X-Ray lasers employing capillary discharges

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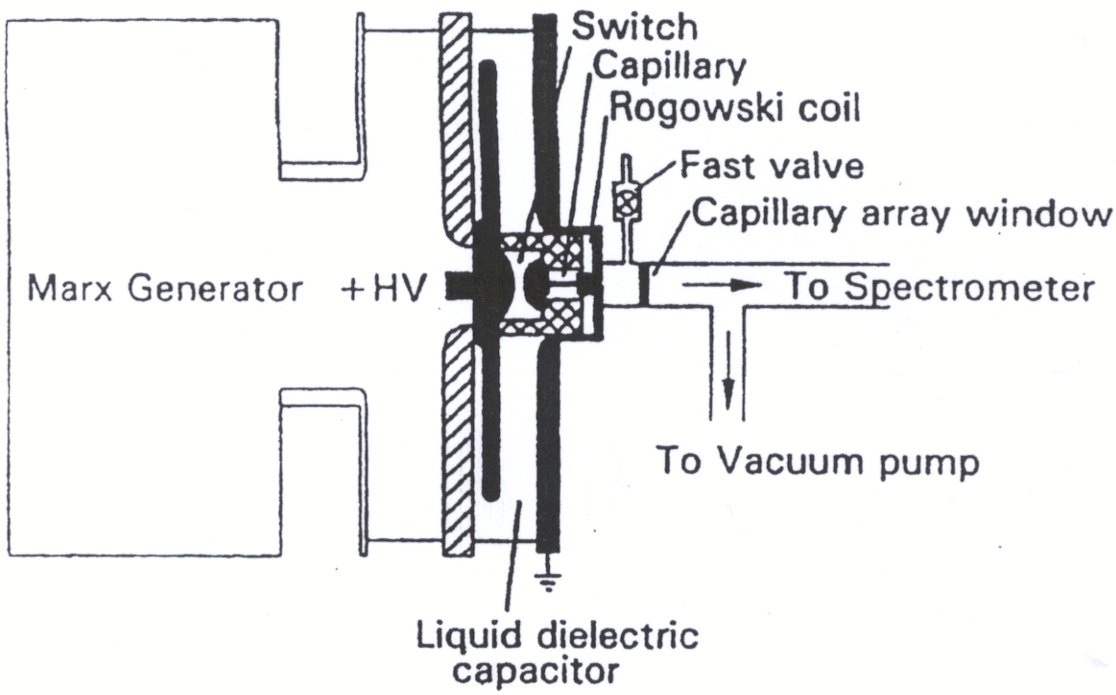
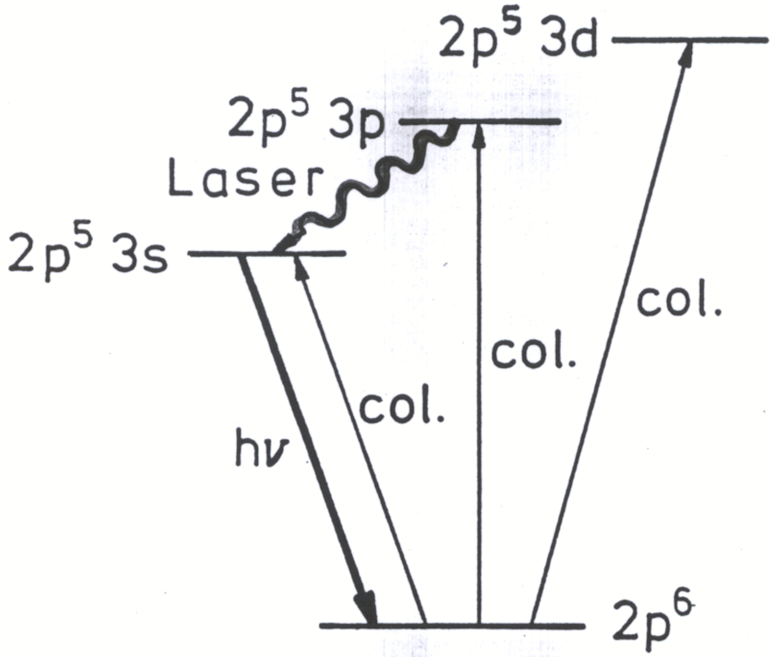
Capillary discharges

a) Gas filling
b) Filled with ablated wall material
a) Group of Rocca and coworkers at Colorado State University was very successful emplying an extremely fast discharge in ArIX at 46.9 nm.



Parameters:	Wavelength	$\lambda = 46{,}9$ nm
	Diameter	$D = 4$ mm
	Length	$L = 20$ cm
	Max. current	$I = 39$kA
	Period	$T/2 = 75$ ns
	Energy	$E \approx$ mJ (!)

X-ray laser scheme using neonlike ions



10 3p levels
4 3s levels

Collisional excitation

$2p \rightarrow 3s$, $2p \rightarrow 3p$, $2p \rightarrow 3d$

of equal magnitude

but

radiative decay of 3p slow

and of 3s very fast

→ population inversion

$$\frac{A}{B} \sim \nu^3$$

Rocca et al. 1994

Capillary discharge, I.D. 4mm,

length up to 20cm in the meantime

Lasing on the A-line of ArIX

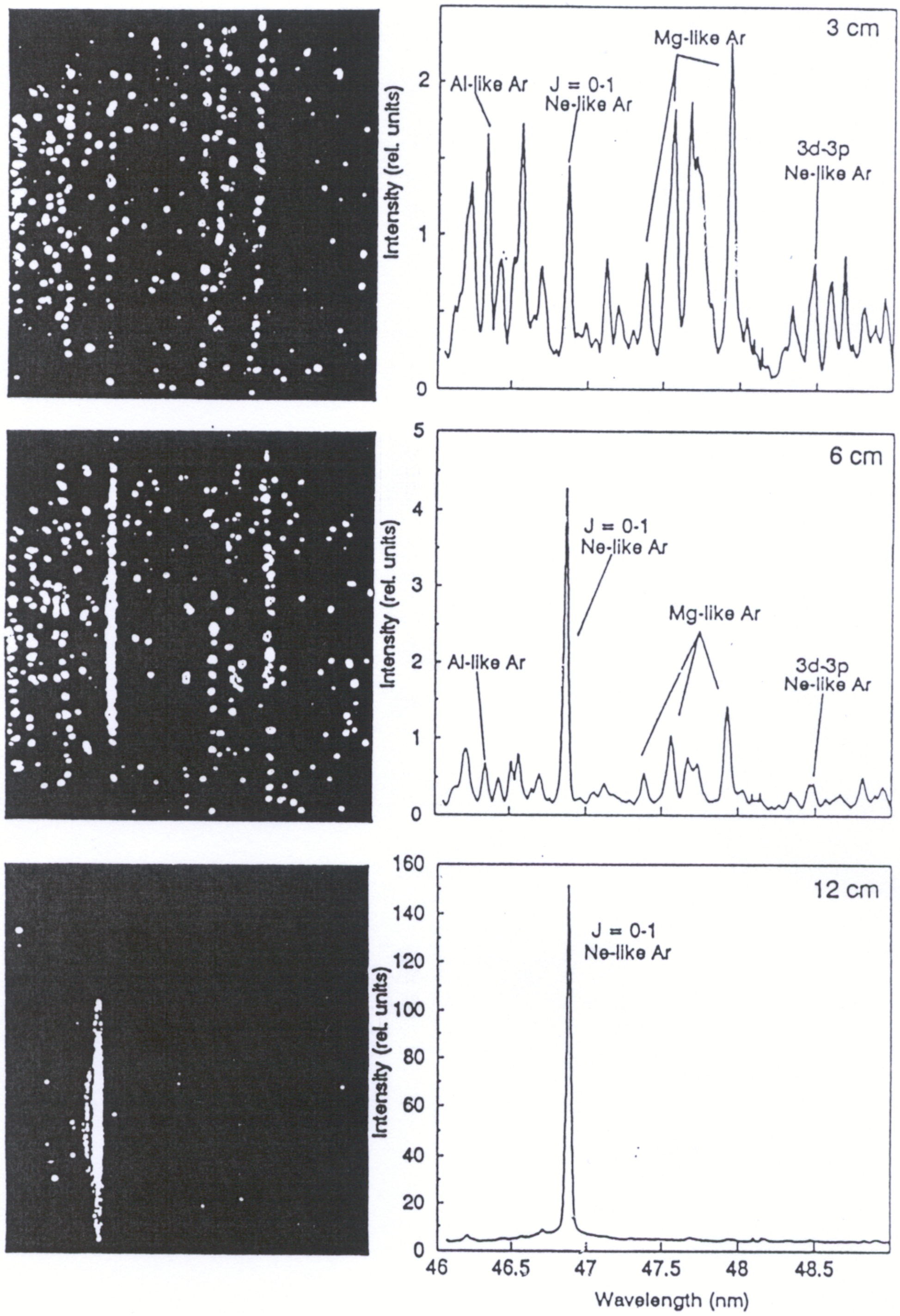


FIGURE 1. Variation of the intensity of the spectral lines in the neighborhood of 47 nm as a function of capillary length. For a 3-cm plasma column, the 46.9 nm $J=0$-1 line of Ne-like Ar is observed to be less intense than the surrounding lines from Mg-like Ar. In the 12-cm plasma column the $J=0$-1 line totally dominates the spectrum.

Capillary discharge in ablated wall material

Experiments were carried out in a number of laboratories (stimulated by early investigations of Bogen and Conrads at Juelich, who found plasma parameters suitable for lasing)

Typical experimental setup (employed, for example, presently in Bochum):

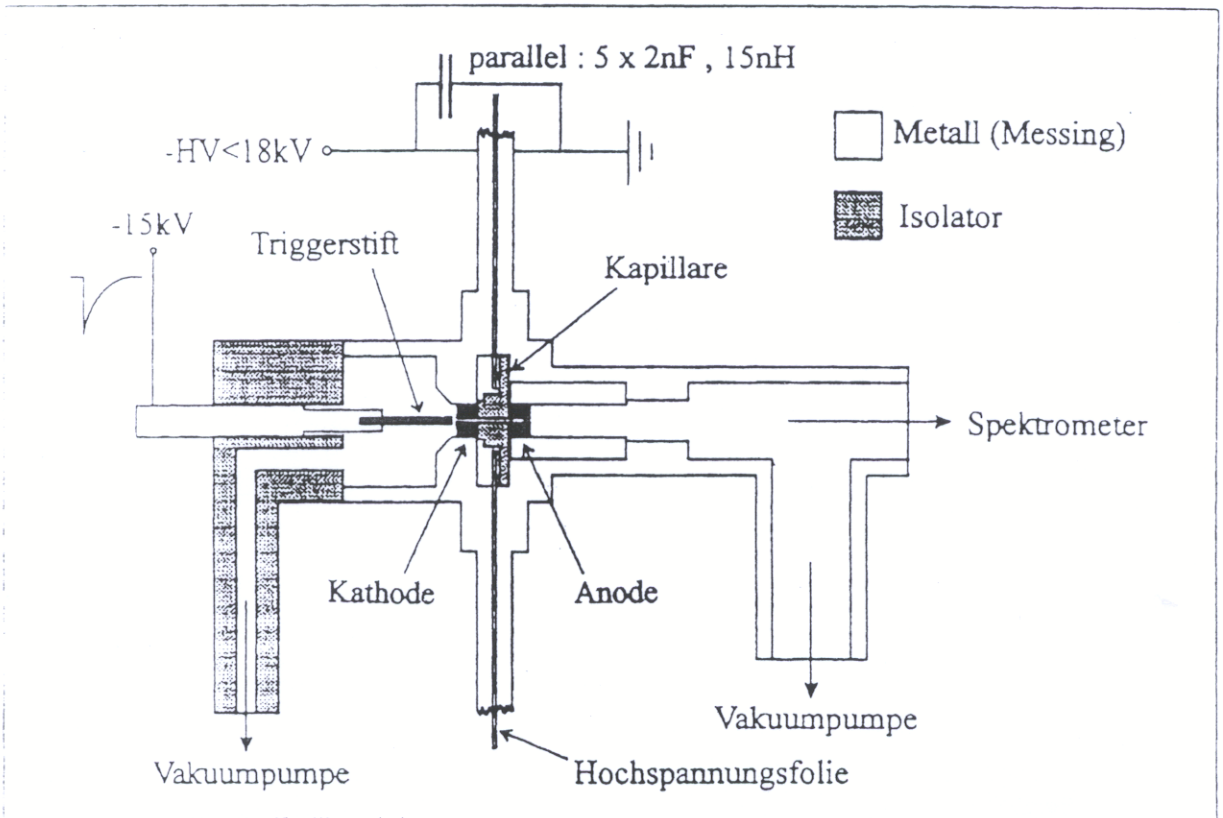
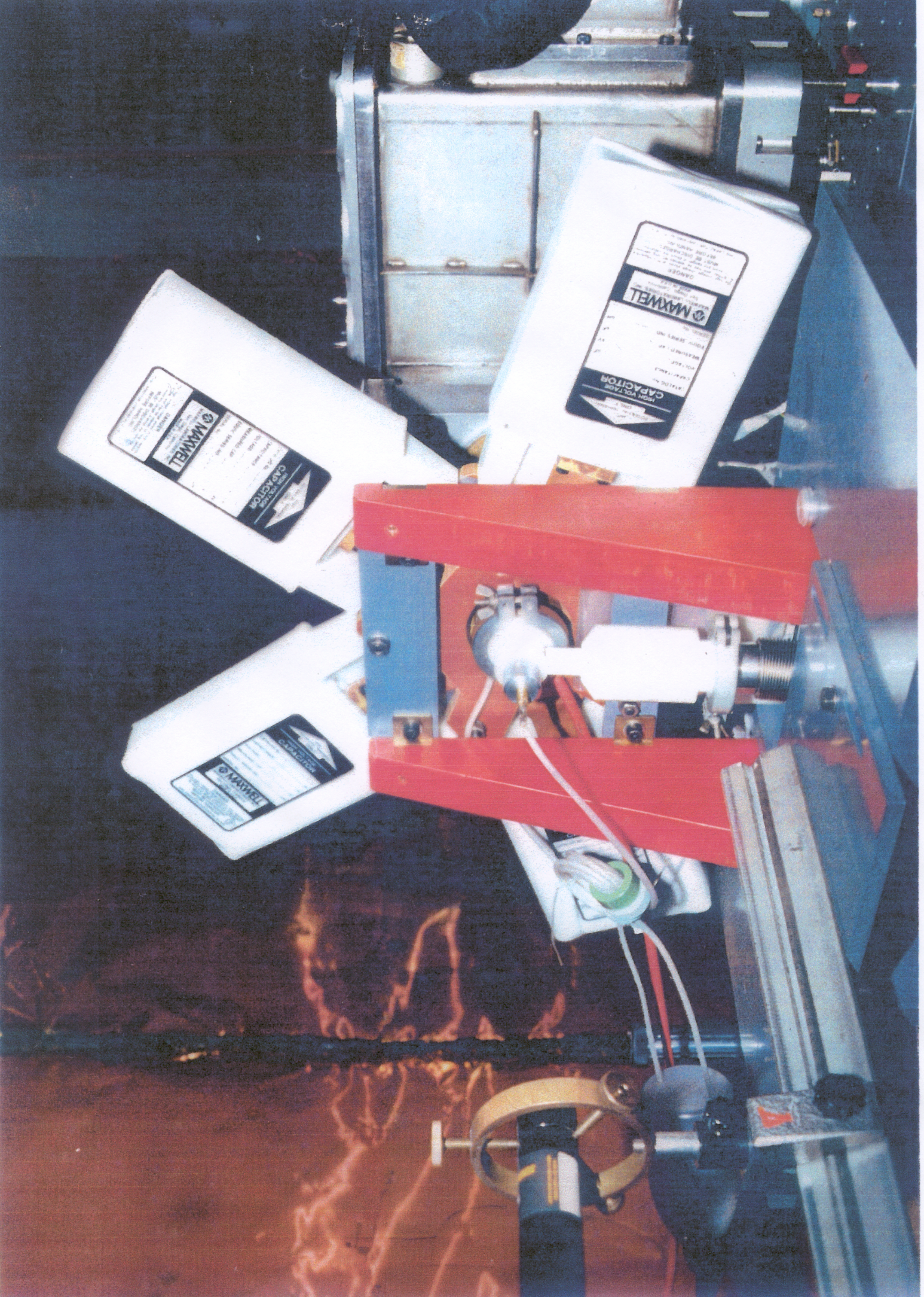
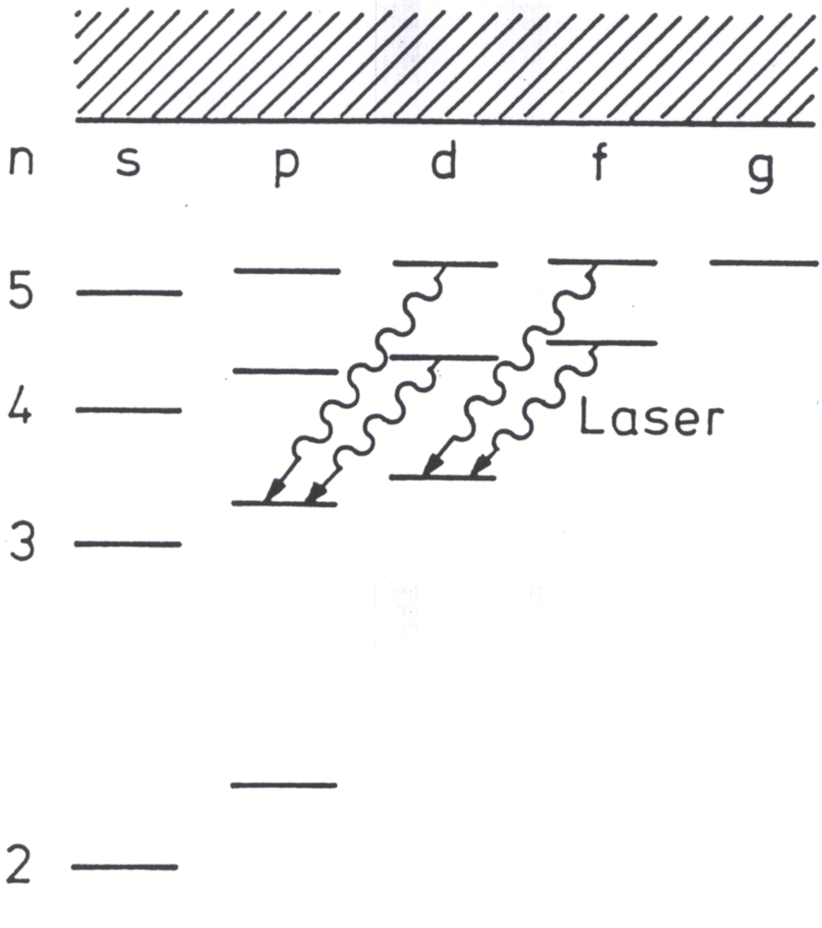


Abb. 3.1 Langsschnitt der Kapillarentladung

Capacitance:	C = 0,1 μF
Period:	T ≈ 180 ns (depends on length of capillary
Diameter:	D = 0,4........1 mm
Length:	L = 1...........5 cm
Wall material	Polyacetal (Polyethylen ?)


MAXWELL
HIGH VOLTAGE
CAPACITOR

X-ray laser scheme using collisional recombination of lithiumlike ions

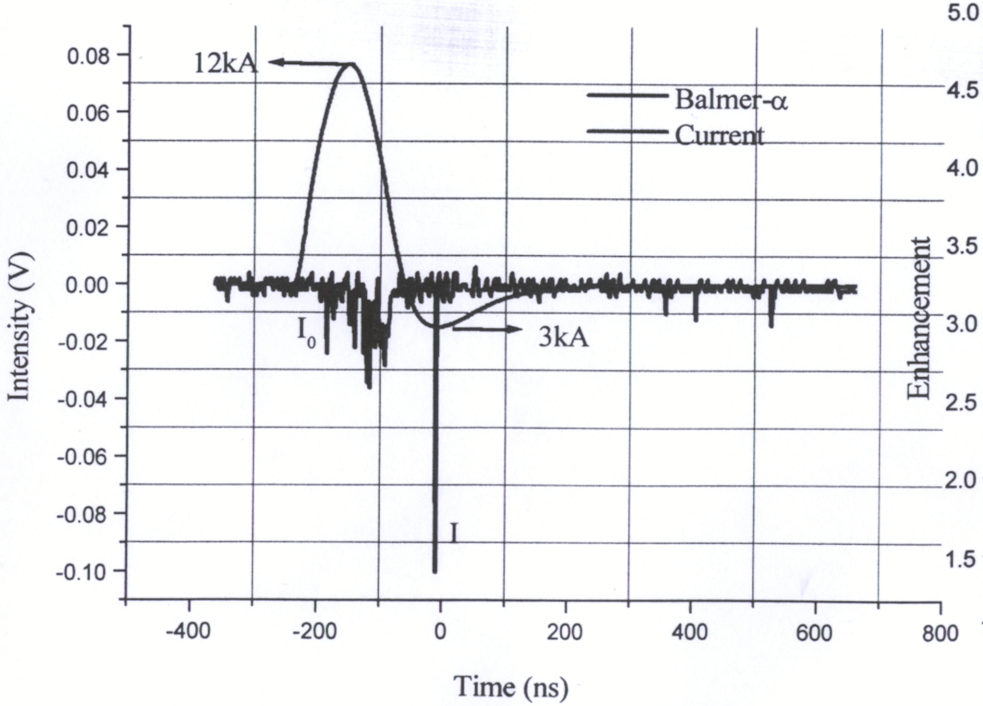


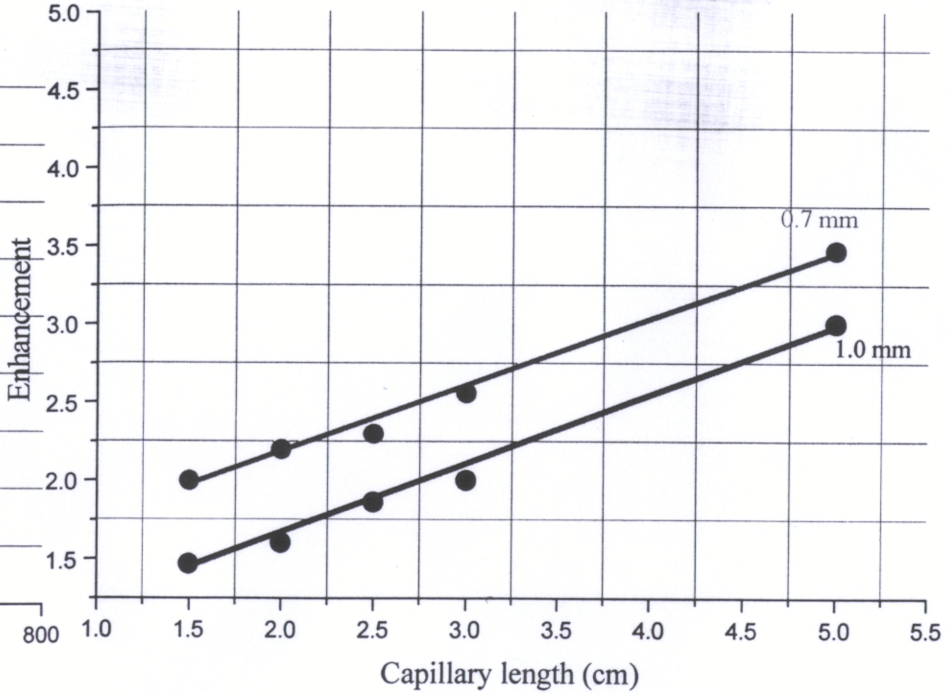
Balmer alpha of CVI at 18.22 nm shows a spike using a straight capillary

Training and Mobility of Researchers

1. The spike occurred during the second half-cycle of the discharge.
2. The spike is not observed on other lines emitted by carbon or oxygen.

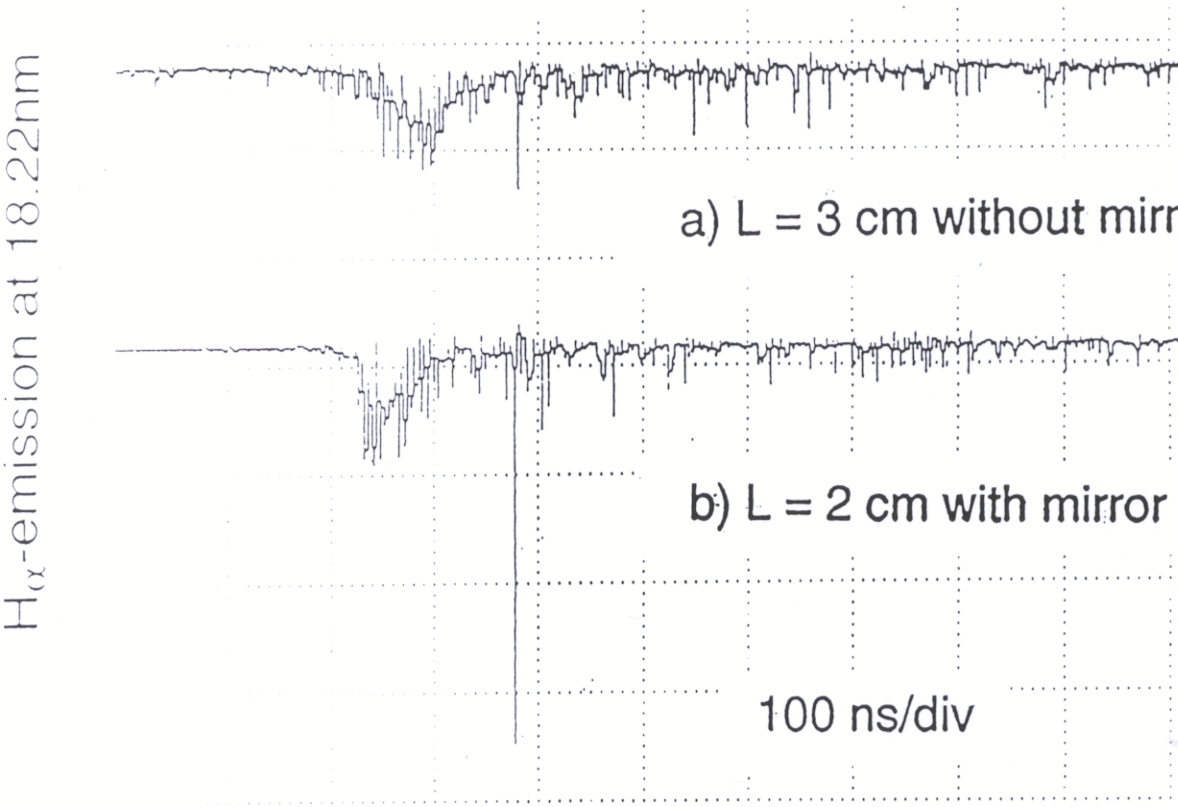
1. An average of 20 shots to represent every point in this figure.
2. All points were taken from the first five discharges.
3. The energy density was kept constant for all the capillaries.





4. Plane multilayer mirror (R = 12%) at one end: spike increases by factors of 1.5 to 1.7 for capillaries of different length corresponding to GL between 2.5 and 2.7.

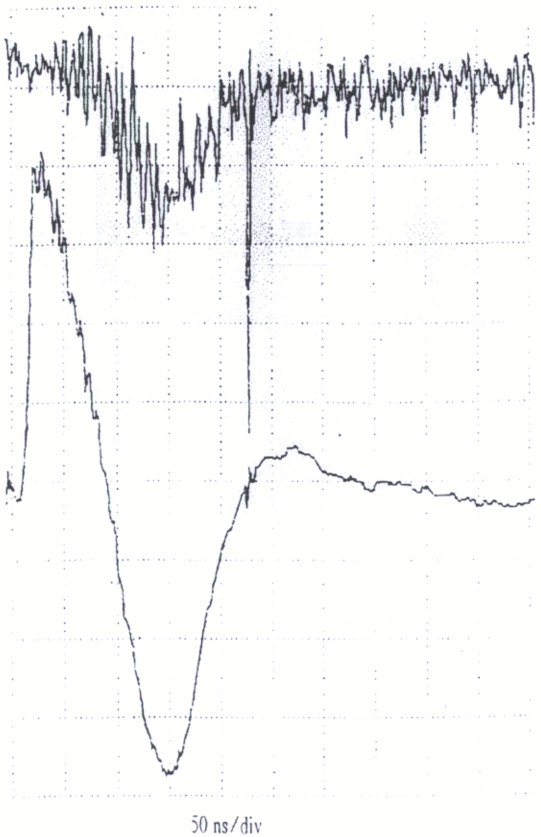
After a few shots effect disappears because multilayer is destroyed !



MHD Instability

dI/dt with a shielded pickup loop

Occurs at the second half of current maximum

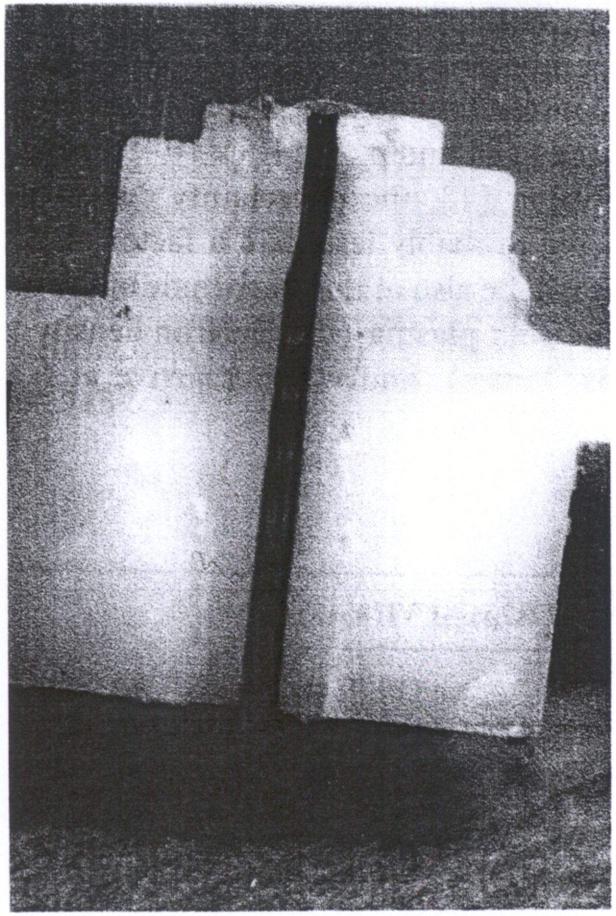


1. Only in one material
2. No correlation between the wavelength of the instability and the length of the capillary.

Evidence of this perturbation is also seen in Z-pinches

Cutting the capillary lengthwise

No spike, no imprint on the inner wall of the capillary



With a_0 = radius of capillary.

and $k = 2\pi/\lambda$ wave number of m=0 instability

we obtained	$ka_0 \approx 2.4$	for	$L = 1$ cm
	$ka_0 \approx 1.6$		$L = 2$ cm
	$ka_0 \approx 0.8$		$L = 3$ cm
	$ka_0 \approx 1.2$		$L = 5$ cm

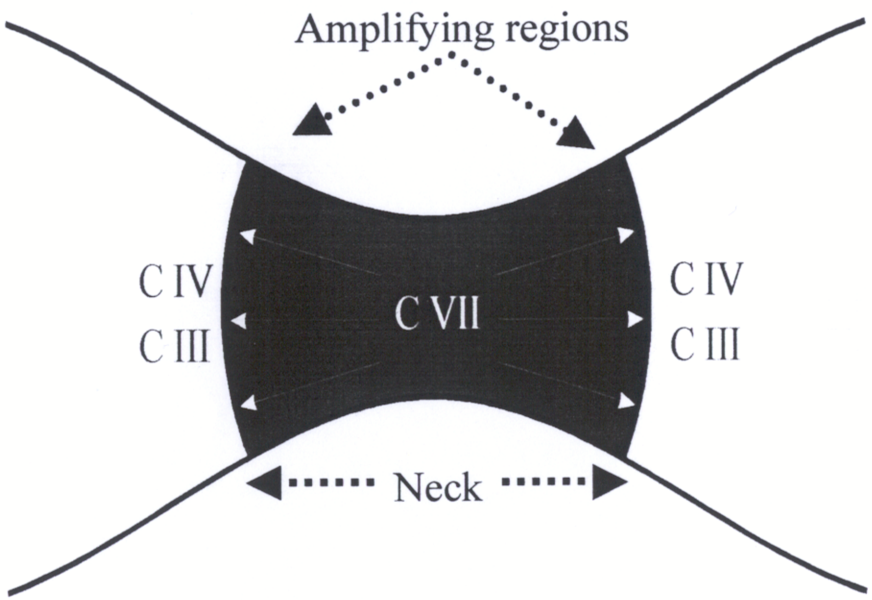
ka_0 is in the range of the maximum growth rate of the $m = 0$ instability ($ka_0 \approx 1$)

and λ increases with L

hence number of active layers per unit length also decreases !

Consequence: enforcing instability with given λ !

Charge Exchange



1. Temperatures above 150 eV are necessary and they are readily obtained in neck regions of an m=0 instability.
2. As a result fully stripped carbon CVII can be obtained at the neck regions.

C VII+ C III (2s2p) ==> C VI (n=3)+C IV

3. We looked at two colliding hot and cold plasmas using carbon targets.

Poster of Lutz Aschke (P.80).

Collision of special interest:

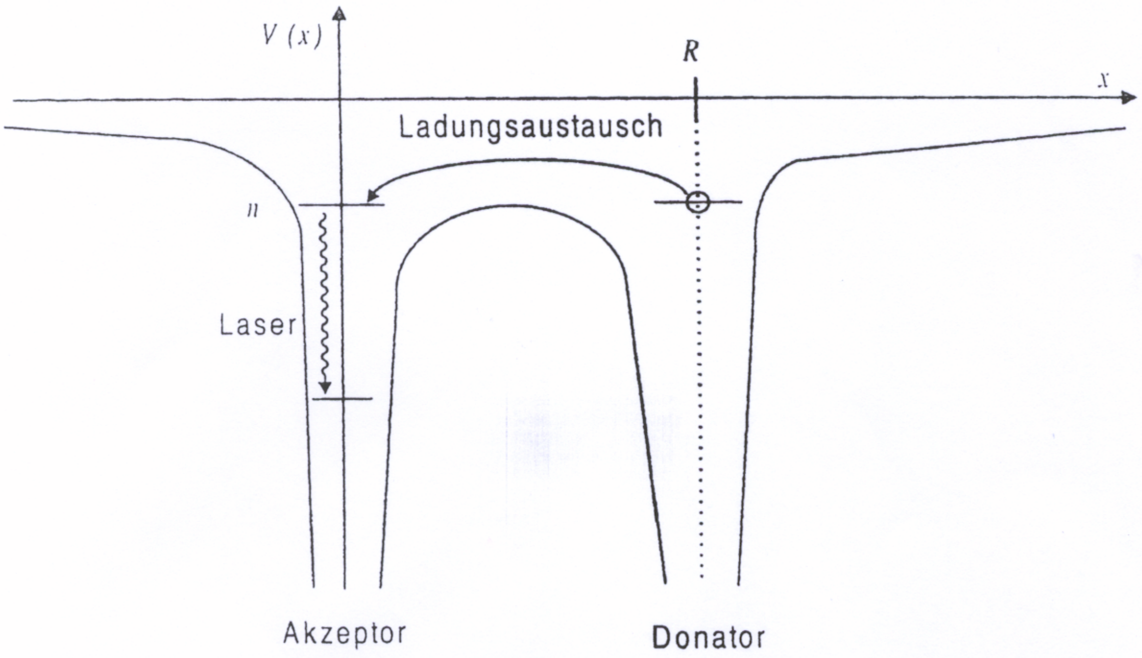
$$C^{6+} + C^{2+} \rightarrow C^{5+}(n{=}3) + C^{3+}$$

Theoretical calculations yielded cross sections

$$\sigma \geq 10^{-15}\ \text{cm}^2$$

at velocities of about 10^7 cm/s

Estimate employing the *overbarrier transition model*



Because of doubts, experimental verification

Theoretische Querschnitte nach Solov'ev

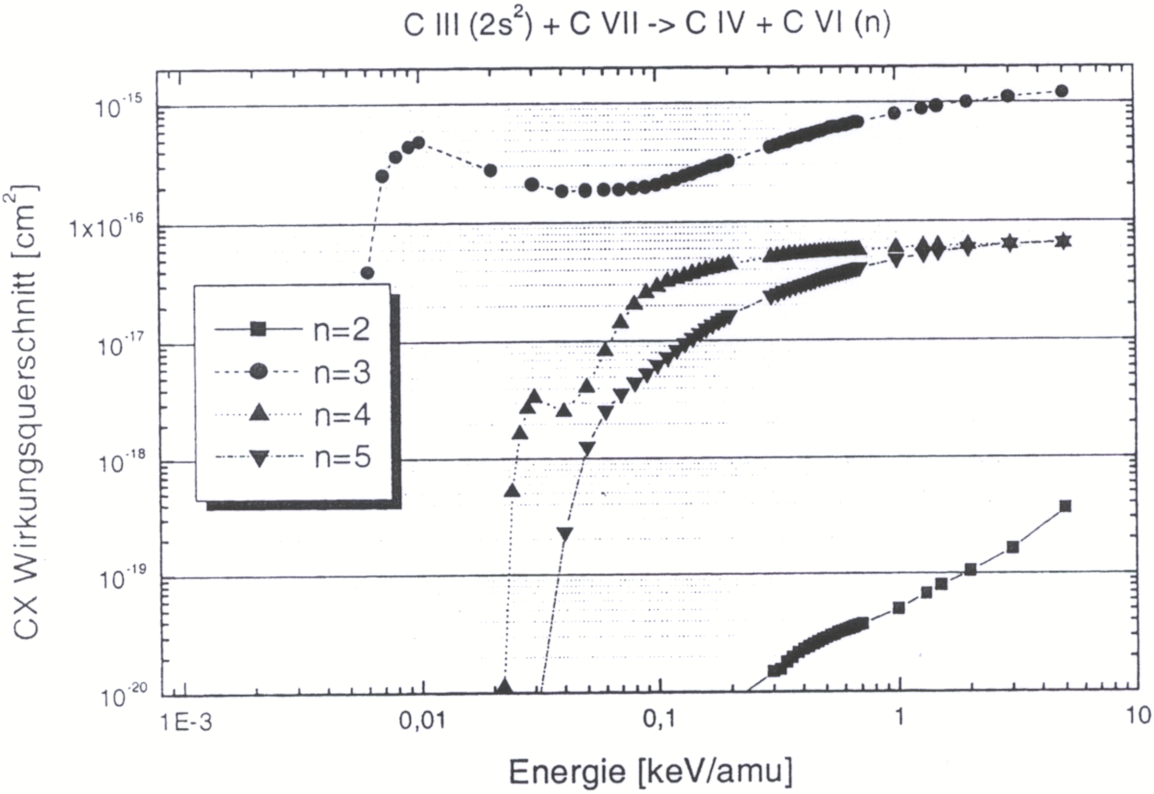


Abb. 2.5: Mit dem Code ARSENY berechnete Wirkungsquerschnitte für Ladungsaustausch von vollionisiertem Kohlenstoff mit C III im Grundzustand nach [Sol99]

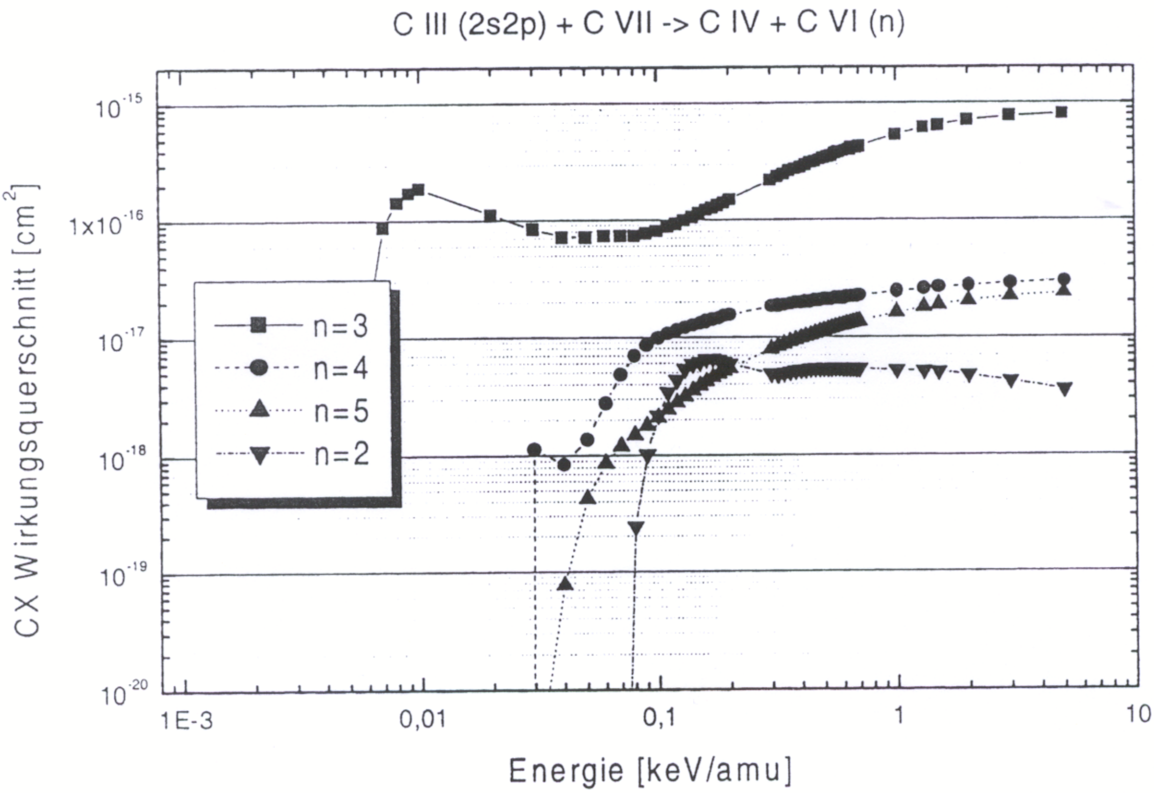
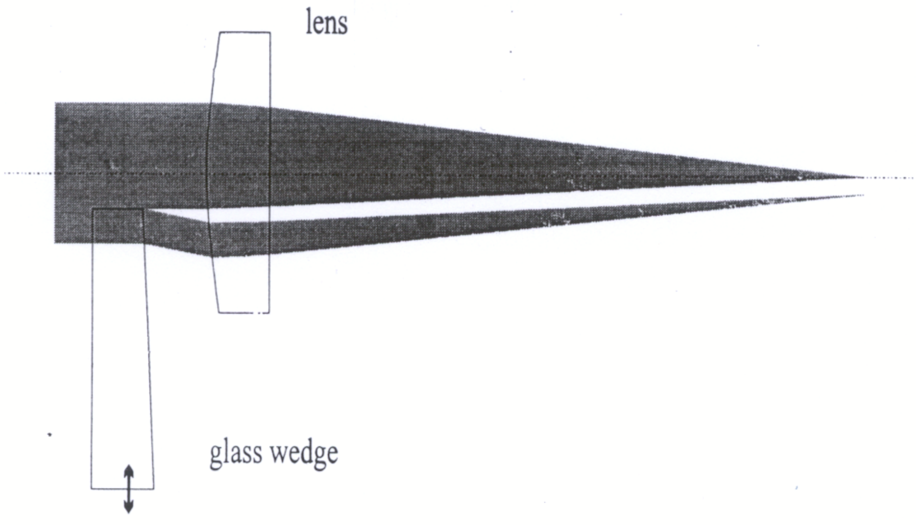
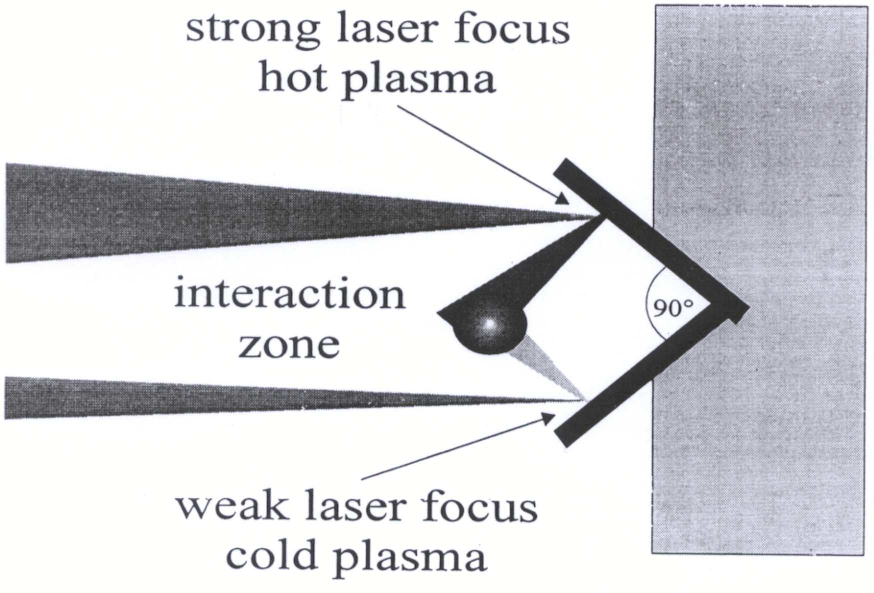


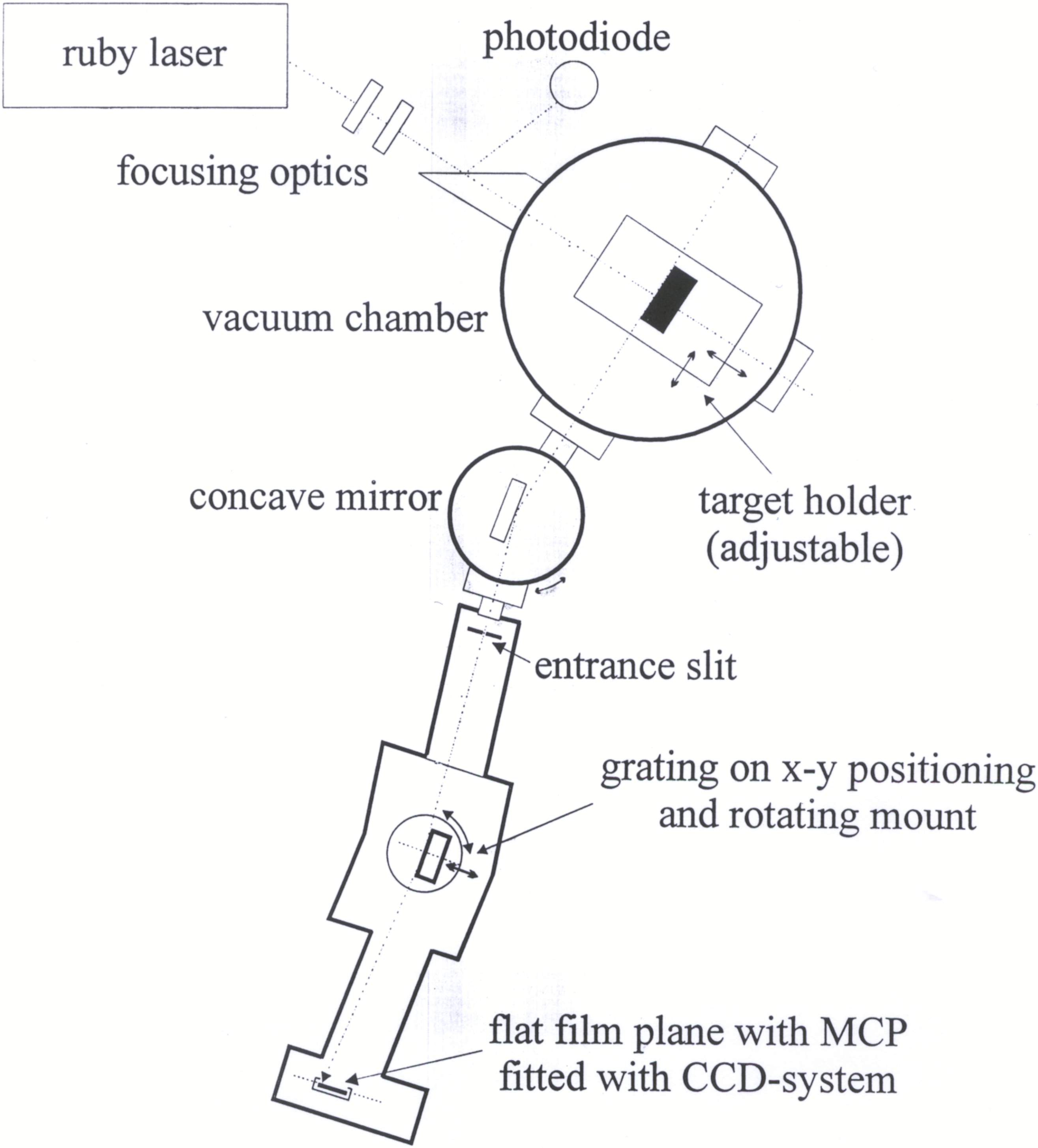
Abb. 2.6: Mit dem Code ARSENY berechnete Wirkungsquerschnitte für Ladungsaustausch von vollionisiertem Kohlenstoff mit C III im ersten angeregten Zustand nach [Sol99]

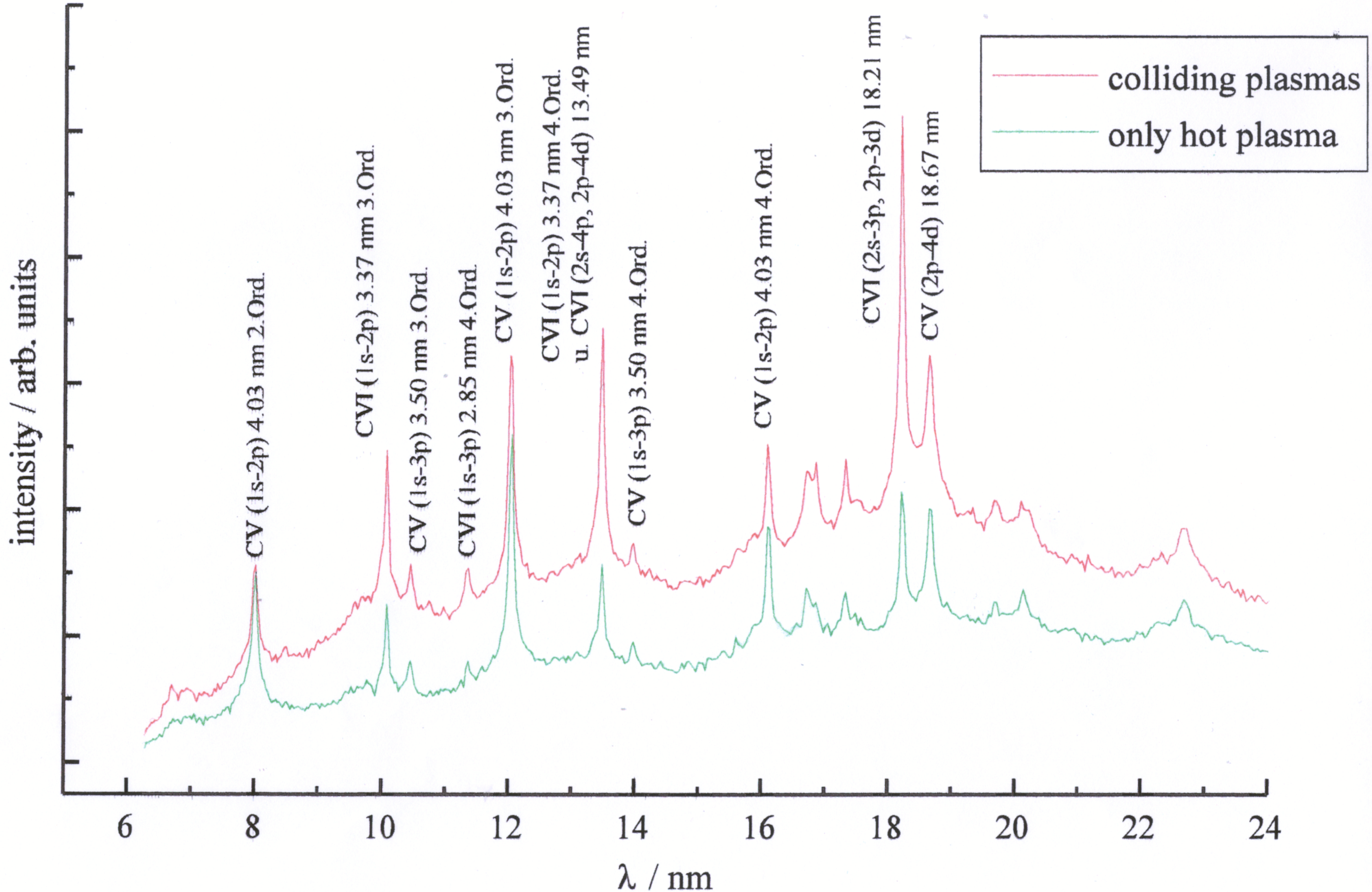
focusing optics

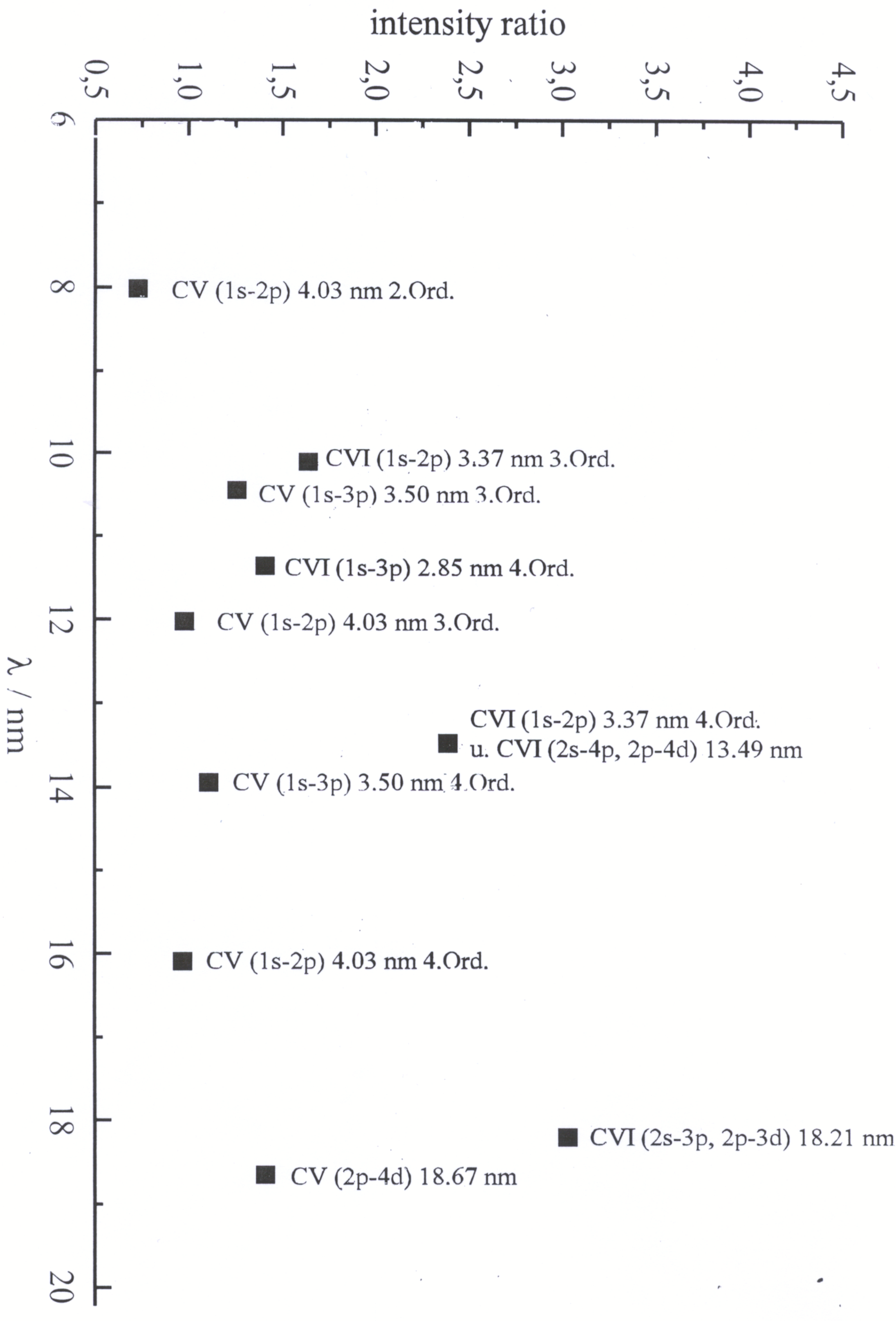


target




ruby laser
photodiode
focusing optics
vacuum chamber
concave mirror
target holder
(adjustable)
entrance slit
grating on x-y positioning
and rotating mount
flat film plane with MCP
fitted with CCD-system


colliding plasmas
only hot plasma
CV (1s-2p) 4.03 nm 2.Ord.
CVI (1s-2p) 3.37 nm 3.Ord.
CV (1s-3p) 3.50 nm 3.Ord.
CVI (1s-3p) 2.85 nm 4.Ord.
CV (1s-2p) 4.03 nm 3.Ord.
CVI (1s-2p) 3.37 nm 4.Ord.
u. CVI (2s-4p, 2p-4d) 13.49 nm
CV (1s-3p) 3.50 nm 4.Ord.
CV (1s-2p) 4.03 nm 4.Ord.
CVI (2s-3p, 2p-3d) 18.21 nm
CV (2p-4d) 18.67 nm
intensity / arb. units
λ / nm
6
8
10
12
14
16
18
20
22
24


intensity ratio
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
λ / nm
6
8
10
12
14
16
18
20
CV (1s-2p) 4.03 nm 2.Ord.
CVI (1s-2p) 3.37 nm 3.Ord.
CV (1s-3p) 3.50 nm 3.Ord.
CVI (1s-3p) 2.85 nm 4.Ord.
CV (1s-2p) 4.03 nm 3.Ord.
CVI (1s-2p) 3.37 nm 4.Ord.
u. CVI (2s-4p, 2p-4d) 13.49 nm
CV (1s-3p) 3.50 nm 4.Ord.
CV (1s-2p) 4.03 nm 4.Ord.
CVI (2s-3p, 2p-3d) 18.21 nm
CV (2p-4d) 18.67 nm

Imprinting structure inside a straight capillary

1. We can fix the wavelength instability and thus, the number of neck regions.
2. We have tested this method by cutting the capillary before using it.
3. We can change the groove spacing.

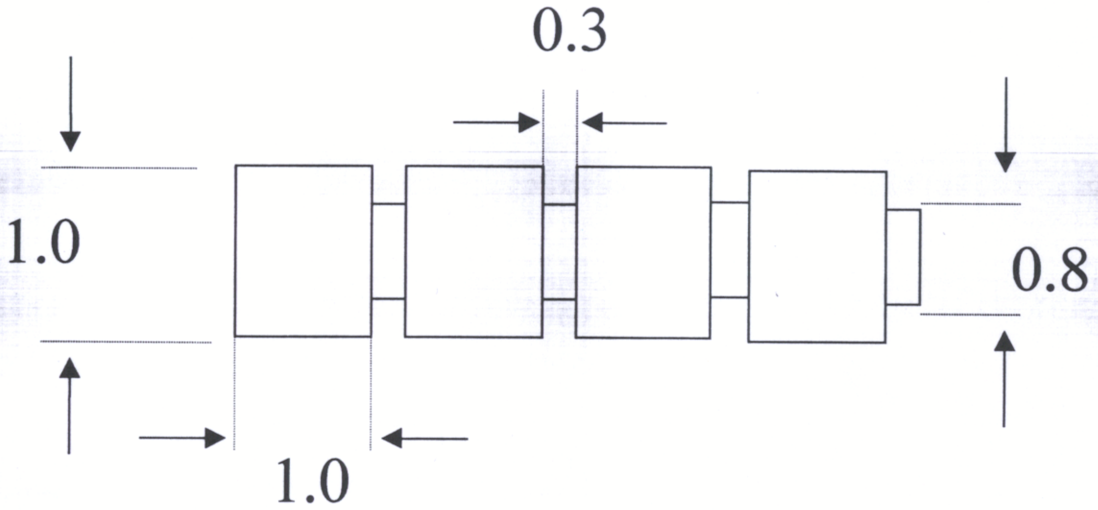


Diagram of steel wire used to make waves in a straight capillary

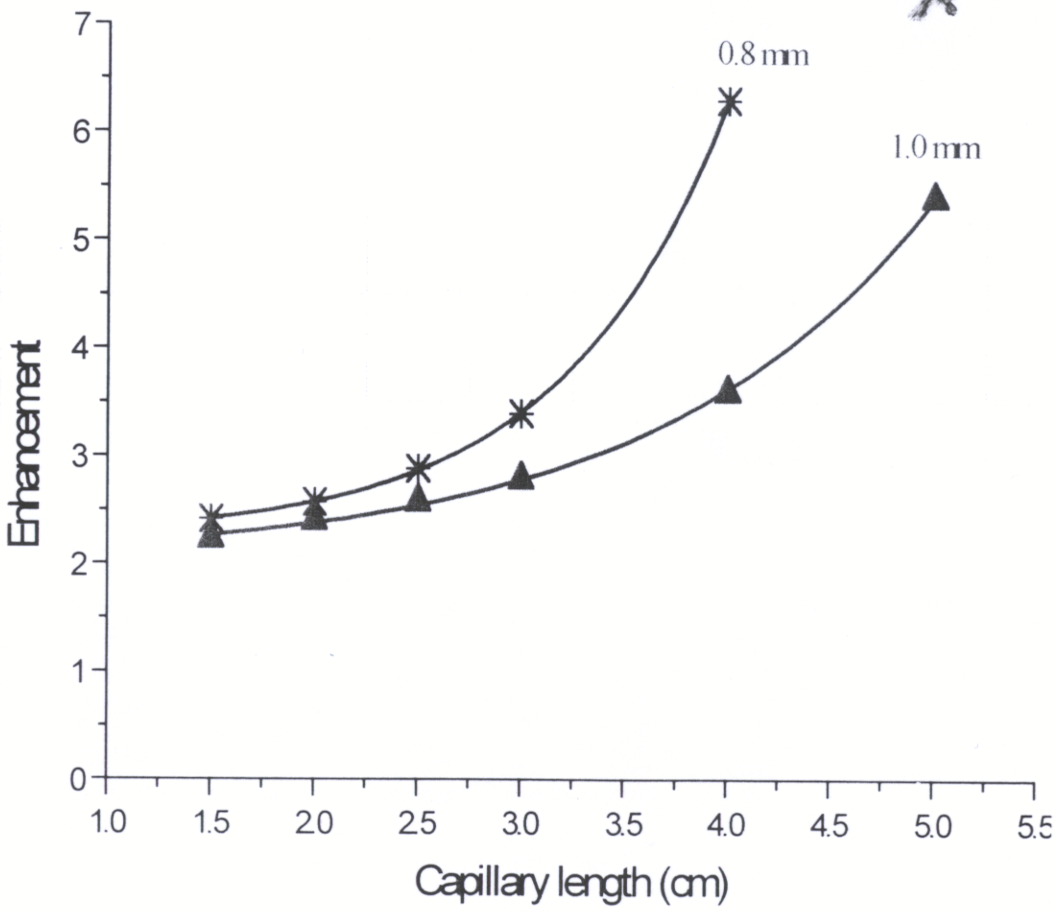
ASE of Balmer-α of CVI at 18.22 nm using a waved capillary

The use of waved capillaries has proven two points

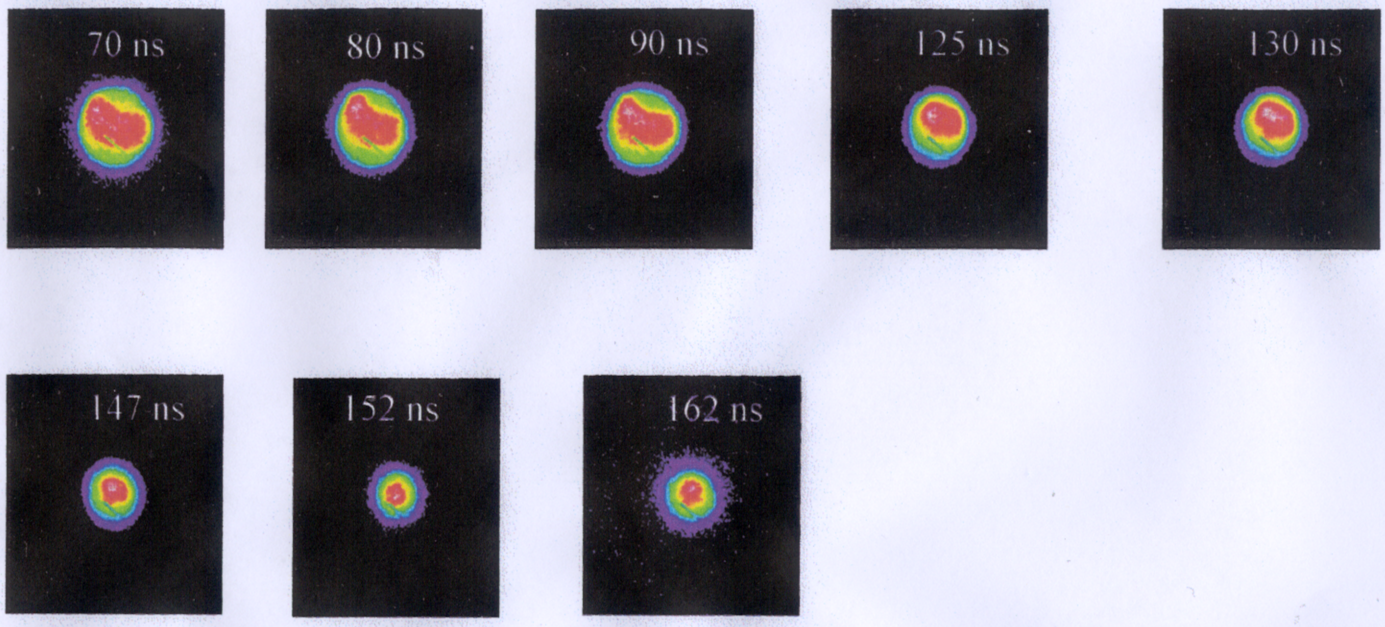
1. The m=0 instability can be forced to follow a certain path or pattern.

However, there is no proof that the instability has followed every groove of the waved structure inside the capillary and that all necks occur within less than 1 ns.

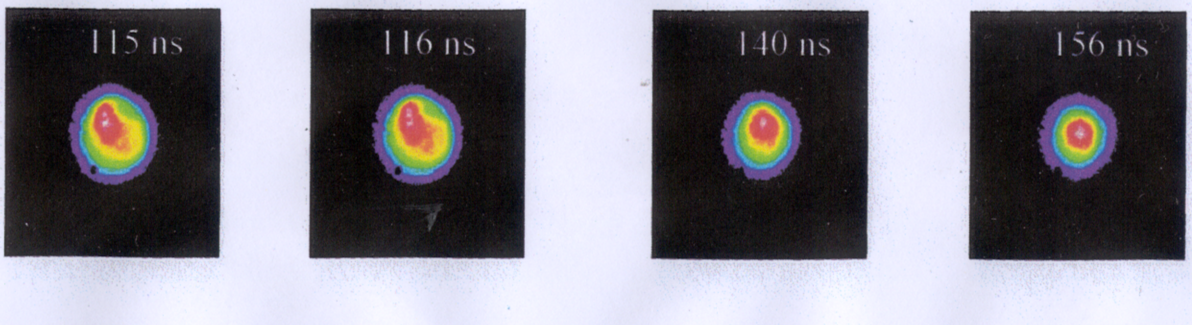
2. The enhancement of the spikes in the waved capillary started to follow an exponential shape.



Lasing capillary POM

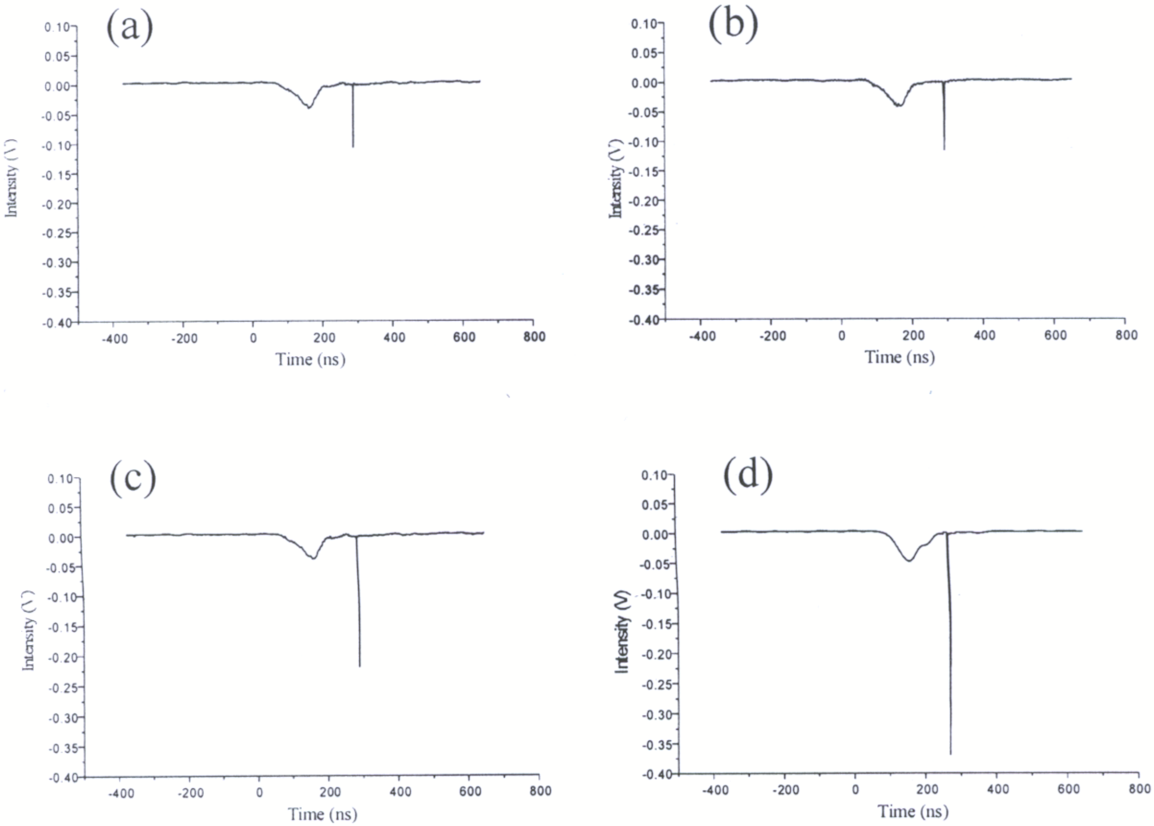


Non Lasing capillary POM



Kapillare mit innerer Wellenstruktur der Wand

Vielfachschichten Spiegel R = 30% bei 18,22 nm



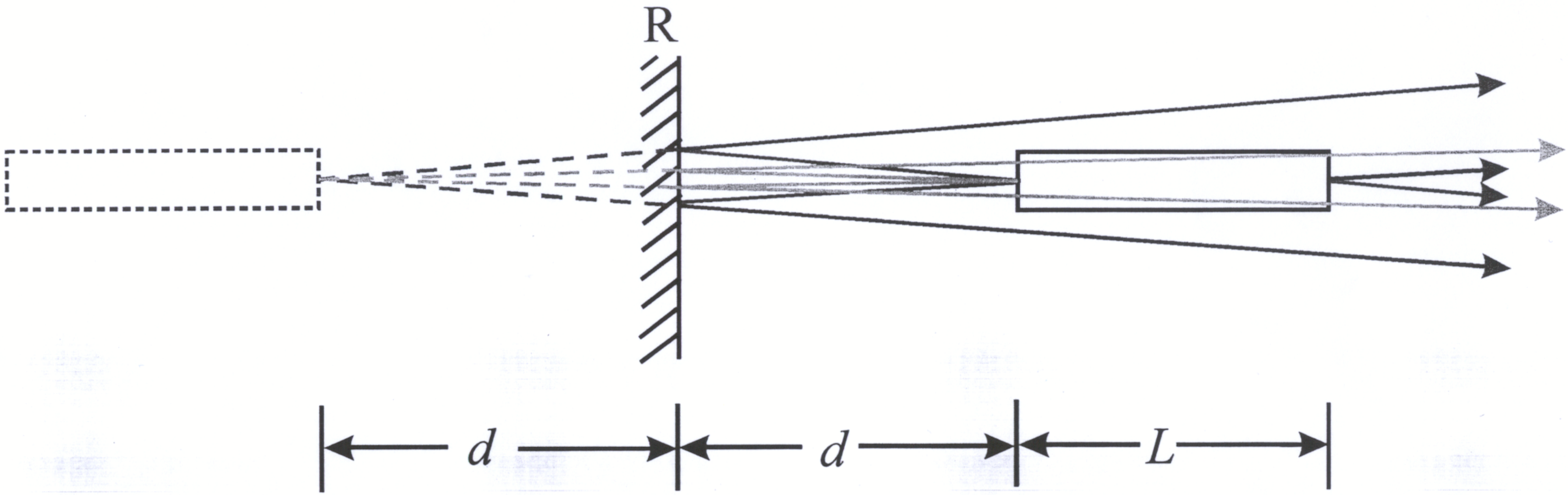
Abstand d: a) ohne Spiegel

b) Abstand 70 mm

c) Abstand 50 mm;

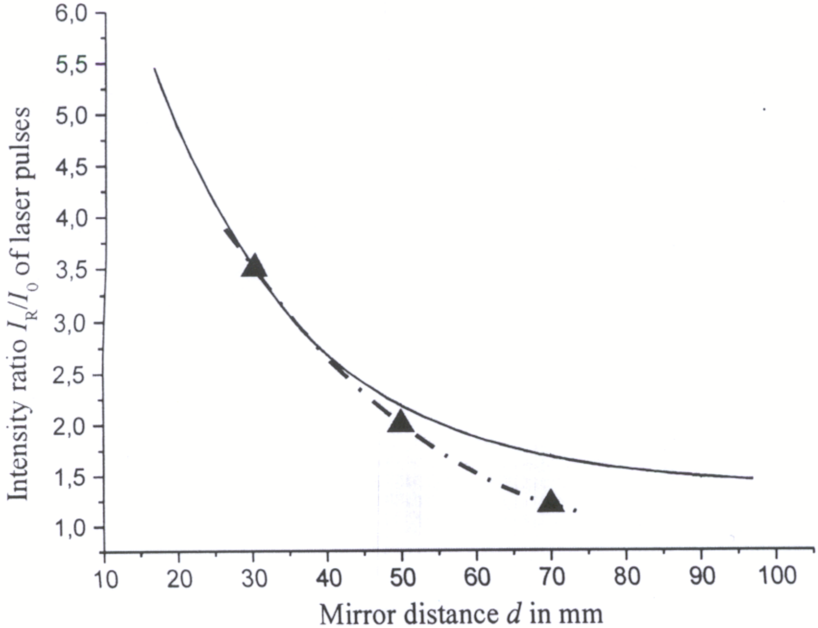
d) Abstand 30 mm

Double pass amplification with mirror



Effective reflectivity $R_{\mathrm{eff}}(d) = R\left[\dfrac{1}{1+2\dfrac{d}{L}}\right]^2$

Observed intensity of laser pulse $I_{\mathrm{R}} = I_0 + I_0 R_{\mathrm{eff}} \exp(GL)$



Deviation between theory and experiment

at $d = 60 \pm 10$ mm

Mean life time of inversion layers

$\tau \approx 400$ ps