Prospects for scaling towards shorter wavelengths of capillary-discharge based soft X-ray lasers

J. Kaiser

Institute of Physical Engineering, Brno University of Technology, Technická 2, 616 69 Brno, Czech Republic

e-mail: kaiser@ufi.fme.vutbr.cz

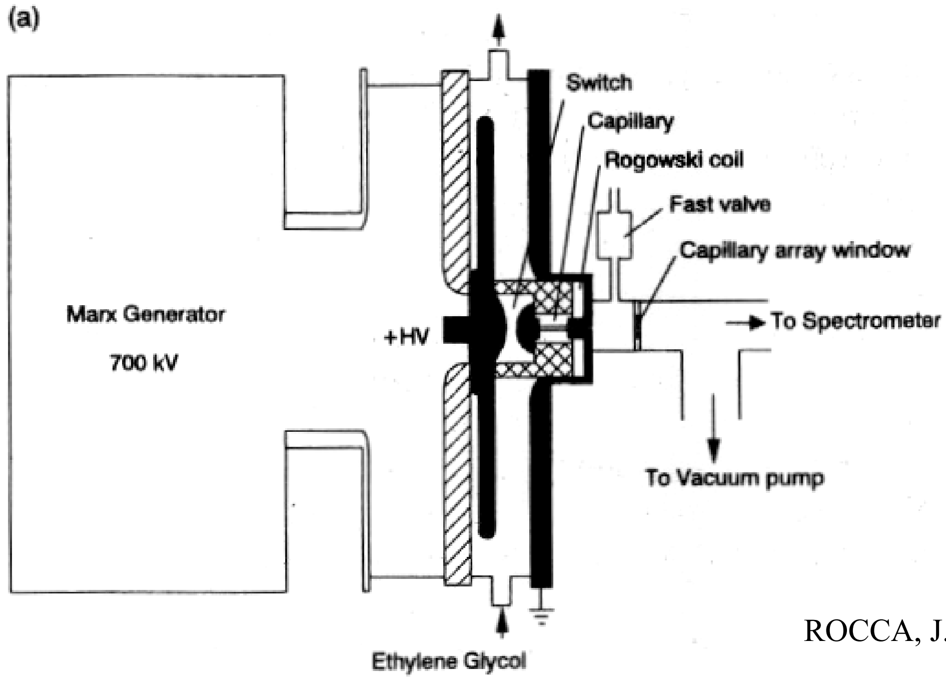
Contents

- Historical remarks.
- Capillary-discharge based Ne-like Ar soft X-ray laser.
- Efforts to decrease the wavelength.
  - How to remain “table-top”?
  - Moving towards non-coherent devices.
- Should we switch to hybrid sources?

Historical remarks

- 1980-X-ray lasing experiment at NevadaTest Side
- 1984-1990 – laser plasma based sources
- 1988-1990 – lasing at 18.2 nm in polyacetal capillary using recombination pumping (H.-J. Kunze) gain ~3.1 cm^{-1}.
- 1991 – gas-filled devices (W. Hartmann *et al*.)
- 1996 –Li-like oxygen (O^{5+}) laser (52 nm, 49.8 nm) (recombination scheme) GL ~ 2.5
- 1992-1996 – collisional excitation pumping, short rise time current pulses (J.J. Rocca)

K. Kolacek: http://www.ipp.cas.cz/lps/capil/index.php?sel=hist



ROCCA, J.J. *et al. Phys. Rev. E* **47**, 1993, 1299-1304.

- amplification in Ne-like argon (Ar^{+8}) at 46.9 nm
- laser in 1994, saturation in 1996 (in polyacetal capillary)
- from 1998 – ceramic (alumina) capillaries
- 2001-2003 several groups realized the lasing in argon-filled capillary

- 2001, 2002 E. Hotta and K. Horioka studied the role of predischarge (preionization) current.
- 2002 group of L. Reale and G. Tomassetti showed lasing in a capillary discharge pumped by “long” current pulse.
- From 1990s – modeling activities (MHD, ablative/non-ablative discharges) N.A. Bobrova, V.N. Shlyaptsev.

Capillary-discharge based Ne-like Ar soft X-ray laser

- preionization pulse (3 - 6 μs, ~20 A)
- current pulse:
  - amplitude 17-20 kA, half-cycle duration 130 - 180 ns
  - slope 3 x 10^{11} A/s, 4.5 x 10^{11} A/s (rise-time 45-60 ns)
- capillary – alumina (Al_2O_3) up to 45 cm long
- Ar pressure 0.25 – 0.6 Torr (flowing gas system)

Applications

- Soft X-ray reflectrometry (J.J. Rocca, 1999)
  - ARTIOUKOV, I.A. *et al.*, *IEEE J. Quantum Electron.* **5**, 1999, 1495-1501.
- Dense plasma shadowgraphy (J.J. Rocca, 2000)
  - MARCONI, M.C. *et al.*, *Phys. Rev. E* **62**, 2000, 7209-7218.
- Dense plasma interferometry (J.J. Rocca, 2002)
  - JANKOWSKA, E. *et al.*, *IEEE Trans. Plasma Sci.* **30**, 2002, 46-47.
- Material ablations (J.J. Rocca, 2003)
  - ROCCA, J.J. *et al.*, *Nucl. Instr. Meth. Phys. Res. A* **507**, 2003, 515-522.
- Testing the LiF detector (L. Reale, G. Tomassetti, 2003)
  - TOMASSETTI, G. *et al.*, *Europhys. Lett.***63**, 2003, 681-686.
- Creating of a plasma waveguide (J.J. Rocca, 2004)
  - LUTHER, B.M. *et al.*, *Phys. Rev. Lett.* **92**, 2004, 235002.

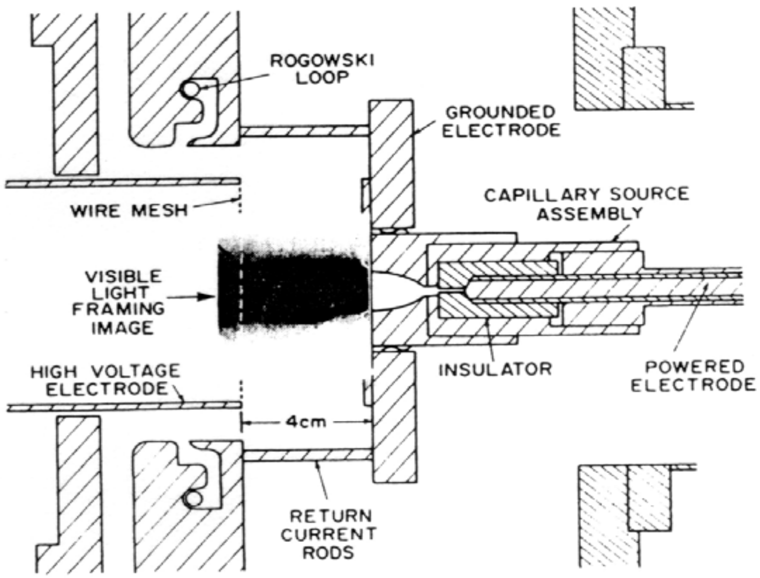
Comparison of compact laser-plasma based and capillary-discharge based lasers

Parameter	Laser-pumped X-ray lasers [1]	Electrically pumped X-ray lasers [2]
Pulse length	2-30 ps	< 2 ns
Repetition rate	~ 1 kHz (pump-laser limited)	< 10 Hz
Wavelength	10-60 nm	46.9 nm
Coherence	20-30 μm transverse[1]	5.4 μm transverse[1] Longitudinal $(10^4\text{-}10^5)\lambda/2$ [1]
Divergence	1-10 mrad	0.6 mrad [3]
Energy/pulse	1-15 μJ	0.88 mJ (at 4 Hz)
Average/Peak power	-	3.5 mW/0.6 MW
Peak spectral brightness photons / (s mrad^2 mm^2 0.01% bandwith)	10^{24}	2×10^{25}
Linewidth	$(10^{-4} – 10^{-5})\ \lambda$	$< 10^{-4}\ \lambda$ [1]

[1] For the transverse coherence the diameter of the equivalent incoherent source is given [1]

[1] JANULEWICZ, K.A. *et al.*, *X-Ray Spectrom.* **33**, 2004, 262-266.
[2] ROCCA, J.J. *et al.*, *Nucl. Instr. Meth. Phys. Res. A* **507**, 2003, 515-522.
[3] RITUCCI, A. *et al.*, *Appl. Phys. B* **78**, 2004, 965-969.

Efforts to decrease the wavelength



YOUNG, F.C. *et al.*: Implosion of sodium-bearing capillary-discharge plasmas for x-ray laser experiments. *Appl. Phys. Lett.* **50**, 1987, 1053-1055.

The NaF plasma was created by a 60 kA, 3.4 μs prepulse inside the capillary and the emerging plasma jet was subsequently excited with a high-current (1.2 MA) main pulse. A peak power of 25 GW in a 20 ns pulse was measured for the He-like sodium (Na^{+9}) $1s2$ - $1s2p1P$ transition at 1.1 nm (He-α line). The 1.1 nm radiation from He-like sodium can resonantly populate the n=4 to n=1 transition in He-like Ne with potential for lasing on the 4-3, 4-2, and 3-2 transitions at wavelengths of 23 nm, 5.8 nm, and 8.2 nm, respectively.

Efforts to decrease the wavelength

Atomic number and symbol of the Element	Wavelengths (nm)	Scheme
$_{79}$Au	3.56	Ni-like
$_{74}$W	4.32	Ni-like
$_{73}$Ta	4.48	Ni-like
$_{72}$Hf	4.65	Ni-like
$_{70}$Yb	5.609, 5.026	Ni-like
$_{67}$Ho	5.63, 6.20	Ni-like
$_{66}$Dy	5.85, 6.41	Ni-like
$_{65}$Tb	5.9, 6.7	Ni-like
$_{64}$Gd	6.33, 6.86	Ni-like
$_{63}$Eu	6.583, 7.100	Ni-like
$_{62}$Sm	7.36, 6.85	Ni-like
$_{60}$Nd	7.92	Ni-like
$_{59}$Pr	8.2	Ni-like
$_{58}$Ce	8.6	Ni-like
$_{57}$La	8.9	Ni-like
$_{54}$Xe	9.64, 9.98	Ni-like
$_{52}$Te	11.1	Ni-like
$_{50}$Sn	11.97	Ni-like
$_{49}$In	12.58	Ni-like
$_{48}$Cd	13.17	Ni-like
$_{47}$Ag	13.89	Ni-like
$_{46}$Pd	14.68	Ni-like
$_{42}$Mo	18.90	Ni-like
$_{41}$Nb	20.33	Ni-like
$_{40}$Zr	22.02	Ni-like
$_{39}$Y	24.01	Ni-like
$_{36}$Kr	32.8	Ni-like

$_{47}$Ag	9.9365, 10.0377	Ne-like
$_{42}$Mo	10.64, 13.10, 13.27	Ne-like
$_{41}$Nb	13.86, 14.04, 14.59	Ne-like
$_{40}$Zr	15.04	Ne-like
$_{39}$Y	15.5	Ne-like
$_{38}$Sr	15.98, 16.41, 16.65,	Ne-like
$_{37}$Rb	16.50, 17.35, 17.61	Ne-like
$_{34}$Se	18.2, 20.6, 20.9	Ne-like
$_{33}$As	21.884, 22.256	Ne-like
$_{32}$Ge	19.6, 23.2, 23.6	Ne-like
$_{31}$Ga	24.670, 25.111	Ne-like
$_{30}$Zn	21.2, 26.2, 26.7	Ne-like
$_{29}$Cu	22.11, 27.93, 28.47	Ne-like
$_{28}$Ni	23.1	Ne-like
$_{26}$Fe	25.49	Ne-like
$_{25}$Mn	22.1, 26.9	Ne-like
$_{24}$Cr	28.55, 40.22	Ne-like
$_{23}$V	26.1, 30.4	Ne-like
$_{22}$Ti	32.63	Ne-like
$_{21}$Sc	31.2, 35.2	Ne-like
$_{20}$Ca	38.3	Ne-like
$_{19}$K	42.1	Ne-like
$_{18}$Ar	46.875	Ne-like

H. Daido: *Rep. Prog. Phys.* **65**, 2002, 1513-1576.

Efforts to decrease the wavelength

From 1999 the team of J.J. Rocca is building an apparatus (200 kA/10 ns) for amplification at shorter wavelengths using Ni-like ions (pumping intensity can be reduced respect to the Ne-like scheme).
They are mainly interested in lasing line for Ni-like cadmium at 13.17 nm and Ni-like silver at 13.9 nm.
The appropriate Ni-like spectra have been characterized for cadmium and silver in 2003 and 2004, respectively.
However, for example the 13.2 nm Ni-like cadmium-line (Cd^{20+}) is clearly visible in the EUV spectrum convincing evidence of lasing on these elements was not
yet presented.
How their set-up is working?

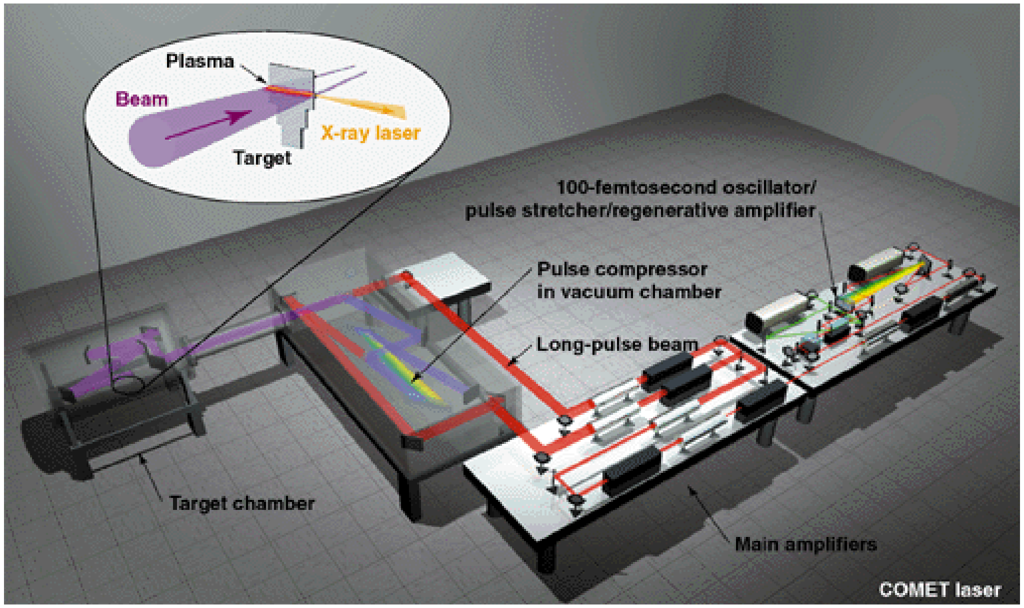
Efforts to decrease the wavelength

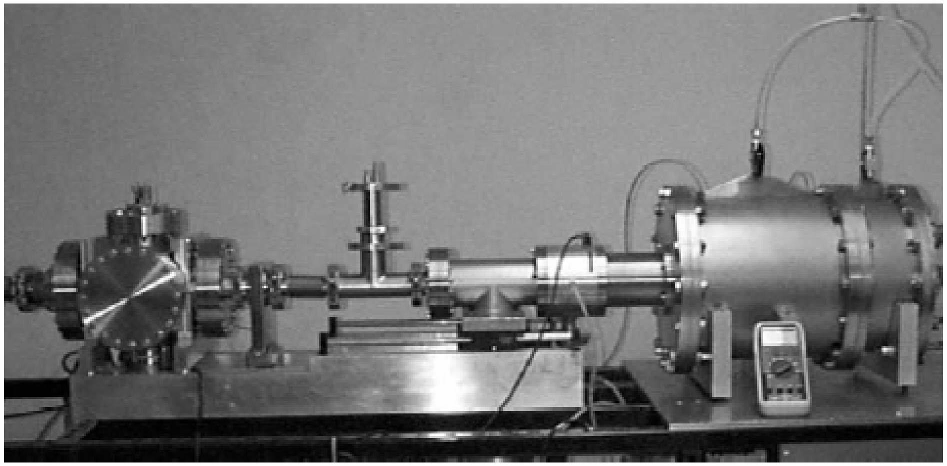
- ICOPS 2004 - Rahman A. - personal communication
  - They are using plastic (polyacetal) capillaries

  (in ceramic capillaries conductive metal layer forms after few shots on the capillary wall)
  - The metal vapor is created by electrode ablation utilizing μs discharges.
  - The desired electron density and temperature is reached by a subsequent main discharge (z-pinch compression).

How to remain “table-top”?

Experimental arrangement of the Livermore’s COMET (compact multipulse terawatt) tabletop X-ray laser. The rendering shows the laser system and the target chamber.
http://www.llnl.gov/str/Dunn.html





Photograph of a table-top capillary discharge soft X-ray laser. The multimeter is shown for size-comparison . ROCCA, J.J. *et al.*, *Nucl. Instr. Meth. Phys. Res. A* **507**, 2003, 515-522.

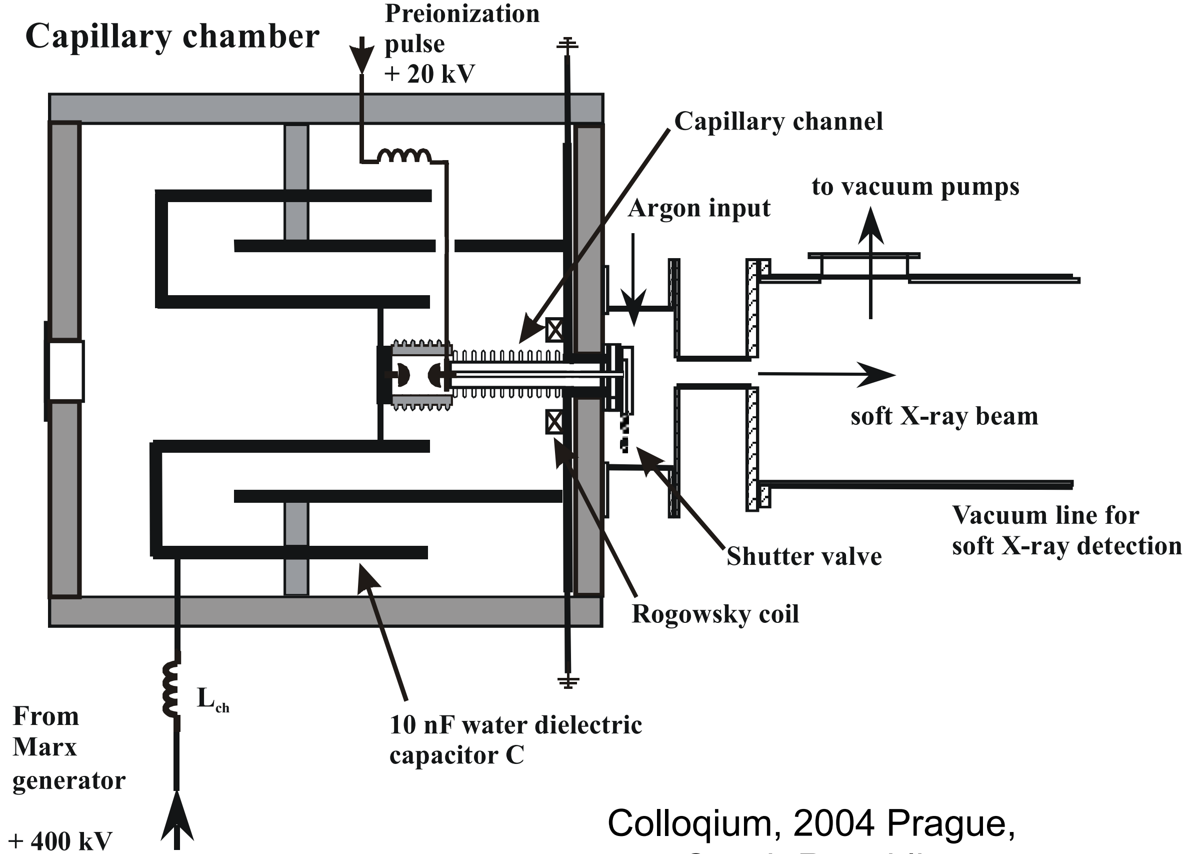
Efforts to decrease the wavelength

Generation of pure, high density and homogenous metal and dielectric vapor plasma by capillary discharge.

S.V. Kukhlevsky et al.: SPIE **3156**, 1997.

Double pulse excitation of x-ray capillary lasers.

S.V. Kukhlevsky et al.: SPIE **3156**, 1997.



Efforts to decrease the wavelength

- Recombination / charge exchange pumping schemes.

  Only relatively small gain-length product was reported (*GL* < 7). In order to utilize these soft X-ray sources for application, further investigation is needed.

- Discharges in methane or nitrogen filled (N^{6+}, 13.4 nm) non-ablative capillaries are considered.

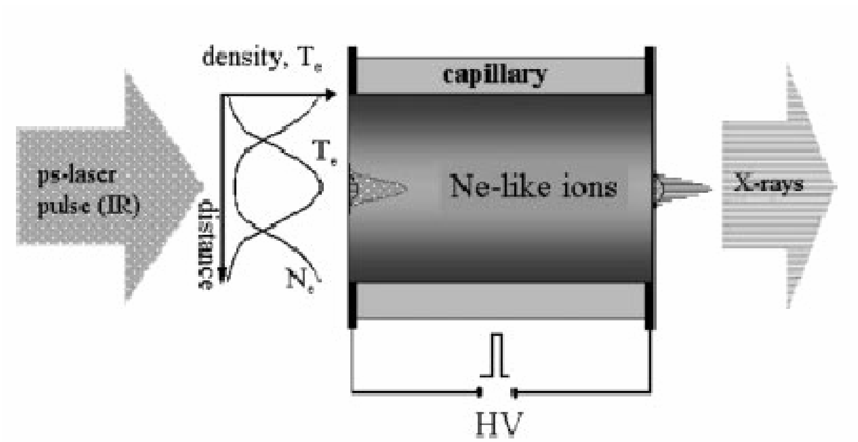
- Optical field ionization and inner-shell transition schemes.

Efforts to decrease the wavelength

- Incoherent EUV sources
  - Main fields of applications (sub-)micro litography, (sub-)micro machining.
- System requirements: high collectable in-band power, low debris production, high-repetition rate and pulse-to pulse repeatability.
- The spectral range of possible EUV sources for microlithography is greatly determined by the available highly reflecting optics in the EUV region. Mo:Si and Mo:Be mirrors attain their highest reflectivity (70%) in the 13-14 nm and 11-12 nm wavelength region, respectively.
- Good results utilizing short, Xe-filled capillary discharges.

Efforts to decrease the wavelength

- Hybrid X-ray lasers.



Experimental arrangement of the hybrid X-ray laser. The concave electron density distribution with minimum on the capillary axis, which is necessary for guiding of the pumping laser pulse, is shown on the left .

- Gas-filled or ablative capillaries are creating a medium, which can be pumped longitudinally by external laser pulse.
- Successful experiment on Ne-like sulfur at 60.8 nm (J.J. Rocca, K.A. Janulewicz in 2001).
- Important to further investigate the waveguiding properties of the created plasma inside the capillary.

Conclusions

- Desired spectral range 11-14 nm (or water-window 4.4-2.2 nm).
- Competitive on size and price.

- Electrically pumped sources
  - *Metal vapor (collisional excitation scheme, Ni-like ions)*
  - Gas filled devices (recombination scheme, N^{6+})

- Hybrid soft X-ray lasers.

- Non-coherent sources

Acknowledgements
J. Kaiser acknowledges the Ministry of Education of Czech Republic (grant J22/98:26L100002) and the Czech Grant Agency (grant GACR202/02/P113).