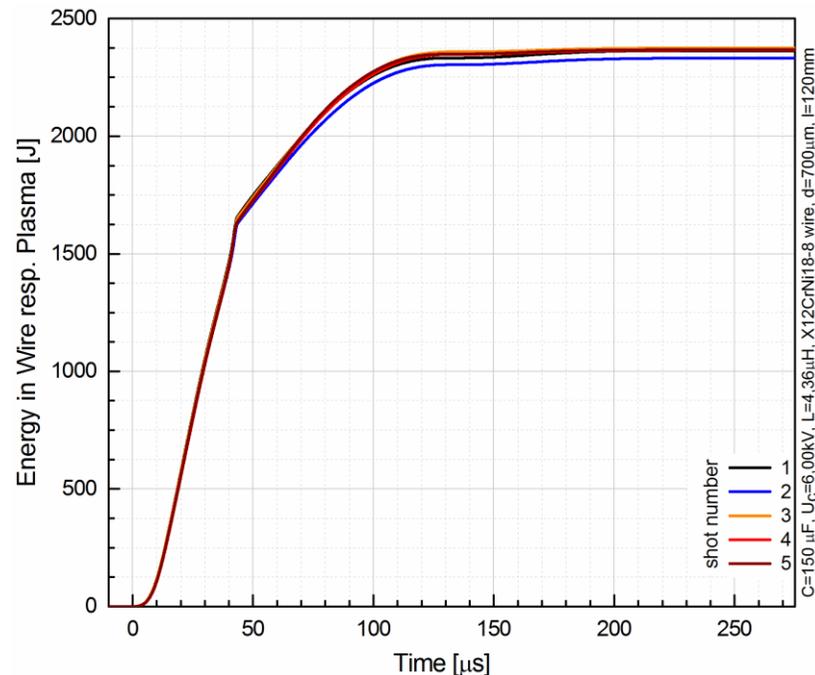
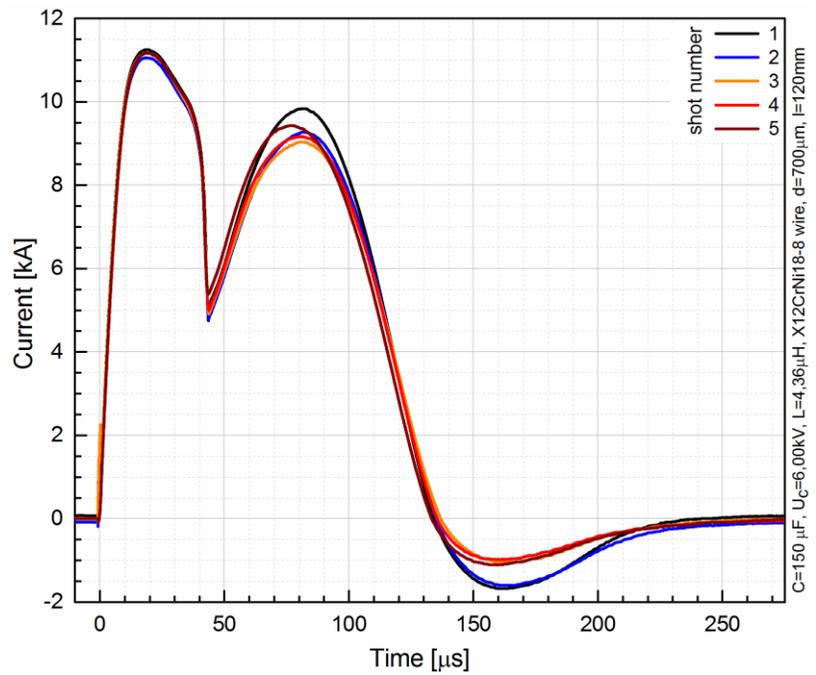
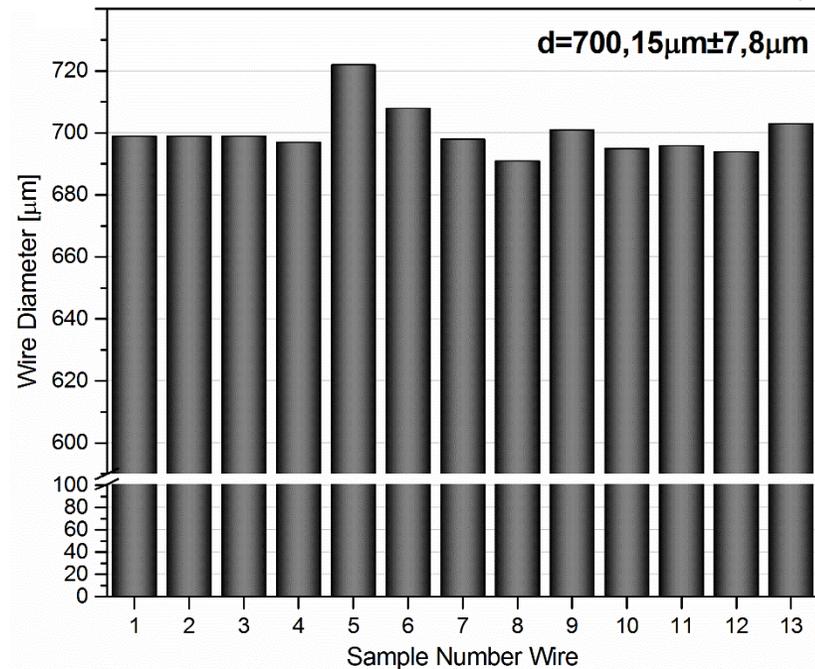
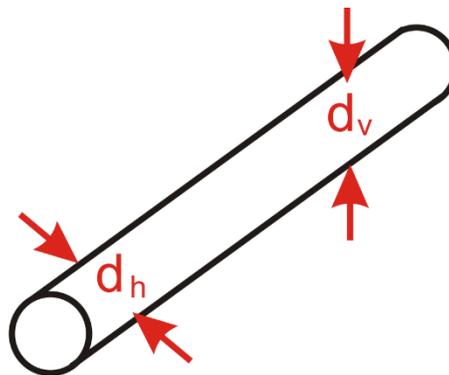
Method of Data Analysis



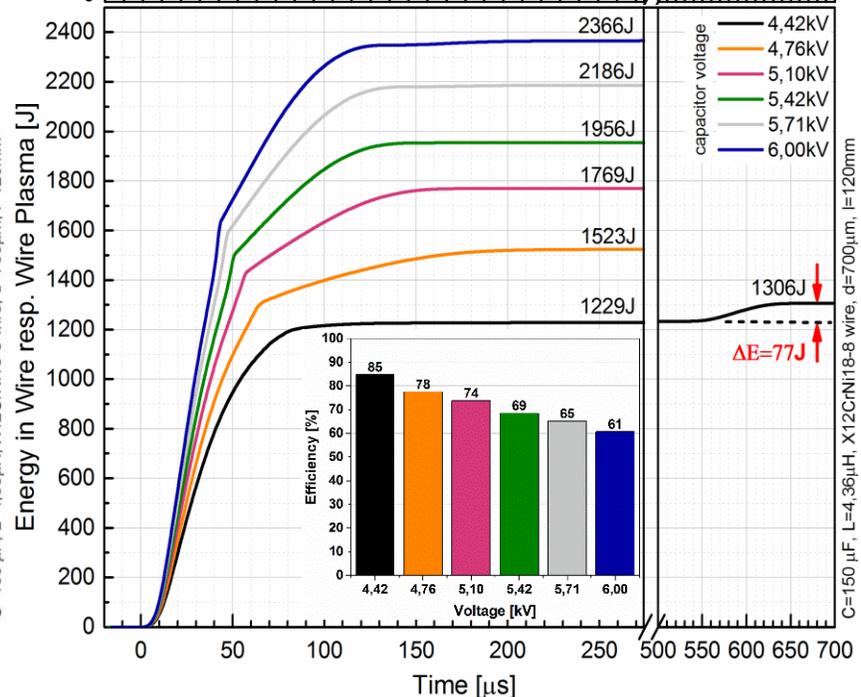
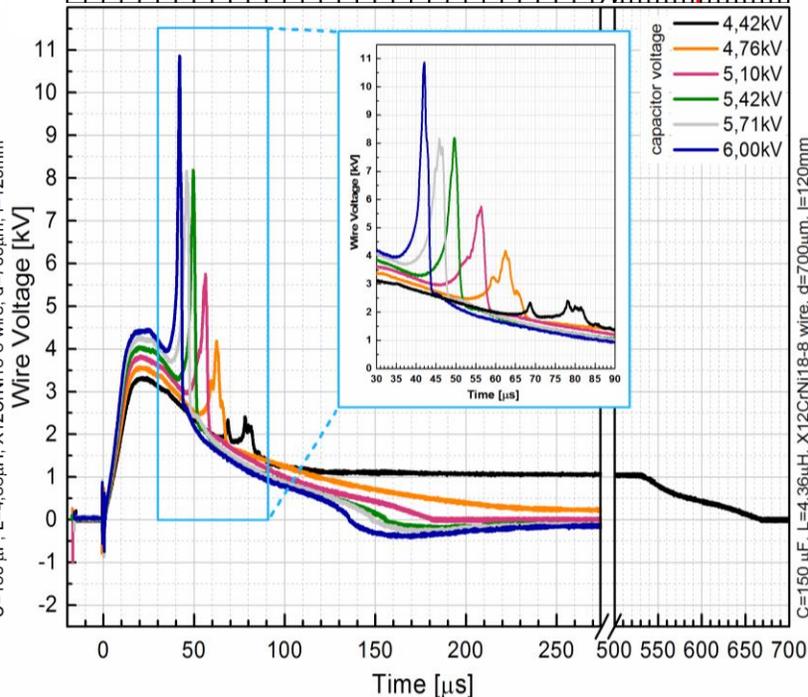
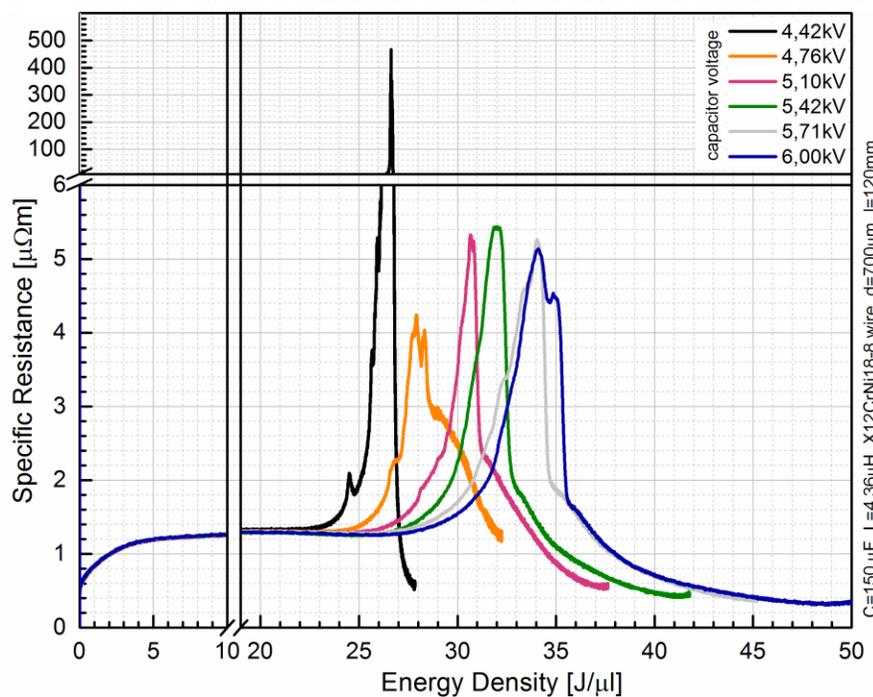
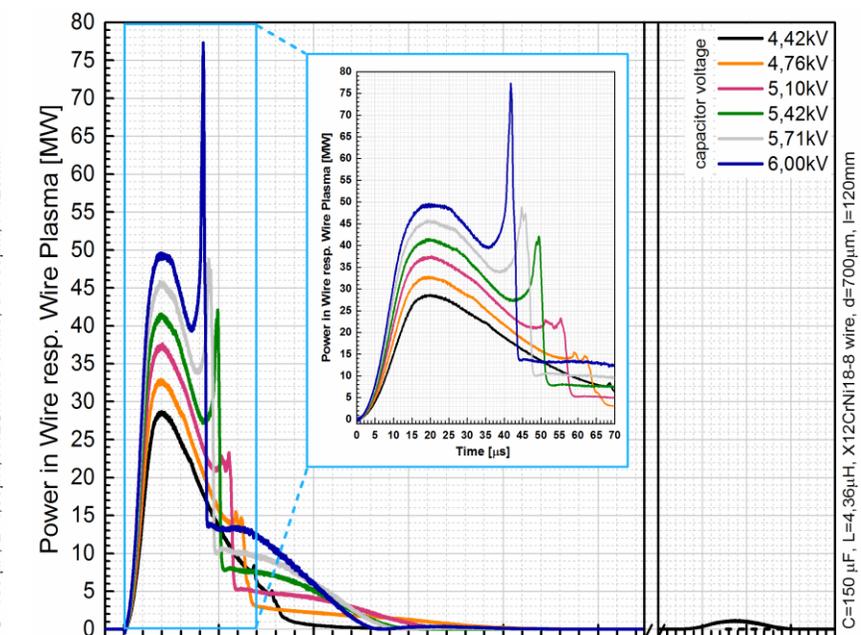
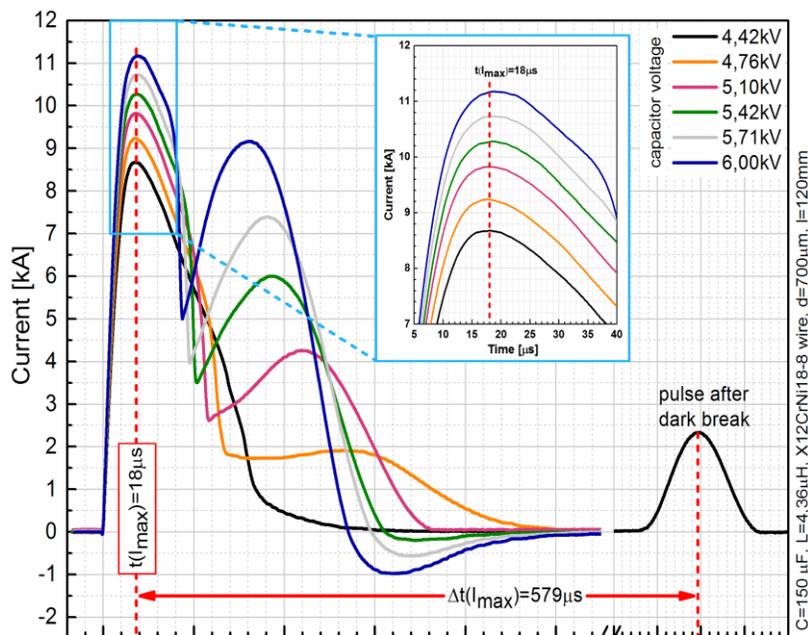
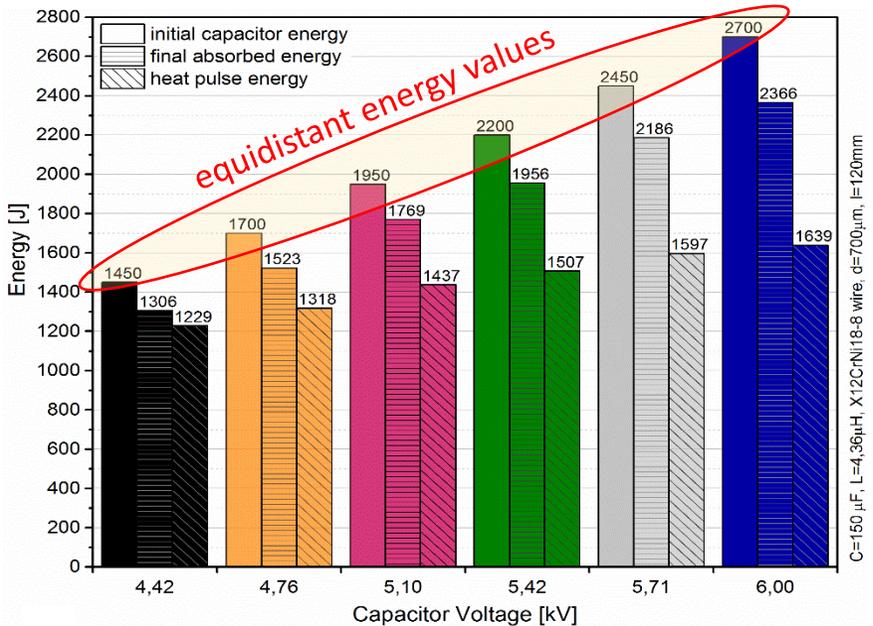
Experimental Investigations of Exploding Wires

Statistical Proof of Repeatability

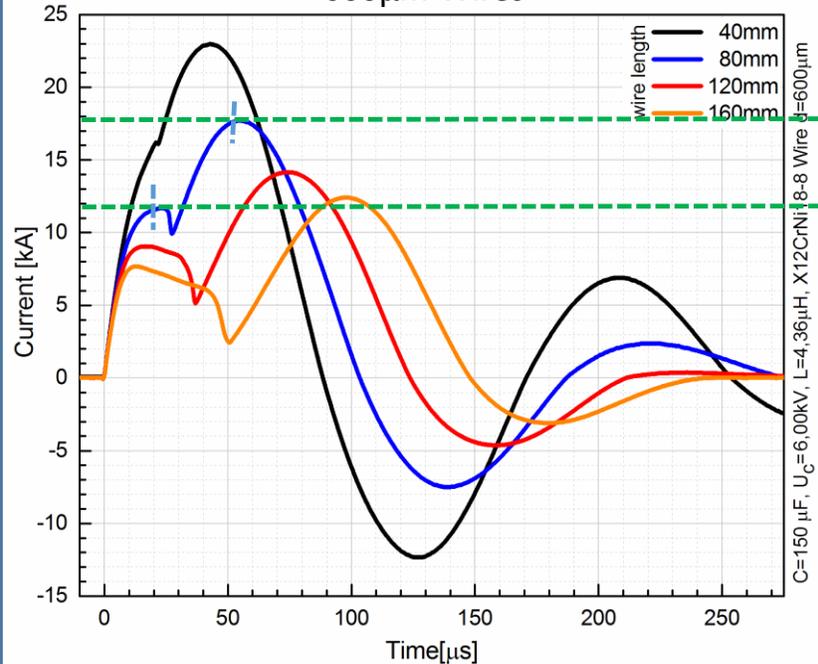
- wire with same length (120mm) and diameter (700 μm) was used
- length variations were less than 1mm: $dL < |\pm 1\text{mm}|$
- diameter variations were measured with a micrometer screw in horizontal (d_h) and vertical (d_v) direction



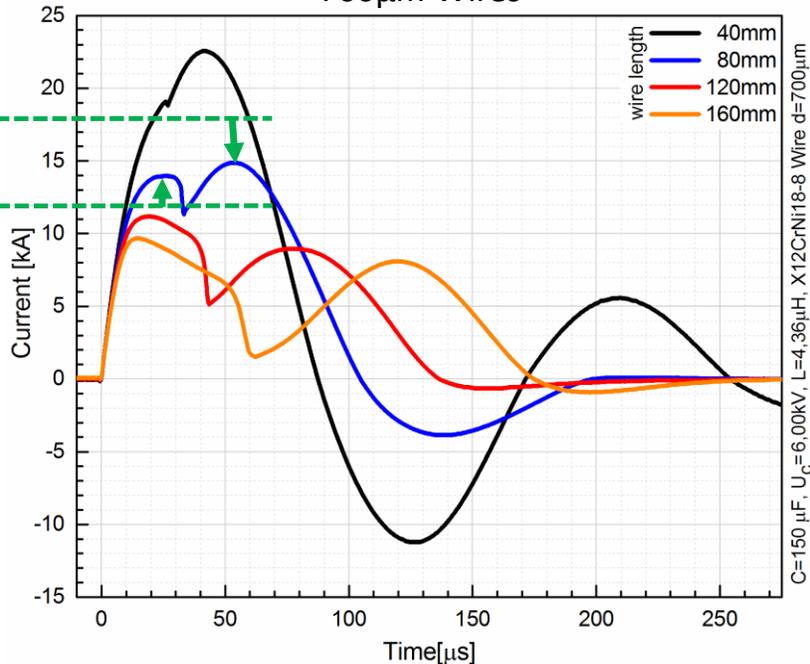
Capacitor Voltage Variations (wires with d=700μm, l=120mm)



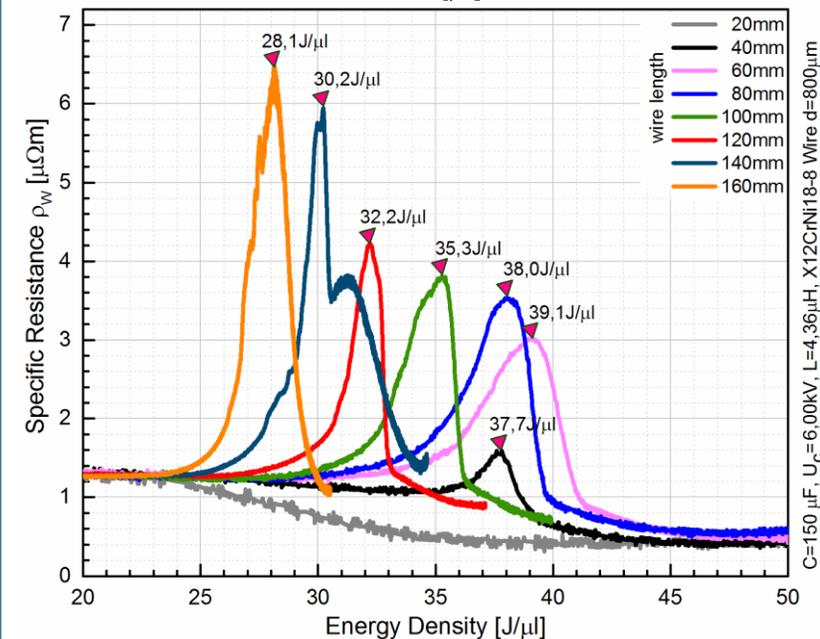
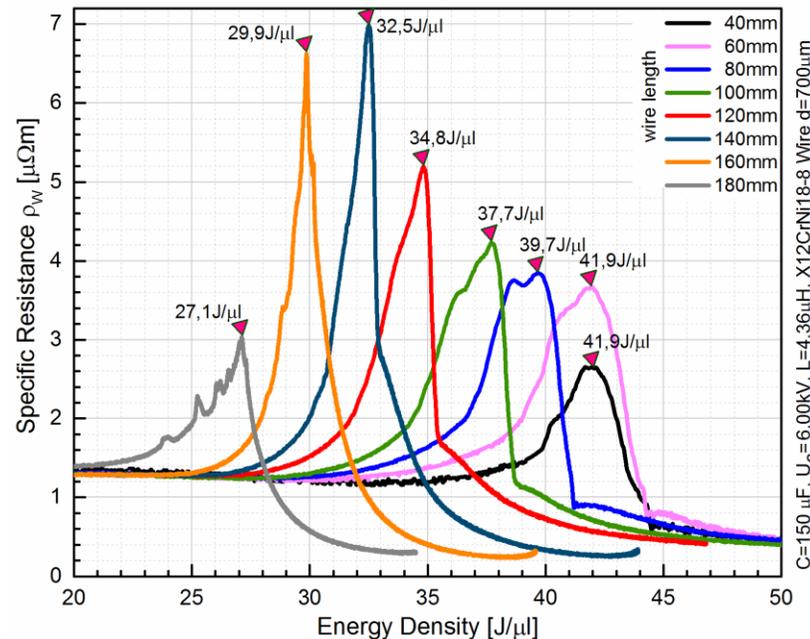
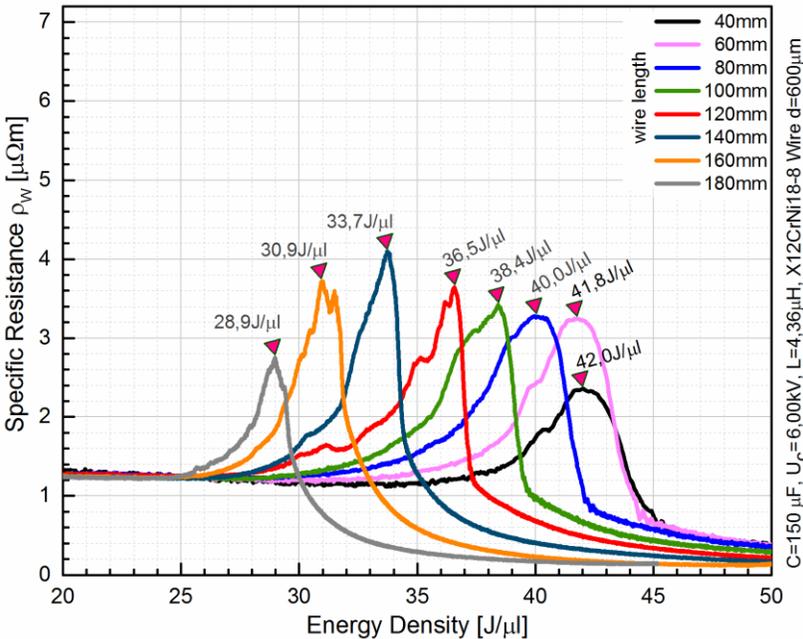
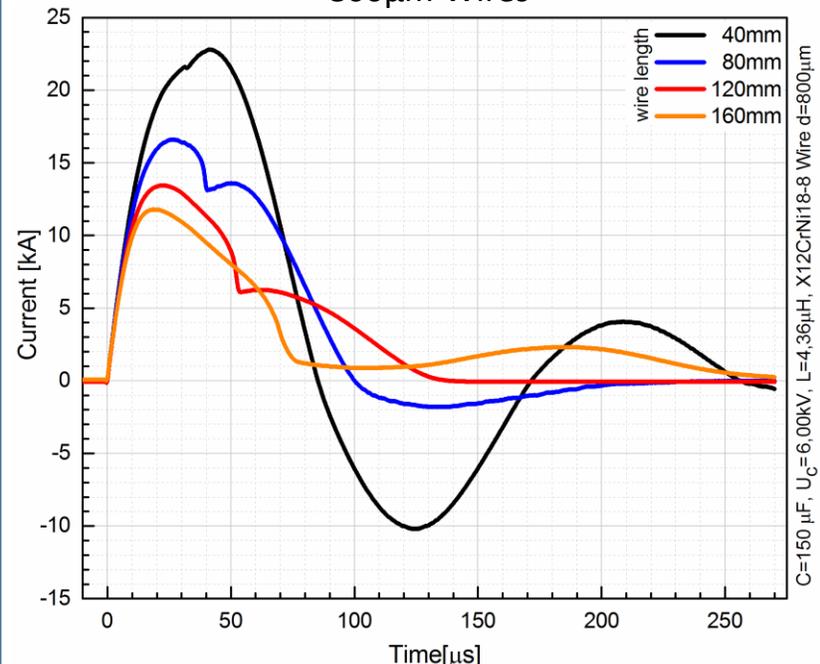
600 μm Wires



700 μm Wires

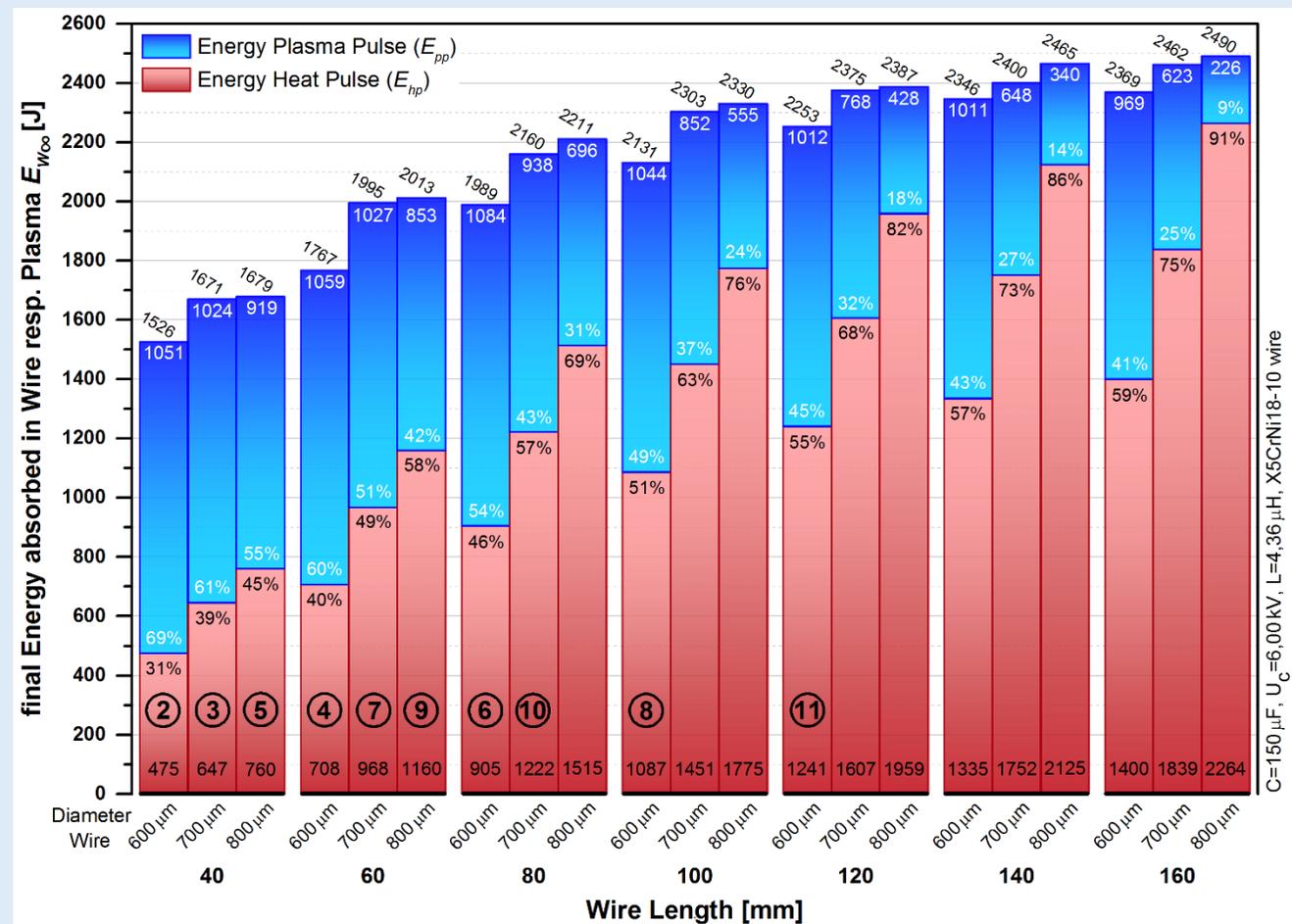
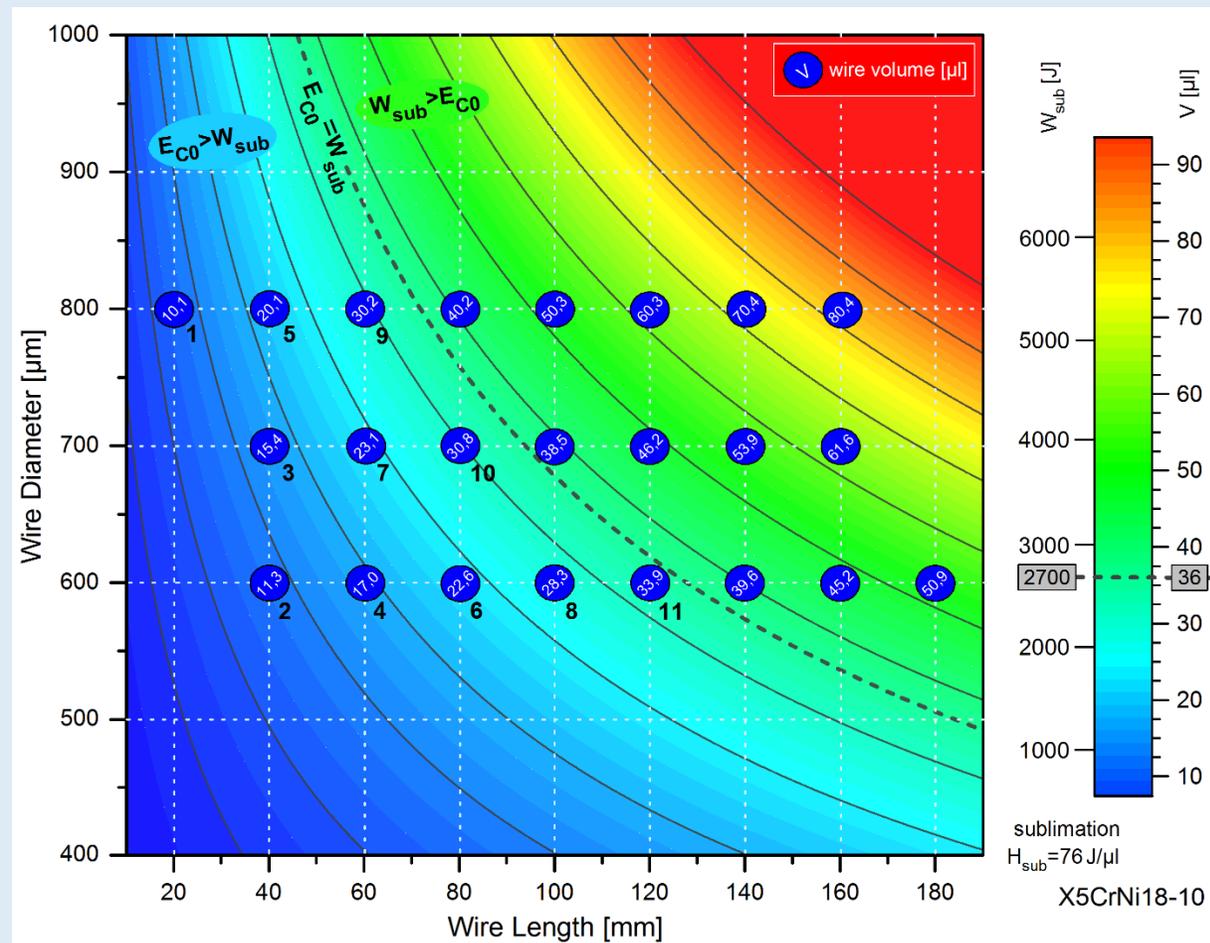


800 μm Wires

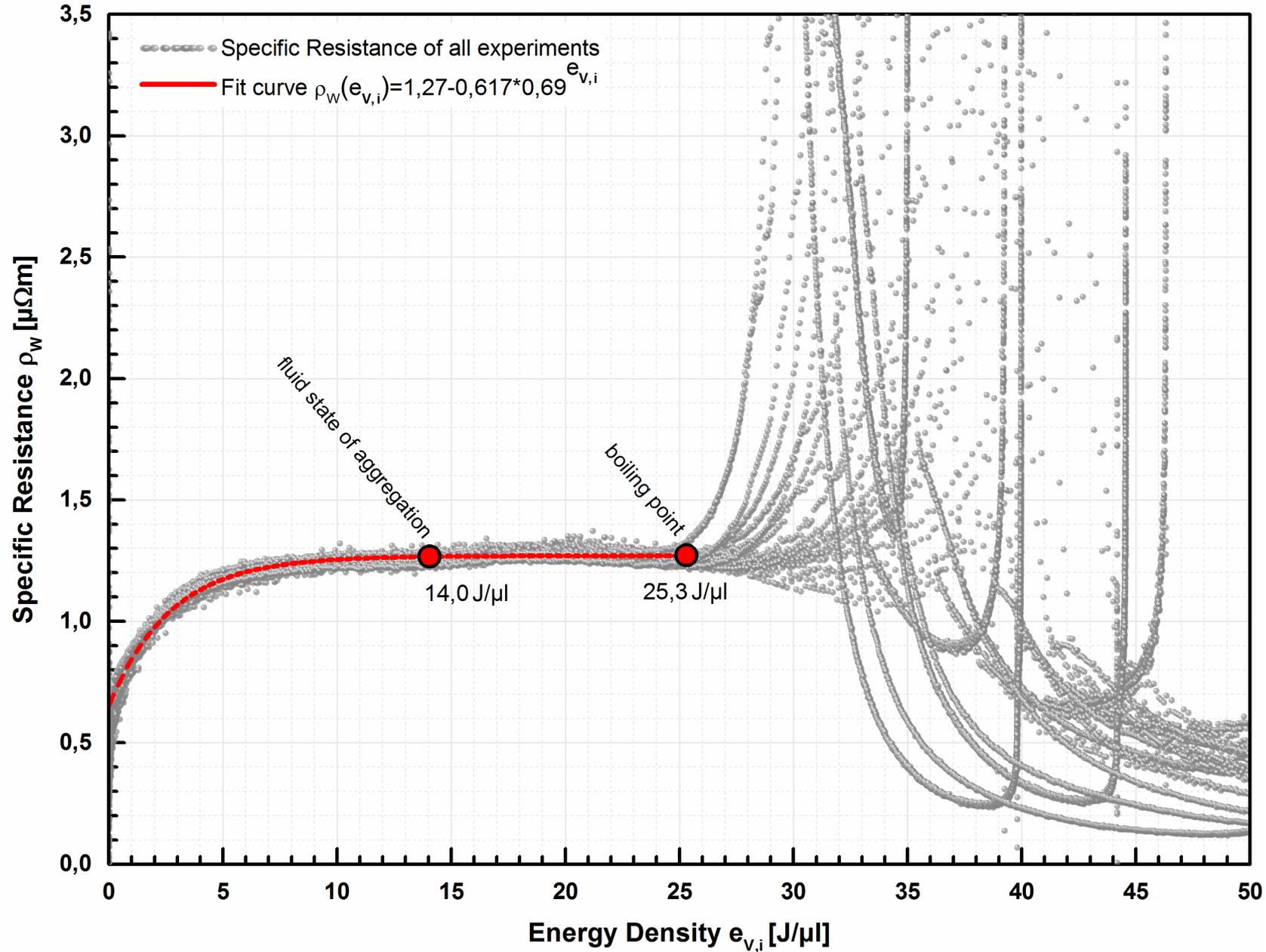


Energy absorbed in the Wire depending on Wire Dimensions

- 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

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

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

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

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

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

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

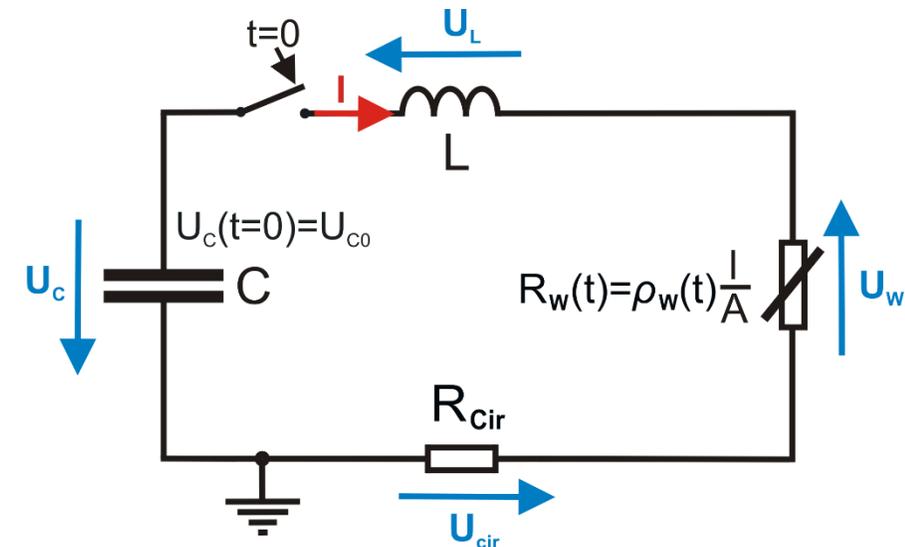
$$\Rightarrow \frac{d^2 I(t)}{dt^2} = -\frac{1}{L} \left[\frac{1}{C} I(t) + m \frac{de(t)}{dt} \frac{l}{S} I(t) + \left(R_{circuit} + (\rho_0 + me(t)) \frac{l}{S} \right) \frac{dI}{dt} \right]$$

power in the wire:

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

volume power density in the wire:

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



formula letters:

L	= total circuit inductance	[H]
R _w	= wire resistance	[Ω]
ρ	= specific resistance wire	[Ωm]
ρ ₀	= initial specific resistance	[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	$\frac{dI(0)}{dt} = \frac{U_C(0)}{L}$	$\frac{ds(t)}{dt} = \frac{d^2I(t)}{dt^2} = -\frac{1}{L} \left[\frac{1}{C} I(t) + \frac{ml}{S^3} (\rho_0 + me(t)) I^3(t) + \left(R_{circuit} + (\rho_0 + me(t)) \frac{l}{S} \right) \frac{dI}{dt} \right]$	$s(t) = \frac{dI(t)}{dt}$
Energy Density	2	$e(0) = 0$	$\frac{de(t)}{dt} = \frac{1}{S^2} (\rho_0 + me(t)) I^2(t)$	$e(t)$
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

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

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

inductive energy

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

wire energy

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

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**

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

Software Implementation

Help and Differential Equations | Resistance Characteristic | Simulation Results | Energy Balance | Data Analysis | Data Export | ■ Stop | **Exploding Wires Simulation Software** | 12.0.2019 Max Bigelmayr

Data Loading | Length to read Data: 20000 | **Method, Accuracy of Simulation** | **Resistance Spline Characteristic**

Current-, Voltage-Curve | Time [Start] 0 us | Runge Kutta | start y-value 0,7 mOhm*m | Spline Number 20
C:\...\Report2\160mm_700um_Current.txt | Cash Karp | Time [End] 250us | Steps 4000 | Accuracy 1E-6 | Start Resistance 0,291026 Oh | Spline Step 20/20

Resistance Characteristic | C:\U...\Report2\ResChar160mm_700um.txt

Capacitor Bank Data | **Wire Data** | **Fitting Methods**

Capacitance 150 uF | Line inductance 4,36 uH | Diameter 0,7 mm | Length 16 cm | Self-Fitting of Resistance Characteris | Use Characteristic Library
Voltage 6000 V | Circle Resistance 0,035 Ohr | Cross section 0,385 mm^2 | Volume 61,575 ul | C:\Users\...\Isurium_Desktop\EW-Stahl\Bibfit290

Progress Simulate

Simulation Graphs and Experimental Data

Simulation | Splines

Current [A], Voltage [V] vs Time [s]

excellent match between experiment and simulation!

- Simulated Current
- Spline Boundaries
- xox
- Simulated Voltage
- Voltage Boundaries
- Measured Current

Resistance Characteristic

Specific Resistance [Ohm*mm] vs Energy Density [J/μl]

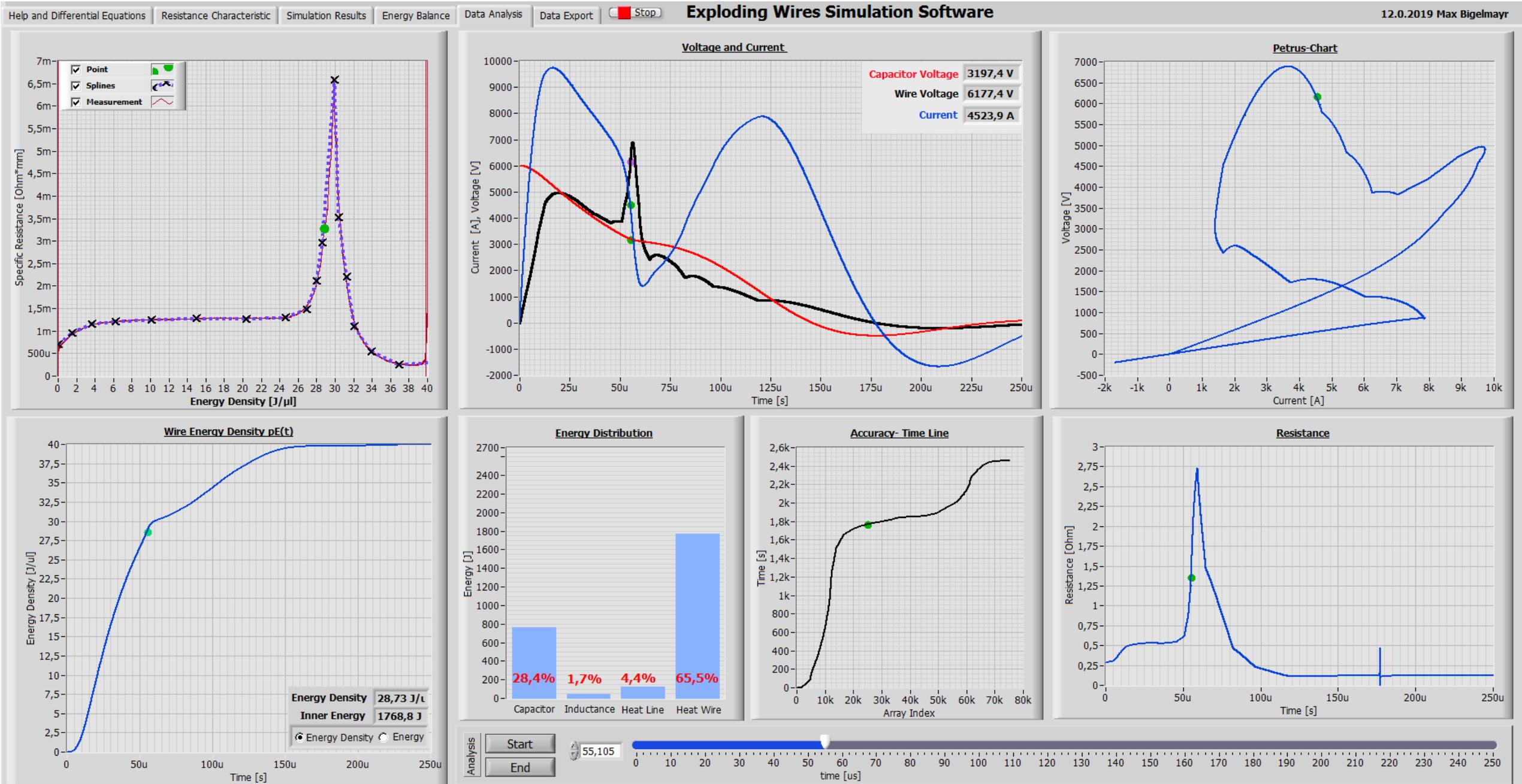
experimental data

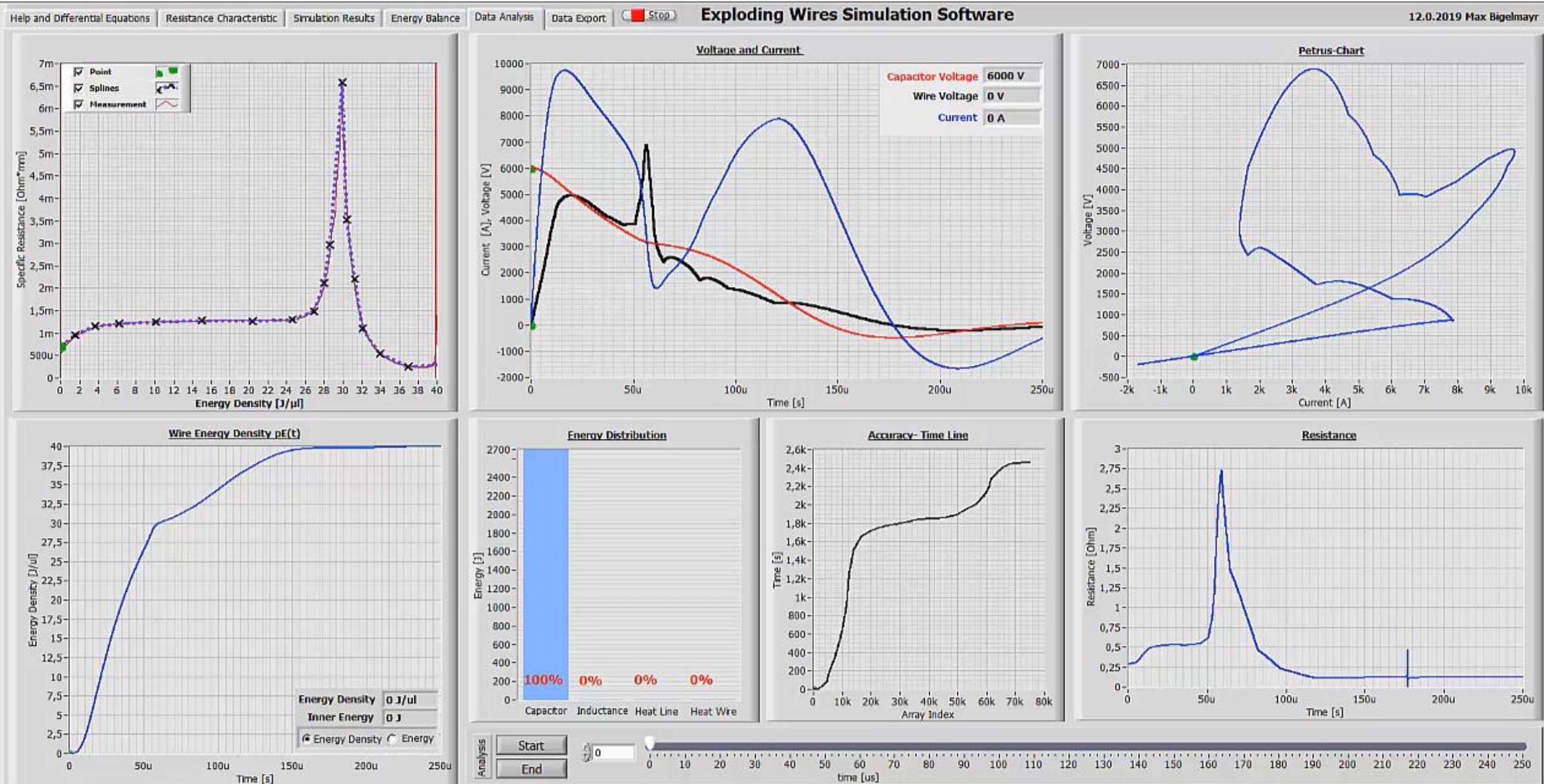
fit splines for simulation

Resistance Fit Points

✗ P 0	1,54229	967,497u
✗ P 1	3,64501	1,16015m
✗ P 2	6,18067	1,21229m
✗ P 3	10,0634	1,2514m
✗ P 4	14,9762	1,27747m
✗ P 5	20,3645	1,26443m
✗ P 6	24,5642	1,30354m
✗ P 7	26,8621	1,48603m
✗ P 8	27,9715	2,12477m
✗ P 9	28,6054	2,95903m
✗ P 10	29,9525	6,58287m
✗ P 11	30,3487	3,51955m

fit spline data for simulation





Summary and Conclusion

- 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 $[0; 25.3\text{J}/\mu\text{l}]$

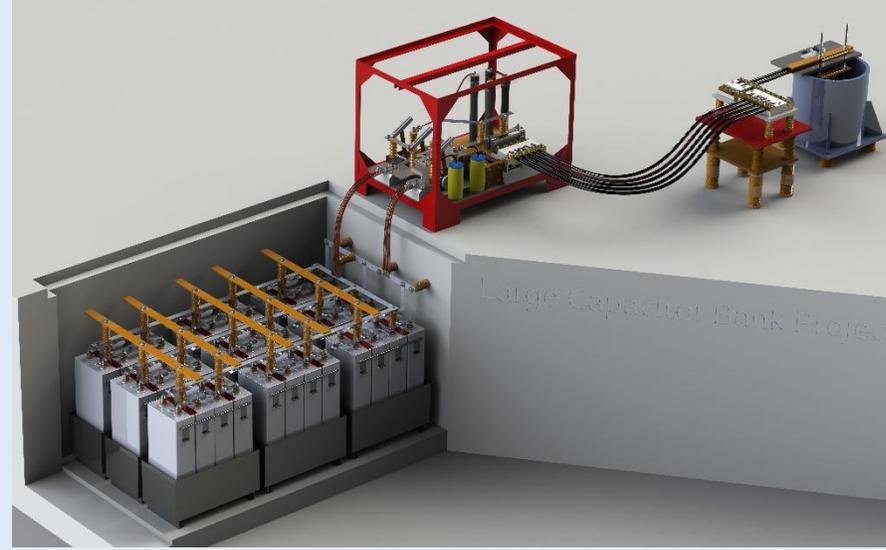
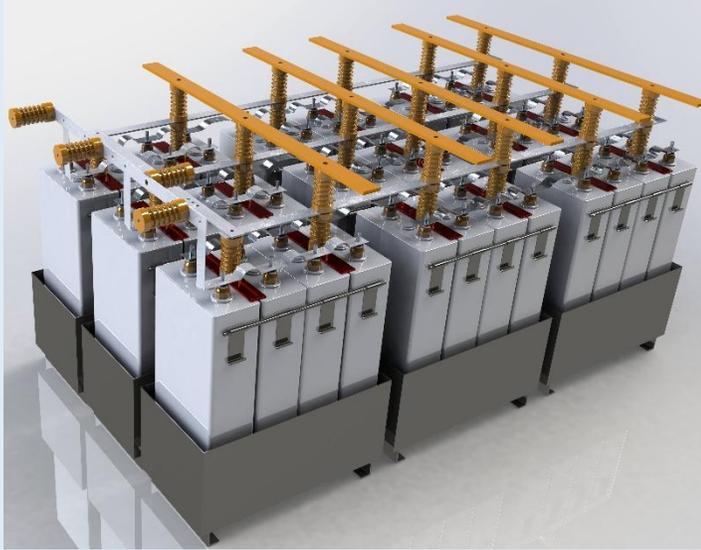
**Experimental investigations
of exploding wires**

- derivation of a coupled differential equation system (ODE)
- successful software implementation
- successful 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

Design of a simulation model

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!