P. Vrba, K. Koláček
IPP AS CR

M. Vrbová
CTU FNSPE CR

N. Bobrová, P. Sasorov
ITEP RU

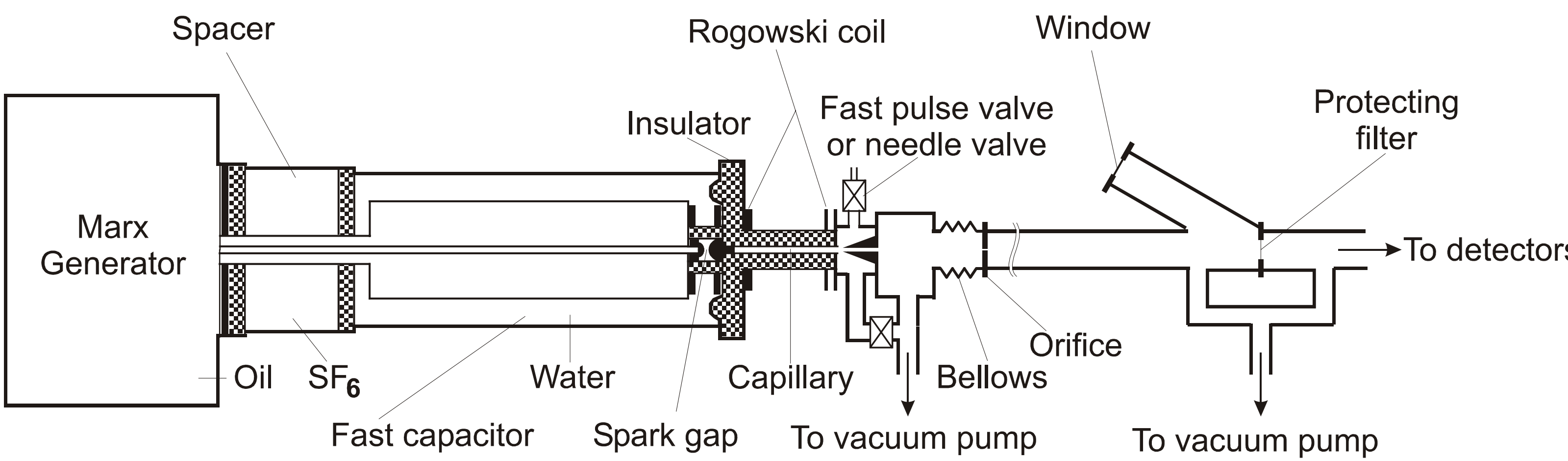
Z-pinch in Argon Filled Capillary

Comparison of Computer and Experimental Results

- MHD simulations
- Soft x-ray emission evaluation
- Dependence of SXR on pressure

CAPEX – IPP AS CR

Experimental setup



Introduction

X - ray laser pumping, based on the Z - pinch capillary discharge, is determined by time dependence of plasma electron density and temperature.

- Choice of capillary radius
- Wall material
- Gas filling pressure
- Parameters of electric circuit

Theoretical analysis of the Z-pinch evolution in argon filled capillary of CAPEX experiment and comparision of time dependencies calculated and measured of X-ray emission is presented.

MHD simulation, code NPINCH

We used one-dimensional, one-fluid and two-temperature MHD equations:

- **plasma motion,**
- **continuity eq.,**
- **Maxwell's eq.,**
- **energy conservation laws for electron and ion components**

$$\rho \frac{dv}{dt} = -\frac{\partial p}{\partial r} - \frac{1}{c} jB - \frac{\partial}{\partial r}\Pi_{rr} - \frac{1}{r}(\Pi_{rr} - \Pi_{\varphi\varphi}), \quad (1)$$

$$\frac{d\rho}{dt} = -\rho \frac{1}{r}\frac{\partial}{\partial r}(vr), \quad (2)$$

$$\frac{d}{dt}\frac{B}{\rho r} = \frac{c}{\rho r}\frac{\partial}{\partial r}E_z^*, \quad (3)$$

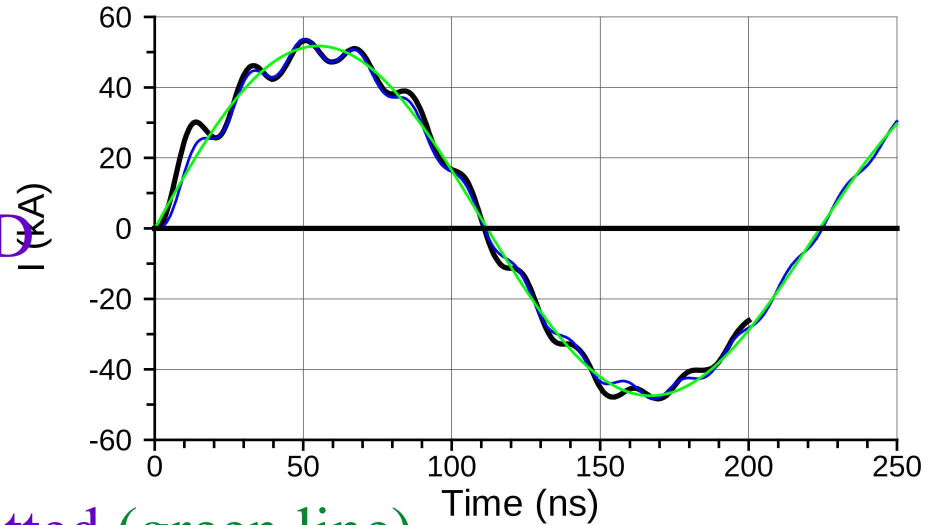
$$\rho \frac{d\varepsilon_e}{dt} + \frac{p_e}{r}\frac{\partial}{\partial r}(rv) = jE_z^* - \frac{1}{r}\frac{\partial}{\partial r}(rq_e) - Q_r + C_{ei}(T_i - T_e). \quad (4)$$

$$\rho \frac{d\varepsilon_i}{dt} + \frac{p_i}{r}\frac{\partial}{\partial r}(rv) = C_{ei}(T_e - T_i) - \Pi_{rr}\frac{\partial v}{\partial r} - \frac{v}{r}\Pi_{\varphi\varphi}. \quad (5)$$

The dissipative processes, ablation and ionisation of the wall material are taken into account. For the equation of state and the degree of ionisation, the approximation of LTE of the electron and ion components is used. The initial state of the wall material is represented as a cold neutral gas of high density.

Measured and fitted discharge current

Measured discharge current ***I(t)*** (black line) is introduced into MHD Eqs. as a driving term.



a) Dumped sinus curve fitted (green line)

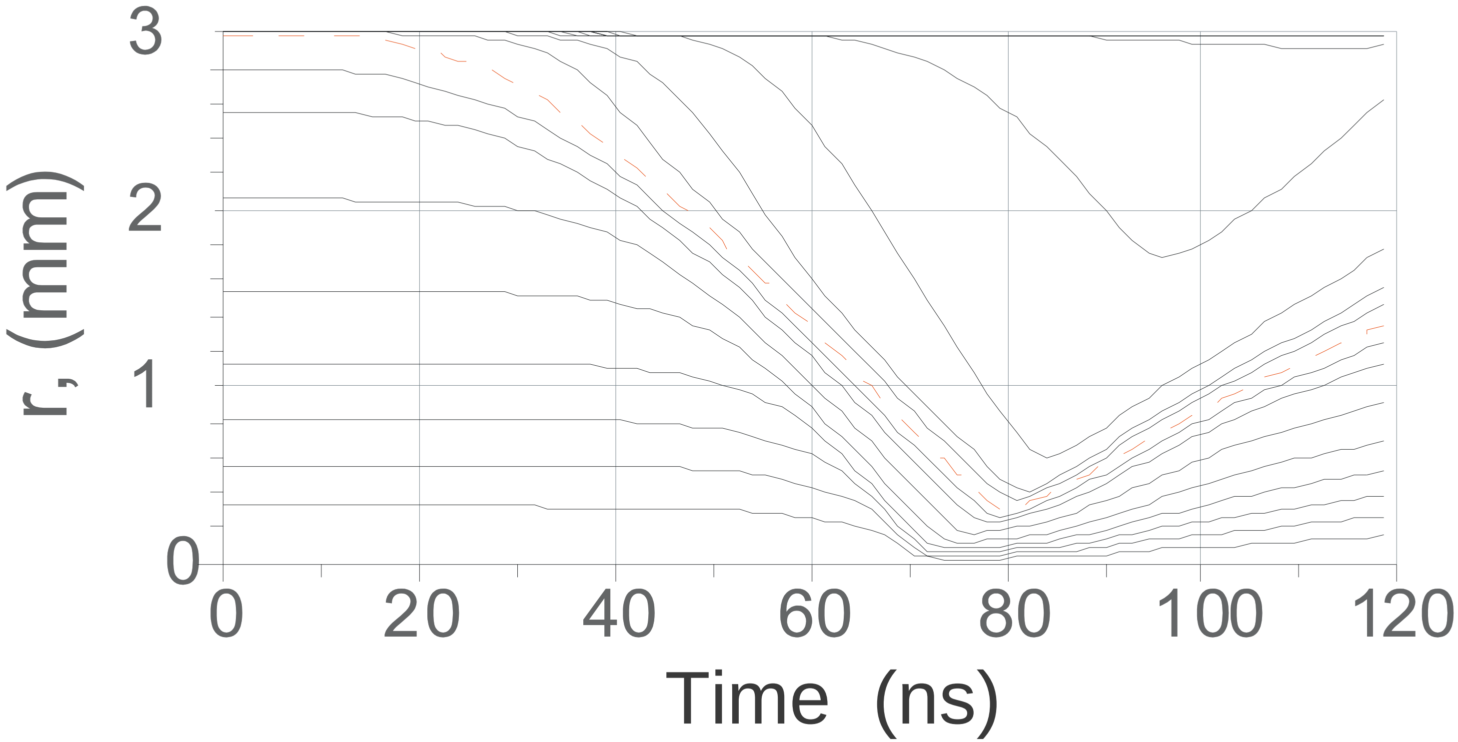
$$I(t) = I_1 \sin \frac{\pi}{2} \frac{t}{t_1} \exp\left(-\frac{t}{t_2}\right)$$

b) Two dumped sinus curves fitted (blue line)

$$I(t) = I_1 \sin \frac{\pi t}{2t_1} \exp\left(-\frac{t}{t_2}\right) + I_2 \frac{t_3}{t_1} \sin \frac{\pi t}{2t_3} \exp\left(-\frac{t}{t_4}\right)$$

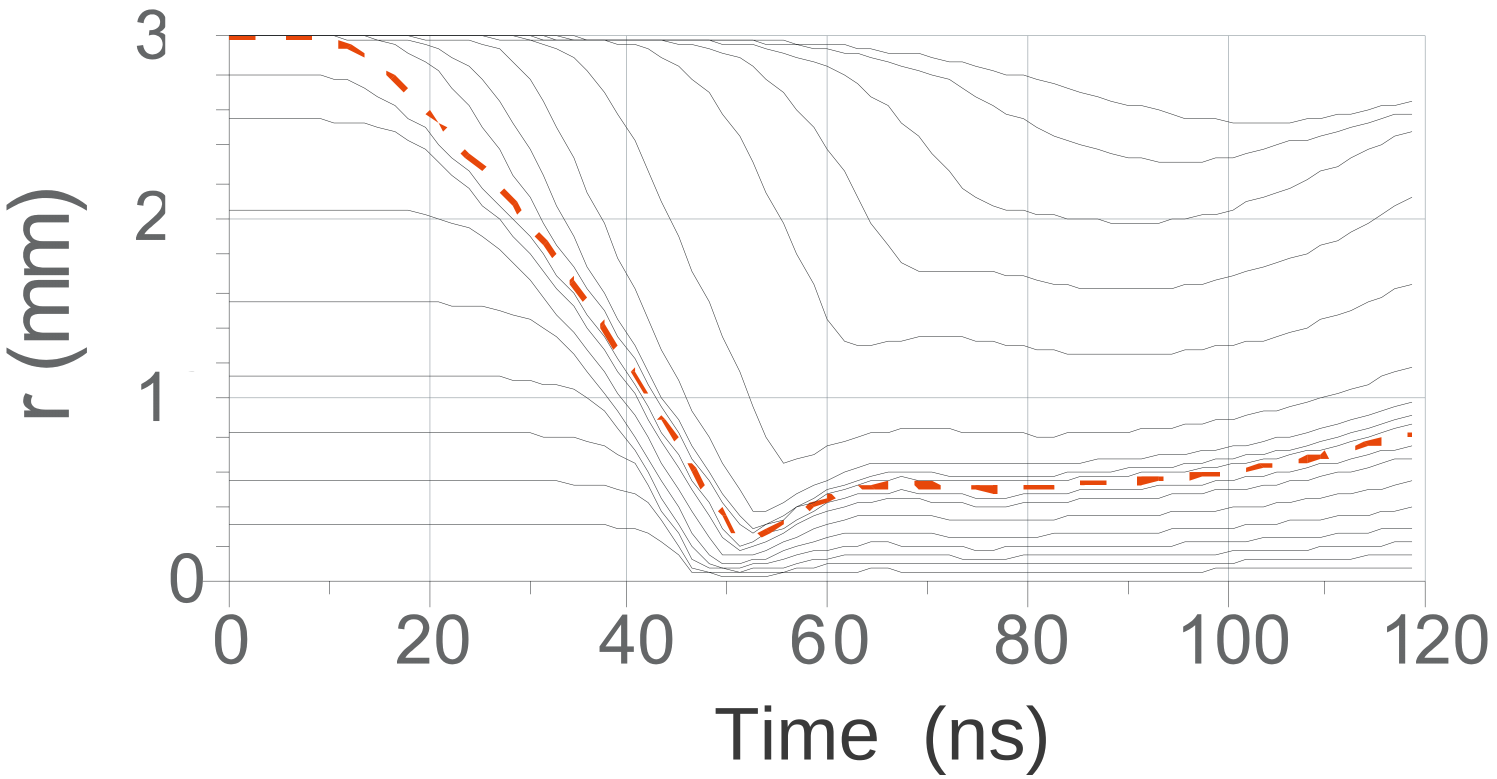
$t_1 = 56$ ns, $t_2 = 1.3$ μs, $t_3 = 4.55$ ns, $t_4 = 100$ n

Motion of Plasma Elements



a) $I_1 = -I_2 =$ **22.2 kA** , $r =$ **3 mm**, $p =$ **17,3 Pa**, **Argon**

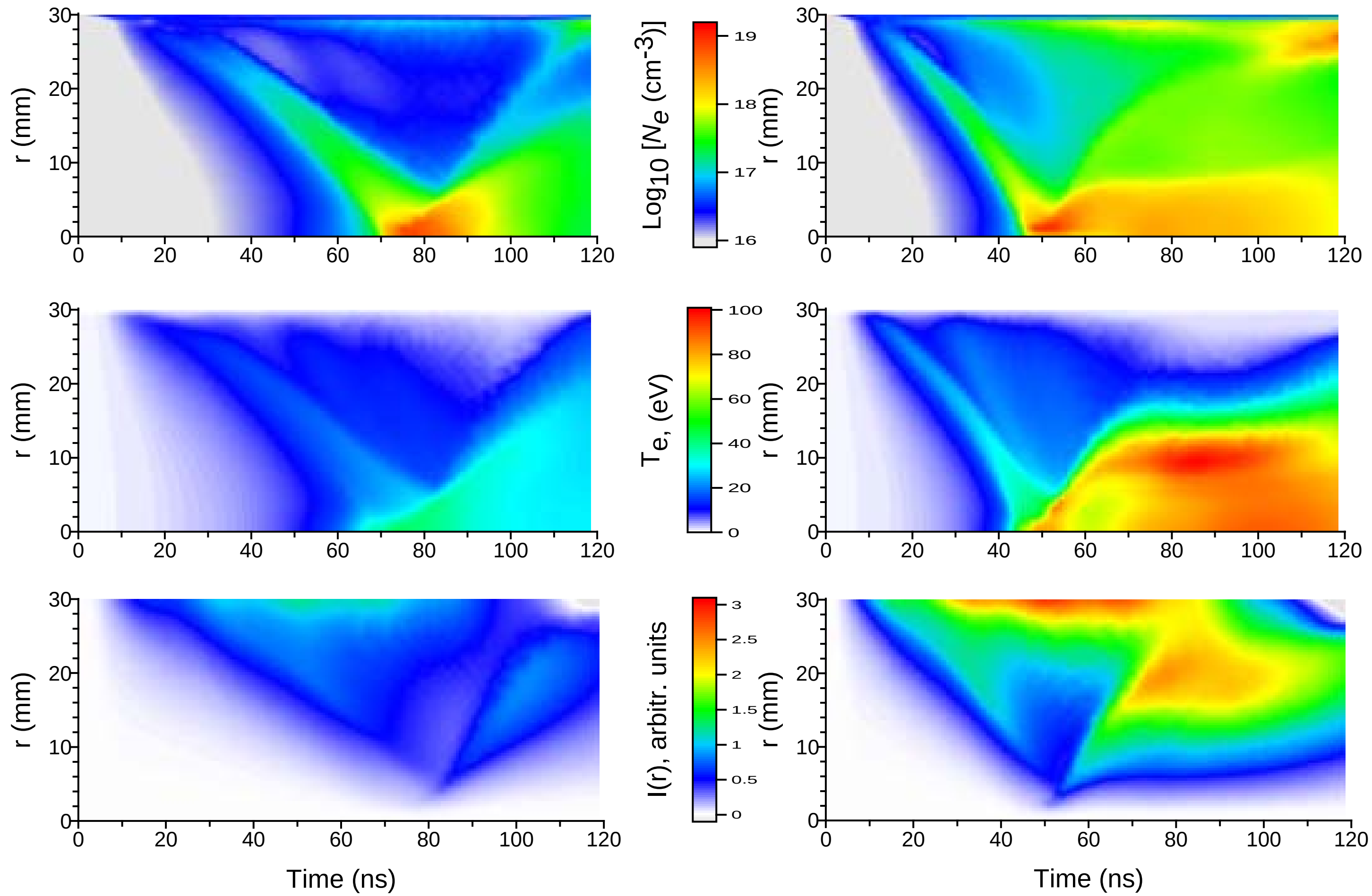
Motion of Plasma Elements



b) $I_1 = -I_2 =$ **53 kA ,** r = **3 mm**, p = **17,3 Pa**, Argon

Space–time dependencies of N_e, T_e and I

a) I_{max} = 22.2 kA **b) I_{max} = 53 kA**



Evaluation of soft x-ray emission

Radiation losses Q_e (Zeldovich - Raizer formula):

$$Q_e = \frac{4\sigma T_e^4}{l_R}$$

σ - Stefan-Boltzmann constant

l_R - **Rosseland free path,** which takes into ccount free-free and bound-free transitions

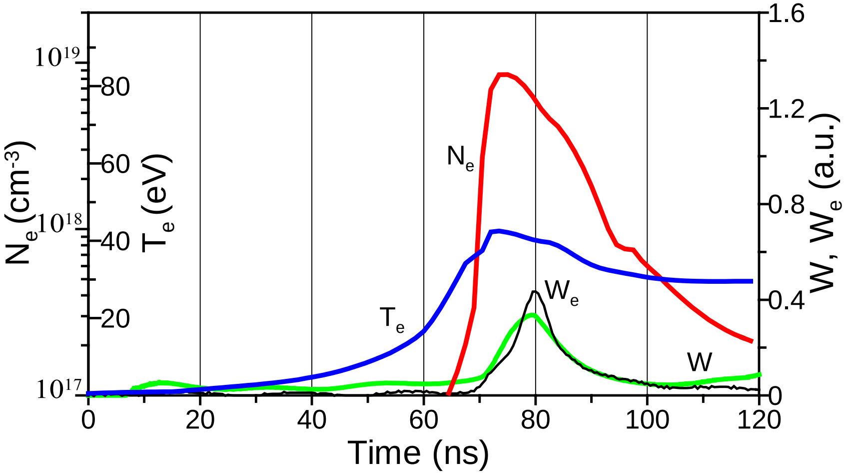
$$l_R = \pi^2 \sqrt{\frac{\pi}{2}} \frac{\eta c m_A}{e^6} \frac{A T_e^2}{\rho} \frac{1}{(j+1)^2} \exp - \frac{\chi_j}{T_e}$$

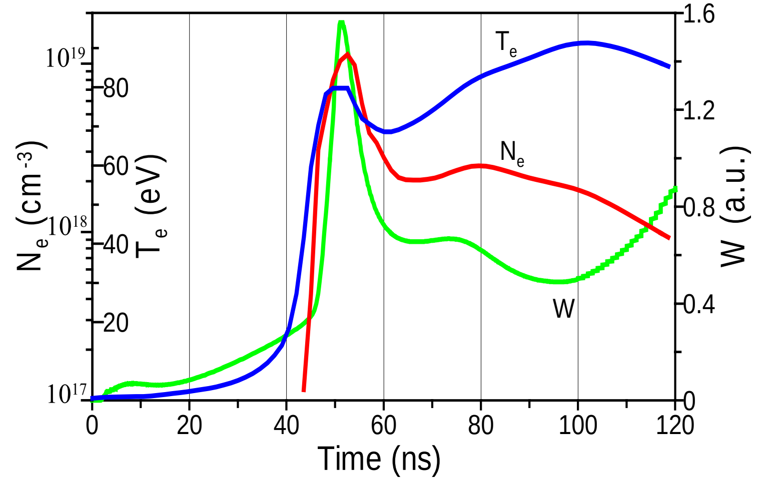
where ***j*** is charge number of the most abundant ions; m_A is the atomic mass; ***A*** is the mass number of atoms;

The **total power *W(t)* of the radiation losses** is obtained by integration of the value Q_e over the plasma volume.

Radiation emission evaluated and measured

- **Axial x-ray emission measured by PIN diode (17-70 nm)**
- **A good correspondence between evaluated emission (green line) and measured broadband SXR (black line)..**
- **Peak emission at the pinch time**

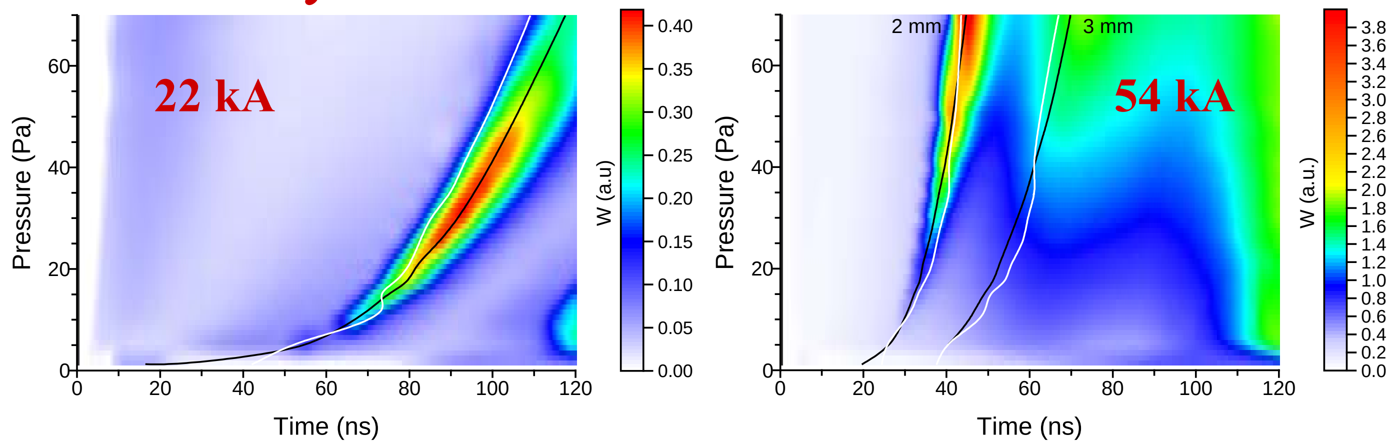




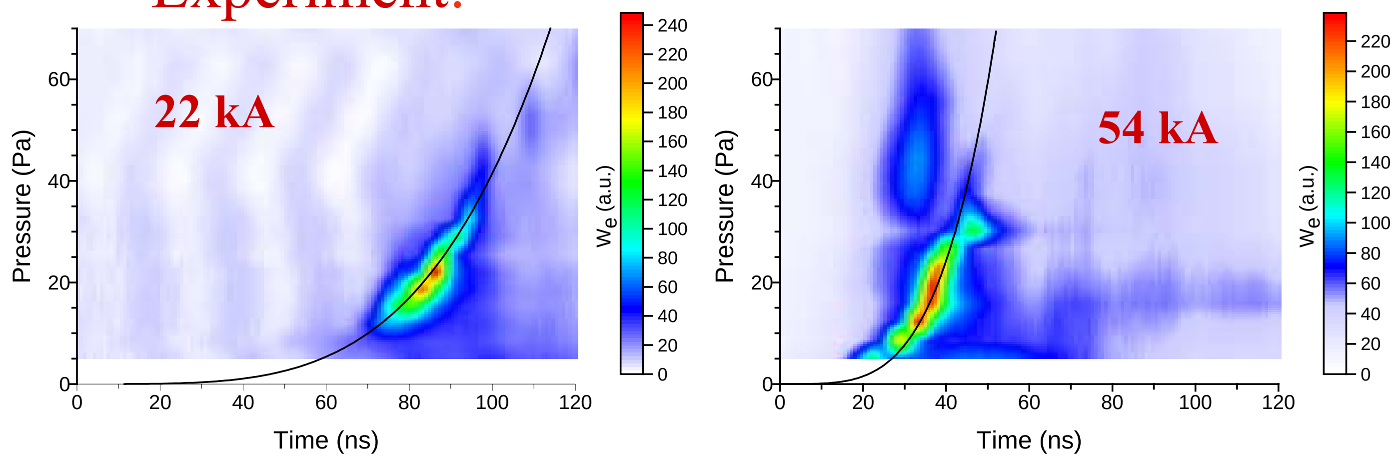
Electron temperature **T_e** and density **N_e** on the axis and intensities **W** and **W_e** of capillary emission simulated **(green lines)** and measured **(black line)**

Dependence of SXR on pressure

Theory:



Experiment:



Pressure dependence

- **Current waveform is insensitive to the pressure changes**
- **X-ray peak emission appears later for higher pressures**
- **MHD simulations and experiments give the same dependencies of the SXR peak time on the pressure**
- **SXR peak time is very near to the pinch time**
- **Scaling law of the characteristic time of Z-pinch evolution is**

$$t_{char} = const.aI_{\max}^{-\frac{1}{2}} p^{\frac{1}{4}}$$

- **Pinch time is proportional to t_{char}**
- **The curves $p = At^4$ were used to interpolate the position of the peak emissions in the p-t experimental diagrams; values $A_c = 4.15 .10^{-7}$ and $A_d = 1.01 .10^{-5}$ were found.**

Conclusions

- The comparison of spectrally integrated radiation emission measured and calculated for various experimental conditions of CAPEX device proves the validity of our extended MHD computer code.
- Scaling law for pinch characteristic time is confirmed.
- The observed and computed peaks of SXR indicate the plasma compression and heating during the pinch, but generally they do not prove the laser action.

Acknowledgements

This work was supported

- by the grant LN00A100 of the Ministry of Education Youth and Sports of the Czech Republic for the Laser Plasma Research Centre and
- by the contract INGO LA055 MEYS CR.

References

[1] P. Vrba K. Koláček, M. Vrbová, J. Schmidt, V. Boháček:
Evolution of Z-pinch in argon filled capillary,
Czech. J. Phys., **50** (2000), 1043 – 1049

[2] N.A. Bobrova, S.V. Bulanov, T.L. Razinkova, P.V. Sasorov:
Dynamics of a Pinch Discharge in Capillaries,
Plasma Physics Reports, **22** (1996), 387-402

[3] P. Vrba, M. Vrbová:
Z-Pinch Evolution in Capillary Discharge,
Contrib. Plasma Phys. **40** (2000), 5-6, 581-595