

MODELOVÁNÍ ZDROJŮ AKUSTICKÉ EMISE

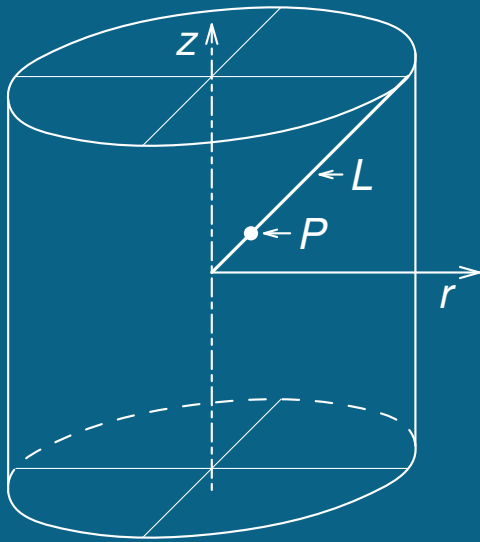
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Ústav termomechaniky AV ČR, v.v.i.

Příspěvek vznikl na základě podpory projektu GA ČR č. 101/09/1630
*Numerické řešení stacionárních a nestacionárních problémů dispersního šíření
vln v mechanických systémech na různých úrovních*
a záměru ÚT AV ČR, v.v.i., AV0Z20760514.

Úvod

- modelování zdrojů akustické emise pomocí COMSOL Multiphysics
- zdroje akustické emise:
 - koncentrovaná síla
 - dvojice koncentrovaných sil
- buzení pulsní silou – 4 průběhy zdrojové síly
- neohraničené médium – ocelový válec
- 3 modely bodové síly:
 - bod
 - kruhová plocha
 - válec
- porovnání vypočtených výchylek s analytickým řešením

Geometrie

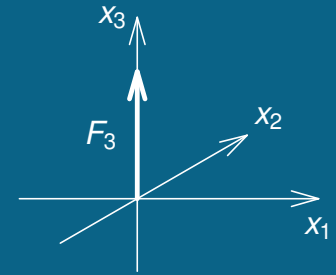


geometrie: válec
poloměr: 50 mm,
výška: 100 mm,
 $P = [10 \text{ mm}, 10 \text{ mm}]$,
 $L: z = r$.

použitý materiál: železo
Youngův modul: $E = 200 \text{ GPa}$,
Poissonovo číslo: $\nu = 0,29$,
hustota: $\rho = 7870 \text{ kg/m}^3$.

Koncentrovaná síla

u_{ij} – výchylka v bodě \mathbf{x} ve směru i
 způsobená silou f působící v bodě ξ ve směru j
 $f(\mathbf{x}, t; \xi) = f_0(t)\delta(\mathbf{x} - \xi)\mathbf{e}_j$



$$4\pi\rho u_{ij}(\mathbf{x}, t) = \frac{3\gamma_i\gamma_j - \delta_{ij}}{r^3} \int_{r/\alpha}^{r/\beta} \tau f_0(t - \tau) d\tau + \frac{\gamma_i\gamma_j}{\alpha^2 r} f_0\left(t - \frac{r}{\alpha}\right) - \frac{\gamma_i\gamma_j - \delta_{ij}}{\beta^2 r} f_0\left(t - \frac{r}{\beta}\right)$$

ρ – hustota materiálu,

$r = |\mathbf{x} - \xi|$ – vzdálenost od zdroje,

$\gamma_i = \frac{x_i - \xi_i}{r}$ – směrové kosiny,

δ_{ij} – Kroneckerovo delta,

$\alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}}$ – rychlost tlakových vln,

$\beta = \sqrt{\frac{\mu}{\rho}}$ – rychlost smykových vln,

λ, μ – Lamého elastické konstanty,

$f_0(t) = at \exp(-bt)$ – zdrojová síla.

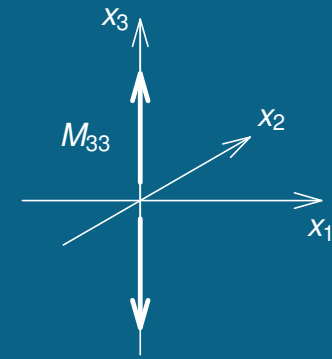
Koncentrovaná dvojitá síla

u_k – výchylka v bodě \mathbf{x} ve směru k způsobená silovým momentem $M_{ij}(t)$ působícím v bodě ξ ,

$$M_{ij}(t) = f_0(t) \bar{M}_{ij},$$

$f_0(t)$ – zdrojová síla,

\bar{M}_{ij} – tenzor popisující prostorovou povahu zdroje.

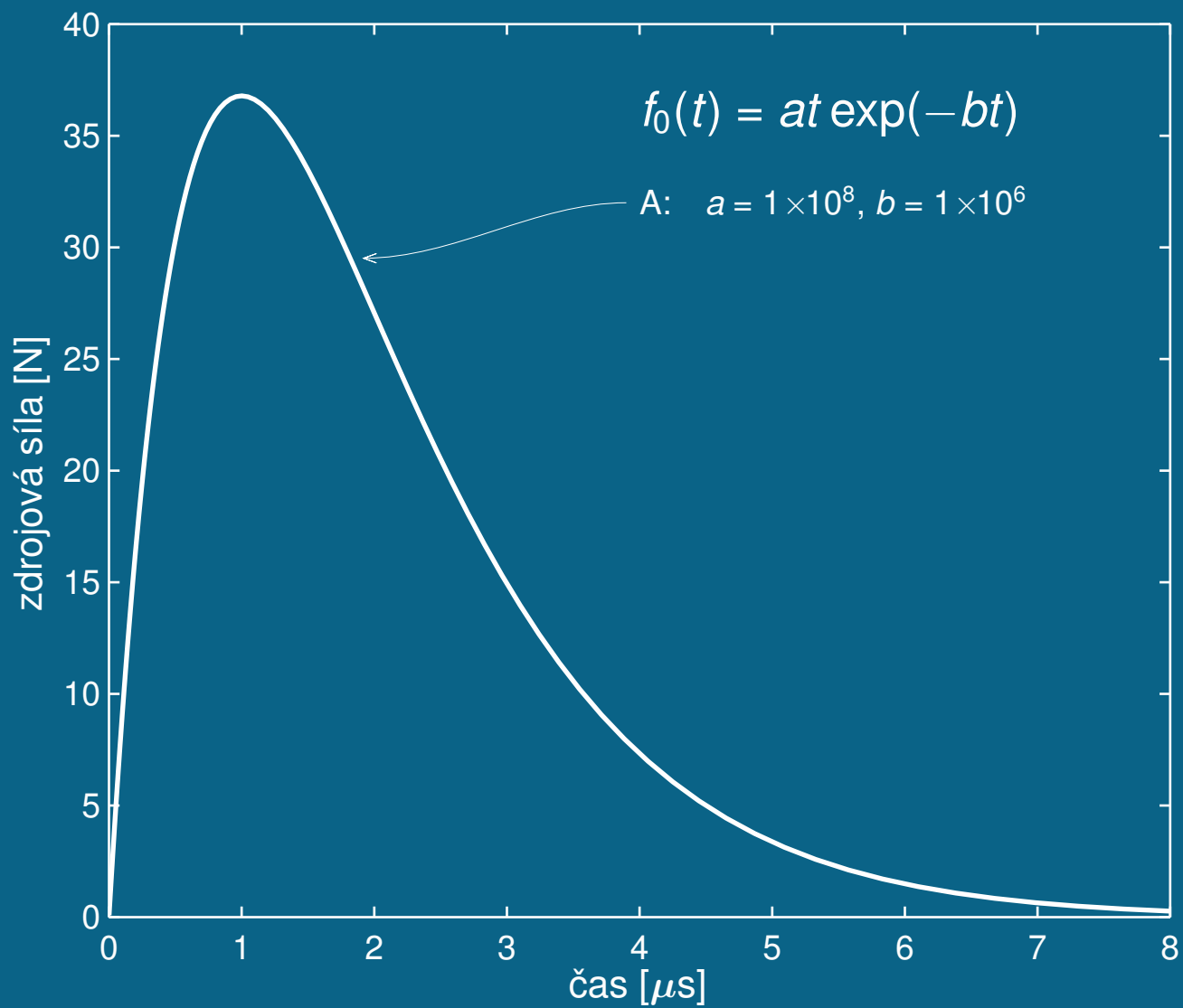


$$\begin{aligned} 4\pi\rho u_k(\mathbf{x}, t) = & (15\gamma_k\gamma_i\gamma_j - 3\gamma_k\delta_{ij} - 3\gamma_i\delta_{kj} - 3\gamma_j\delta_{ki}) \frac{1}{r^4} \int_{r/\alpha}^{r/\beta} \tau M_{ij}(t - \tau) d\tau \\ & + (6\gamma_k\gamma_i\gamma_j - \gamma_k\delta_{ij} - \gamma_i\delta_{kj} - \gamma_j\delta_{ki}) \frac{1}{\alpha^2 r^2} M_{ij}\left(t - \frac{r}{\alpha}\right) \\ & - (6\gamma_k\gamma_i\gamma_j - \gamma_k\delta_{ij} - \gamma_i\delta_{kj} - 2\gamma_j\delta_{ki}) \frac{1}{\beta^2 r^2} M_{ij}\left(t - \frac{r}{\beta}\right) \\ & + \gamma_k\gamma_i\gamma_j \frac{1}{\alpha^3 r} \dot{M}_{ij}\left(t - \frac{r}{\alpha}\right) - (\gamma_k\gamma_i - \delta_{ki}) \gamma_j \frac{1}{\beta^3 r} \dot{M}_{ij}\left(t - \frac{r}{\beta}\right) \end{aligned}$$

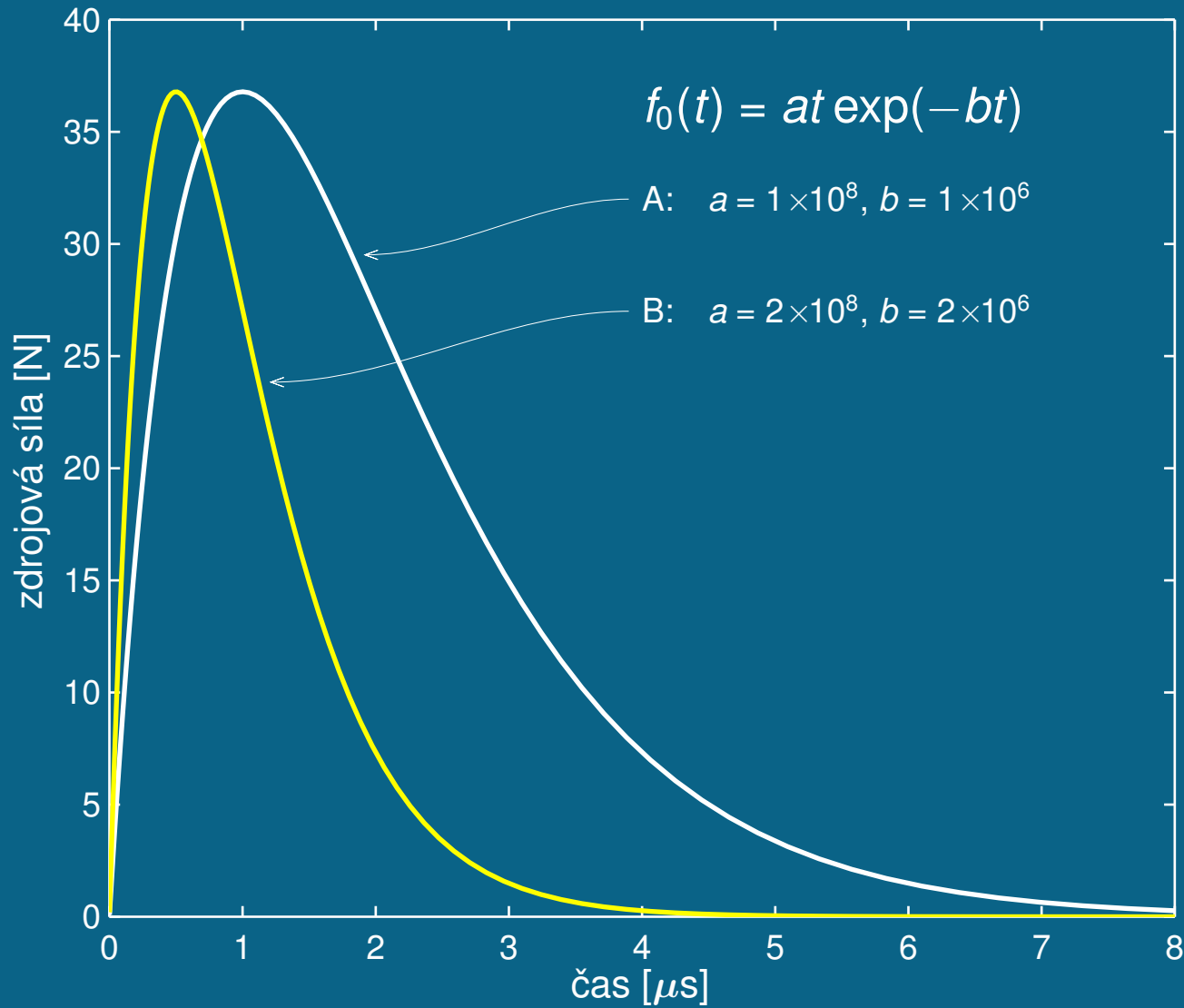
ρ , r , γ_i , δ_{ij} , α a β mají stejný význam jako v předešlém případě,

\dot{M}_{ij} – časová derivace silového momentu.

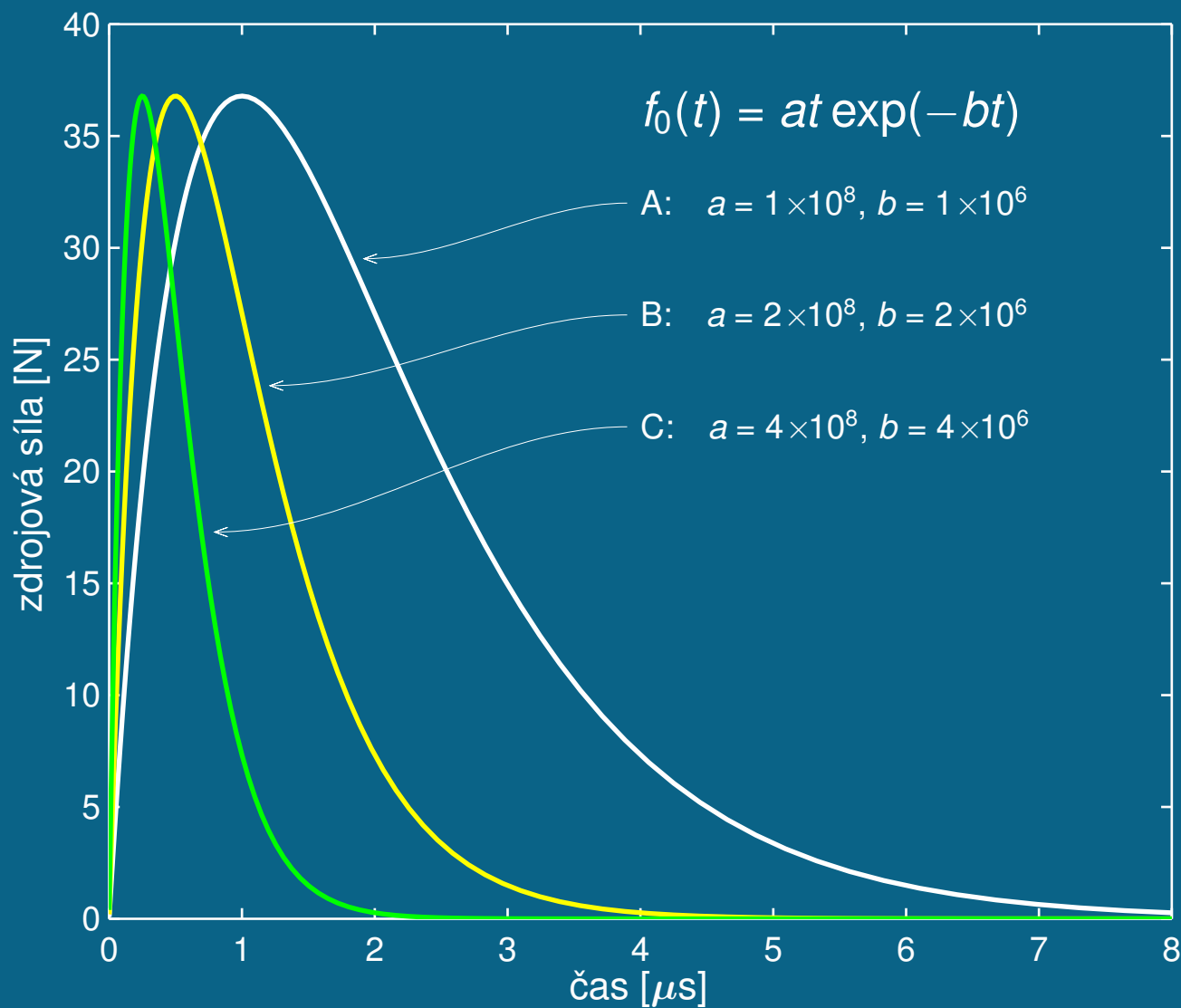
Funkce zdrojové síly



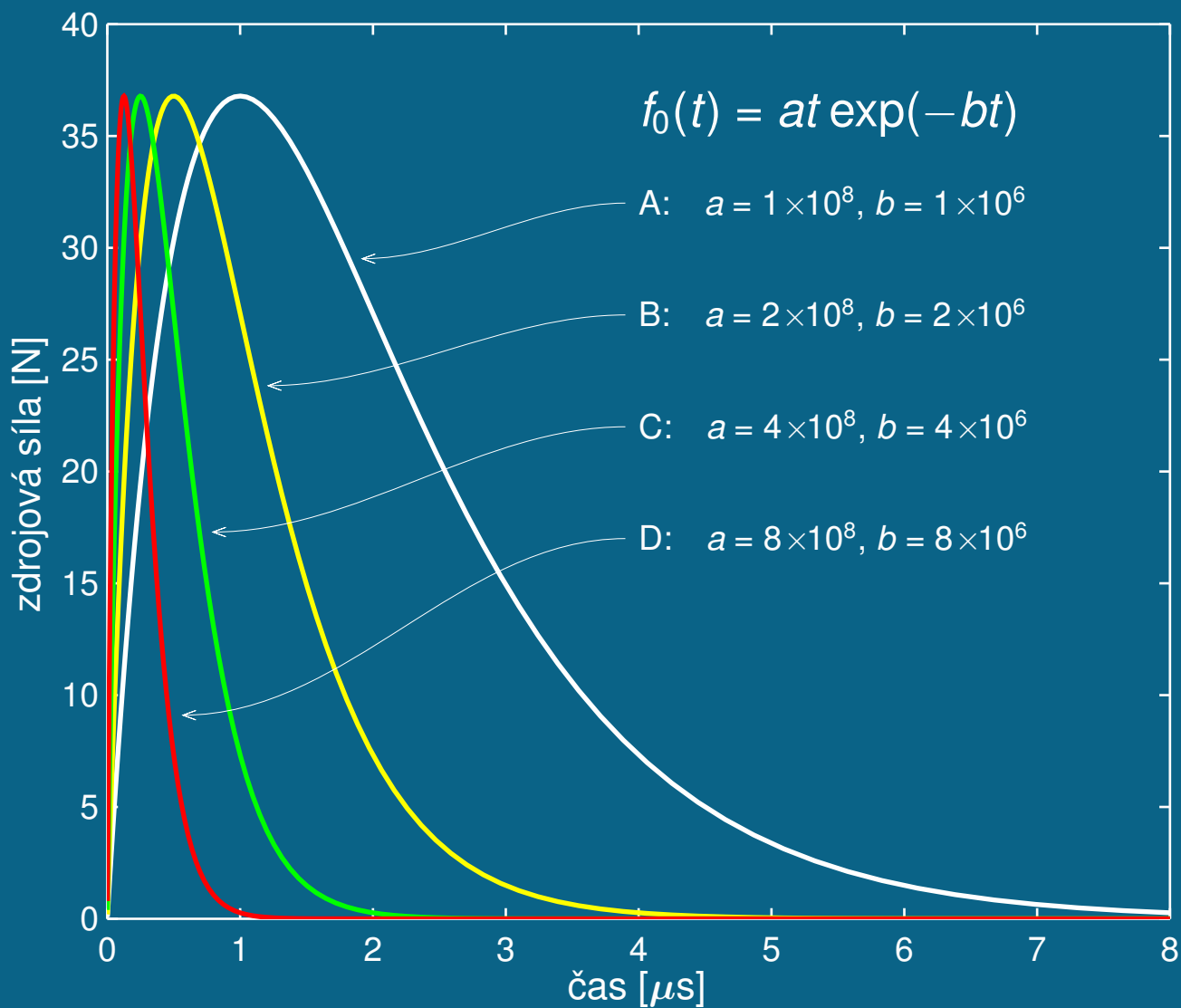
Funkce zdrojové síly



Funkce zdrojové síly



Funkce zdrojové síly



Analýza metodou konečných prvků

COMSOL Multiphysics

- aplikační modul: strukturální mechanika
- aplikační mód: 2D–rotační symetrie
- prvky: Lagrangeovy – kvadratické
- lineární řešič (UMFPACK)

Analýza metodou konečných prvků

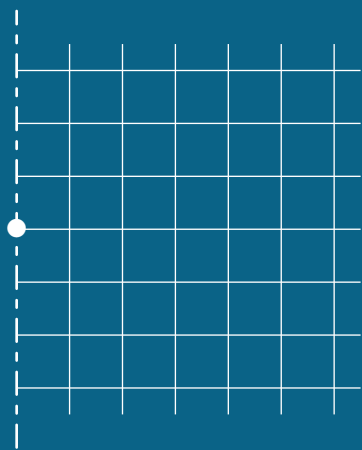
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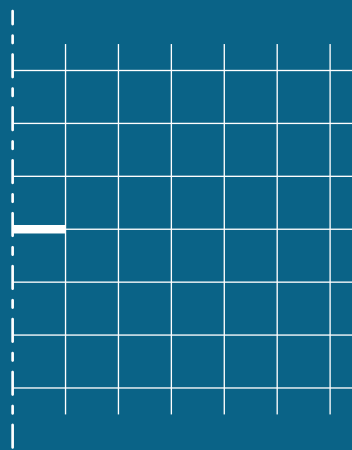
Analýza časové závislosti

- buzení předepsané funkcí
- čas od 0 do $8 \mu\text{s}$ s krokem $0,01 \mu\text{s}$
- relativní tolerance: 10^{-5} , absolutní tolerance: 10^{-10}
- čtvercová síť – velikost prvku $0,5 \times 0,5 \text{ mm}$

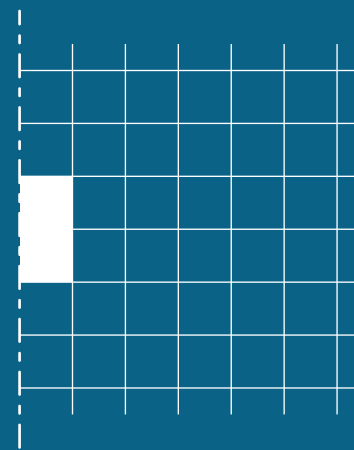
MKP – modely koncentrované síly



bod (•)

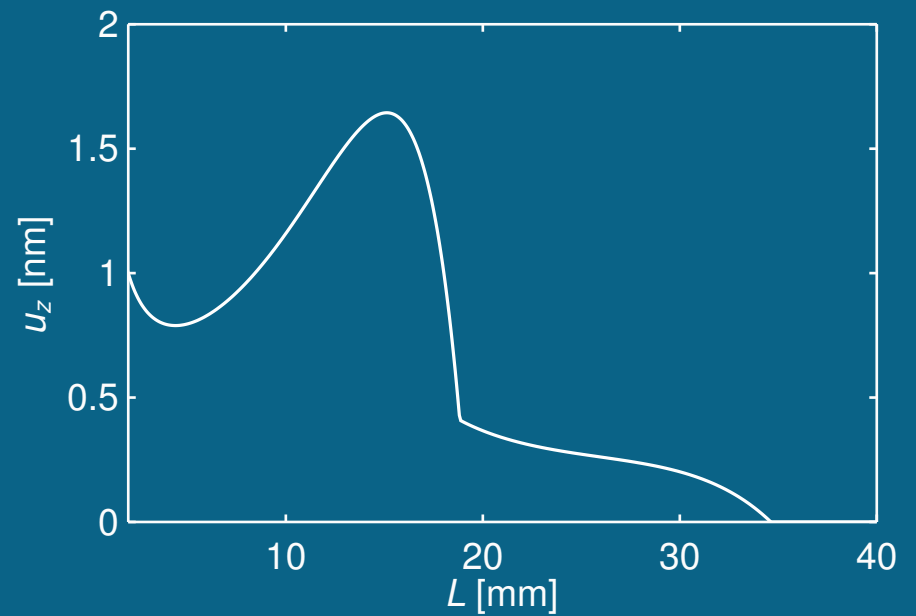
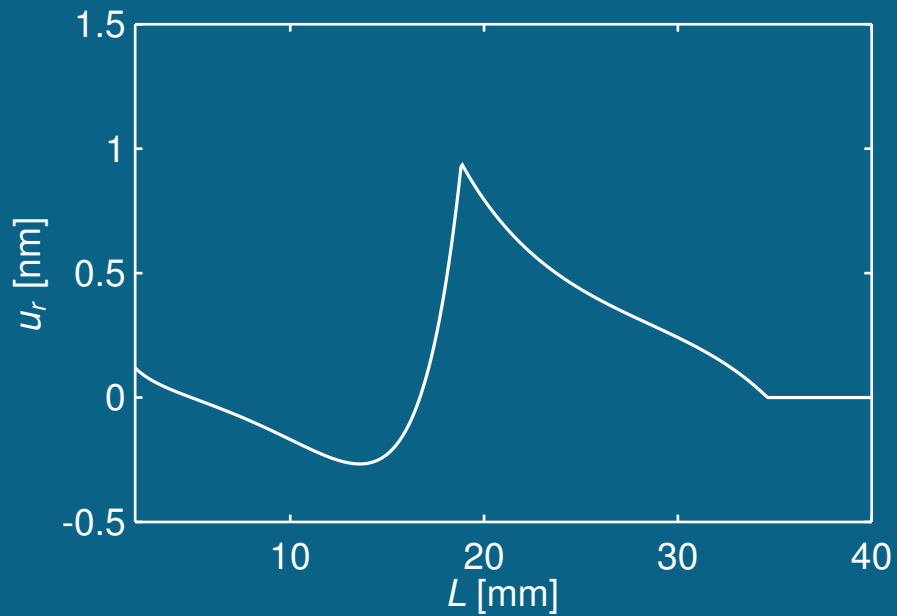


kruhová plocha (○)
 $r = 0,5 \text{ mm}$

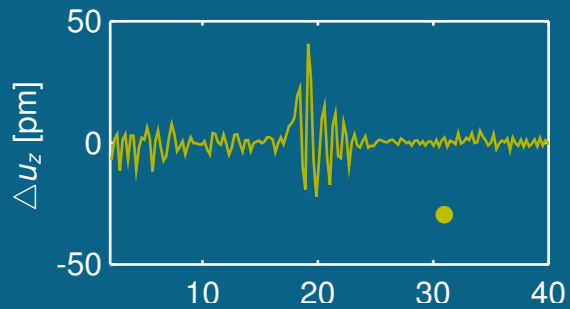
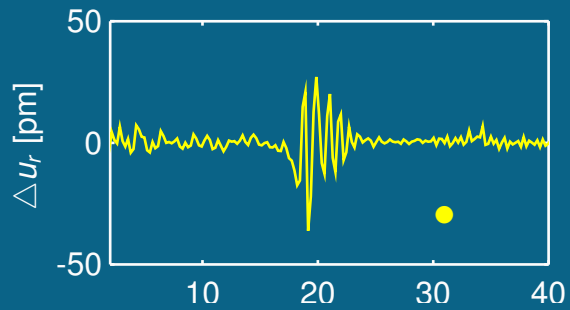
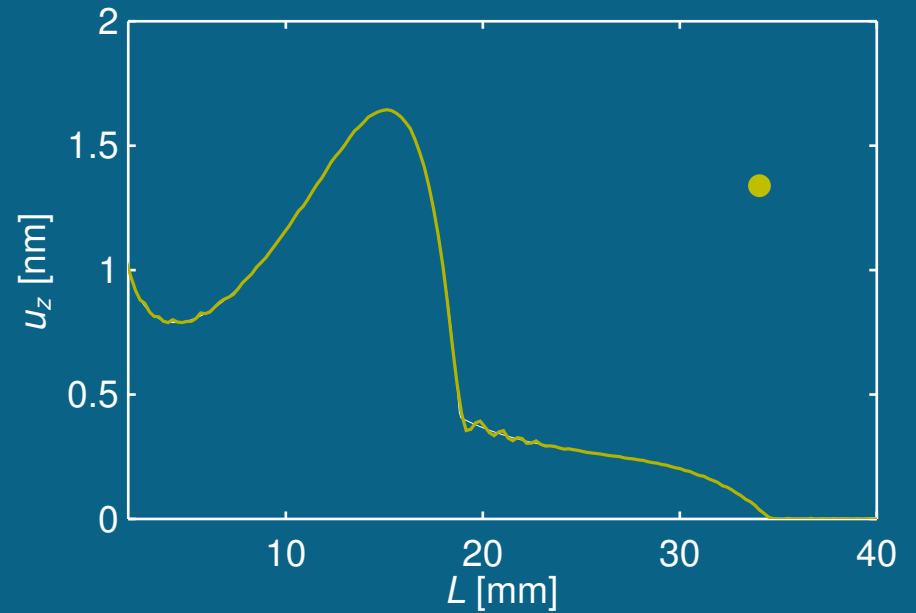
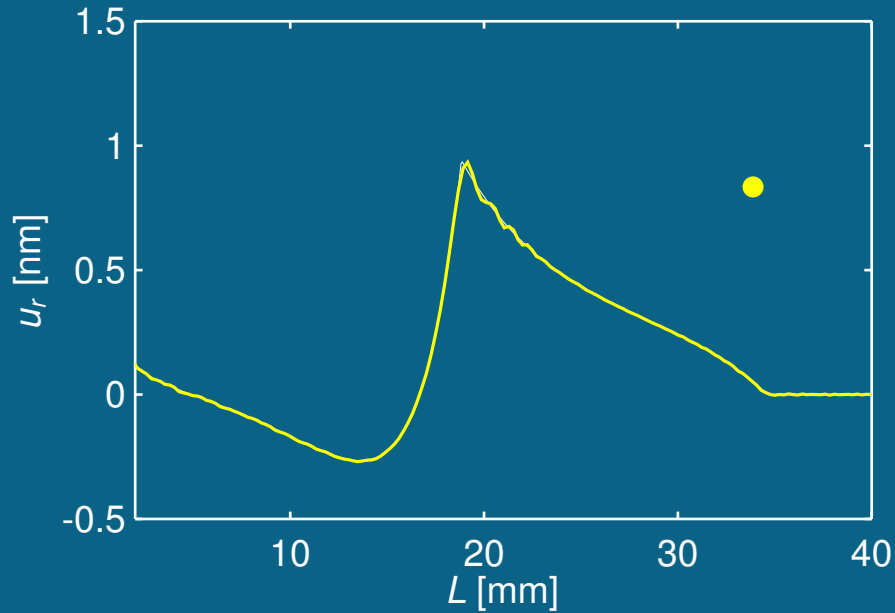


válec (⊞)
 $r = 0,5 \text{ mm}$
 $z = 1 \text{ mm}$

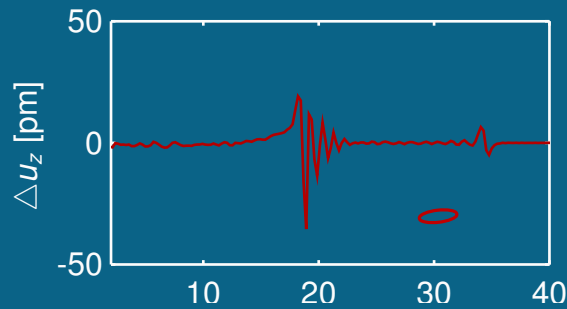
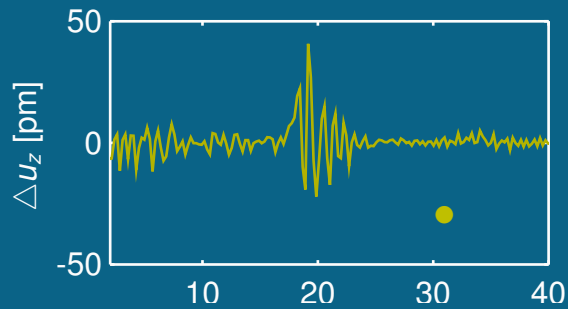
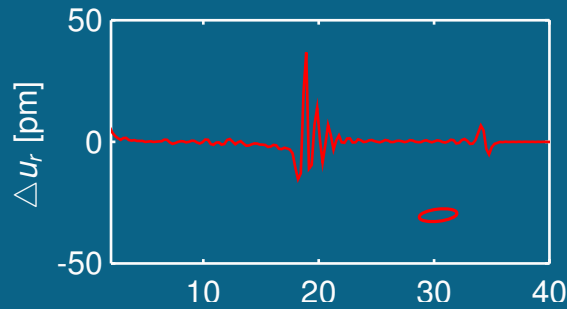
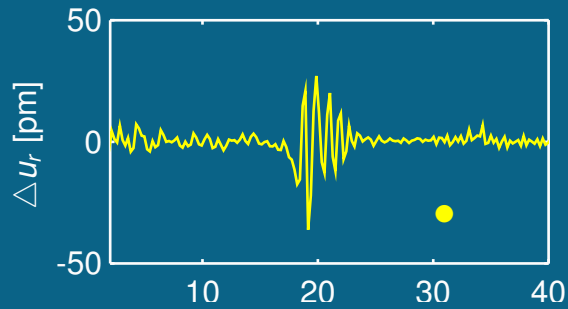
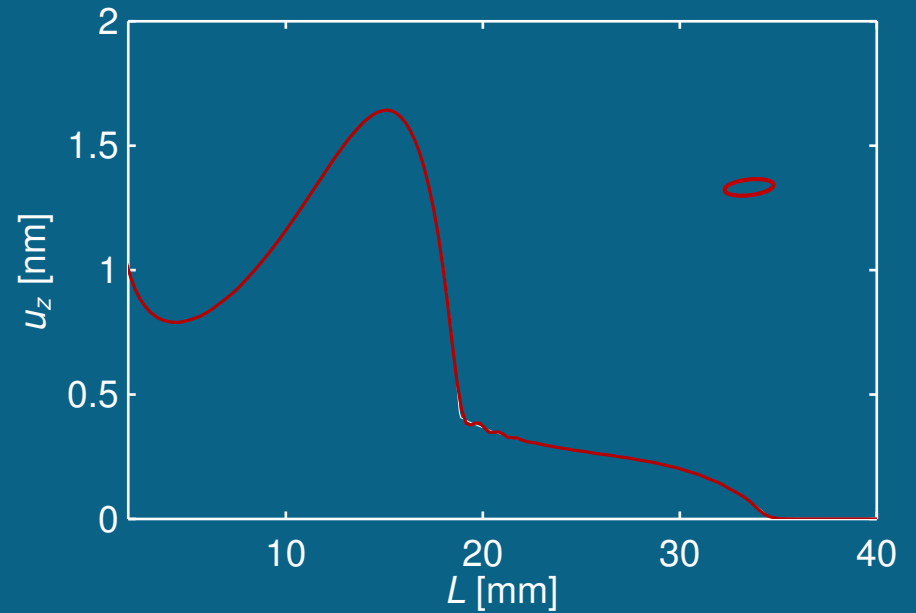
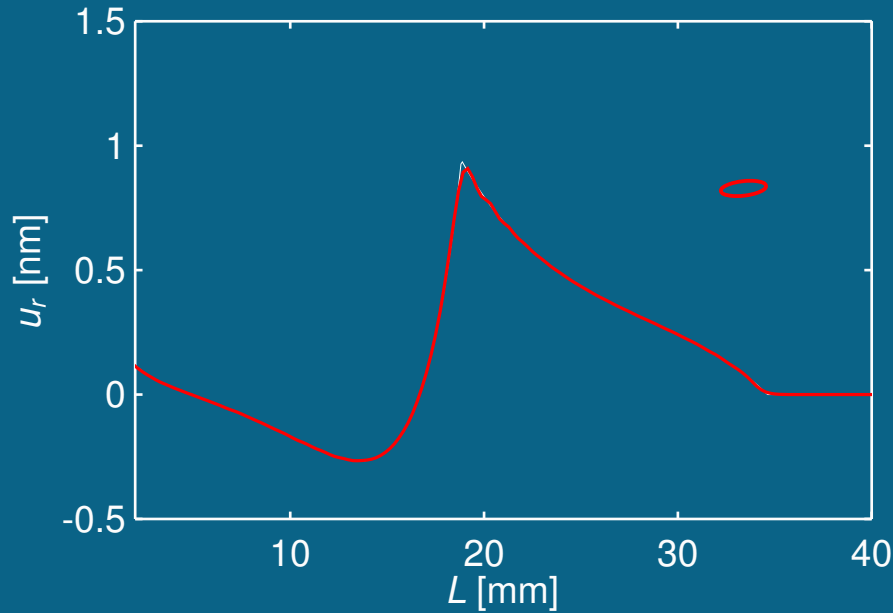
Bodová síla – porovnání modelů MKP – čas $6 \mu s$



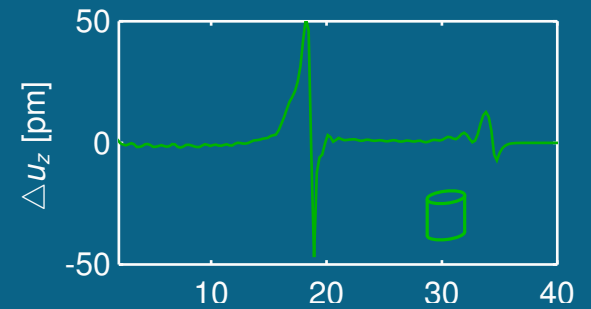
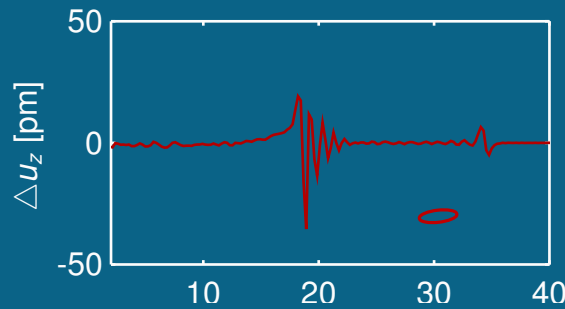
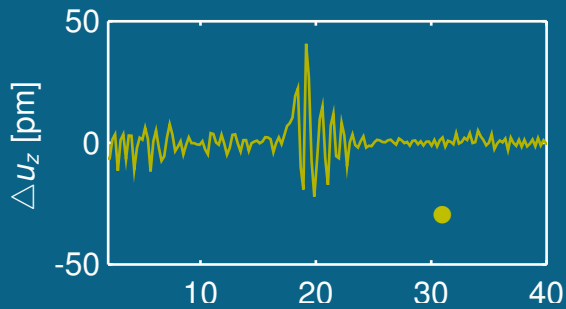
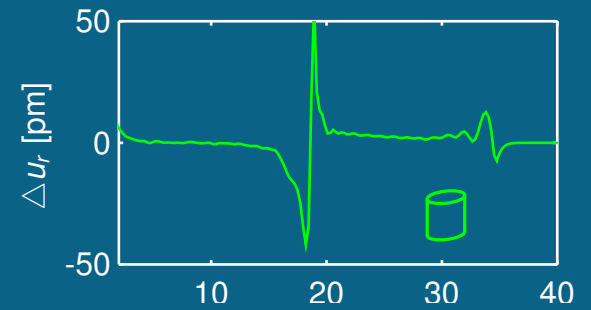
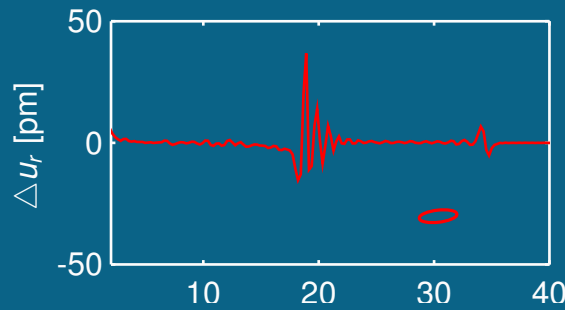
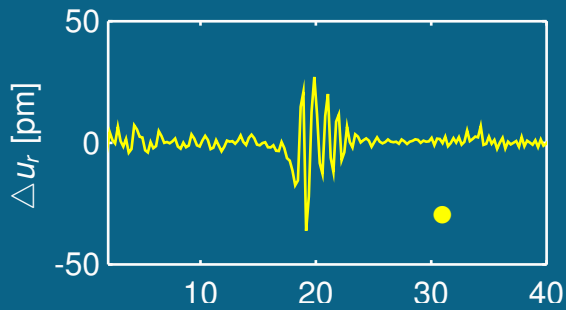
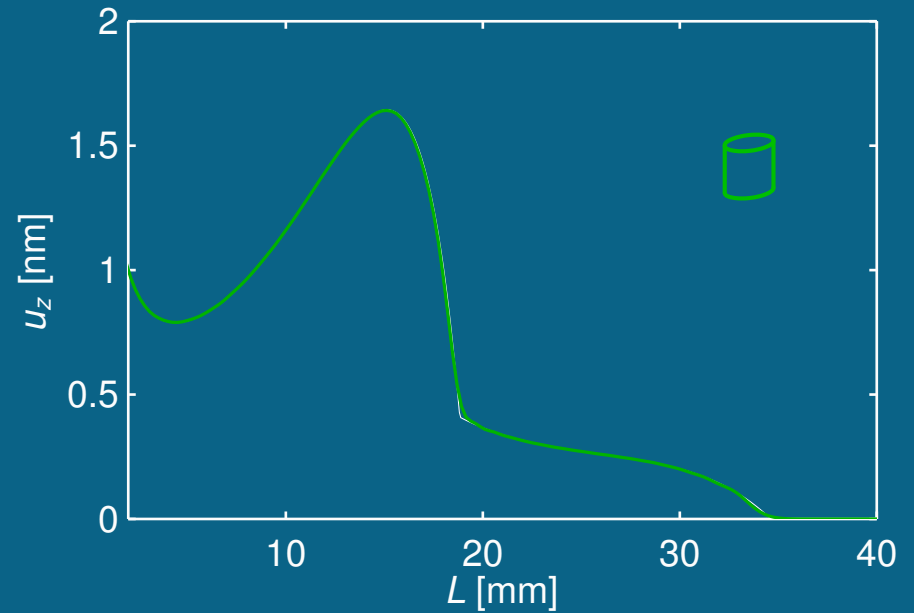
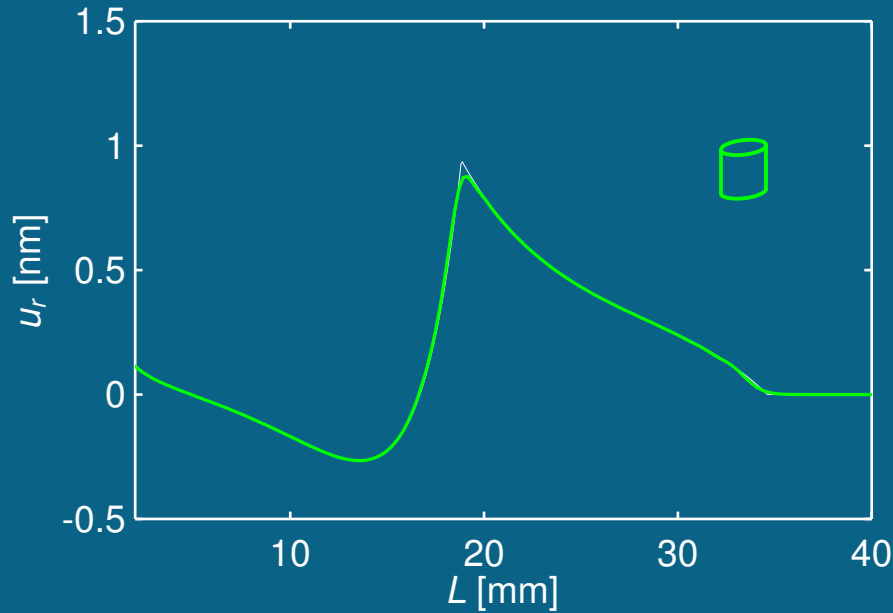
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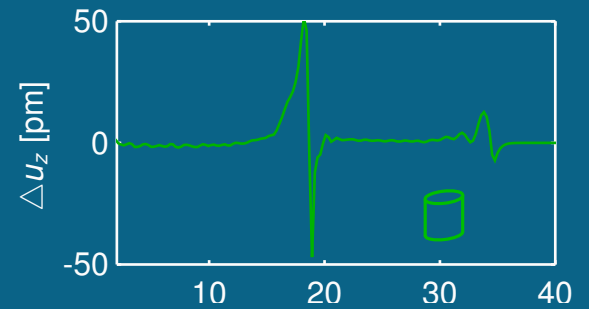
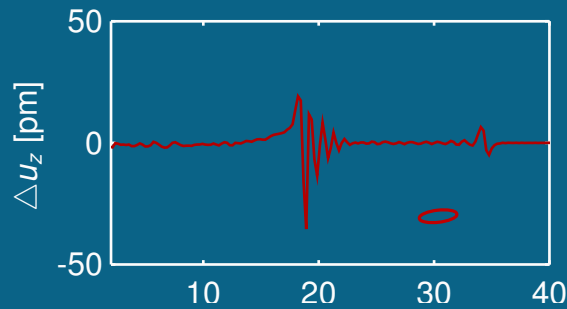
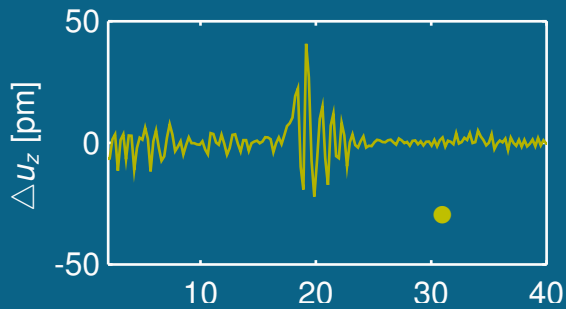
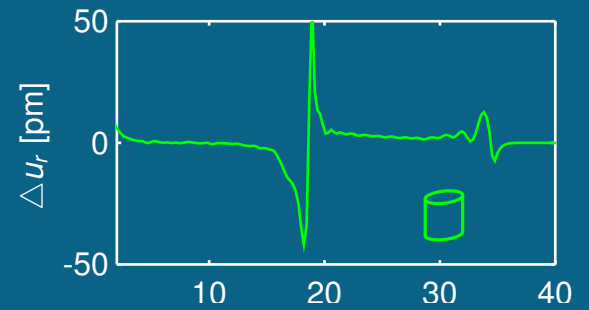
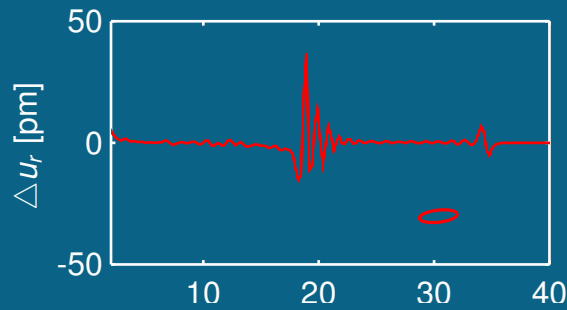
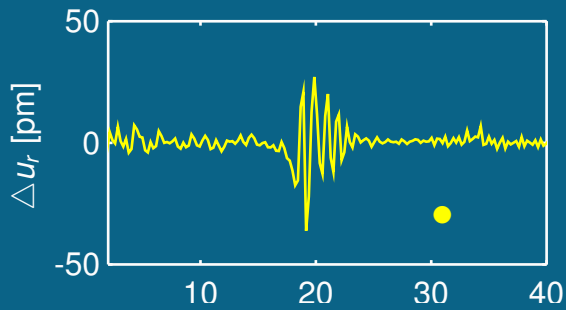
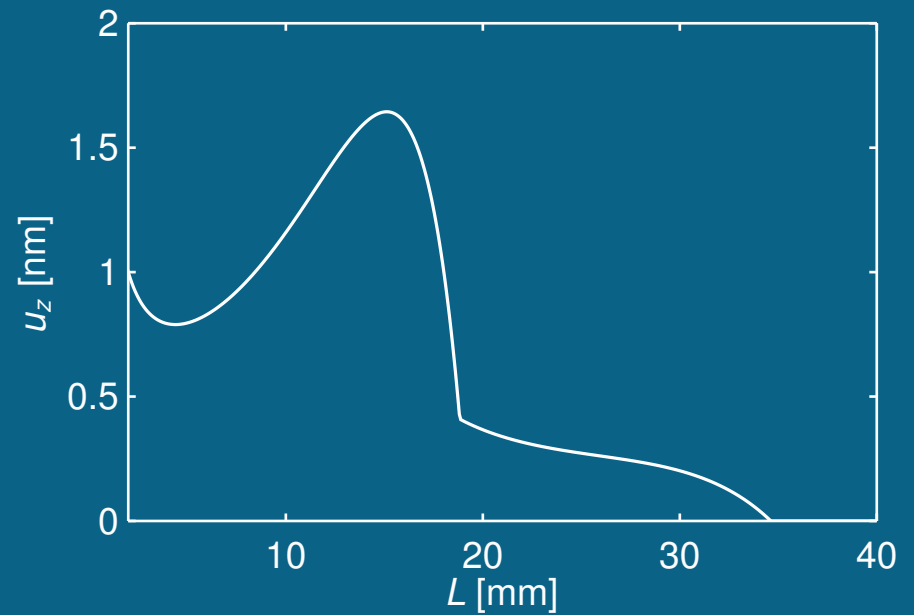
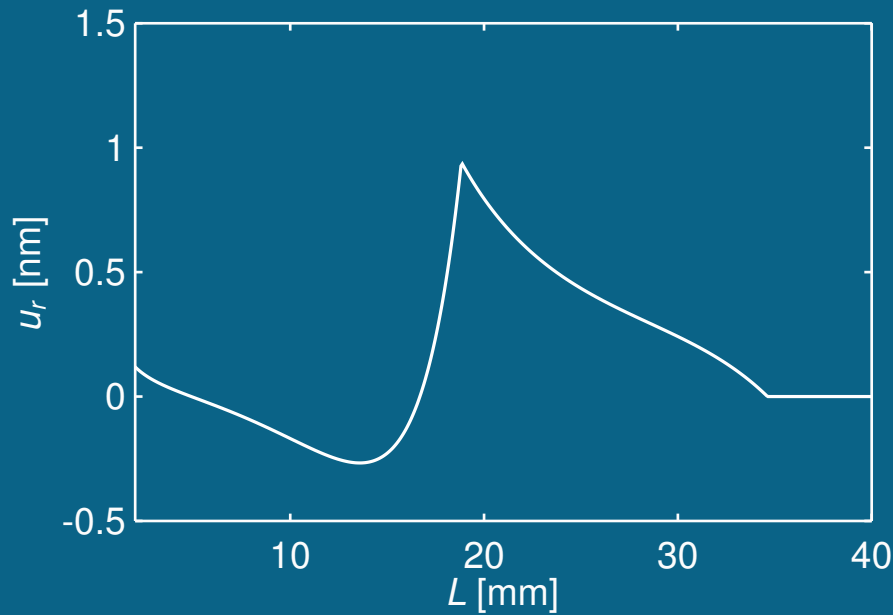
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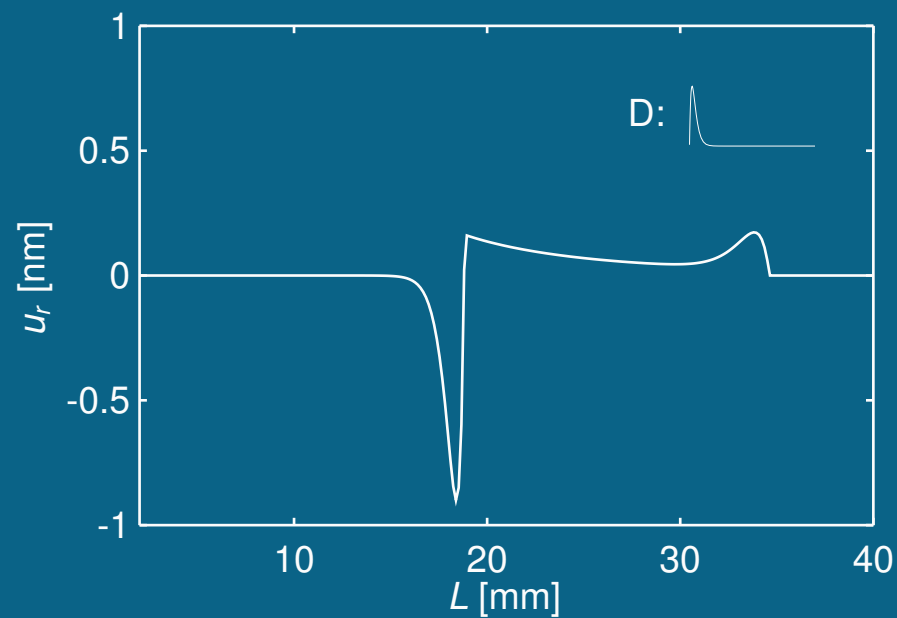
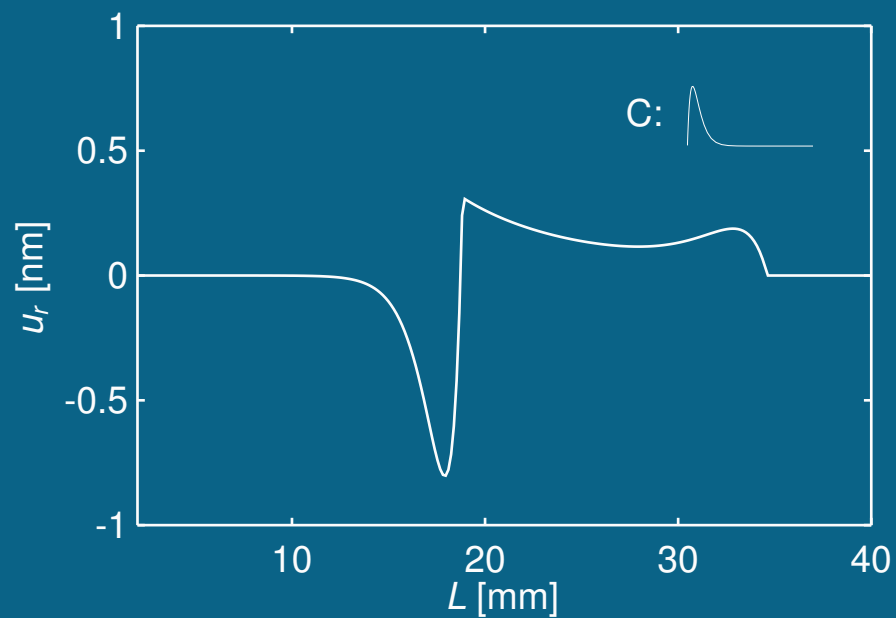
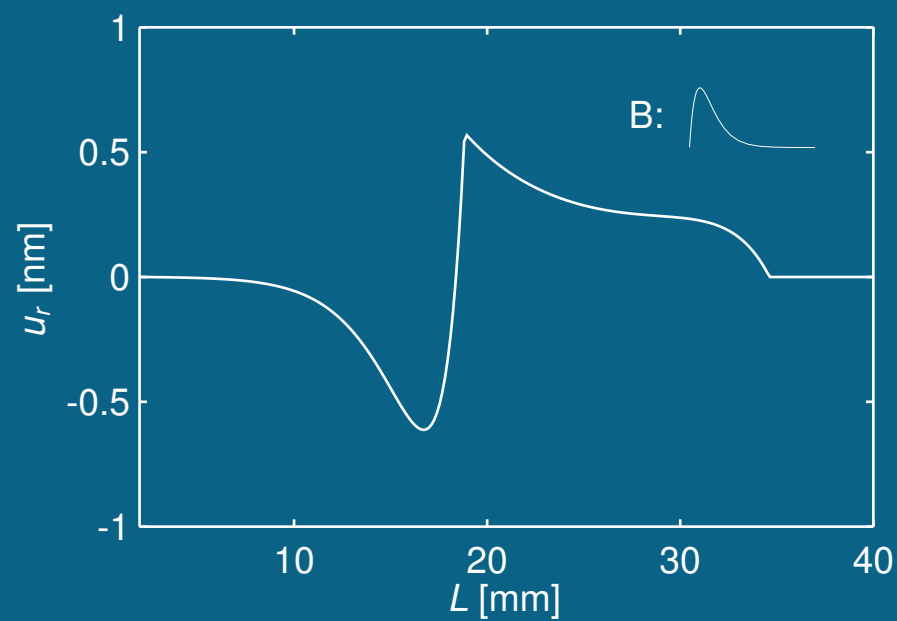
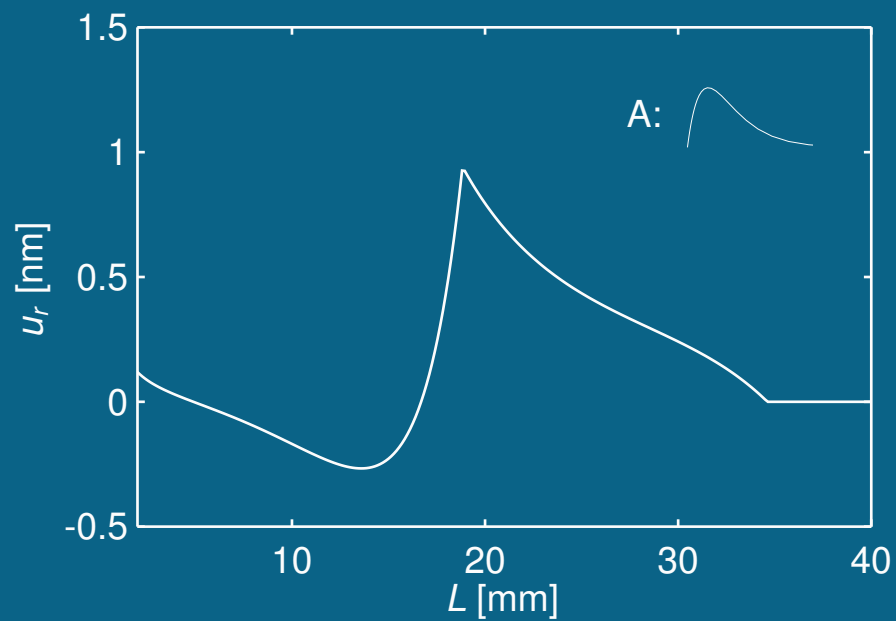
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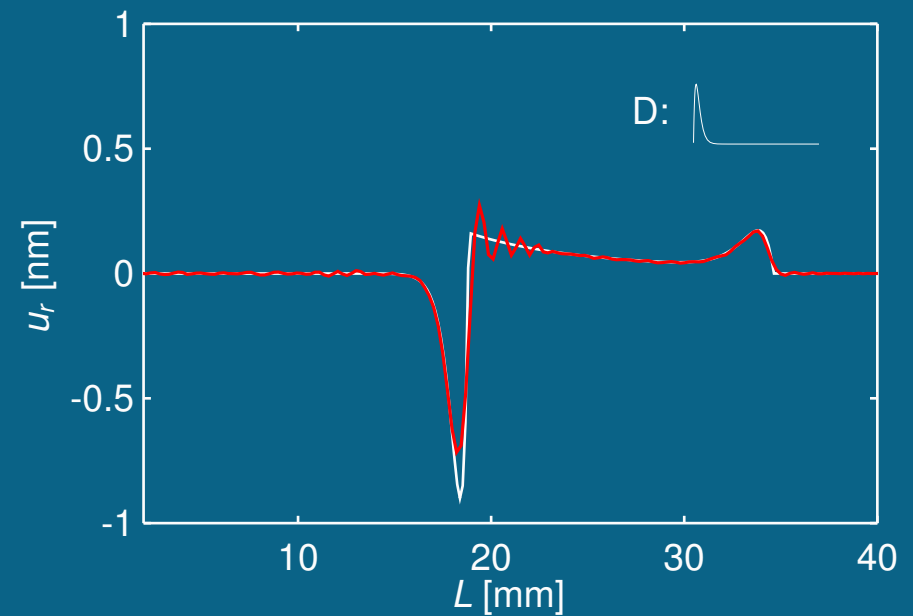
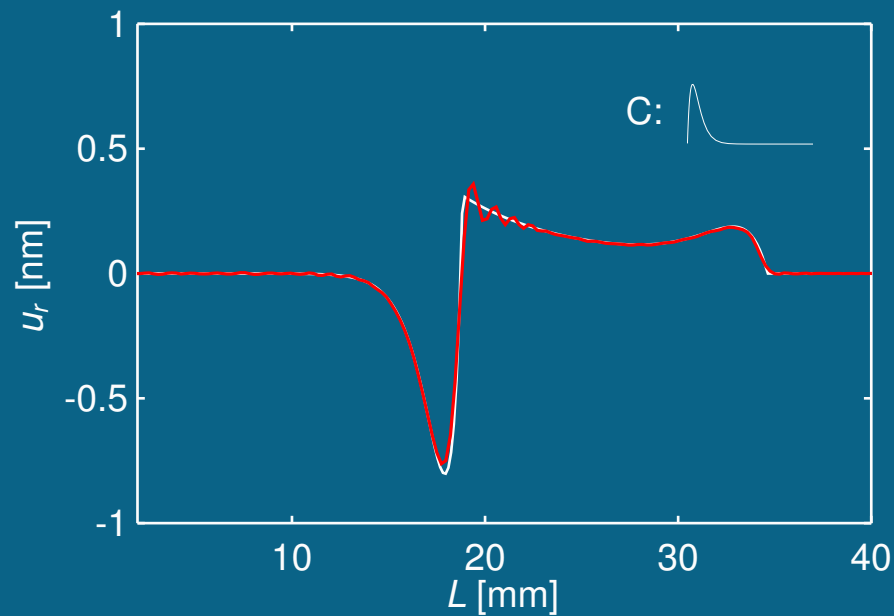
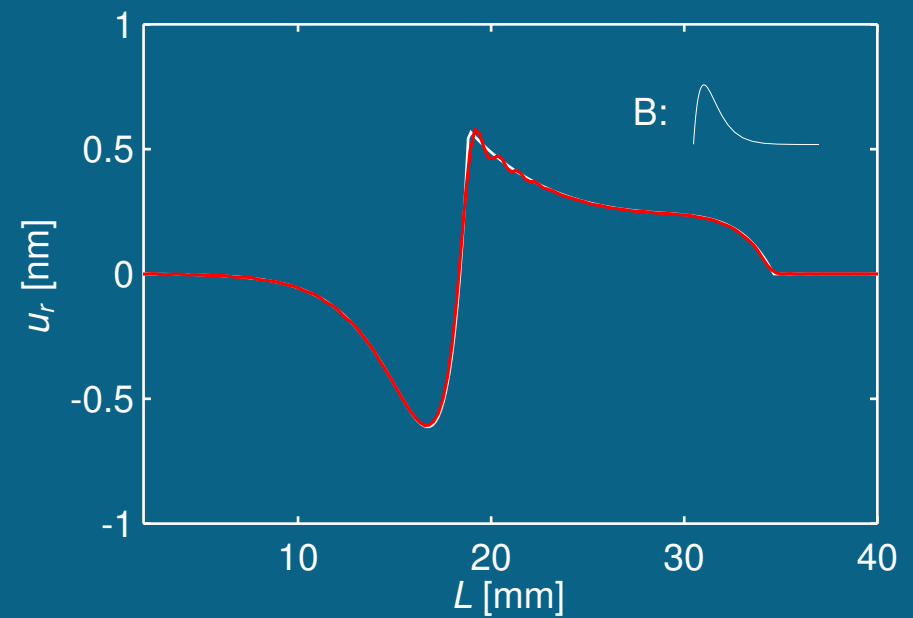
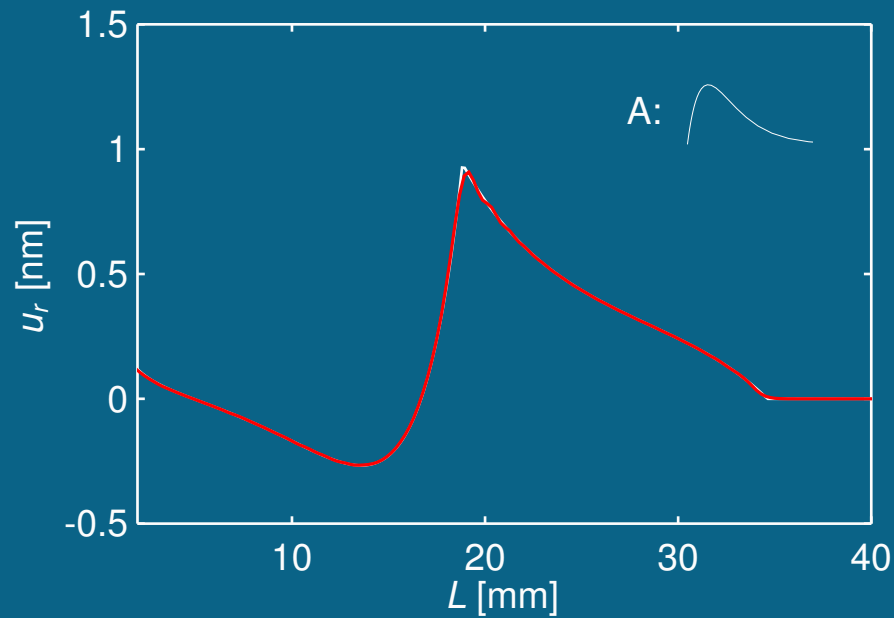
Bodová síla – porovnání modelů MKP – čas 6 μ s



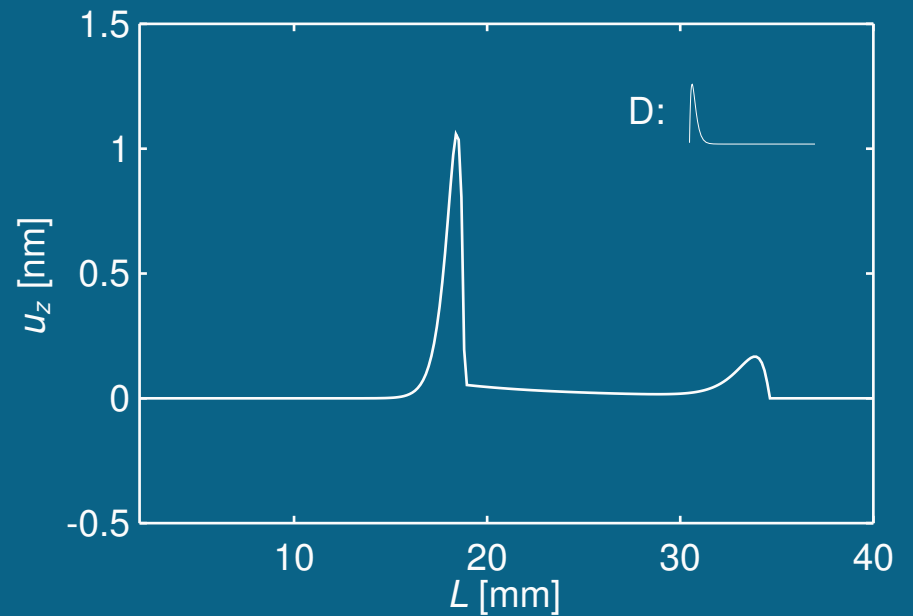
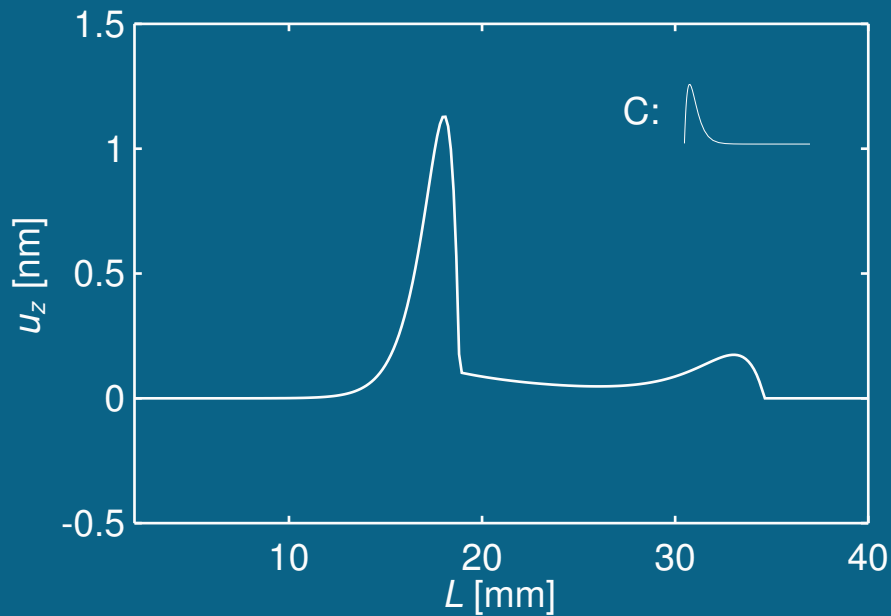
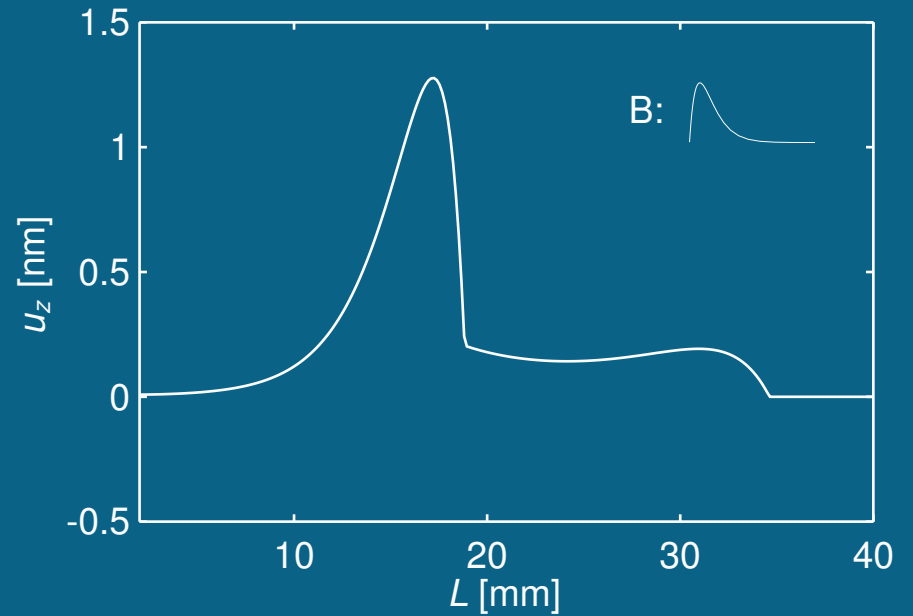
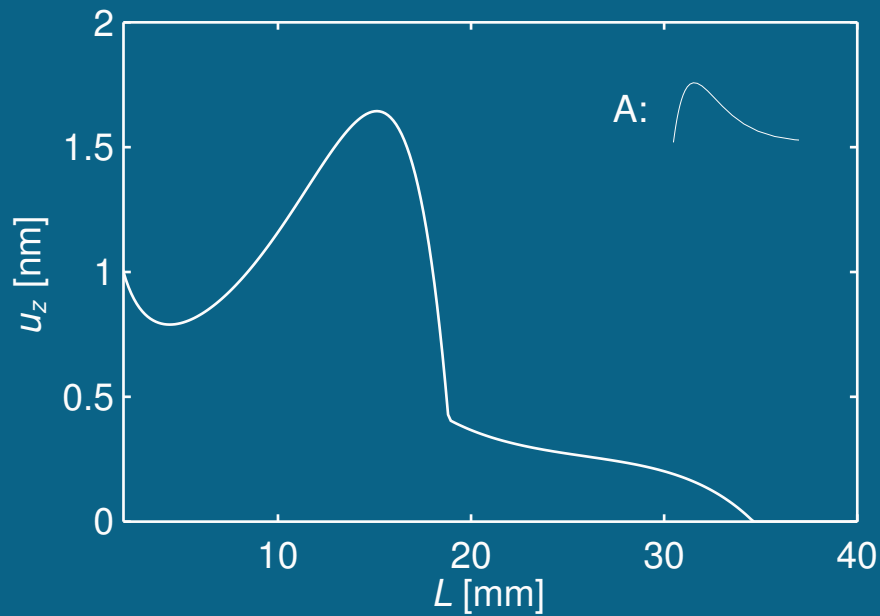
Vliv tvaru zdrojové funkce – u_r v čase $6 \mu s$



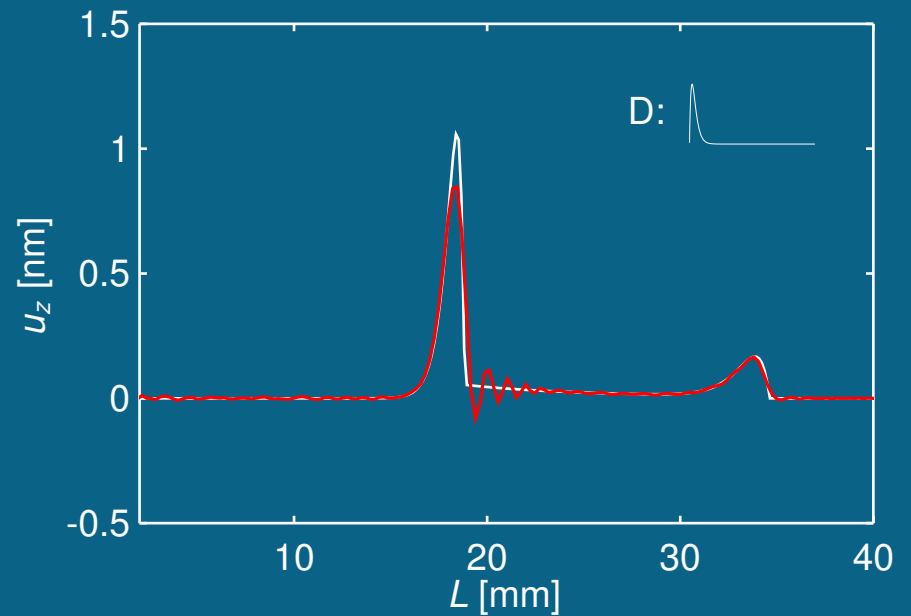
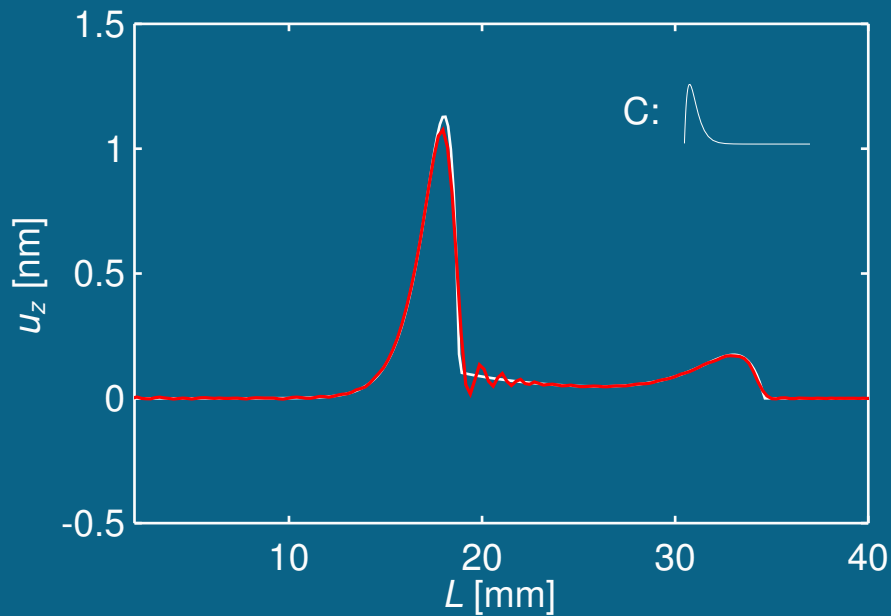
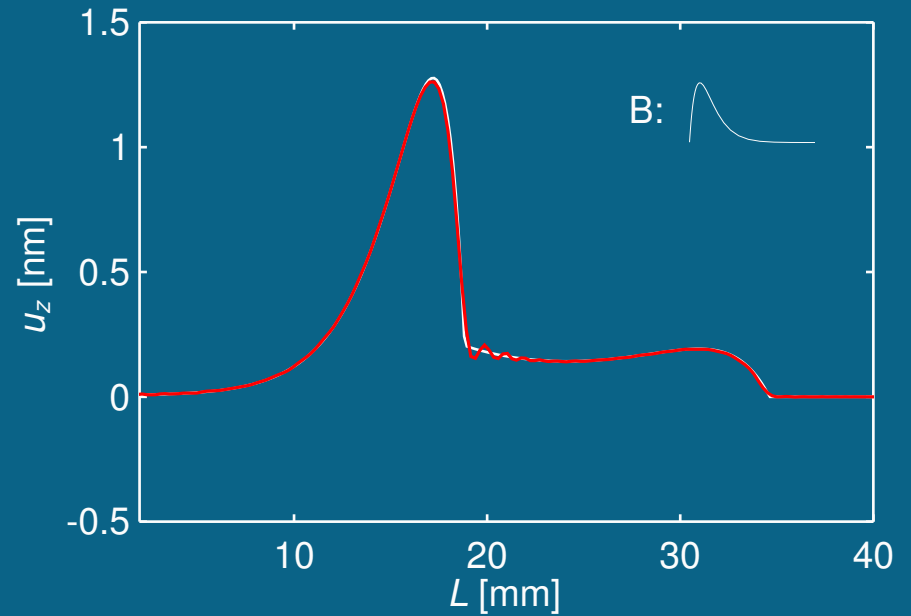
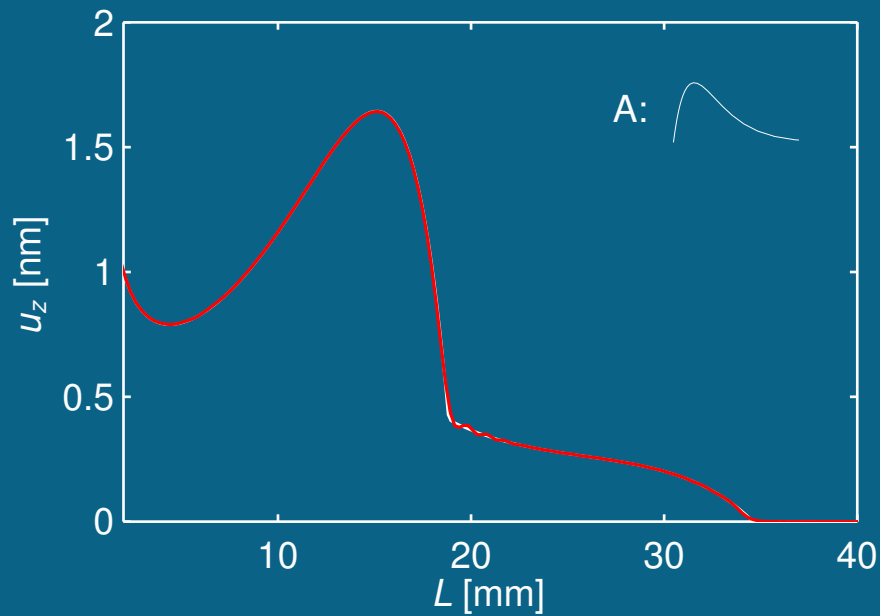
Vliv tvaru zdrojové funkce – u_r v čase $6 \mu s$



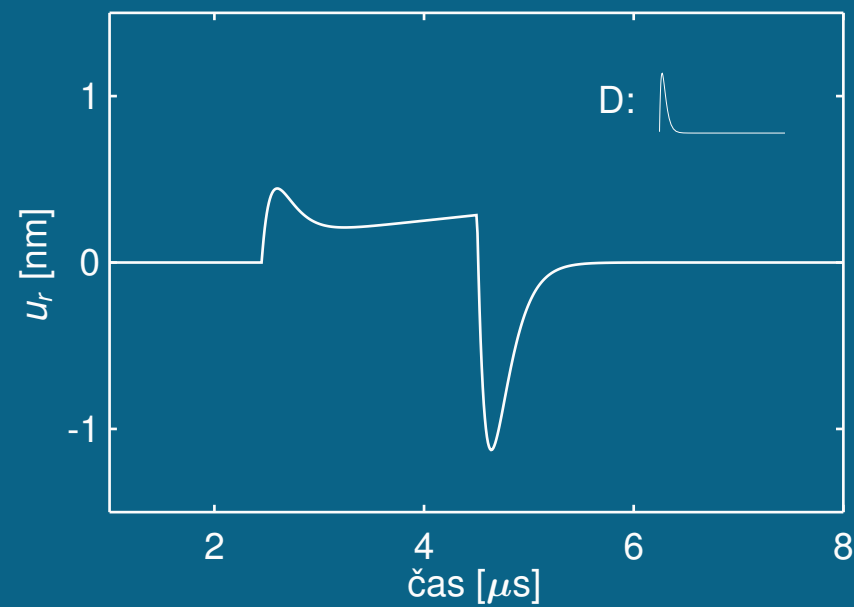
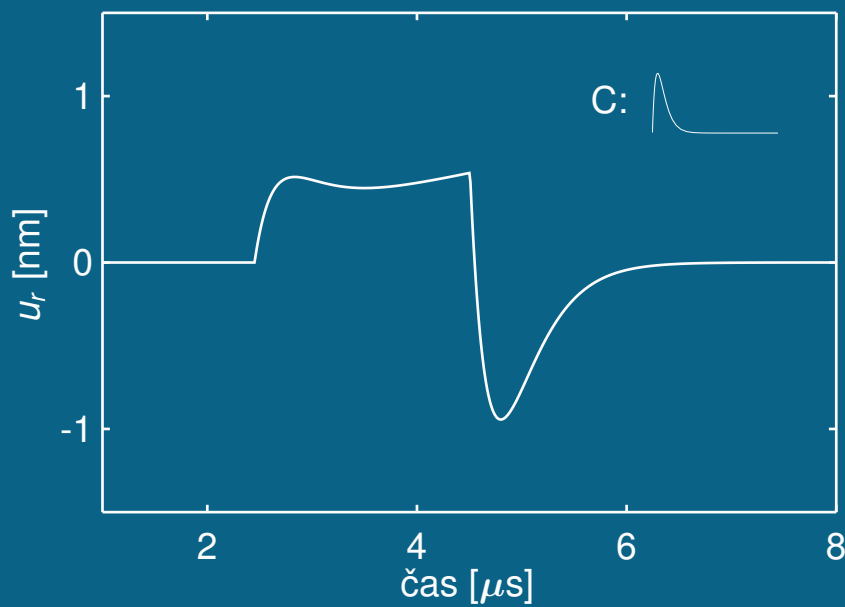
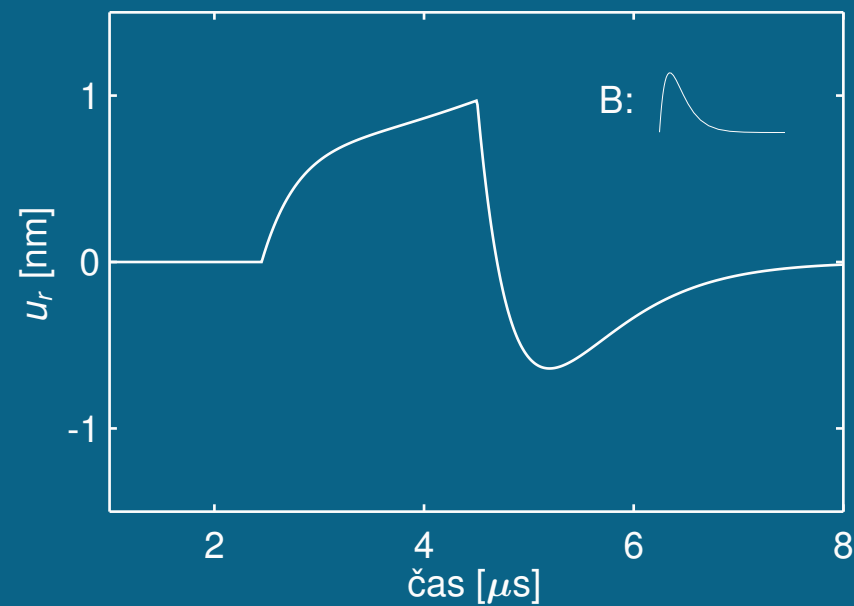
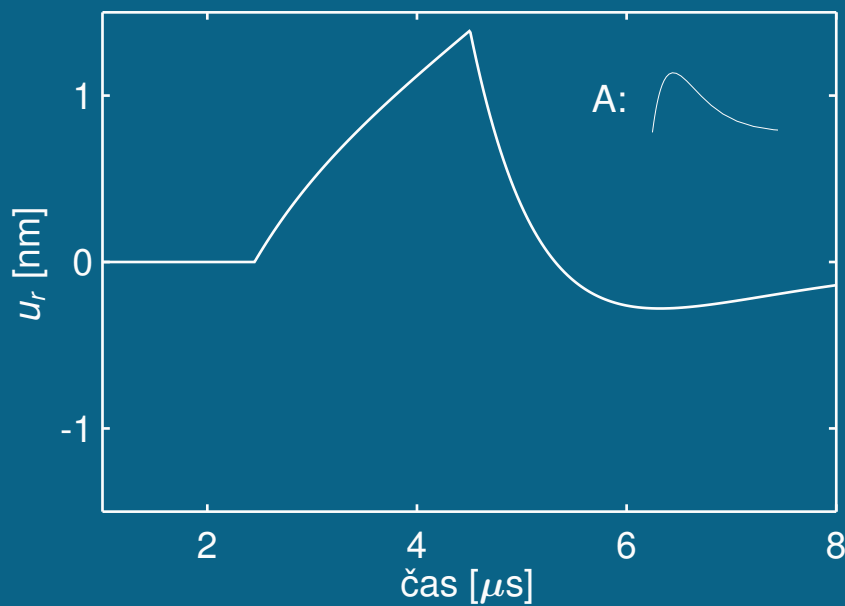
Vliv tvaru zdrojové funkce – u_z v čase $6 \mu s$



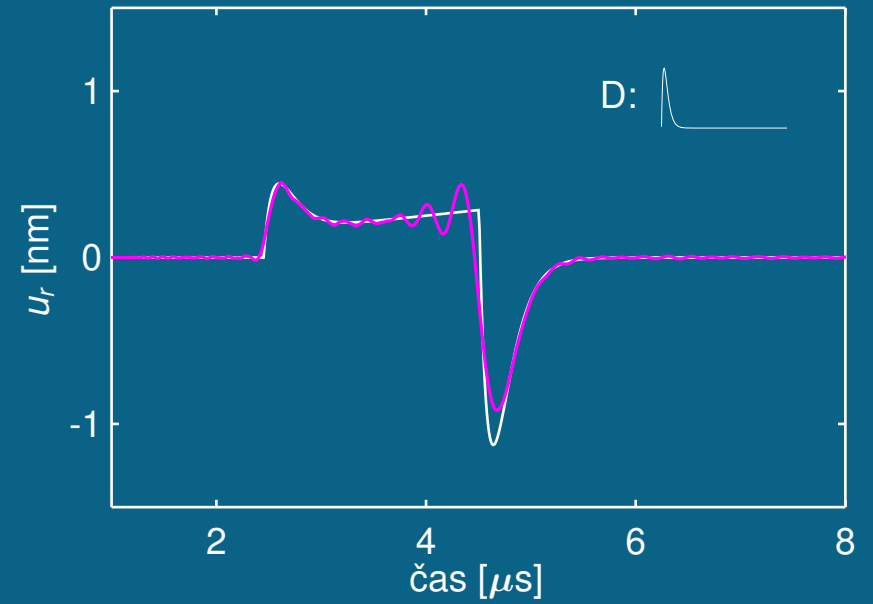
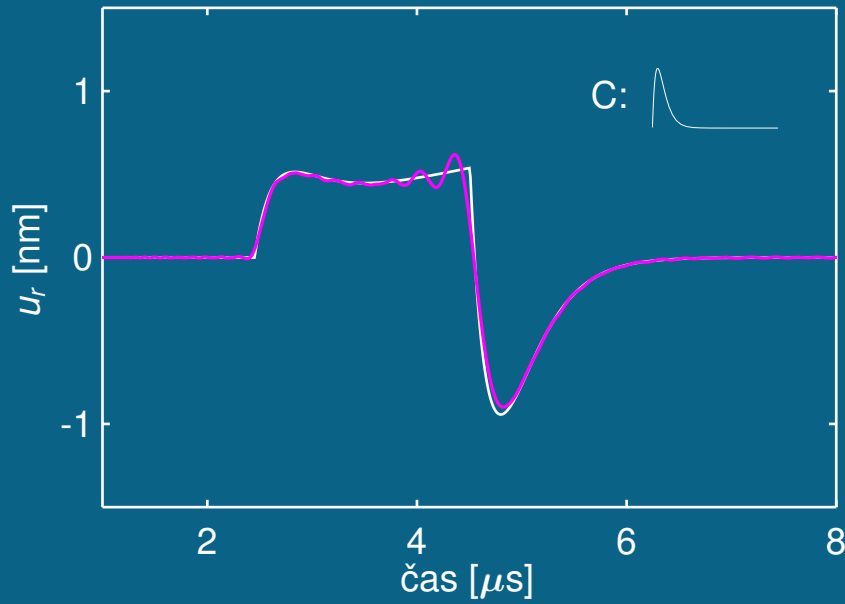
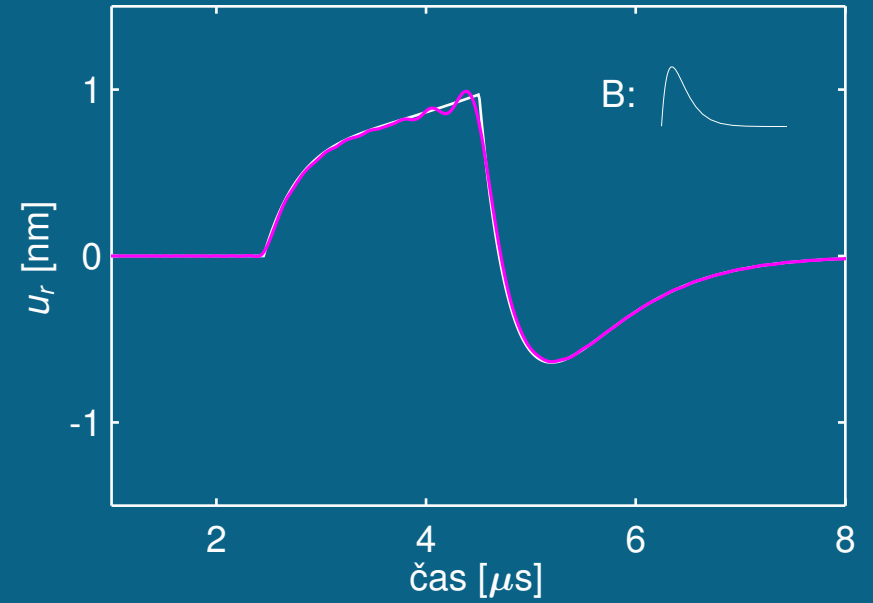
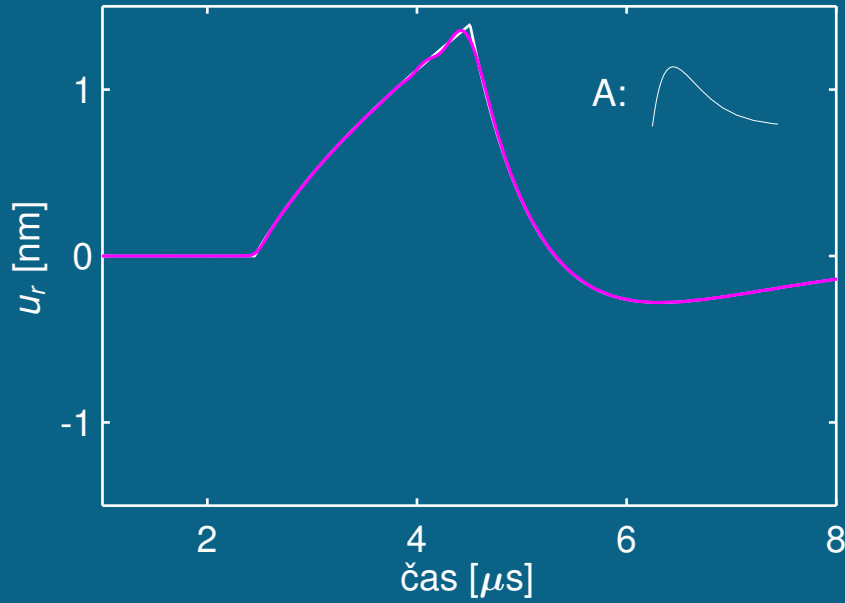
Vliv tvaru zdrojové funkce – u_z v čase $6 \mu s$



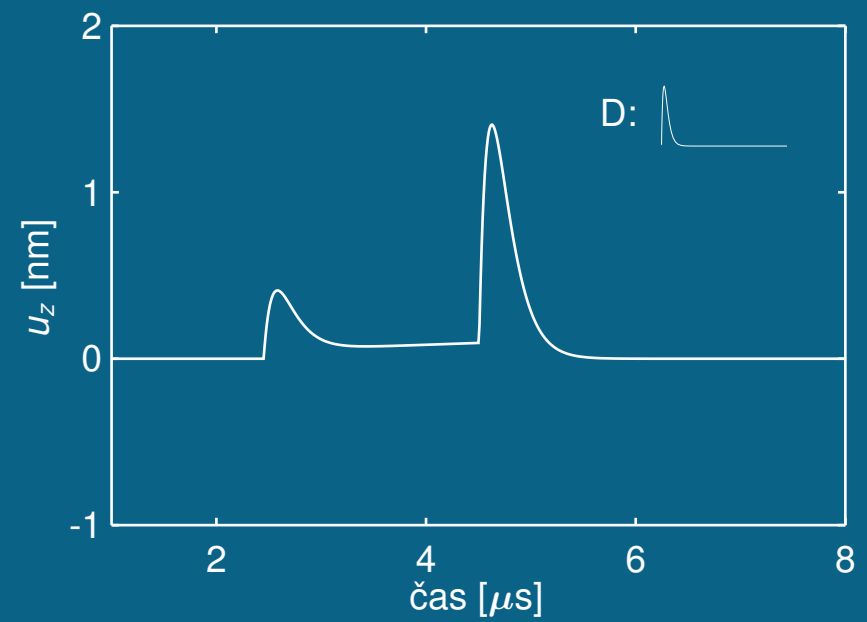
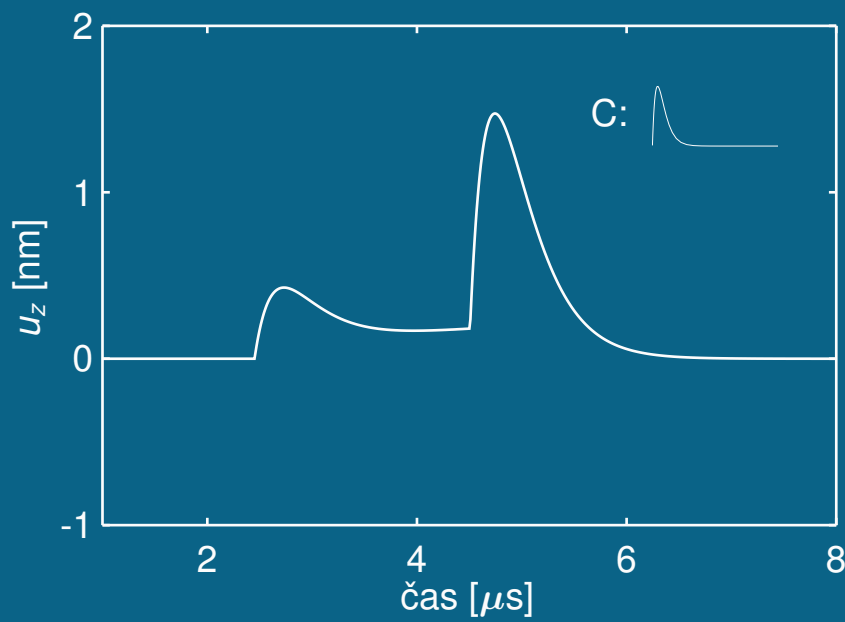
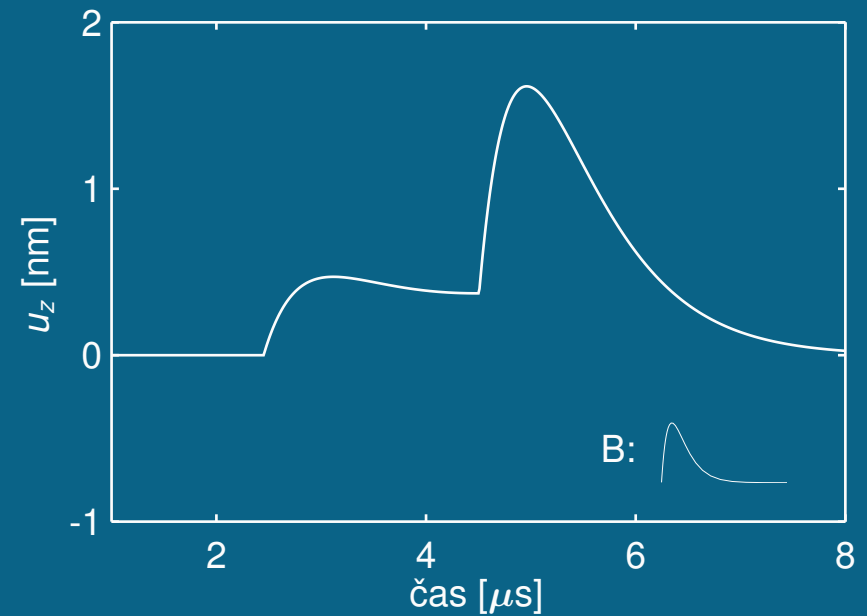
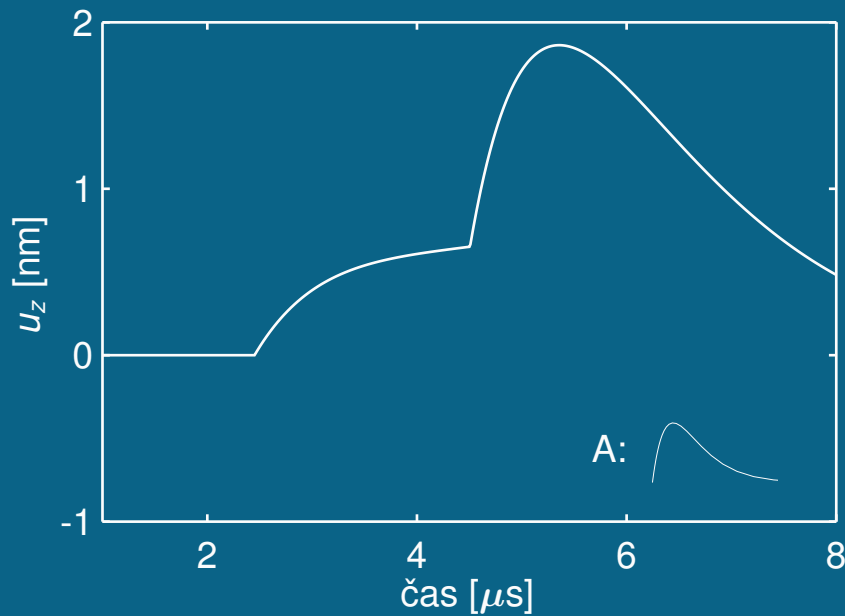
Vliv tvaru zdrojové funkce – u_r v bodě P



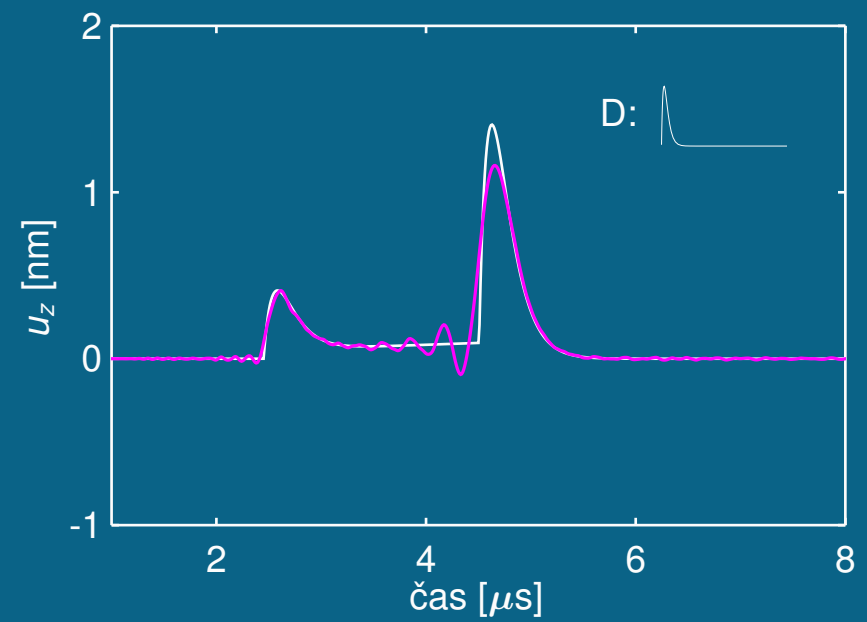
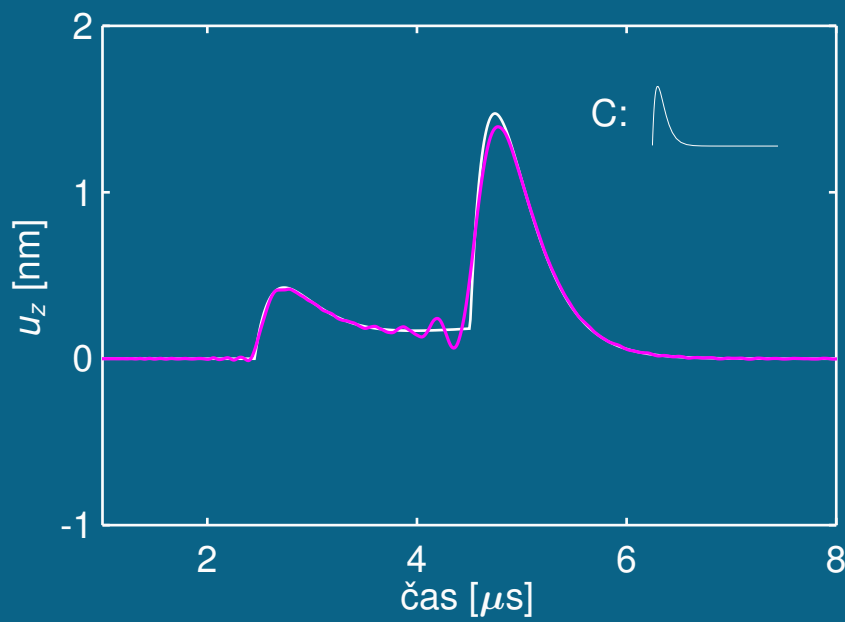
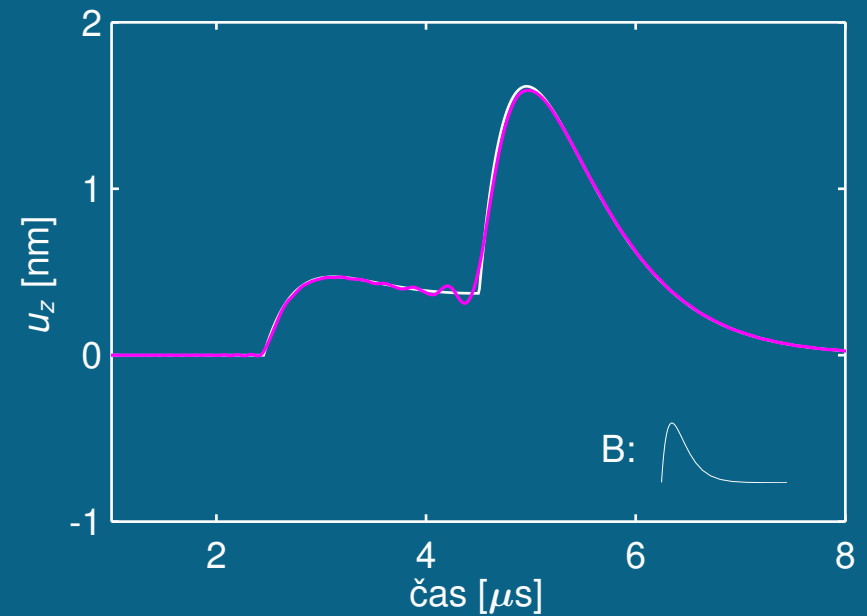
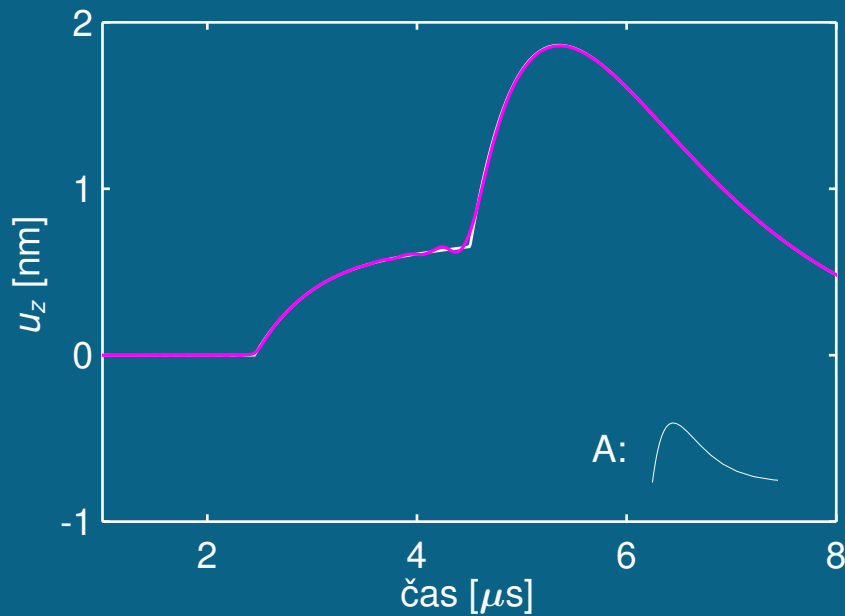
Vliv tvaru zdrojové funkce – u_r v bodě P



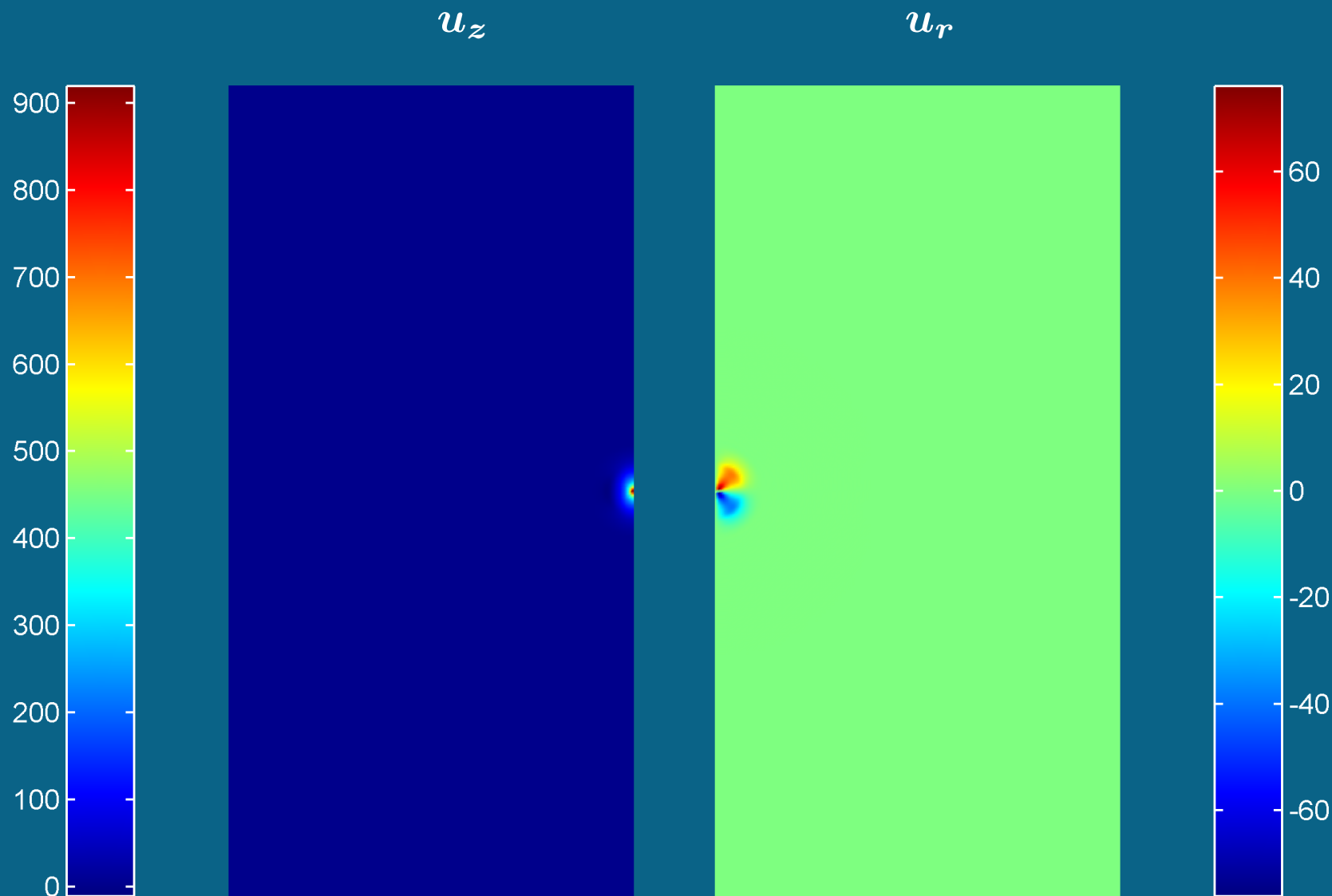
Vliv tvaru zdrojové funkce – u_z v bodě P



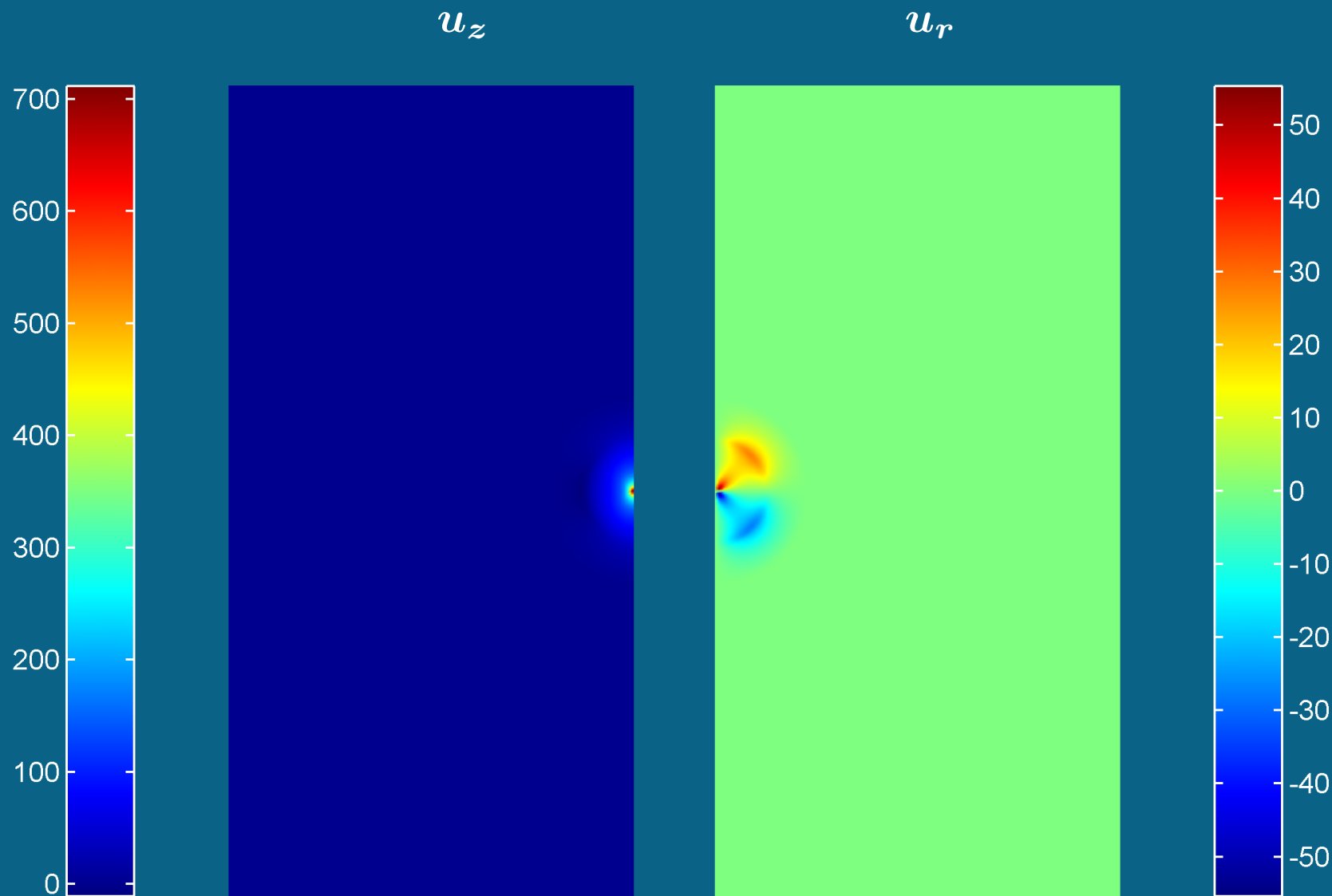
Vliv tvaru zdrojové funkce – u_z v bodě P



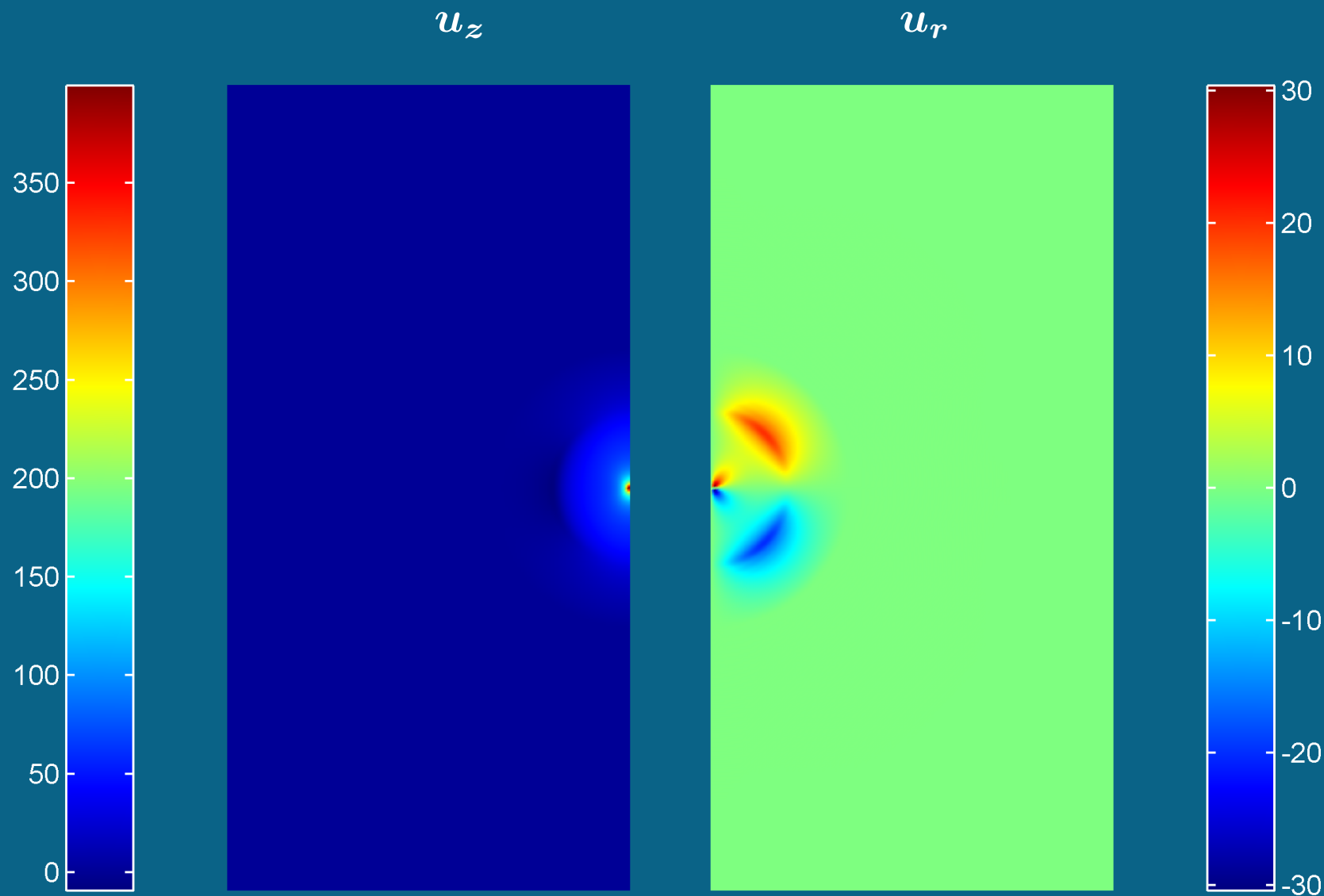
Budící funkce A – čas $1 \mu s$



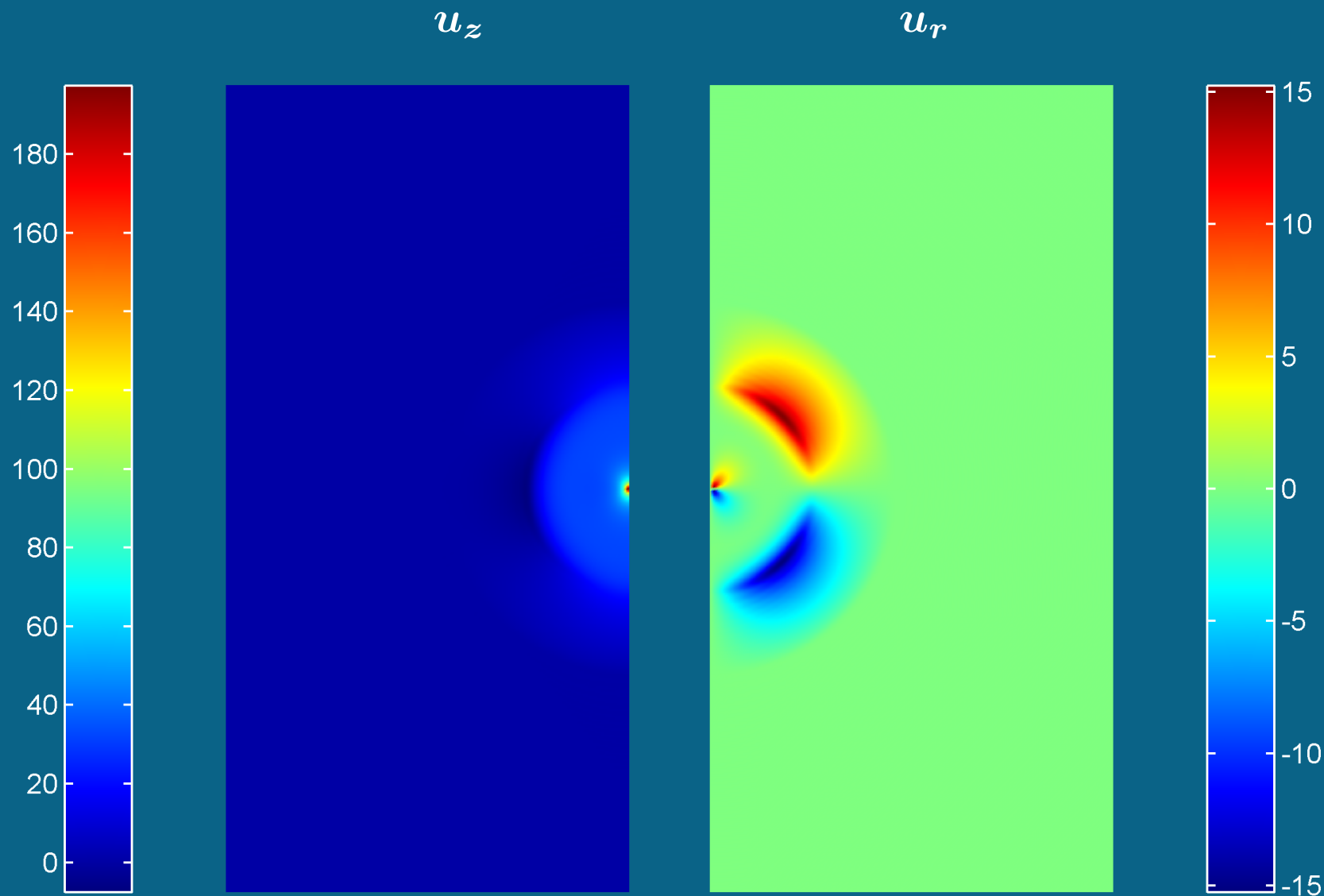
Budící funkce A – čas $2 \mu s$



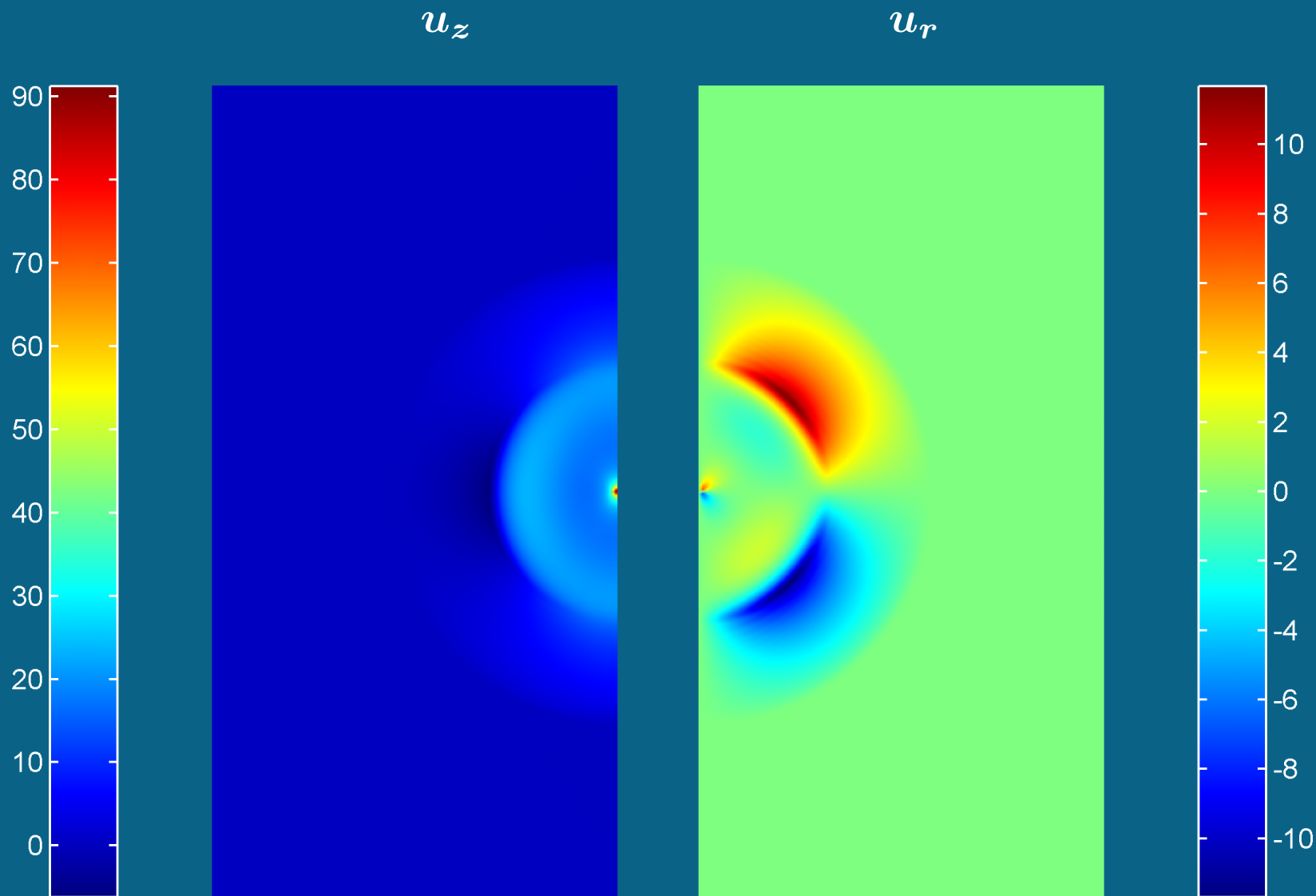
Budící funkce A – čas $3 \mu s$



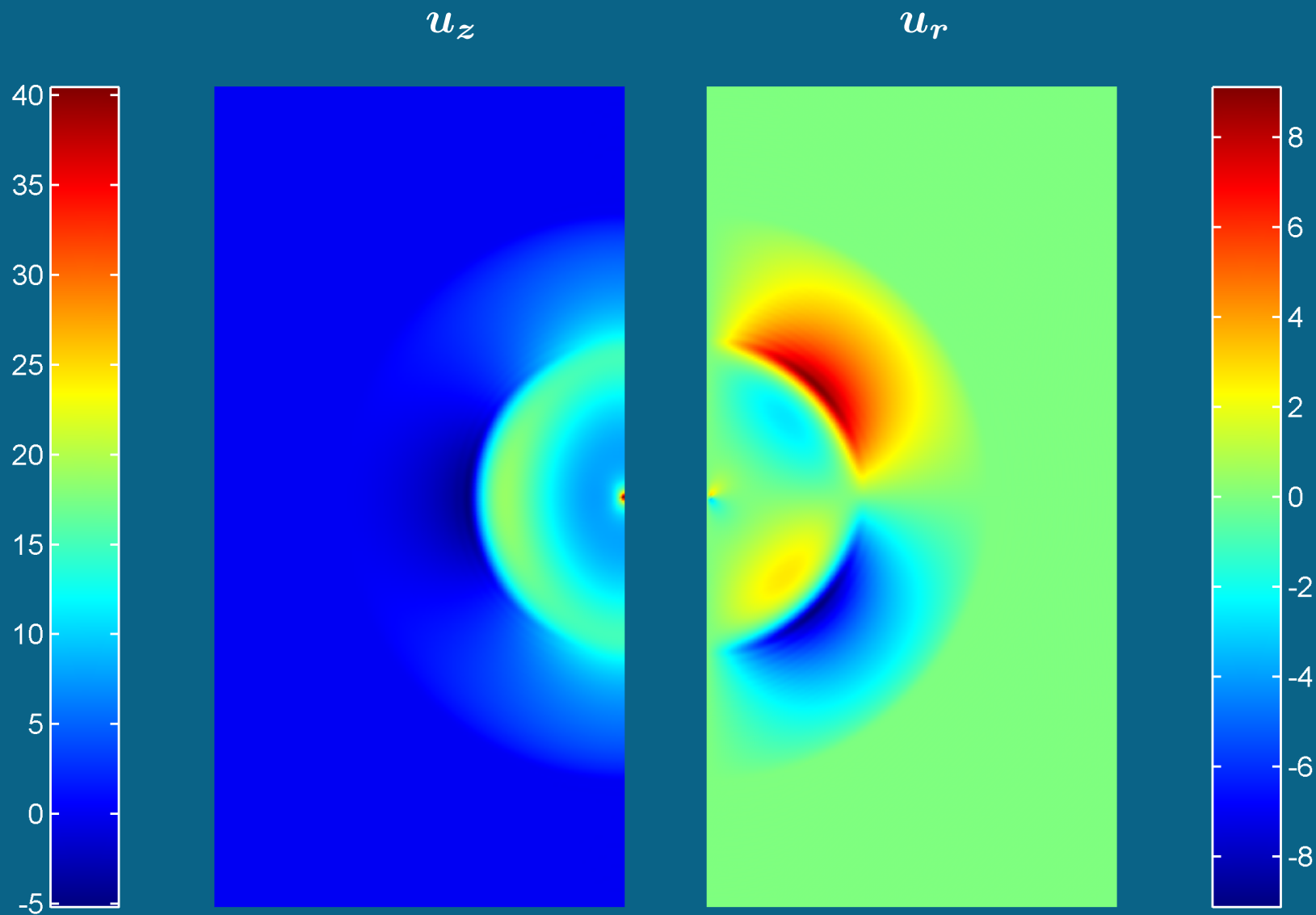
Budící funkce A – čas $4 \mu s$



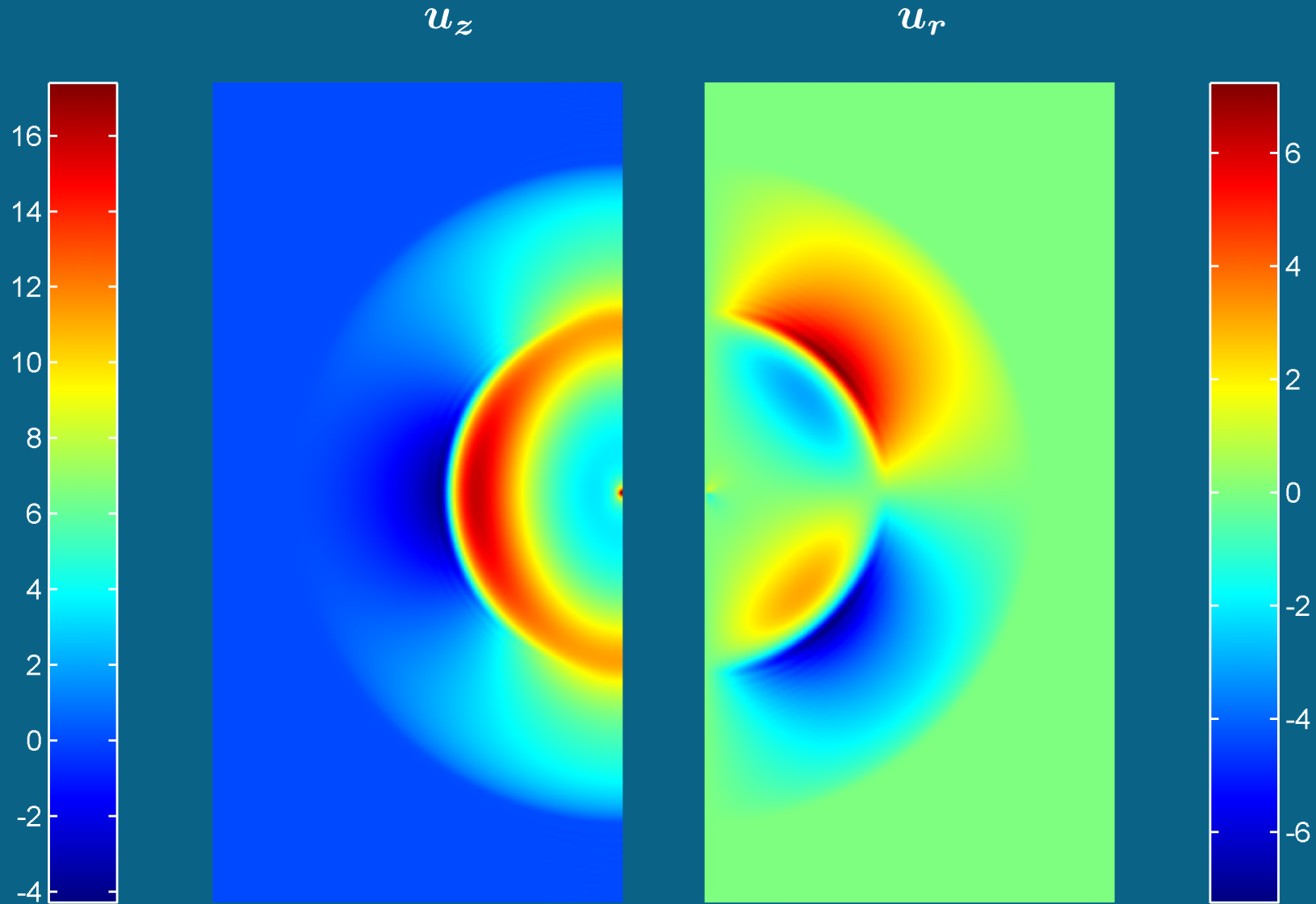
Budící funkce A – čas $5 \mu s$



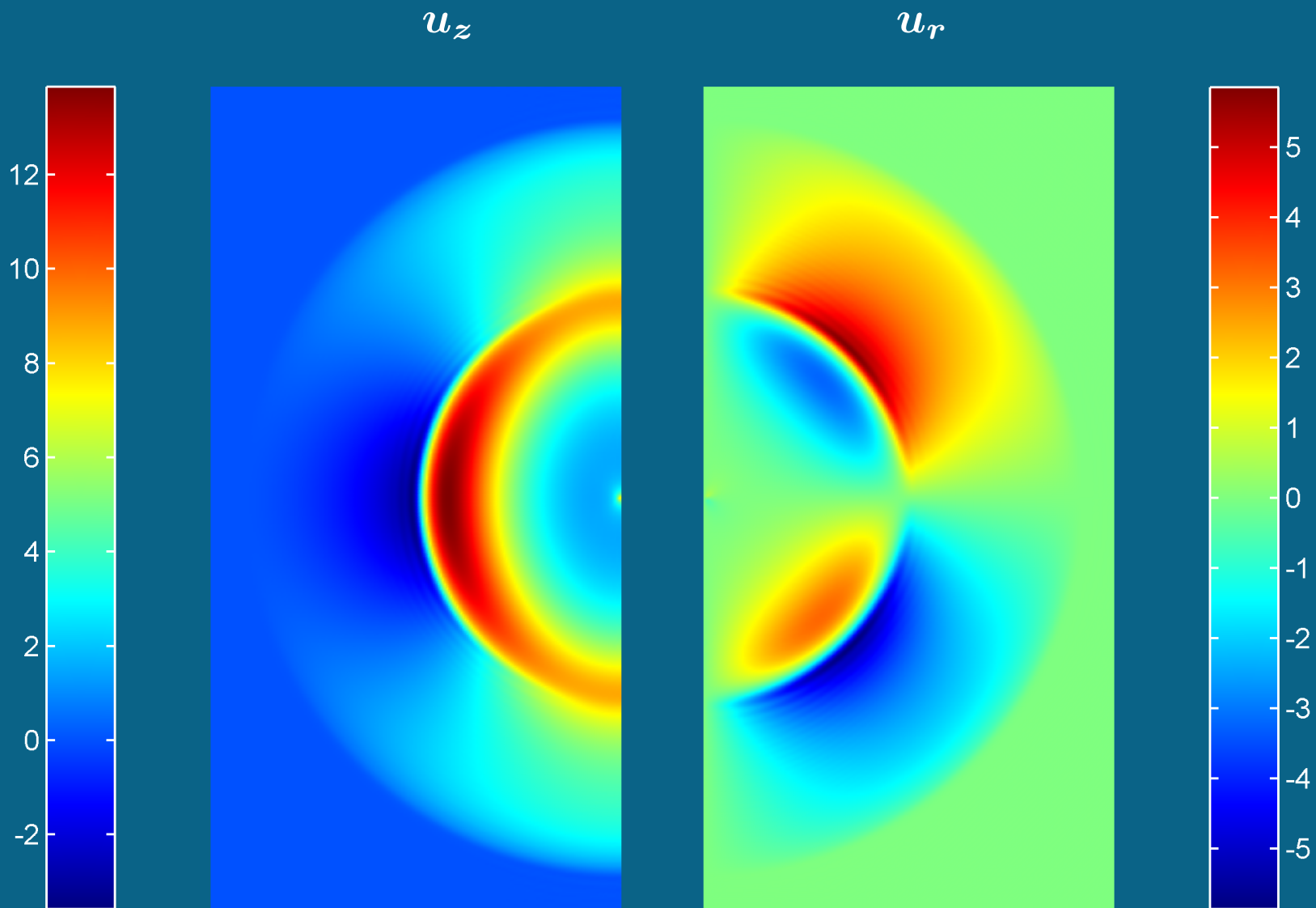
Budící funkce A – čas $6 \mu s$



Budící funkce A – čas $7 \mu s$

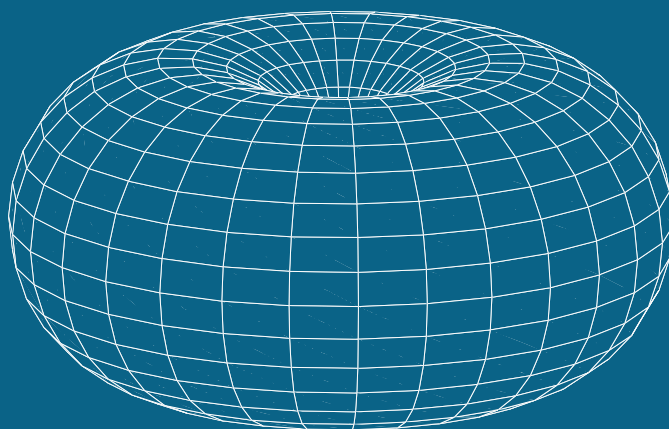


Budící funkce A – čas $8 \mu s$

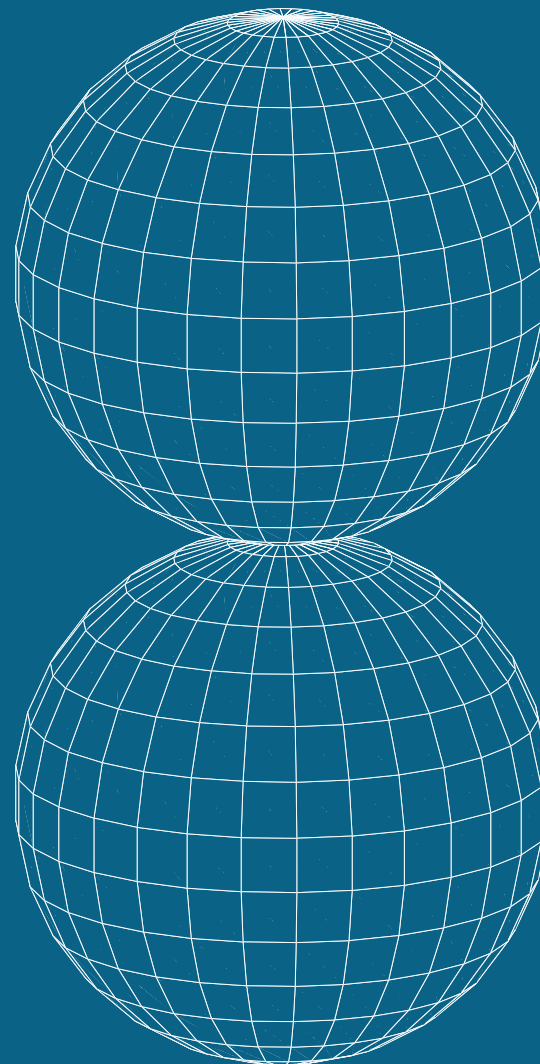


Vyzařovací charakteristiky ve vzdáleném poli

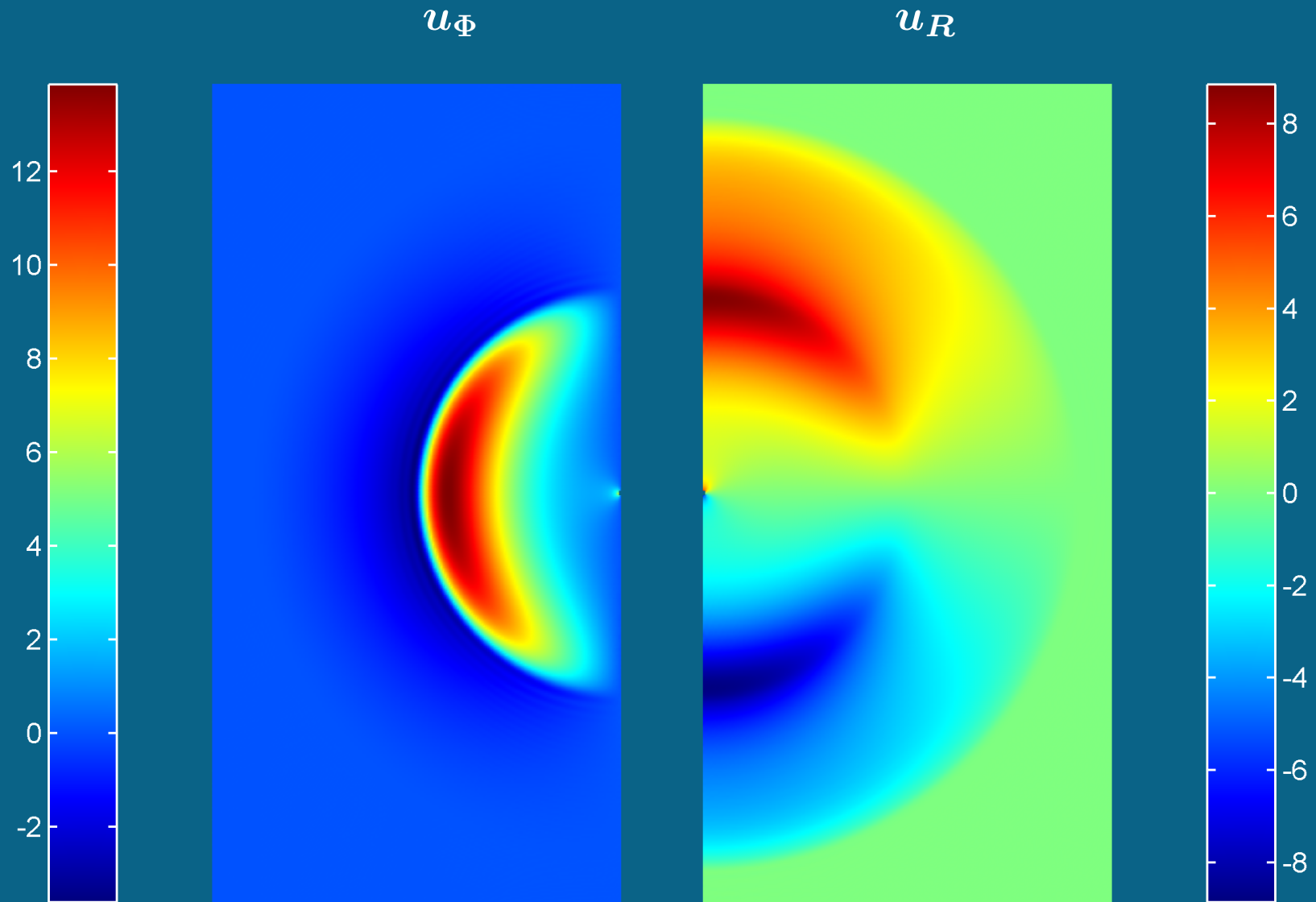
$$S (\approx \sin \theta)$$



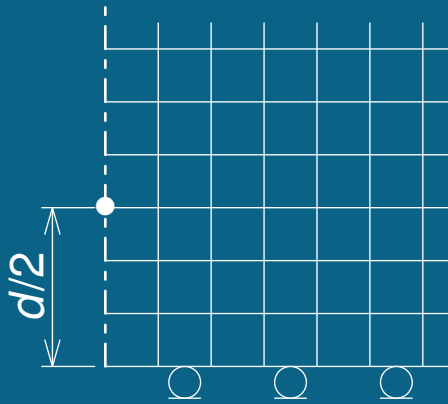
$$P (\approx \cos \theta)$$



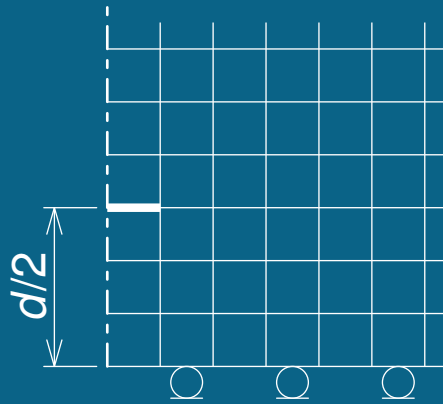
Budící funkce A – čas $8 \mu s$



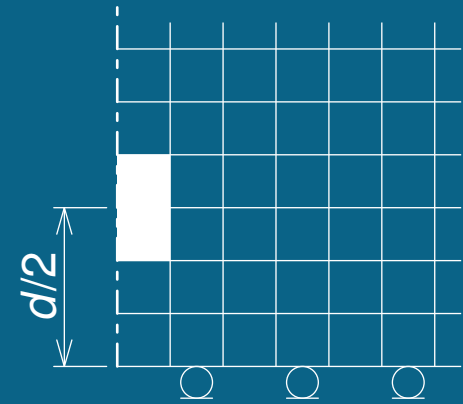
MKP – modely dipólu



bod



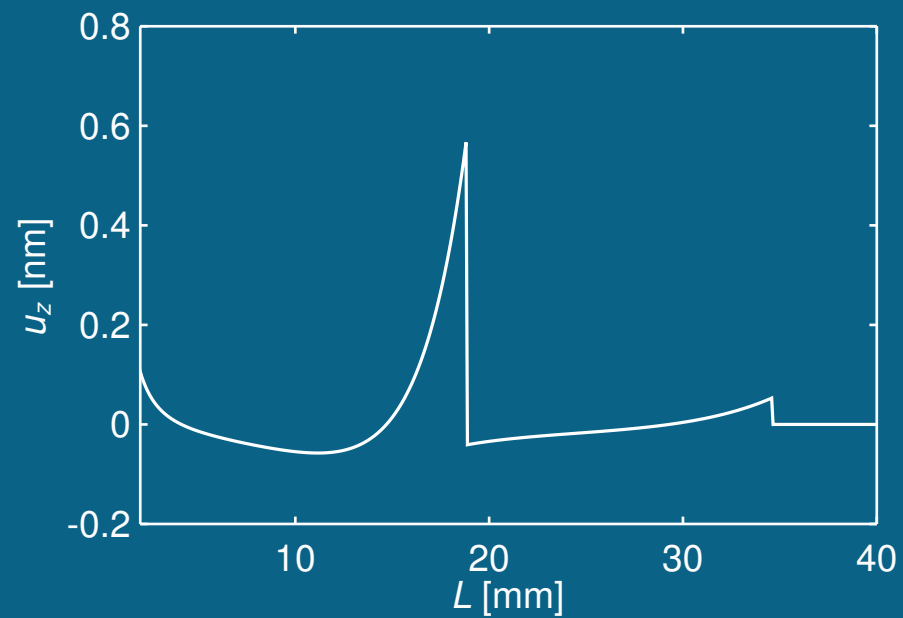
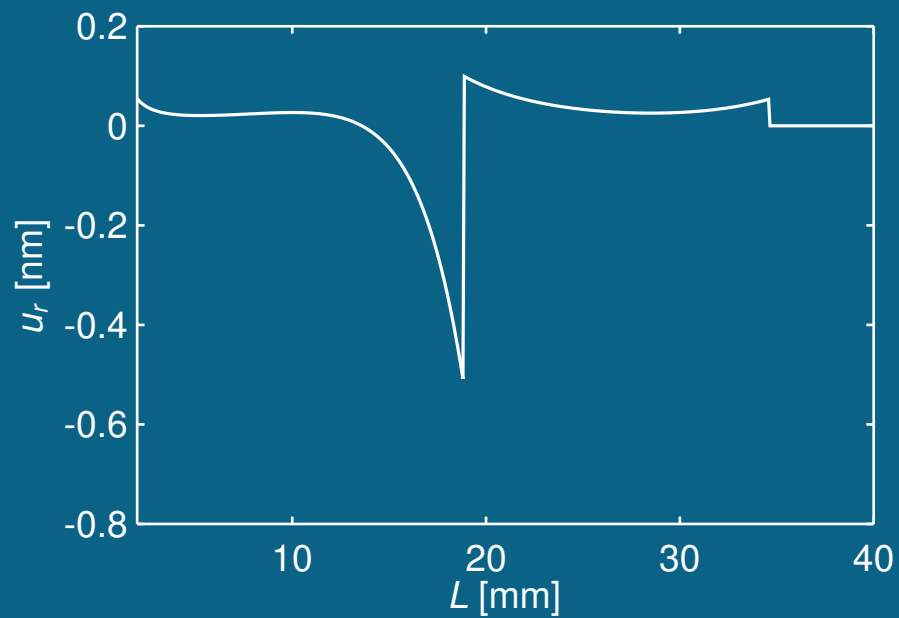
kruhová plocha
 $r = 0,5 \text{ mm}$



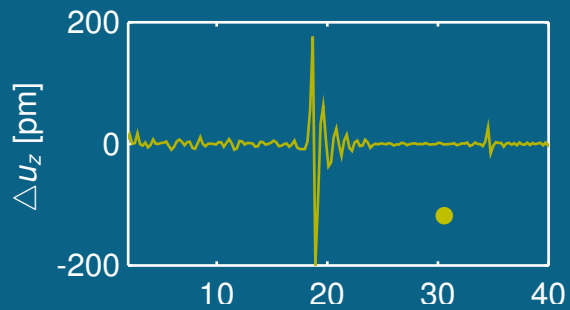
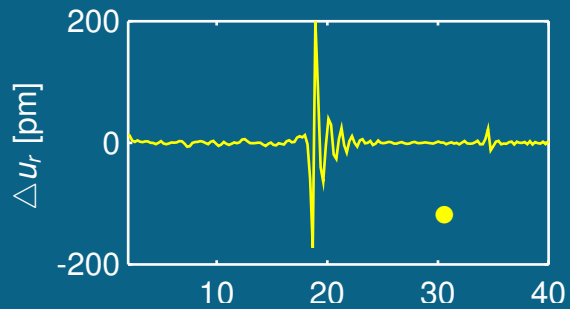
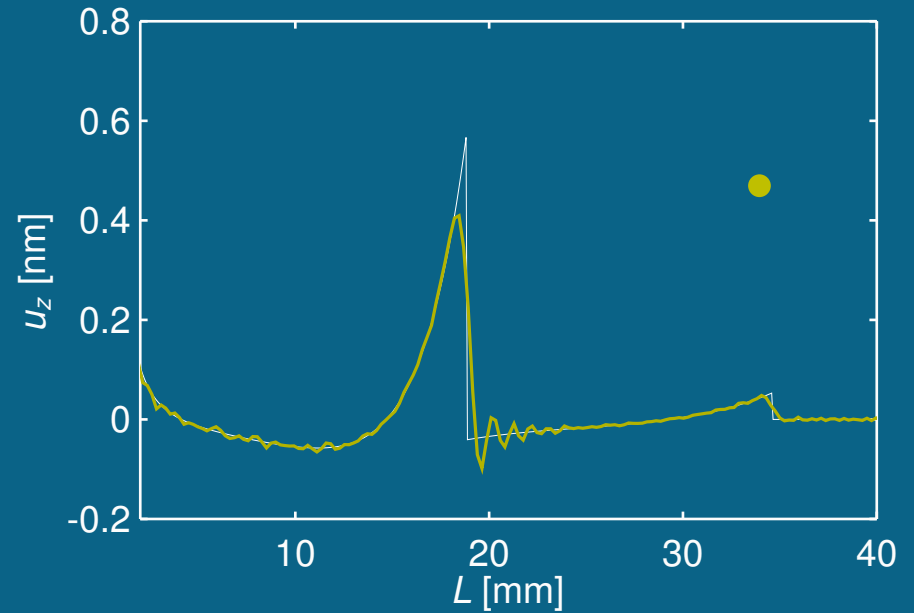
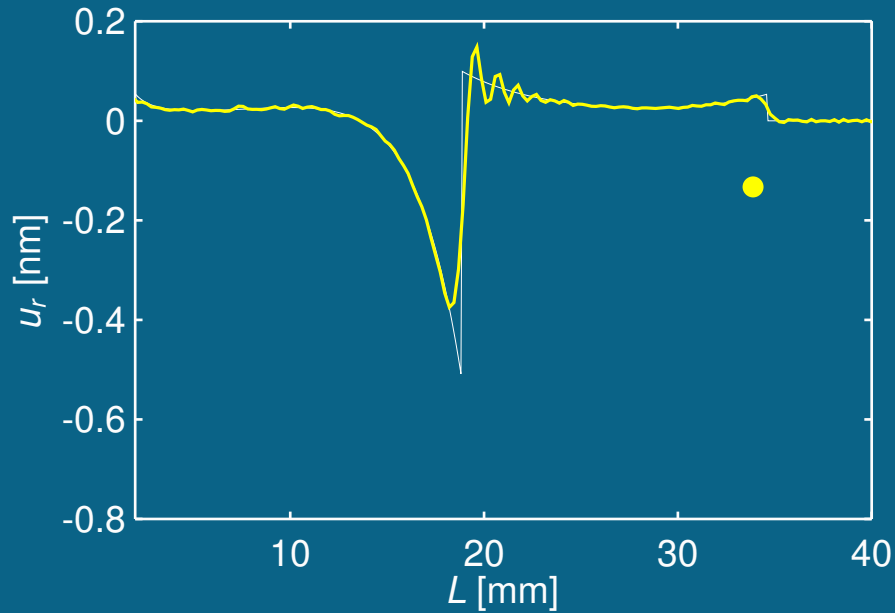
válec
 $r = 0,5 \text{ mm}$
 $z = 1 \text{ mm}$

MKP výpočty provedeny pro $d = 1, 2, 3$ a 4 mm .

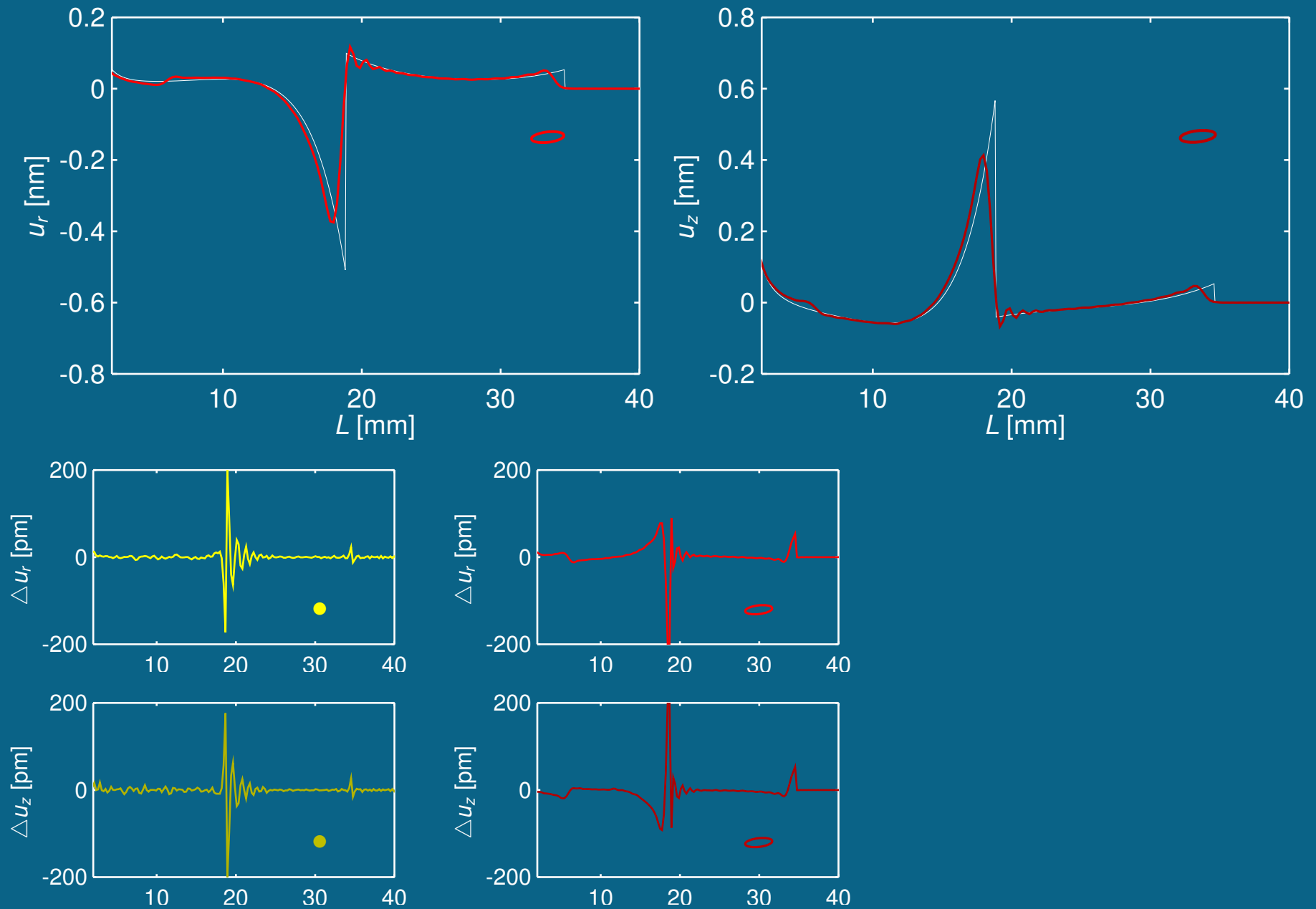
Dipol – porovnání modelů MKP – čas $6 \mu s$



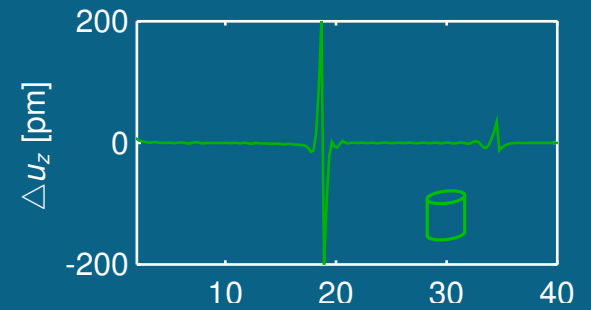
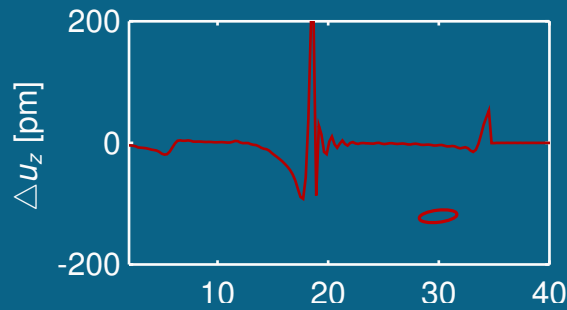
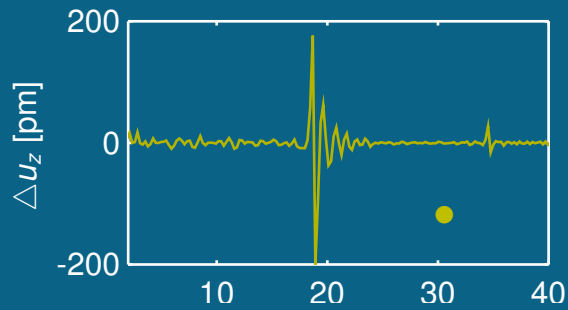
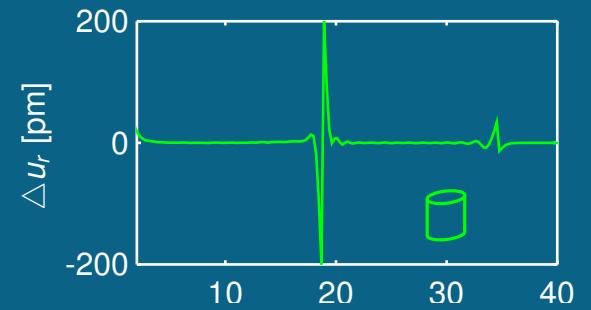
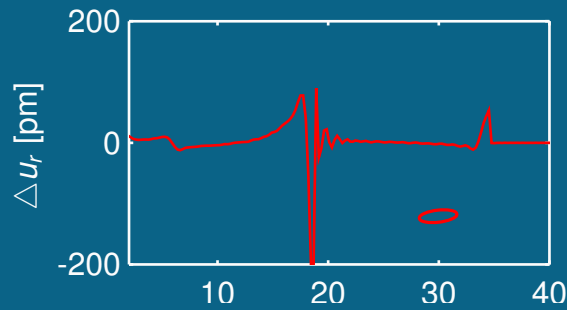
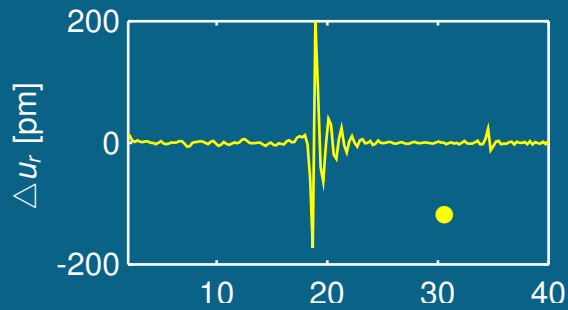
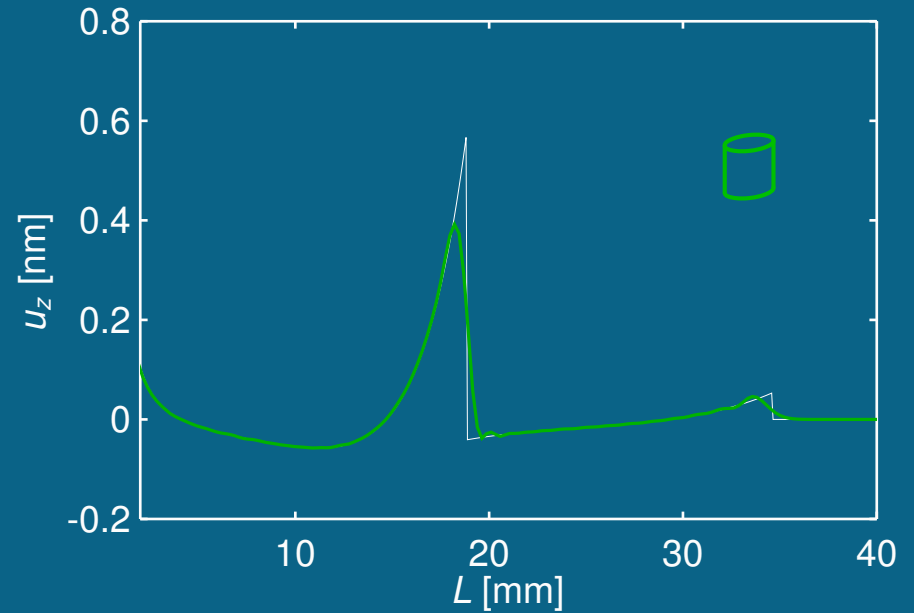
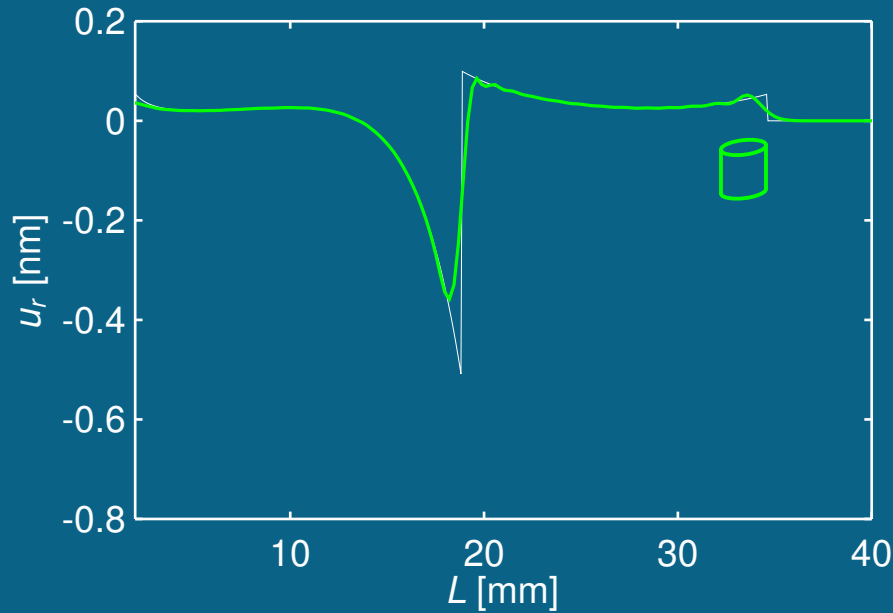
Dipol – porovnání modelů MKP – čas $6 \mu s$



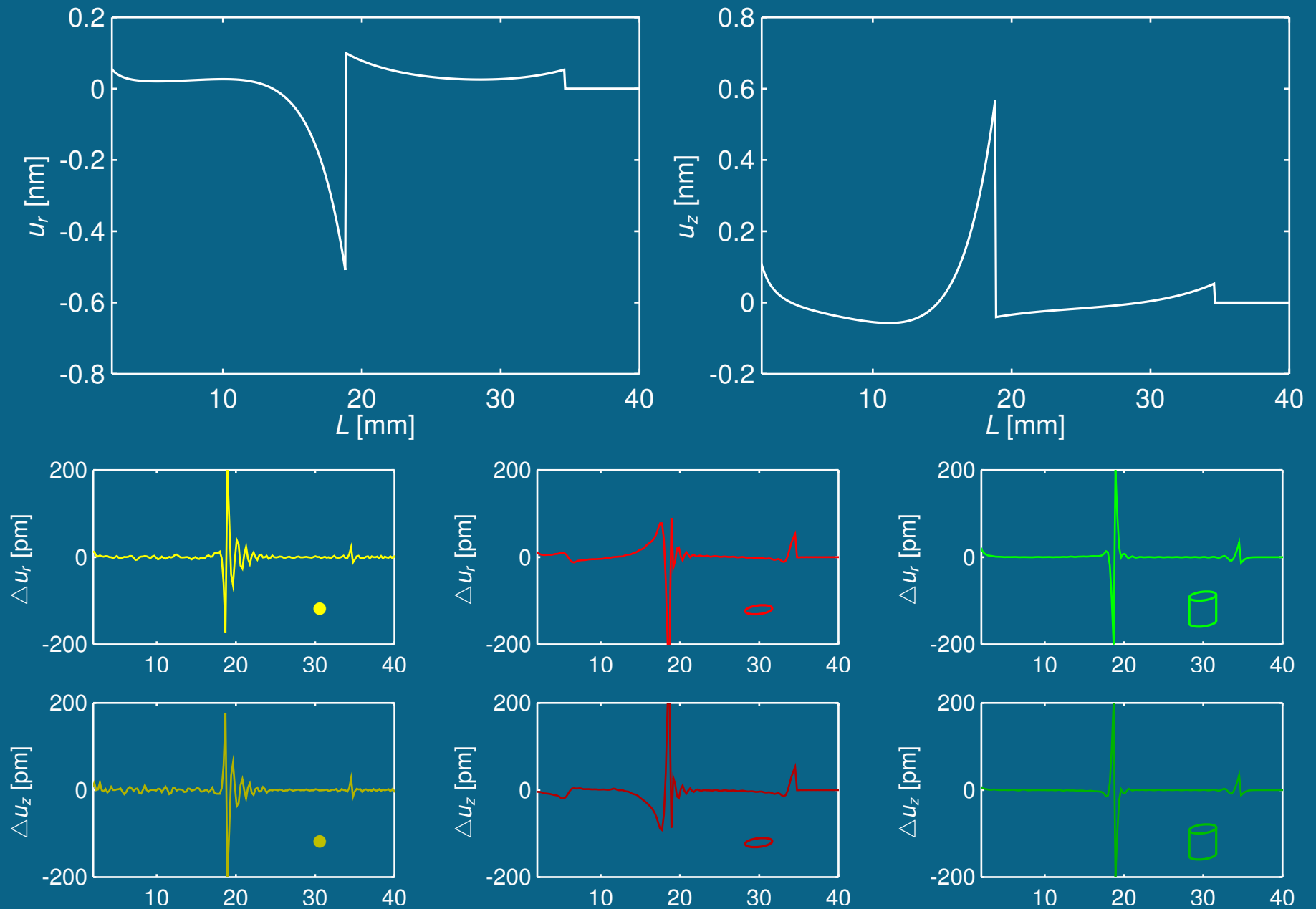
Dipol – porovnání modelů MKP – čas $6 \mu s$



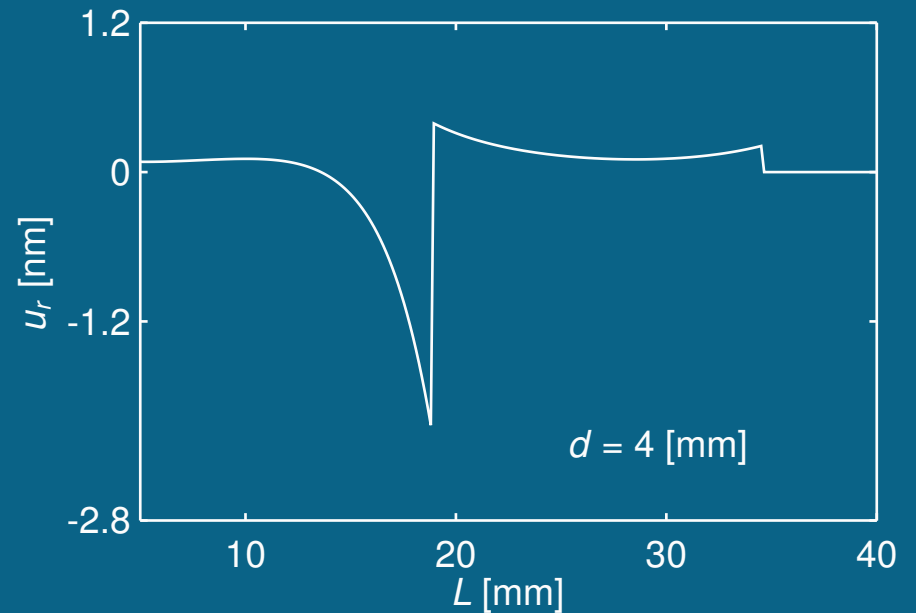
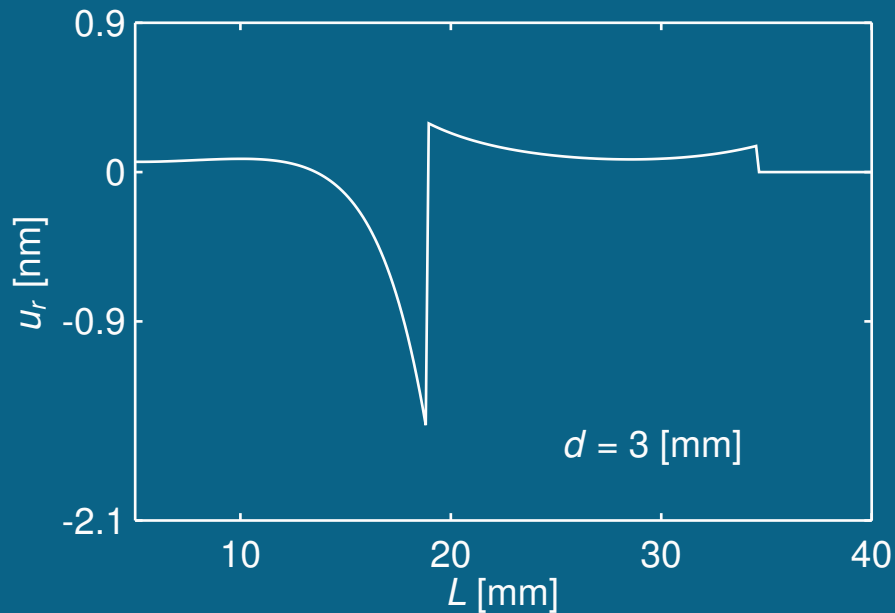
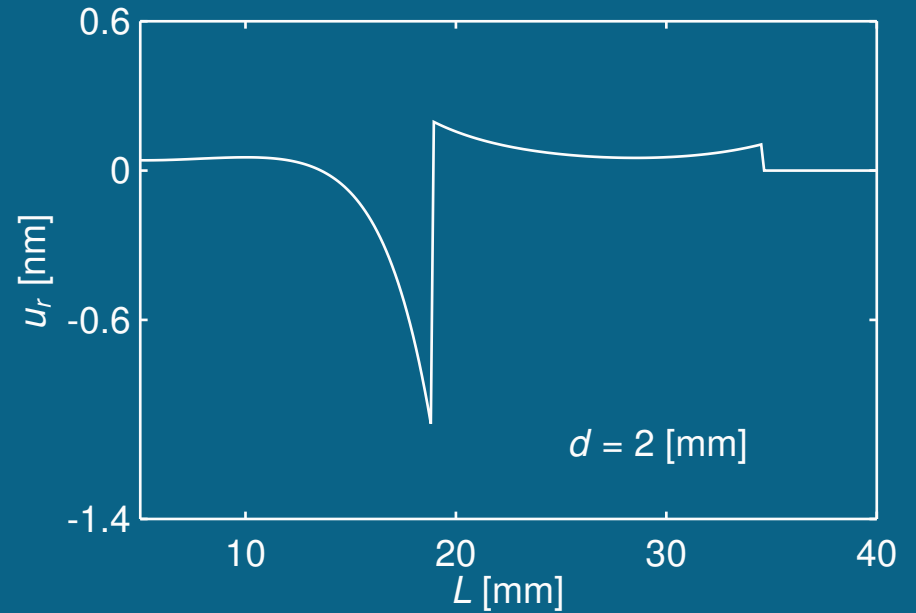
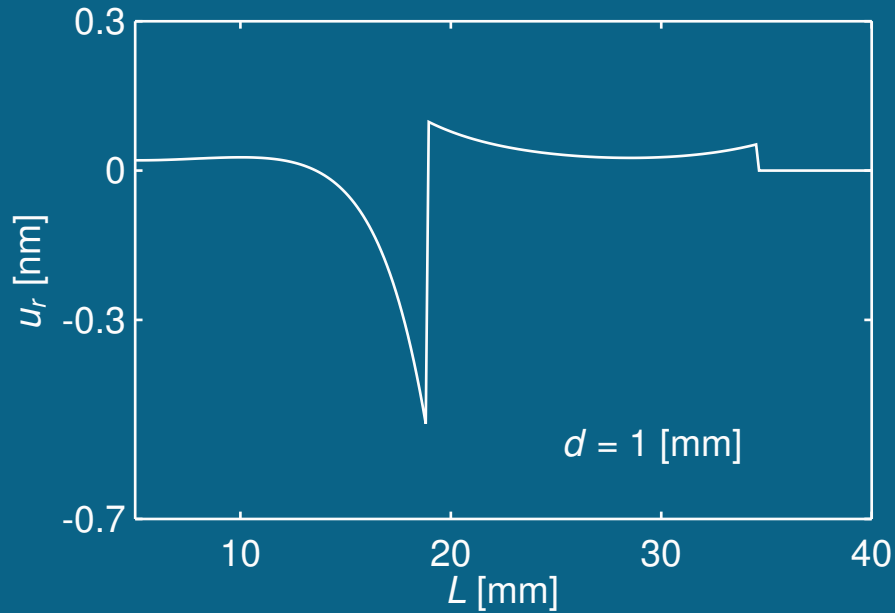
Dipol – porovnání modelů MKP – čas 6 μs



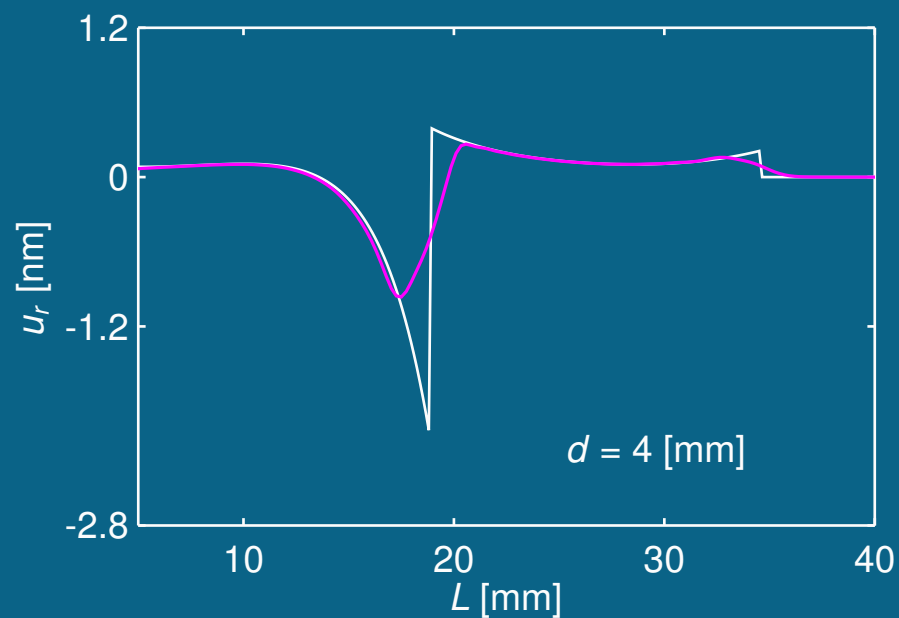
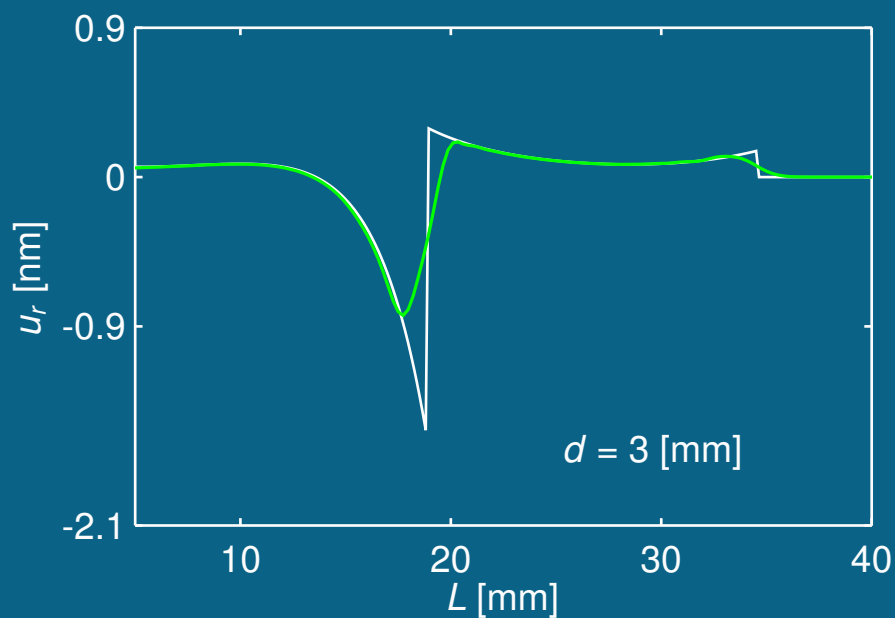
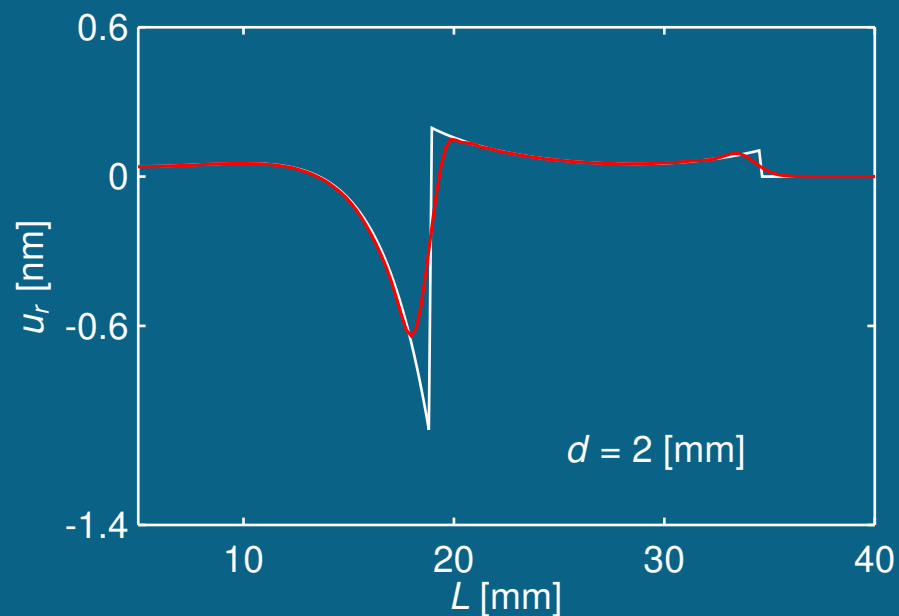
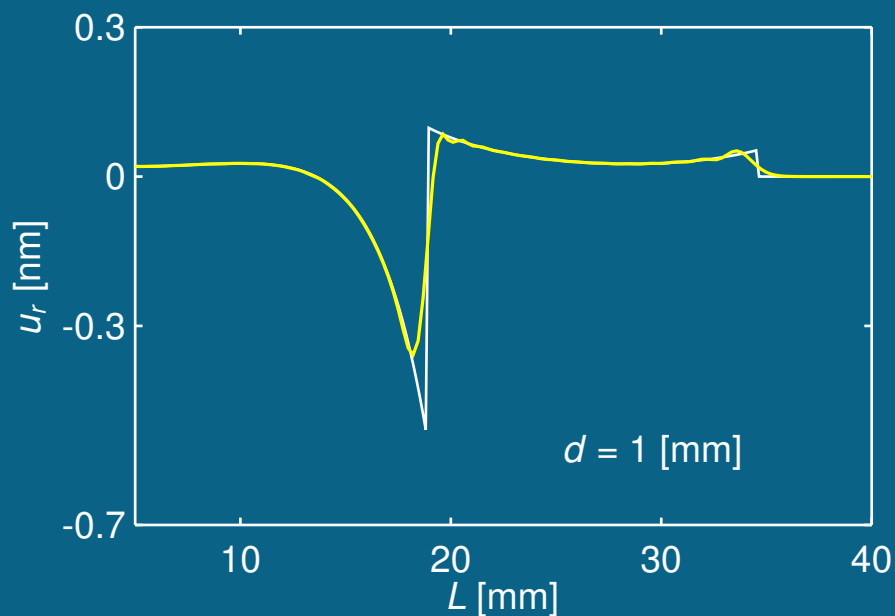
Dipol – porovnání modelů MKP – čas $6 \mu s$



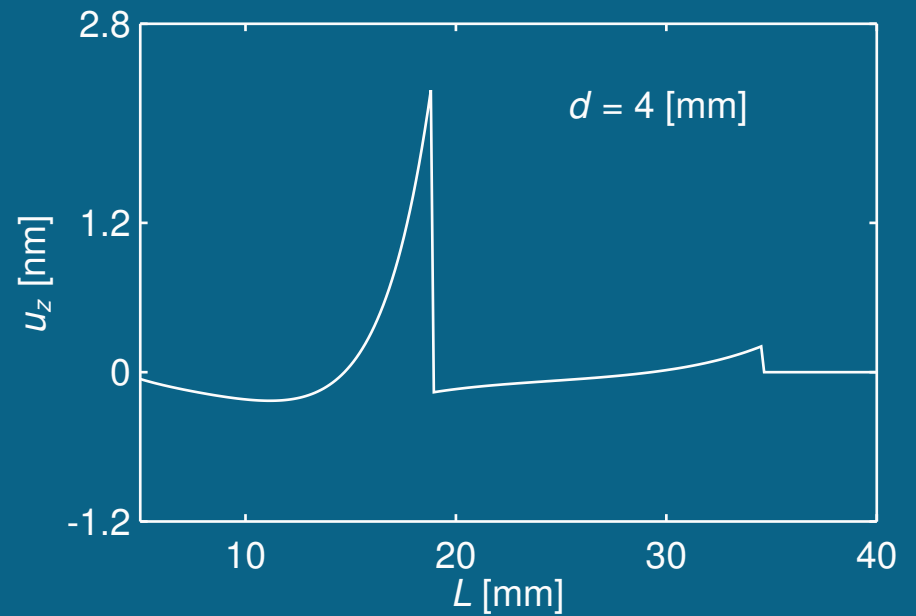
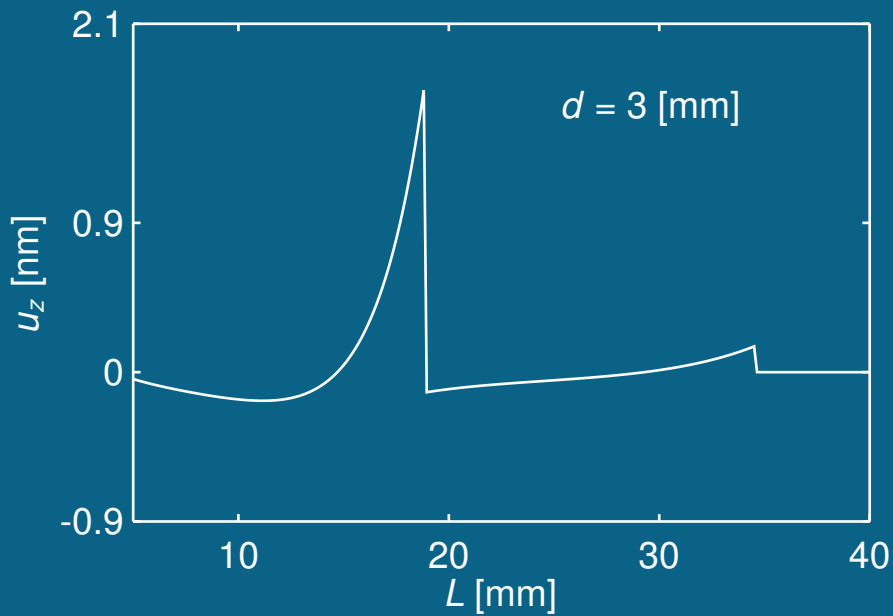
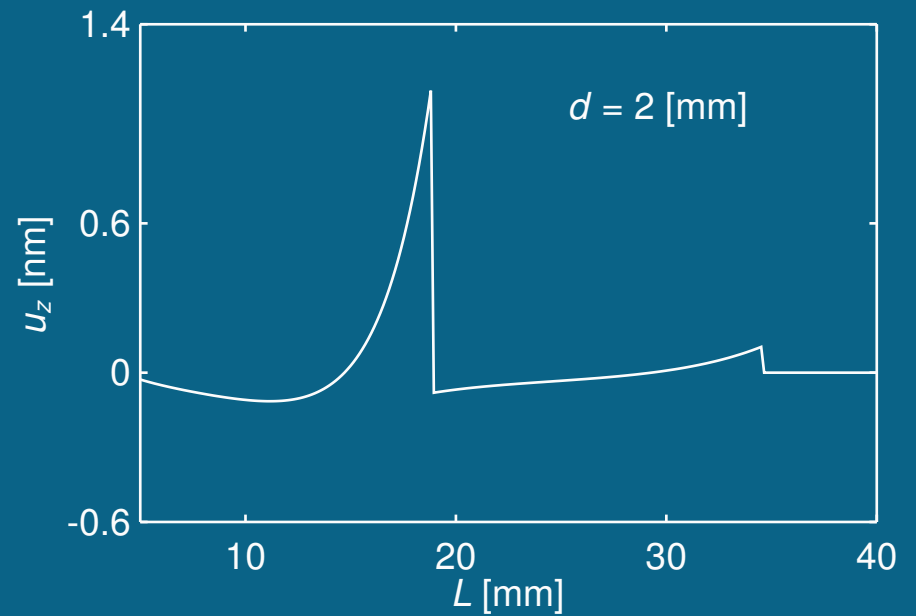
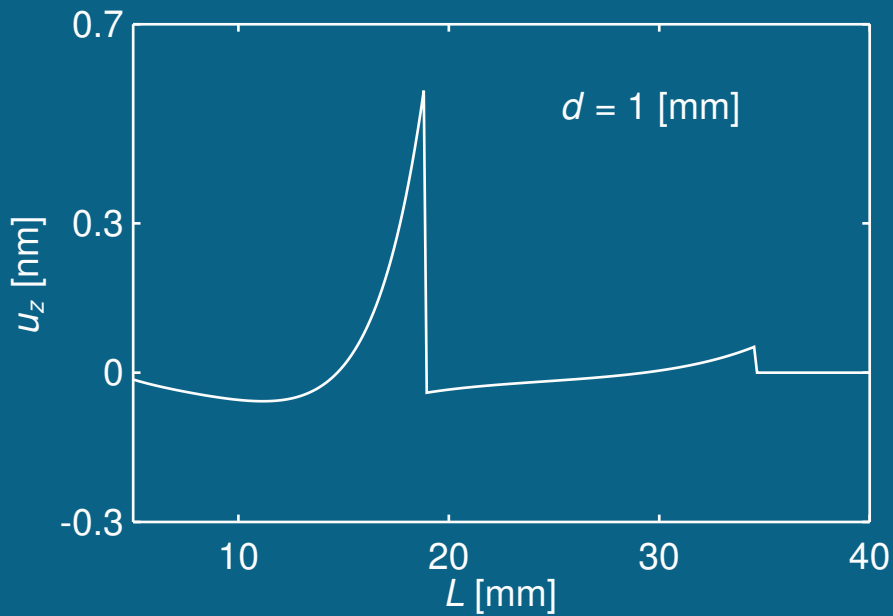
Dipól – vliv délky ramene – u_r v čase $6 \mu s$



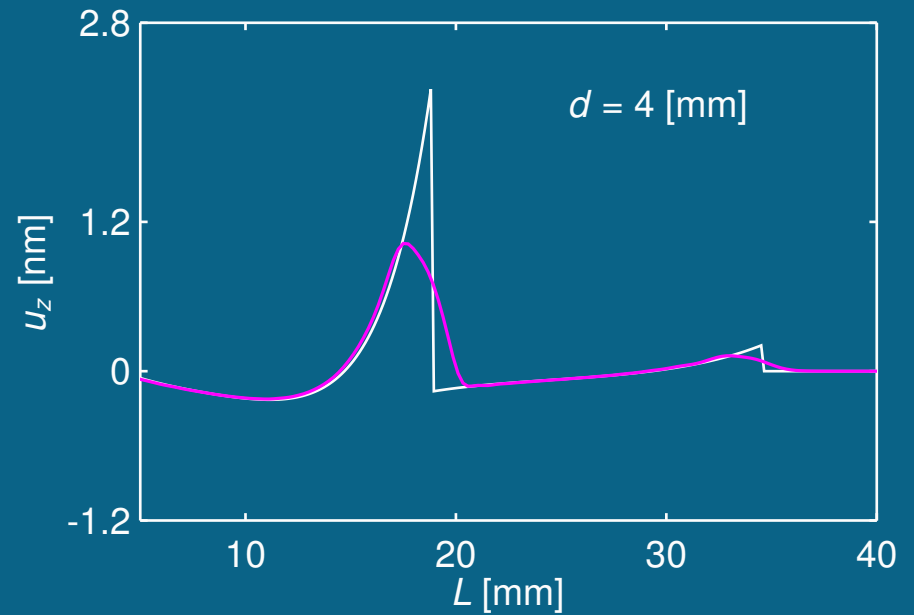
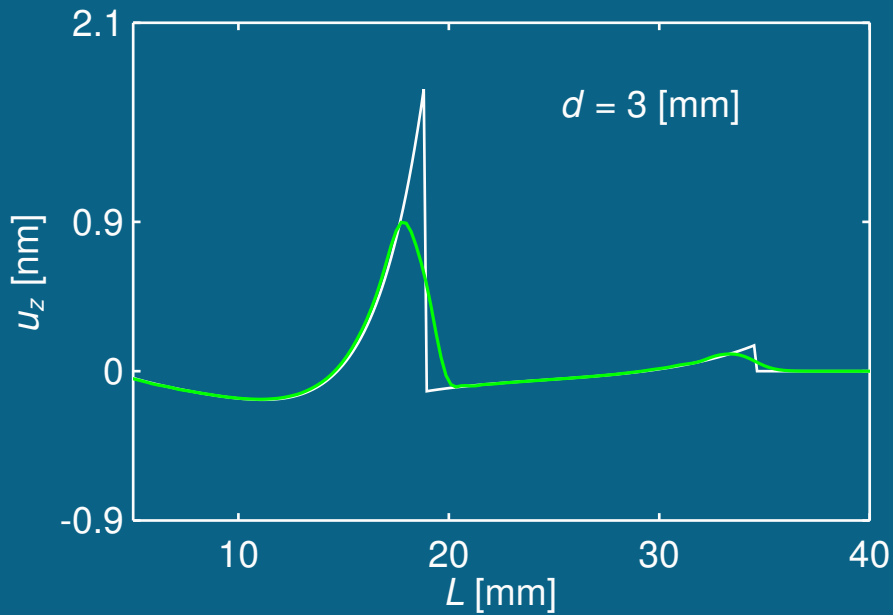
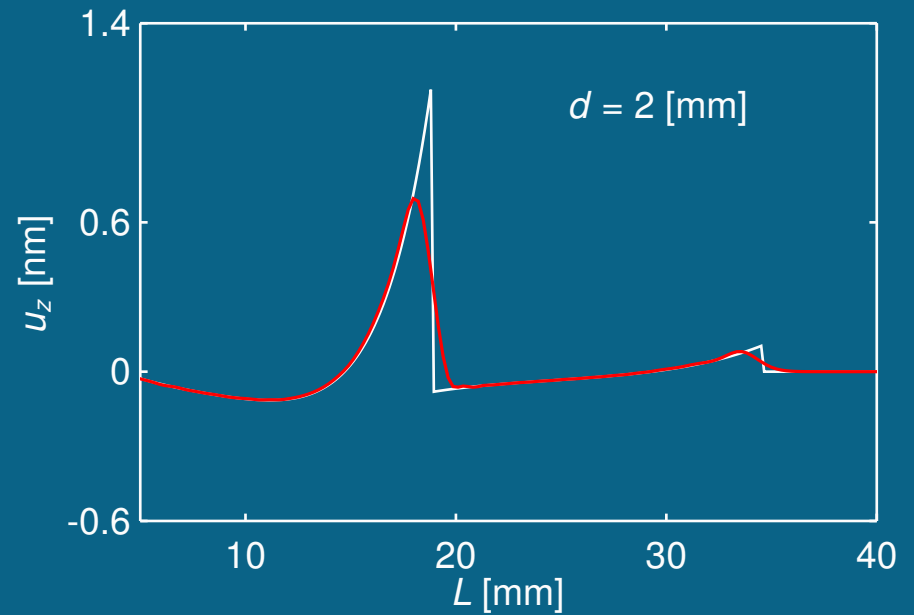
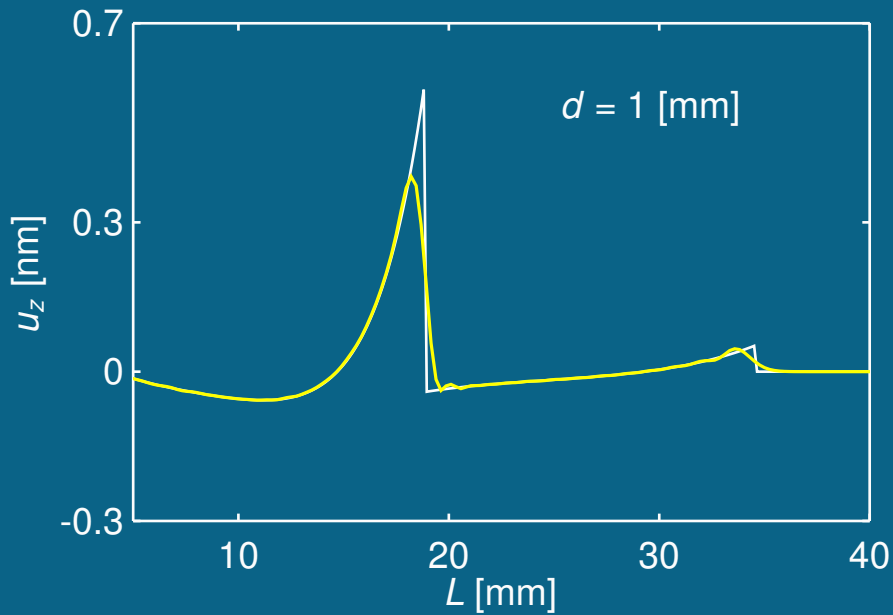
Dipól – vliv délky ramene – u_r v čase $6 \mu s$



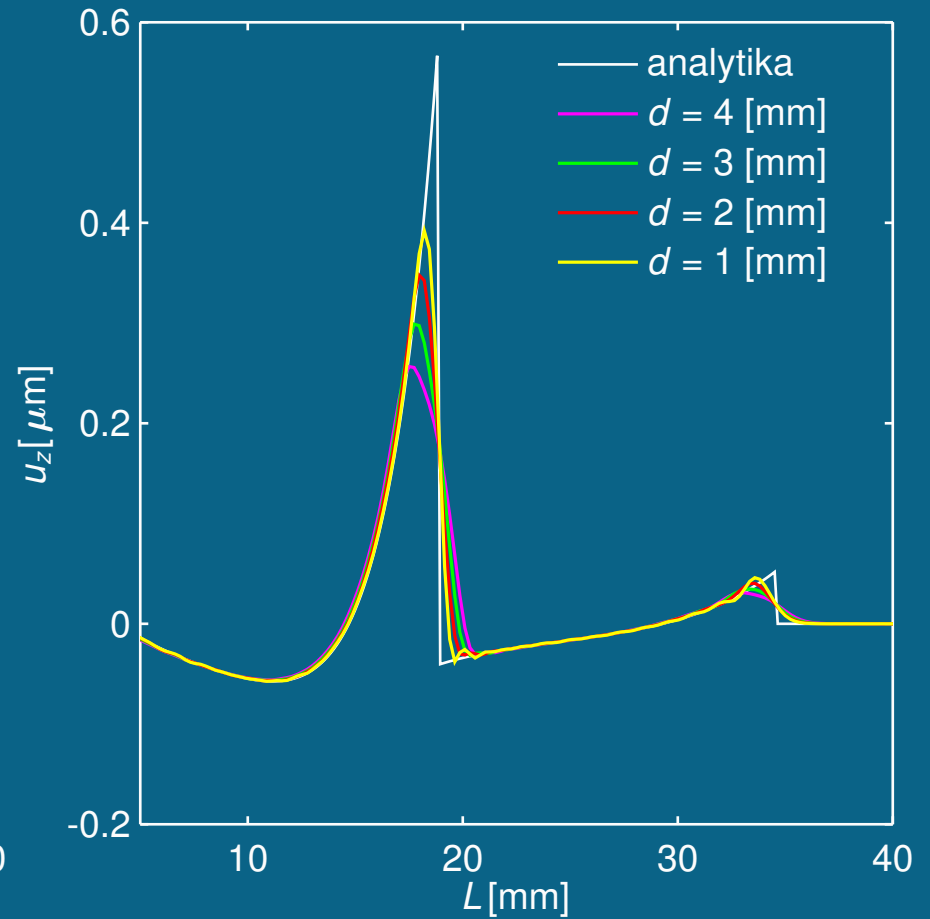
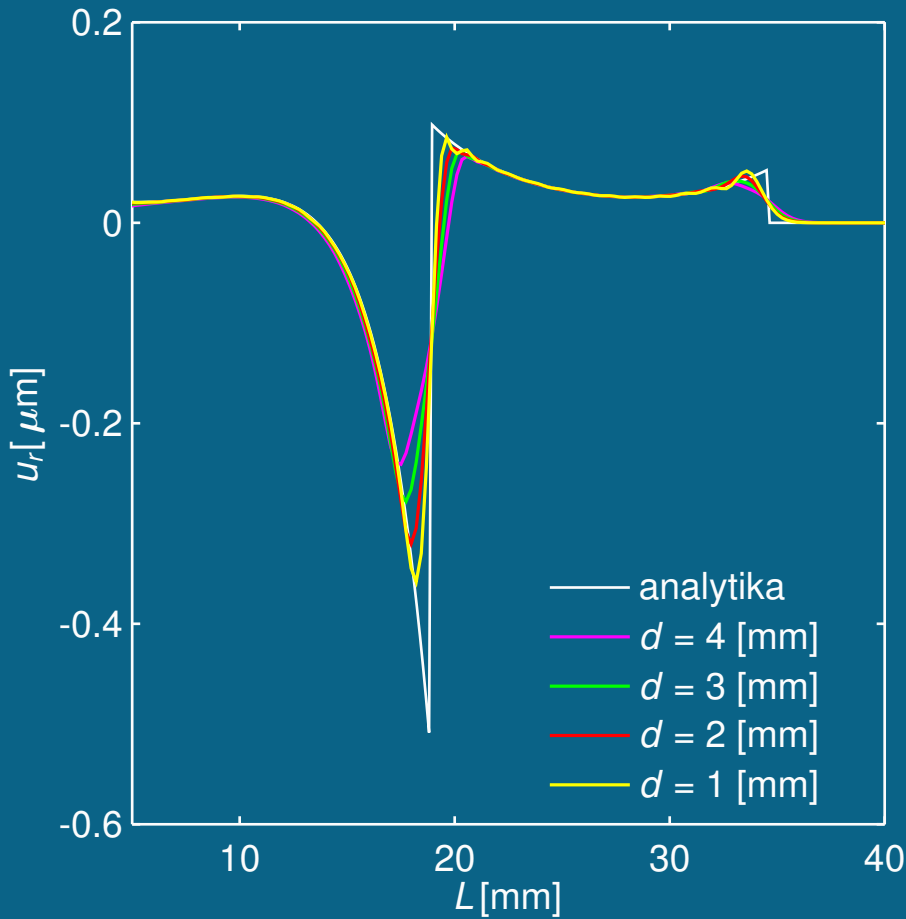
Dipól – vliv délky ramene – u_z v čase $6 \mu s$



Dipól – vliv délky ramene – u_z v čase $6 \mu s$

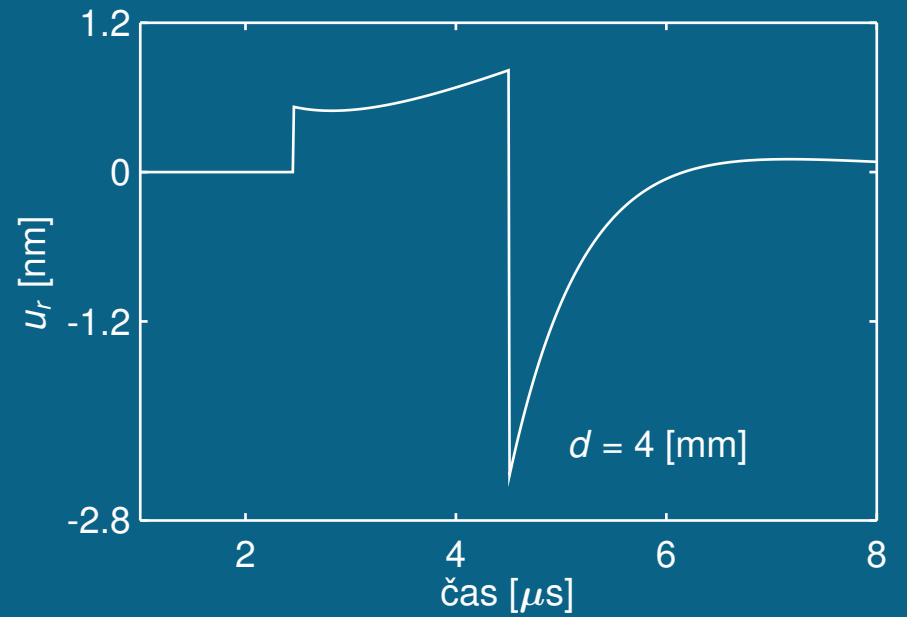
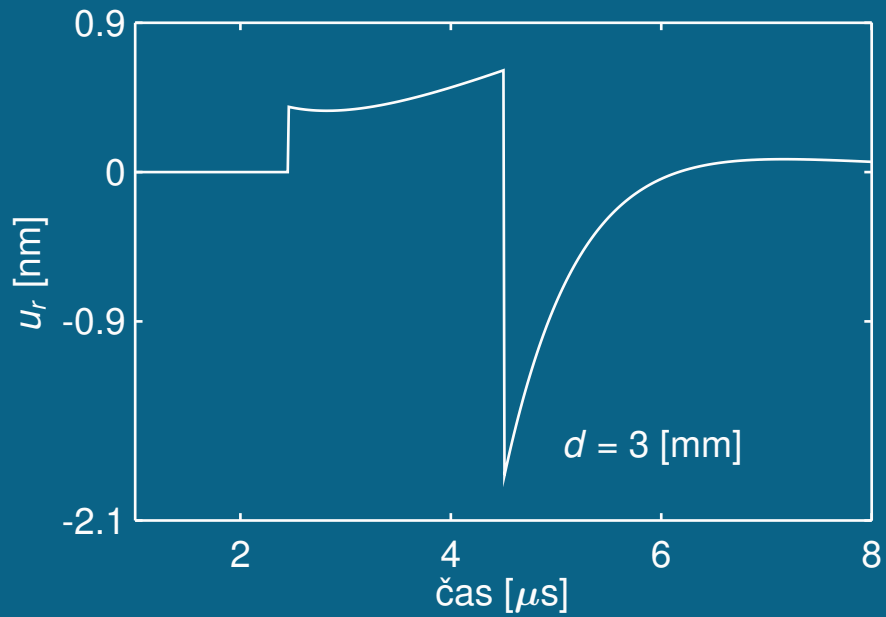
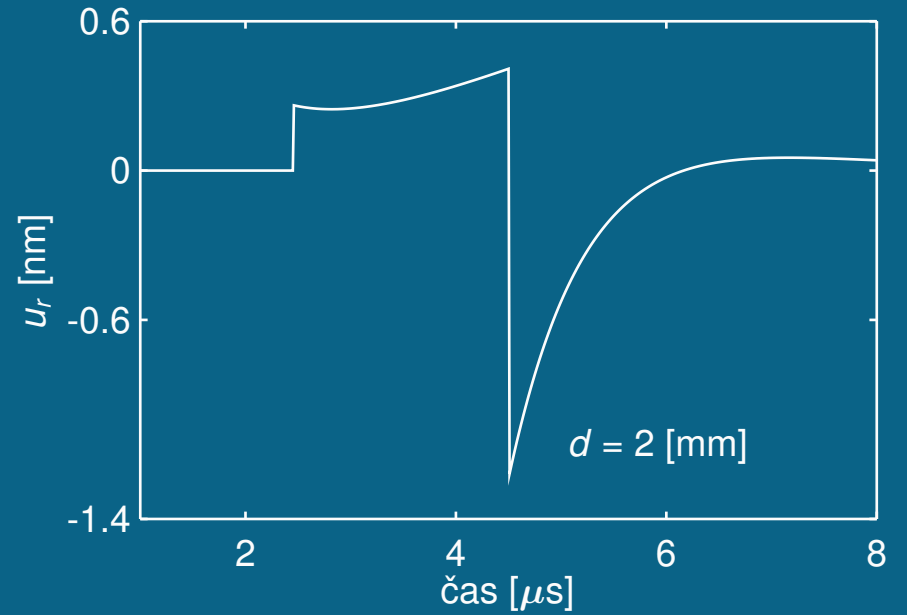
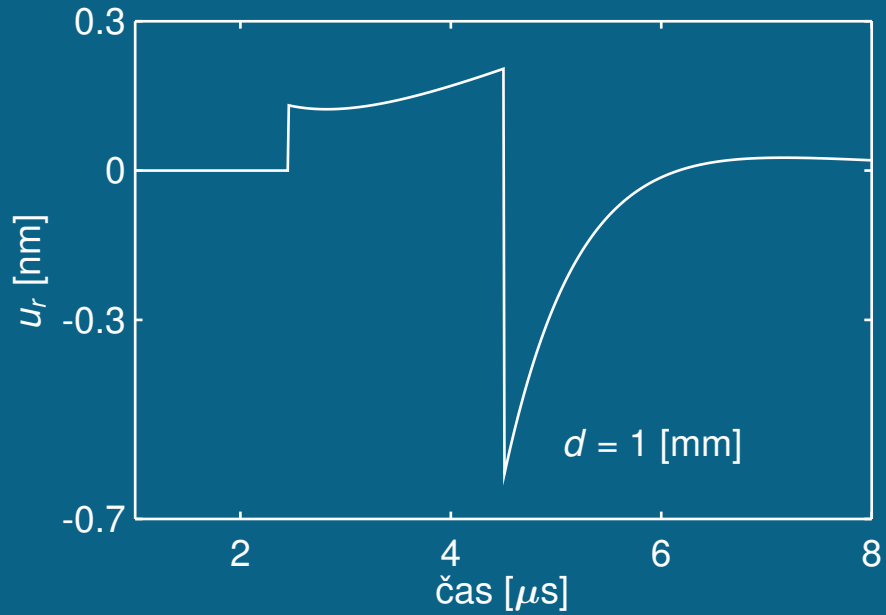


Dipól – vliv délky ramene – čas $6 \mu s$

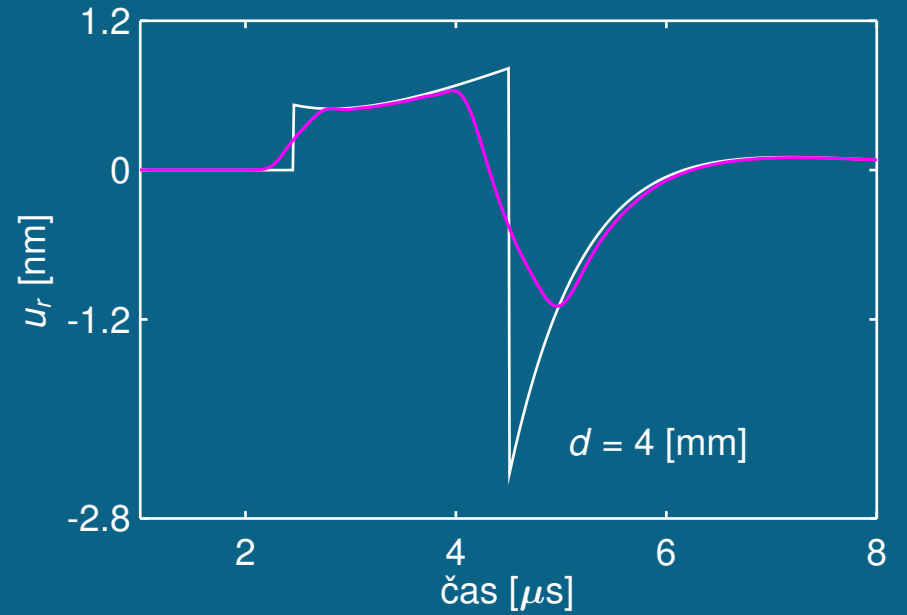
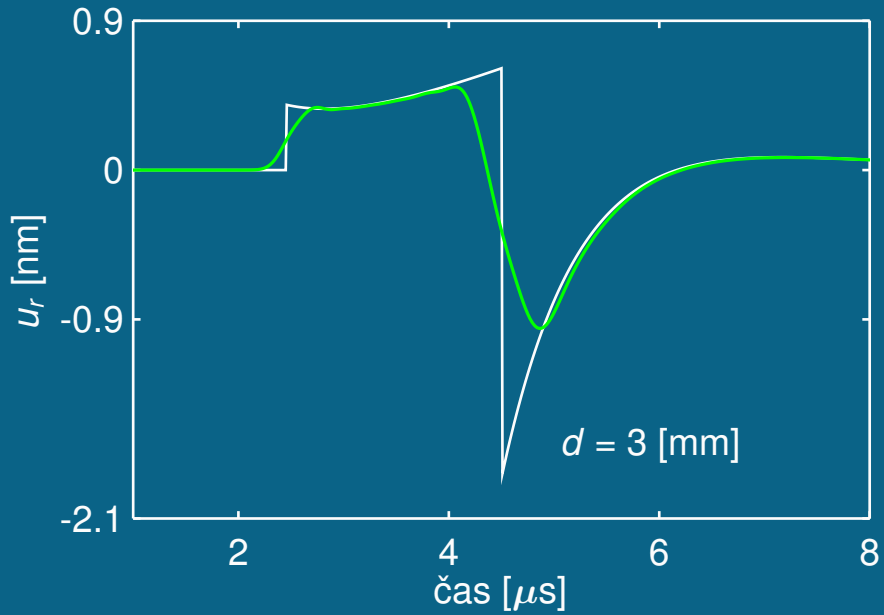
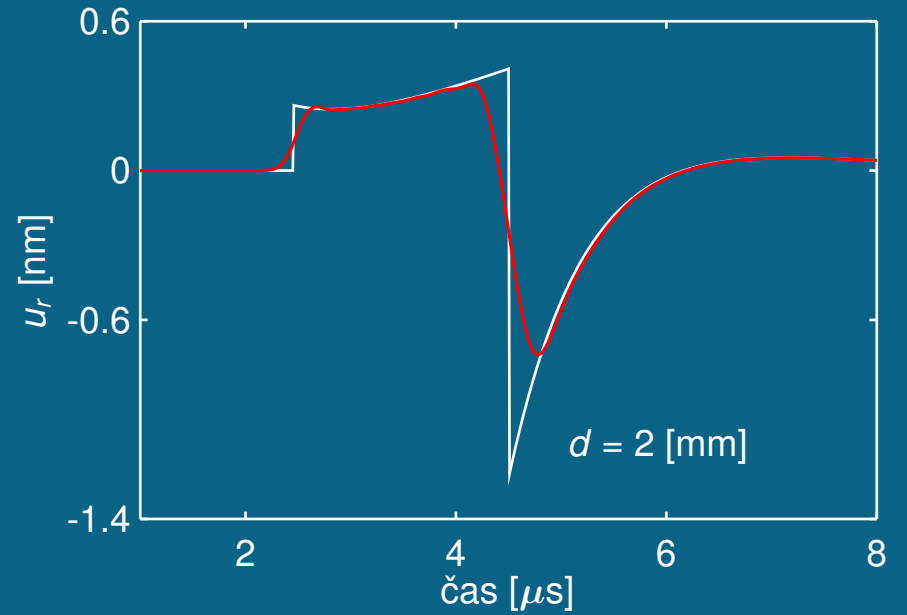
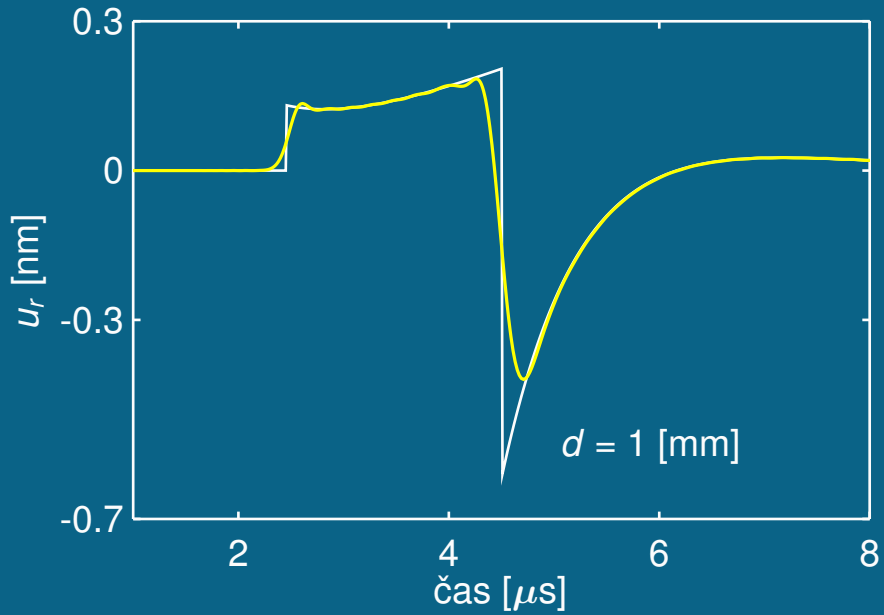


- výchylka vypočtená MKP je vždy dělená délkou ramene

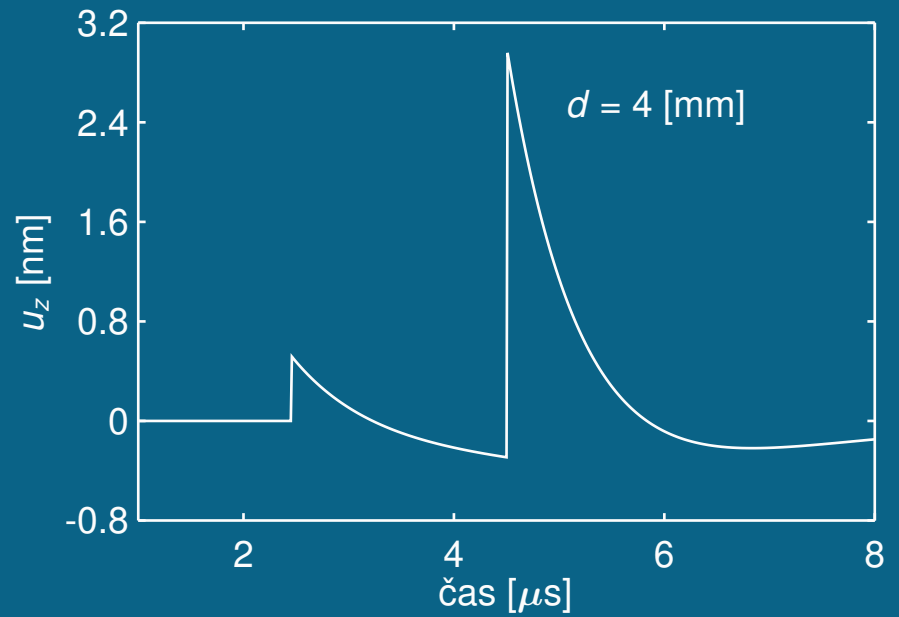
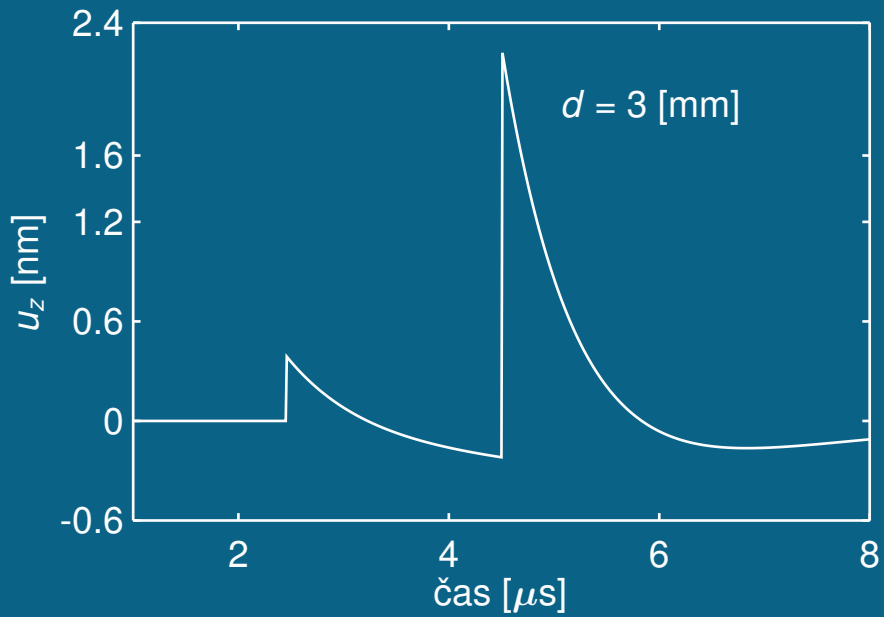
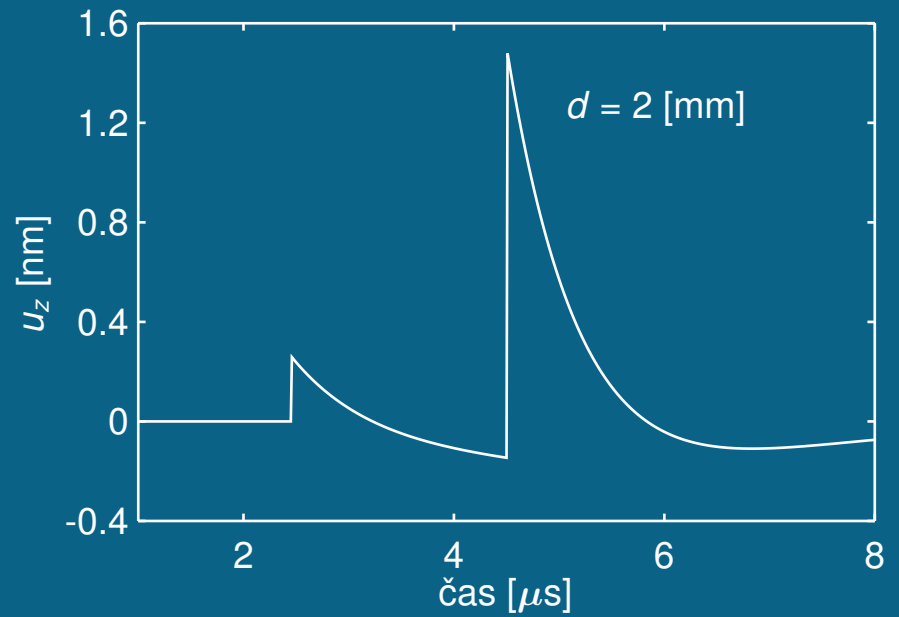
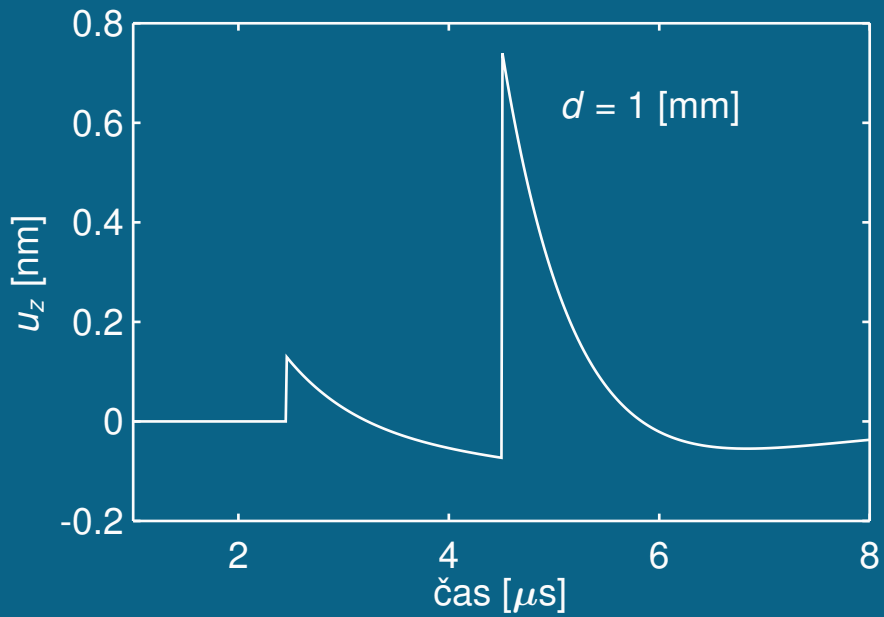
Dipól – vliv délky ramene – u_r v bodě P



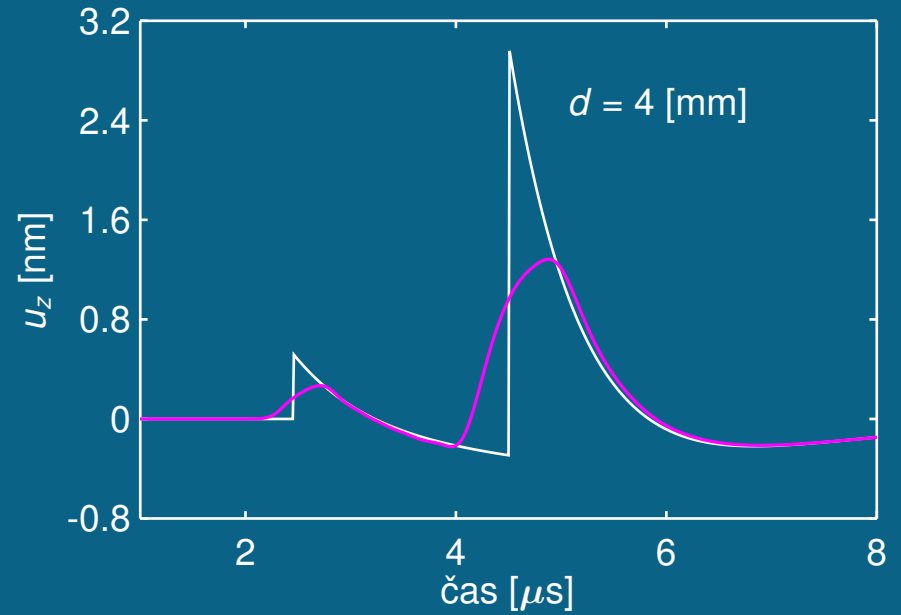
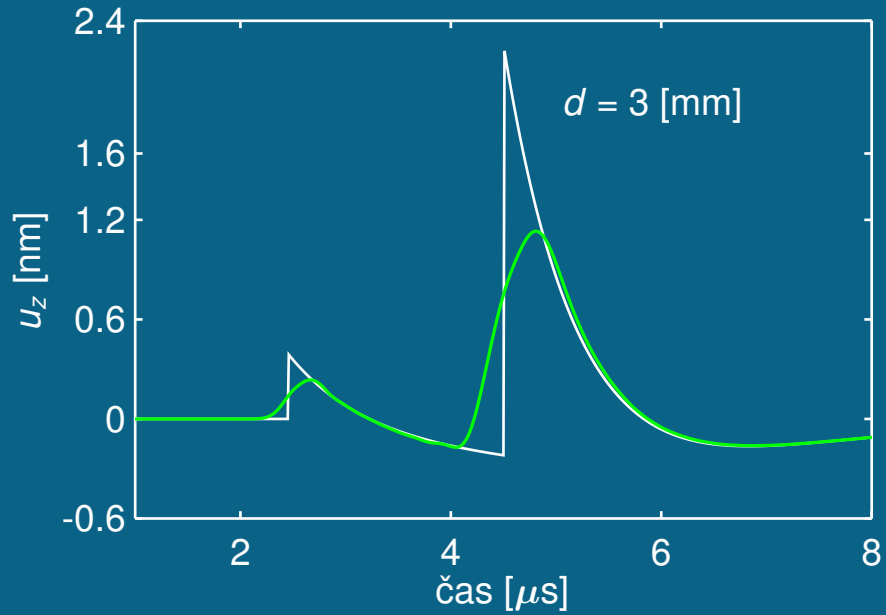
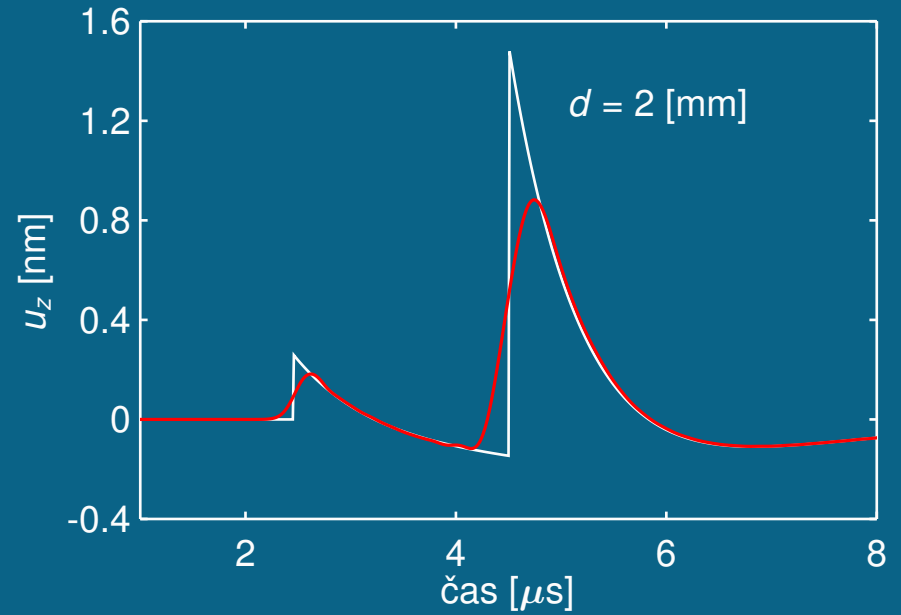
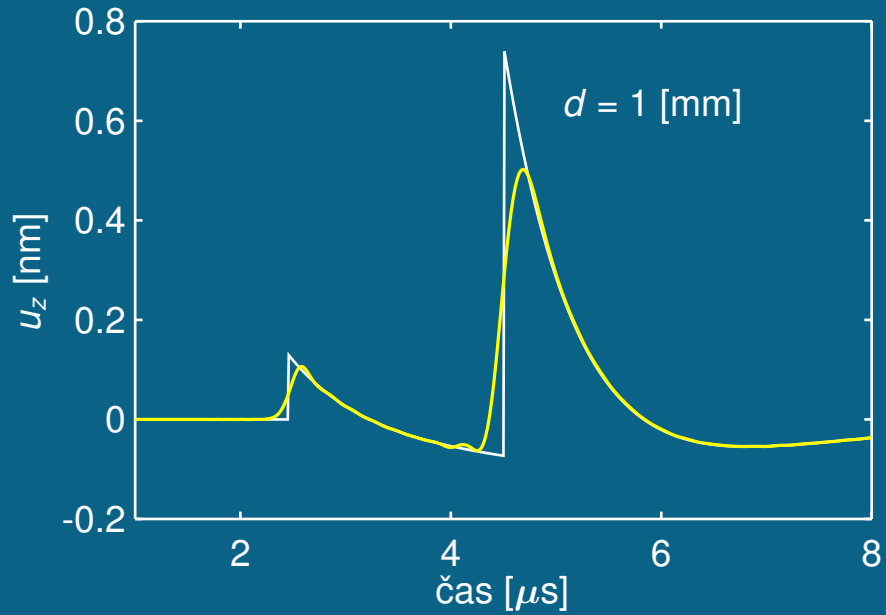
Dipól – vliv délky ramene – u_r v bodě P



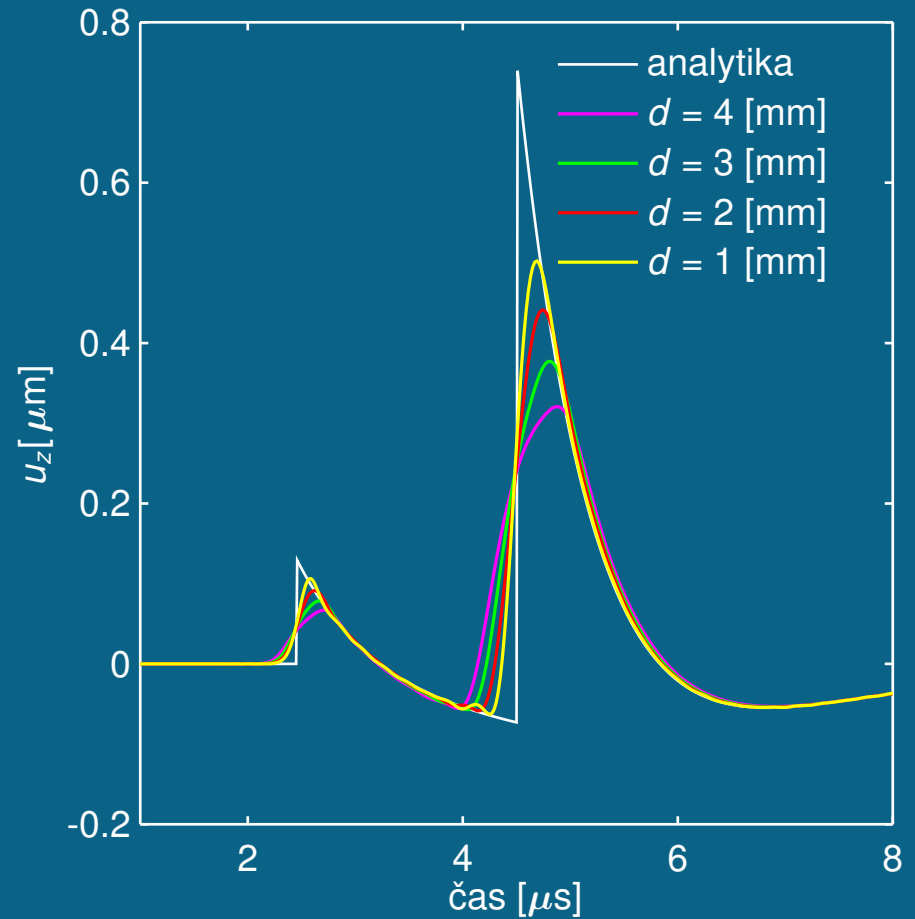
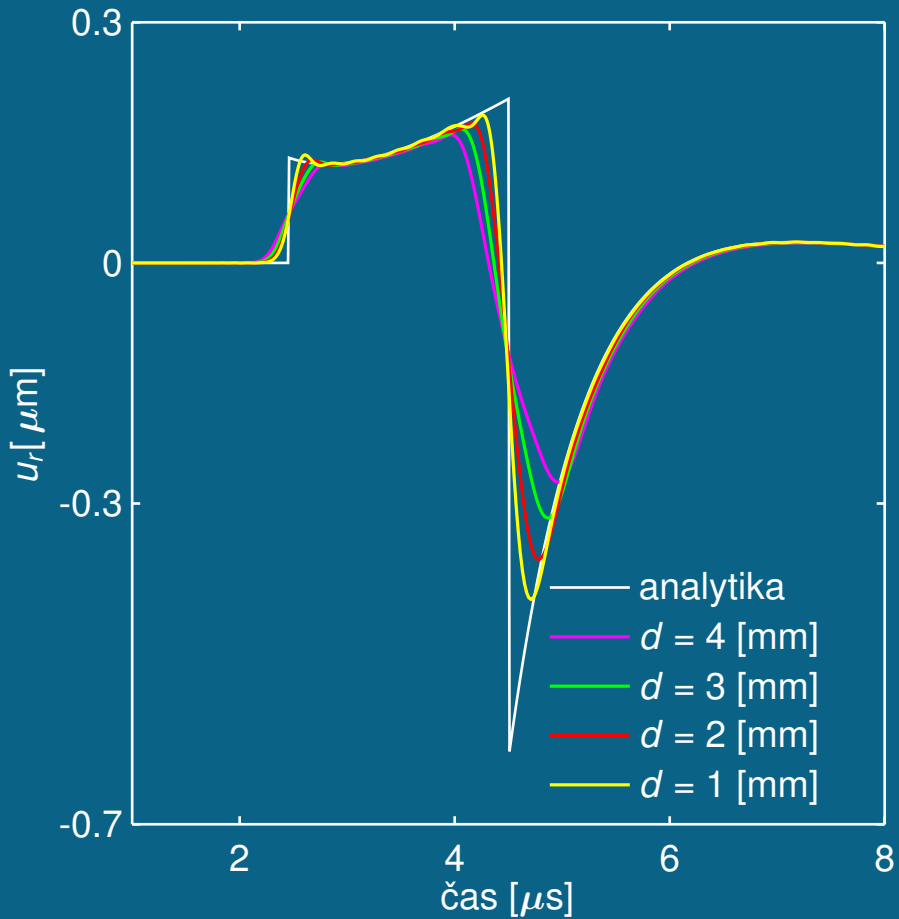
Dipól – vliv délky ramene – u_z v bodě P



Dipól – vliv délky ramene – u_z v bodě P

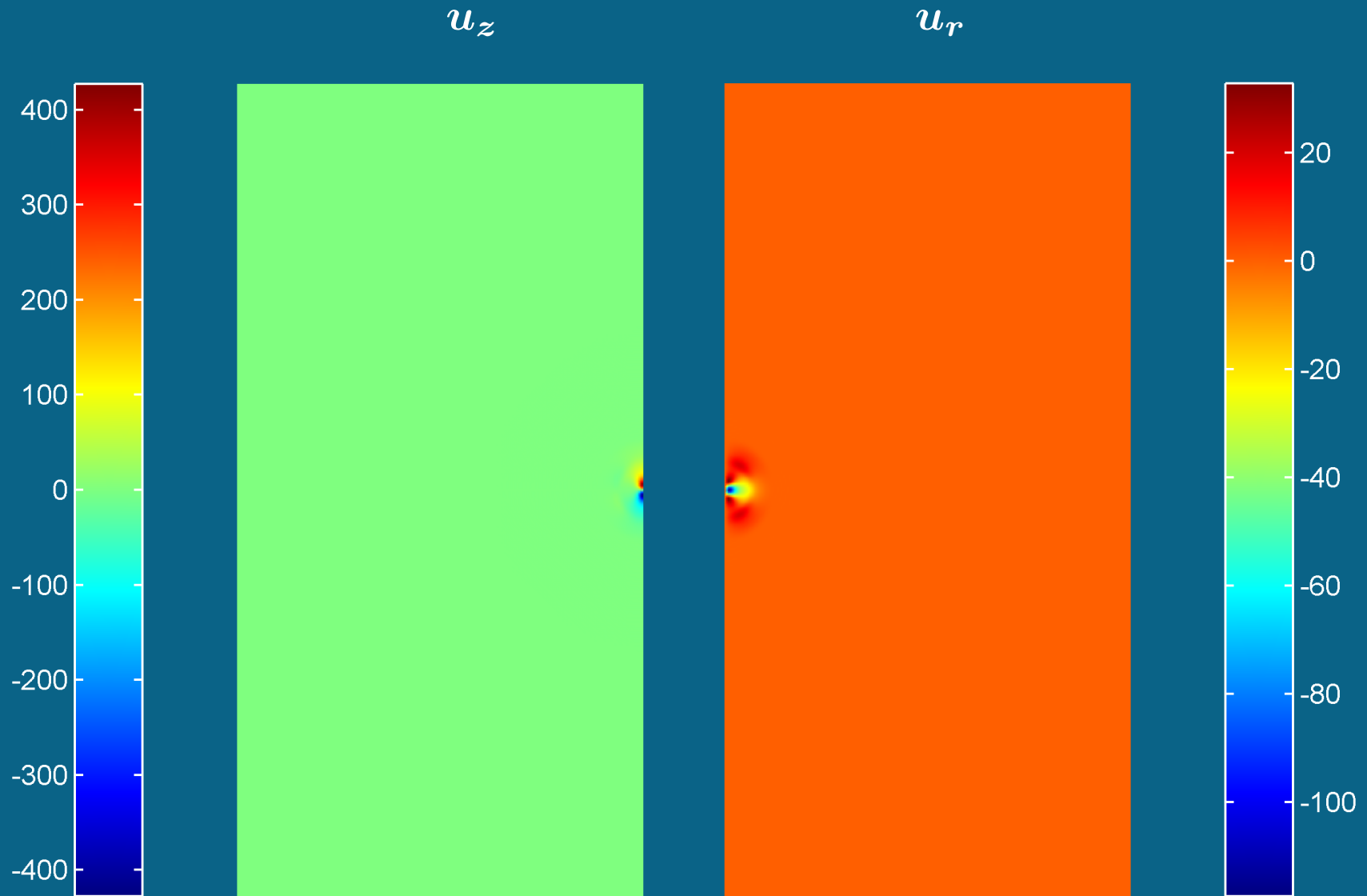


Dipól – vliv délky ramene – v bodě P

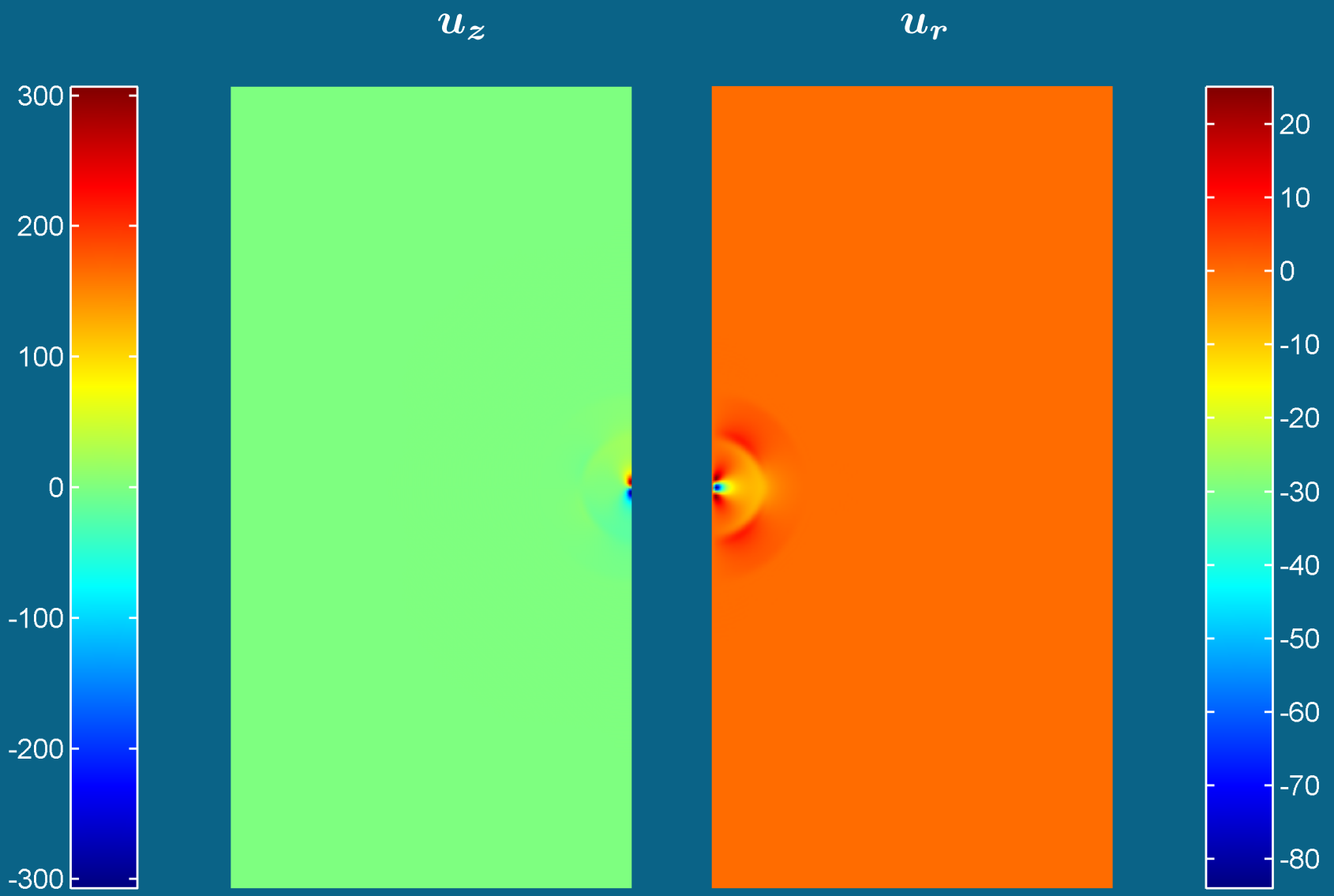


- výchylka vypočtená MKP je vždy dělená délkou ramene

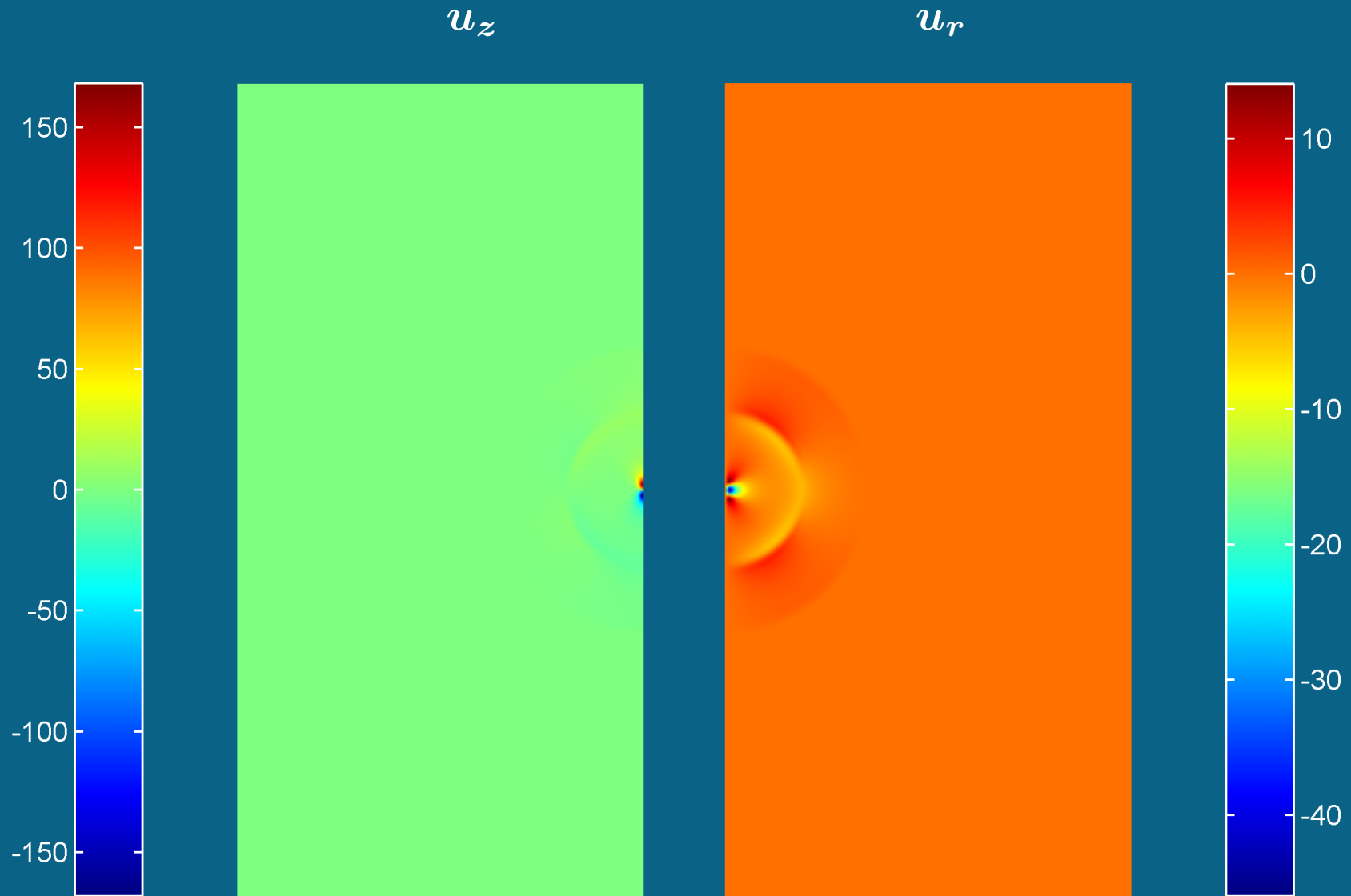
Rameno 1 mm – čas 1 μ s



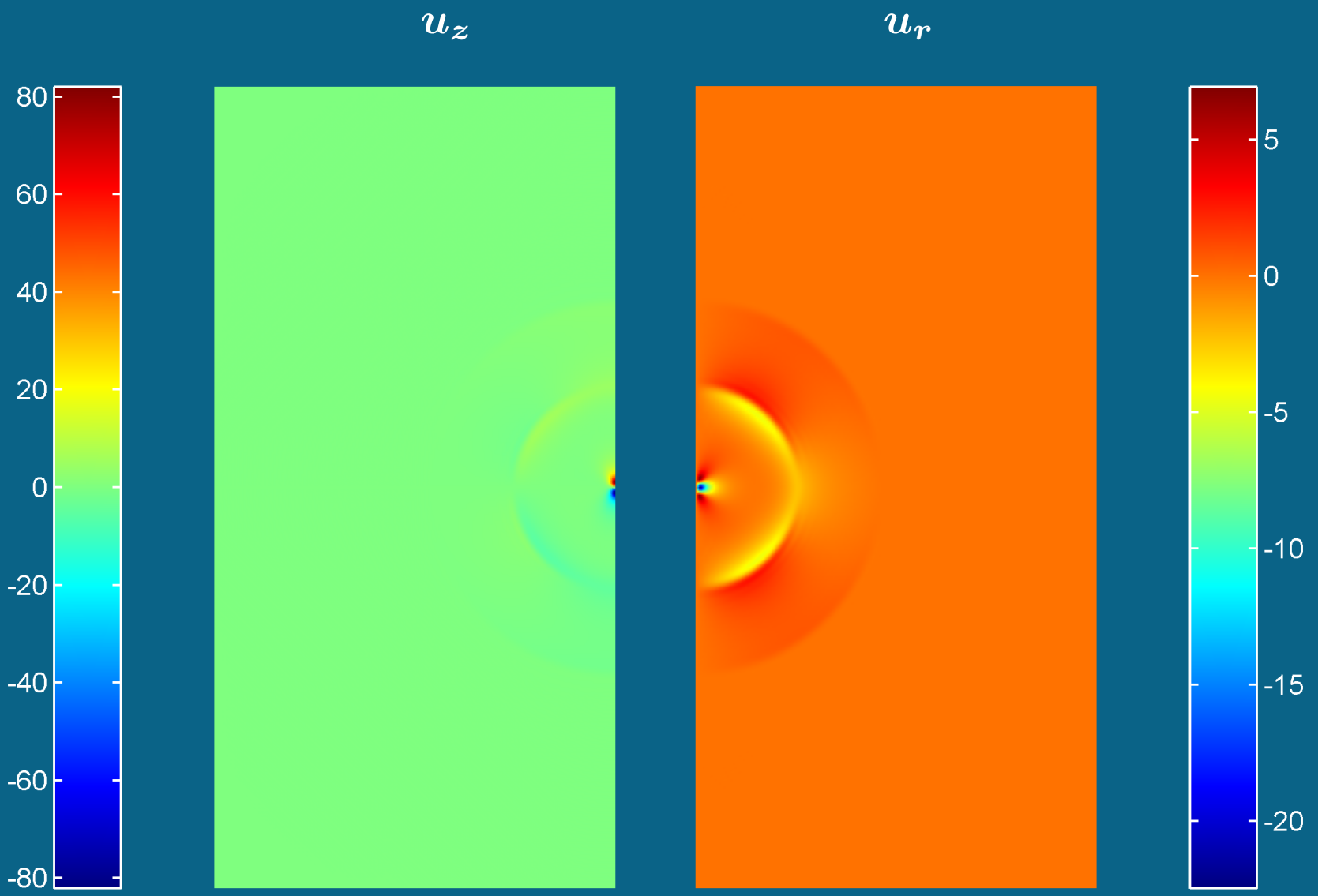
Rameno 1 mm – čas 2 μ s



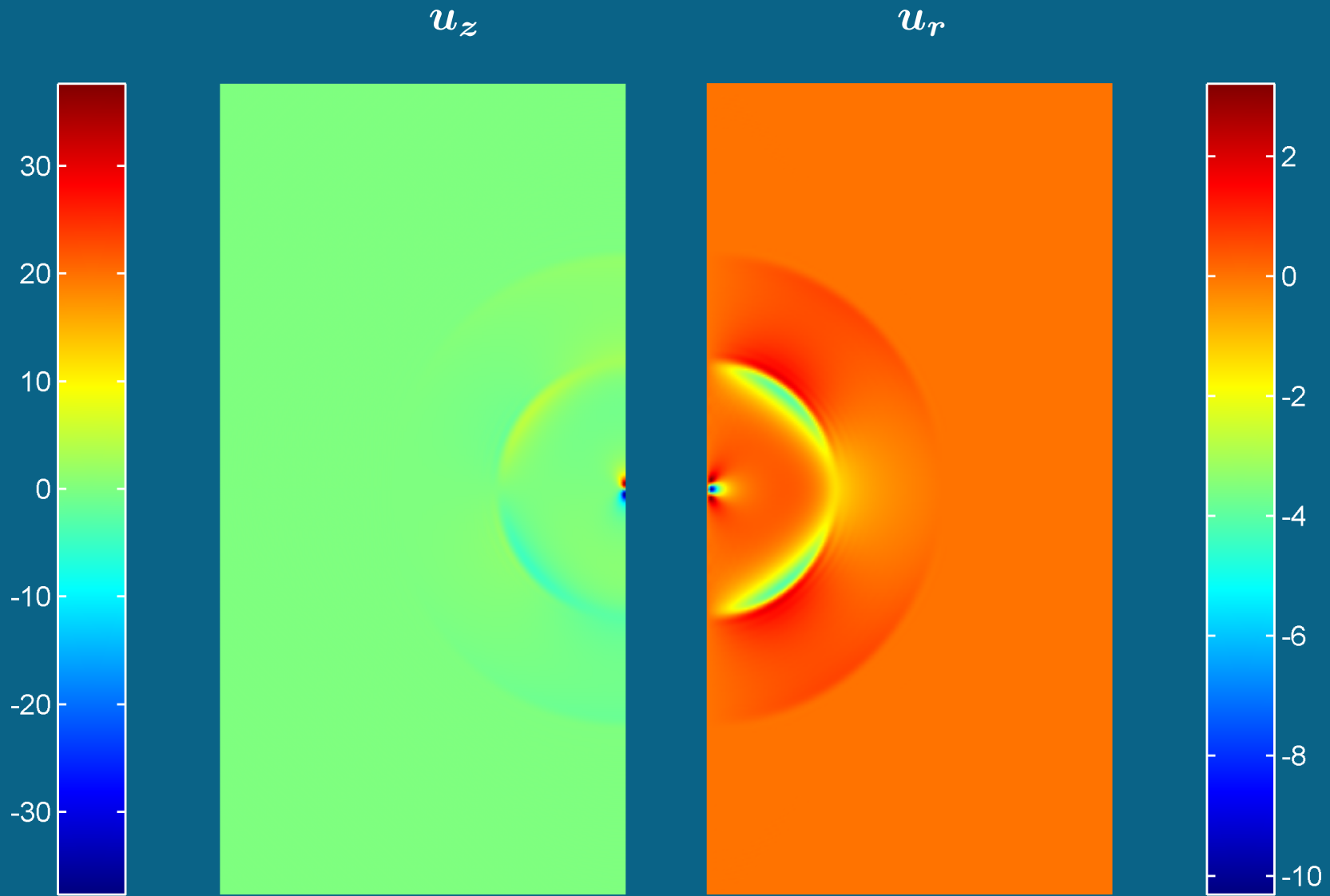
Rameno 1 mm – čas 3 μ s



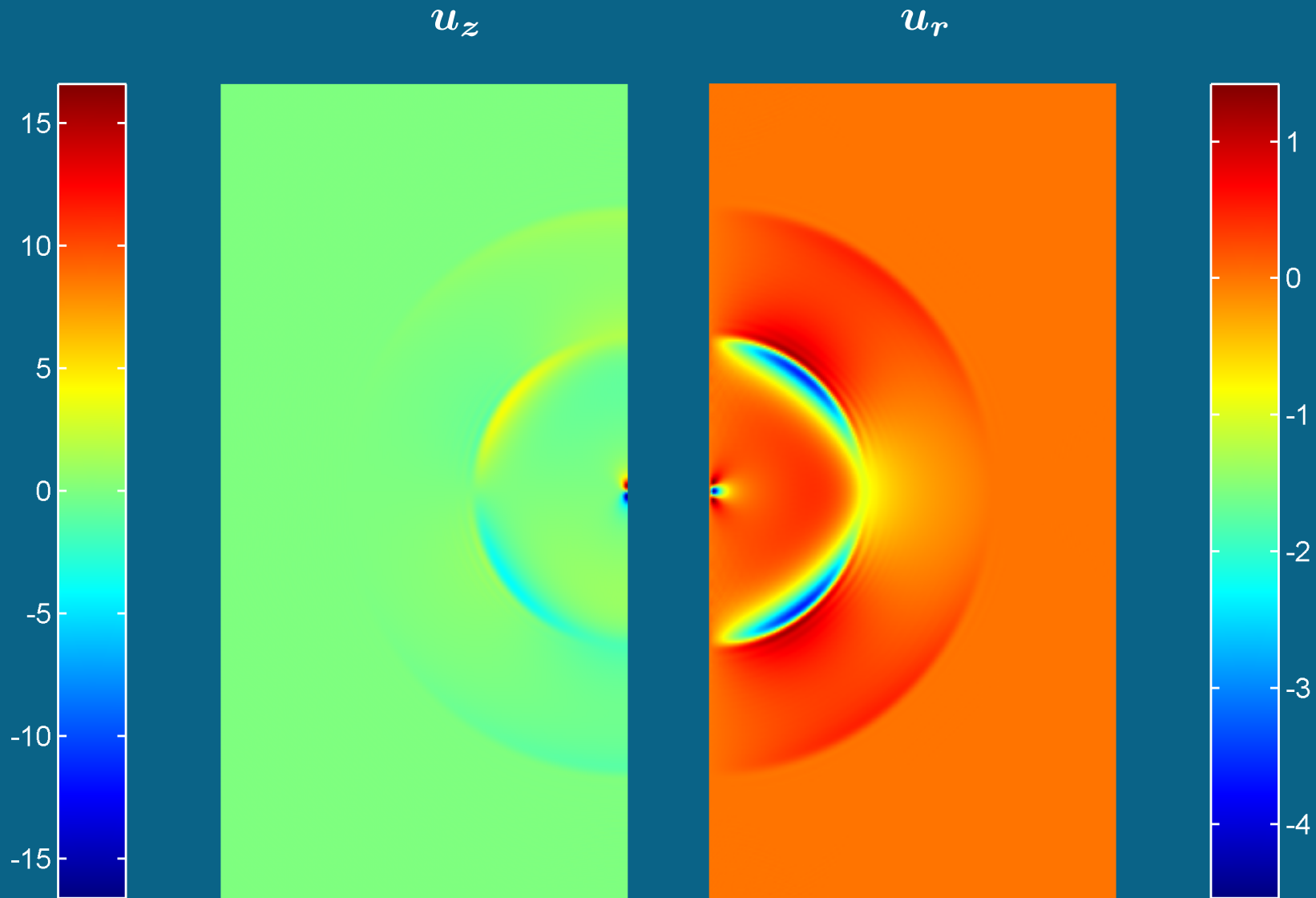
Rameno 1 mm – čas 4 μ s



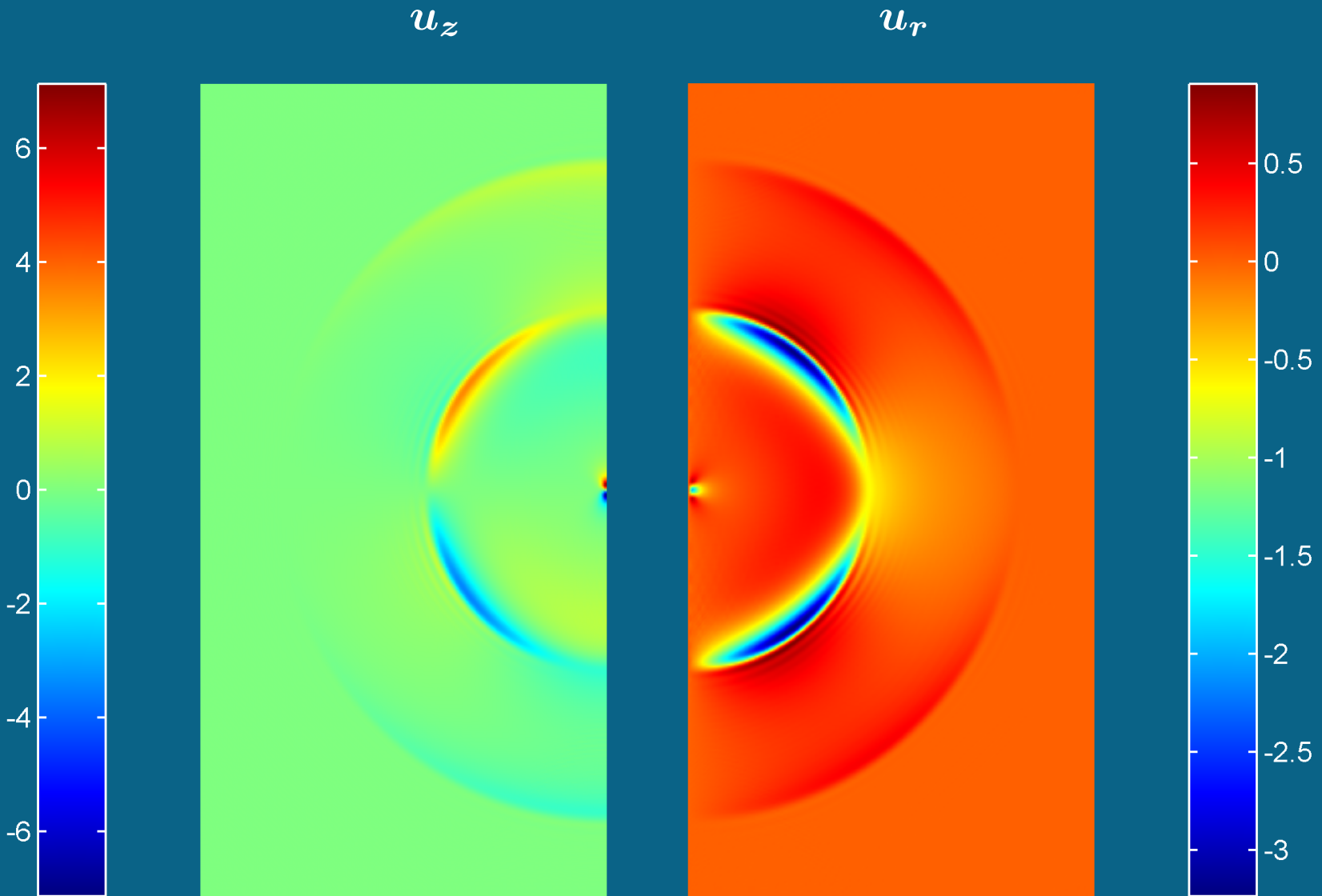
Rameno 1 mm – čas $5 \mu s$



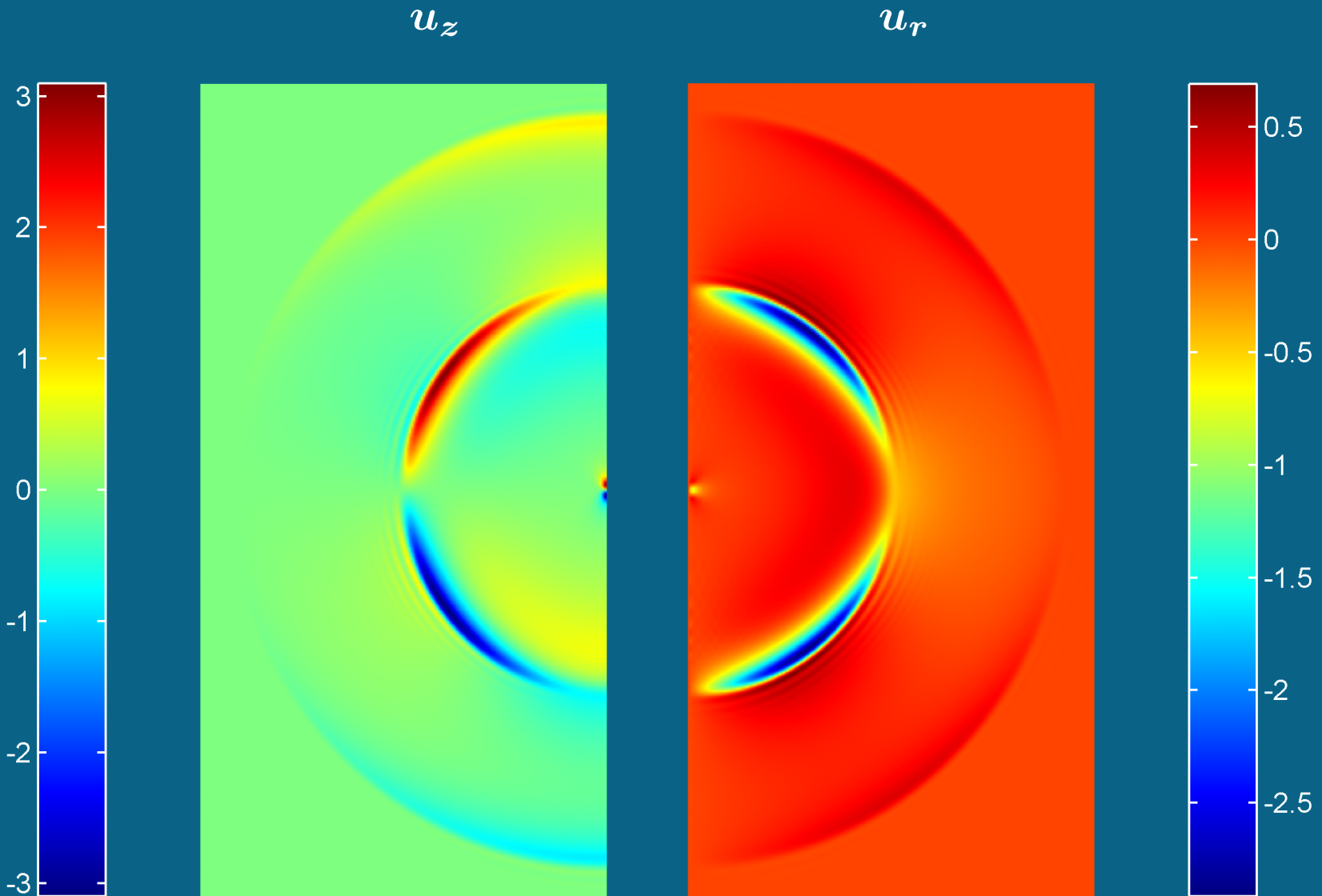
Rameno 1 mm – čas 6 μs



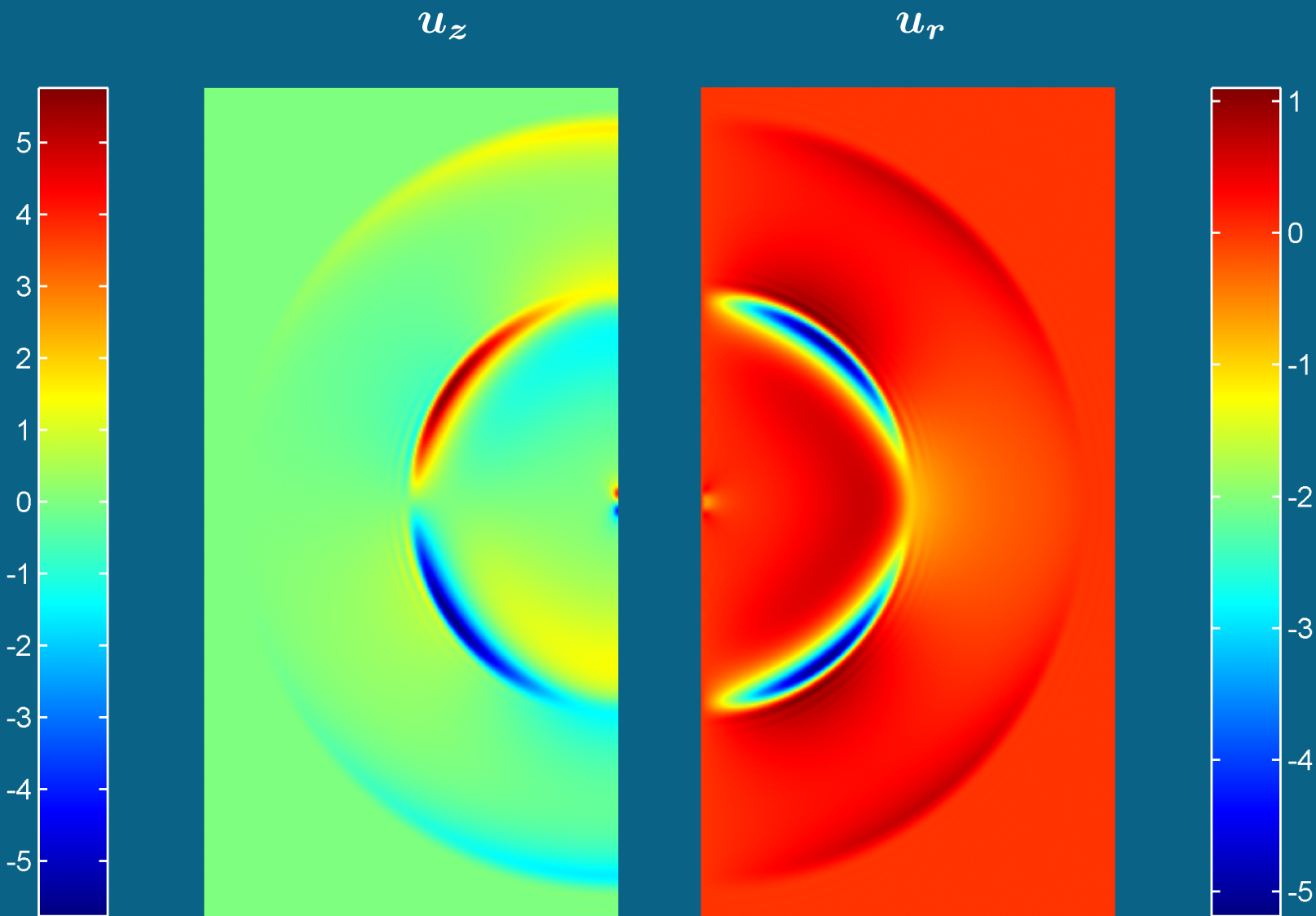
Rameno 1 mm – čas $7 \mu s$



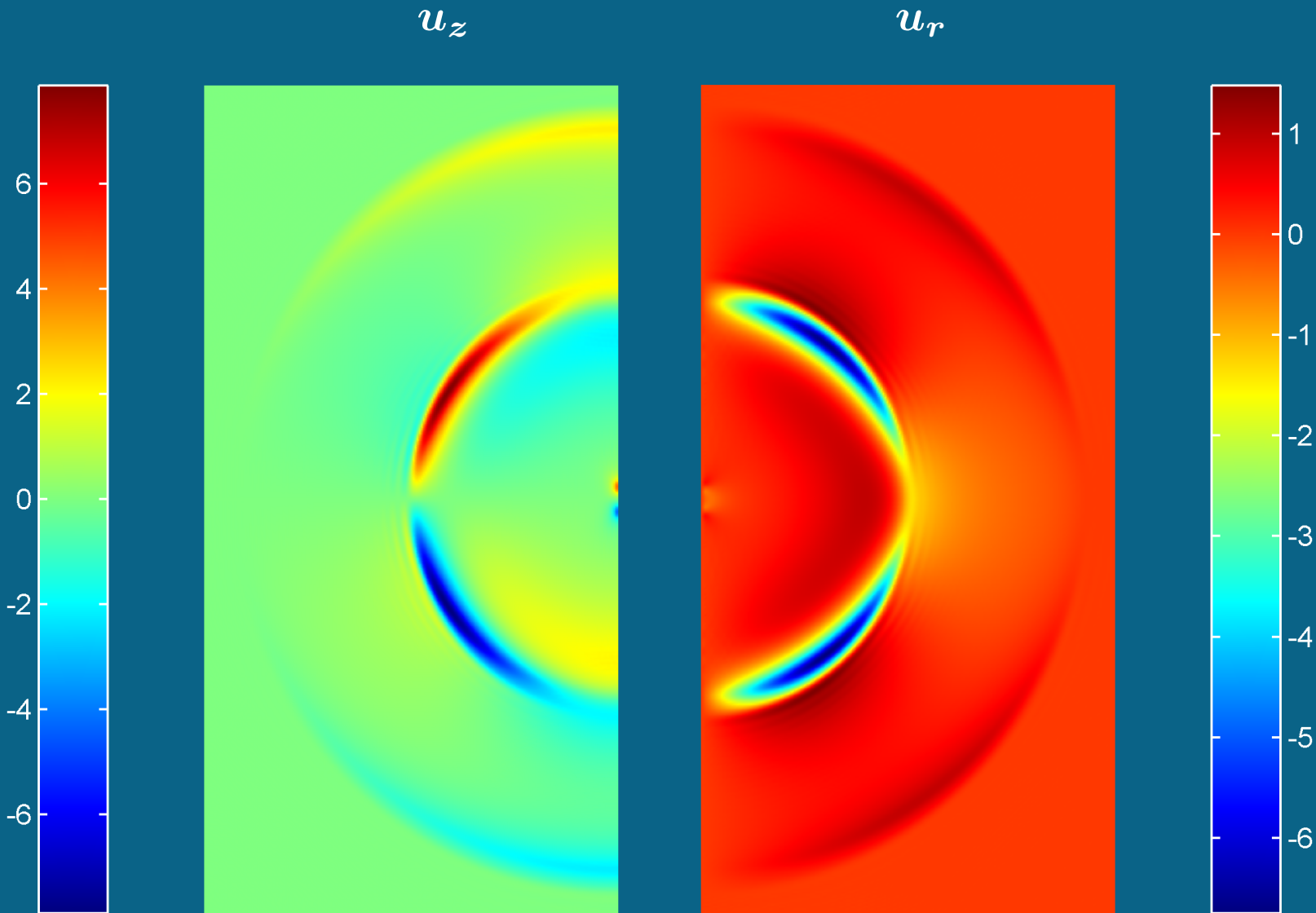
Rameno 1 mm – čas 8 μ s



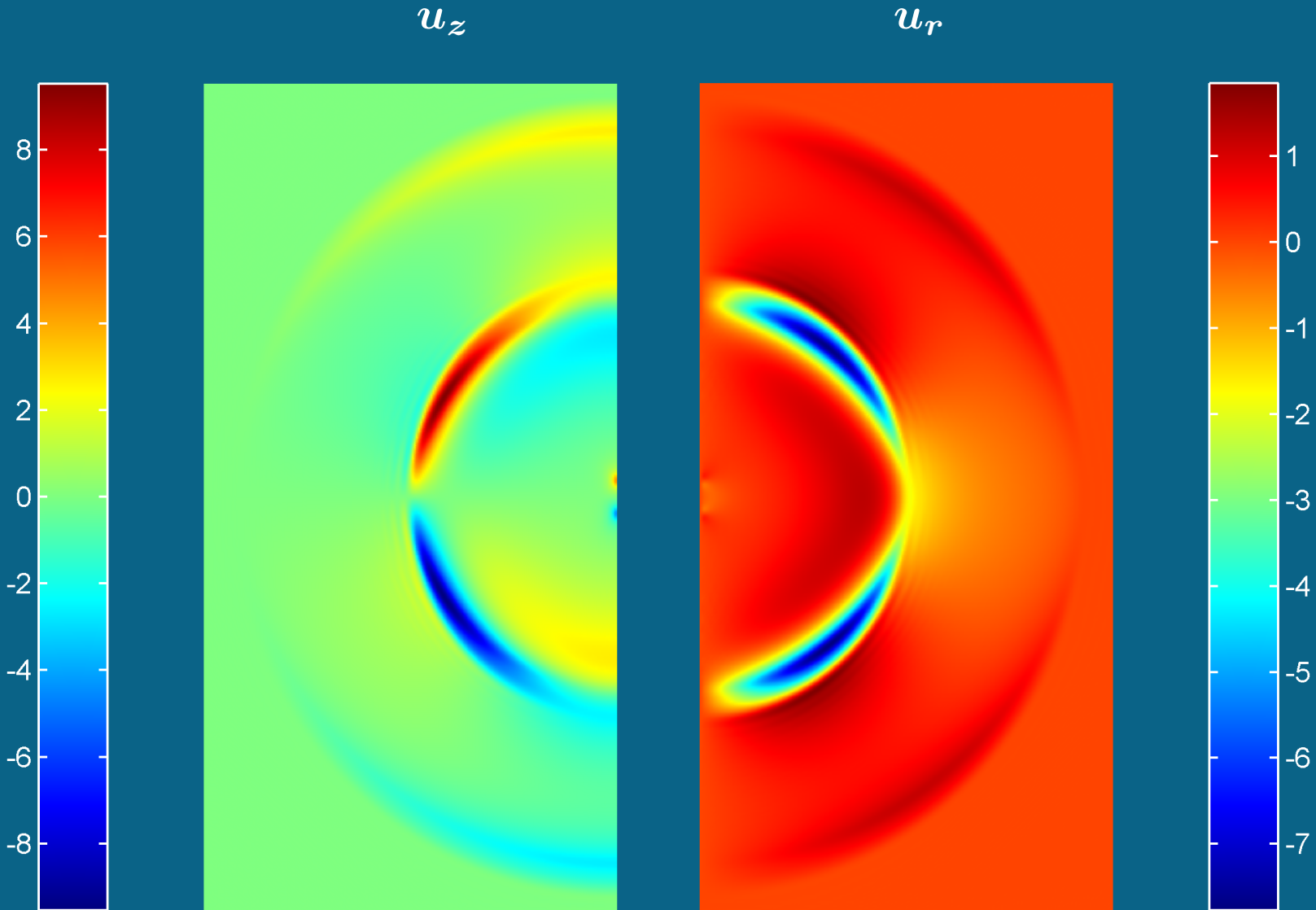
Rameno 2 mm – čas 8 μ s



Rameno 3 mm – čas 8 μ s

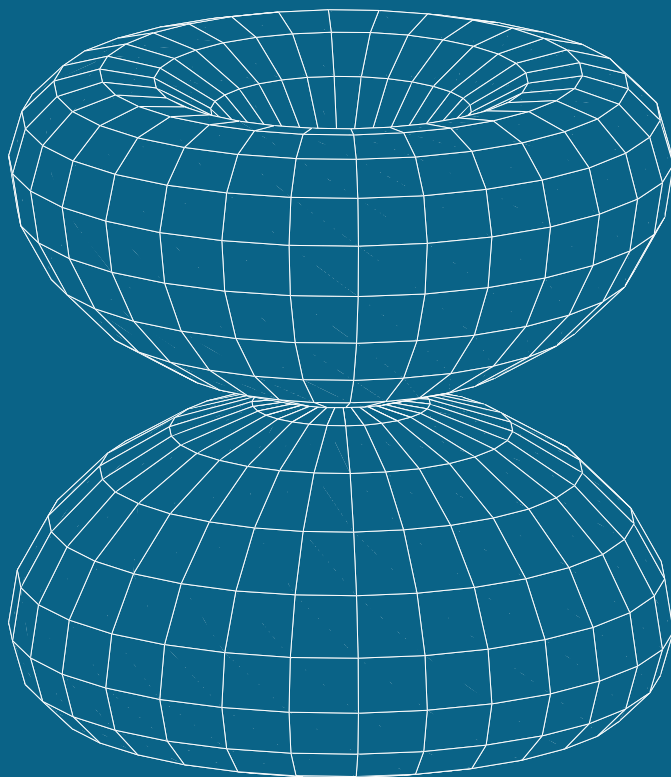


Rameno 4 mm – čas 8 μ s

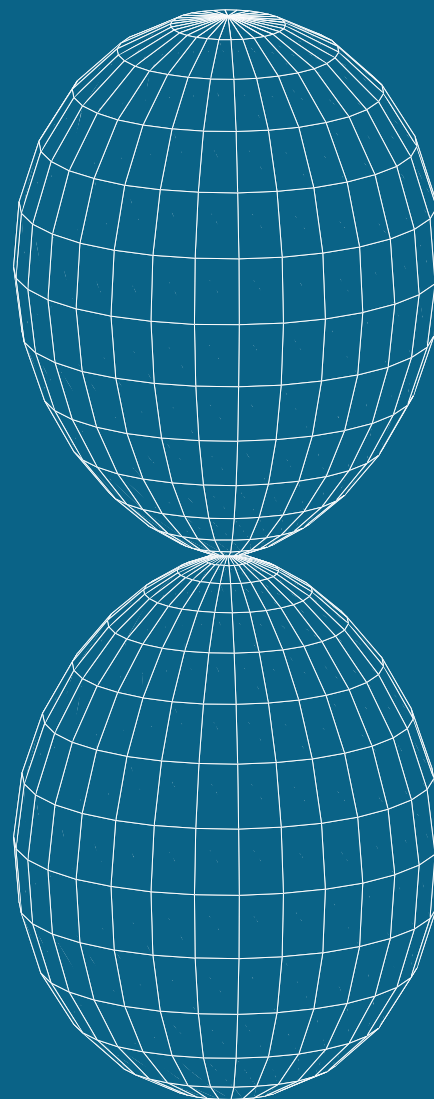


Vyzařovací charakteristiky ve vzdáleném poli

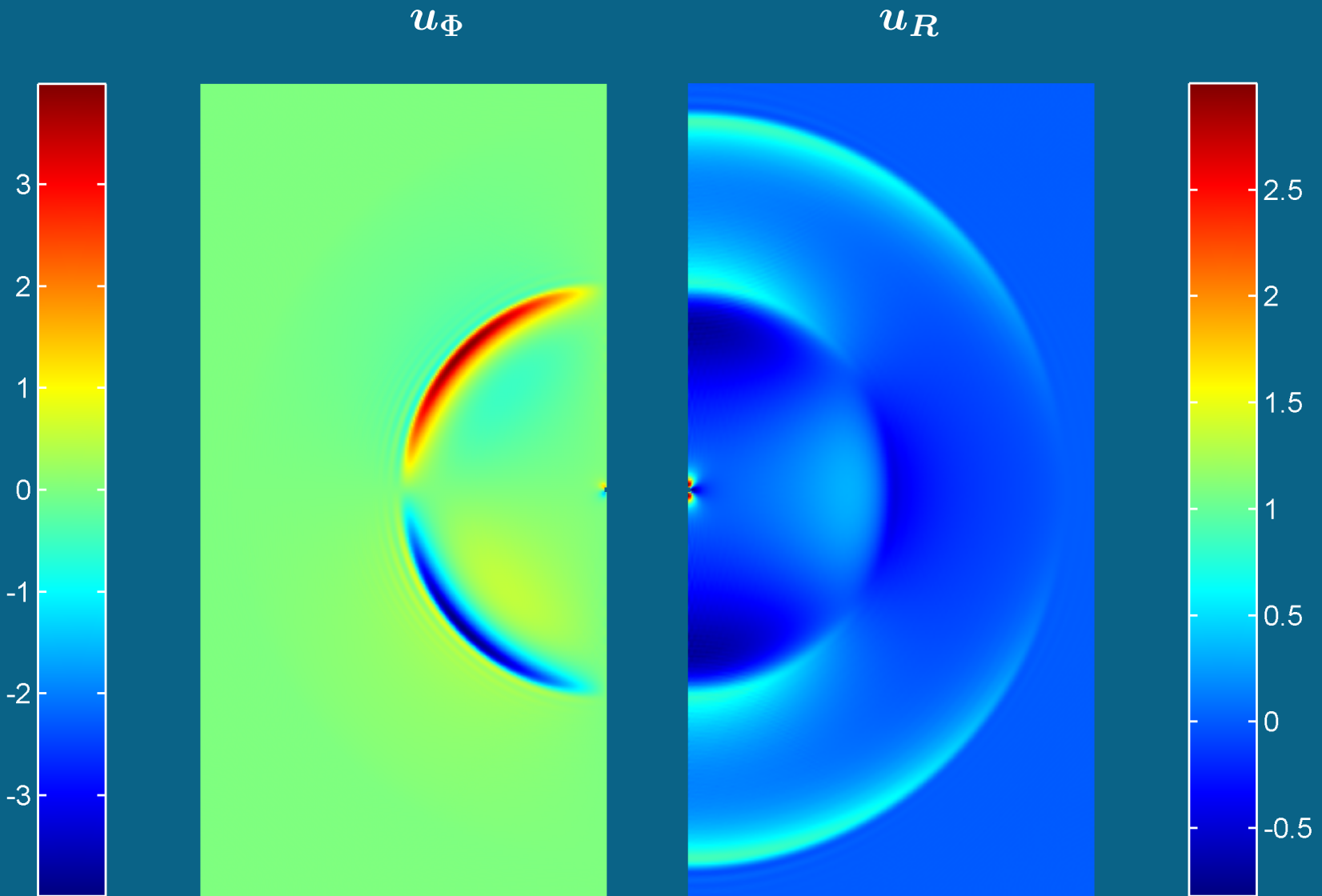
$$\mathbf{S}(\approx \sin \theta \cos \theta)$$



$$\mathbf{P}(\approx \cos^2 \theta)$$



Rameno 1 mm – čas 8 μs



Závěr

- modelování zdrojů akustické emise pomocí Comsolu Multiphysics
- zdroje akustické emise
 - koncentrovaná síla
 - dvojice koncentrovaných sil
- 4 průběhy zdrojové síly
- ocelový válec – neohraničené médium
- porovnání MKP modelu s analytickým řešením

- Pro koncentrovanou sílu bylo největší shody dosaženo buzením kruhovou ploškou.
- Pro dvojici koncentrovaných sil bylo největší shody dosaženo buzením válečkem.

OBSAH

Geometrie

Koncentrovaná síla

Koncentrovaná dvojitá síla

Funkce zdrojové síly

Analýza metodou konečných prvků

MKP – modely koncentrované síly

Bodová síla – porovnání modelů MKP – čas $6 \mu s$

Vliv tvaru zdrojové funkce – v čase $6 \mu s$

Vliv tvaru zdrojové funkce – v bodě P

Animace

MKP – modely dipólu

Dipól – porovnání modelů MKP – čas $6 \mu s$

Dipól – vliv délky ramene – v čase $6 \mu s$

Dipól – vliv délky ramene – v bodě P

Animace