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UČENÍ TECHNICKÉ
V PRAZE

Plasma current stabilization on the tokamak GOLEM Mariánská presentation

Czech Technical University in Prague

Faculty of Nuclear Sciences and Physical Engineering

Department on Physics

Field of study: Plasma Physics and Thermonuclear fusion

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Year: 2026

Outline

1. Introduction to the current state of current stabilization

- **Introduction to the schematic**
- **Designed coil for current stabilization**
- **Power supply used for current stabilization**

2. Current stabilization on the tokamak GOLEM

- **Control voltage mode**
- **Control current mode**

3. Numerical model for current stabilization

- **Transformation of transformer equations into state-space form**
- **Numerical model of chamber discharge**
- **Numerical model of discharge with plasma**
- **Comparison of numerical results with experiment**

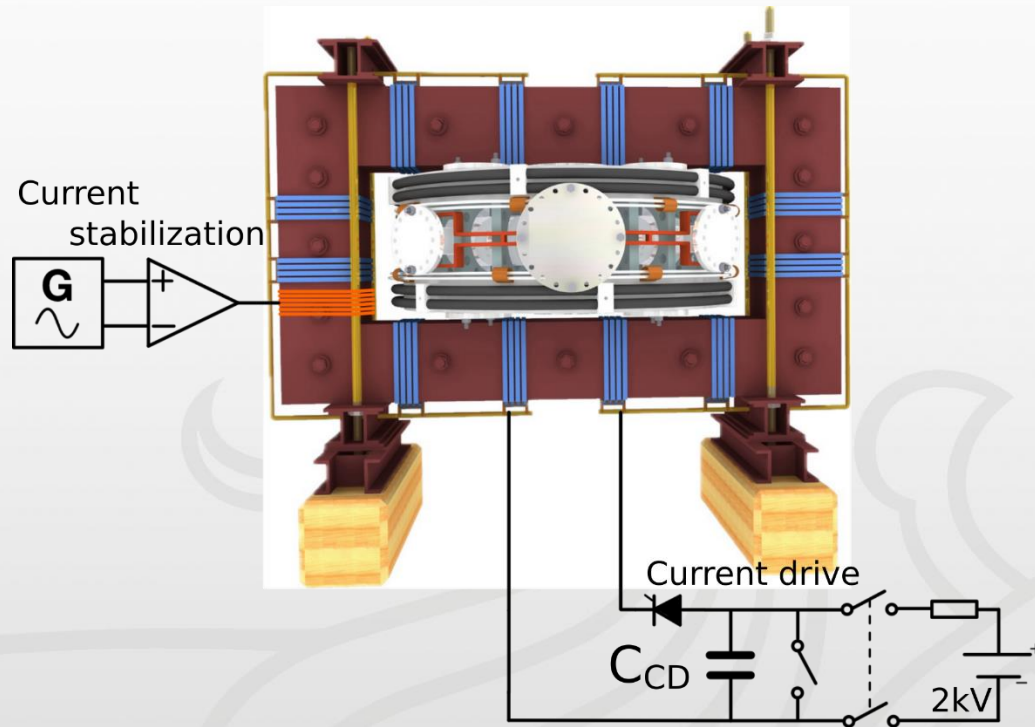
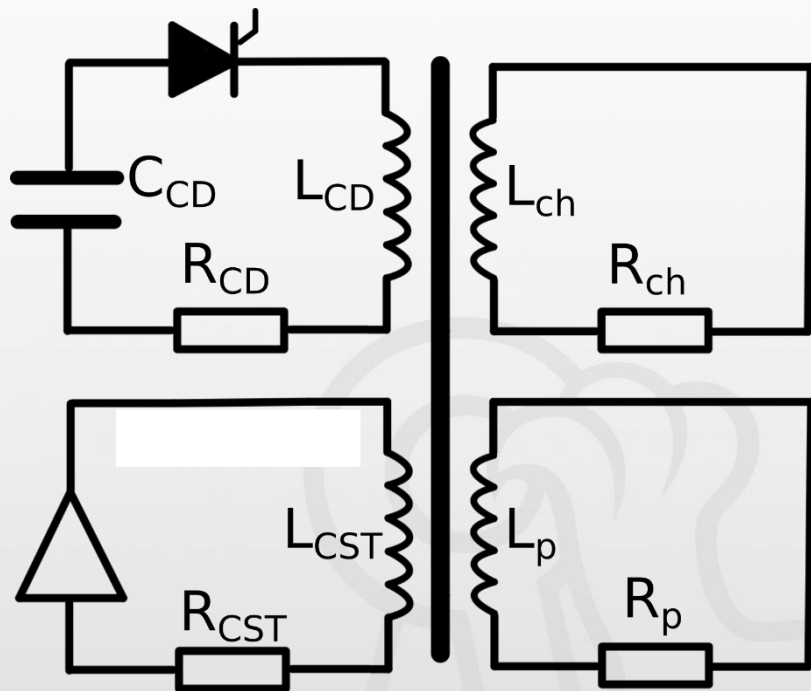
4. Future plans

- **Increase of the stabilization system power**
- **Tuning of the stabilization coil**
- **Development of an autonomous system for current stabilization**

1. Current state of plasma current generation on the tokamak GOLEM

Current state of plasma current generation on the GOLEM tokamak

- Simplified electrical schematic of the GOLEM tokamak
- Implementation of stabilization in the form of an additional primary winding powered by current amplifiers



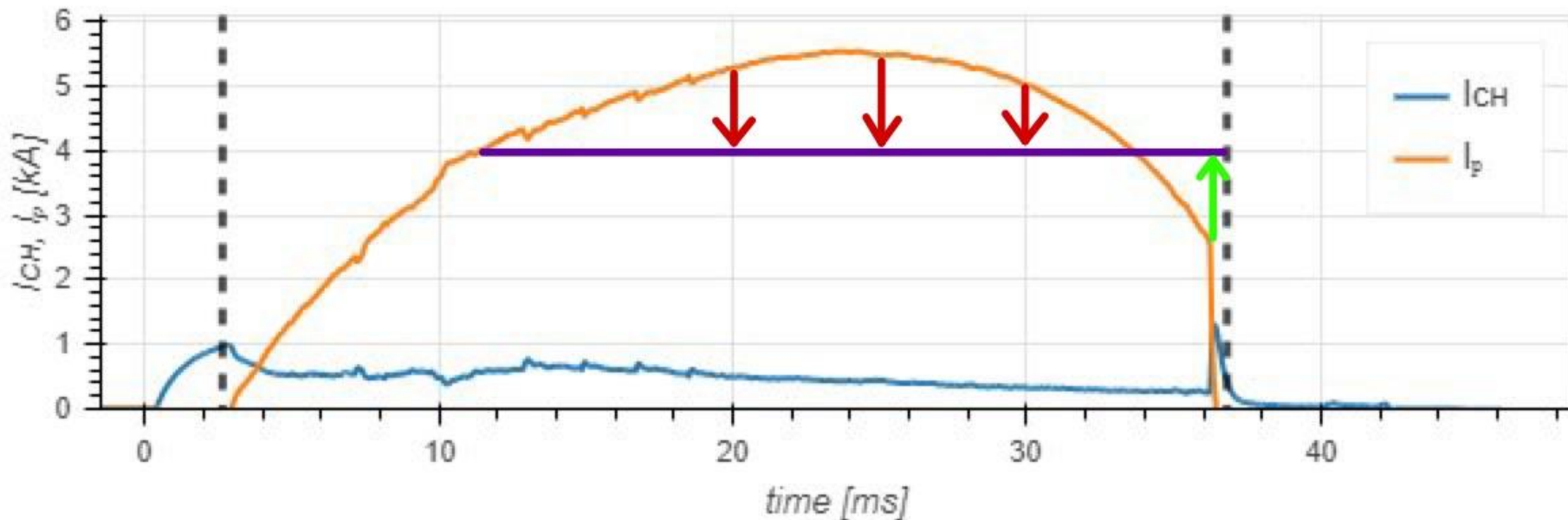
1. Current state of plasma current generation on the tokamak GOLEM

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Current state of plasma current generation on the GOLEM tokamak

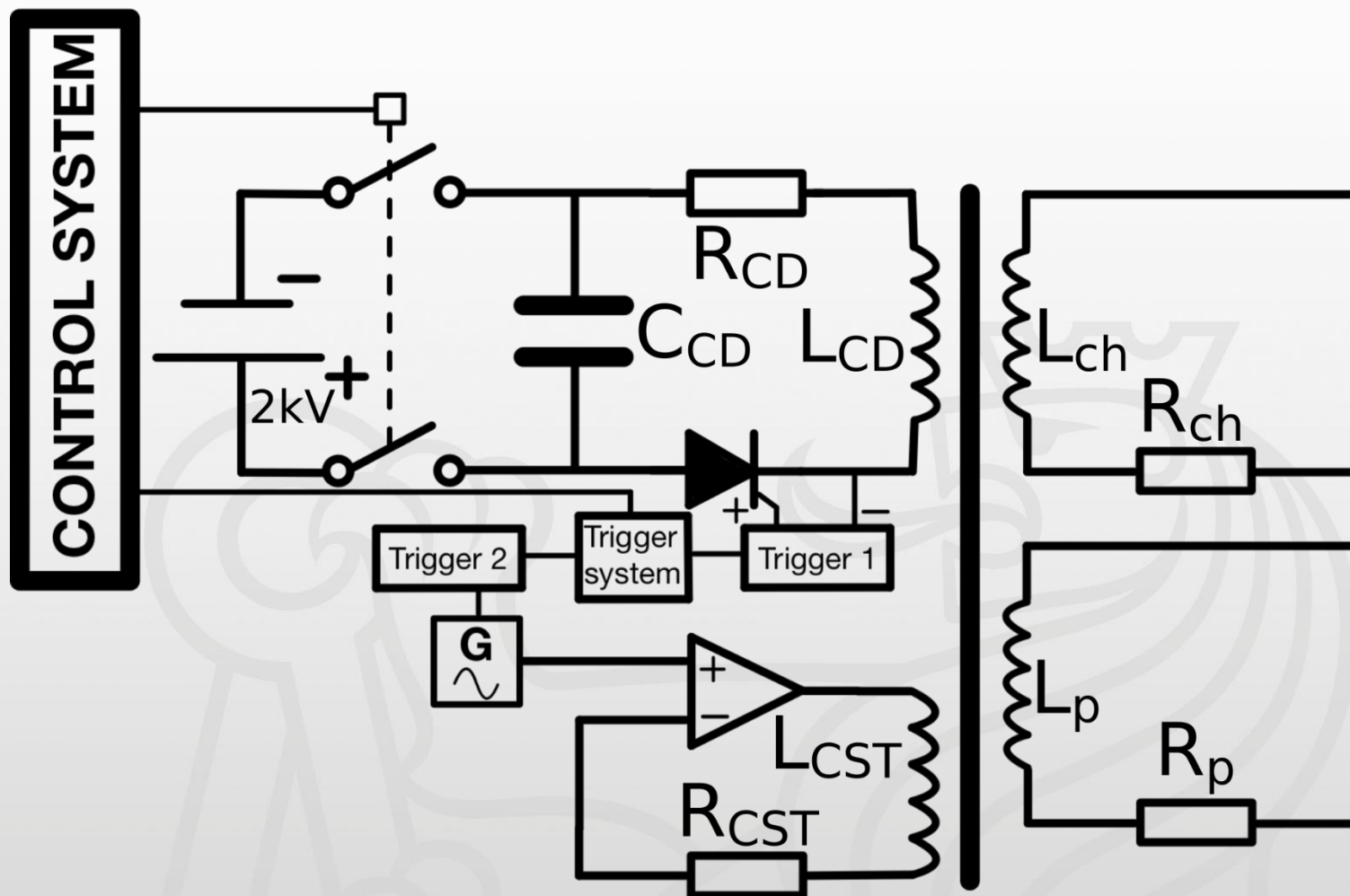
- **Simplified electrical schematic of the GOLEM tokamak**
- **Implementation of stabilization in the form of an additional primary winding powered by current amplifiers**

Why we need current stabilization on the tokamak GOLEM?



1. Current state of plasma current generation on the tokamak GOLEM

Simplified technological schema



1. Current state of plasma current generation on the tokamak GOLEM

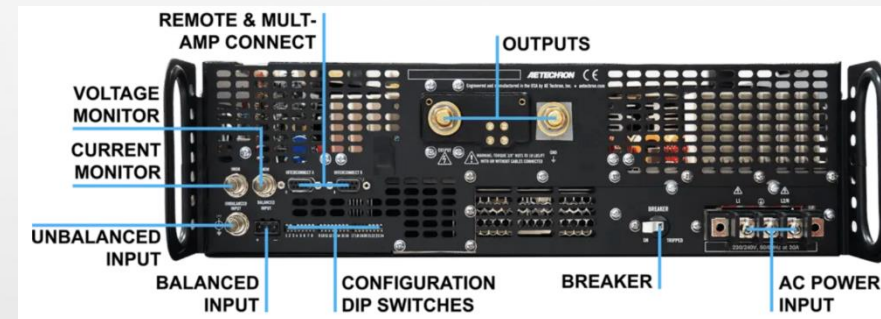
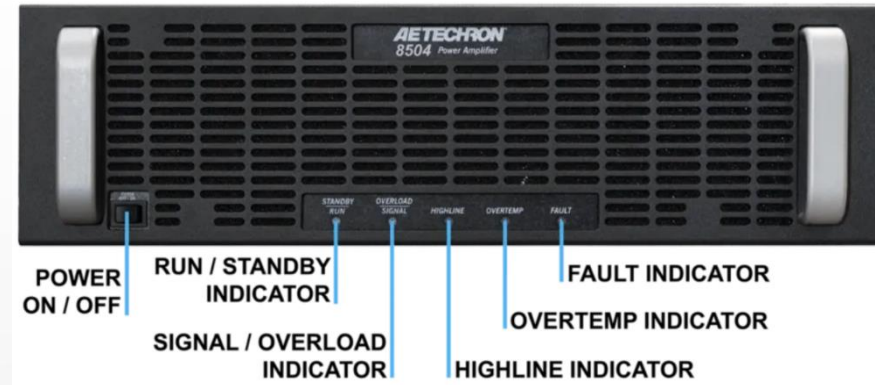
Parameters of additional primary winding

- **The installed winding was originally calibrated for the KEPCO amplifier systém, however, during the execution of the tasks, the amplifier was changed**
- **The number of turns was chosen to be 50 windings and later was reduced by modulation to half**



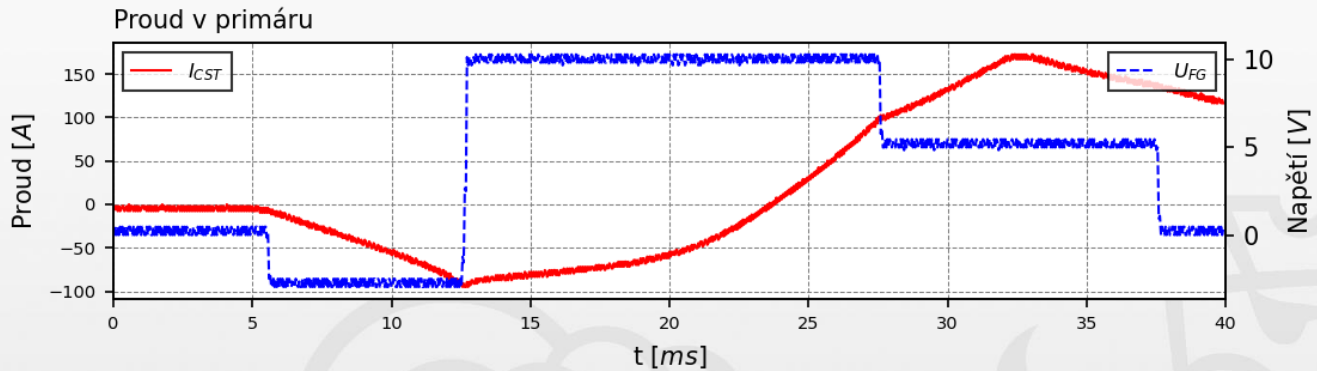
2. Current state of plasma current generation on the tokamak GOLEM

- **The amplifier was replaced with a switched-mode AETECHRON power supply.**
- **The AETECHRON 8504 model was tested**
- **wideband power amplifier up to 50 kHz**
- **voltage of the same polarity up to 400 V**
- **continuous current up to 80 A; in *surge rating mode*, current pulses up to 160 A for durations on the order of milliseconds**
- **operating in both voltage and current control modes.**

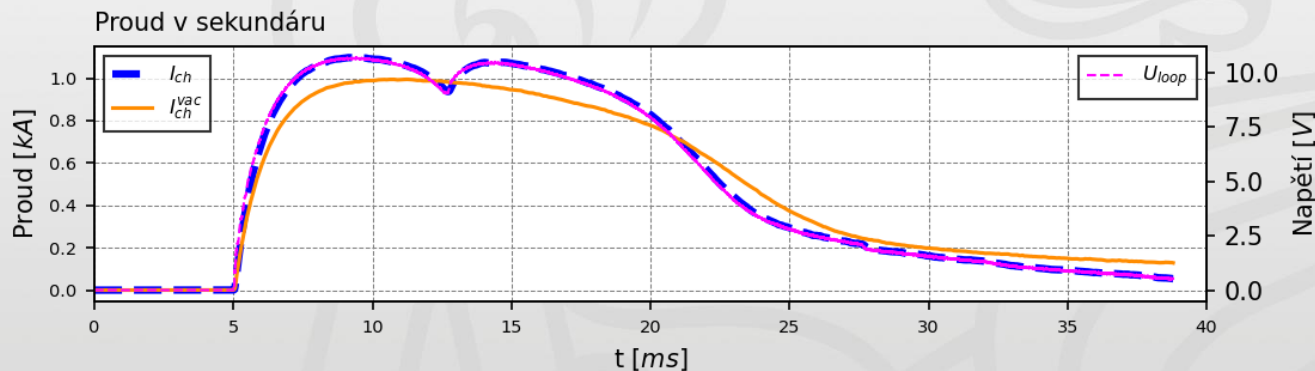
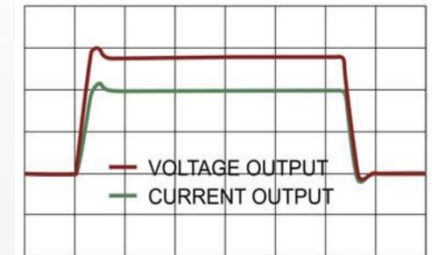


Control voltage mode – with chamber only

Vakuový výboj pro 300V z výboje 47454 se stabilizací

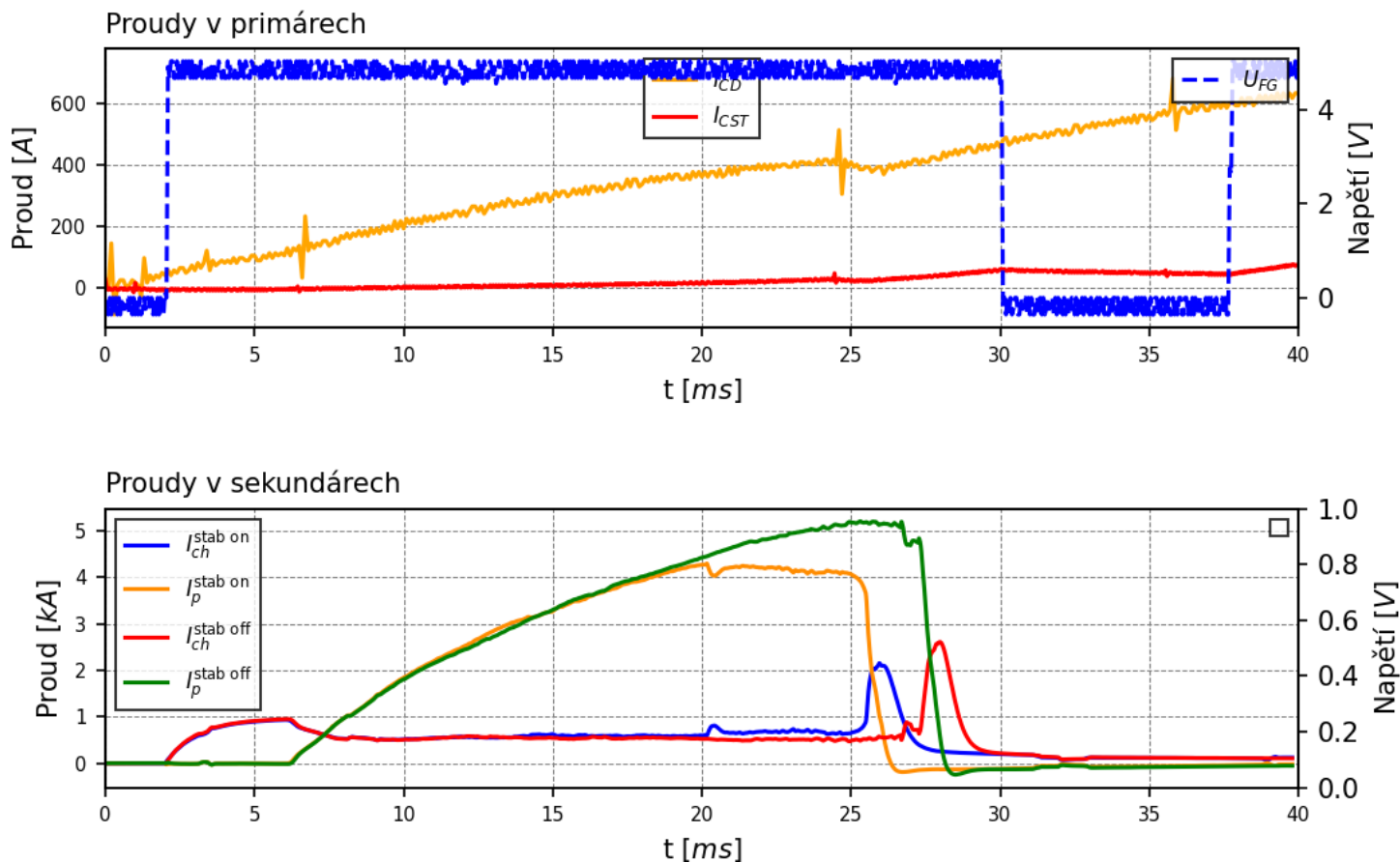


CONTROLLED-VOLTAGE MODE



Control voltage mode – with chamber and plasma

Porovnání výboje bez stabilizace #48003 a výboje se stabilizací #48006

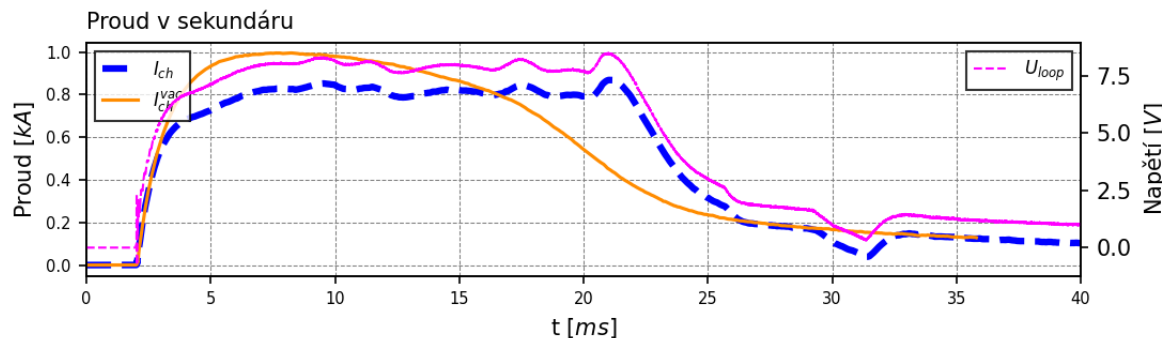
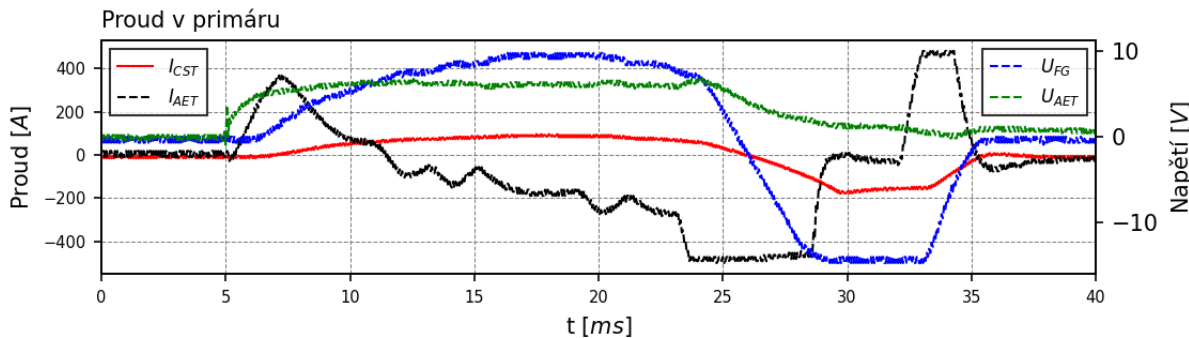


2. Current stabilization on the tokamak GOLEM

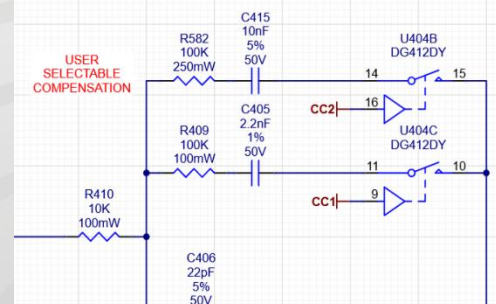
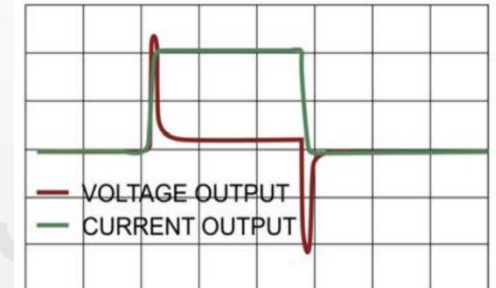
Control current mode - with chambre only

- Use an RC filter to smooth the input waveform
- Improvement of the waveform using piecewise linear function

Proudový režim z výboje 49173

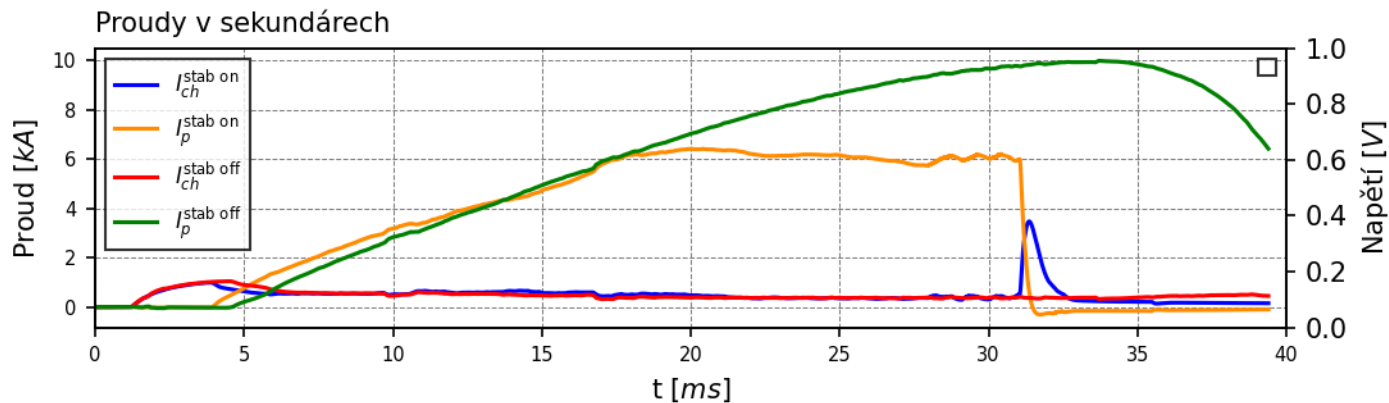
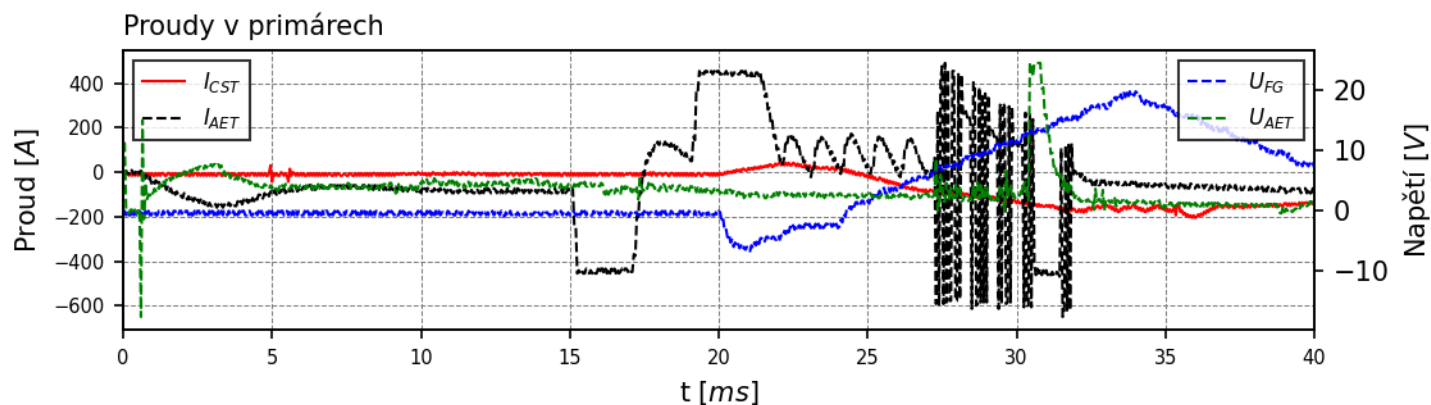


CONTROLLED-CURRENT MODE



Control current mode – with chamber and plasma

Porovnání výboje bez stabilizace #48554 a výboje se stabilizací #48726



3. Numerical model of Current stabilizaton

Transformation of transformer equations into state-space form

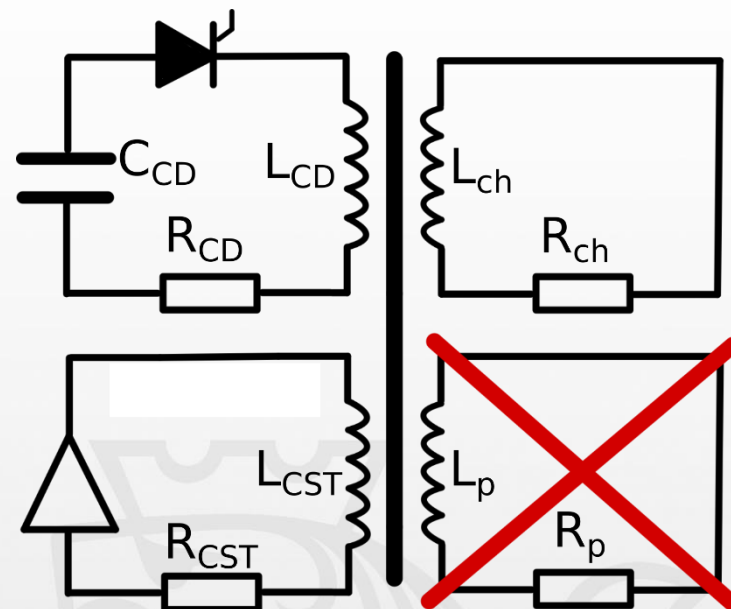
- **The state-space method is suitable for dynamic systems described by a system of first-order differential equations.**
- **An advantage is the explicit representation of the internal dynamics of the system using state variables.**
- **Another significant advantage is the possibility of controlling the model, for example using PID controllers (e.g. current control in coils on the TCV tokamak in Lausanne).**

$$\begin{aligned}\dot{\vec{x}}(t) &= \mathbf{A}\vec{x}(t) + \mathbf{B}\vec{u}(t) \\ \vec{y}(t) &= \mathbf{C}\vec{x}(t) + \mathbf{D}\vec{u}(t).\end{aligned}$$

- **$\mathbf{x}(t)$ - is the vector of state variables describing the current state of the system,**
- **$\mathbf{u}(t)$ - is the vector of input variables,**
- **$\mathbf{y}(t)$ - is the vector of output variables,**
- **\mathbf{A} - is the state matrix describing the internal dynamics of the system,**
- **\mathbf{B} - is the input matrix,**
- **\mathbf{C} - is the output matrix,**
- **\mathbf{D} - is the direct feedthrough matrix.**

3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form



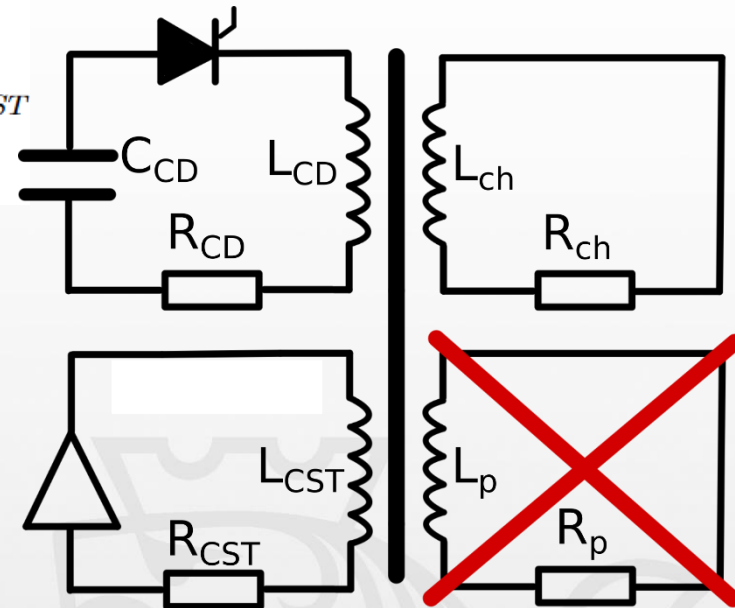
3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form

$$R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} = 0,$$

$$R_{CST} I_{CST} + L_{CST} \dot{I}_{CST} + M_{CST,ch} \dot{I}_{ch} + M_{CST,CD} \dot{I}_{CD} = U_{CST}$$

$$R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} = 0$$



3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form

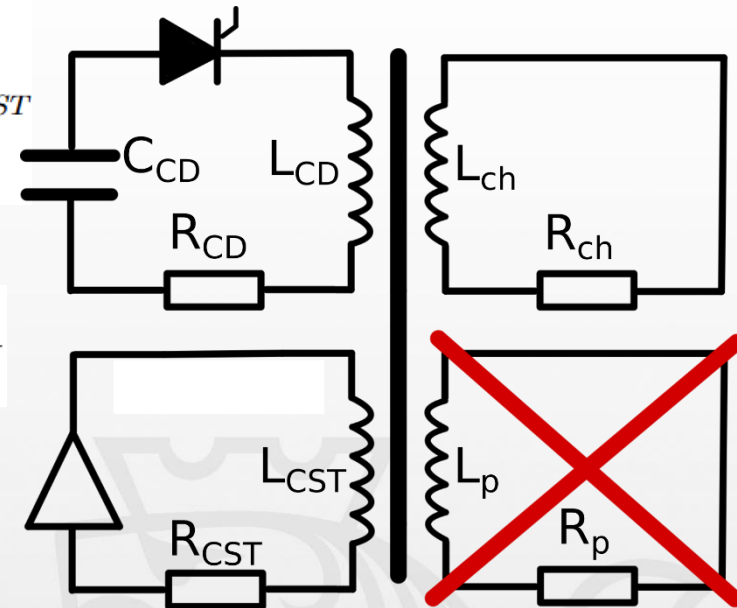
$$R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} = 0,$$

$$R_{CST} I_{CST} + L_{CST} \dot{I}_{CST} + M_{CST,ch} \dot{I}_{ch} + M_{CST,CD} \dot{I}_{CD} = U_{CST}$$

$$R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} = 0$$

We add an equation

$$U_C(t) = \frac{Q_{CD}(t)}{C_{CD}} \xrightarrow{\frac{d}{dt}} \dot{U}_C(t) = \frac{\dot{Q}_{CD}(t)}{C_{CD}} = \frac{I_{CD}(t)}{C_{CD}}$$



3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form

$$R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} = 0,$$

$$R_{CST} I_{CST} + L_{CST} \dot{I}_{CST} + M_{CST,ch} \dot{I}_{ch} + M_{CST,CD} \dot{I}_{CD} = U_{CST}$$

$$R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} = 0$$

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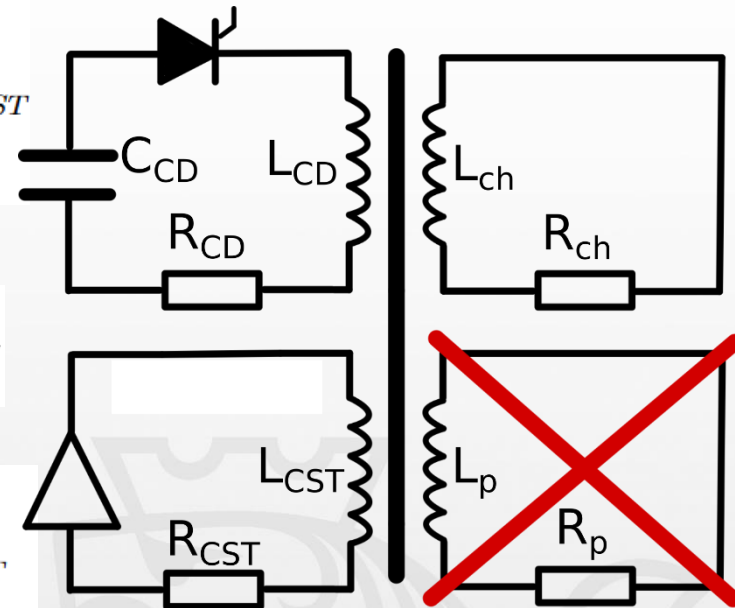
Overall, we have

$$R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} = 0,$$

$$R_{CST} I_{CST} + L_{CST} \dot{I}_{CST} + M_{CST,ch} \dot{I}_{ch} + M_{CST,CD} \dot{I}_{CD} = U_{CST}$$

$$R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} = 0$$

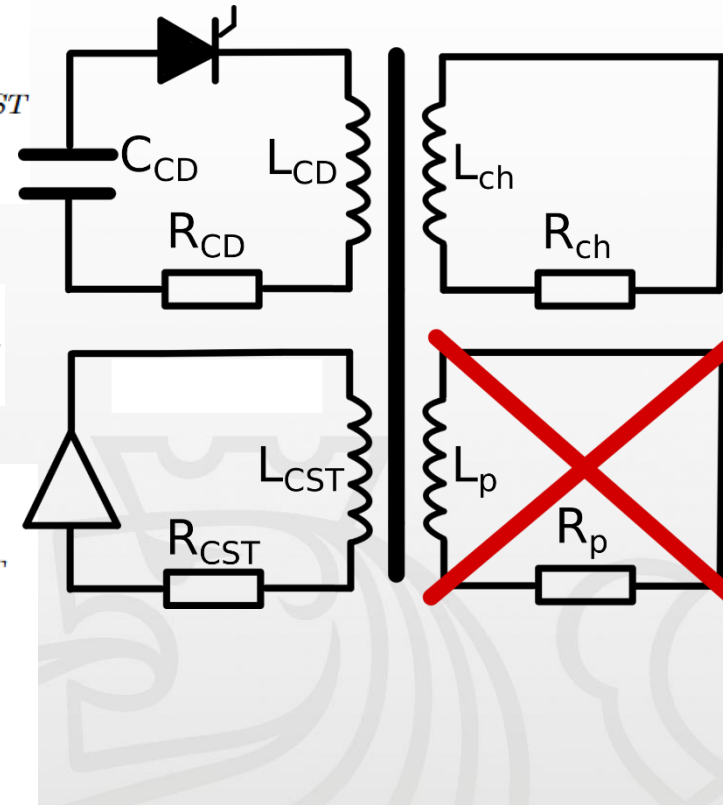
$$\dot{U}_C = \frac{I_{CD}}{C_{CD}}$$



3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form

$$\begin{aligned}
 R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} &= 0, \\
 R_{CST} I_{CST} + L_{CST} \dot{I}_{CST} + M_{CST,ch} \dot{I}_{ch} + M_{CST,CD} \dot{I}_{CD} &= U_{CST} \\
 R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} &= 0
 \end{aligned}$$



We add an equation

$$U_C(t) = \frac{Q_{CD}(t)}{C_{CD}} \xrightarrow{\frac{d}{dt}} \dot{U}_C(t) = \frac{\dot{Q}_{CD}(t)}{C_{CD}} = \frac{I_{CD}(t)}{C_{CD}}$$

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 R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} &= 0
 \end{aligned}$$

$$\dot{U}_C = \frac{I_{CD}}{C_{CD}}$$

Matrix form

$$\underbrace{\begin{bmatrix} L_{CD} & M_{CD,CST} & M_{CD,ch} & 0 \\ M_{CST,CD} & L_{CST} & M_{CST,ch} & 0 \\ M_{ch,CD} & M_{ch,CST} & L_{ch} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{M}} \cdot \underbrace{\begin{bmatrix} \dot{I}_{CD} \\ \dot{I}_{CST} \\ \dot{I}_{ch} \\ \dot{U}_C \end{bmatrix}}_{\dot{\mathbf{x}}} + \underbrace{\begin{bmatrix} R_{CD} & 0 & 0 & 1 \\ 0 & R_{CST} & 0 & 0 \\ 0 & 0 & R_{ch} & 0 \\ -\frac{1}{C_{CD}} & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{R}} \cdot \underbrace{\begin{bmatrix} I_{CD} \\ I_{CST} \\ I_{ch} \\ U_C \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} 0 \\ U_{CST} \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{u}}$$

3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form

$$\begin{aligned}
 R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} &= 0, \\
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 R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} &= 0
 \end{aligned}$$

We add an equation

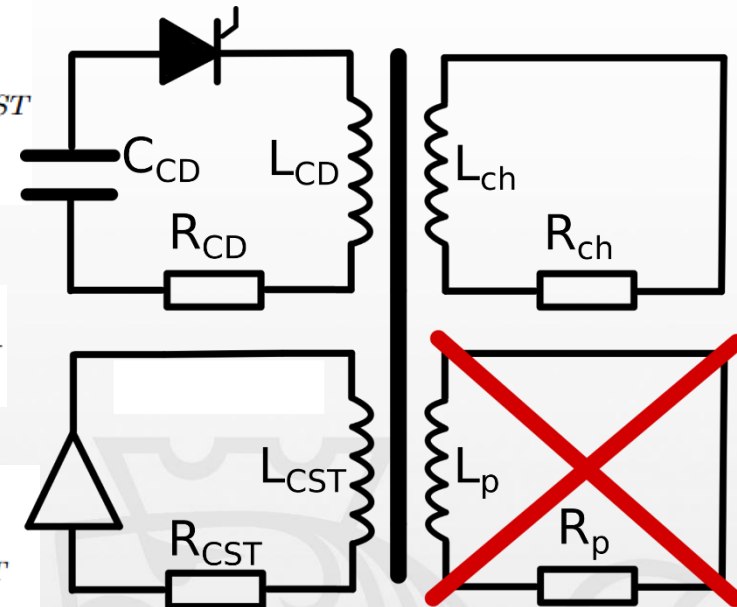
$$U_C(t) = \frac{Q_{CD}(t)}{C_{CD}} \xrightarrow{\frac{d}{dt}} \dot{U}_C(t) = \frac{\dot{Q}_{CD}(t)}{C_{CD}} = \frac{I_{CD}(t)}{C_{CD}}$$

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 R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} &= 0
 \end{aligned}$$

Matrix form

$$\underbrace{\begin{bmatrix} L_{CD} & M_{CD,CST} & M_{CD,ch} & 0 \\ M_{CST,CD} & L_{CST} & M_{CST,ch} & 0 \\ M_{ch,CD} & M_{ch,CST} & L_{ch} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{M}} \cdot \underbrace{\begin{bmatrix} \dot{I}_{CD} \\ \dot{I}_{CST} \\ \dot{I}_{ch} \\ \dot{U}_C \end{bmatrix}}_{\dot{\mathbf{x}}} + \underbrace{\begin{bmatrix} R_{CD} & 0 & 0 & 1 \\ 0 & R_{CST} & 0 & 0 \\ 0 & 0 & R_{ch} & 0 \\ -\frac{1}{C_{CD}} & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{R}} \cdot \underbrace{\begin{bmatrix} I_{CD} \\ I_{CST} \\ I_{ch} \\ U_C \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} 0 \\ U_{CST} \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{u}}$$



$$\mathbf{M}\dot{\mathbf{x}} + \mathbf{R}\mathbf{x} = \mathbf{u}$$

3. Numerical model of chamber current stabilization

Transformation of transformer equations into state-space form

$$\begin{aligned}
 R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} &= 0, \\
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 R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} &= 0
 \end{aligned}$$

We add an equation

$$U_C(t) = \frac{Q_{CD}(t)}{C_{CD}} \xrightarrow{\frac{d}{dt}} \dot{U}_C(t) = \frac{\dot{Q}_{CD}(t)}{C_{CD}} = \frac{I_{CD}(t)}{C_{CD}}$$

Overall, we have

$$\begin{aligned}
 R_{CD} I_{CD} + L_{CD} \dot{I}_{CD} + U_C + M_{CD,ch} \dot{I}_{ch} + M_{CD,CST} \dot{I}_{CST} &= 0, \\
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 R_{ch} I_{ch} + L_{ch} \dot{I}_{ch} + M_{ch,CD} \dot{I}_{CD} + M_{ch,CST} \dot{I}_{CST} &= 0
 \end{aligned}$$

Matrix form

$$\underbrace{\begin{bmatrix} L_{CD} & M_{CD,CST} & M_{CD,ch} & 0 \\ M_{CST,CD} & L_{CST} & M_{CST,ch} & 0 \\ M_{ch,CD} & M_{ch,CST} & L_{ch} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{M}} \cdot \underbrace{\begin{bmatrix} \dot{I}_{CD} \\ \dot{I}_{CST} \\ \dot{I}_{ch} \\ \dot{U}_C \end{bmatrix}}_{\dot{\mathbf{x}}} + \underbrace{\begin{bmatrix} R_{CD} & 0 & 0 & 1 \\ 0 & R_{CST} & 0 & 0 \\ 0 & 0 & R_{ch} & 0 \\ -\frac{1}{C_{CD}} & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{R}} \cdot \underbrace{\begin{bmatrix} I_{CD} \\ I_{CST} \\ I_{ch} \\ U_C \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} 0 \\ U_{CST} \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{u}}$$

$$\dot{\mathbf{x}} = -\mathbf{M}^{-1} \mathbf{R} \mathbf{x} + \mathbf{M}^{-1} \mathbf{u}$$

$$\mathbf{y} = \mathbf{C} \mathbf{x} + \mathbf{D} \mathbf{u}$$

$$\mathbf{A} = -\mathbf{M}^{-1} \mathbf{R} \quad \mathbf{B} = \mathbf{M}^{-1}$$

$$\mathbf{C} = \mathbf{I}_4 \quad \mathbf{D} = \mathbf{0}$$

$$\dot{\vec{x}}(t) = \mathbf{A} \vec{x}(t) + \mathbf{B} \vec{u}(t)$$

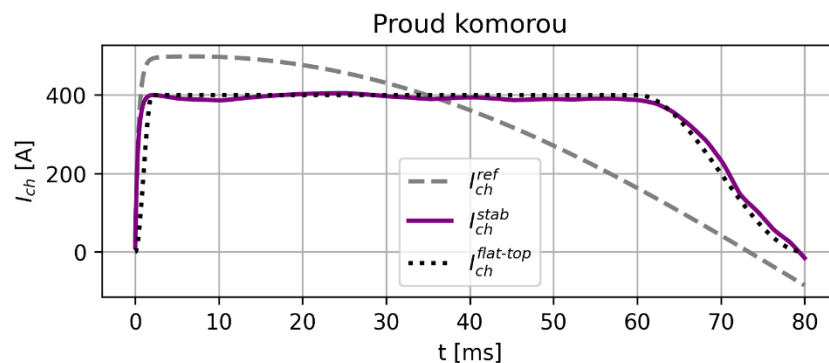
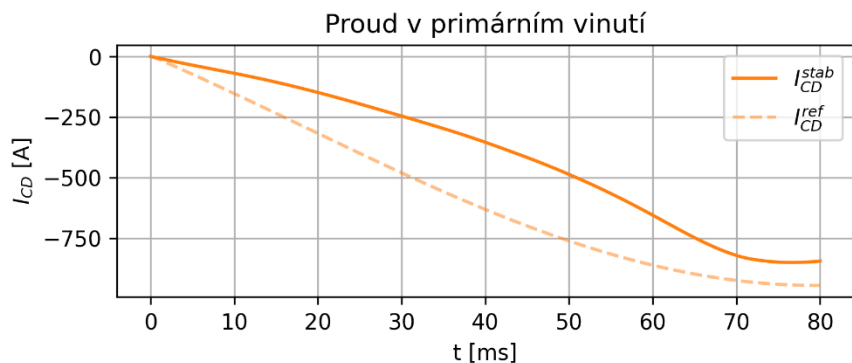
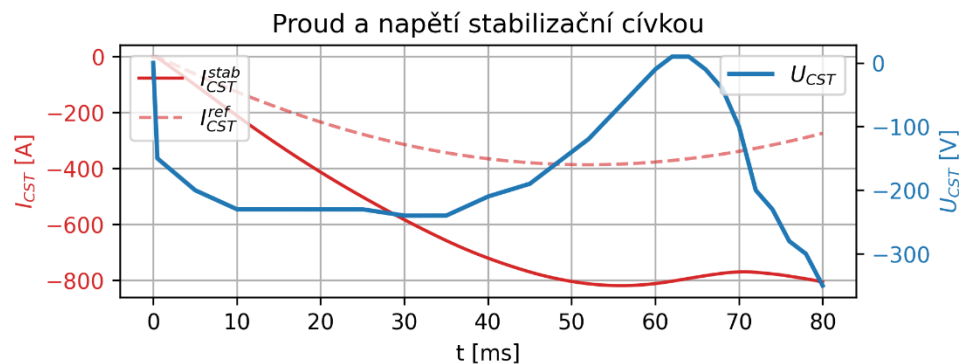
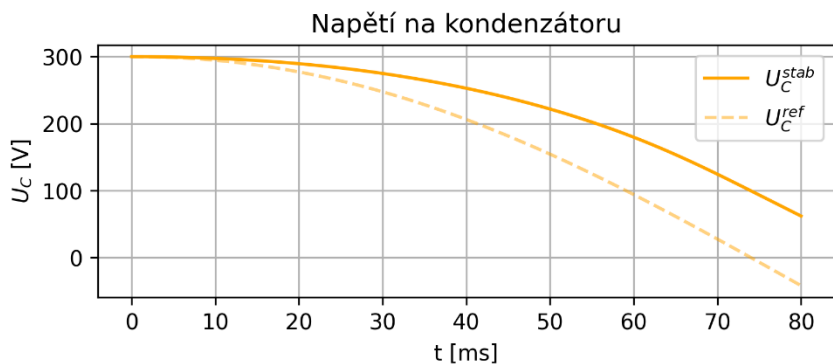
$$\vec{y}(t) = \mathbf{C} \vec{x}(t) + \mathbf{D} \vec{u}(t)$$

$$\mathbf{M} \dot{\mathbf{x}} + \mathbf{R} \mathbf{x} = \mathbf{u}$$

3. Numerical model of chamber current stabilization

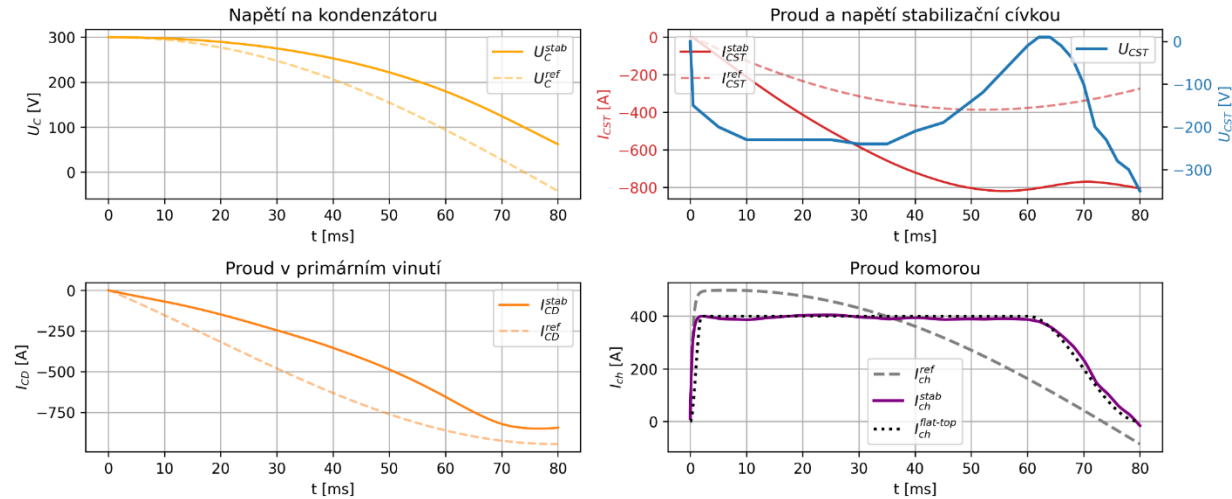
Implementation of the State-space form of transformer equations in Python

- The amplifier input voltage is defined using a piecewise linear function.
- The voltage value is set manually for each time interval.
- The `scipy.signal` library is used (StateSpace)



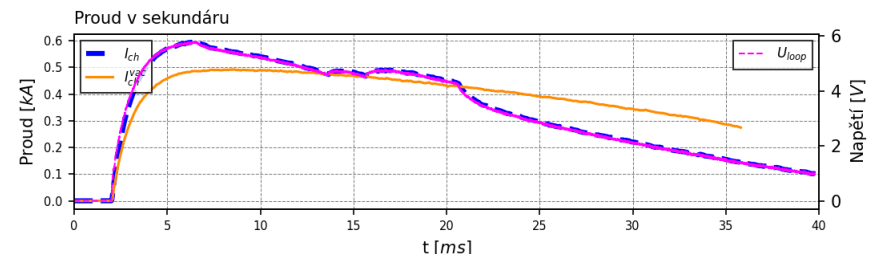
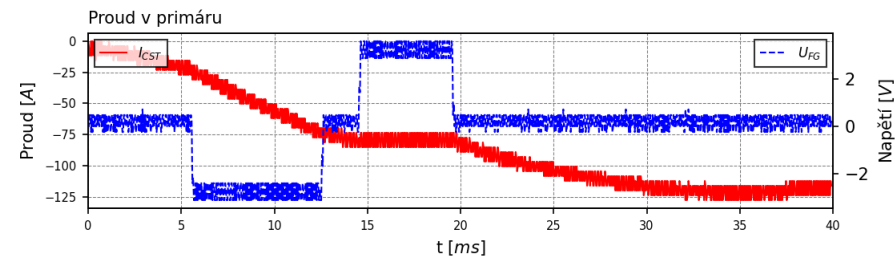
3. Numerical model of chamber current stabilization

Comparison of the numerical model with measured data on the GOLEM



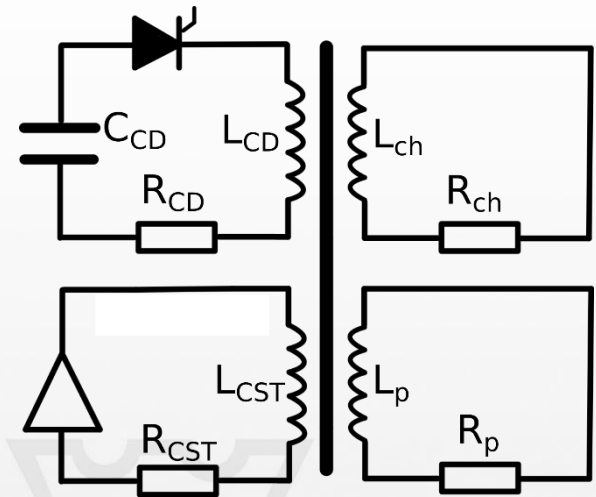
- **In this case, stabilization was performed only using a stepwise function, which could be directly prescribed.**
- **An RC filter was not used here to smooth the waveform.**

Vakuový výboj pro 100V z výboje 47413 bez záchvěvů



3. Extended numerical model of stabilization with plasma

Transformation of transformer equations into state-space form





3. Extended numerical model of stabilization with plasma

Transformation of transformer equations into state-space form

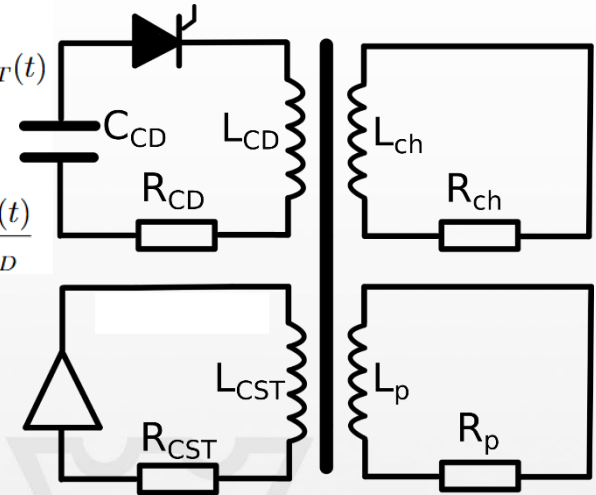
$$R_{CD}I_{CD}(t) + L_{CD}\dot{I}_{CD}(t) + U_C(t) + M_{CD,ch}\dot{I}_{ch}(t) + M_{CD,CST}\dot{I}_{CST}(t) + M_{CD,p}\dot{I}_p(t) = 0$$

$$R_{CST}I_{CST}(t) + L_{CST}\dot{I}_{CST}(t) + M_{CST,ch}\dot{I}_{ch}(t) + M_{CST,CD}\dot{I}_{CD}(t) + M_{CST,p}\dot{I}_p(t) = U_{CST}(t)$$

$$R_{ch}I_{ch}(t) + L_{ch}\dot{I}_{ch}(t) + M_{ch,CD}\dot{I}_{CD}(t) + M_{ch,CST}\dot{I}_{CST}(t) + M_{ch,p}\dot{I}_p(t) = 0$$

$$R_pI_p(t) + L_p\dot{I}_p(t) + M_{p,CD}\dot{I}_{CD}(t) + M_{p,CST}\dot{I}_{CST}(t) + M_{p,ch}\dot{I}_{ch}(t) = 0$$

$$\dot{U}_C(t) = \frac{I_{CD}(t)}{C_{CD}}$$



3. Extended numerical model of stabilization with plasma

Transformation of transformer equations into state-space form

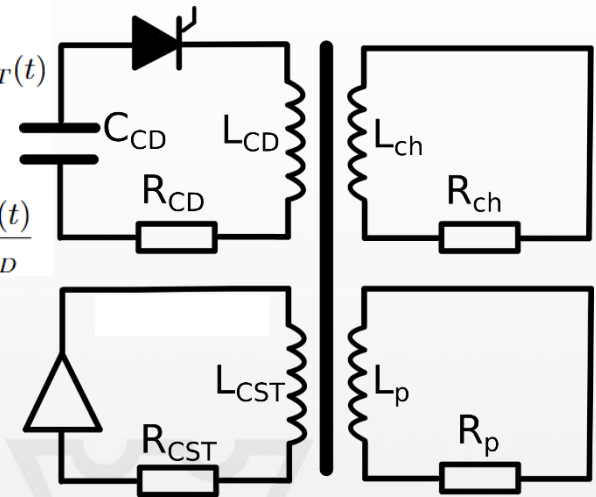
$$R_{CD}I_{CD}(t) + L_{CD}\dot{I}_{CD}(t) + U_C(t) + M_{CD,ch}\dot{I}_{ch}(t) + M_{CD,CST}\dot{I}_{CST}(t) + M_{CD,p}\dot{I}_p(t) = 0$$

$$R_{CST}I_{CST}(t) + L_{CST}\dot{I}_{CST}(t) + M_{CST,ch}\dot{I}_{ch}(t) + M_{CST,CD}\dot{I}_{CD}(t) + M_{CST,p}\dot{I}_p(t) = U_{CST}(t)$$

$$R_{ch}I_{ch}(t) + L_{ch}\dot{I}_{ch}(t) + M_{ch,CD}\dot{I}_{CD}(t) + M_{ch,CST}\dot{I}_{CST}(t) + M_{ch,p}\dot{I}_p(t) = 0$$

$$R_pI_p(t) + L_p\dot{I}_p(t) + M_{p,CD}\dot{I}_{CD}(t) + M_{p,CST}\dot{I}_{CST}(t) + M_{p,ch}\dot{I}_{ch}(t) = 0$$

$$\dot{U}_C(t) = \frac{I_{CD}(t)}{C_{CD}}$$



Matix form



$$\underbrace{\begin{bmatrix} L_{CD} & M_{CD,CST} & M_{CD,ch} & M_{CD,p} & 0 \\ M_{CST,CD} & L_{CST} & M_{CST,ch} & M_{CST,p} & 0 \\ M_{ch,CD} & M_{ch,CST} & L_{ch} & M_{ch,p} & 0 \\ M_{p,CD} & M_{p,CST} & M_{p,ch} & L_p & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{M}} \cdot \underbrace{\begin{bmatrix} \dot{I}_{CD} \\ \dot{I}_{CST} \\ \dot{I}_{ch} \\ \dot{I}_p \\ \dot{U}_C \end{bmatrix}}_{\dot{\mathbf{x}}} + \underbrace{\begin{bmatrix} R_{CD} & 0 & 0 & 0 & 1 \\ 0 & R_{CST} & 0 & 0 & 0 \\ 0 & 0 & R_{ch} & 0 & 0 \\ 0 & 0 & 0 & R_p & 0 \\ -\frac{1}{C_{CD}} & 0 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{R}} \cdot \underbrace{\begin{bmatrix} I_{CD} \\ I_{CST} \\ I_{ch} \\ I_p \\ U_C \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} 0 \\ U_{CST}(t) \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{u}}$$

3. Extended numerical model of stabilization with plasma

Transformation of transformer equations into state-space form

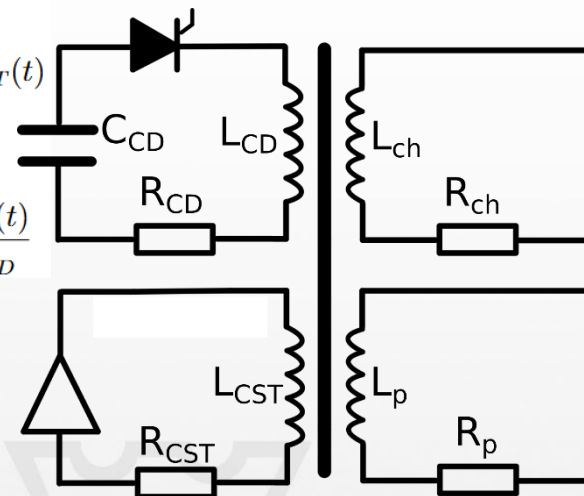
$$R_{CD}I_{CD}(t) + L_{CD}\dot{I}_{CD}(t) + U_C(t) + M_{CD,ch}\dot{I}_{ch}(t) + M_{CD,CST}\dot{I}_{CST}(t) + M_{CD,p}\dot{I}_p(t) = 0$$

$$R_{CST}I_{CST}(t) + L_{CST}\dot{I}_{CST}(t) + M_{CST,ch}\dot{I}_{ch}(t) + M_{CST,CD}\dot{I}_{CD}(t) + M_{CST,p}\dot{I}_p(t) = U_{CST}(t)$$

$$R_{ch}I_{ch}(t) + L_{ch}\dot{I}_{ch}(t) + M_{ch,CD}\dot{I}_{CD}(t) + M_{ch,CST}\dot{I}_{CST}(t) + M_{ch,p}\dot{I}_p(t) = 0$$

$$R_pI_p(t) + L_p\dot{I}_p(t) + M_{p,CD}\dot{I}_{CD}(t) + M_{p,CST}\dot{I}_{CST}(t) + M_{p,ch}\dot{I}_{ch}(t) = 0$$

$$\dot{U}_C(t) = \frac{I_{CD}(t)}{C_{CD}}$$



Matrix form

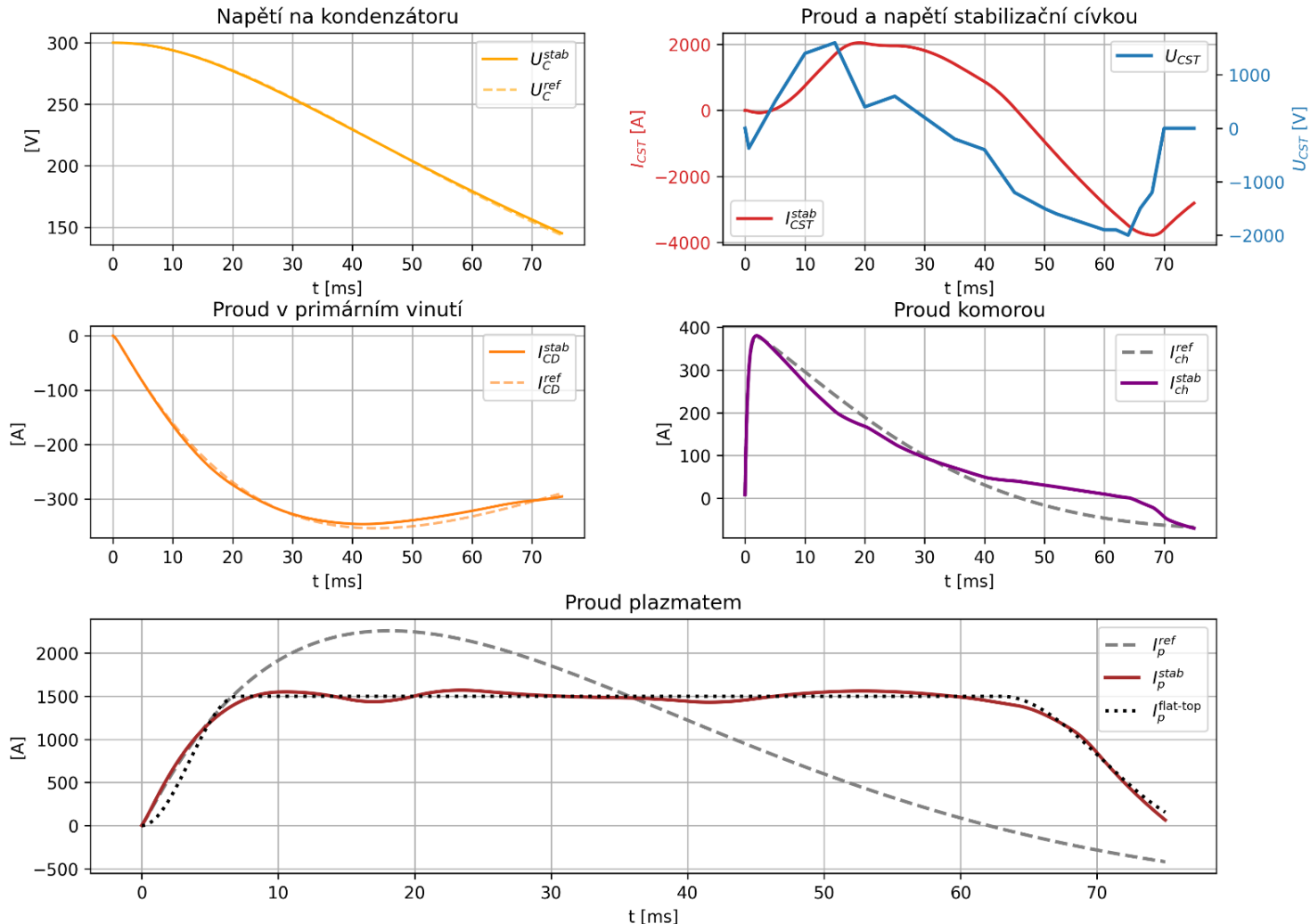
$$\underbrace{\begin{bmatrix} L_{CD} & M_{CD,CST} & M_{CD,ch} & M_{CD,p} & 0 \\ M_{CST,CD} & L_{CST} & M_{CST,ch} & M_{CST,p} & 0 \\ M_{ch,CD} & M_{ch,CST} & L_{ch} & M_{ch,p} & 0 \\ M_{p,CD} & M_{p,CST} & M_{p,ch} & L_p & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{M}} \cdot \underbrace{\begin{bmatrix} \dot{I}_{CD} \\ \dot{I}_{CST} \\ \dot{I}_{ch} \\ \dot{I}_p \\ \dot{U}_C \end{bmatrix}}_{\dot{\mathbf{x}}} + \underbrace{\begin{bmatrix} R_{CD} & 0 & 0 & 0 & 1 \\ 0 & R_{CST} & 0 & 0 & 0 \\ 0 & 0 & R_{ch} & 0 & 0 \\ 0 & 0 & 0 & R_p & 0 \\ -\frac{1}{C_{CD}} & 0 & 0 & 0 & 0 \end{bmatrix}}_{\mathbf{R}} \cdot \underbrace{\begin{bmatrix} I_{CD} \\ I_{CST} \\ I_{ch} \\ I_p \\ U_C \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} 0 \\ U_{CST}(t) \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{u}}$$

$$\mathbf{M}\dot{\mathbf{x}} + \mathbf{R}\mathbf{x} = \mathbf{u}$$



3. Extended numerical model of stabilization with plasma

Implementation of the State-space form of transformer equations in Python



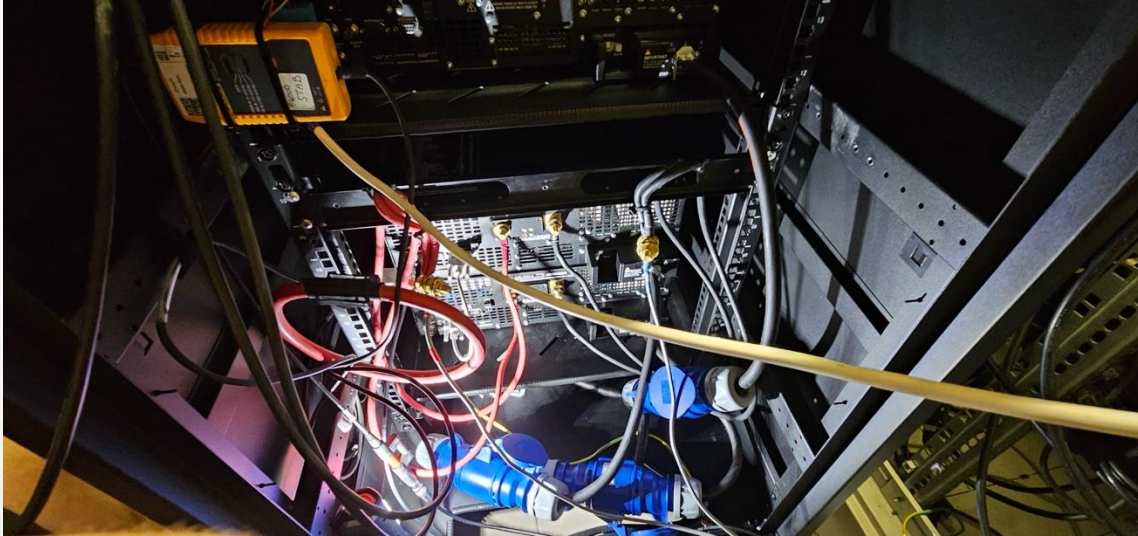
4. Future plans

- **Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current**



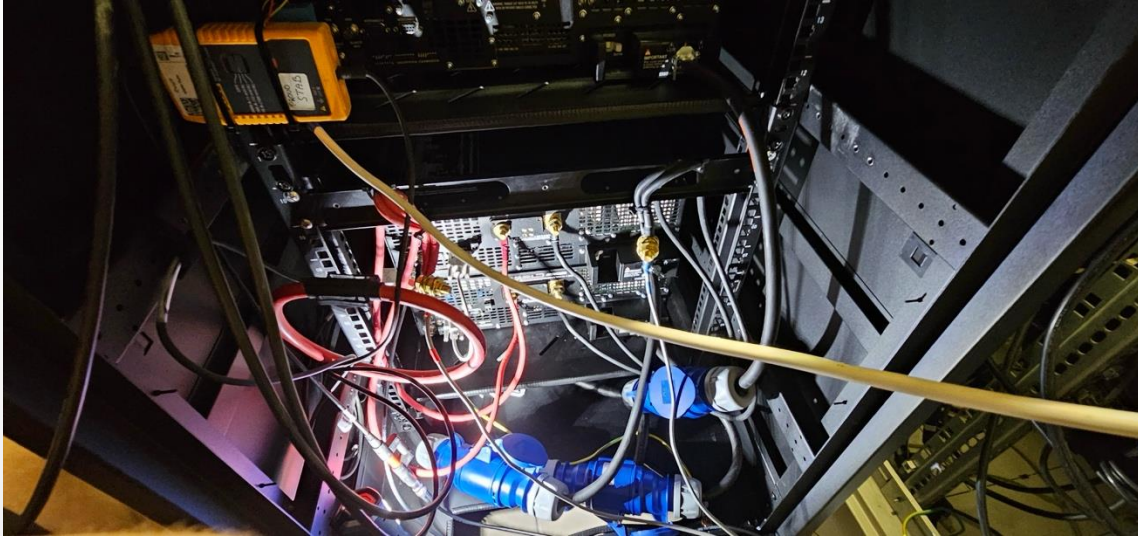
4. Future plans

**- Increase of the stabilization system power using two amplifiers
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4. Future plans

- Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current



4. Future plans

- Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current

- Tuning of the stabilization coil

$$R = \rho \frac{l}{S}$$

- **Use a conductor with a larger diameter (16 mm²), the currently used conductor has a cross-sectional area of 10 mm².**
- **Construct a similar coil in which the number of turns can be varied, allowing different operating modes to be tested.**

- Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current

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- Development of an autonomous system for current stabilization**

4. Future plans

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$$R = \rho \frac{l}{S}$$

User interface
Setting of input
parameters

- **Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current**

- **Tuning of the stabilization coil**

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- **Use a conductor with a larger diameter (16 mm²), the currently used conductor has a cross-sectional area of 10 mm².**
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- **Development of an autonomous system for current stabilization**

User interface

Setting of input parameters

Data mining

Take data from the previous discharge

- **Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current**
- **Tuning of the stabilization coil**
 - **Use a conductor with a larger diameter (16 mm²), the currently used conductor has a cross-sectional area of 10 mm².**
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- **Development of an autonomous system for current stabilization**

$$R = \rho \frac{l}{S}$$



- **Increase of the stabilization system power using two amplifiers parallel connect to maximize range of current**

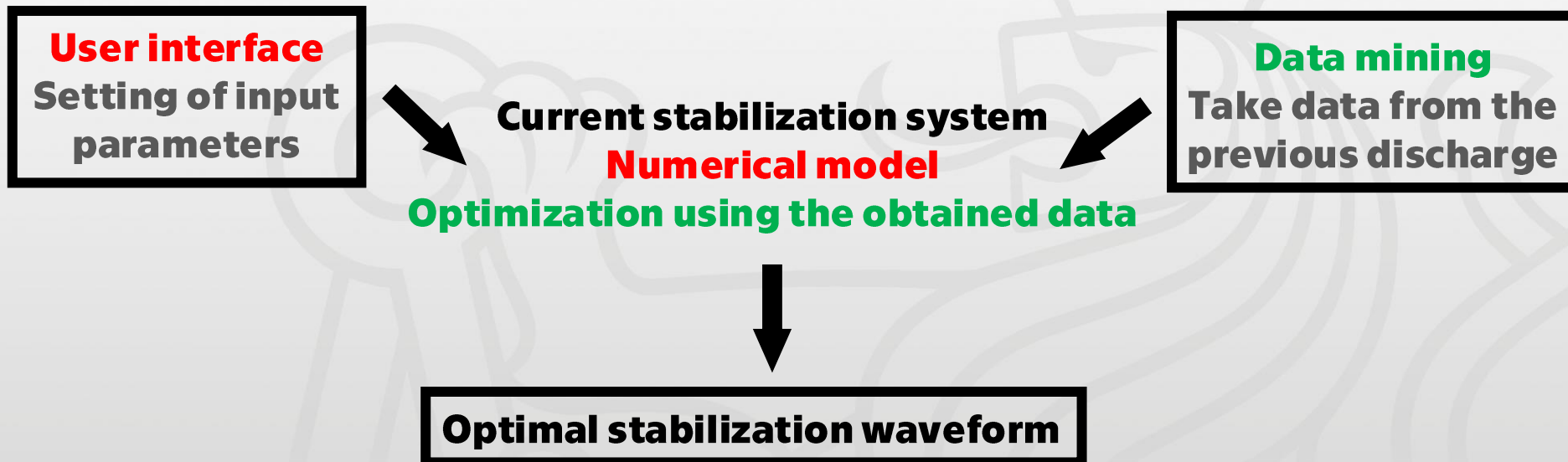
- **Tuning of the stabilization coil**

$$R = \rho \frac{l}{S}$$

- **Use a conductor with a larger diameter (16 mm²), the currently used conductor has a cross-sectional area of 10 mm².**

- **Construct a similar coil in which the number of turns can be varied, allowing different operating modes to be tested.**

- **Development of an autonomous system for current stabilization**



**Thank you for your
attention**



1. Charakteristiky obvodů pro vlečení proudu na tokamaku GOLEM 2

Parametry primárního vinutí

- Nahrazení tyristoru mechanickým spínačem
- Pro RLC obvod existuje analytické řešení, kterým lze data snadno fitovat

$$\delta = \frac{R_{CD}}{2L_{CD}}$$

$$\omega_0 = \frac{1}{\sqrt{L_{CD}C_{CD}}}$$

$$\omega = \sqrt{\omega_0^2 - \delta^2}$$

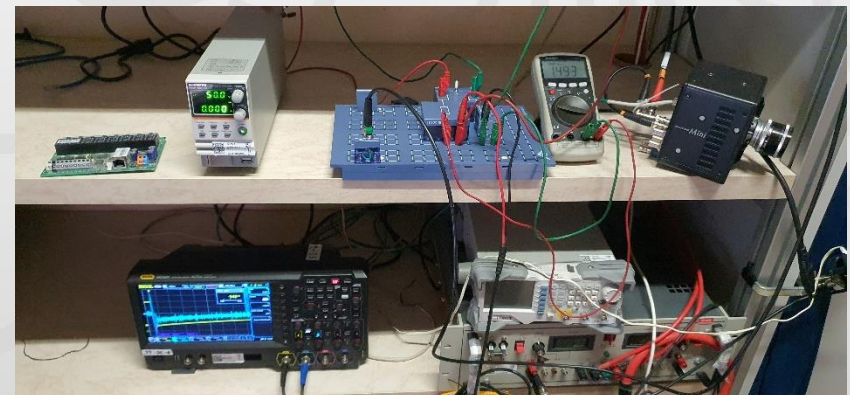
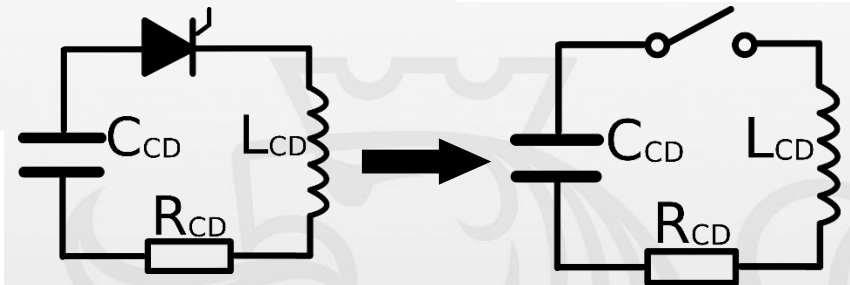
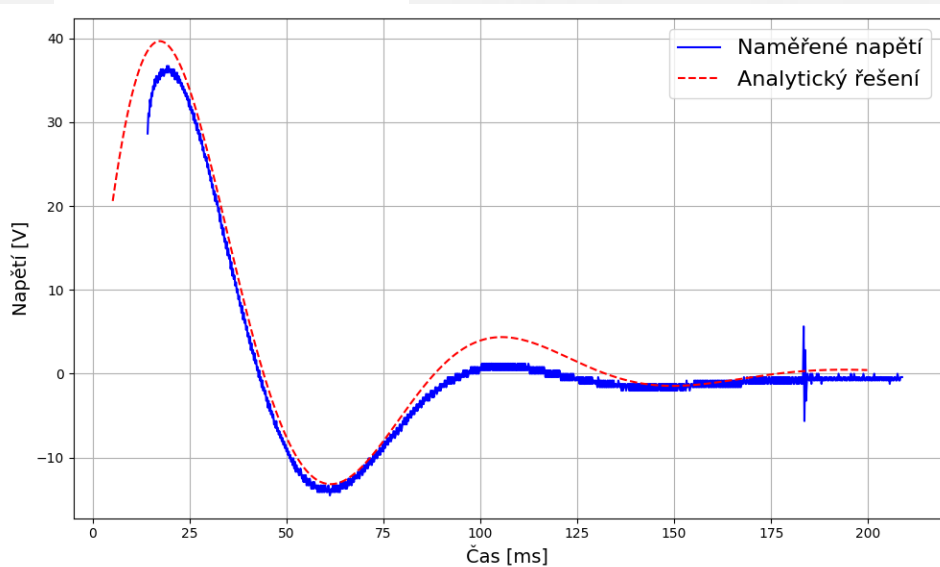
$$U_C(t) = U_C(0) \cdot e^{-\delta t} \cdot \left(\cos \omega t + \frac{\delta}{\omega} \sin \omega t \right)$$

$$I(t) = -U_C(0)C_{CD} \frac{\omega^2 + \delta^2}{\omega} \cdot e^{-\delta t} \sin \omega t$$

$$R_{CD} = 0.65 \Omega$$

$$L_{CD} = 13 \text{ mH}$$

$$C_{CD} = 13.5 \text{ mF}$$



1. Charakteristiky obvodů pro vlečení proudu na tokamaku GOLEM 3

Parametry tokamakové komory

- Předpoklad výboje pouze do komory + zanedbání vlivu přidavného vinutí skrze vzájemnou indukčnost
- Fitování pomocí funkce napětí na závit v různých časech

$$R_{ch}I_{ch}(t) + L_{ch}\frac{dI_{ch}(t)}{dt} + \underbrace{M_{ch,CD}\frac{dI_{CD}(t)}{dt}}_{-U_{loop}} + \underbrace{M_{ch,CST}\frac{dI_{CST}(t)}{dt}}_{zanedbáme} = 0$$

$$R_{ch} = 9.7 \text{ m}\Omega$$

$$L_{ch} = 1 \text{ }\mu\text{H}$$

Výboj #47875 zkoumáno od 6ms do 30ms

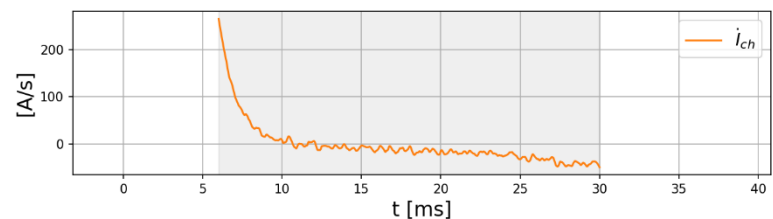
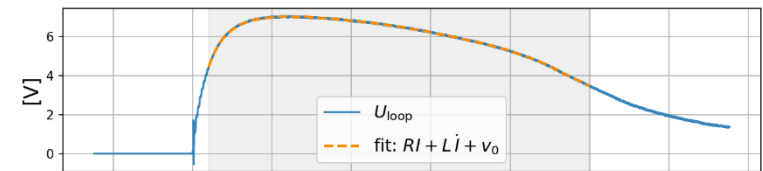
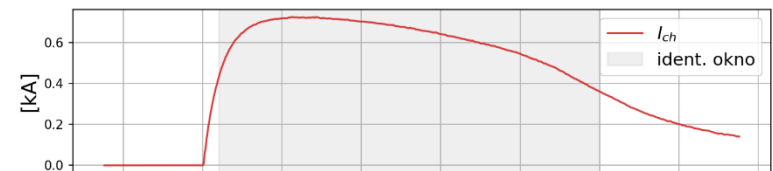
$$U_{loop}(t) = R_{ch} I_{ch}(t) + L_{ch} \frac{dI_{ch}(t)}{dt} + v_0$$

$$U = \begin{bmatrix} I_{ch}(t_1) & \dot{I}_{ch}(t_1) & 1 \\ I_{ch}(t_2) & \dot{I}_{ch}(t_2) & 1 \\ \vdots & \vdots & \vdots \\ I_{ch}(t_N) & \dot{I}_{ch}(t_N) & 1 \end{bmatrix} \begin{bmatrix} R_{ch} \\ L_{ch} \\ v_0 \end{bmatrix} + \varepsilon$$

\mathbf{X} $\boldsymbol{\theta}$

$$\begin{bmatrix} \hat{R}_{ch} \\ \hat{L}_{ch} \\ \hat{v}_0 \end{bmatrix} = \arg \min_{\boldsymbol{\theta}} \|\mathbf{U} - \mathbf{X}\boldsymbol{\theta}\|_2^2 = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{U}$$

$$\mathbf{U} = [U_{loop}(t_1), \dots, U_{loop}(t_N)]^T$$





1. Charakteristiky obvodů pro vlečení 4 proudu na tokamaku GOLEM

Parametry plazmatu

- **Předpoklad modelu plazmatu s konstantní vodivostí (indukčnost a odpor jsou konstantní)**
- **Využití ohmova zákona a průměrování odporu plazmatu v úseku s přibližně konstantním proudem plazmatu (flat-top)**

$$R_p I_p(t) + L_p \frac{dI_p(t)}{dt} + \underbrace{M_{p,CD} \frac{dI_{CD}(t)}{dt} + M_{p,CST} \frac{dI_{CST}(t)}{dt} + M_{p,ch} \frac{dI_{ch}(t)}{dt}}_{-U_{loop}} = 0 \quad \longrightarrow \quad R_p \approx \frac{U_{loop}}{I_p}$$

$$U_{loop}(t) = R_p I_p(t) + L_p \frac{dI_p(t)}{dt}$$

$$L_p = 9.3 \mu\text{H}$$
$$R_p = 0.6 \text{ m}\Omega$$

$$\int_0^t U_{loop}(\tau) d\tau - R_p \int_0^t I_p(\tau) d\tau = L_p I_p(t) + \Phi_0 \quad \longrightarrow \quad W(t) = L_p I_p(t) + \Phi_0$$

1. Charakteristiky obvodů pro vlečení proudu na tokamaku GOLEM 7

Parametry přídavného primárního vinutí

- Nainstalované vinutí bylo původně kalibrováno na soustavu zesilovačů KEPCO ale během plnění úkolů došlo ke změně zesilovače.
- Měření odporu proběhlo pomocí měření proudu a napětí na zesilovači a následné aplikaci Ohmova zákona
- Měření indukčnosti proběhlo opět fitováním na základě znalosti měření proudů z daných výbojů

$$R_{CST} = \frac{U_{CST}}{I_{CST}}$$



$$R_{CST} = 0.3 \Omega$$

Proudový režim		
I [A]	U [V]	R [Ω]
0.2	0.1	0.50
1.0	0.3	0.30
2.0	0.7	0.35
3.0	1.0	0.33
5.0	1.6	0.32
7.0	2.3	0.33
10.0	3.2	0.32
12.5	4.0	0.32
15.0	4.7	0.31
20.0	6.3	0.31
Průměr		0.32

Napěťový režim		
U [V]	I [A]	R [Ω]
0.1	0.5	0.20
0.3	0.9	0.33
0.5	1.5	0.33
1.0	3.1	0.32
1.5	4.8	0.31
1.9	6.1	0.31
2.1	6.7	0.31
2.3	7.4	0.31
2.4	7.9	0.30
2.5	8.2	0.31
Průměr		0.31



1. Charakteristiky obvodů pro vlečení proudu na tokamaku GOLEM 8

Parametry přídavného primárního vinutí

- Nainstalované vinutí bylo původně kalibrováno na soustavu zesilovačů KEPCO ale během plnění úkolů došlo ke změně zesilovače.
- Měření odporu proběhlo pomocí měření proudu a napětí na zesilovači a následné aplikaci Ohmova zákona
- Měření indukčnosti proběhlo opět fitováním na základě znalosti měření proudů z daných výbojů

$$U_{CST}(t) = R_{CST} I_{CST}(t) + L_{CST} \dot{I}_{CST}(t) + M_{CST,ch} \dot{I}_{ch}(t) + M_{CST,CD} \dot{I}_{CD}(t) + v_0$$

Bylo změřeno: $I_{CST}(t)$, $I_{ch}(t)$, $I_{CD}(t)$ a napětí $U_{CST}(t)$

Fitem bylo třeba zjistit: L_{CST} , $M_{CST,ch}$ a $M_{CST,p}$

$$R_{CST} = 0.3 \Omega$$

$$L_{CST} = 6 \mu\text{H}$$

$$M_{CST,ch} = -38.246 \text{ mH}$$

$$M_{CST,CD} = 0.143 \text{ mH}$$

$$v_0 = 17.264 \text{ V}$$



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Výpočet vzájemné indukčnosti

$$M_{i,j} = k_{i,j} \cdot \sqrt{L_i L_j}$$

1. Charakteristiky obvodů pro vlečení 4 proudu na tokamaku GOLEM

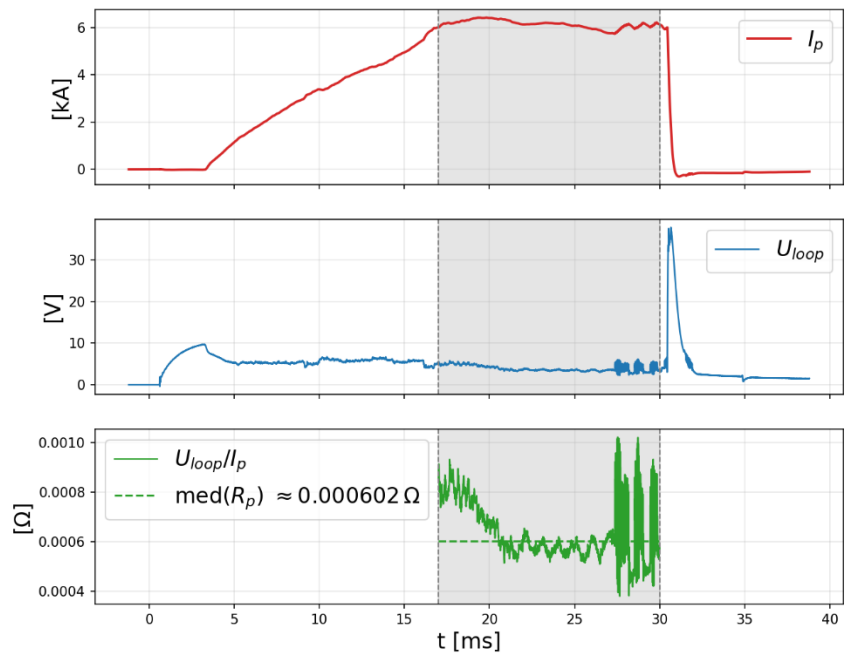
Parametry plazmatu

- **Předpoklad modelu plazmatu s konstantní vodivostí (indukčnost a odpor jsou konstantní)**
- **Využití ohmova zákona a průměrování odporu plazmatu v úseku s přibližně konstantním proudem plazmatu (flat-top)**

$$R_p I_p(t) + \underbrace{L_p \frac{dI_p(t)}{dt}}_{\dot{I}_p=0} + \underbrace{M_{p,CD} \frac{dI_{CD}(t)}{dt} + M_{p,CST} \frac{dI_{CST}(t)}{dt} + M_{p,ch} \frac{dI_{ch}(t)}{dt}}_{-U_{loop}} = 0 \quad \longrightarrow \quad R_p \approx \frac{U_{loop}}{I_p}$$

Výboj #48726 zkoumáno od 17ms do 30ms

$$R_p = 0.000602 \Omega \approx 0.6 \text{ m}\Omega$$



1. Charakteristiky obvodů pro vlečení proudu na tokamaku GOLEM 5

Parametry plazmatu

- Předpoklad modelu plazmatu s konstantní vodivostí (indukčnost a odpor jsou konstantní)
- Lineární nárůst proudu plazmatem (ramp up) pro lineární fit

$$U_{\text{loop}}(t) = R_p I_p(t) + L_p \frac{dI_p(t)}{dt}$$

Integrace

$$\int_0^t U_{\text{loop}}(\tau) d\tau - R_p \int_0^t I_p(\tau) d\tau = L_p I_p(t) + \Phi_0$$

Označení

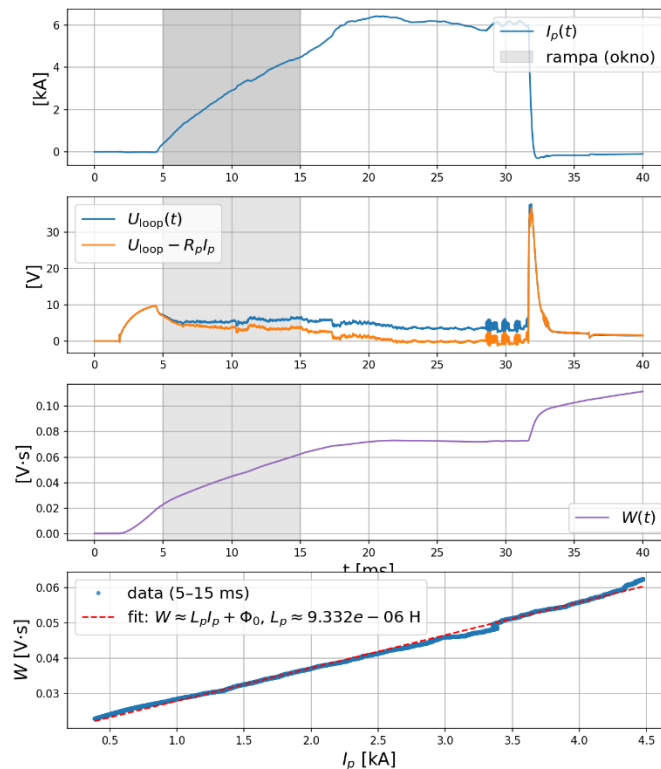
$$W(t) = \int_0^t (U_{\text{loop}}(\tau) - R_p I_p(\tau)) d\tau$$

Celková fitovací funkce

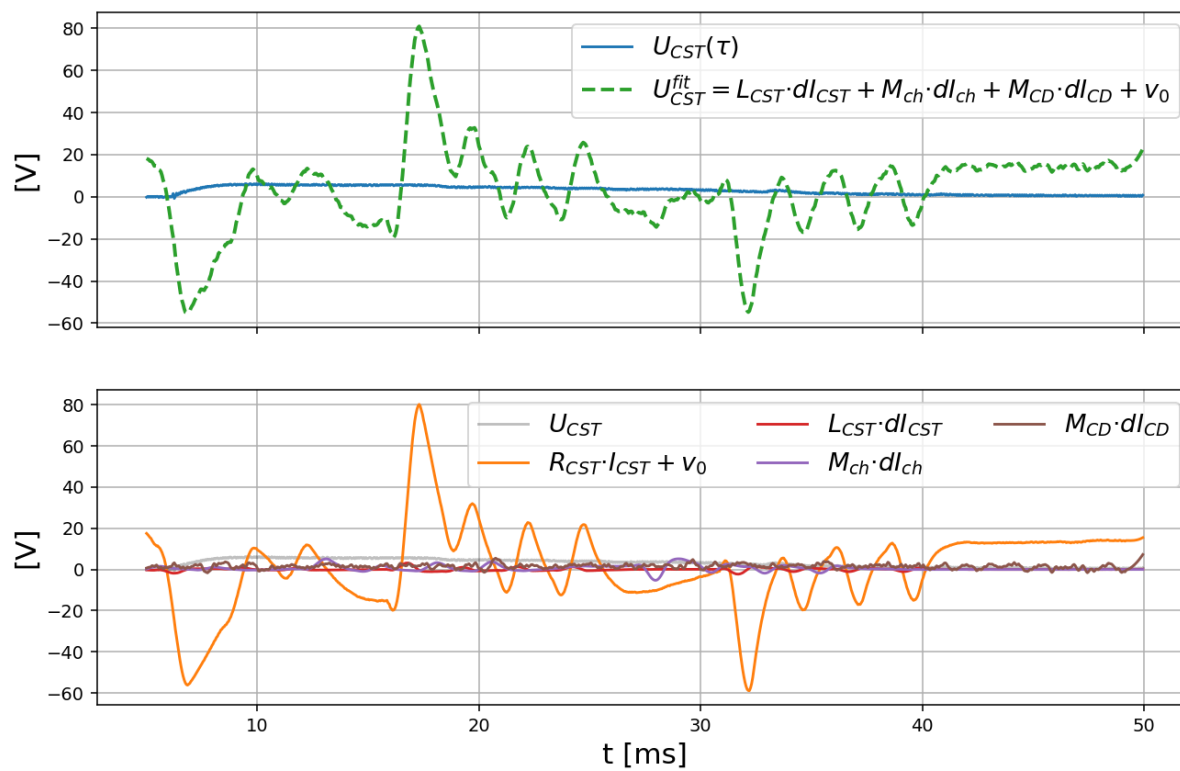
$$W(t) = L_p I_p(t) + \Phi_0$$

$$L_p \approx 9.3 \mu\text{H}$$

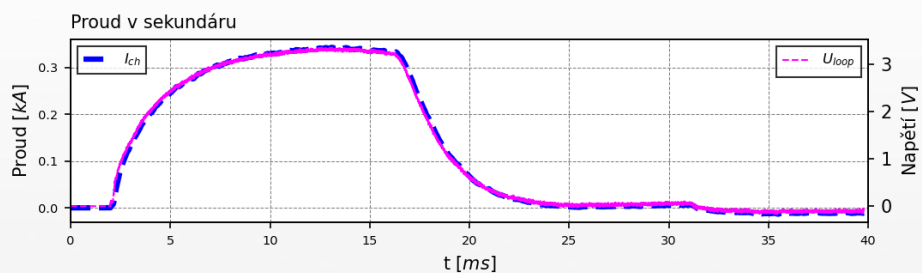
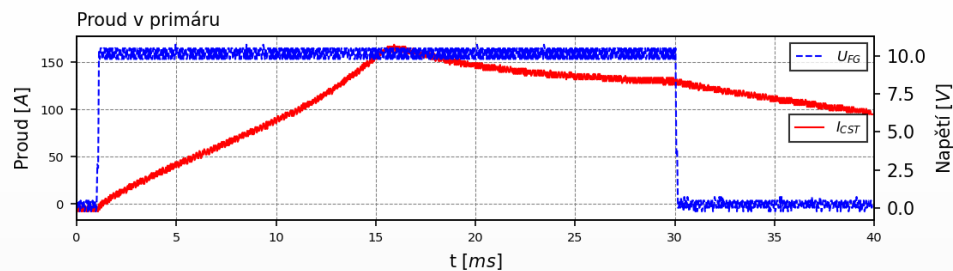
Výboj #48726 zkoumáno od 5ms do 15ms



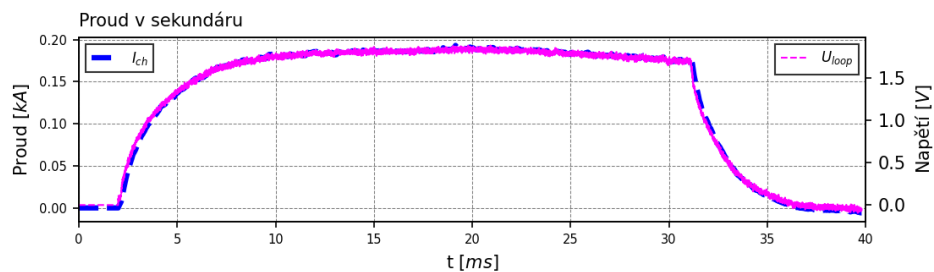
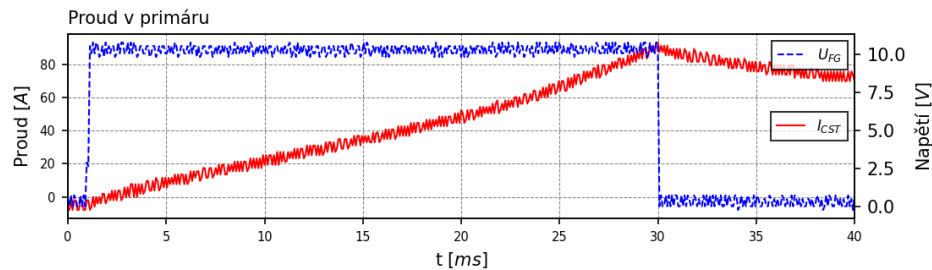
Výboj #48508 zkoumán celý rozsah



Maximální výkon zesilovače z výboje 47410 při 25 závitech



Maximální výkon zesilovače z výboje 47393 při 50 závitech





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DEFAULT DIP SWITCH
SETTINGS SHOWN

DIP SWITCH SETTINGS

	UP	DOWN
1 UNBALANCED INPUT	ON	OFF
2 BALANCED INPUT	ON	OFF
3 DC SERVO	ON	OFF
4 OPERATION MODE	CV	CC
5 COMPENSATION NETWORK 2	ON	OFF
6 COMPENSATION NETWORK 1	ON	OFF
7 CONTROL CONFIGURATION	MASTER	FOLLOWER
8 COUPLING	DC	AC
9 GAIN BIT 8 (MSB)	20	OFF
10 GAIN BIT 7	10	OFF
11 GAIN BIT 6	5	OFF
12 GAIN BIT 5	2.5	OFF
13 GAIN BIT 4	1.25	OFF
14 GAIN BIT 3	0.63	OFF
15 GAIN BIT 2	0.31	OFF
16 GAIN BIT 1 (LSB)	0.16	OFF
17 ELECTRONIC GAIN MATCHING	ON	OFF
18 SYNTHETIC IMPEDANCE BIT 3 (MSB)	0.5Ω	OFF
19 SYNTHETIC IMPEDANCE BIT 2	0.25Ω	OFF
20 SYNTHETIC IMPEDANCE BIT 1 (LSB)	0.125Ω	OFF
21 CURRENT LIMIT BIT 4 (MSB)	+80A	OFF
22 CURRENT LIMIT BIT 3	+40A	OFF
23 CURRENT LIMIT BIT 2	+20A	OFF
24 CURRENT LIMIT BIT 1 (LSB)	+10A	OFF

- Enable unbalanced input signal connector
- Enable balanced input signal connector
- Enable DC Servo
- Controlled-voltage or controlled-current operation
- Enable Compensation network #2 (for controlled-current operation)
- Enable Compensation network #1 (for controlled-current operation)
- Multi-amp configuration
- DC enable or DC block

ALL OFF = 0
ALL UP = 40

Set Amplifier Gain (0 to 40)

Enable electronic gain matching (for parallel multi-amp operation)

Enable Synthetic Impedance (0.125 ohms to 0.875 ohms)

Enable Current Limit (10A to 150A)

NOTE: ALL BIT SWITCHES ARE ADDITIVE. UP = ON.

RED = FACTORY DEFAULT

Napěťový režim

Proudový režim



Cívka pod tokamakem připojená k primárnímu vinutí

- **Dalších extra 120 závitů
bez indukční vazby**
- **Celkově má primární
vinutí 148 závitů**
- **Existuje výboj, kde je
pouze připojen primár
bez této cívky např. výboj
#47745 ze kterého by se
dalo zjistit kolik má tato
cívka indukčnost, protože
pro dvě sériově zapojené
cívky se vlastní
indukčnosti sčítají**

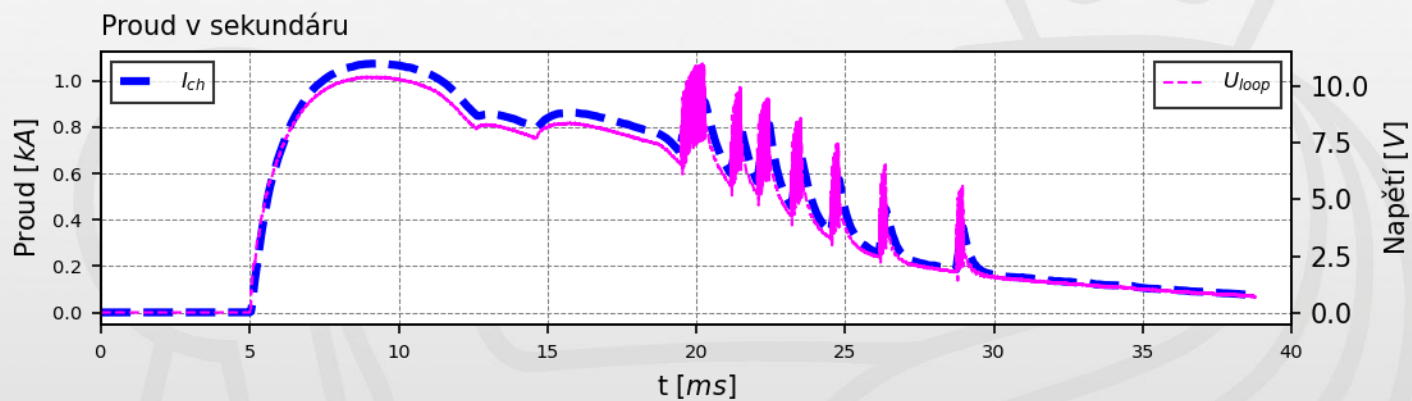
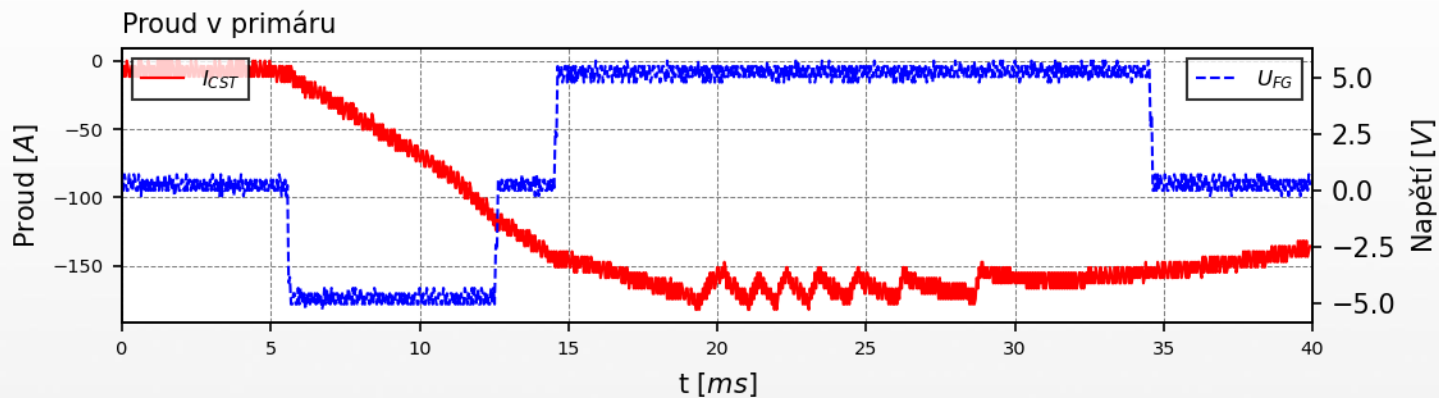




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Vakuový výboj pro 300V z výboje 47417 se záchvěvy

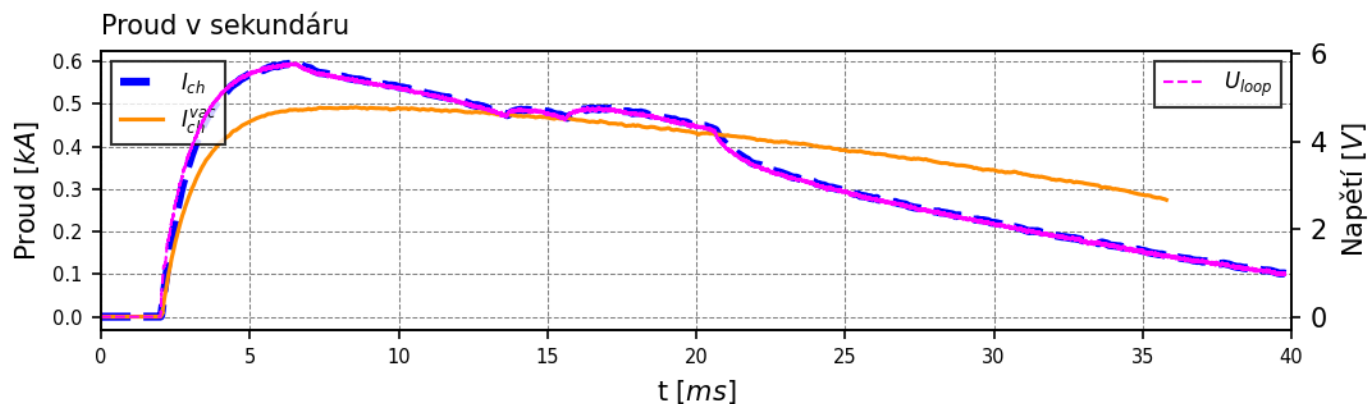
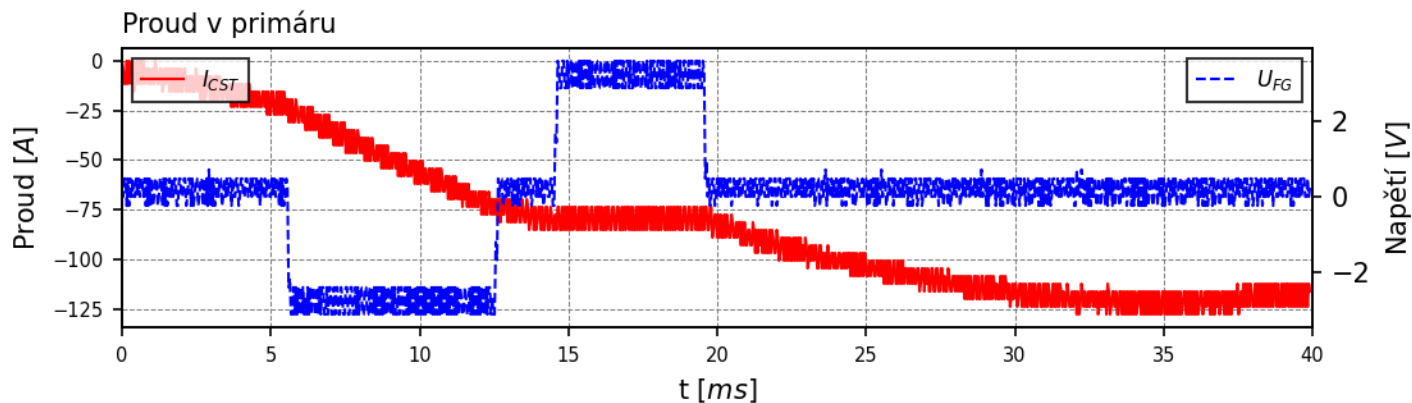




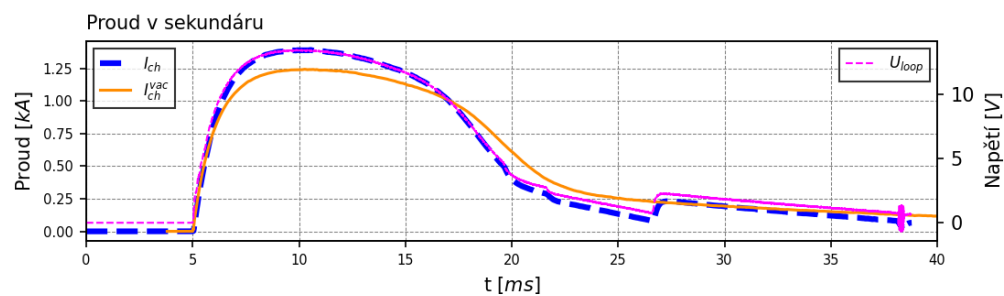
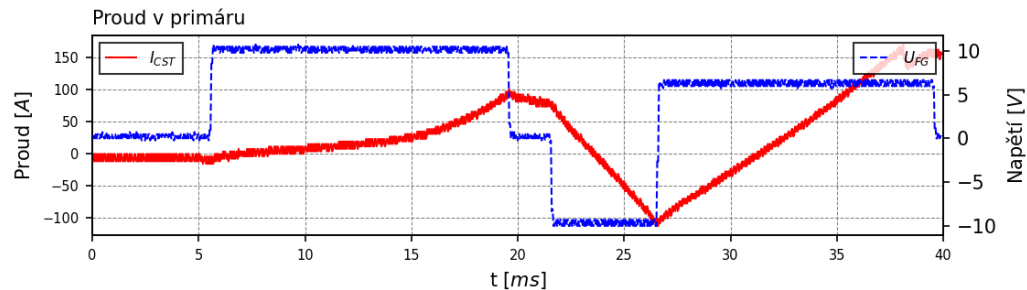
ČVUT

ČESKÉ VYSOKÉ
UČENÍ TECHNICKÉ
V PRAZE

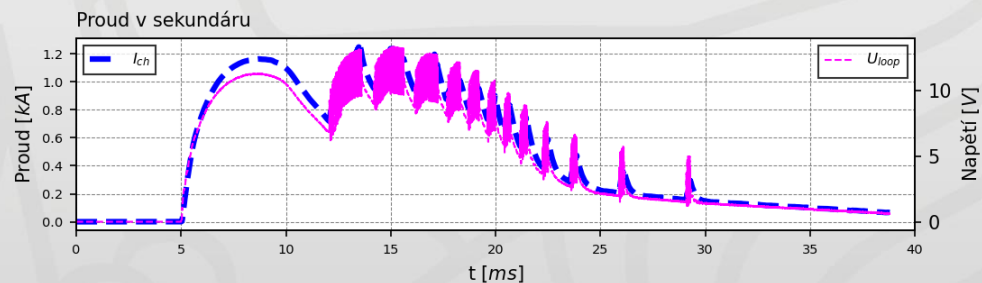
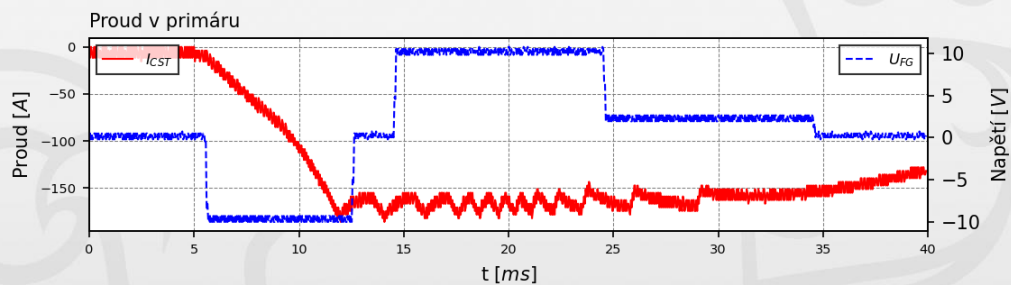
Vakuový výboj pro 100V z výboje 47413 bez záchvěvů



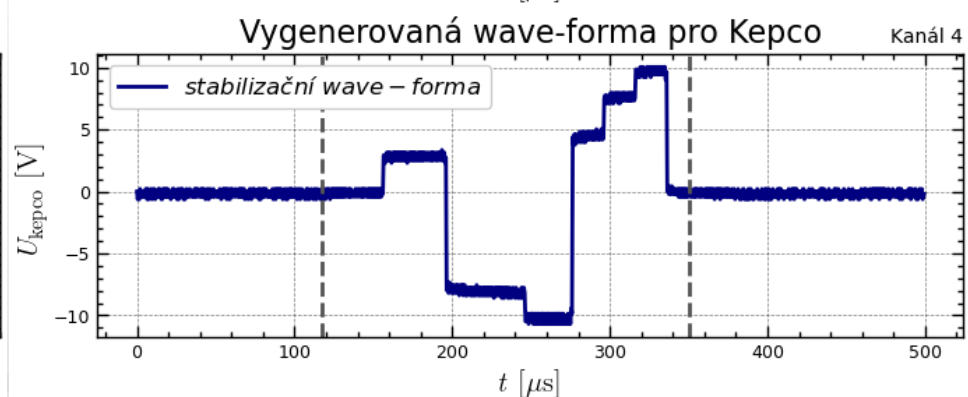
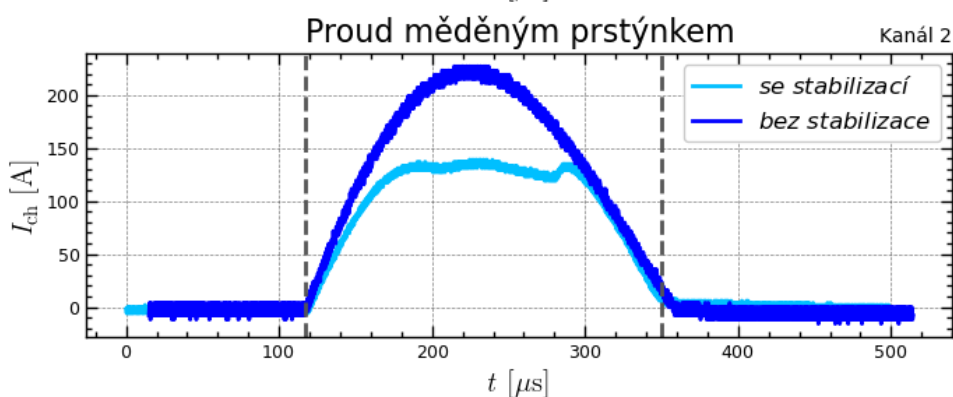
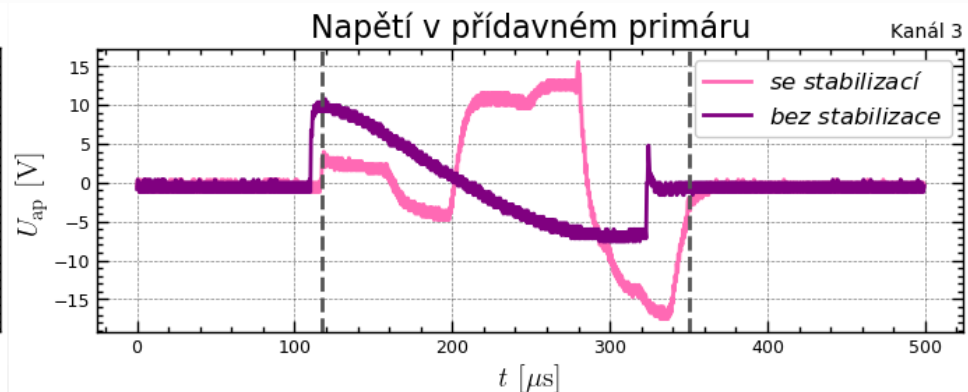
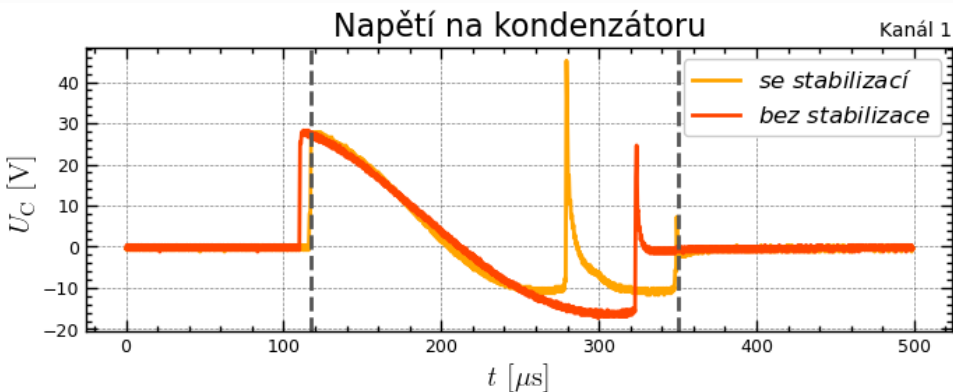
Vakuový výboj pro 400V z výboje 47431 bez záchvěvů



Vakuový výboj pro 400V z výboje 47427 se záchvěvy



Výsledky z table-top experimentu

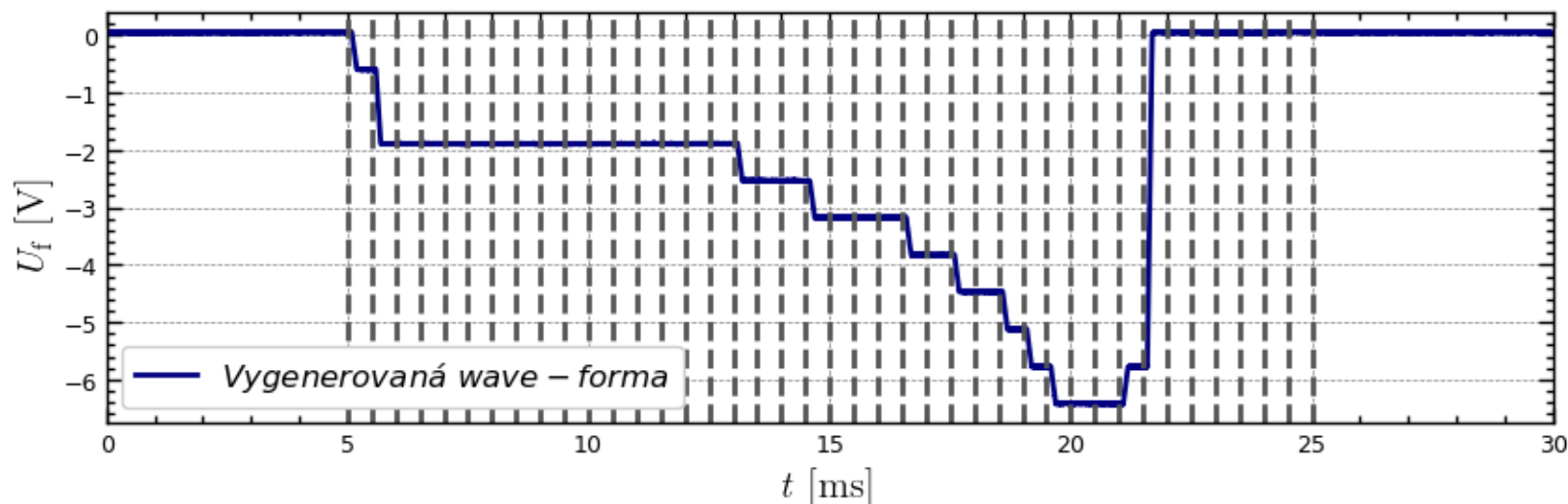


Ovlivnění proudu komorou pomocí proudového zesilovače KEPCO

Napětí na kondenzátoru $U_c(0) = 20\text{ V}$

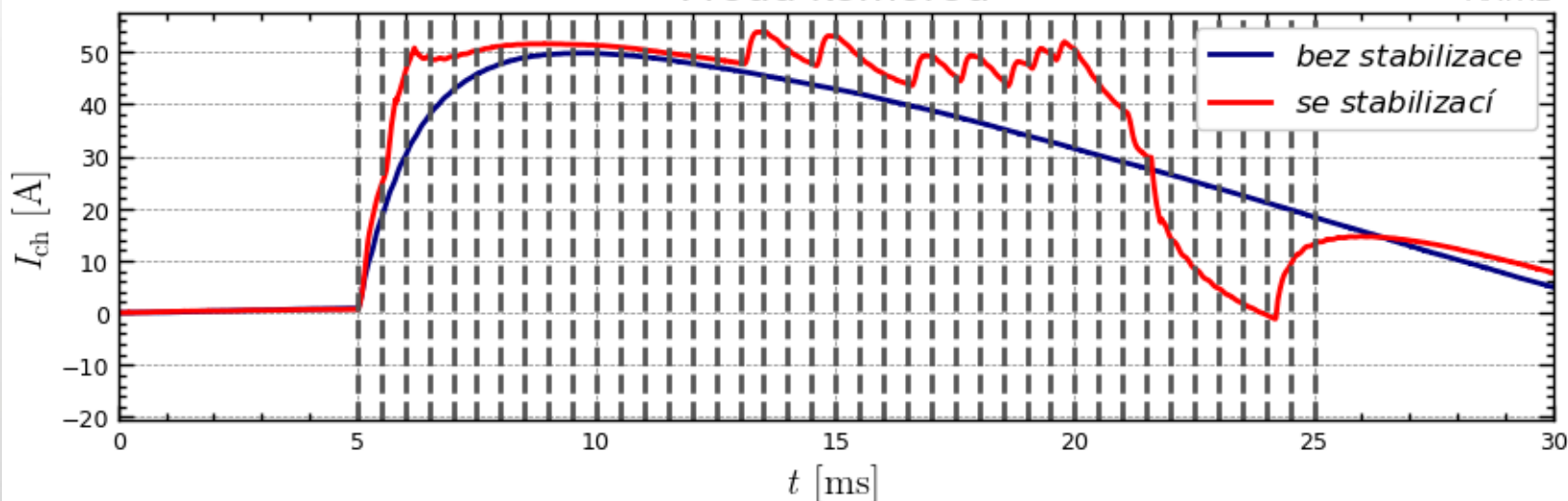
Wave-forma

Kanál 5



Proud komorou

MATH2



Napětí na kondenzátoru $U_C(0) = 60\text{ V}$

