Argon filled capillary discharge for EUV laser pumping

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- MHD Simulations
- Kinetic description
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- Conclusion

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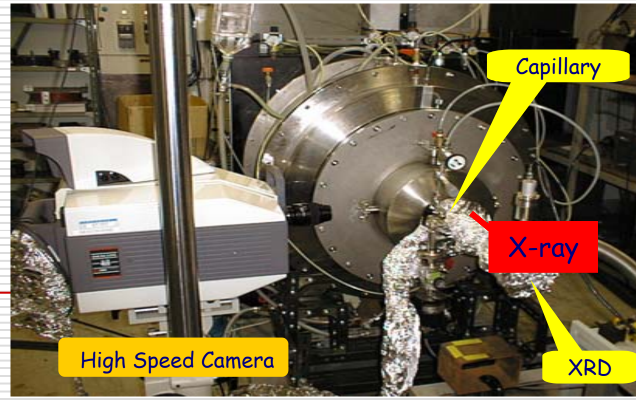
Introduction

- **Capillary discharge** may efficiently pump soft X-ray argon laser emitting radiation with wavelength 46.9 nm.
- To get efficient lasing **a high population of the upper laser level transition** is needed, (strongest line corresponds to the Ar^{8+} **3s $^1P_1$ – 3p $^1S_0$** transition).
- The discharge plasma should have in the same time a **high neon-like argon ion density**, or **proper ionization state**, and **proper plasma electron temperature**. On the other hand, the electron density must be low enough to prevent **collisional mixing** between the laser energy levels.
- Details of the pinch evolution in non-ablating capillaries depend on **four optional discharge system parameters {d_0, p_0, $T_{1/4}$, I_{max}}** and cannot be easily forecasted. Computer model of the pinch plasma, based on **magneto-hydrodynamic** (MHD) simulations and **ion kinetics** evaluations by means of a post-processor, has been developed. Its validity is checked by comparison of calculated and measured laser characteristics.

Experimental data



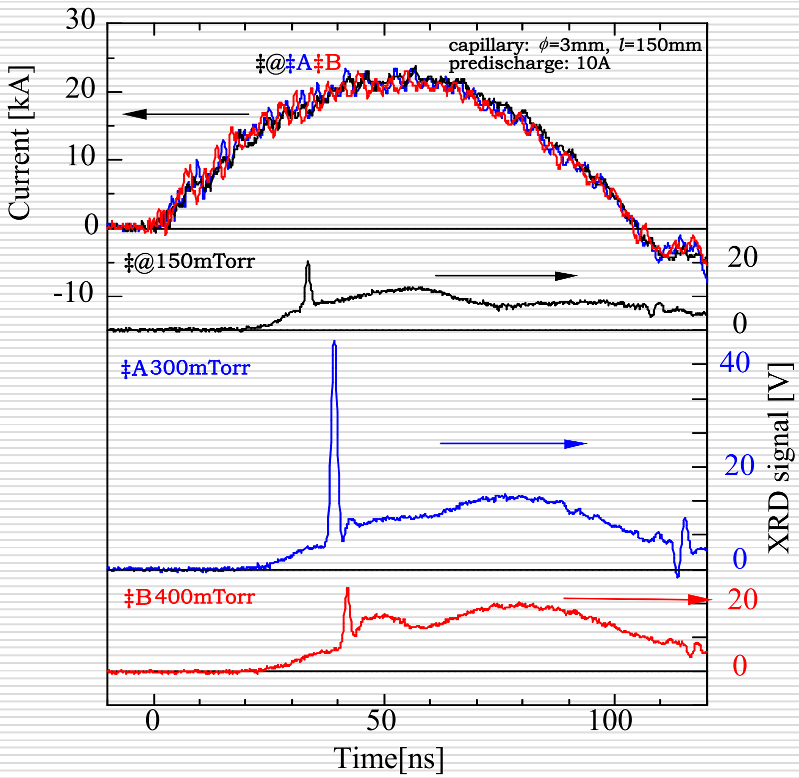


Fig. 1 : (a) Electric current, **(b)**, **(c)** and **(d)** X - ray signals for various argon pressures

Experiments done in **the laboratories of the Tokyo Institute of Technology** are judged in details. Non-ablating aluminum **3 mm diameter** capillary filled by argon was used.

Discharge current of **sinusoidal pulse shape with quarter period $T_{1/4}$ = 52 ns** was achieved with the experimental setup.

Initial filling pressure was varied in the range of **150-400 mTorr**. The varying delay of x-ray spikes illustrates the dependence of pinching time on the initial pressure.

Experimental data

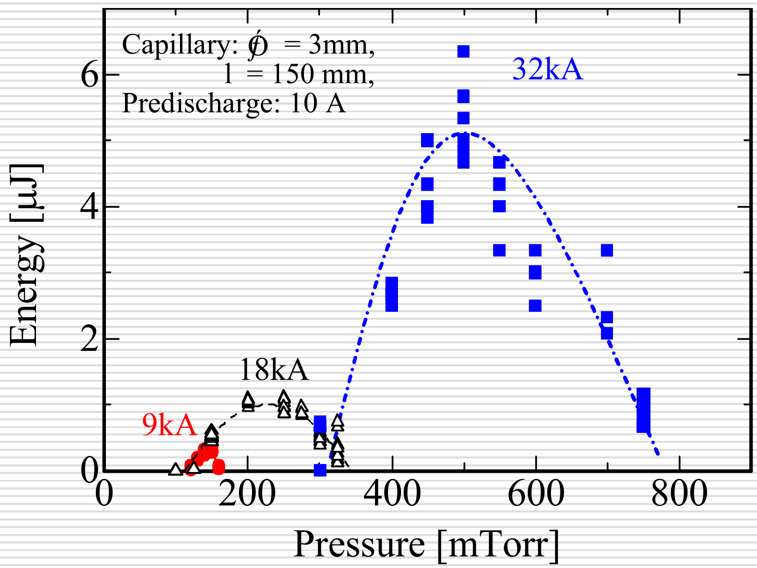
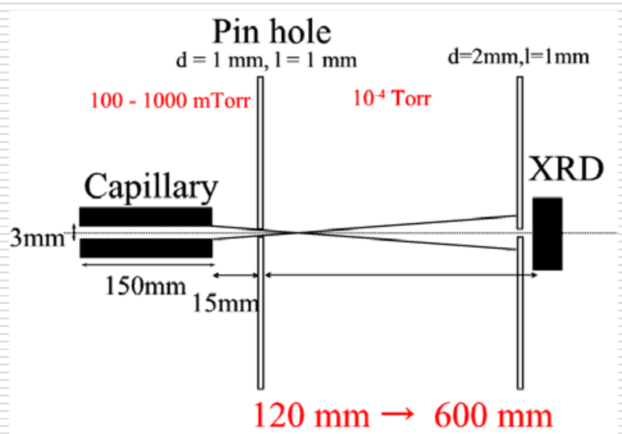


Fig. 2 : Pressure dependence of the output X - ray energy for various peak currents

The optimum value of pressure increases with increasing current amplitude.



Experimental data

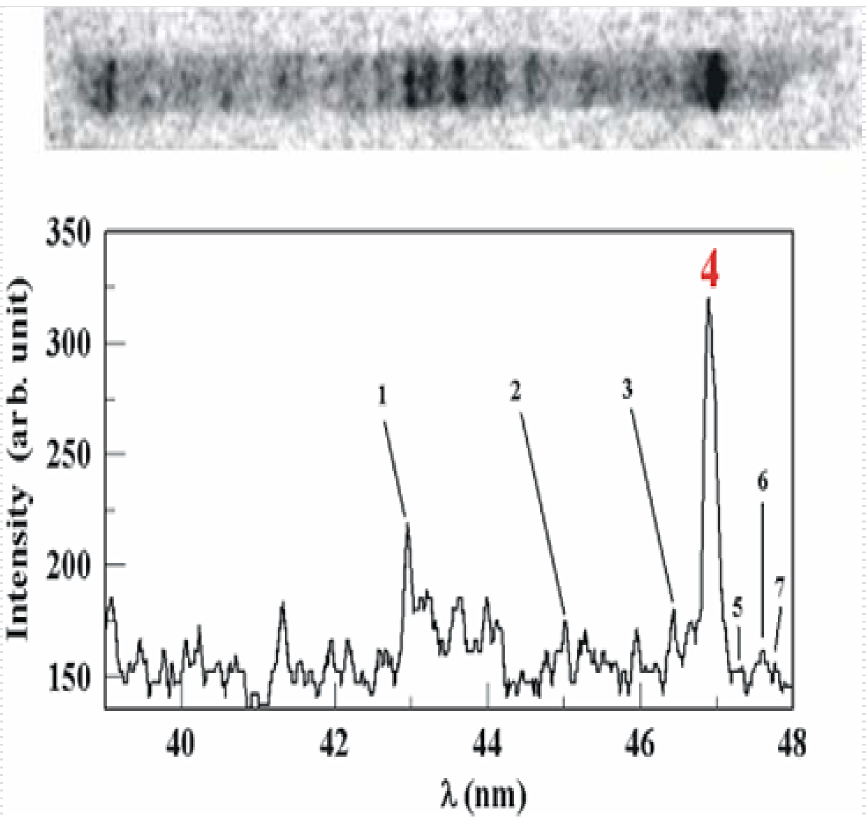


Fig. 3 : Measured time integrated spectrum ($2R_0$=3 mm, p_0 = 300 mTorr, I_{max} = 22.5 kA)

Time integrated spectra measured for I_{max} **= 22.5 kA and** p_0 **= 300 mTorr** proved the presence of several spectral lines related to **Ar8+** and **Ar6+** in the range 43 nm – 48 nm.

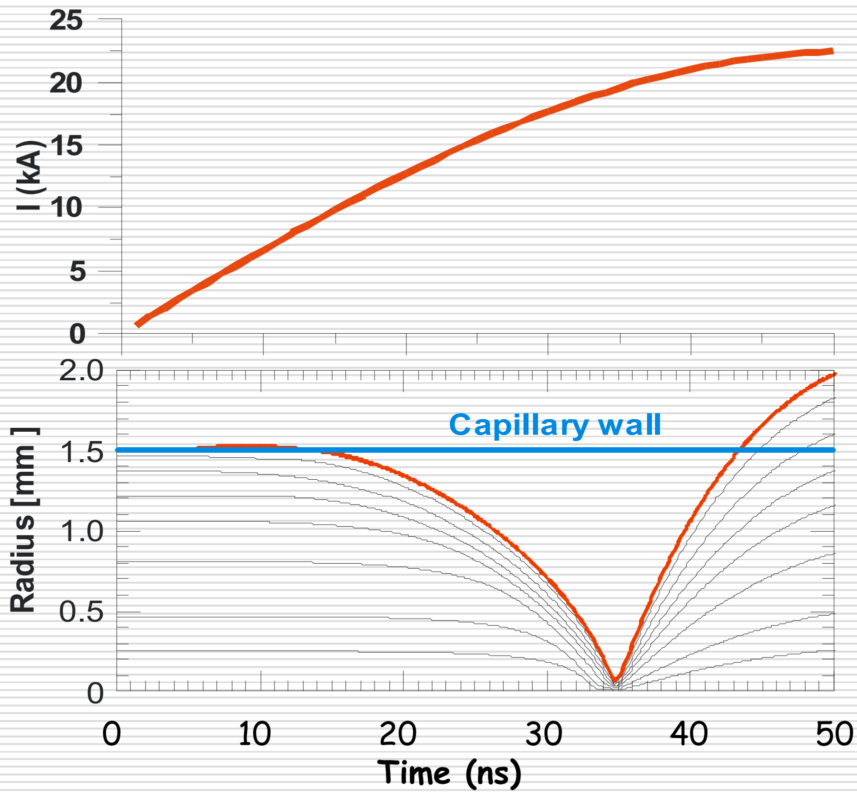
Ions	Transition	λ nm
Ar^{8+}	3s $^3P_1$ – 3p $^1S_0$	**43.1123**
Ar^{8+}	3p $^1P_1$ – 3d $^1P_1$	**45.0660**
Ar^{8+}	3p $^1P_1$ – 3d $^1P_1$	**46.5118**
Ar^{8+}	3s $^1P_1$ – 3p $^1S_0$	**46.8793**

The strongest line corresponds to the **Ar^{8+} 3s $^1P_1$ – 3p $^1S_0$ transition**.

Ions	Transition	λ nm
Ar^{6+}	3s3p – 3s3d	**47.3934** J = 0-1
Ar^{6+}	3s3p – 3s3d	**47.5654** J = 1-2
Ar^{6+}	3s3p – 3s3d	**47.9379** J = 2-3

MHD Simulations

Fig. 3: Time development of (a) current pulse and (b) trajectories



Capillary discharge plasma quantities have been evaluated by means of **the NPINCH code** under 1-dimensional 2-temperature, 1-fluid MHD approximation

Two very different stages is recognized during the plasma Z-pinch.

- **plasma is compressed and heated.**
- **highly ionized plasma expands to** capillary wall being cooled.

In the particular case, if a capillary with d_0 **=3 mm**, p_0 **=300 mTorr**, I_{max} **=22.5 kA and** $T_{1/4}$ **= 52 ns** the calculated pinch time $t_p \cong$ **35 ns.**

Our computer model is valid **up to 45 ns** when outer part of pinched plasma reaches the wall.

MHD Simulations

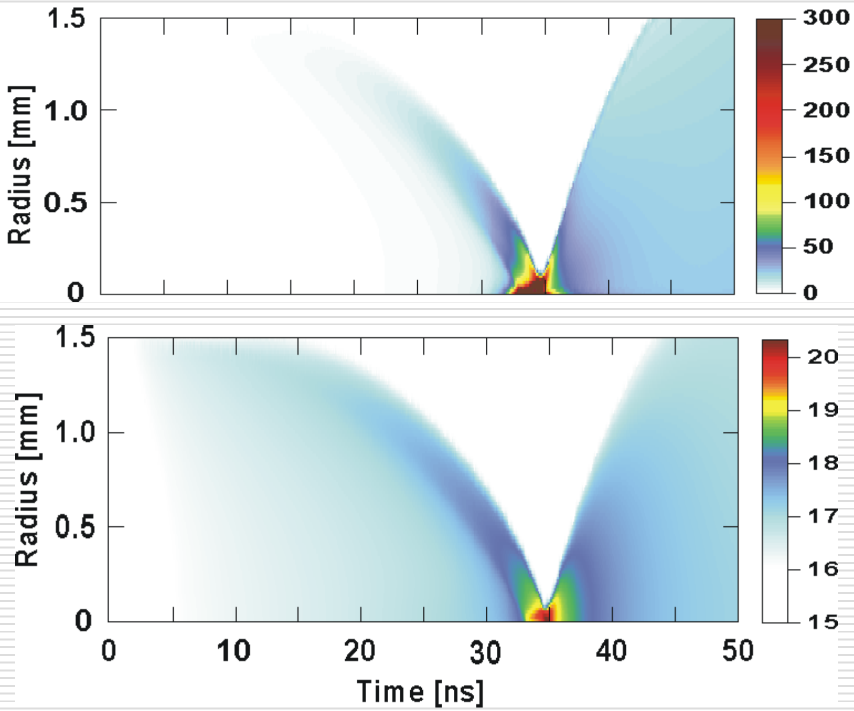


Fig.4 : Space-time development of plasma electron (a) temperature Te and (b) logarithm density Ne

Resulting peak values of plasma electron temperature and density on the axis are $T_{e,max} \cong 300$ **eV** and $N_e \cong 10^{20}$ **cm**$^{-3}$.

Hot plasma core with the dimension r_{core} = 0.15 mm is formed during the Z-pinch

Values of plasma quantities are changed very quickly in comparison to ionization and energy level population relaxation times.

Kinetic description

Gain and outgoing **soft X-ray spectra** were calculated in a post - processor mode. Axial capillary plasma values were taken from NPINCH code.

Atomic model includes **556 states, 2662 radiative transitions** of **Ar**.

Transient eqns. for level populations were solved.

Time evolutions of ***Ne***, ***Te***, and **<Z>** on axis are seen from Fig. 5.

Peak value of **<Z>** ≅ **14** is obtained **at pinch time.** At this level of ionization density of laser ions **Ar** $^{8+}$ is small, plasma is **overionized** and **overheated** for the purpose of lasing.

The ionization state with **<Z>** ≅ **8**, required for **high concentration of lasing ions,** is achieved about **2 ns before the pinch** collapse.

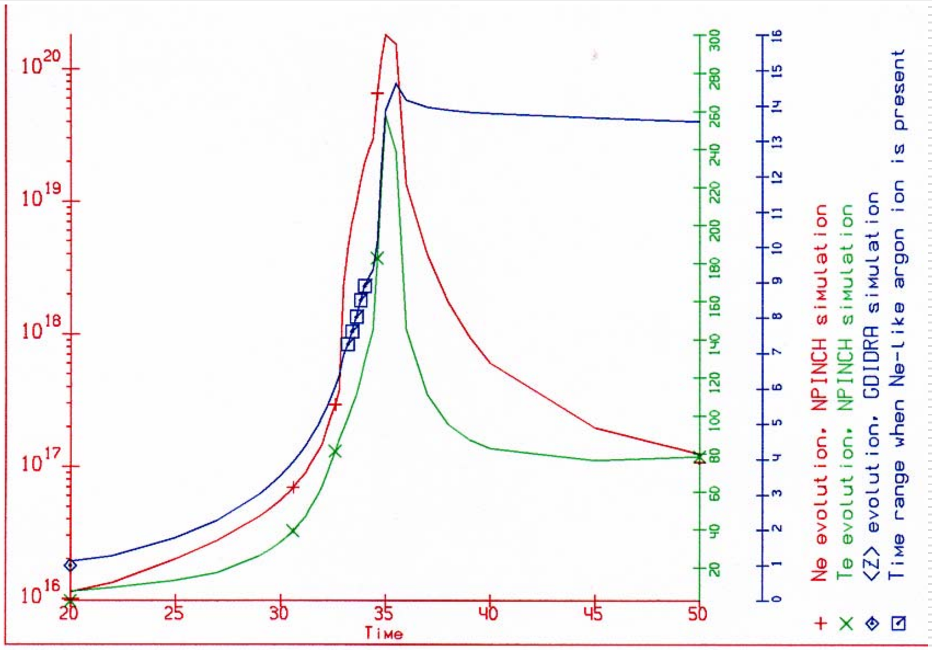


Fig. 5 : Time dependences of axial values of **(a)** electron density N_e, **(b)** temperature T_e, **(c)** averaged ionization **<Z>**

Kinetic description

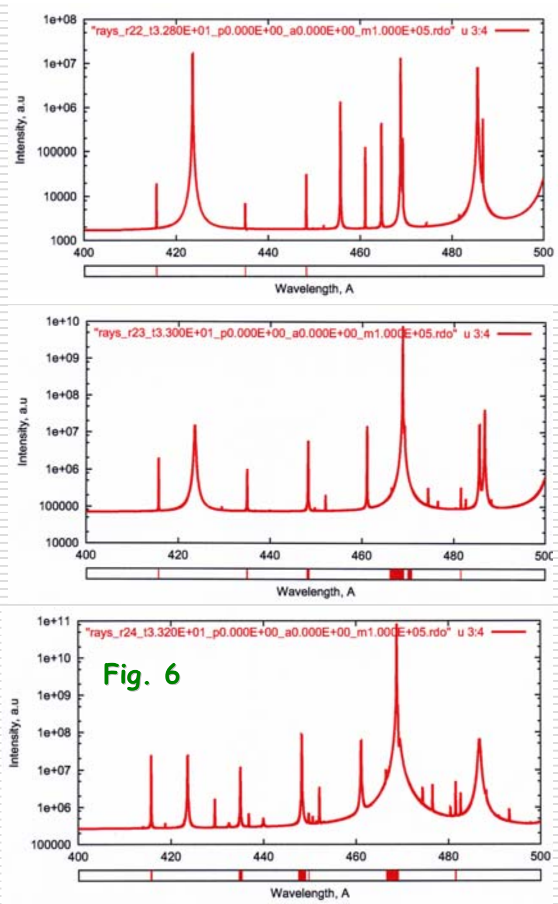


Fig. 6

Calculated instantaneous spectra of Ar plasma radiation at selected time moments demonstrate quick changes of structure around the time when **<Z> ≅ 8**. On the bars below the spectrum plots regions where radiation is amplified are indicated. The strongest lasing occur on transition **2p5 3s $^1P_1$ – 2p5 3p $^1S_0$** in Ne-like argon.

Calculated spectra demonstrate **amplification at λ = 46.8763 nm only for a short period of 0.5 ns with peak value at 33.2 ns.** At this time ***Te* = 100 eV**, and **N_e = 4.3 10^{18} cm^{-3}**.

A very short laser period is caused by very quick change of plasma ionization state. The plasma electron density is one order lower than the critical density for energy level population mixing.

Kinetic description

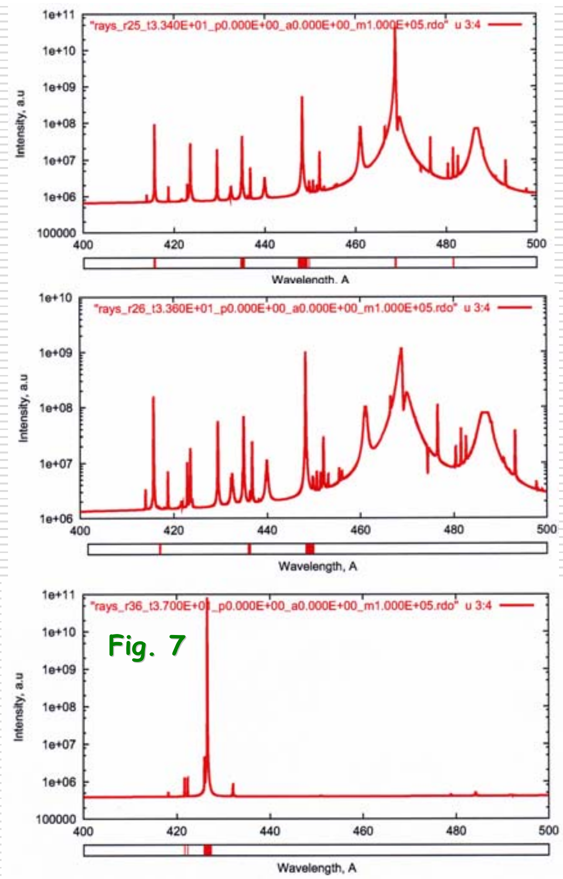


Fig. 7

Evaluated spectra forecast also strong **lasing with the wavelength λ = 42.6 nm at t = 37 ns,** when T_e **= 105 eV**, and N_e **= 3.14 10^{18} cm^{-3}** .

This lasing on **2p-2s Be-like argon ion transition** is achieved by recombination pumping.

Degree of ionization corresponds to high density of lasing **Ar^{14+} ions**. Plasma is remarkably under-cooled at this time and electron density is much lower than is the critical value for collisional mixing.

Pinch optimization

Evalution of pinching plasma is followed in phase sub-space N_e-T_e. Rather complicated trajectory may be found.

Both lasing points (green triangles) with **collisional pumped Ar^{8+}** and **recombination pumped Ar^{14+}** ions correspond to $T_e \cong 100$ **eV** and $N_e \cong 3.\ 10^{18}$ **cm^{-3}**.

For Ar^{8+} ions the plasma is slightly over-heated and for Ar^{14+} plasma is remarkably under-cooled. In both cases $N_e < N_{cr} = 3.\ 10^{19}$ **cm^{-3}** for collisional mixing.

Optimum laser system parameters are found if results of MHD simulations are judged according to trajectories in N_e-T_e space.

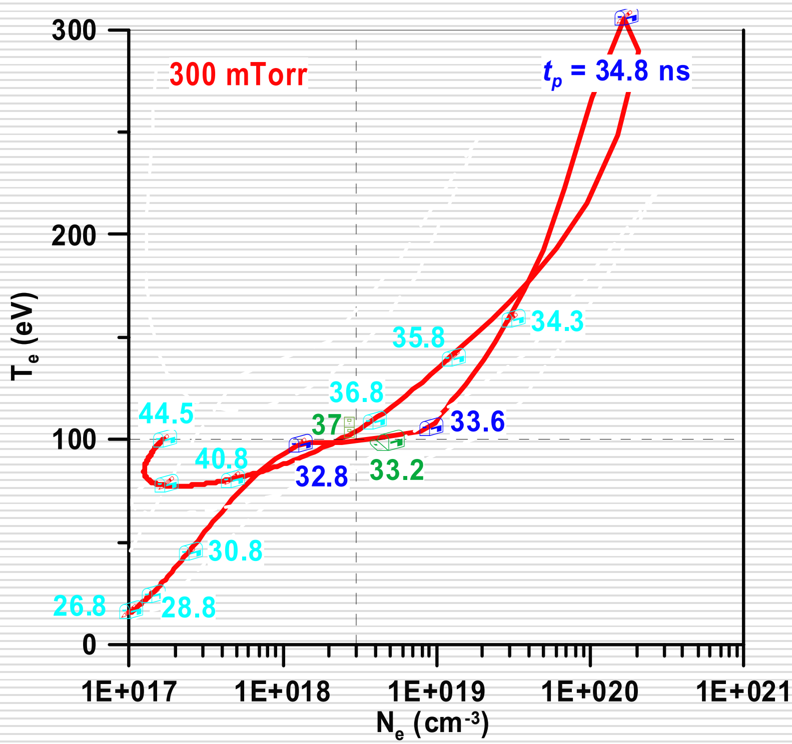


Fig. 8 : Diagram of electron temperature T_e and density N_e ,labels denote time in ns

Pinch optimization

Trajectory should pass trough region specified by $3.10^{18} < Ne < 1.\ 10^{19}\ cm^{-3}$ and $80\ eV < Te < 100\ eV$ during the pinch. To check validity our criterion we have done MHD simulations for three current peak values I_{max} = 9, 18, 32 kA and various pressures. Best lasing may be expected at pressures 125 mTorr for I_{max} = **9** kA, at 200-250 mTorr for I_{max} =**18** kA, at 500-600 mTorr for I_{max} = **32** kA.

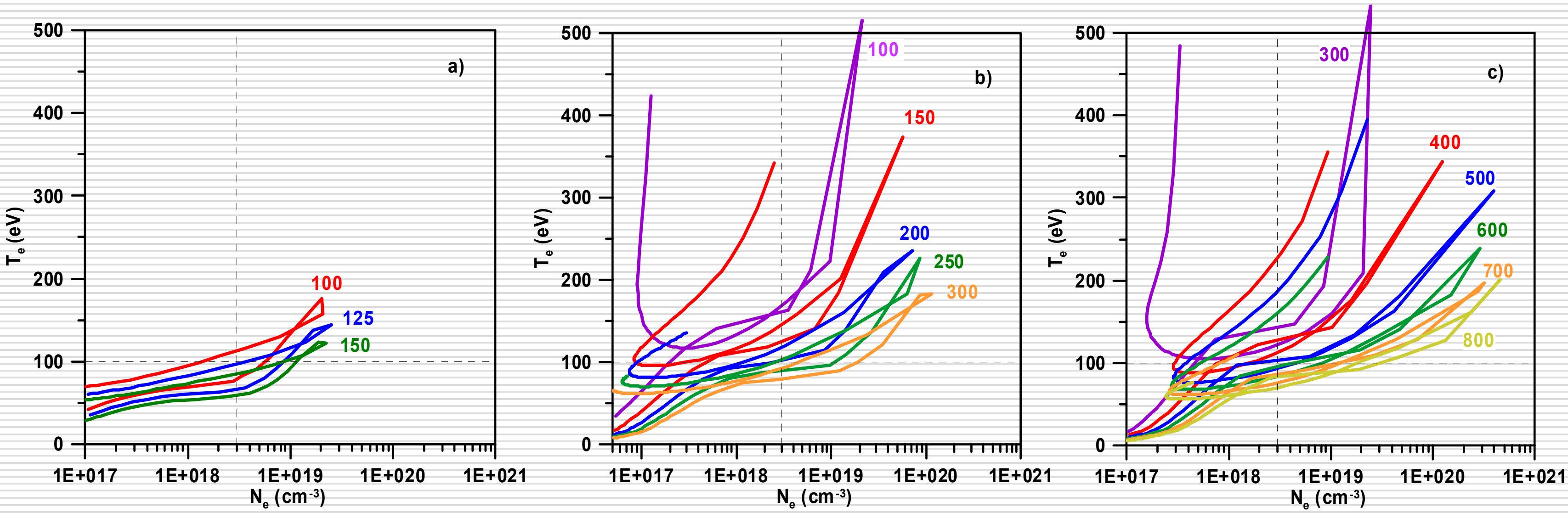


Fig. 9 : Pinch plasma evolution in phase-space N_e - T_e for d_0 **= 3 mm** and various filling pressures; a) I_{max} = **9** kA, b) I_{max} =**18** kA, c) I_{max} =**32 kA**

Pinch optimization

Computer simulations may be very helpful with capillary radius optimization. It is expected that for current pulse with amplitude I_{max} = **22.5 kA** and quarter period $T_{1/4}$ = **52 ns** best diameter would be **$2R_0$= 4.4 mm**, if the filling pressure is about **250 – 300 mTorr**.

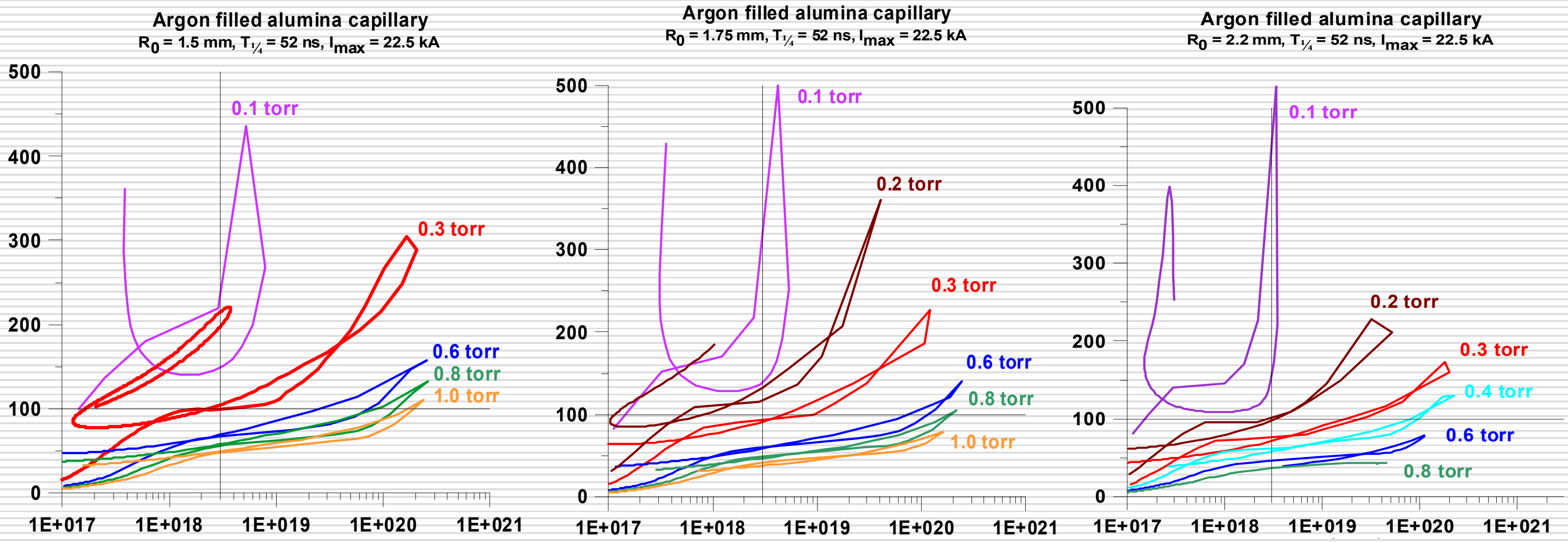


Fig. 10 : Pinch plasma evolution in N_e-T_e space a) $2R_0$= 3mm, b) $2R_0$= 3.5 mm, c) $2R_0$= 4.4 mm

Pinch optimization

If the lower current peak I_{max} =18 kA is chosen, higher lasing efficiency is expected with capillary the diameter of which is $2R_0$ = 4.4 mm and the gas filling pressure is in the range of about **150 – 200 mTorr.**

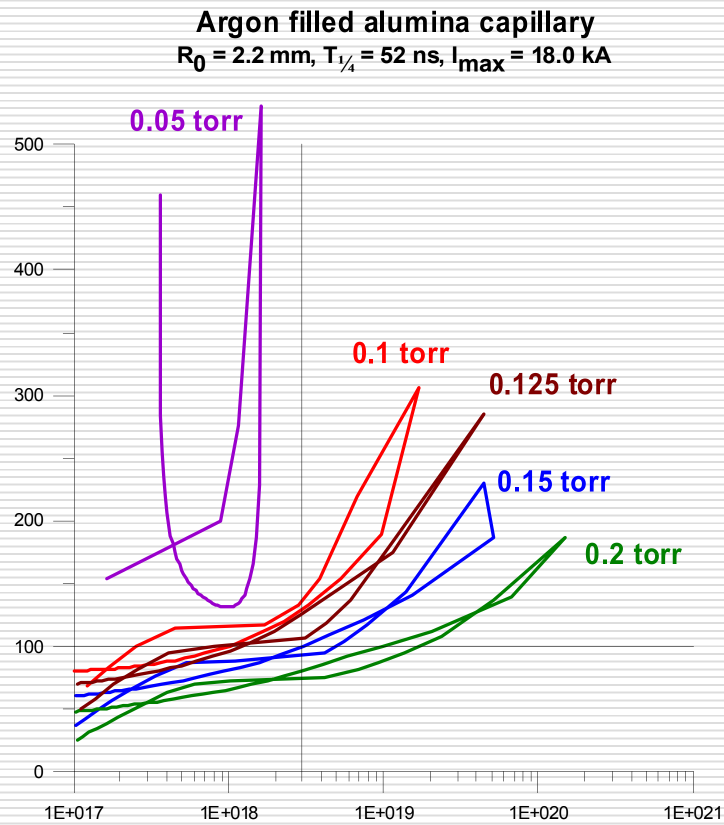


Fig. 11 : Pinch plasma evolution in N_e - T_e phase-space for various filling pressures; I_{max} = 18 kA, $2R_0$ = 4.4 mm

Conclusion

- A computer model of argon ion EUV laser pumping was developed.
- Its validity was proved on the basis of comparison of computer code and laboratory experiments.
- Further optimization, based on the MHD discharge analysis in the Ne-Te phase space is suggested.
- It may be useful for further optimization namely, for optimization of the capillary radius.

Acknowledgement

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References

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