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WORKSHOP ON PLASMA PHYSICS

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Laboratory Plasmas as Radiation Sources for the EUV and X-Ray Region

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These are preliminary lecture notes, intended only for distribution to participants.

RUHR-UNIVERSITÄT BOCHUM
INSTITUT FÜR EXPERIMENTALPHYSIK V

Laboratory Plasmas as Radiation Sources for the EUV and X-Ray Region

H.-J. Kunze

Plasma Radiation Sources for the X-Ray Region

Intensive radiation sources for the vacuum-uv and x-ray region are of great interest.

Major developments

a) x-ray lasers (coherent radiation)

b) compact synchrotrons (incoherent)

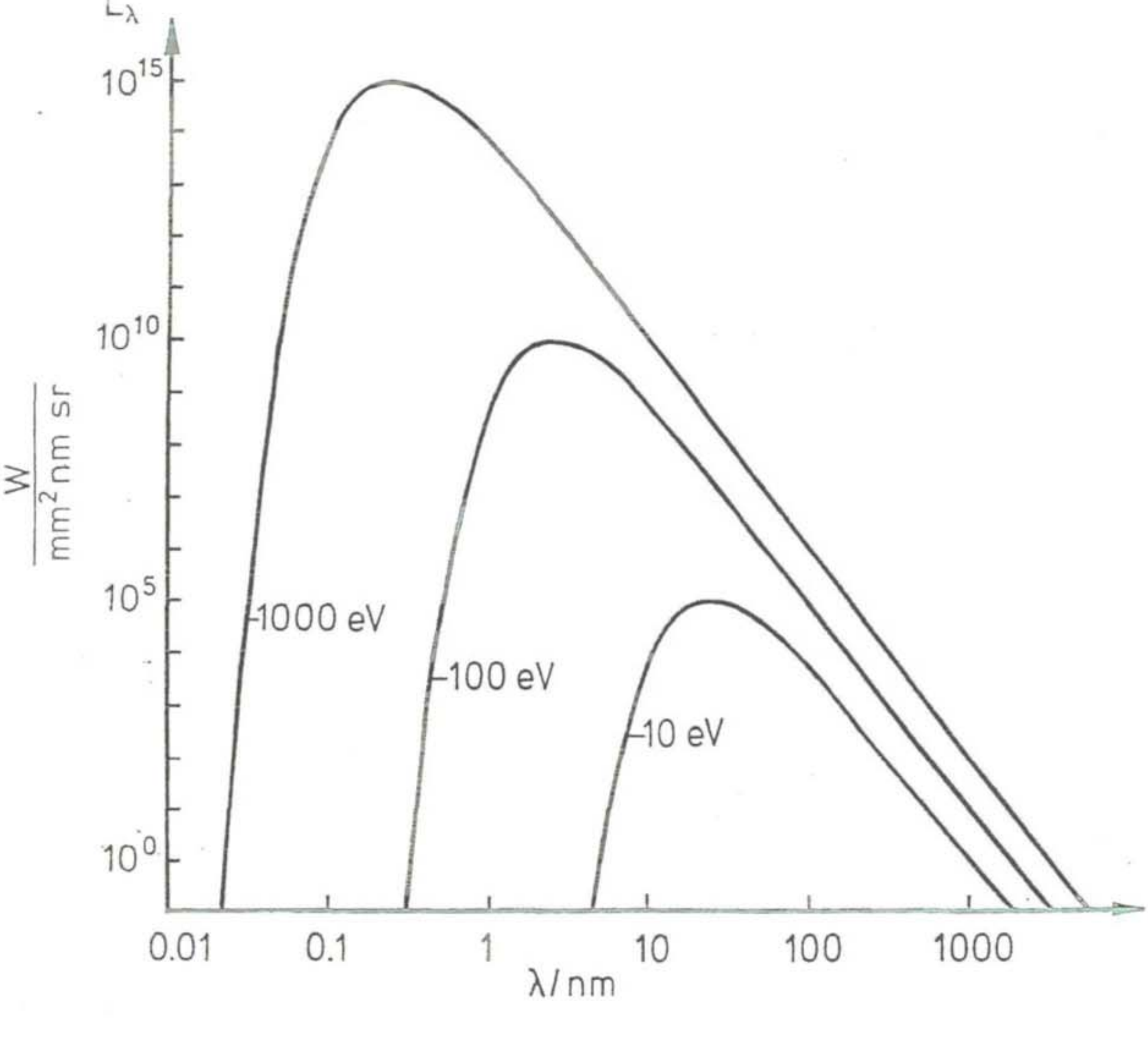
Alternative: incoherent plasma radiation,
although emitted into
solid angle 4π
but now multilayer mirrors!

Applications:

x-ray lithography
x-ray microscopy
radiation source for pumping short-wavelength lasers
medium for short-wavelength lasers
EXAFS
Material irradiation

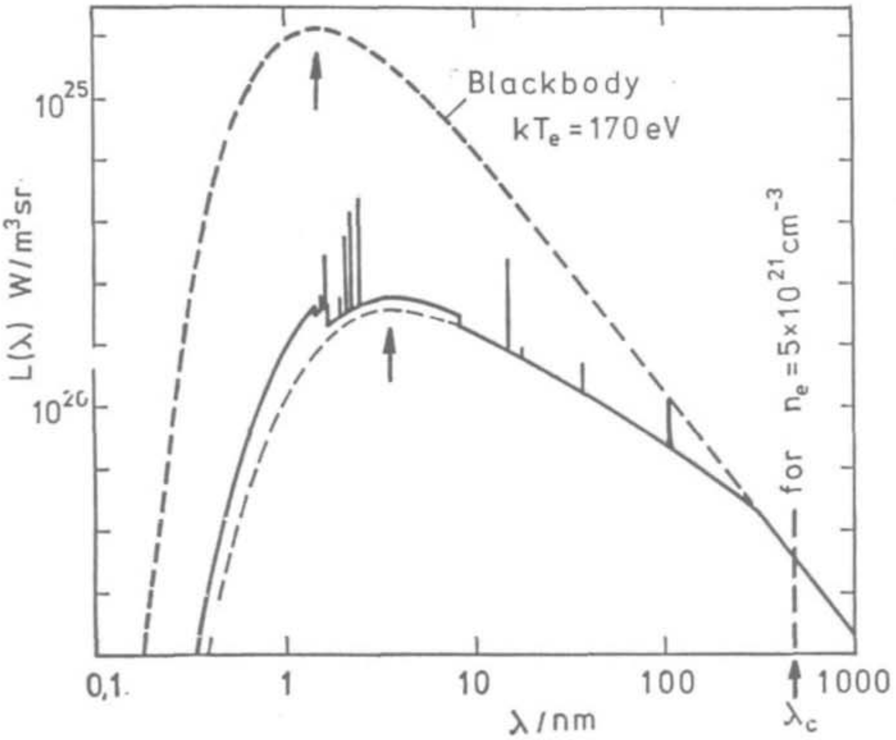
Blackbody radiator at

kT = 10 eV, kT = 100 eV, kT = 1000 eV



Plasmas and the Generation of X-Rays

Hot plasmas emit intense radiation in the x-ray region



Continuum radiation or bremsstrahlung

free - free transitions

Recombination radiation

free - bound transitions

Line radiation

bound - bound transitions

Is it possible to realize a plasma, which radiates like a blackbody ?

Plasma must be optically thick!

Optical depth

$$\tau = \varkappa(\lambda)\, d \geq 5$$

For bremsstrahlung

$$\frac{\varkappa(\lambda)}{\mathrm{m}^{-1}} = 3{,}45\times10^{-57}\, Z^2 \left\{\frac{\lambda}{\mathrm{nm}}\right\}^{3} \left\{\frac{E_H}{kT}\right\}^{1/2} \times$$

$$\times\, G^{ff}\, \frac{n_e}{\mathrm{m}^{-3}}\, \frac{n_i}{\mathrm{m}^{-3}}$$

Mit $Z n_i \simeq n_e$

kT / eV	λ_{max} / nm	Z	$\frac{n_e^2\, d}{\mathrm{m}^{-5}}$
1000	0.25	11 (Na)	7.2×10^{58}
100	2.5	6 (C)	4.2×10^{55}
10	25	3 (Li)	2.7×10^{52}

kT/eV	n_e/cm^{-3}	
	d = 10 cm	d = 1 mm
1000	8.5×10^{23}	8.5×10^{24}
100	2.0×10^{22}	2.0×10^{23}
10	5.2×10^{20}	5.2×10^{21}

Energy of plasma (≈1 keV):

$3/2\,(n_e + n_i)kT + E_{ion} \rightarrow$ megajoules / cm^3

Line radiation !

Optical depth of a line

$$\tau(\lambda) = \pi\, r_e\, \lambda^2\, f_{qp}\, n(q)\, S(\lambda)\, d$$

r_e = classical electron radius

f_{qp} = oscillator strength

$n(q)$ = density of the atoms in the lower level q

$S(\lambda)$ = line profile function

We now consider the center λ_0 of a Doppler broadened strong line

i.e. $f_{qp} \approx 1$:

$$\tau = 1.08 \times 10^{-19} \frac{\lambda_0}{\mathrm{nm}} \frac{n(q)}{\mathrm{m}^{-3}} \frac{d}{\mathrm{m}} \left\{\frac{m_A/u}{kT/eV}\right\}^{1/2}$$

$$\underline{\tau(\lambda_0) \sim \lambda_0}$$

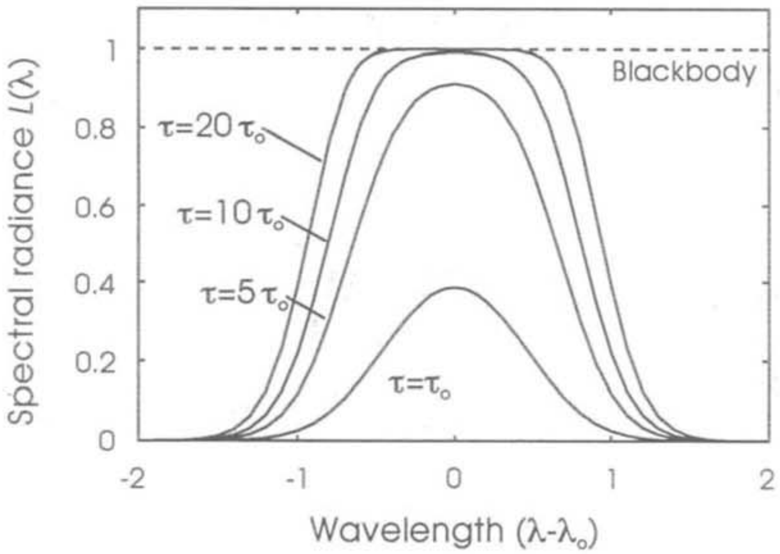
Example:

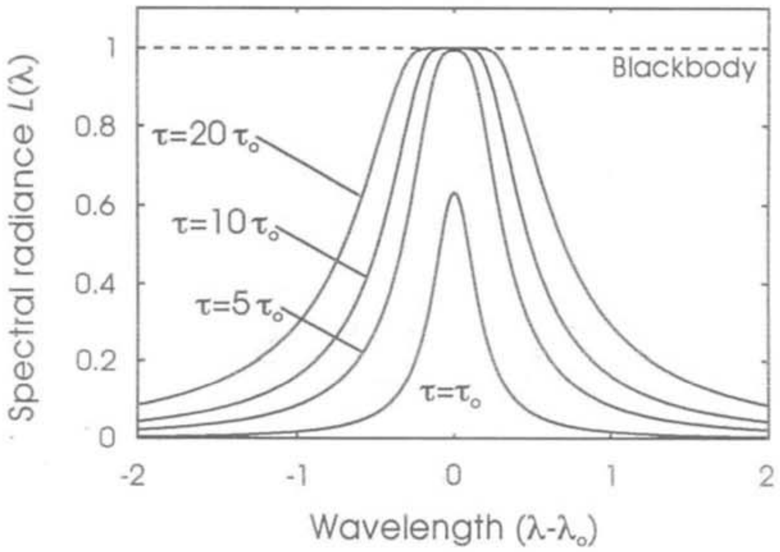
For $\tau(\lambda_0) \geq 5$ where $\lambda_0 = \lambda_{max}$ (at λ_{max} be the maximum of the blackbody radiation)

$m_A = 20$

kT/eV	λ_{max}/nm	$n(q)$ / cm^{-3}	
		d = 10cm	d = 1mm
1000	0.25	1.3×10^{16}	$1,3 \times 10^{18}$
100	2.5	4.1×10^{14}	4.1×10^{16}
10	25	1.3×10^{13}	1.3×10^{15}

Although the spectral radiance of these lines corresponds to that of a blackbody, the total energy content of the plasma can be relatively small!


Spectral radiance $L(\lambda)$
Wavelength $(\lambda-\lambda_o)$
Blackbody
$\tau=20\,\tau_o$
$\tau=10\,\tau_o$
$\tau=5\,\tau_o$
$\tau=\tau_o$
0
0.2
0.4
0.6
0.8
1
-2
-1
0
1
2


Spectral radiance $L(\lambda)$
Wavelength $(\lambda-\lambda_o)$
Blackbody
$\tau=20\,\tau_o$
$\tau=10\,\tau_o$
$\tau=5\,\tau_o$
$\tau=\tau_o$
0
0.2
0.4
0.6
0.8
1
-2
-1
0
1
2

Which radiance is obtained in a single line?

For $\tau(\lambda_0) = 5$ the width of an optically thick line is approximately

$$\Delta\lambda \approx \Delta\lambda^{D}_{1/2}$$

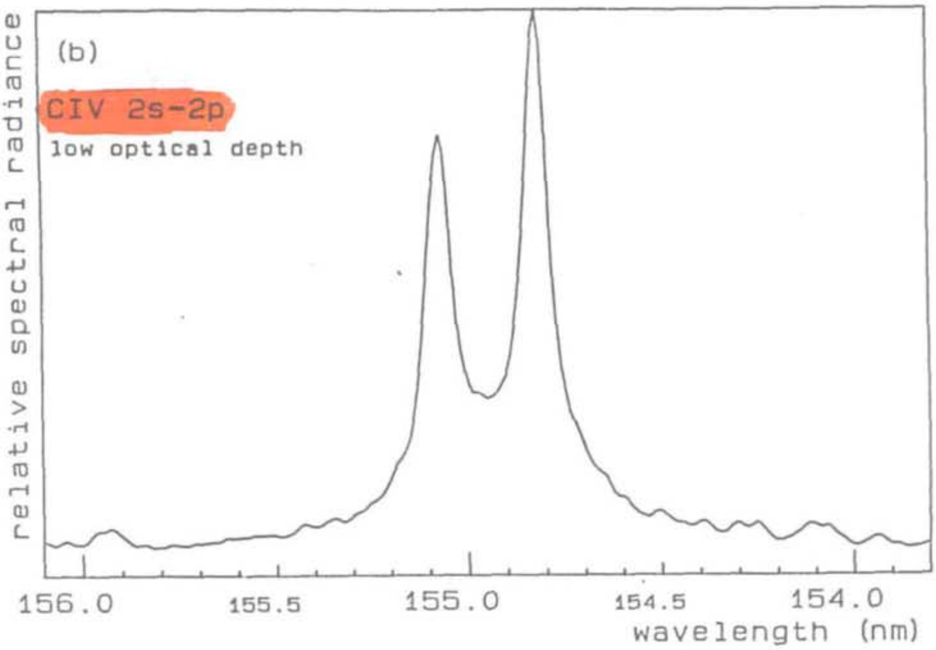
We take again $m_A = 20$

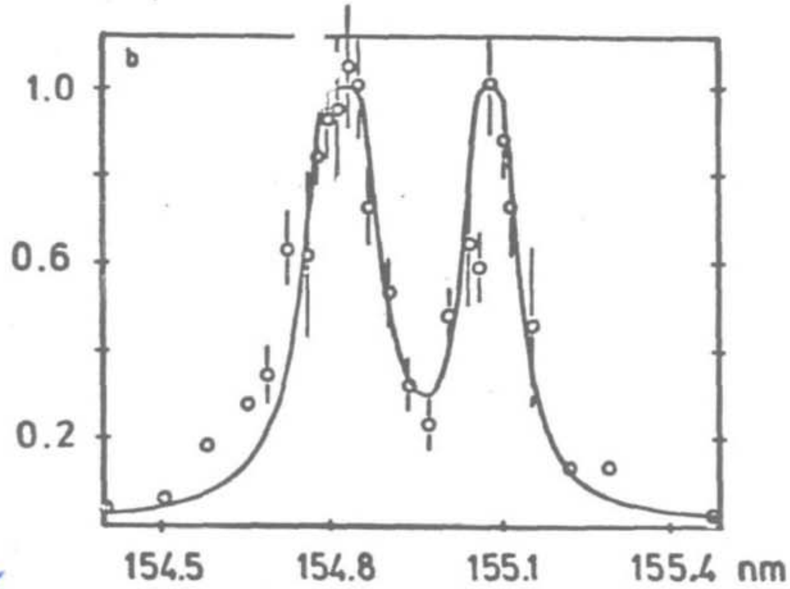
$$\lambda^{D}_{1/2} = 7.7 \times 10^{-5} \left\{\frac{kT/eV}{m_A/u}\right\}^{1/2} \lambda_0$$

We obtain:

kT/eV	$L_\lambda \Delta\lambda$ / $W\,mm^{-2}\,sr^{-1}$
1000	1.2×10^{11}
100	3.7×10^{6}
10	1.2×10^{2}

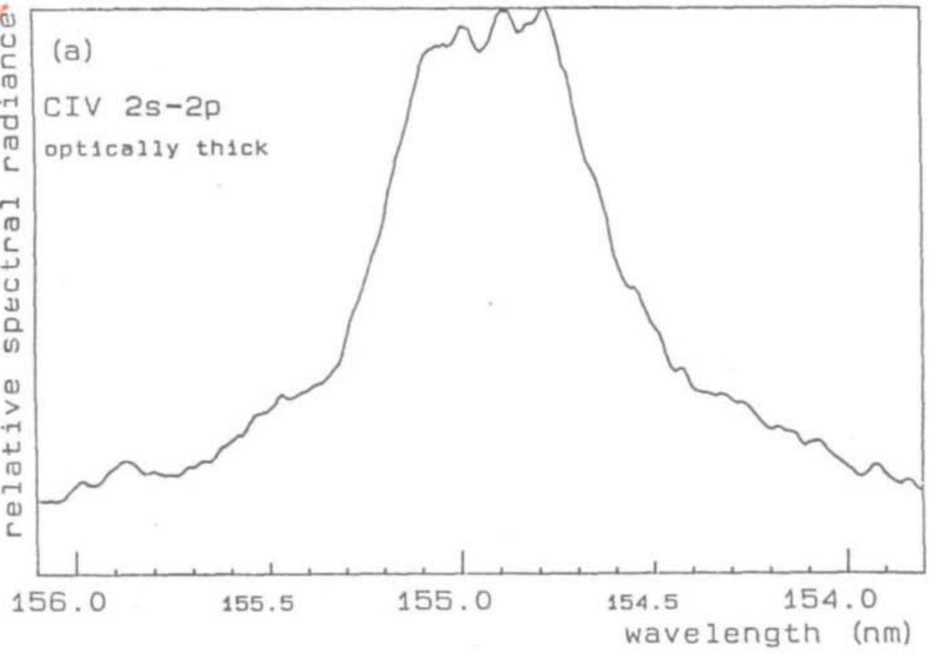
Lifetime of such plasmas?
Emitted energy?





$T = 120\,000\,K$

$L = 100\,\frac{kW}{cm^2}$



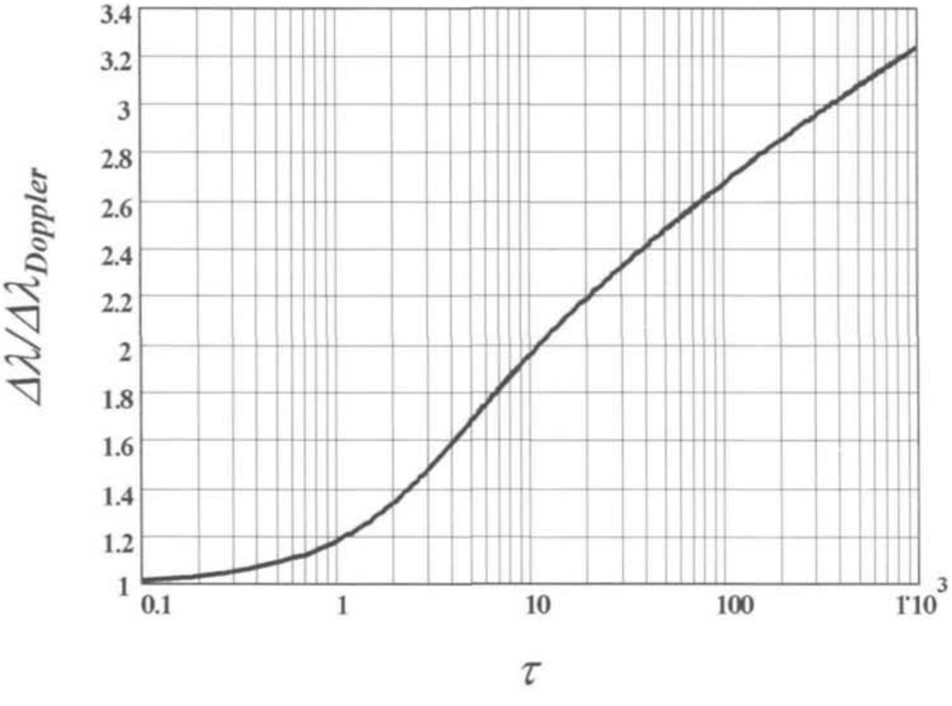
The spectral radiance L_λ at the plasma surface:

$$L_\lambda = S_\lambda \cdot \left(1 - e^{-\tau(\lambda)}\right)$$

S_λ is the source function,
$\tau(\lambda)$ is the optical depth along the line of sight

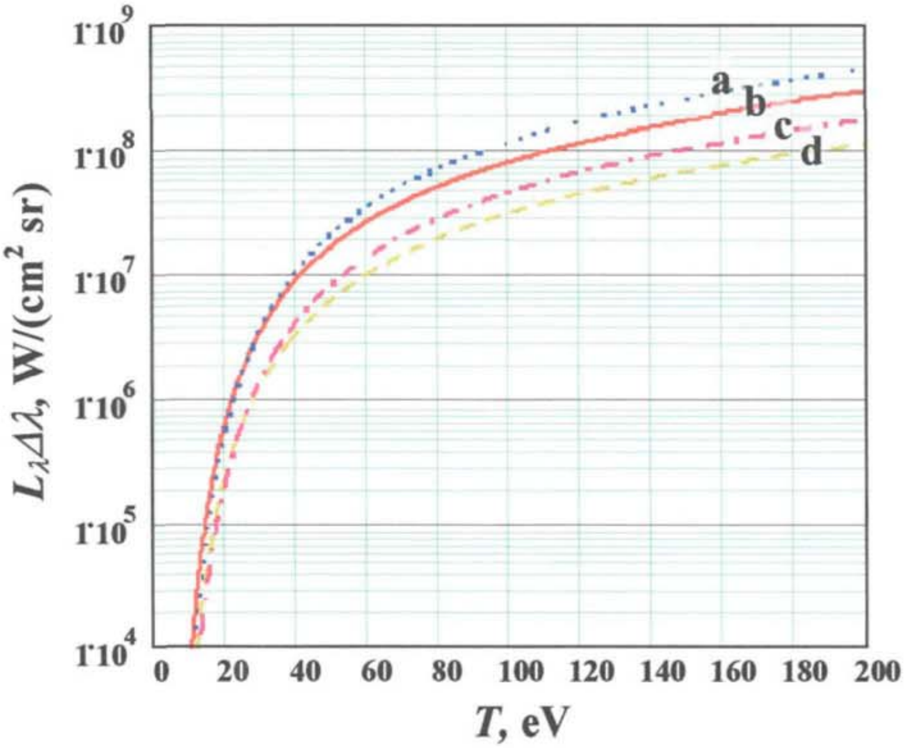
Boltzmann distribution of the population densities $n_{q,p}$
=> S_λ corresponds to the Planck function

$\tau(\lambda_0) \geq 5$ => $L(\lambda_0)$ to the Planck function
=> we have a Planck radiator in $\Delta\lambda$
$\Delta\lambda$ is the FWHM of this optically thick line



T_{plasma} = const => $L(\lambda_0)$ = const
=> for $L_\lambda\Delta\lambda \nearrow$ => $\Delta\lambda \nearrow$ => $\tau \nearrow$

Radiance of optical thick lines



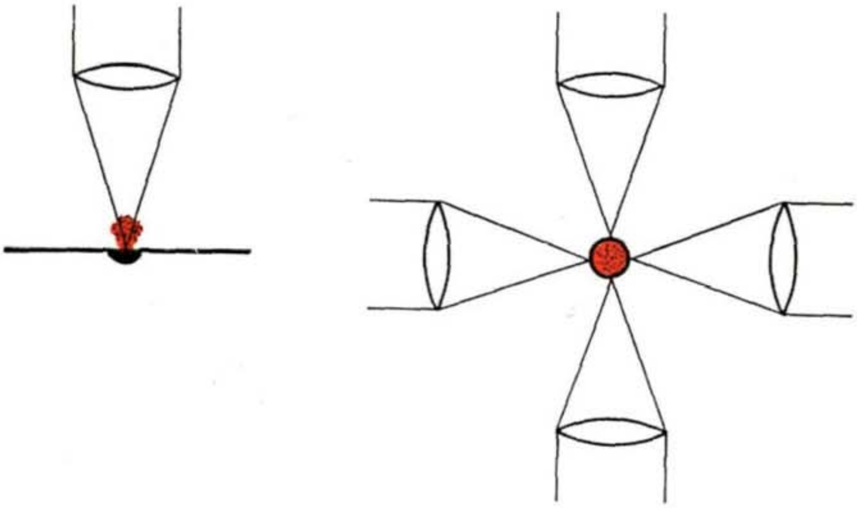
a : λ_0 = 11,5 nm, M = 20,2 (Neon)
b : λ_0 = 13,5 nm, M = 20,2 (Neon)
c : λ_0 = 11,5 nm, M = 131,3 (Xenon)
d : λ_0 = 13,5 nm, M = 131,3 (Xenon)

Ω = 0,05 sr, A = 1 mm^2 => 10^4 to 10^5 W for 50 to 200 eV
200 mJ at the wafer => 20 to 2 μs exposure times
0,2 μs radiation pulse => 100 to 10 discharges

OVI ($T_{optimum}$ ~ 20 – 40 eV)	11,58 to 11,73 nm
NeVI (30 – 50 eV)	13,85 nm
KrIX (~ 40 eV)	11,54 nm
XeXI, XeXII	

Typical plasma sources

Laser produced plasmas

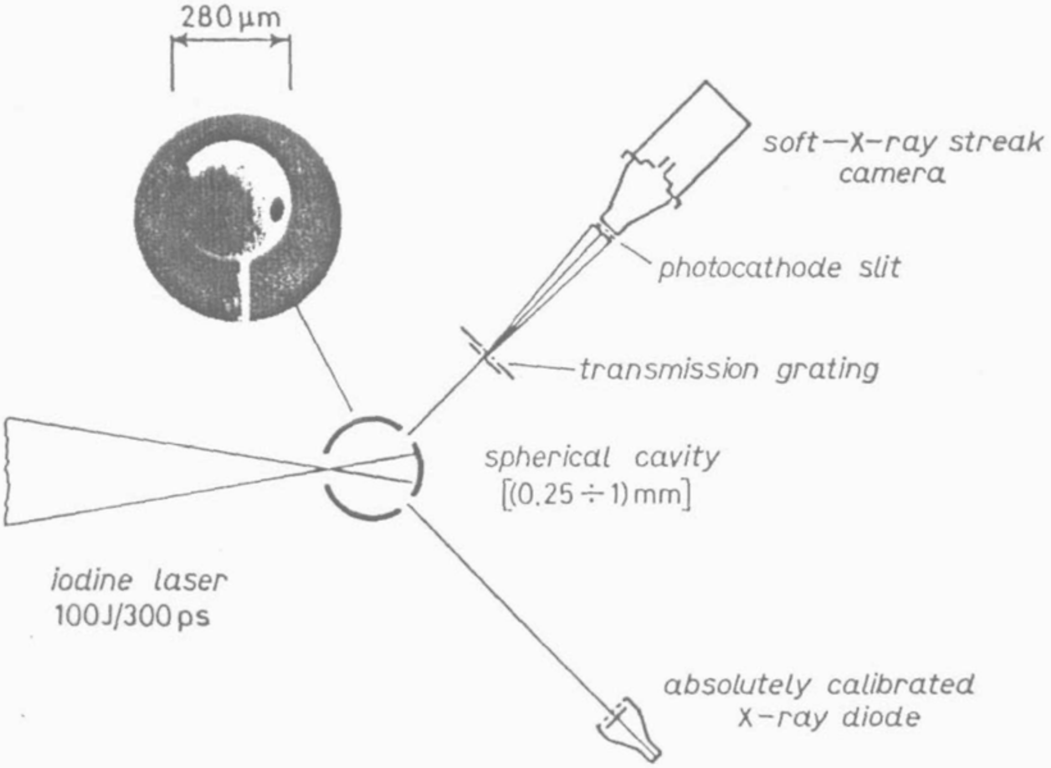


Quite a number of applications are reported in the literature (Radiometry, lithography, EXAFS, microscopy, laser pumping)

Conversion of laser energy into energy of x-rays ...... up to 10%
Conversion rates up to 50% are reported, too.

Spectrum can be variied easily by changing targets.

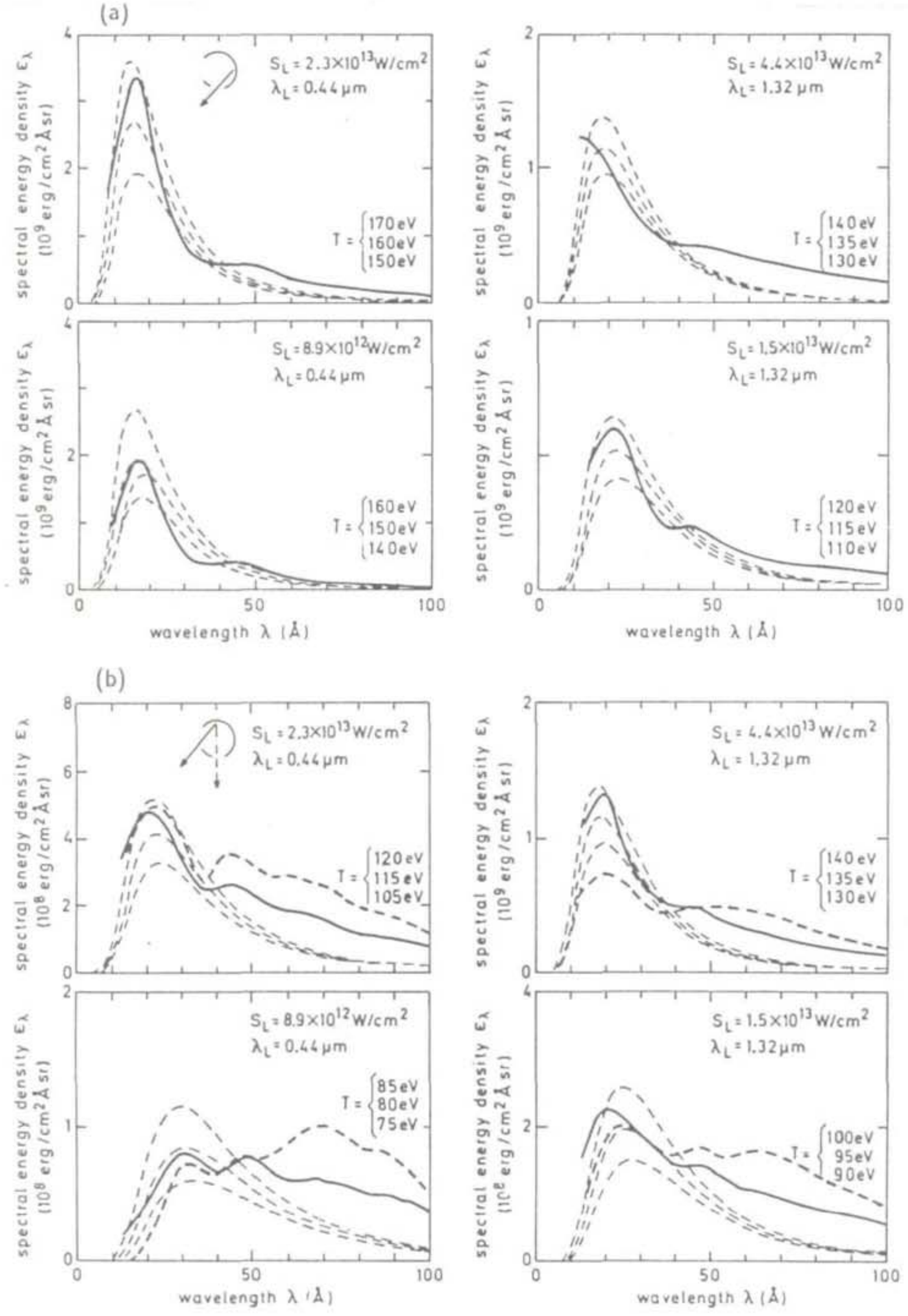
Laser heated cavities:



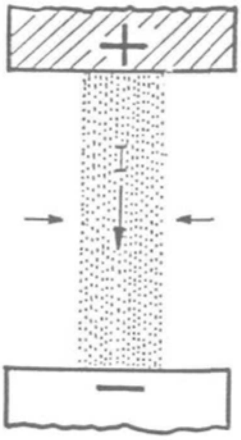
Radiation from laser heated cavities

(Sakabe, Sigel, Tsakiris, Földes, and
Herrmann, Phys. Rev. A **38**, 5756 (1988)

--- Planck curves



Z pinch



High-current discharge through a gas
(at high pressures, preionization
by an intense laser beam)

Discharge through a fiber

Early experiments

typically $n_e \approx 10^{19}$ cm^{-3}
$kT \approx 10$ eV
$\Delta t \approx 0.1 - 1$ μs

Today

large pulsed power generators, PGS

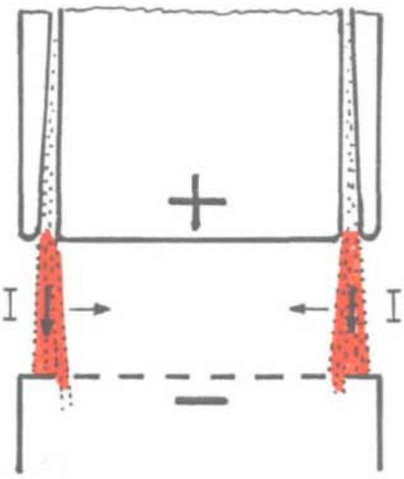
Recent report:

Z-machine at Sandia

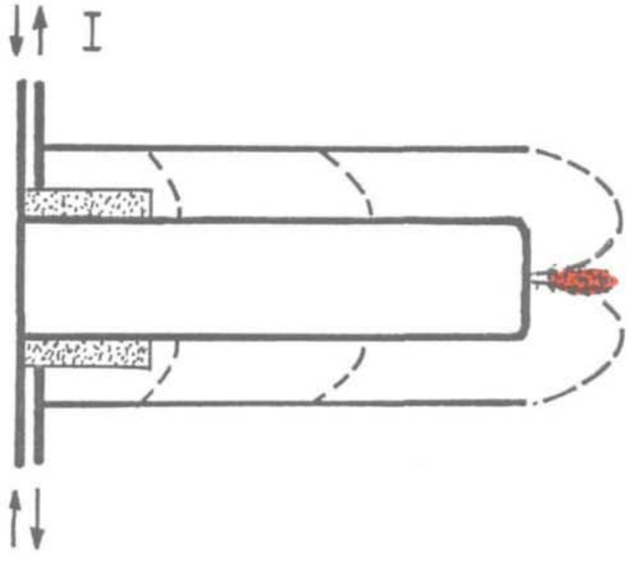
a wire array z-pinch

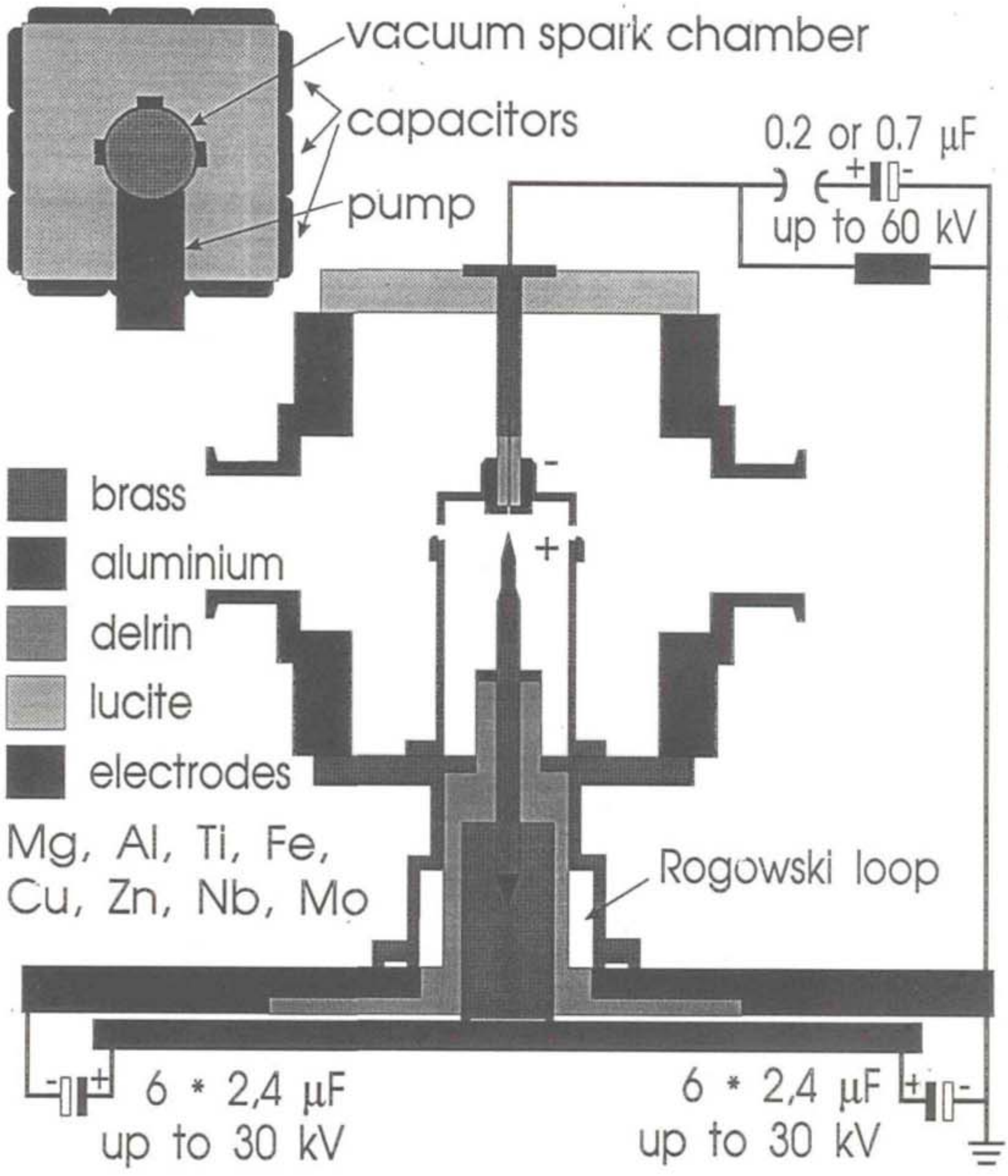
1 - 2 MJ in x-rays in 100 – 200 TW bursts

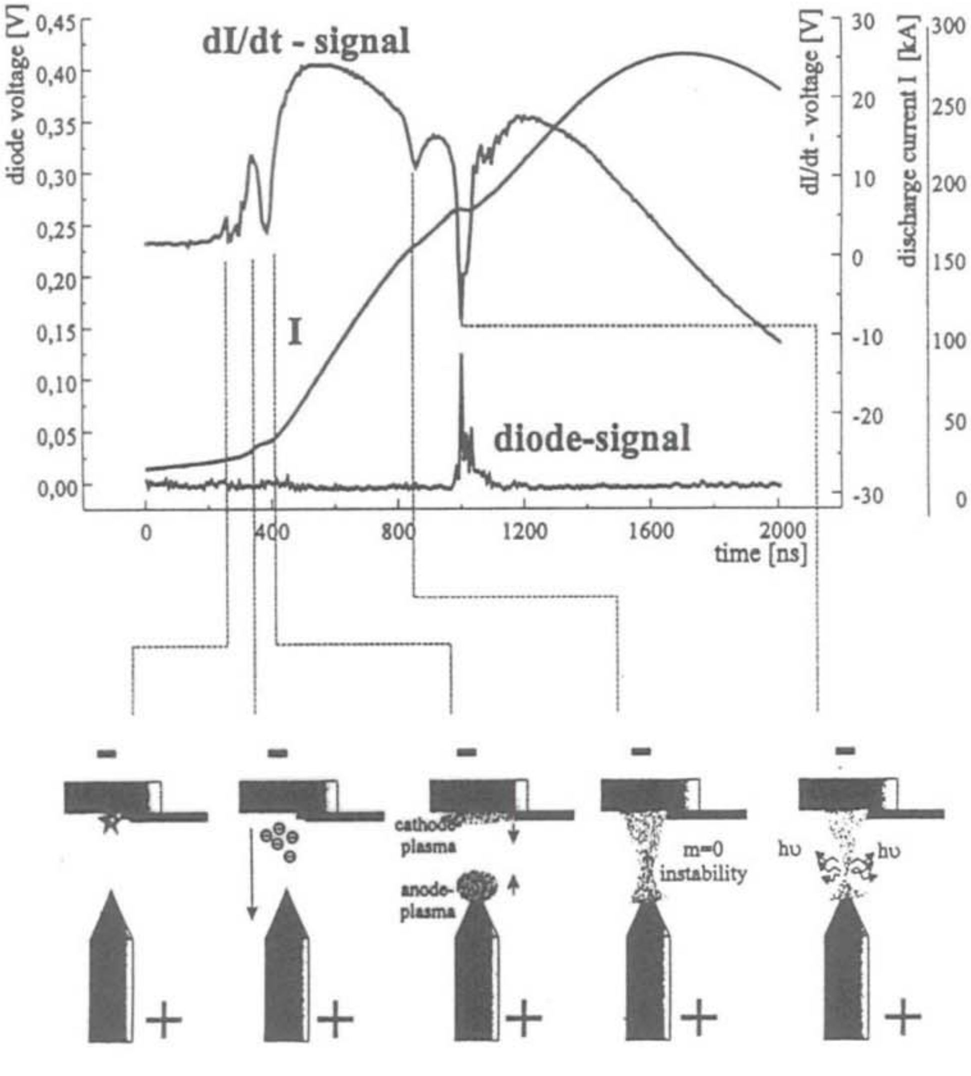
Gas-puff pinch

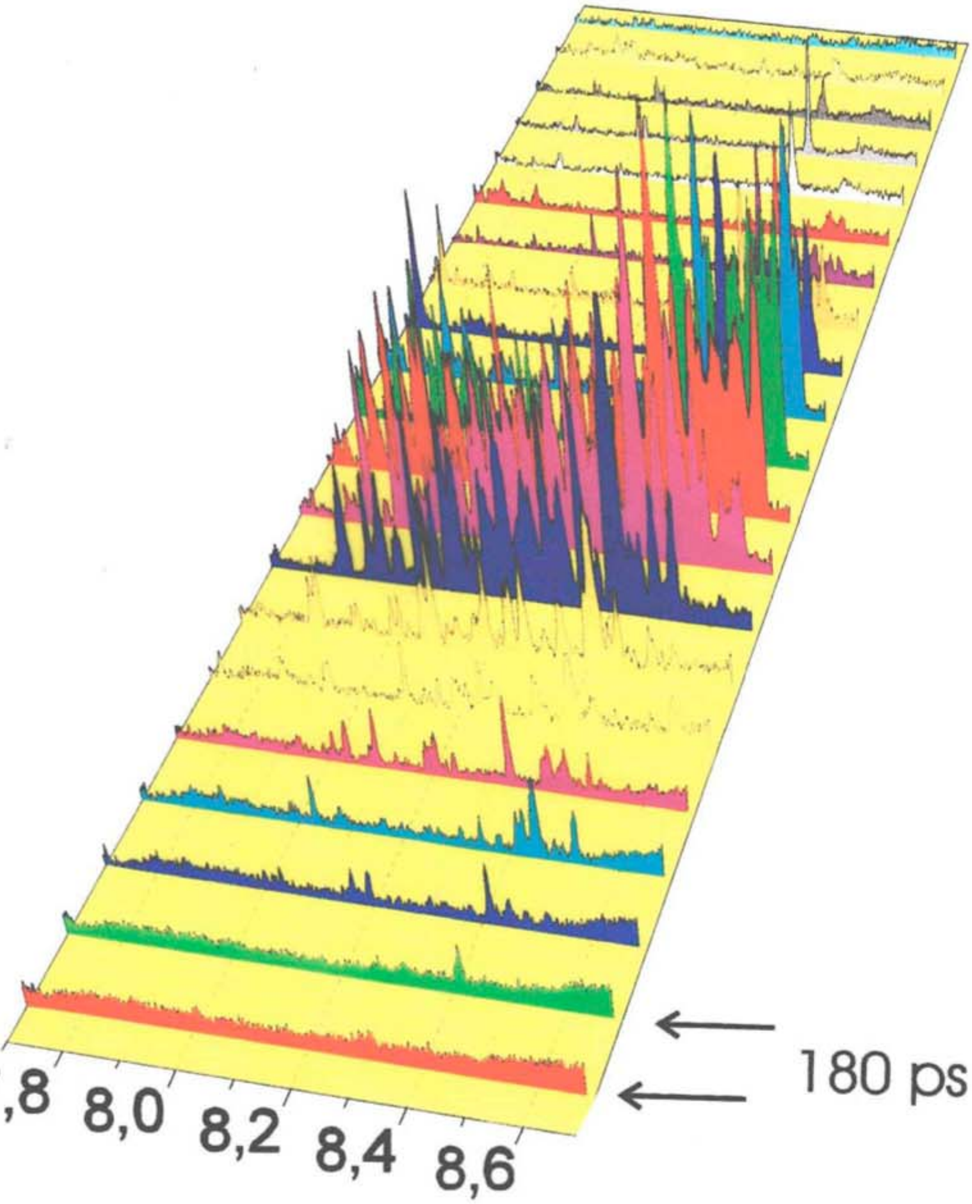


Plasma focus




vacuum spark chamber
capacitors
pump
0.2 or 0.7 μF
+
-
up to 60 kV
-
+
brass
aluminium
delrin
lucite
electrodes
Mg, Al, Ti, Fe,
Cu, Zn, Nb, Mo
Rogowski loop
-
+
6 * 2,4 μF
up to 30 kV
6 * 2,4 μF
up to 30 kV
+
-

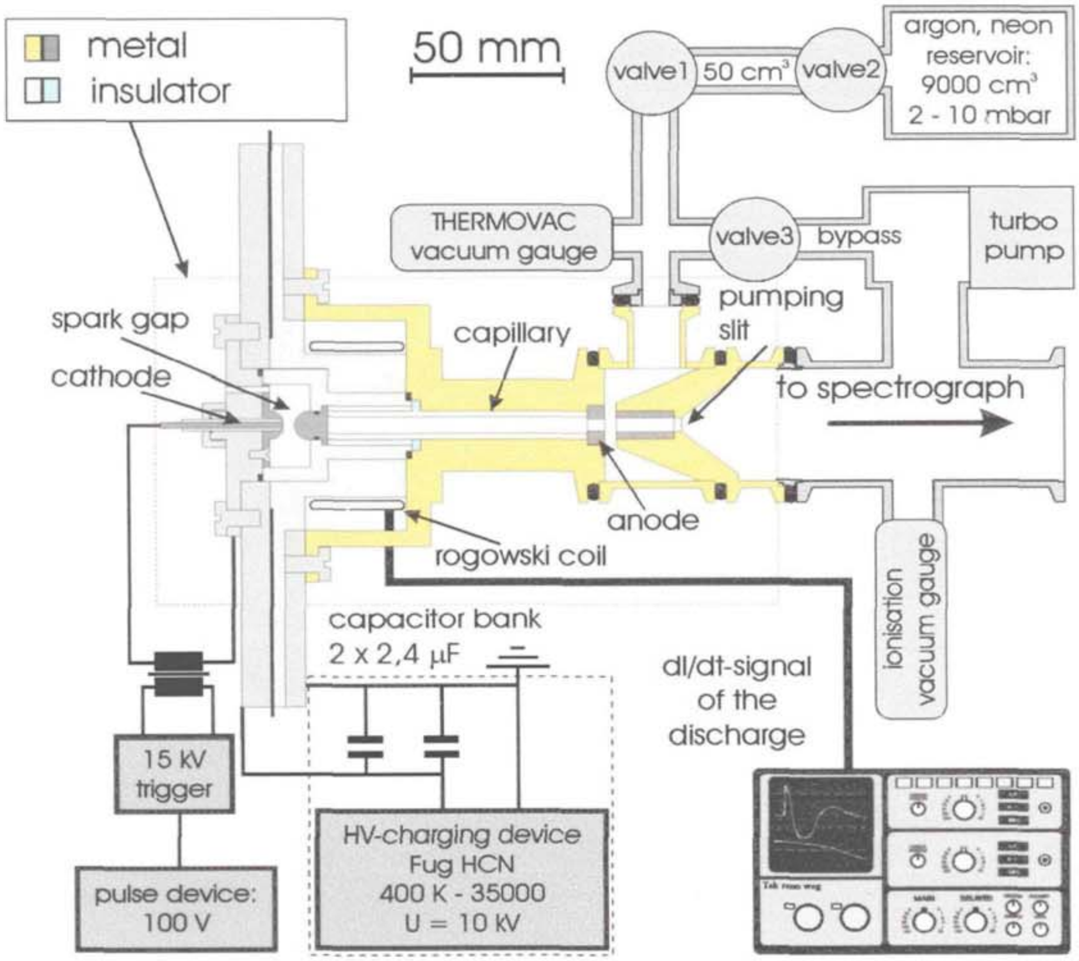

dI/dt - signal
I
diode-signal
diode voltage [V]
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
dI/dt - voltage [V]
30
20
10
0
-10
-20
-30
discharge current I [kA]
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
time [ns]
cathode-plasma
anode-plasma
m=0 instability
hυ
hυ
−
+



Streak 5

parameter (final stage)	Al	Fe	Mo
optimum U_{MC} range (kV)	4 - 8	10 - 12	14 - 16
applied U_{MC} (kV)	5	10	16
I_{Pinch} (kA)	70	190	350
λ [K_α - K_β] (Å)	7 - 8	1.7 - 2	0.62 - 0.72
R_{min} (μm)	20 - 30	4 - 8	4 - 6 ($\leq$ 1*)
kT_e (keV)	0.4 - 0.5	3 - 5	$>$ 10
n_e (cm^{-3})	0.3 - $1 \cdot 10^{22}$	$1 \cdot 10^{23}$	$> 1 \cdot 10^{23}$
lifetime t_{He} (ps)	200	30 - 50 *	1 - 5 *
emission phase He	compression	compression	expansion ?
emission phase H	compression	expansion	-
$I(K_\alpha, K_\beta)/I(\mathrm{He})$	0.1	≈5	>20
comparison theory/exp.	excellent	excellent	good

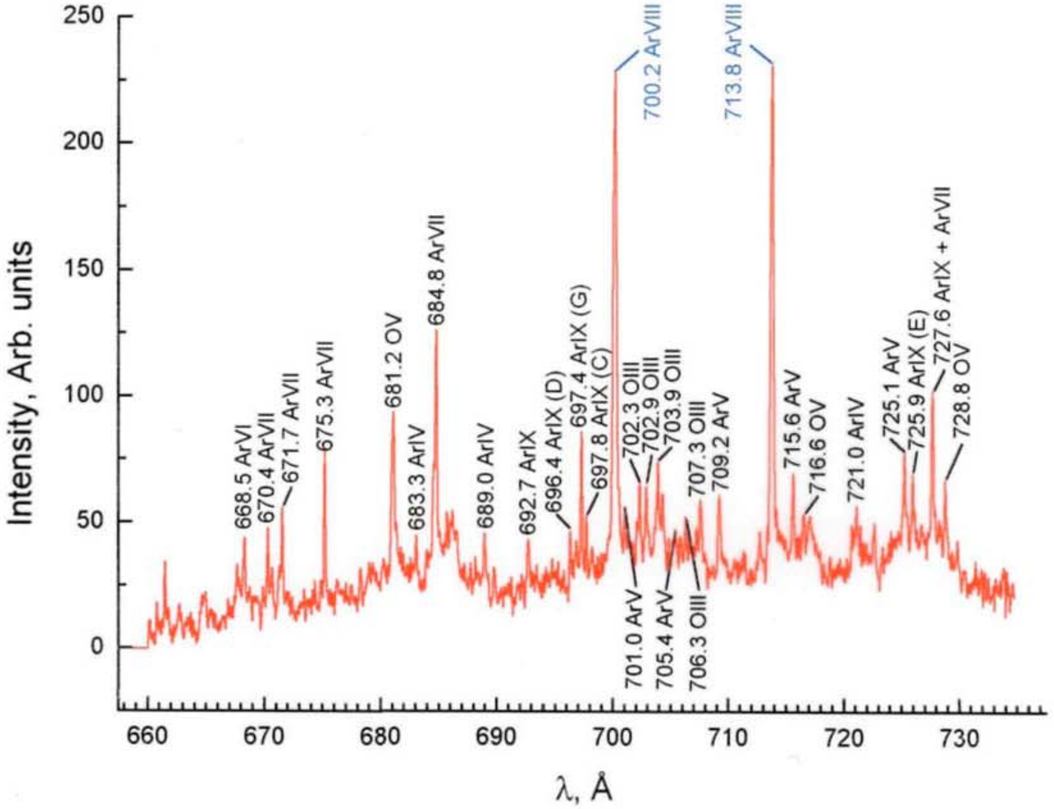
Capillary discharge at the Ruhr-University Bochum



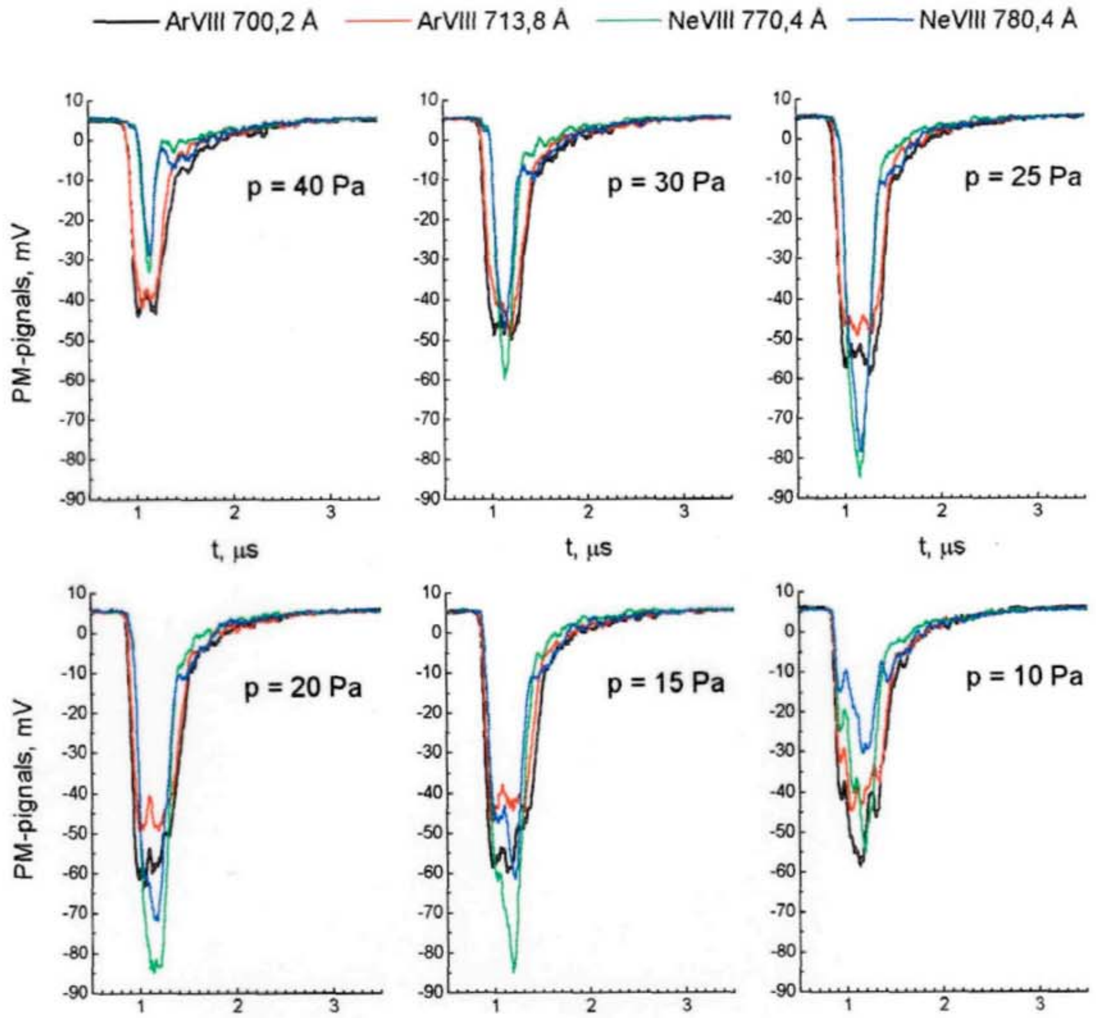
Technical Data

Capacity	**4.75 μF**	**Capillary**	**Al_2O_3 (ceramic)**
Charging voltage	**10 kV**	**93.5 mm lang, 6mm ID, 10 mm OD**	
Energy	**240 J**	**Gas pressure**	
Resistance	**0.2 Ω**	**Argon**	**5 - 60 Pa**
Inductance	**50 nH**	**Neon**	**10 - 100 Pa**
Discharge current	**60 kA**	**Electron density**	**$\sim 7x10^{17}$ cm^{-3}**
Current rise time	**0.7 μs**	**Electron temperature**	**~ 30 - 40 eV**

Time integrated spectrum of the plasma radiation at the argon pressure of 20 Pa.

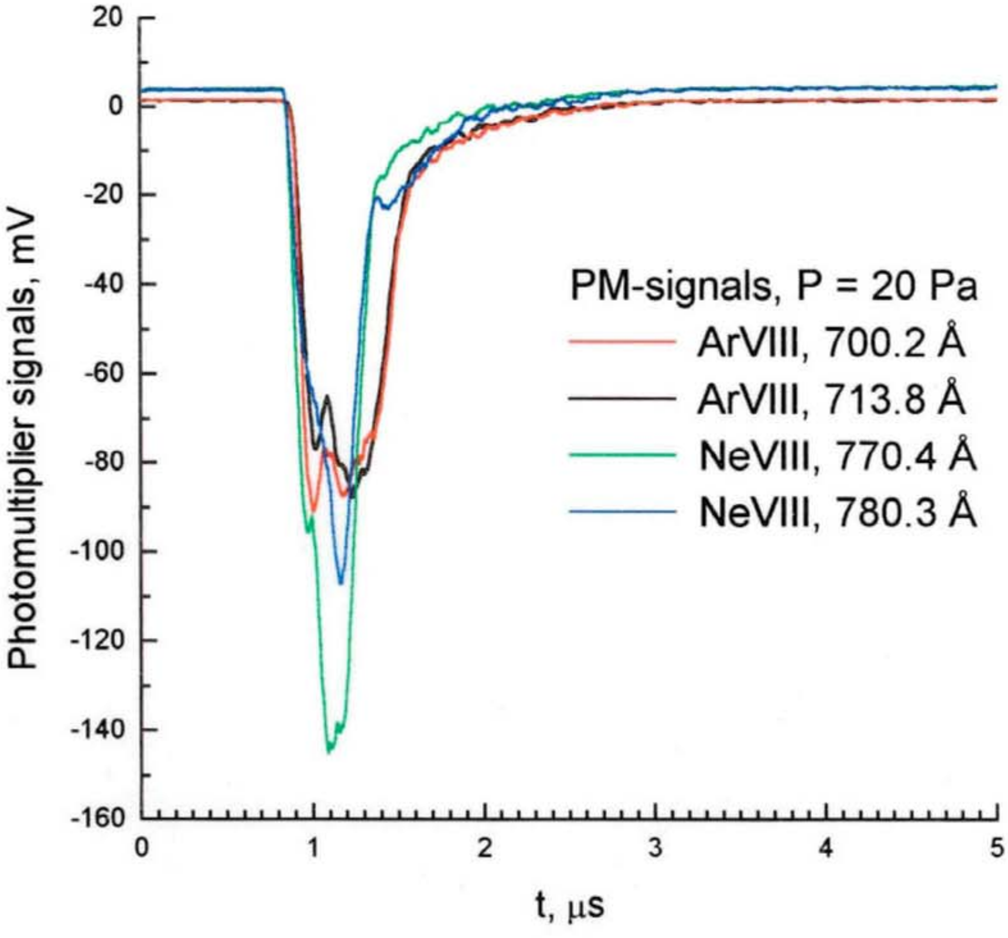


Radiation time dependence of the resonance ArVIII and NeVIII lines at different filling gas pressures for the mixture with Ar:Ne at 1:1 ratio.



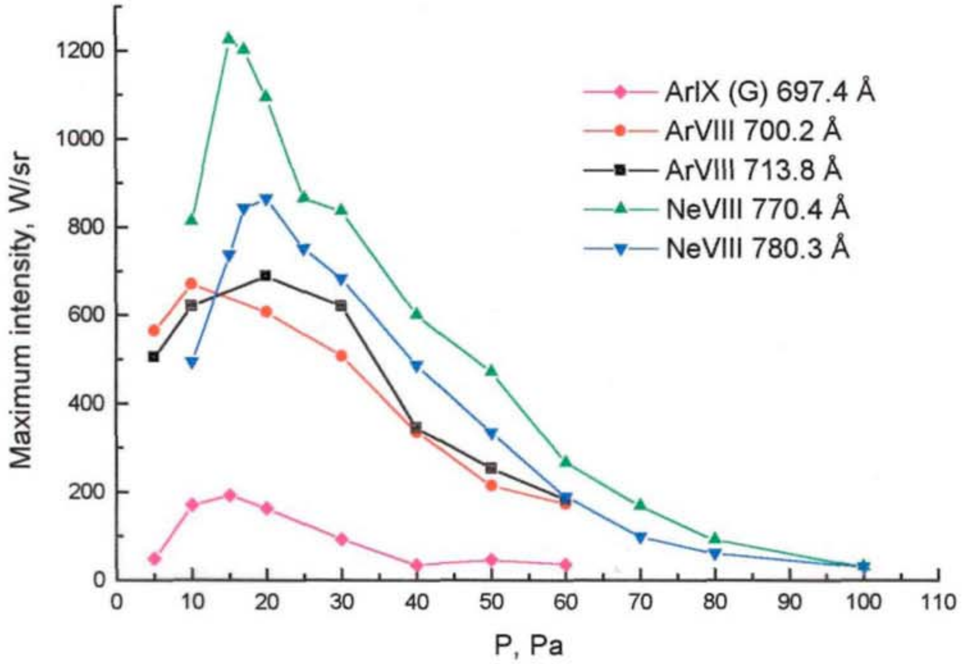
total energy emitted from the plasma in the spectral region of 700 - 800 Å is 1.5 mJ/sr

Radiation time dependence of the resonance ArVIII and NeVIII lines.

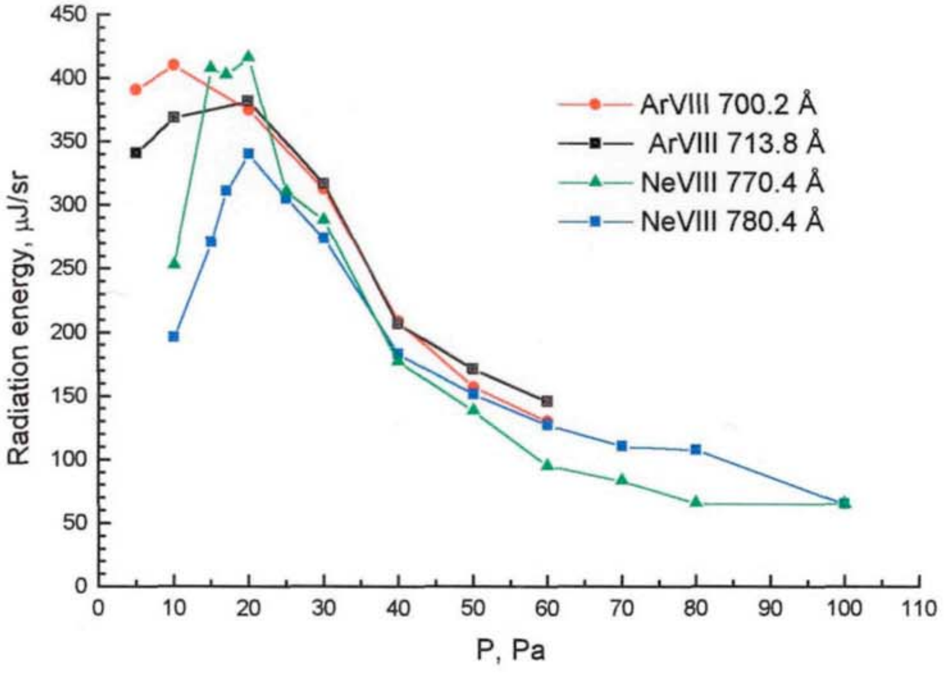


	argon lines 700.2 and 713.8 Å	neon lines 770.4 and 780.3 Å	
duration	700 ns	500 ns	
maximum intensity	700 W/sr	1200 W/sr	850 W/sr
energy	370 μJ/sr	400 μJ/sr	330 μJ/sr

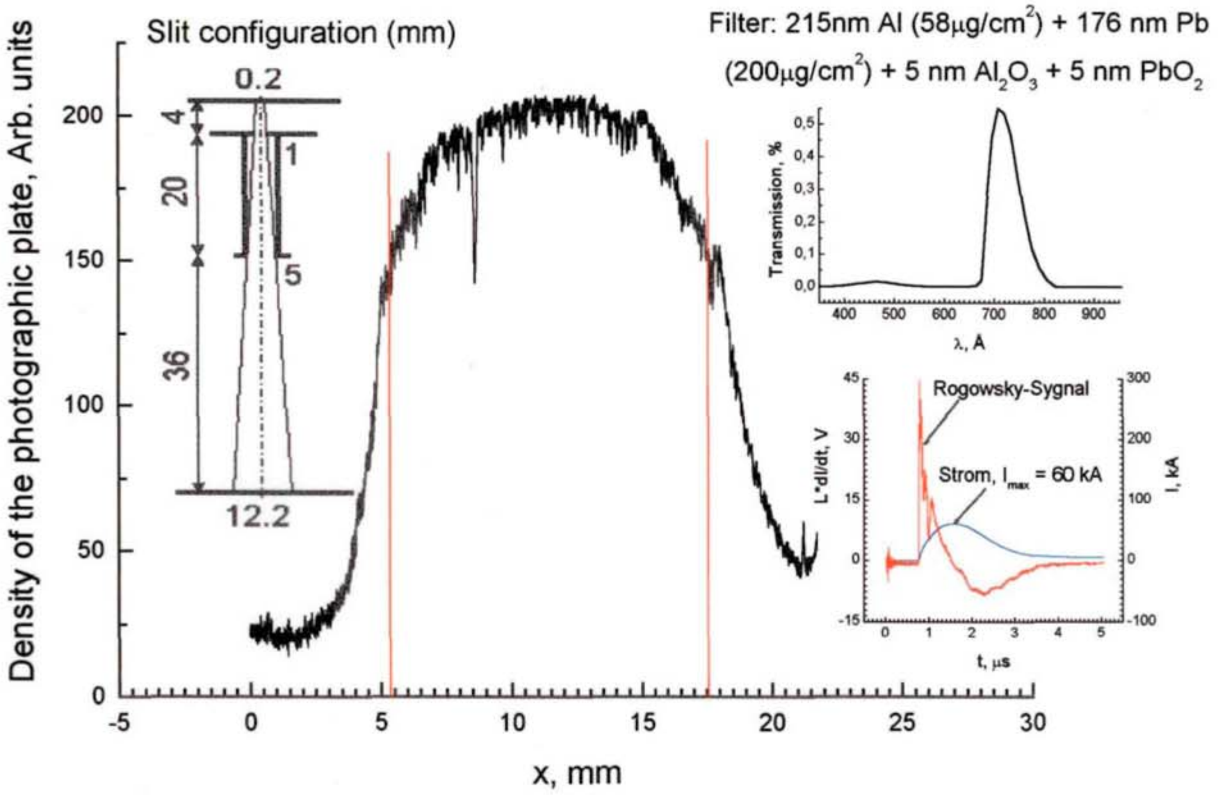
Dependence of the maximum intensity of argon and neon lines on the filling gas pressure.



Dependence of the radiation energy of resonance argon and neon lines on the filling gas pressure.



Angular distribution of the radiation of the resonance ArVIII lines at the gas pressure of 20 Pa and a discharge voltage of 10 kV.



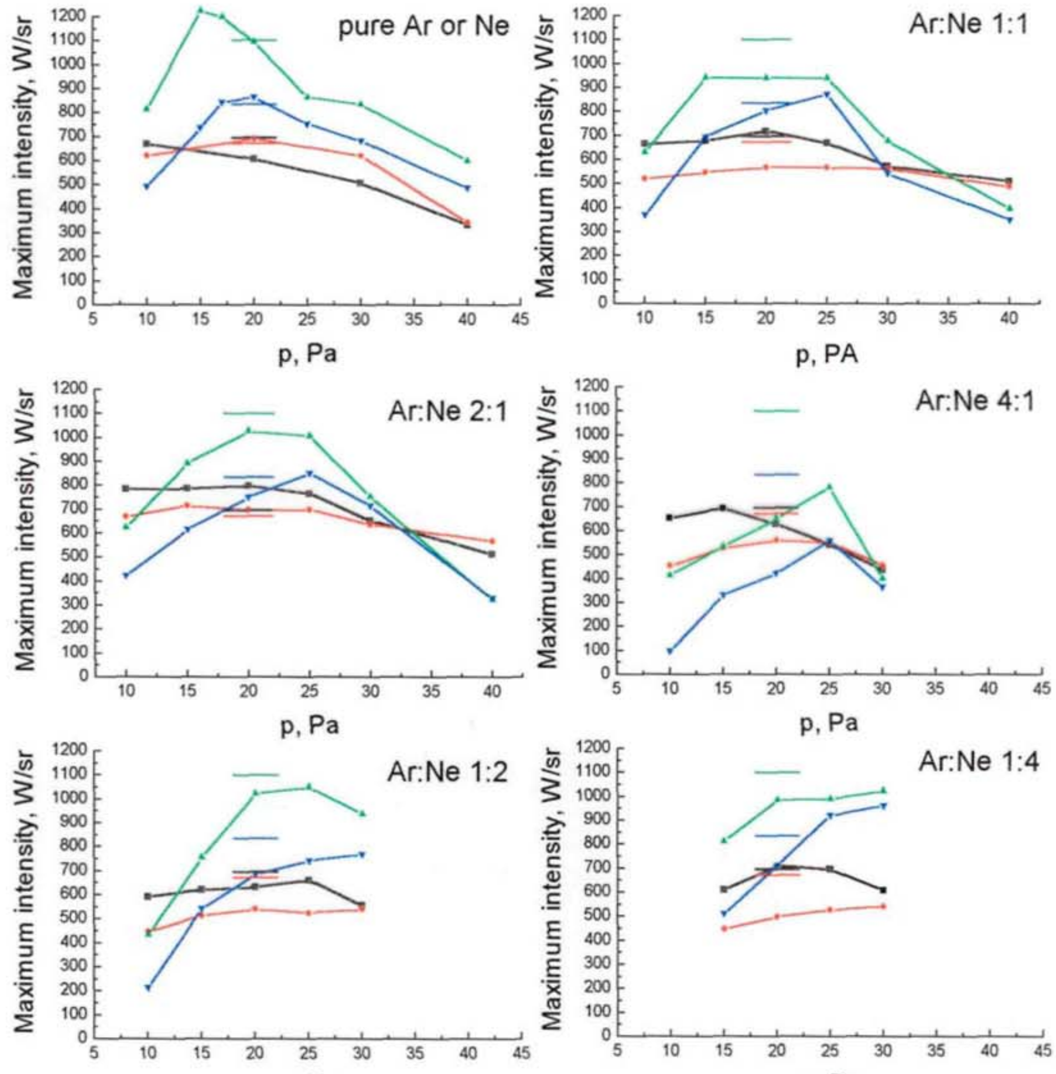
=> angle within which the plasma emits most intense and uniform: ~ 0.16 rad => solid angle: 2×10^{-2} sr

=> minimum plasma length from which up the radiation of the resonance argon lines becomes optically thick: 1 cm

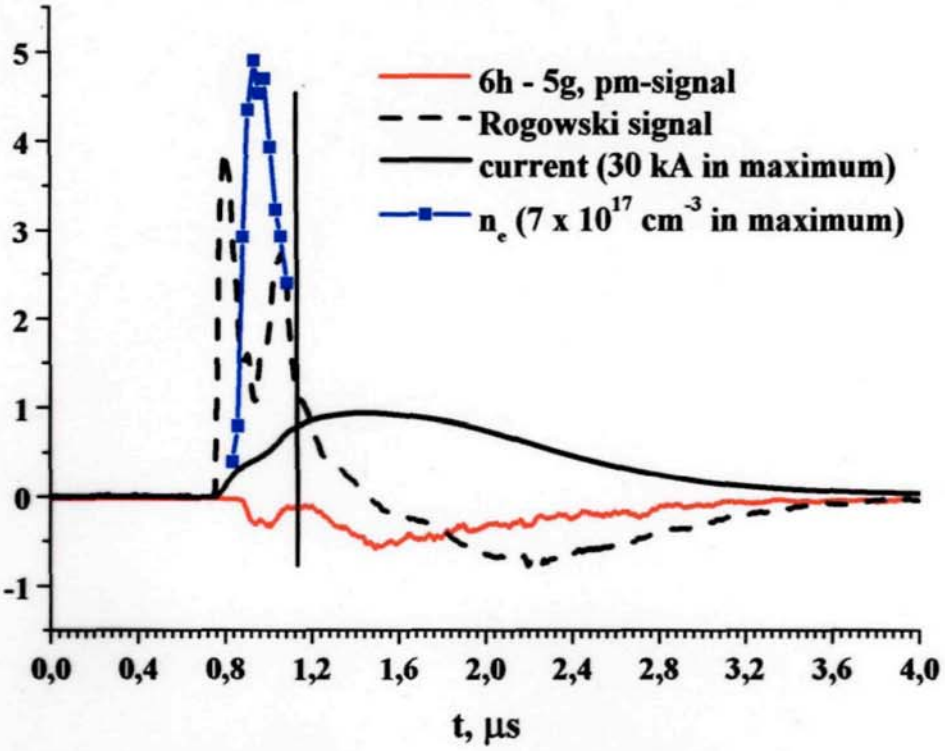
Dependence of the maximum intensity of argon and neon lines on the filling gas pressure for different mixtures of argon and neon.

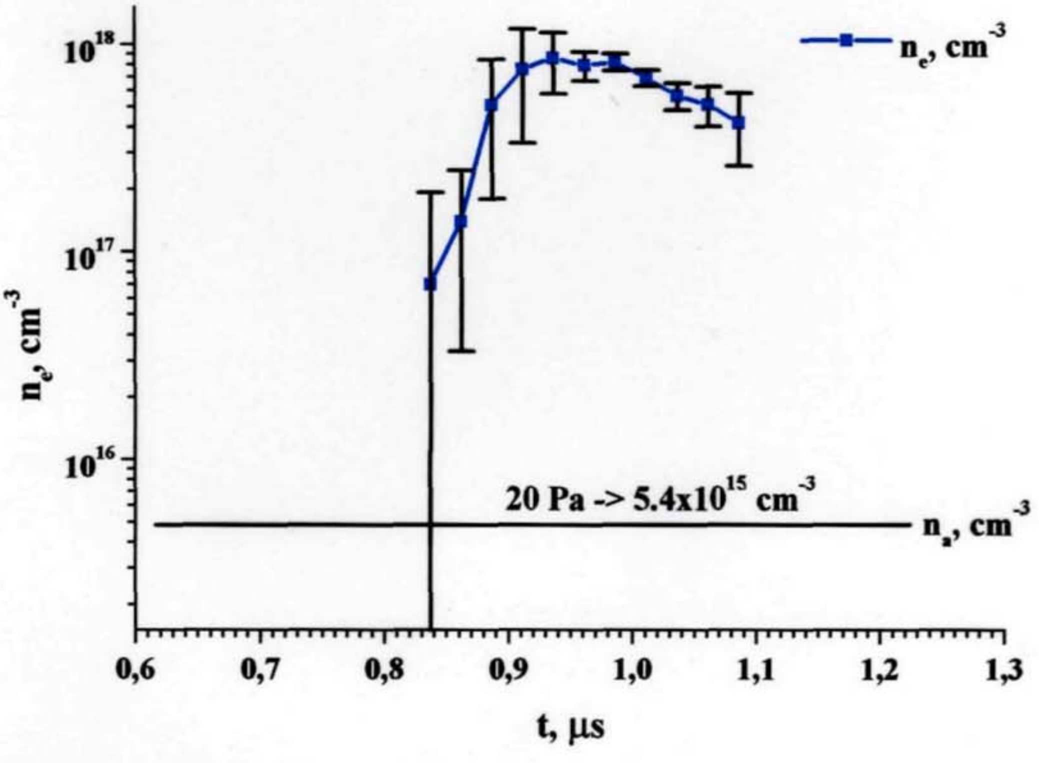
ArVIII 700,2 Å ArVIII 713,8 Å NeVIII 770,4 Å NeVIII 780,4 Å

, , values measured in the discharges with pure argon or neon at the same conditions: U_{PM} = -700 V, entr./exit = 25/50 μm, U = 10 kV, p = 20 Pa



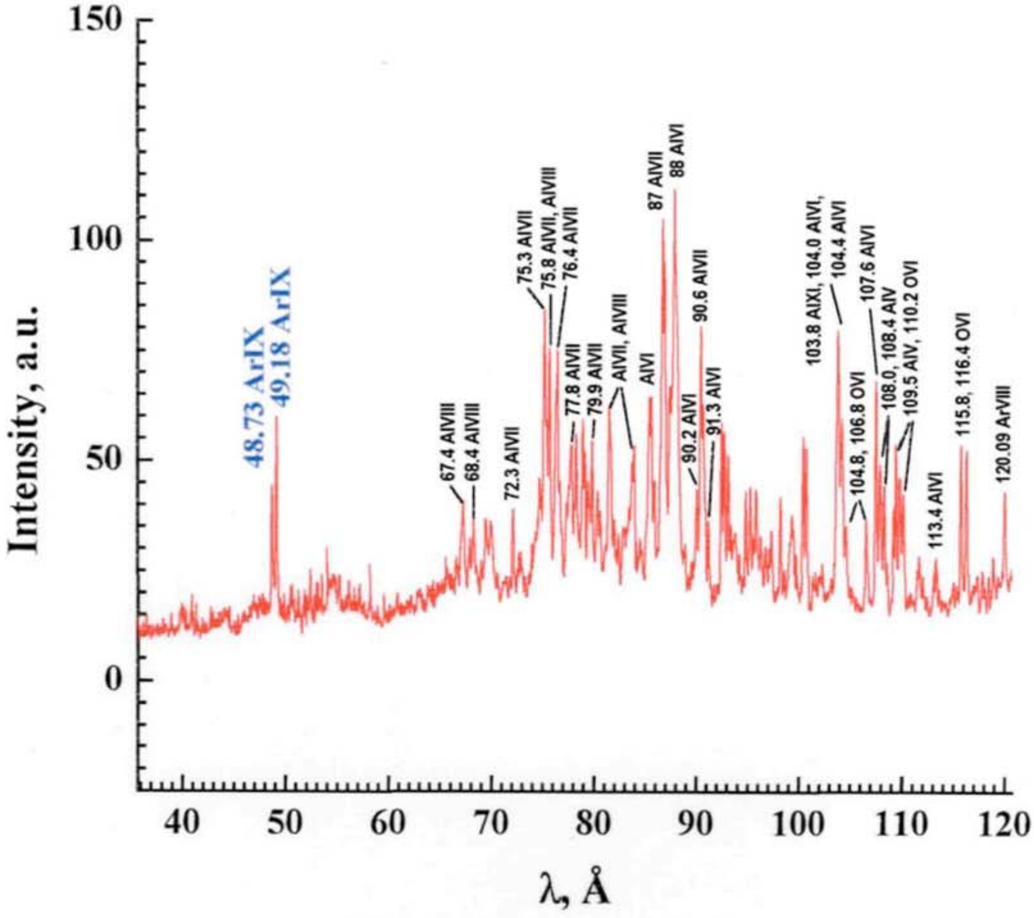
Time dependence of the electron density





Messung von n_e: Stark-Breite von ArVIII, KrIII,
geeicht im Gas-Liner-Pinch

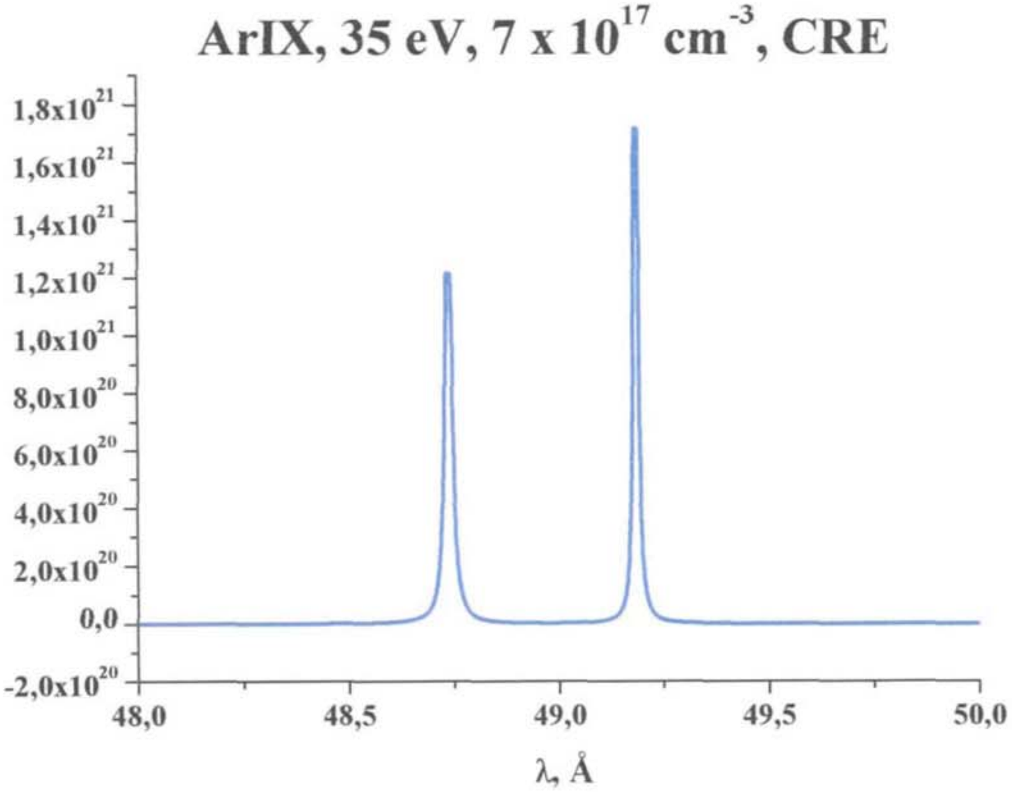
Time integrated spectrum of the plasma radiation at the argon pressure of 10 Pa

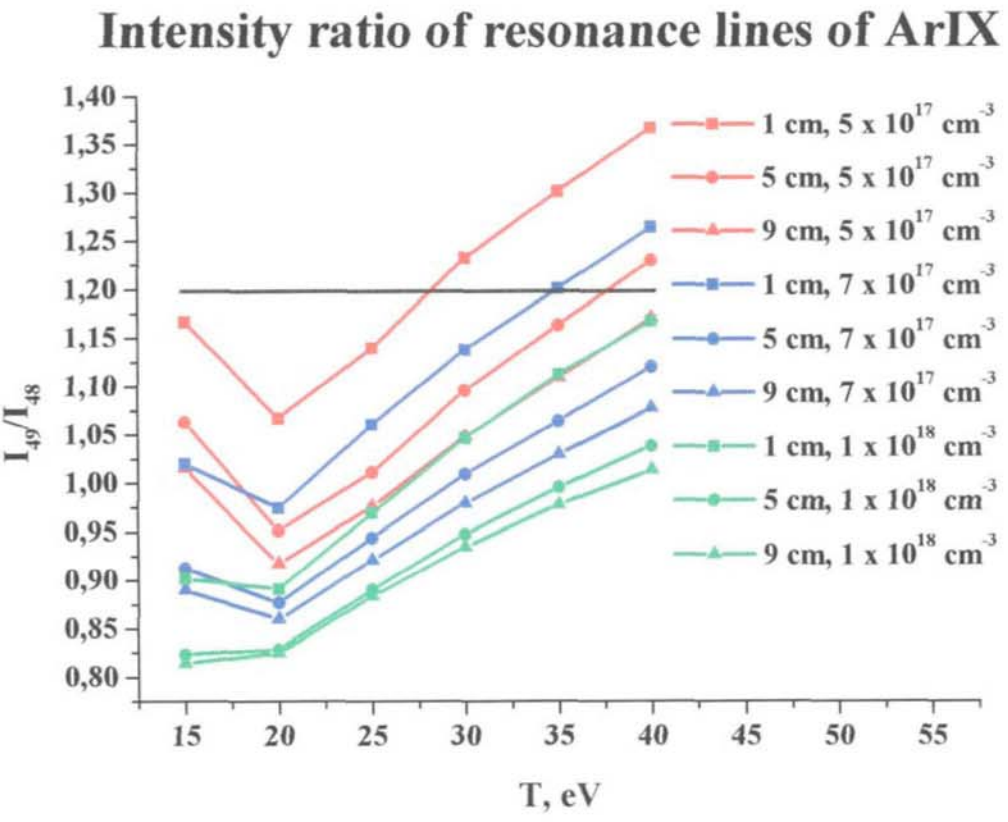


Resonanzlinien von ArIX:

$2p^6 - 2p^5(^2P^o_{3/2})3s$ 49.18 Å

$2p^6 - 2p^5(^2P^o_{1/2})3s$ 48.73 Å


ArIX, 35 eV, 7 x 10^{17} cm^{-3}, CRE
1,8x10^{21}
1,6x10^{21}
1,4x10^{21}
1,2x10^{21}
1,0x10^{21}
8,0x10^{20}
6,0x10^{20}
4,0x10^{20}
2,0x10^{20}
0,0
-2,0x10^{20}
48,0
48,5
49,0
49,5
50,0
λ, Å


Intensity ratio of resonance lines of ArIX
1,40
1,35
1,30
1,25
1,20
1,15
1,10
1,05
1,00
0,95
0,90
0,85
0,80
I_{49}/I_{48}
15
20
25
30
35
40
45
50
55
T, eV
1 cm, 5 x 10^{17} cm^{-3}
5 cm, 5 x 10^{17} cm^{-3}
9 cm, 5 x 10^{17} cm^{-3}
1 cm, 7 x 10^{17} cm^{-3}
5 cm, 7 x 10^{17} cm^{-3}
9 cm, 7 x 10^{17} cm^{-3}
1 cm, 1 x 10^{18} cm^{-3}
5 cm, 1 x 10^{18} cm^{-3}
9 cm, 1 x 10^{18} cm^{-3}

EUV lithography

Mo:Si and Mo:Be multilayer mirrors at 135 and 112 Å

$L_\lambda \Delta\lambda$ ↗ => T_{plasma} ↗

$t_{emission}$ ↗ => **high ionized ions with** $T_{optimum} = T_{plasma}$

Boltzmann distribution of $n_{q,p}$ =>

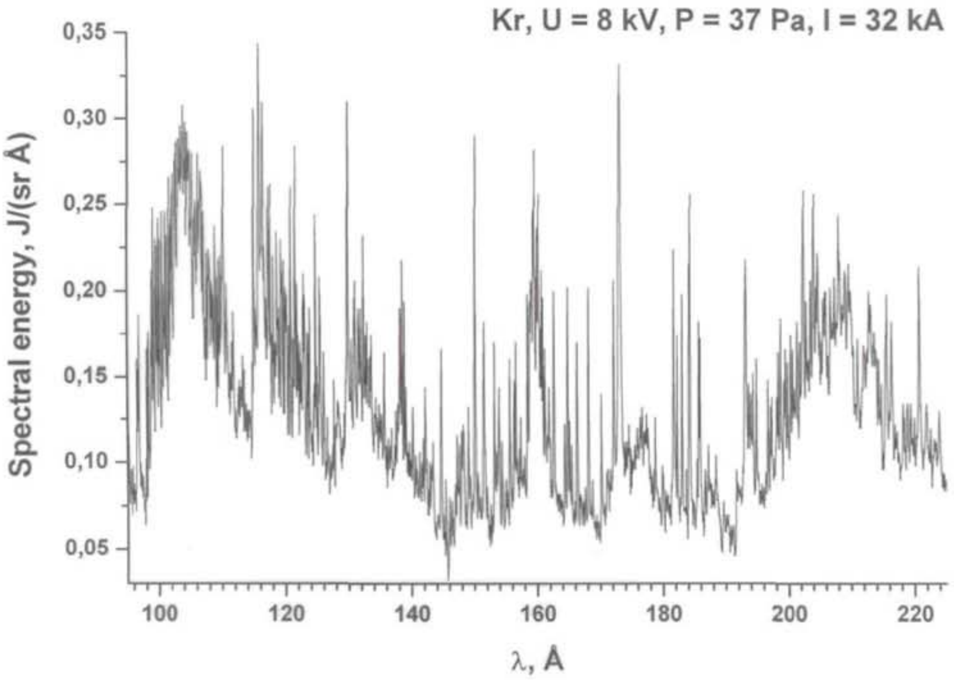
$$n_e \geq 9 \cdot 10^{17} \cdot \left(\frac{E_p - E_q}{E_H} \right)^3 \cdot \left(\frac{kT}{E_H} \right)^{1/2} \qquad cm^{-3},$$

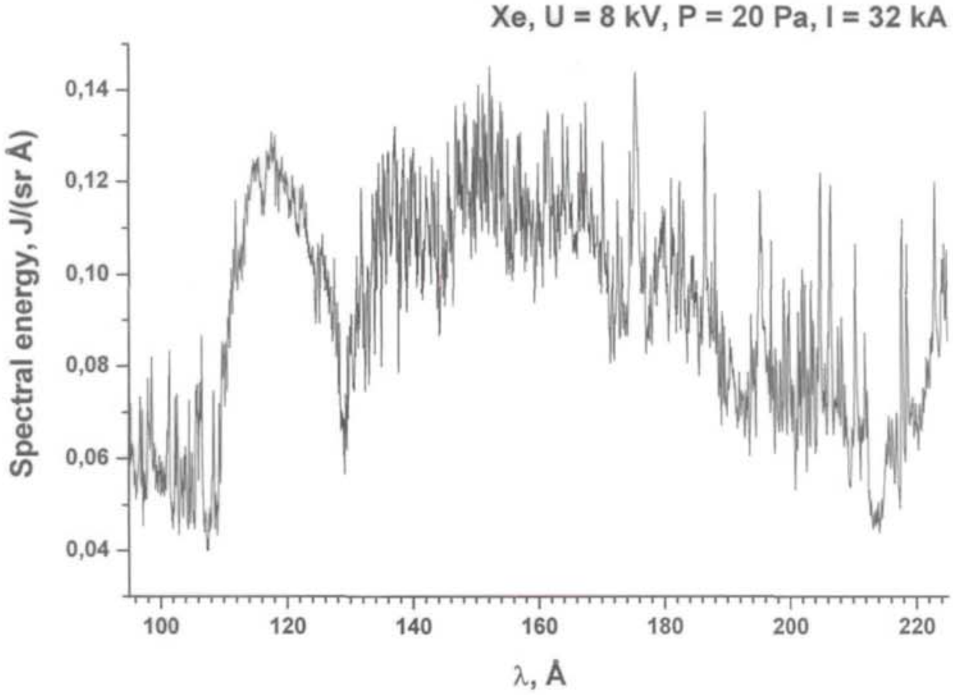
where $E_H = 13.6\ eV$ => **at** $T_{plasma} = 50\ eV \quad n_e \geq 7 \cdot 10^{20}\ cm^{-3}$

=> τ **along the plasma diameter** ≥ 5

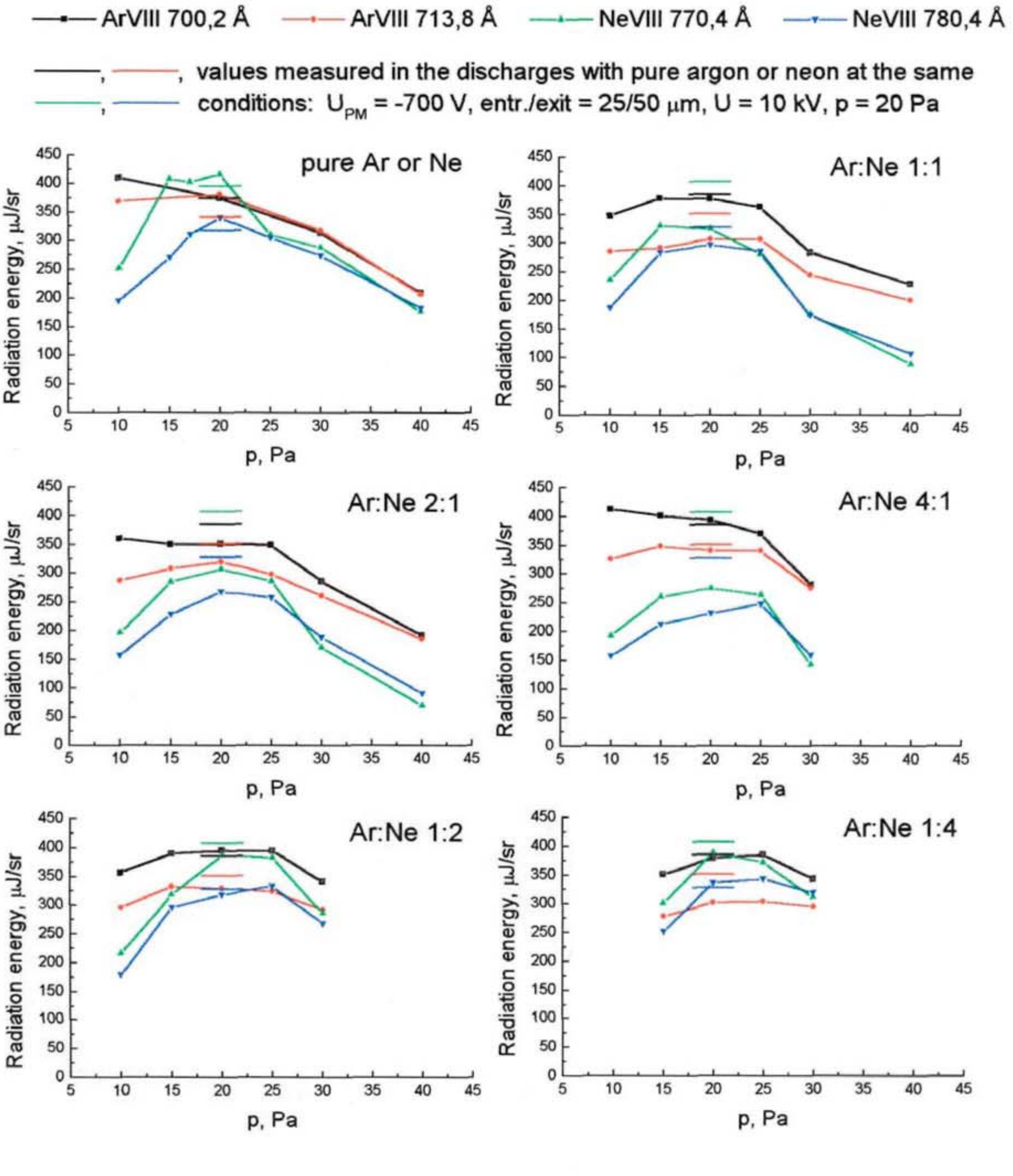
Resonance doublet of KrIX: 115.4 Å

Spectral energy of Kr and Xe radiation


Kr, U = 8 kV, P = 37 Pa, I = 32 kA


Xe, U = 8 kV, P = 20 Pa, I = 32 kA

Dependence of the radiation energy of resonance argon and neon lines on the filling gas pressure for different mixtures of argon and neon.

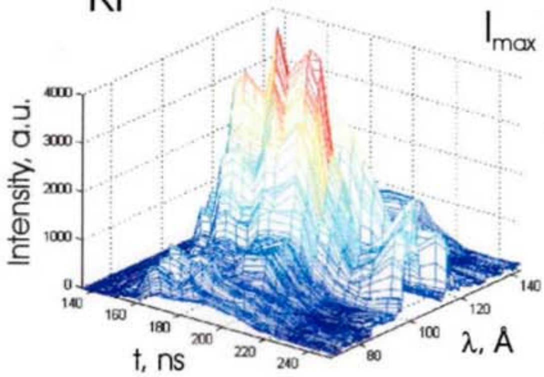


—, —, —, —, values measured in the discharges with pure argon or neon at the same conditions: U_{PM} = -700 V, entr./exit = 25/50 μm, U = 10 kV, p = 20 Pa

Time dependence of Kr and Xe radiation at 20 Pa

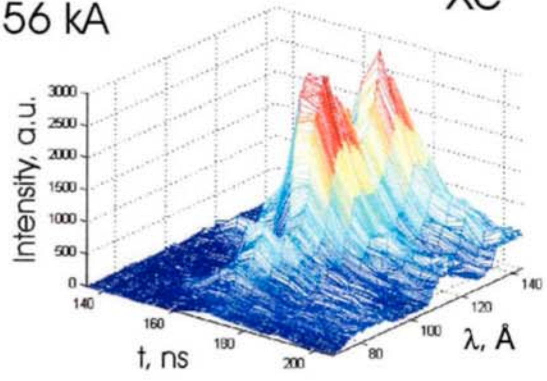
U = 7 kV
I_{max} = 56 kA

Kr



Max: 5.2×10^3

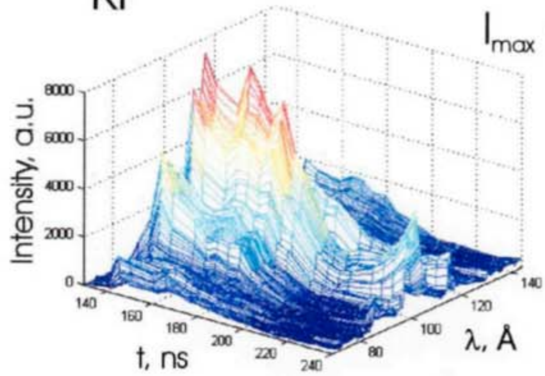
Xe



Max: 3.0×10^3

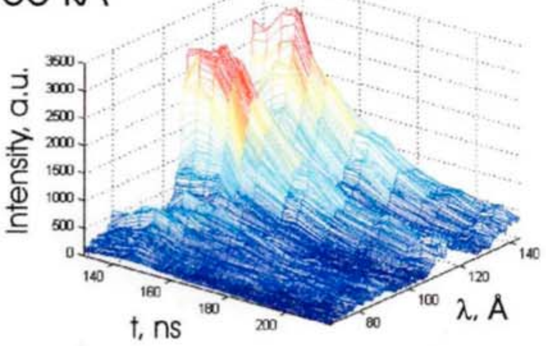
U = 8 kV
I_{max} = 66 kA

Kr



Max: 8.4×10^3

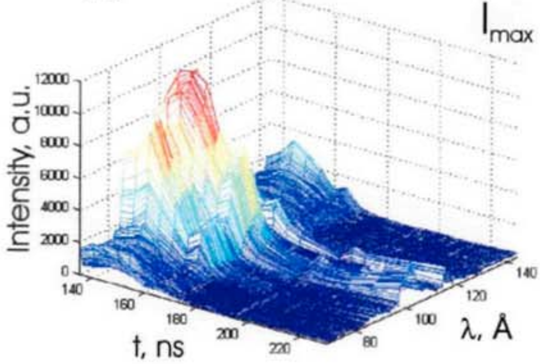
Xe



Max: 3.3×10^3

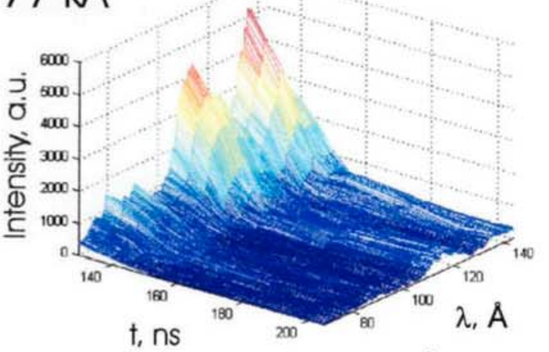
U = 9 kV
I_{max} = 77 kA

Kr



Max: 10.6×10^3

Xe



Max: 5.3×10^3

Industrial application in lithography

Conversion efficiency is crucial : target 2%

Main reason: heat load of electrodes sets a

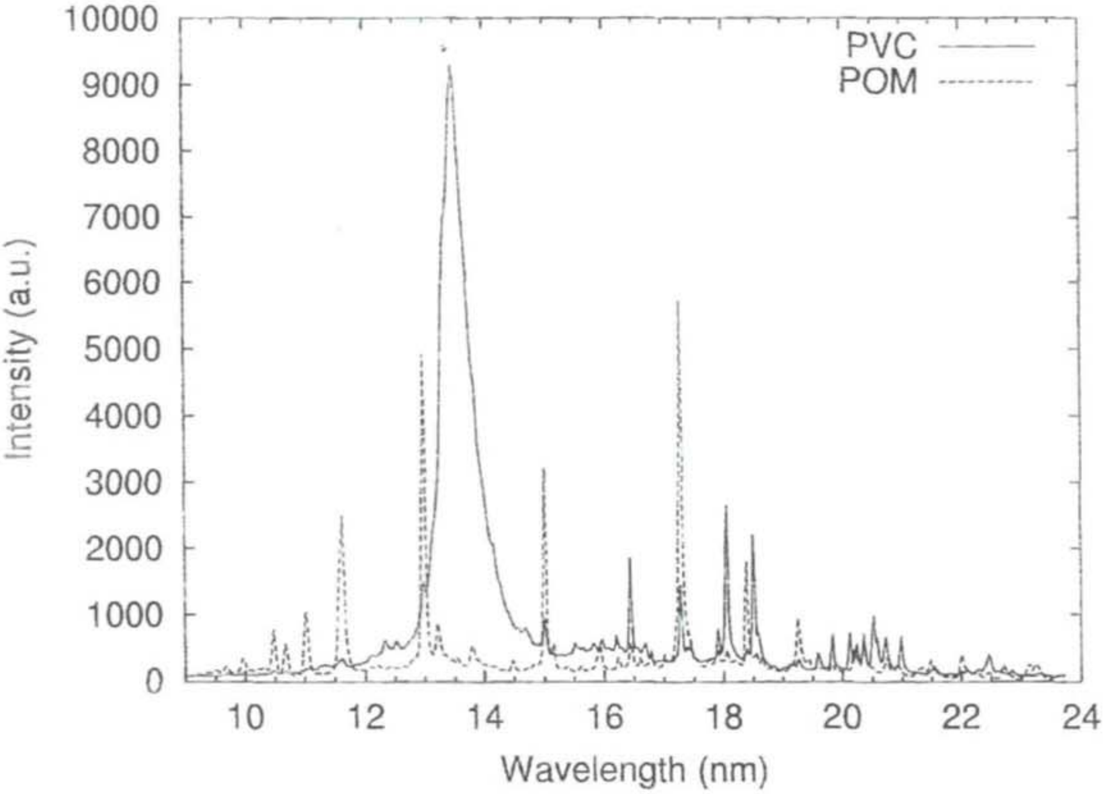
limit

13.5 nm multilayer available
Mo : Si

Spectral bandwidth 2%
i.e. 0.27nm

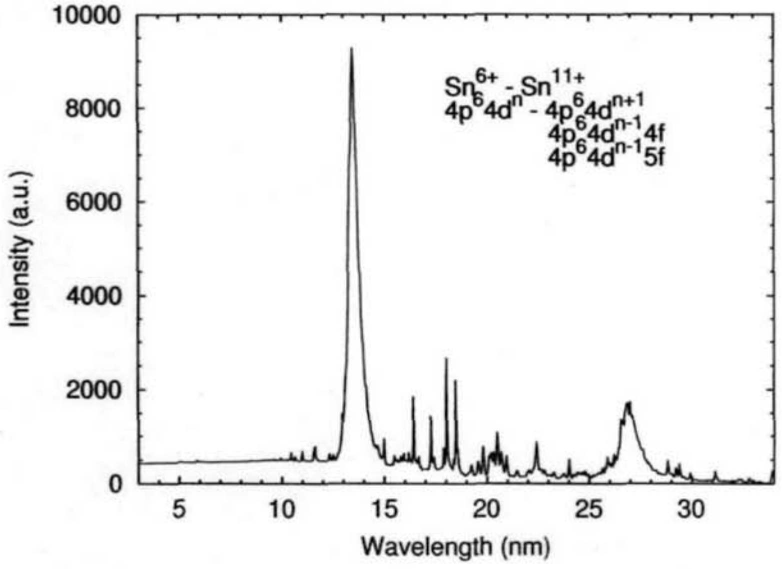
Power at intermediate focus
> 100 W

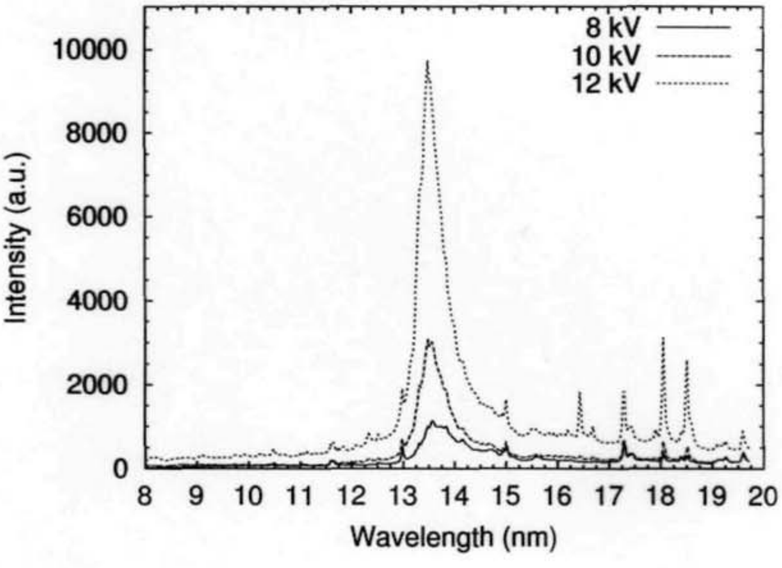
Debris problem



PVC
POM
Intensity (a.u.)
Wavelength (nm)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
10
12
14
16
18
20
22
24

PVC with 0.37% Sn as stabilizer





Inband radiant energy at 13.5 nm, (2% bandwidth)

0.48 ±0.02 mJ/sr