Modelling of capillary Z-pinch recombination pumping of carbon extreme ultraviolet laser

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Abstract. Numerical study in the field of developing capillary discharge pumped EUV lasers on hydrogen-like ions, carried out in the Institute of Plasma Physics Acad. Sci. and Czech Technical University Prague, is presented. Results of simulations for capillary filled with carbon are reported and compared with previous ones achieved for boron and nitrogen filled capillary. Computer modelling of fast capillary discharge is performed to investigate a new laser active medium created by exited hydrogen-like carbon ions leading to lasing at the wavelength 18.22 nm. Recombination excitation of the carbon ions is expected in the undercooled pinching plasma created during the expansion phase of the pinch. In all cases, the same nonablative capillary with radius of 1.6 mm is presumed and the current pulse with peak value 50 kA and current slope varying between $1*10^{12}$ A.s^{-1} to $2*10^{12}$ A.s^{-1} are taken into account. Evaluated pressure optimized gains 2.2, 1.58, and 1.4 cm^{-1} are found for carbon, boron, and nitrogen filled capillary, respectively. Spatial gain evolution is calculated for optimized case.

1. Introduction

Non-stationary plasma of a fast capillary electrical discharge was studied as a potential active medium for a soft X-ray laser [1]. The aim was to achive an optimum set of characteristics for lasing at 18.2 nm wavelength H-like carbon C^{5+} in an alumina capillary and to compare the obtained set of characteristics with previous rusults for oxygen, nitrogen [5, 6] and boron [9] respectively.

Capillary pinch dynamics is determined by many selected parameters: capillary geometry (radius and capillary length), the substance of the capillary wall, the substance of the gas filling (different atomic numbers), the initial filling pressure and the electric current time dependance. This dependance, in particular, is given by an electric circuit which is joined to the capillary. A capillary discharge Z-pinch acting as a medium for a soft X-ray laser uses ASE, the “Amplified Spontaneous Emission” effect, and electron-collisional recombination pumping [3]. The main variable for ASE is the gain, and the most important goal of this paper is to find specific parameters of a capillary to obtain the maximum gain, see also [9].

It was assumed that ablation from inner walls has only an imperceptible effect, therefore, it was not included in the calculations [8]. The capillary discharge plasma quantities were calculated by means of the NPINCH [2] code under the one-dimensional, two-temperature, one-fluid MHD approximation. The output data was then processed by means of the FLY [7] code, which enables the creation of a history file of the population on the individual levels along the capillary axis. On the basis of the populations history, the gain and the gain history can be calculated. Optimization itself involves searching the maximum in the four-dimensional space of the parameters. Two parameters relate to the current-impulse shape, the third parameter is initial density (or pressure), and the fourth is the radius of the capillary for selected elements. Plasma behaviour is modelled for the capillary radius R_0 = 1.6 mm, the current pulse specified by the current slope $dI/dt_{|t=0}$ and I_{max} [4].

2. Results of numerical modelling

2.1 Gain dependences on the filling pressure

The results for I_{max} = 30 kA, I_{max} = 40 kA, I_{max} = 50 kA, and I_{max} = 60 kA are in Fig. 1-4. The maximum gain value G_{max}, the current slope $dI/dt_{|t=0}$, initial carbon density N_0, the time of achieving the current maximum t_{Imax}, and the time of achieving the gain maximum t_{Gmax} are situated in the Tab. 1. The calculated data resembled the Gauss function, so they were fitted by this function and the deviation between the calculated data and the fitted function was minimal.

I_{max} kA	$dI/dt_{\|t=0}$ A/s	N_0 cm^{-3}	t_{Imax} ns	t_{Gmax} ns	G_{max} cm^{-1}
30	1.00 10^{12}	1.4 10^{17}	50	53	0.046
40	1.50 10^{12}	2.2 10^{17}	53	51.6	0.68
50	1.75 10^{12}	3.2 10^{17}	47	48	2.21
60	2.25 10^{12}	4.1 10^{17}	43.6	44.4	3.37

***Tab.1**. Parameters for optimal setting*

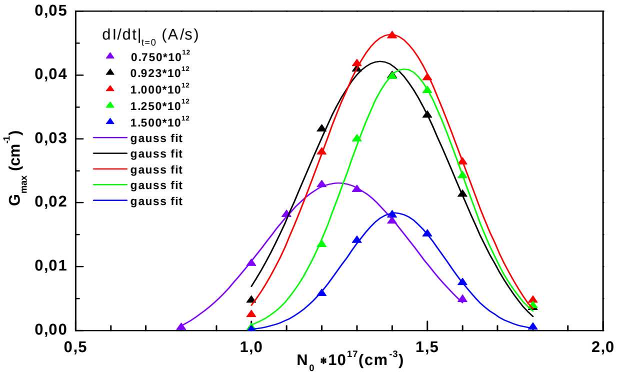

***Fig.1**. Maximum G_{max} against initial density for various current derivations at I_{max} = 30 kA. The data is fitted by the Gauss function*

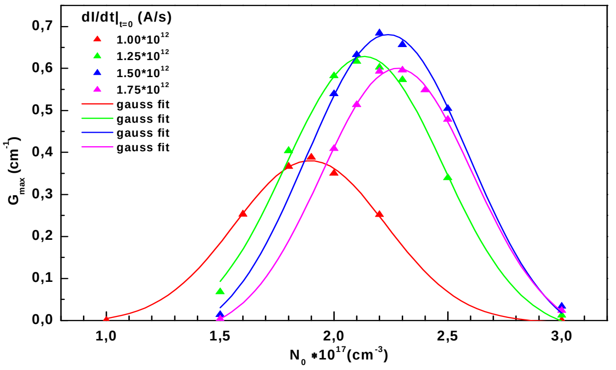

***Fig.2**. Maximum G_{max} against initial density for various current derivations at I_{max} = 40 kA. The data is fitted by the Gauss function*

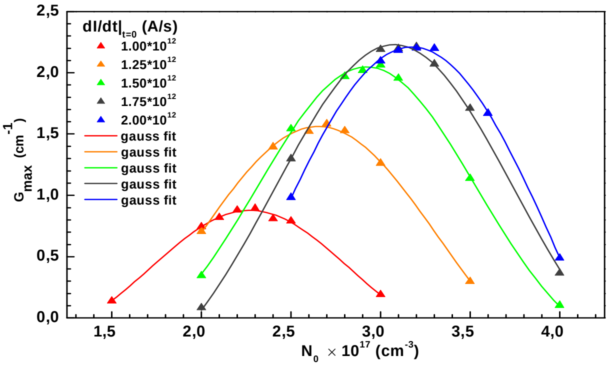

***Fig.3**. Maximum G_{max} against initial density for various current derivations at I_{max} = 50 kA. The data is fitted by the Gauss function*

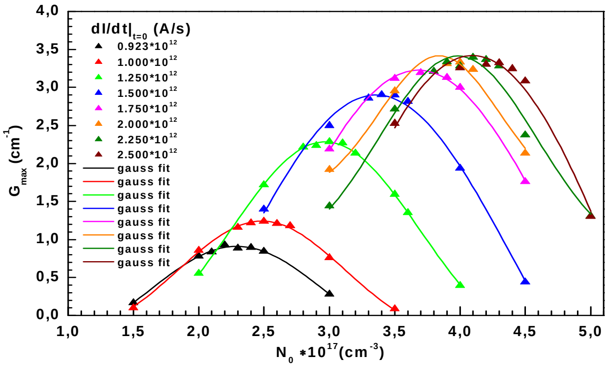

***Fig.4**. Maximum G_{max} against initial density for various current derivations at I_{max} = 60 kA. The data is fitted by the Gauss function*

2.2 Comparison of the optimized gain for various atom gases filling

We report here results of computer optimization of the capillary pinching discharge system with boron, carbon, nitrogen and oxygen gas filling. The model takes into account four parameters of the experimental apparatus: capillary radius R_0 = 0.16 cm, peak value of the current pulse I_{max} = 50 kA and I_{max} = 60 kA, variable initial current slope $dI/dt_{|t=0}$, and variable initial atom densities N_0. Changing the initial pressure p_0 (initial atom N_0 or mass densities ρ_0 and) for every gas fillings, the pressure optimized pinch (using Mhd code NPINCH) was evaluated. For higher atomic number Z the pinch time t_p is shorter and better compression ratio ρ_0/ρ_p is achieved. The electron temperature $T_{e,p}$ and atom density $N_{e,p}$ on the capillary axis at the pinch time increases with higher value of Z (see Tab. 2. and Tab. 4.).

The characteristics of optimized laser active media for our selected gas fillings are summarized in Tab. 3. and Tab. 4. The gain is determined according to $G = \sigma_{stim} \mathbf{N}_u F$, where σ_{stim} is cross-section for stimulated emission, $\mathbf{N}_u$ is the upper state density and F is inversion factor [3], which are in the tables evaluated at the time t_{Gmax}, when the value G_{max} is achieved. It can also be seen in the tables and in the Fig. 6., that t_{Imax} (current maximum time) for optimal settings are closest to t_{Gmax}. The difference time t_d from between t_p and t_{Gmax} is decreasing with increasing Z. The Fig. 5. shows that the gain profile width in time is shortened with increasing Z.

I_{max} = 50 kA

Element	**Z**	**A**	**N_0** cm^{-3}	**ρ_0** g.cm^{-3}	**$dI/dt_{\|t=0}$** A/s	**t_p** ns	**ρ_p/ρ_0**	**$T_{e,p}$** eV	**$N_{e,p}$** cm^{-3}
Boron	5	10.81	$5.1\ 10^{17}$	$9.1581\ 10^{-6}$	$1.50\ 10^{12}$	50.4	113	79.3	$2.30\ 10^{20}$
Carbon	6	12.01	$3.2\ 10^{17}$	$6.3841\ 10^{-6}$	$1.75\ 10^{12}$	45.6	178	101.8	$2.85\ 10^{20}$
Nitrogen	7	14.01	$2.3\ 10^{17}$	$5.3522\ 10^{-6}$	$2.00\ 10^{12}$	40.2	214	139.7	$2.95\ 10^{20}$

Tab. 2. MHD parameters of pressure-optimized pinch (I_{max} = 50kA)

Element	**Z**	**λ** nm	**σ_{stim}** cm^2	**t_{Imax}** ns	**t_d** ns	**t_{Gmax}** ns	**N_u** cm^{-3}	**F**	**G_{max}** cm^{-1}
Boron	5	26.2	$3.99\ 10^{-15}$	55.5	10.4	60.8	$1.35\ 10^{15}$	$2.92\ 10^{-1}$	1.58
Carbon	6	18.2	$2.97\ 10^{-15}$	47	2.8	48.4	$2.30\ 10^{15}$	$3.21\ 10^{-1}$	2.21
Nitrogen	7	13.4	$2.18\ 10^{-15}$	41	1.6	41.8	$1.67\ 10^{15}$	$3.88\ 10^{-1}$	1.41

Tab. 3. Characteristics of optimized laser active media (I_{max} = 50kA)

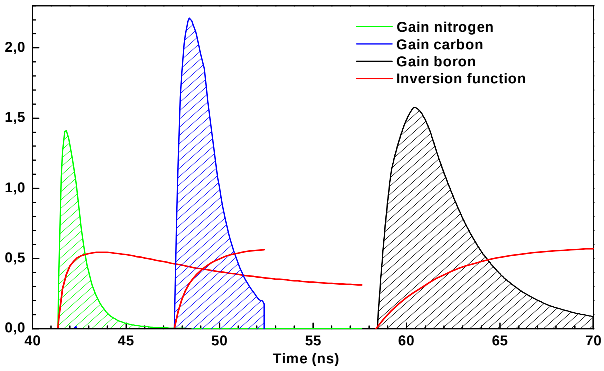

Fig. 5. Behaviour of inversion function F and gain (cm^{-1}) for optimal parameters and for various elements (I_{max} = 50 kA).

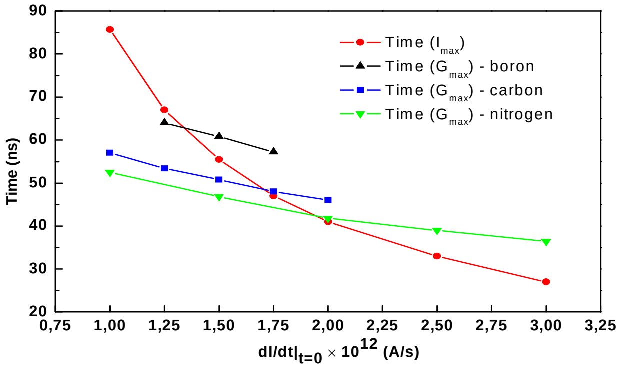

***Fig.6.**Comparison of achieving time of maximum gain T_G and curren T_I in dependence on $dI/dt_{|t=0}$ for boron, carbon, and nitrogen (I_{max} = 50 kA).*

I_{max} = 60 kA

Element	**Z**	**A**	**N_0** cm^{-3}	**ρ_0** g.cm^{-3}	**$dI/dt_{\|t=0}$** A/s	**t_p** ns	**ρ_p/ρ_0**	**$T_{e,p}$** eV	**$N_{e,p}$** cm^{-3}
Boron	5	10.81	$5.8\ 10^{17}$	$10.411\ 10^{-6}$	$2.25\ 10^{12}$	44.8	68.4	85.8	$1.59\ 10^{20}$
Carbon	6	12.01	$4.1\ 10^{17}$	$8.1796\ 10^{-6}$	$2.25\ 10^{12}$	41.2	165.1	107.3	$3.39\ 10^{20}$
Nitrogen	7	14.01	$2.8\ 10^{17}$	$6.5100\ 10^{-6}$	$2.25\ 10^{12}$	38.4	234.2	149.7	$3.93\ 10^{20}$
Oxygen	8	16.00	$2.3\ 10^{17}$	$6.1106\ 10^{-6}$	$2.25\ 10^{12}$	37.8	353.6	171.2	$5.69\ 10^{20}$

Tab. 4. MHD parameters of pressure-optimized pinch (I_{max} = 60kA)

Element	Z	λ nm	σ_{stim} cm^2	t_{Imax} ns	t_d ns	t_{Gmax} ns	N_u cm^{-3}	F	G_{max} cm^{-1}
Boron	5	26.2	3.99 10^{-15}	43.6	8.7	53.5	1.7 10^{15}	0.247	1.65
Carbon	6	18.2	2.97 10^{-15}	43.6	3.2	44.4	4.1 10^{15}	0.272	3.37
Nitrogen	7	13.4	2.18 10^{-15}	43.6	2.1	40.5	4.9 10^{15}	0.298	3.15
Oxygen	8	10.2	1.78 10^{-15}	43.6	1.3	39.1	2.2 10^{15}	0.425	1.68

Tab. 5. Characteristics of optimized laser active media (I_{max} = 60kA)

2.3 Off Axial Gain

Following the plasma parameters along the plasma trajectories, the off axial gain may be also evaluated. The values of electron N_e and temperature T_e along the selected plasma tube are used as input data for the FLY code. Gain along the plasma tube is evaluated in the same way as along the capillary axis. The result of radial-time evolution for the carbon optimal parameters is seen in the Fig. 7.

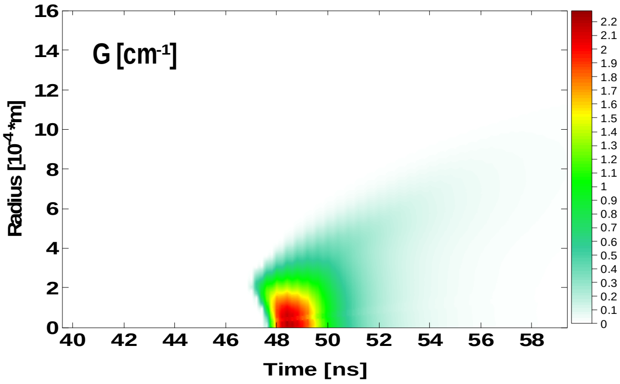

Fig.7. *Radial and time evolution of the gain evaluated for carbon filling and parameters* $N_0 = 3.2*10^{17}$ cm^{-3}, $dI/dt_{|t=0} = 1.75*10^{12}$ A/s, r_0 = 1.6 mm, *and* I_{max} = 50 kA.

Conclusion

The optimal conditions with carbon filling for achieving maximum gain for initial density and electric current pulse shape have been obtained for current maxima I_{max} = 30 kA, I_{max} = 40 kA, I_{max} = 50 kA, I_{max} = 60 kA, and capillary radius r = 1.6 mm. The achievable gain is higher than that with nitrogen, or boron but initial current slope $dI/dt_{|t=0}$ have to increase with increasing Z. That also presents higher demands for used electric current source.

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