3rd International EUVL Symposium, Nov. 1-4, 2004, Myiazaki, Japan.

Stopping ions, clusters and out-of-band radiation by Kr for clean EUV sources.

G. Baldacchini, S. Bollanti, A. Conti*, P. Di Lazzaro, F. Flora, N. Lisi**, L. Mezi, D. Murra, A. Torre, and C.E. Zheng***.

ENEA, FIS-ACC, Via E. Fermi 45, 00044,Frascati, Italy

* ENEA guest

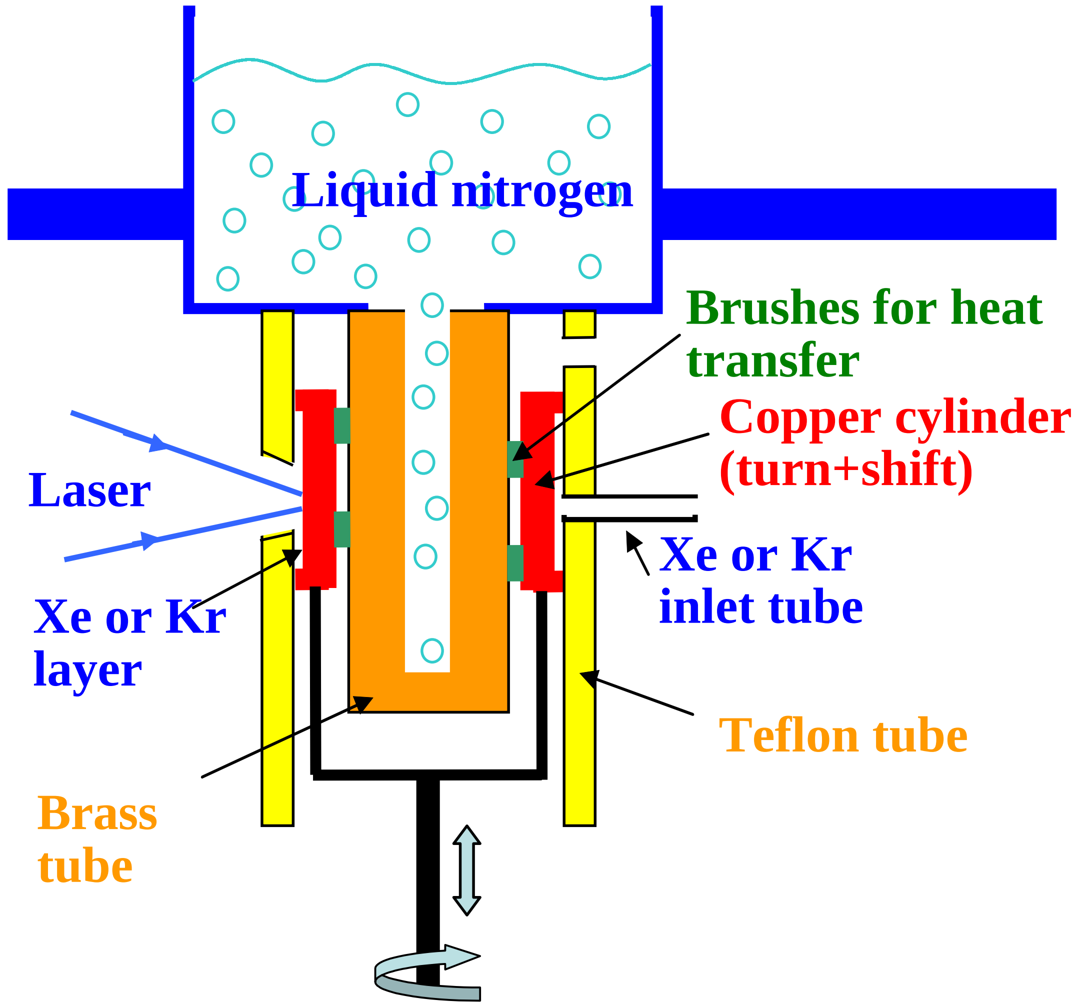
** ENEA, MAT-TEC, Santa Maria in Galeria, Roma, Italy

***EL.EN. S.p.a. Calenzano, (Florence), Italy

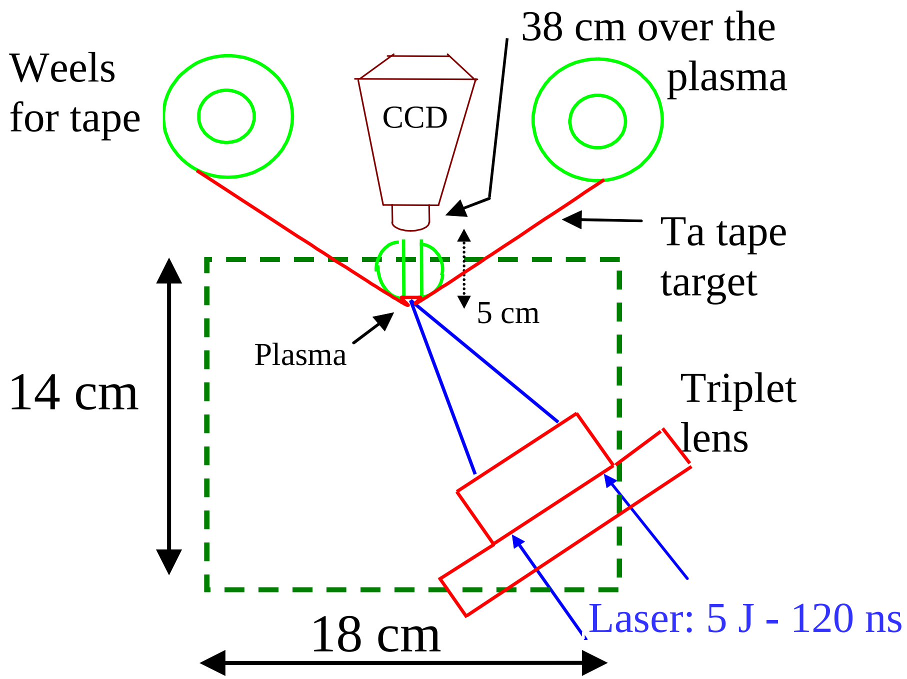
The ENEA EUV source

Site: ENEA Frascati (Rome), Italy
Source: laser-plasma
Laser: Hercules (excimer XeCl, λ=308 nm, E_L=6 J, τ_L=120 ns)
Target: a tape of tantalum, tin, indium, cryo
Optimum intensity on target for EUV emiss.: $I_L = 10^{10}$ W/cm^2
Source size and duration: Φ_{EUV}= 500 μm τ_{EUV}= 100 ns
Max. rep. Rate: 10 Hz max
E_{out}= 20 mJ/shot (in 1 sr and 2.5% B.W.)

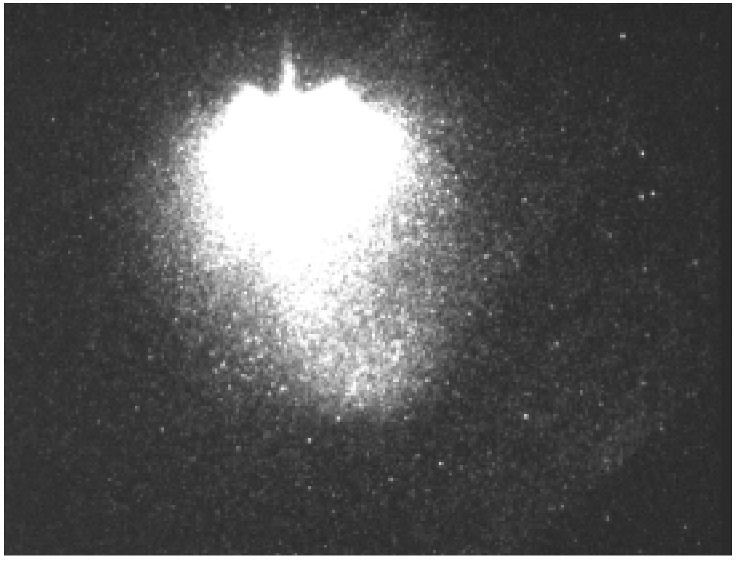
Draft of cryogenic target (More Moore activity) similar to Mochizuki proposal (see 2nd EUVL symposium, Antwerp, Belgium)



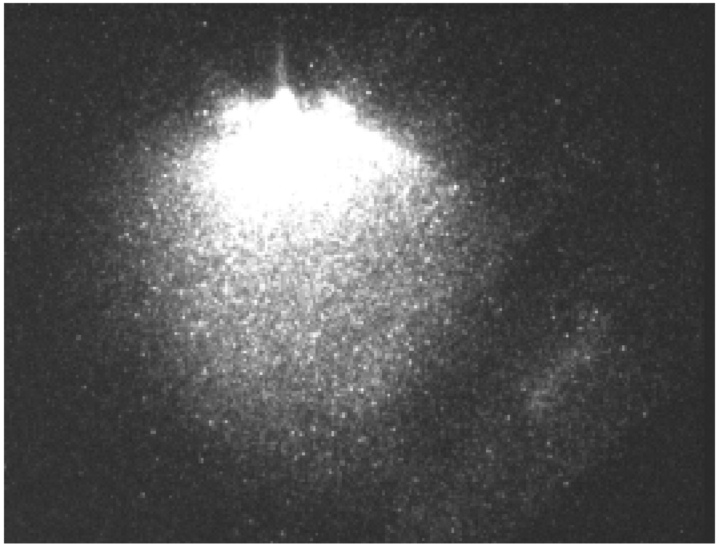
Plasma (ionic debris) detection by gated CCD



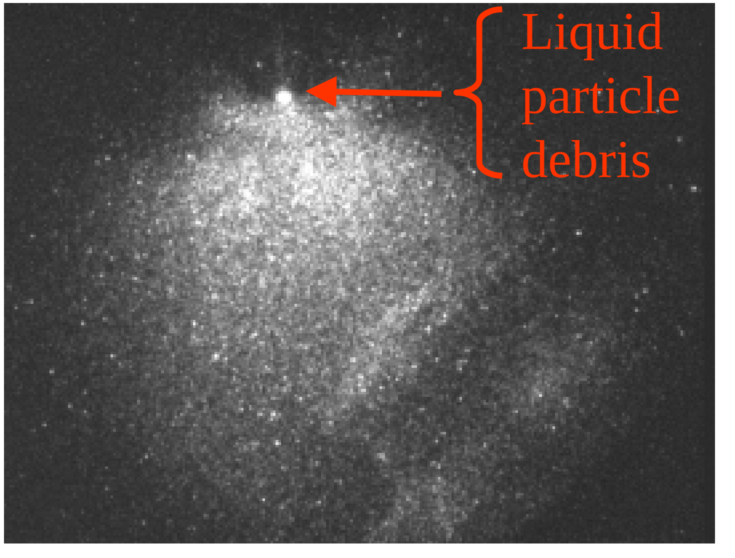
t=2 μs after laser shot



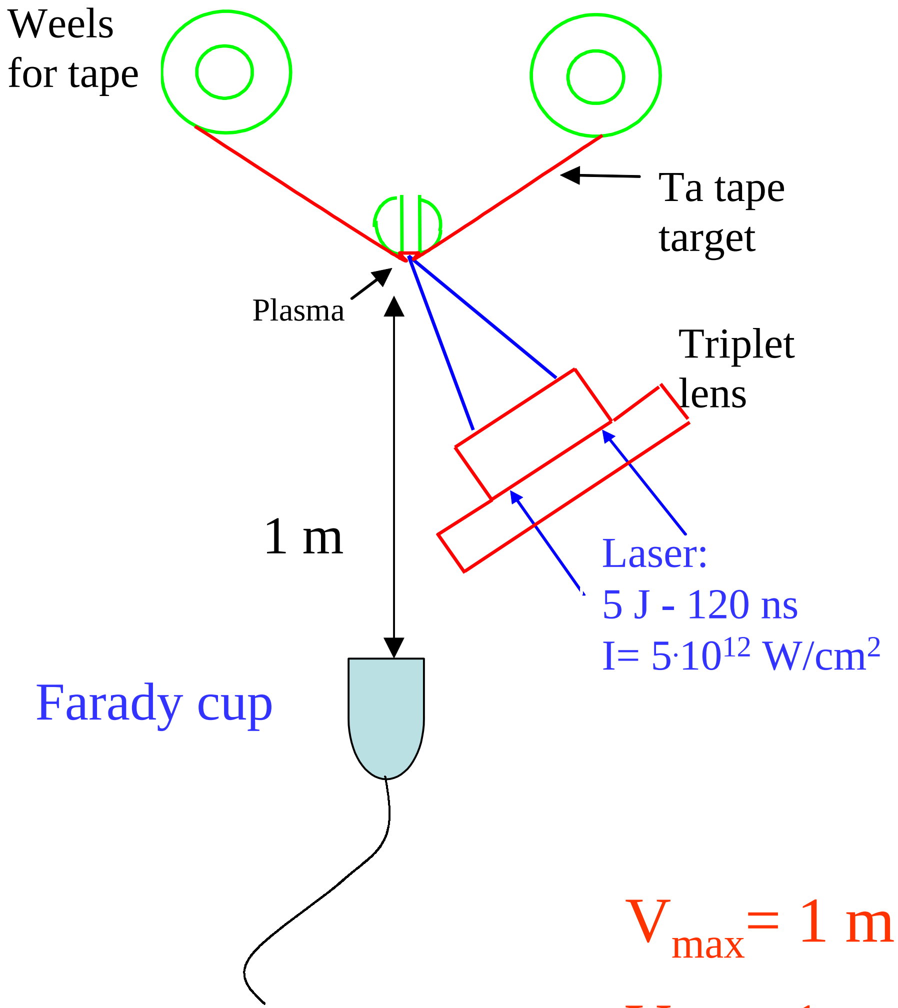
t= 3 μs

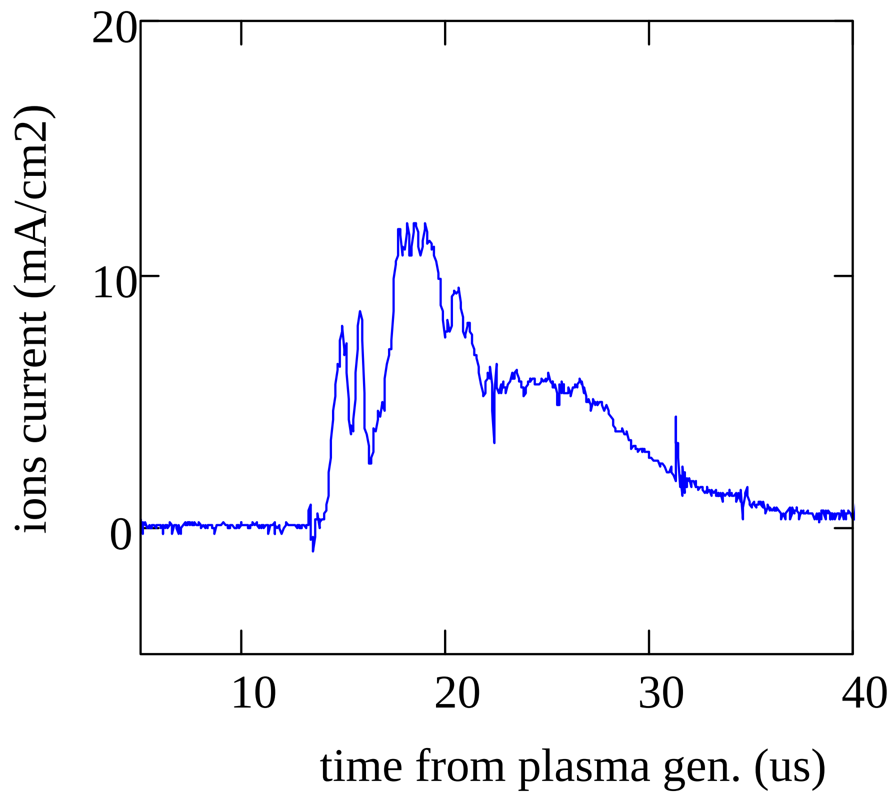


t= 4 μs



Ionic debris characterization by Faraday cup (from Ta tape target)

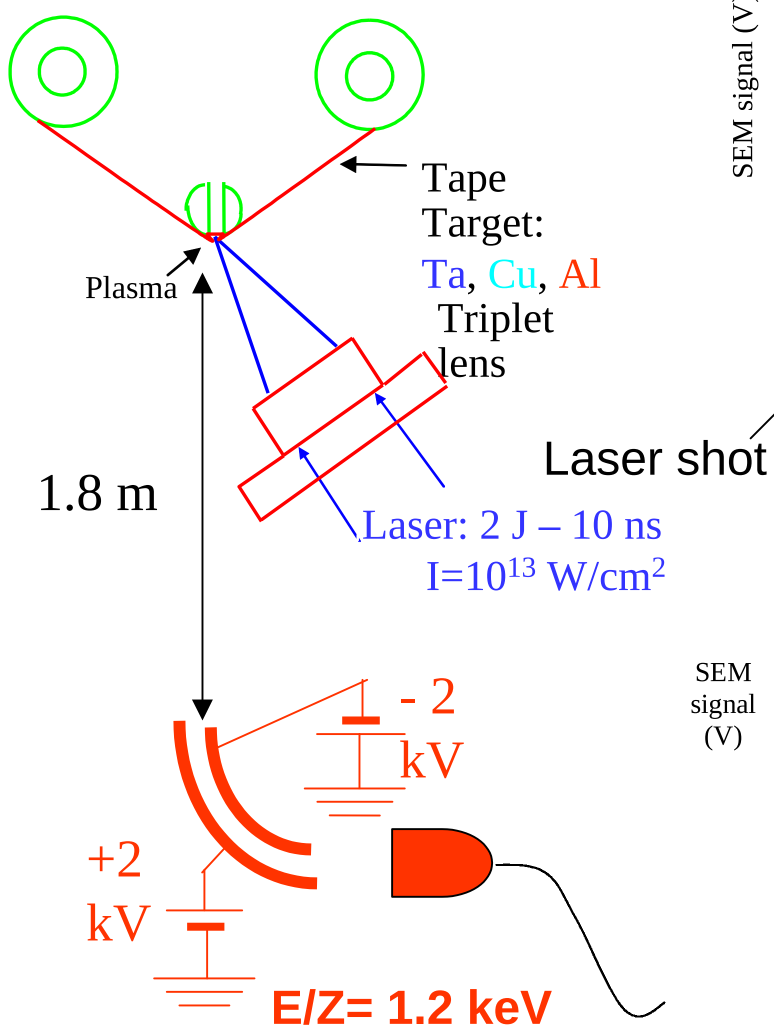


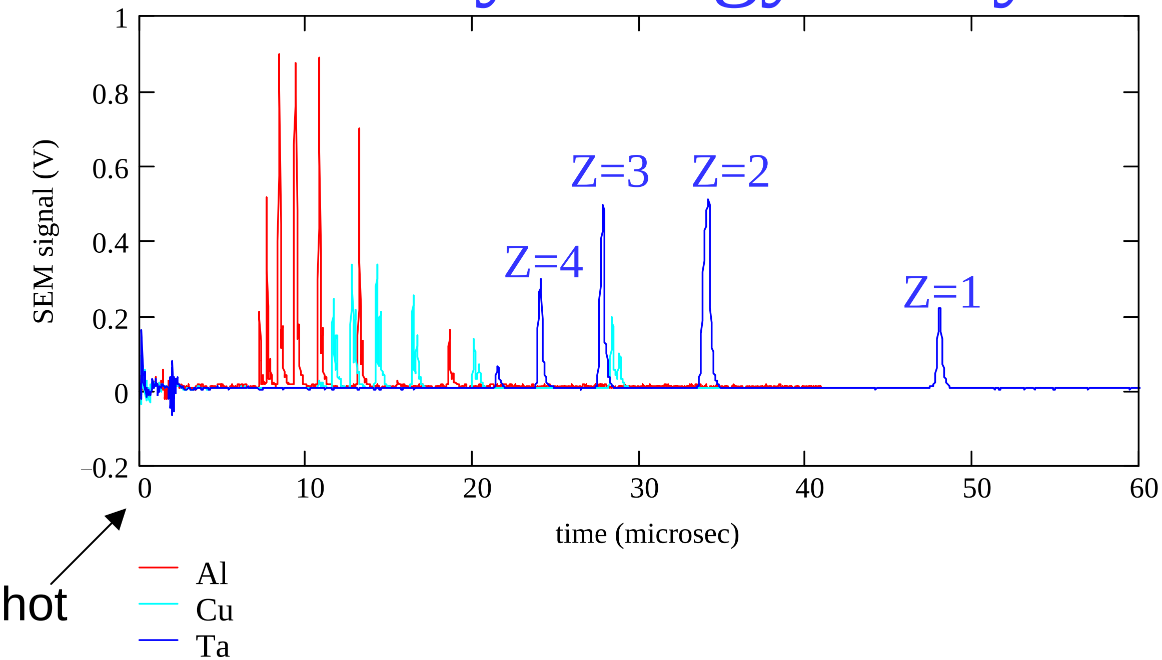


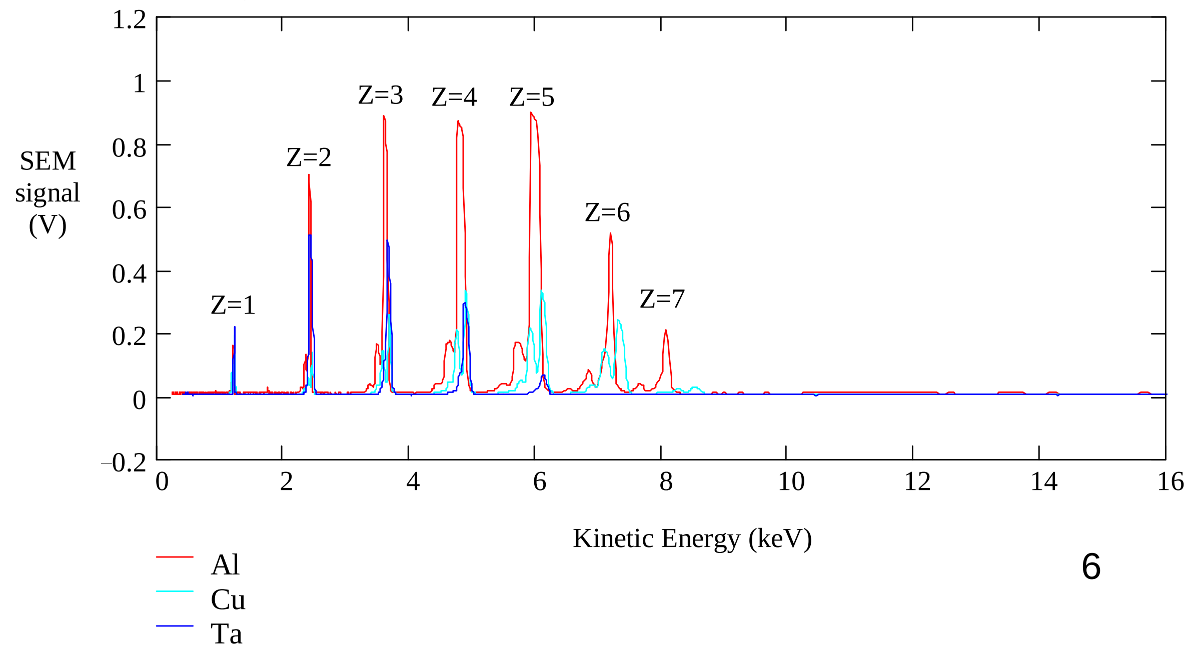
V_{max}= 1 m /12 μs = 83 km/s (= 2.9 keV)

V_{min}= 1 m /38 μs = 26 km/s (= 0.28 keV)

Ionic debris characterization by energy analyzer

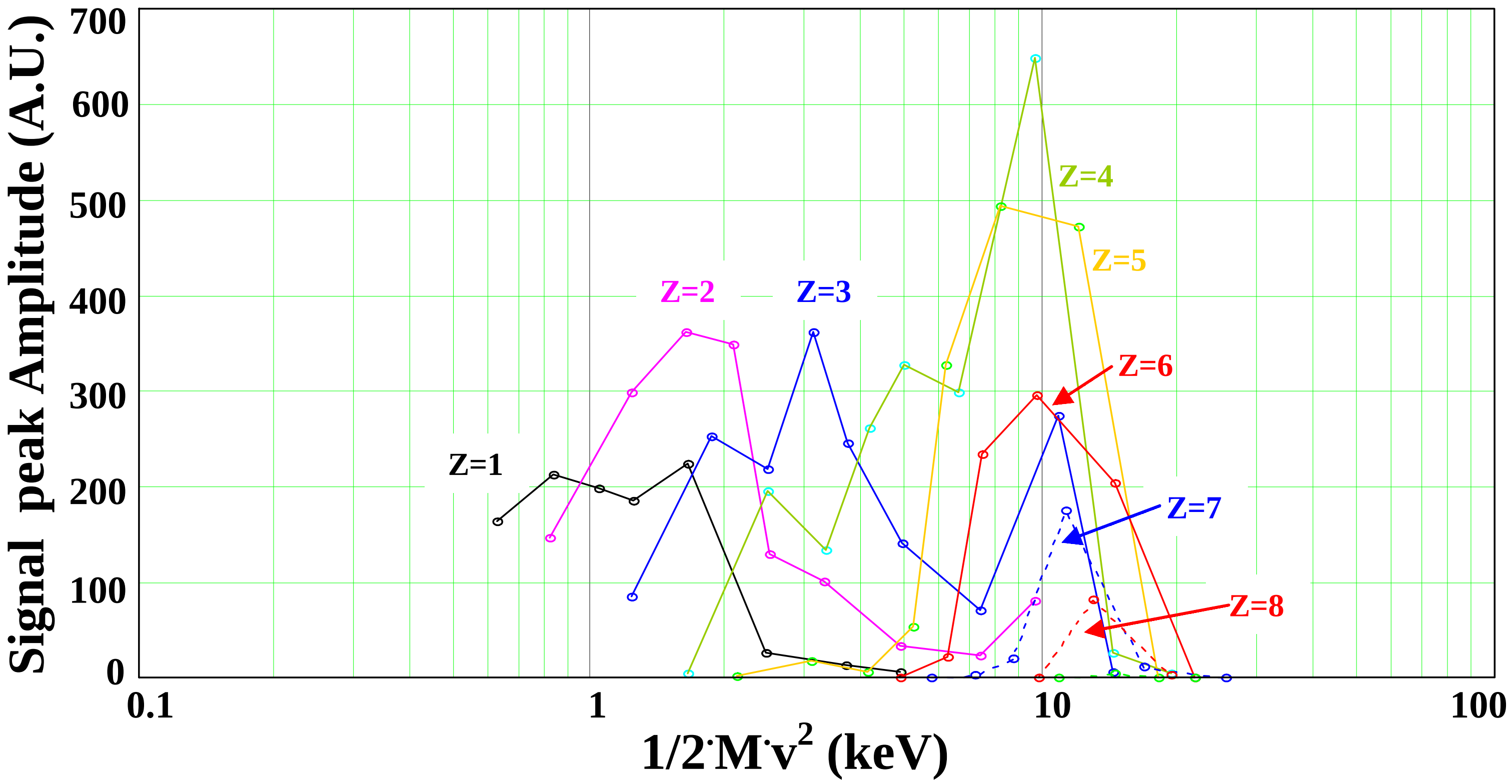






Elaboration of the Aluminum data by changing E/Z

(CONFIDENTIAL)

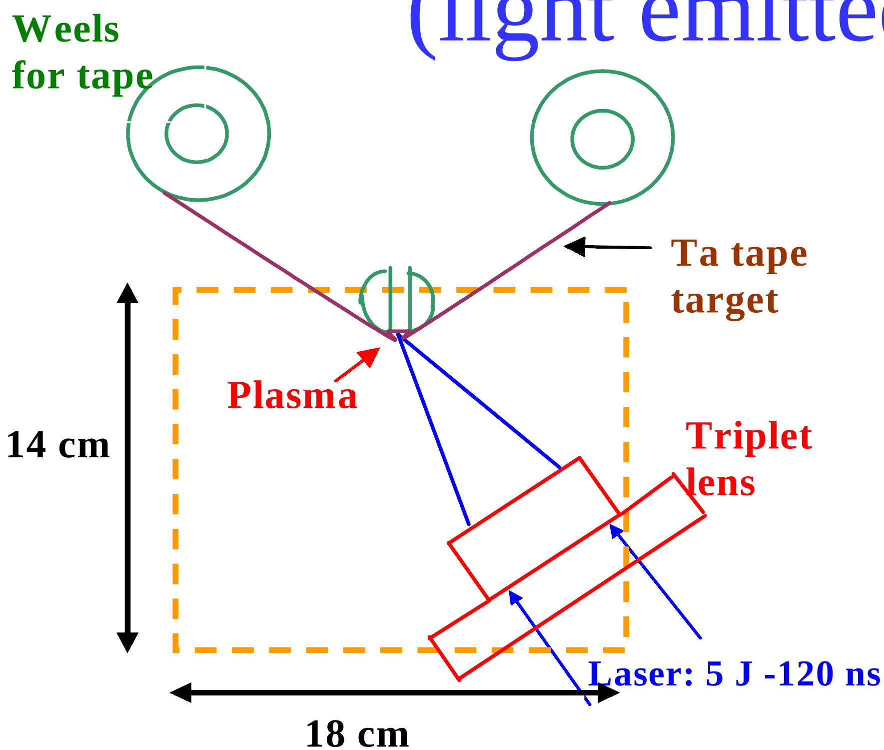


Conclusions:

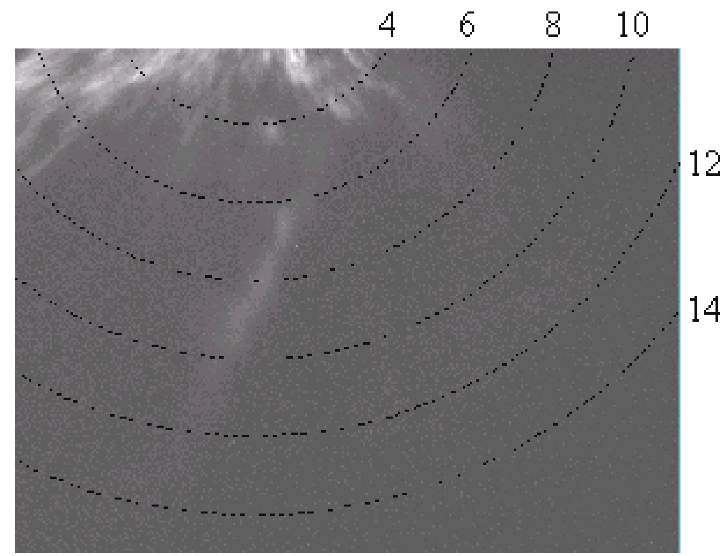
$E_{k\ peak} >> KT$ (200 eV)

$E_{k\ peak}$ is proportional to the charge state

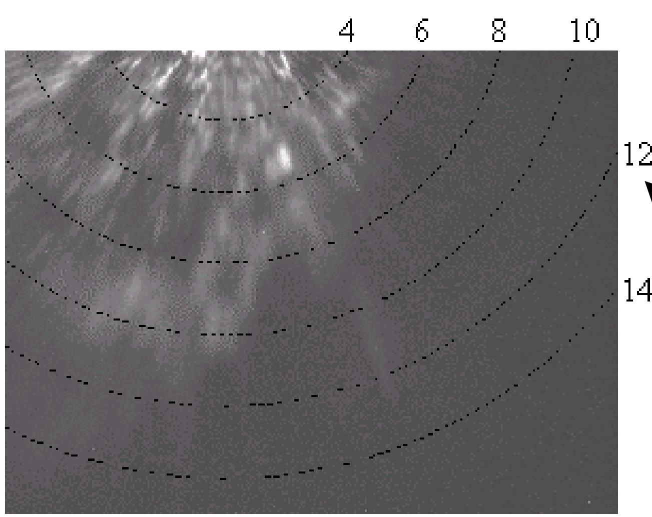
Particle debris detection by gated CCD camera (light emitted by black-body)



t=150 µs after laser shot

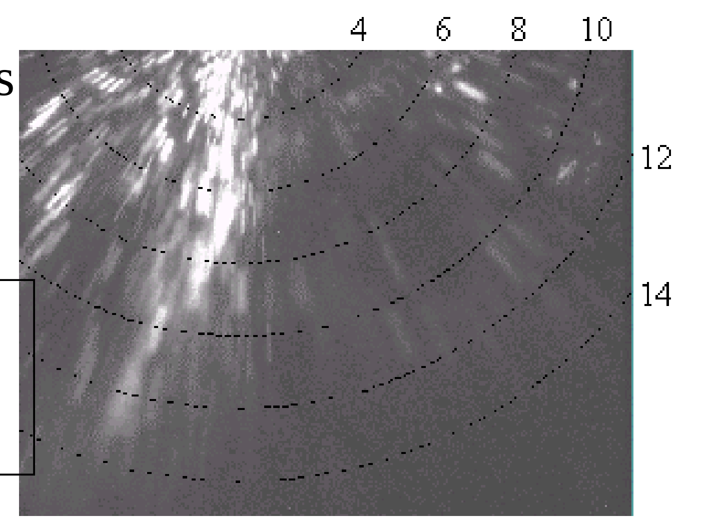


t= 250 µs

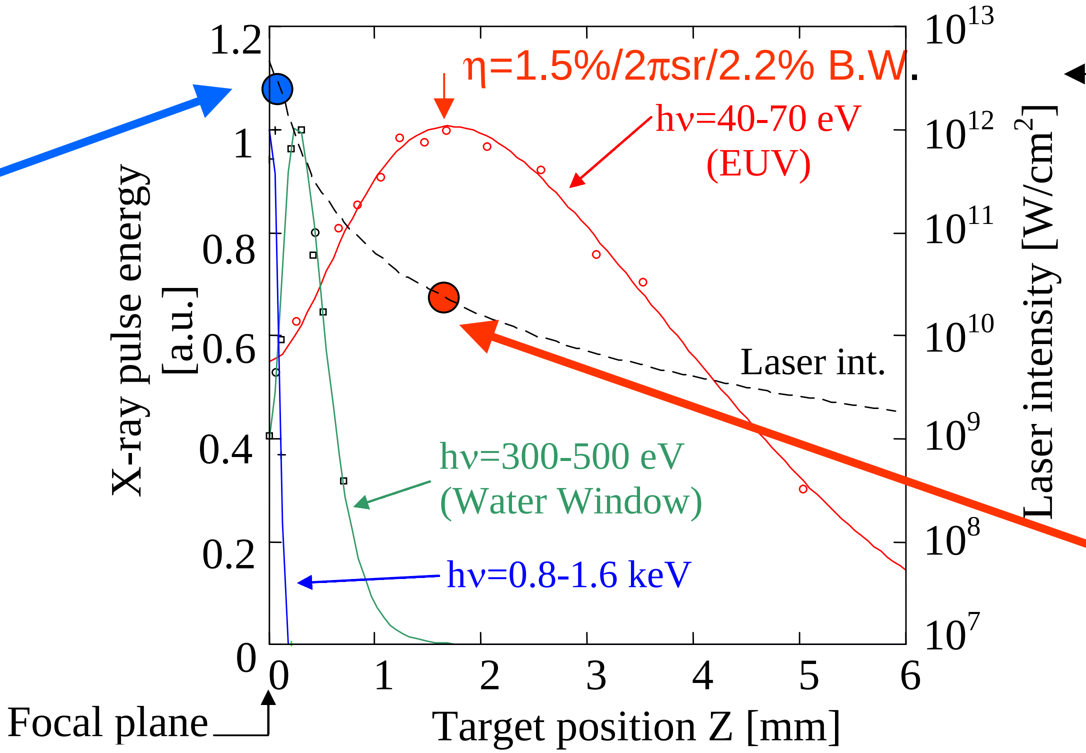


Distance from target (cm)

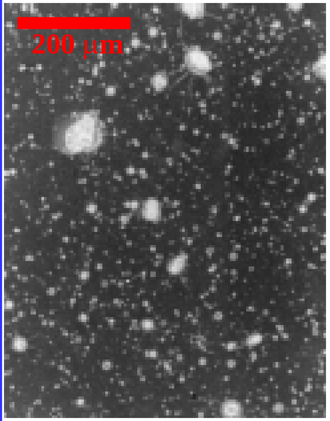
t= 500 µs



EUV emission & debris amount vs. laser intensity

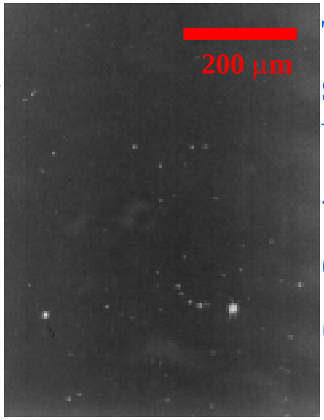


From a Cu tape target



Y target, 450 shots @ $I_L=10^{12}$ W/cm^2 in He:

~ 9000 deb/sr/J/shot (Φ> 0.5 µm)



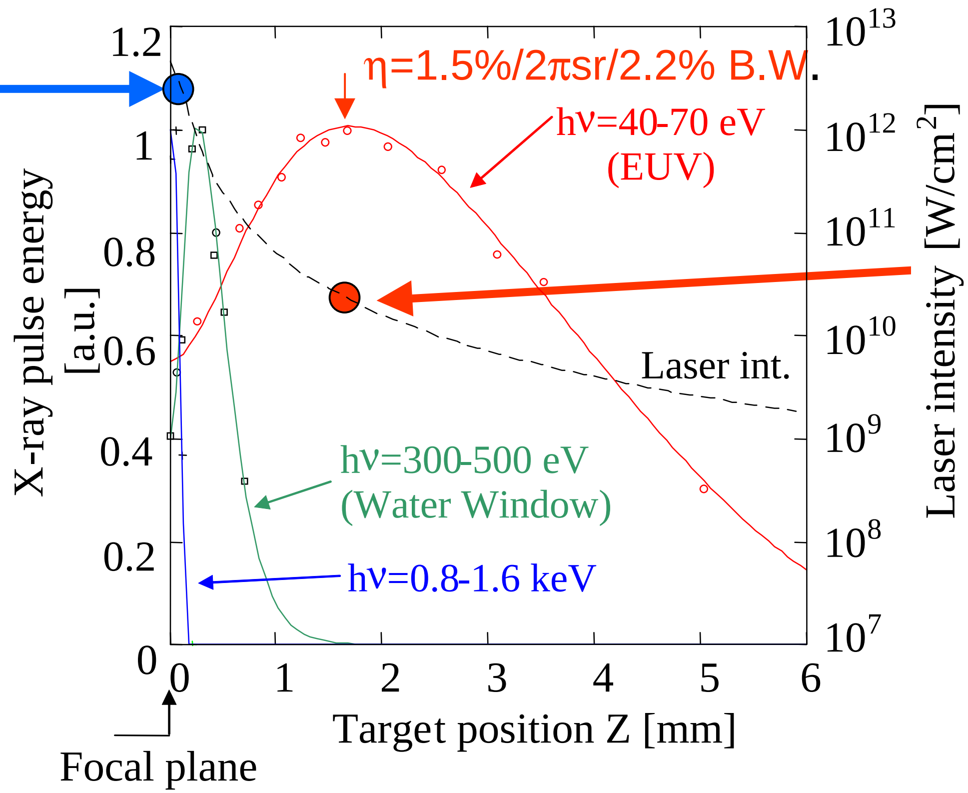
Ta target, 600 shots @ $I_L=10^{12}$ W/cm^2 in He:

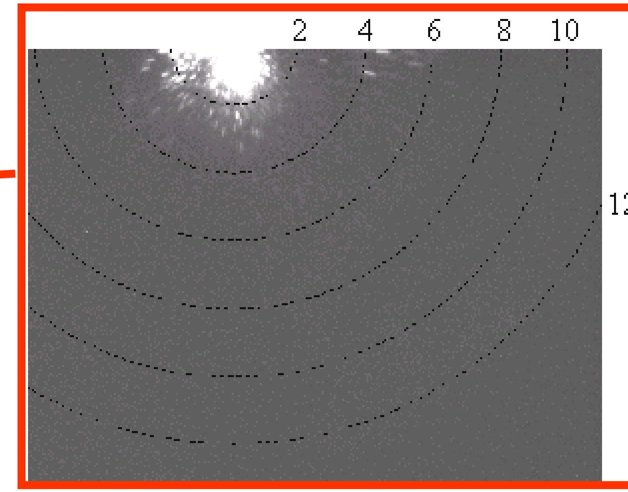
~ 300 deb/sr/J/shot (Φ> 0.5 µm)

Ta target, 500 shots @ $I_L=10^{10}$ W/cm^2 in vacum:

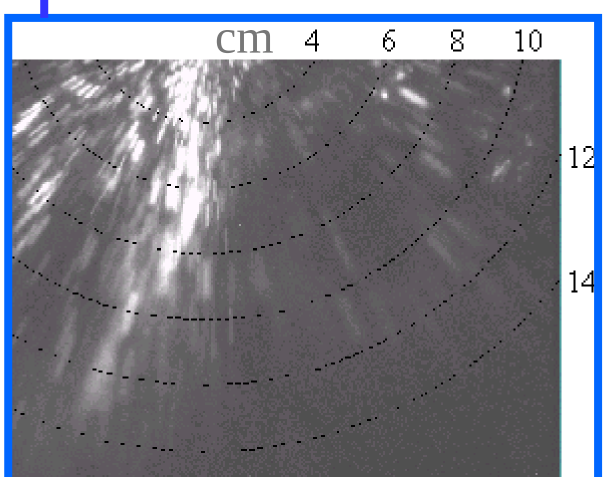
~ 30 deb/sr/J/shot (Φ> 0.5 µm)

EUV emission & Ta debris speed vs laser int.





t= 500 μs V_{max}=100 m/s



t= 500 μs

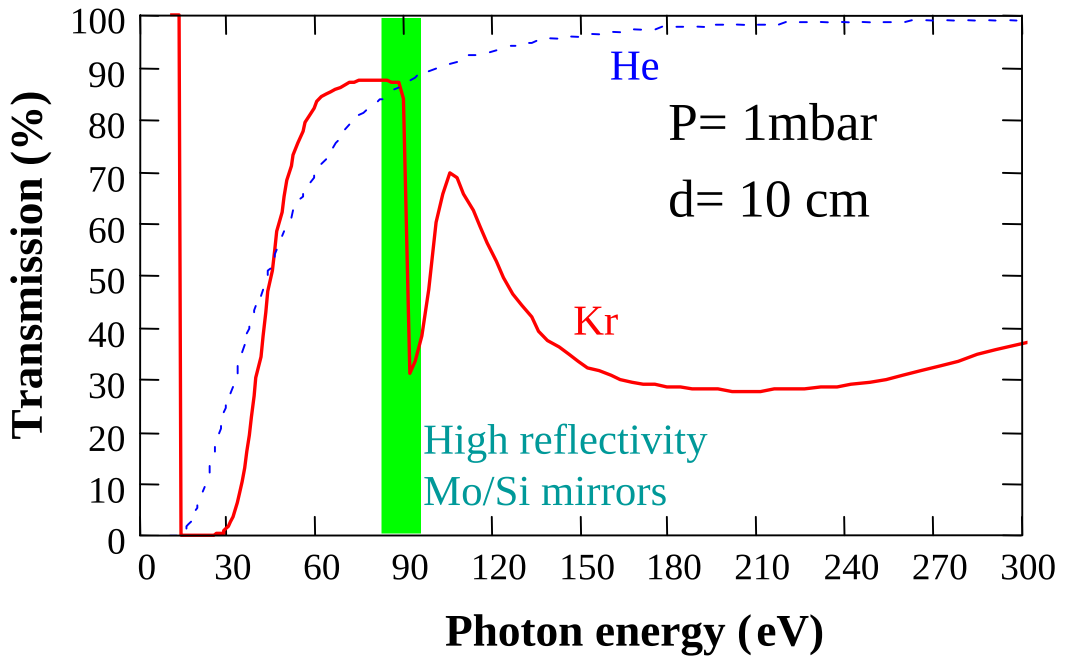
V_{max} =500 m/s

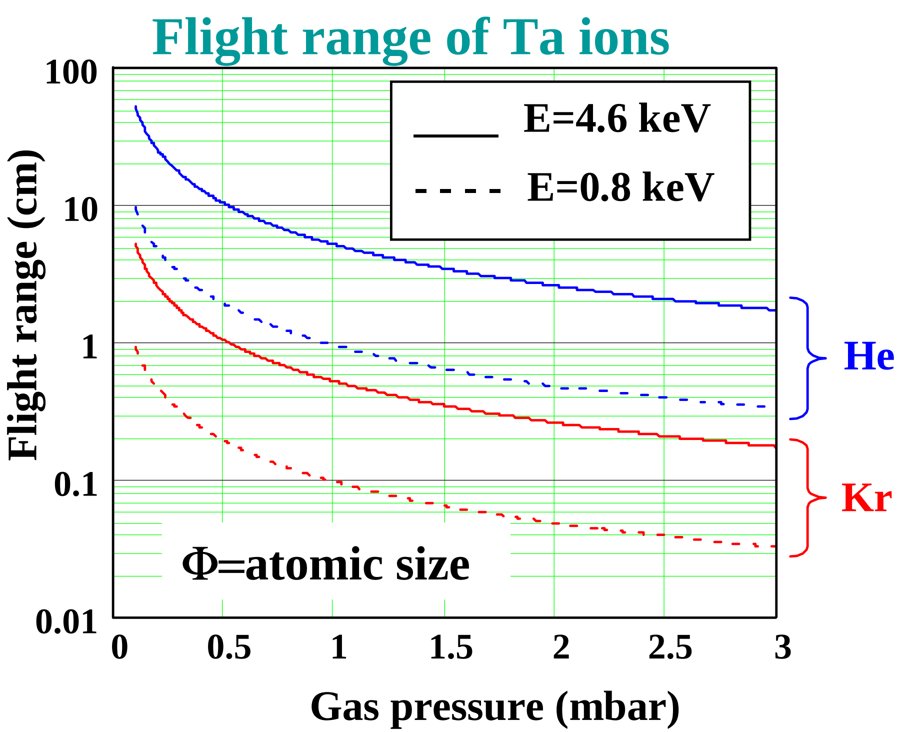
@ $I_L=10^{10}$ W/cm²:

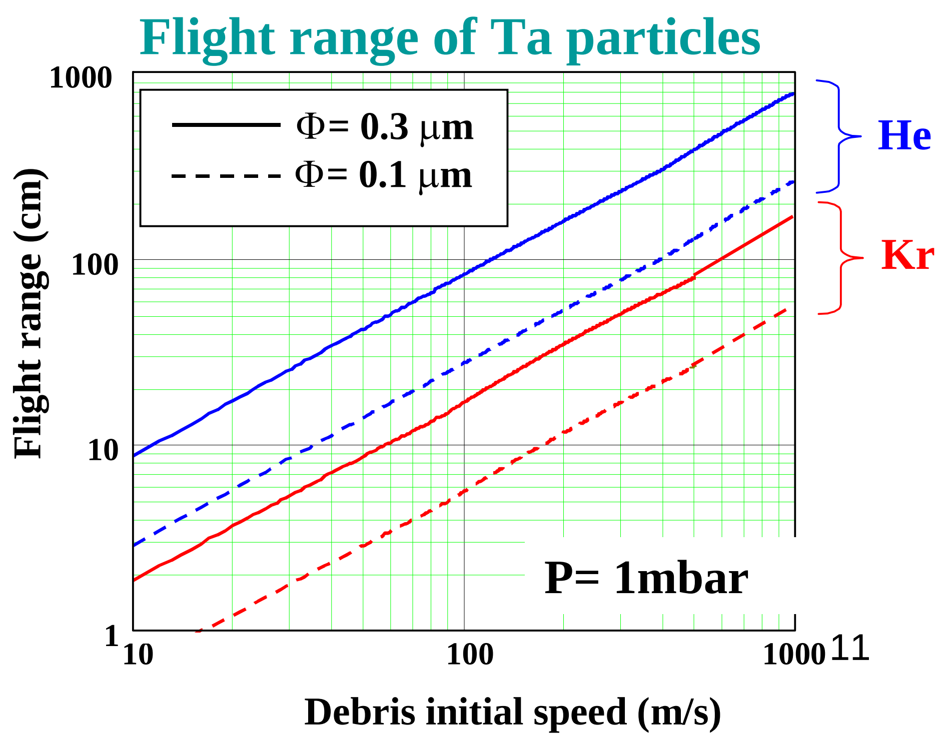
- **Improved conversion eff.**
- **Reduced debris emission**
- **Reduced debris speed!**

The Debris Mitigation System of ENEA

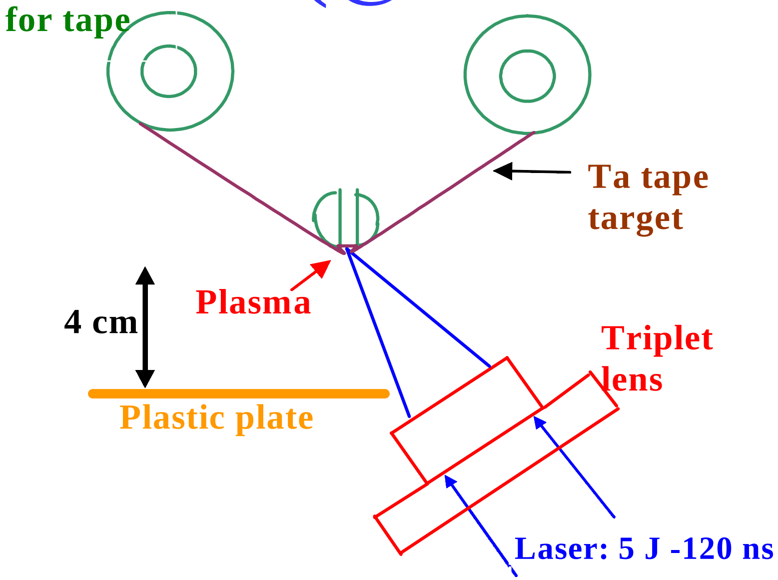
Krypton buffer!

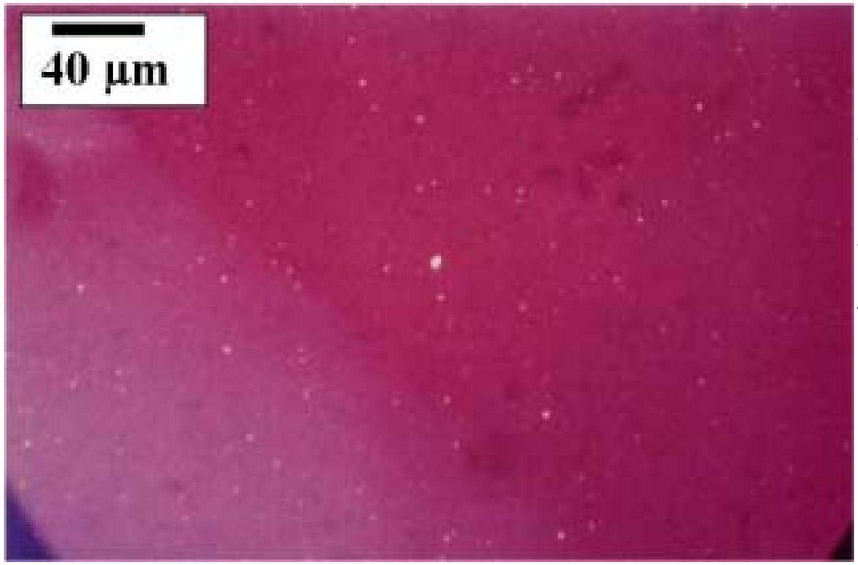






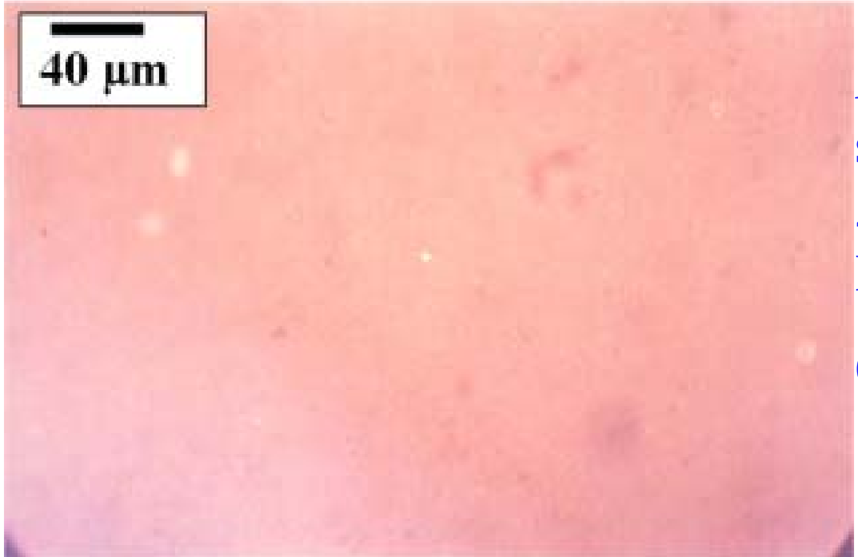
The effect of only Krypton on Ta debris (@ d= 4 cm and I_L=10^{10} W/cm^2)





After 400 shots in the vacuum

OD=0.6



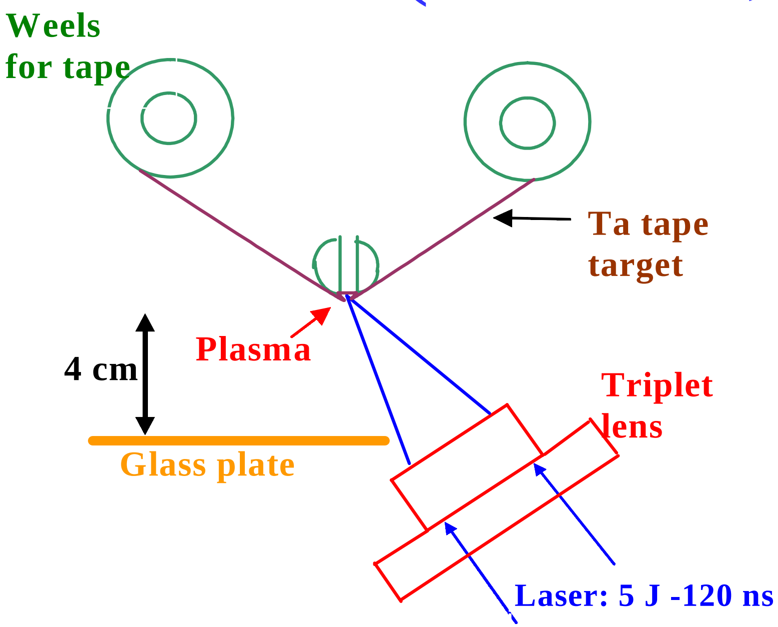
After 400 shots in 2.5 mbar Krypton

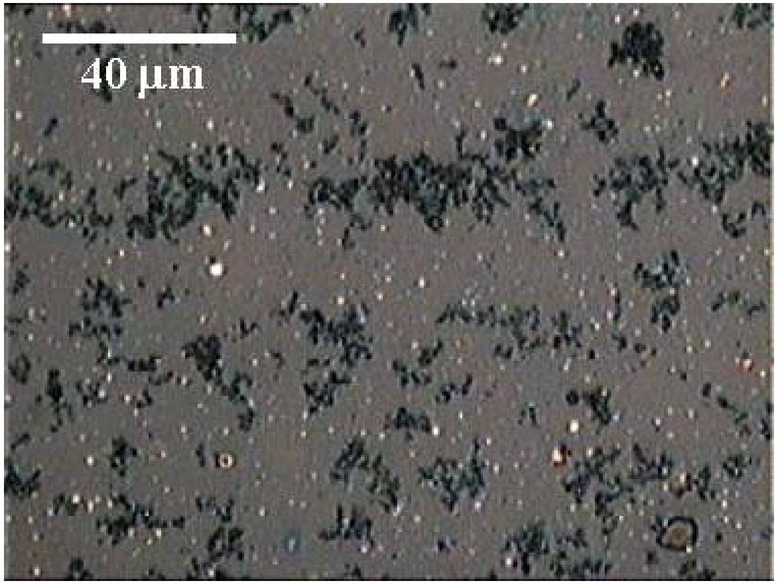
OD=0.01

Mitigation on particles: > 100

Mitigation on ions = 60

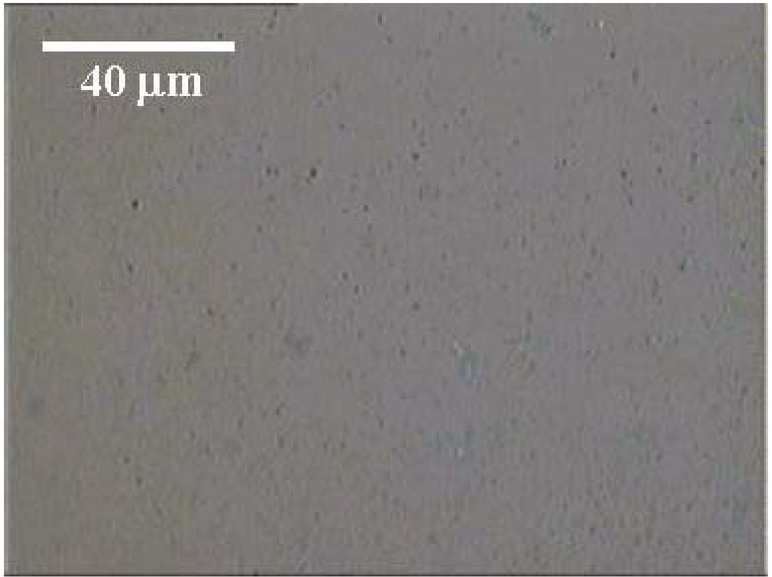
The effect of only Krypton on Cu debris
(d= 4 cm; $I_L=10^{10}$ W/cm^2)





After 500 shots in the vacuum

OD=0.6



After 500 shots in 2.5 mbar Krypton

OD=0.015

Mitigation on particles: > 100

Mitigation on ions = 40

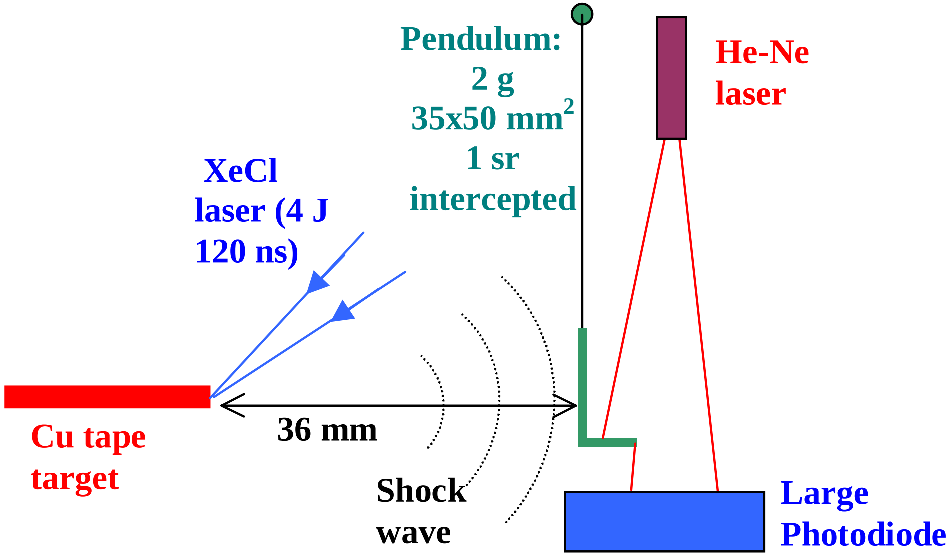
The mitigation of ions + neutrals results to be much lower than that expected from their short range-of-flight (see above graph). Why?

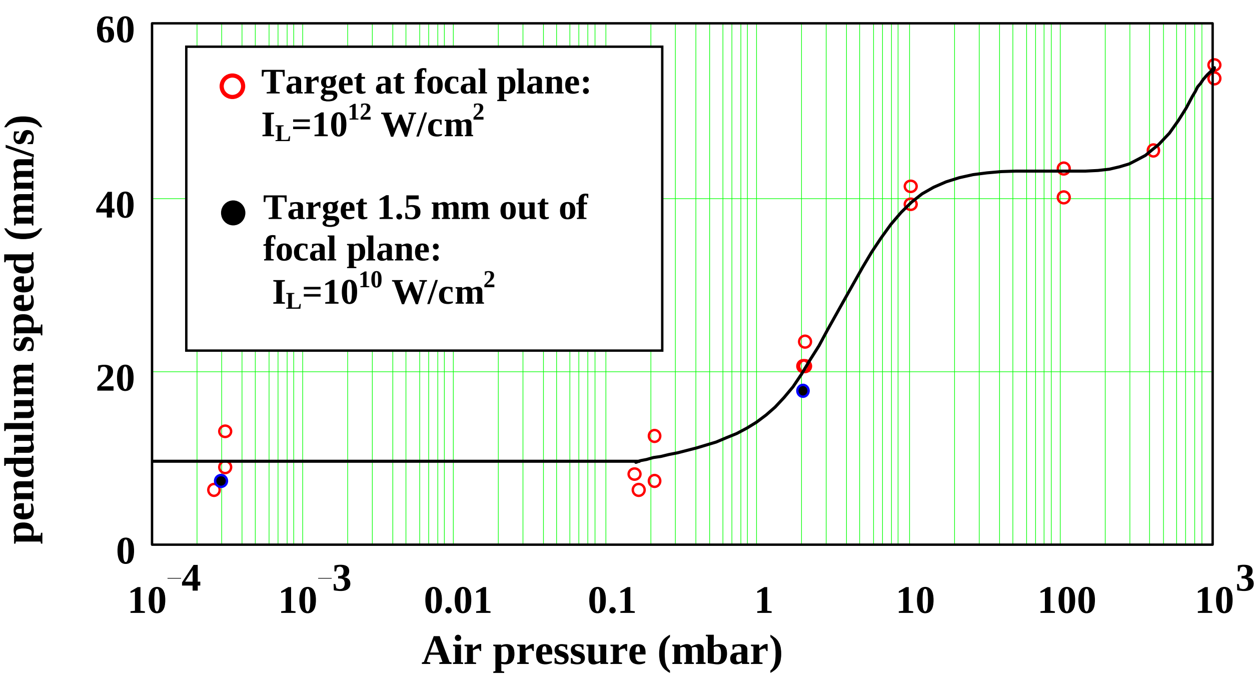
Possible answer:

The ionic debris are really arrested after few mm of flight but they transfer a momentum to the krypton gas, so that a dirty krypton traveling cloud is generated.

If this is true, both the particle debris as well as the dirty krypton cloud might be arrested by a mechanical device like a couple of counter-turning disks. This is the main idea of the DMS patented by ENEA.

Measurement of the momentum given by Cu ions

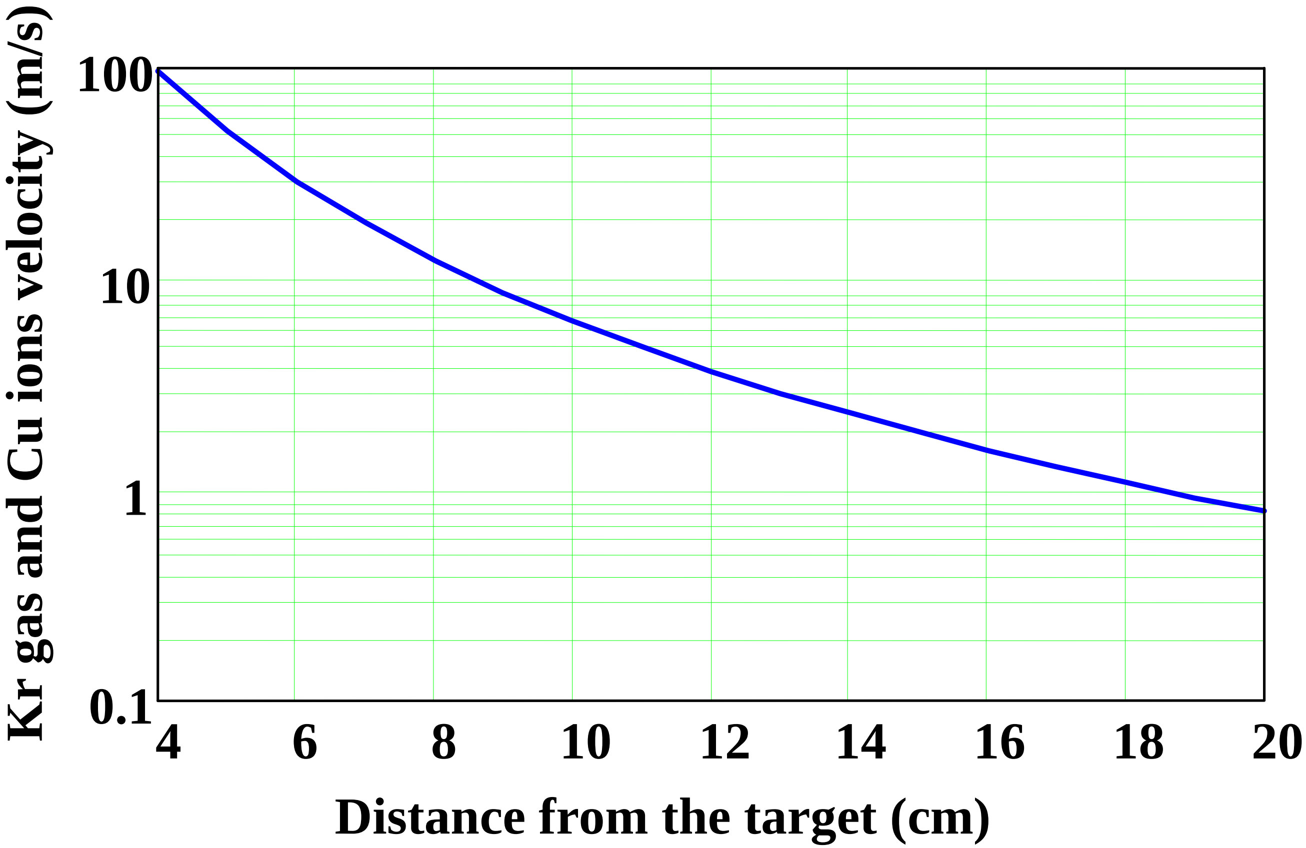




debris momentum = $2{\cdot}10^{-5}$ Kg·m/s /sr

Sufficient to push Kr @ 1 mbar up to 10 - 100 m/s !

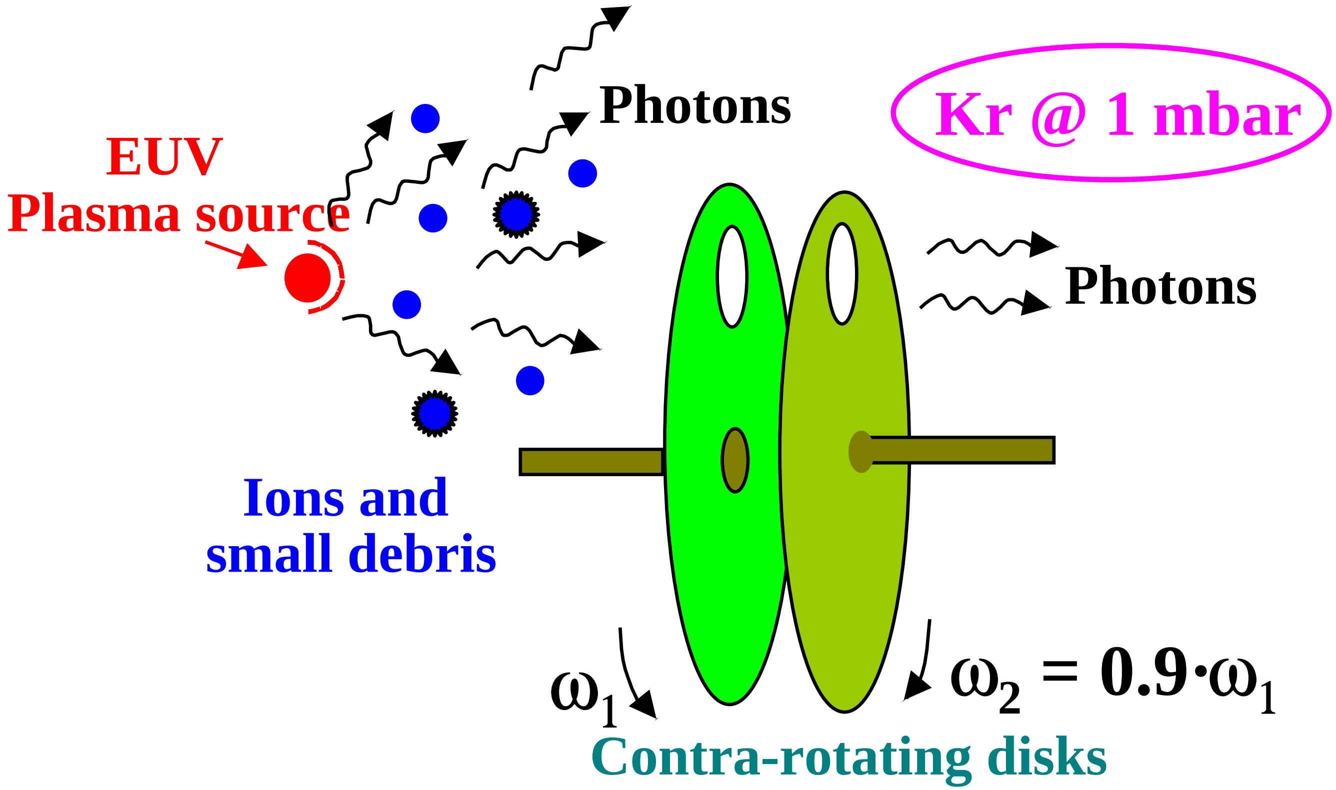
The momentum of ions, transferred to krypron, generates a travelling dirty Kr cloud



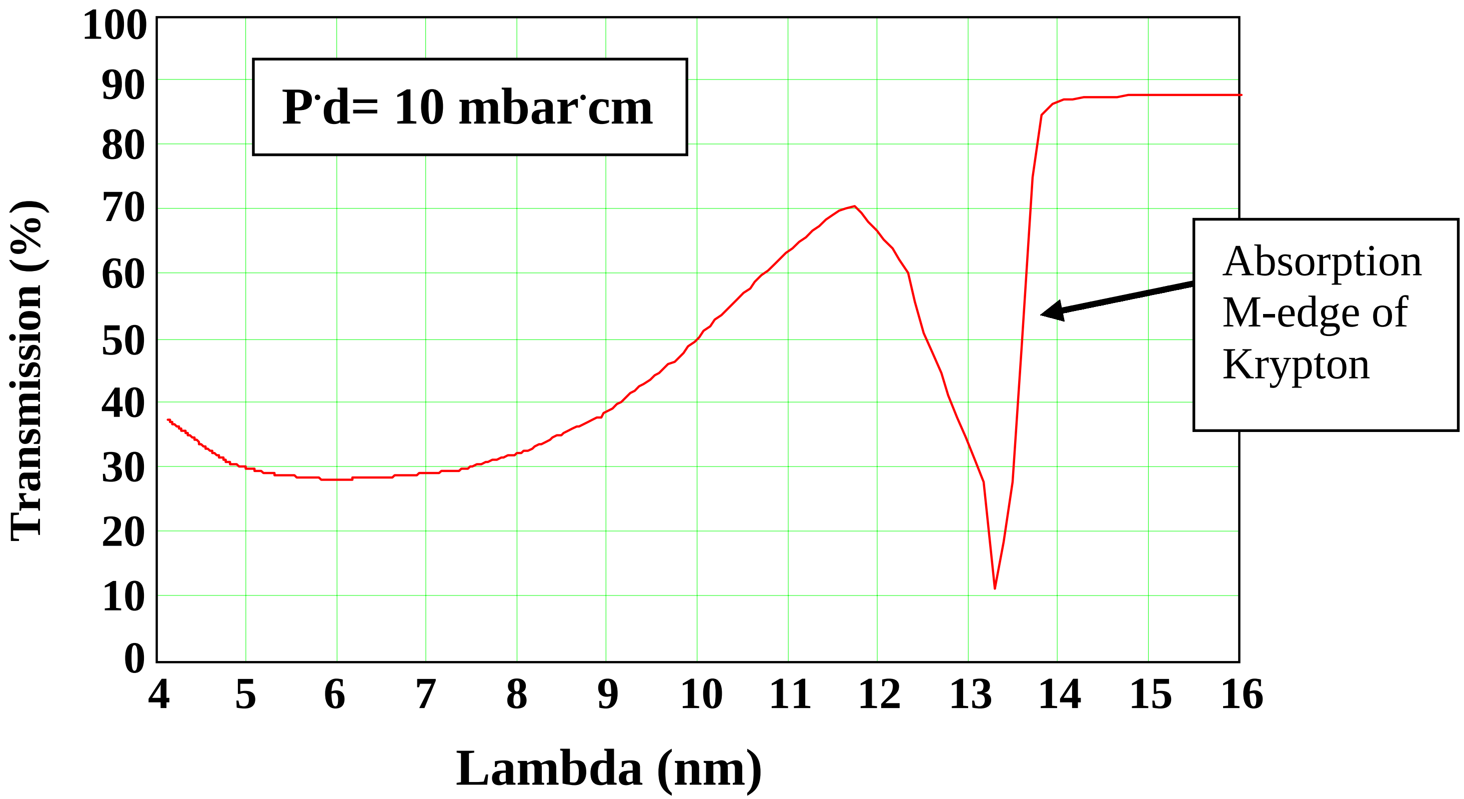
Krypton plus copper ions/neutrals speed in 1 sr cone vs the distance from the Cu target for a krypton pressure of 2.5 mbar. The ions emission is assumed to be isotropic in the 1 sr cone.

ENEA DMS operation principle:

- When the holes of two turning disks coincide, the laser is fired: photons pass through while ions are captured in Kr to form a traveling dirty cloud
- When the cloud and the particulate debris reach the disks the path is closed! Due to the disk velocity difference, many turns are needed before the path will be open again.



Drawback of Kr use: the EUV λ must be > 13.8 nm



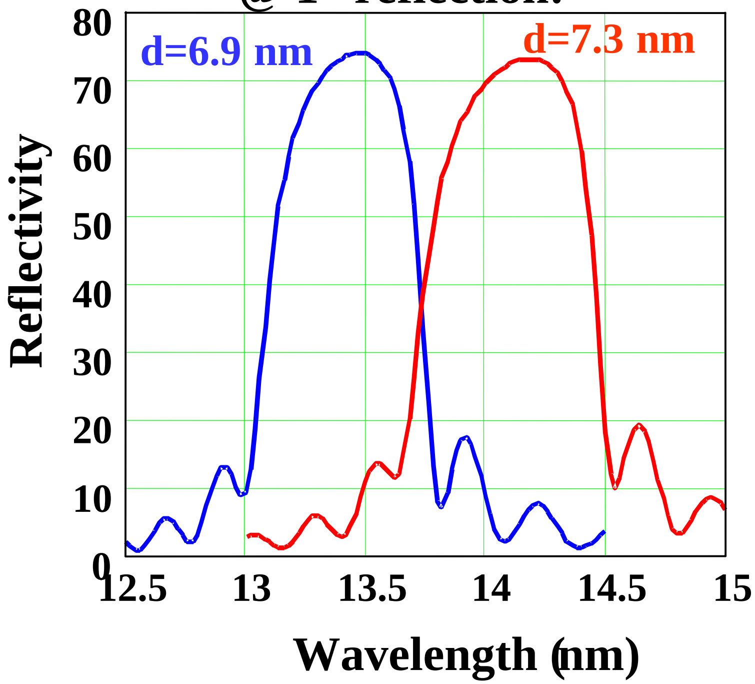
Transmission of Krypton gas @ P·d= 10 mbar·cm

For Mo/Si multilayer mirrors this is not a problem!

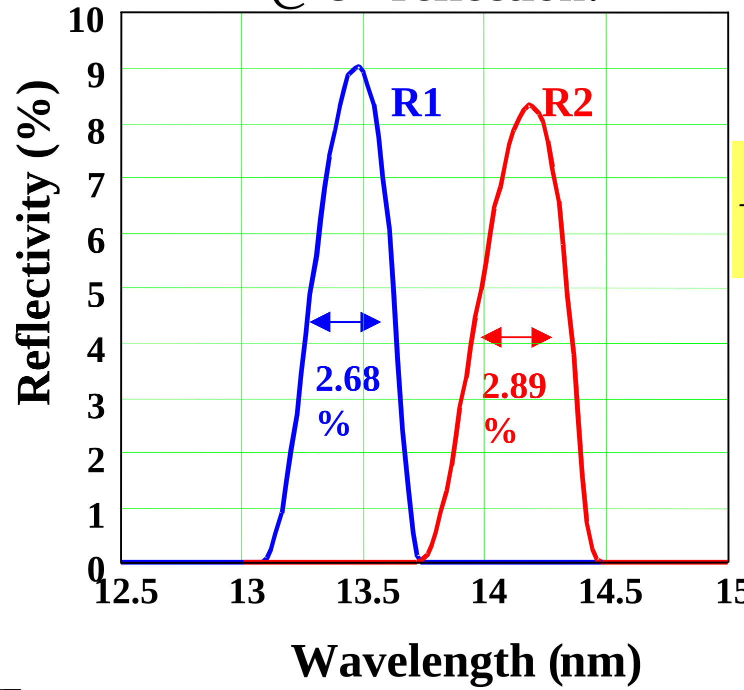
Comparison of Mo/Si at 13.4 nm (92.5 eV) and at 14.2 nm (88 eV)

(from web site: http://www-cxro.lbl.gov/optical_constants/)

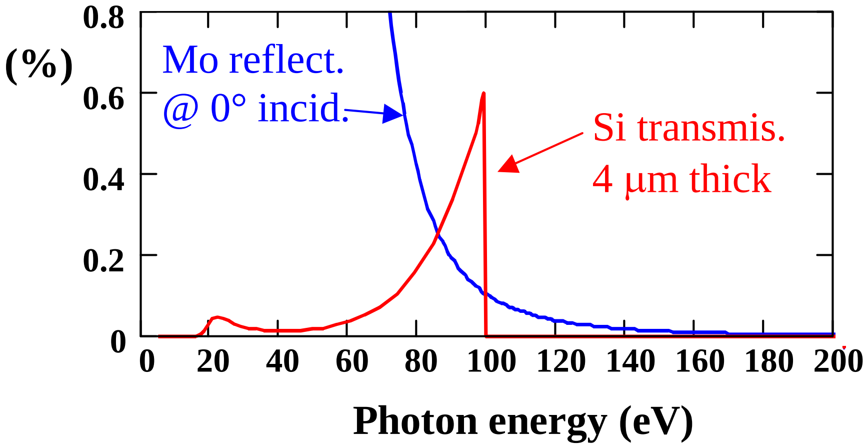
@ 1st reflection:



@ 8th reflection:

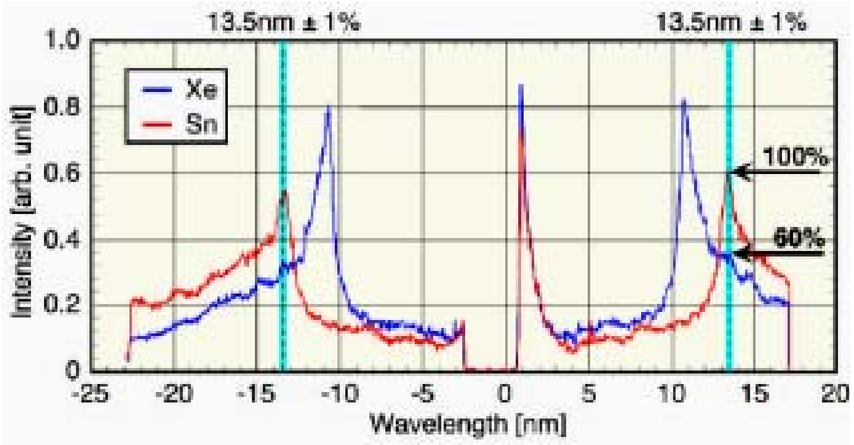


$$\frac{\int R2(\lambda)d\lambda}{\int R1(\lambda)d\lambda} = 1.04$$



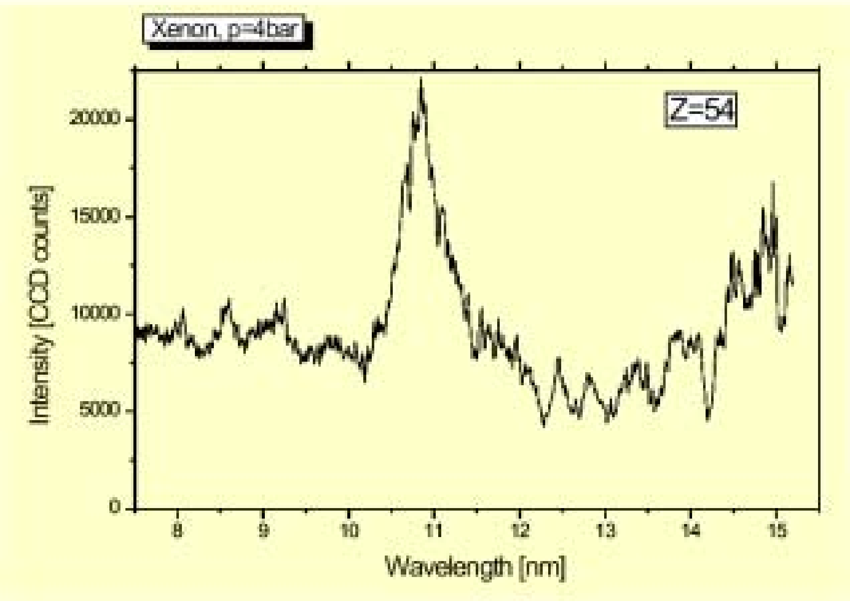
For a shift to longer wavelengths (lower hν), the lower Si transmission is compensated by the higher Mo reflection!

For most of the EUV sources the shift to 14.2 nm represents a small problem:



Emission from cryo Xe target:

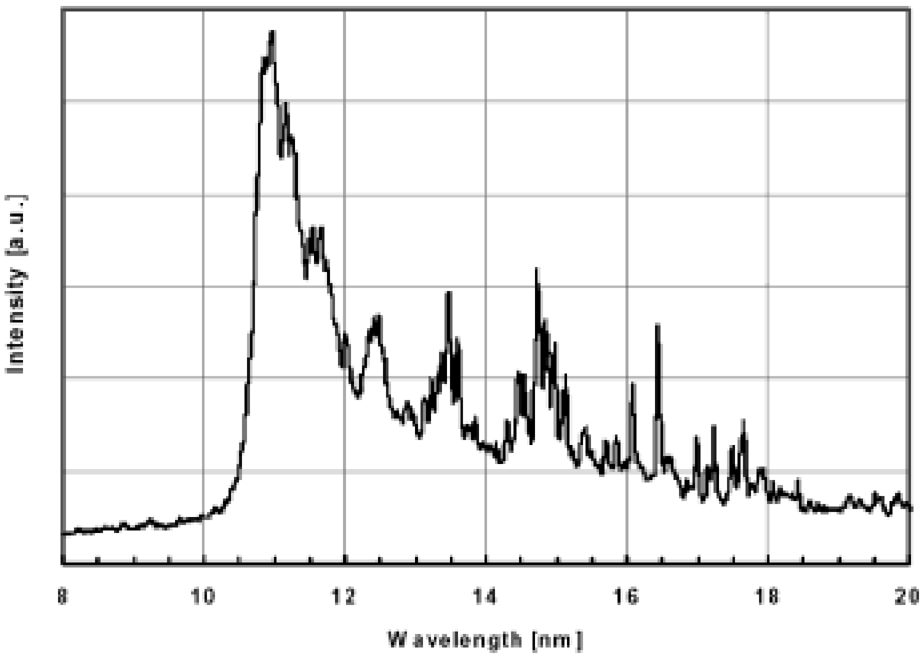
T. Mochizuki et al.: "*Studies on x-ray conversion efficiency in Xe cryogenic targets*" 2nd International EUVL Symposium, Antwerp, Belgium, 2003



Emission from Xe gas jet target:

K. Mann et al.: "*Table-top laser-based EUV source for metrology*" 2nd EUVL symposium, Antwerp, Belgium, 2003 (www.llg.gwdg.de).

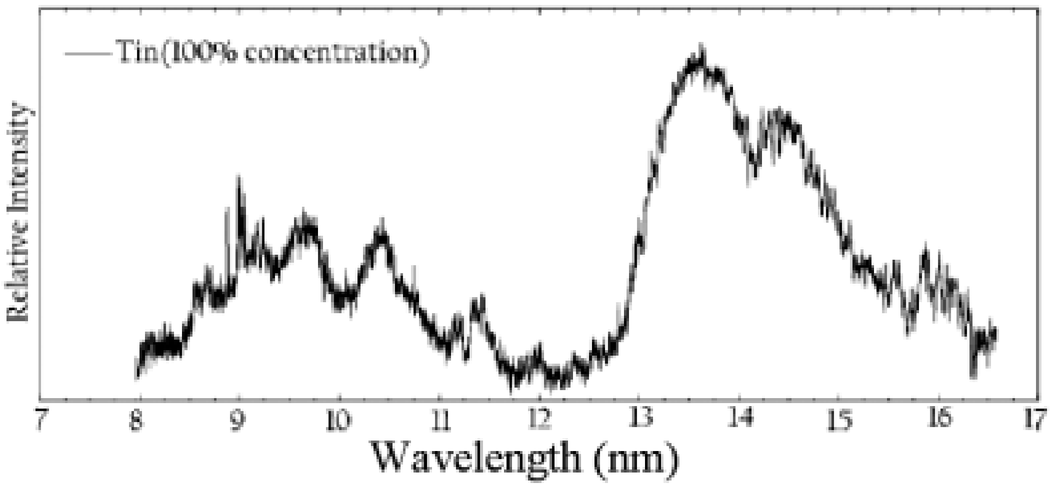
Xe gas target



Emission from Xe gas target:

Akira Endo et al.: “*Design of high average power clean EUV light source based on laser produced Xenon plasma*”, SPIE 48th annual meeting, San Diego 2003, Vol. 5196, pp. 256-262

(50 mJ – 30 ns Nd-YAG)

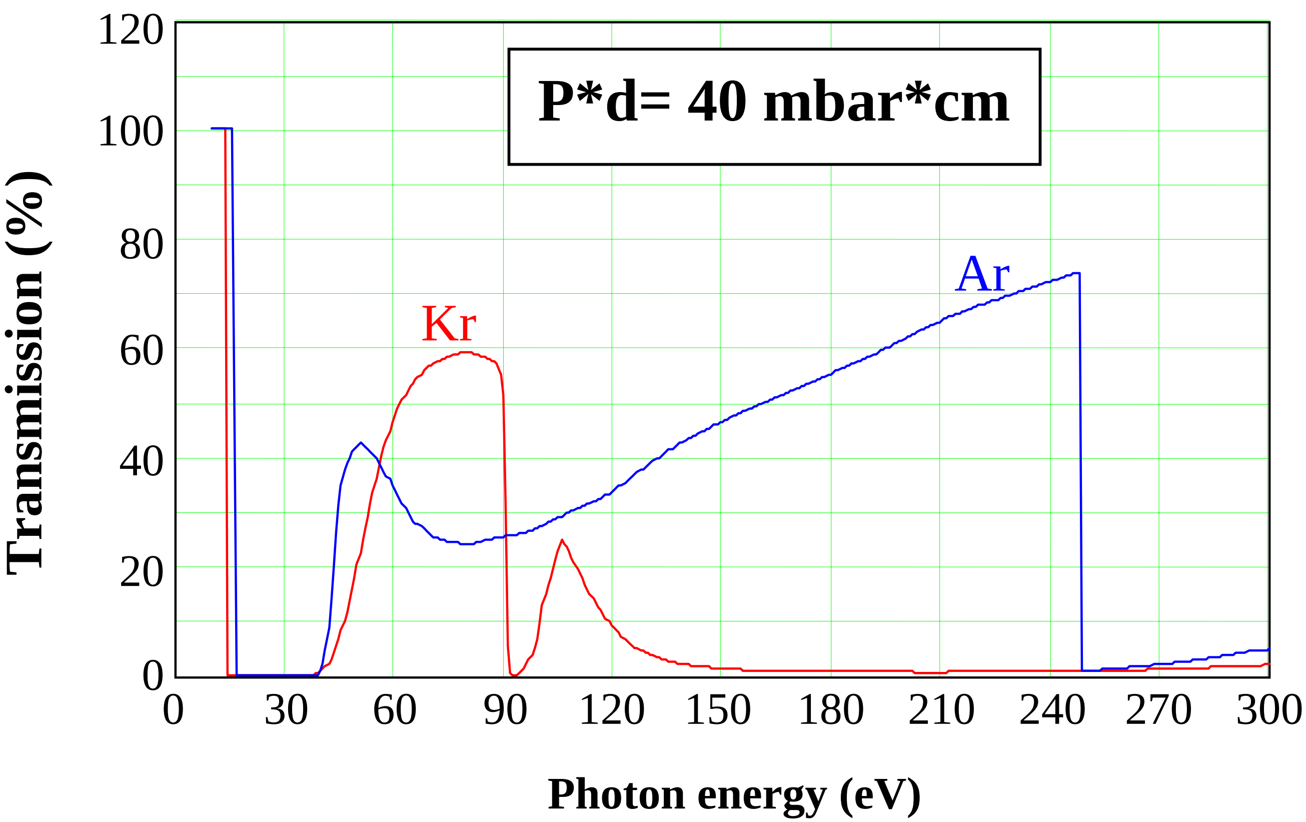


Emission from Sn target:

Gerry O’Sullivan et al.: “*Optimising an EUV source for 13.5 nm*”, SPIE 48th annual meeting, San Diego 2003, Vol. 5196, pp. 273-281

(0.7 J – 15 ns Nd-YAG $5 \cdot 10^{11}$ W/cm^2 on target)

The advantage of using Kr, compared with other gases like Ar: the out-of-band cut!



For Ar:

T_{IN}(@13.5nm)= 26%

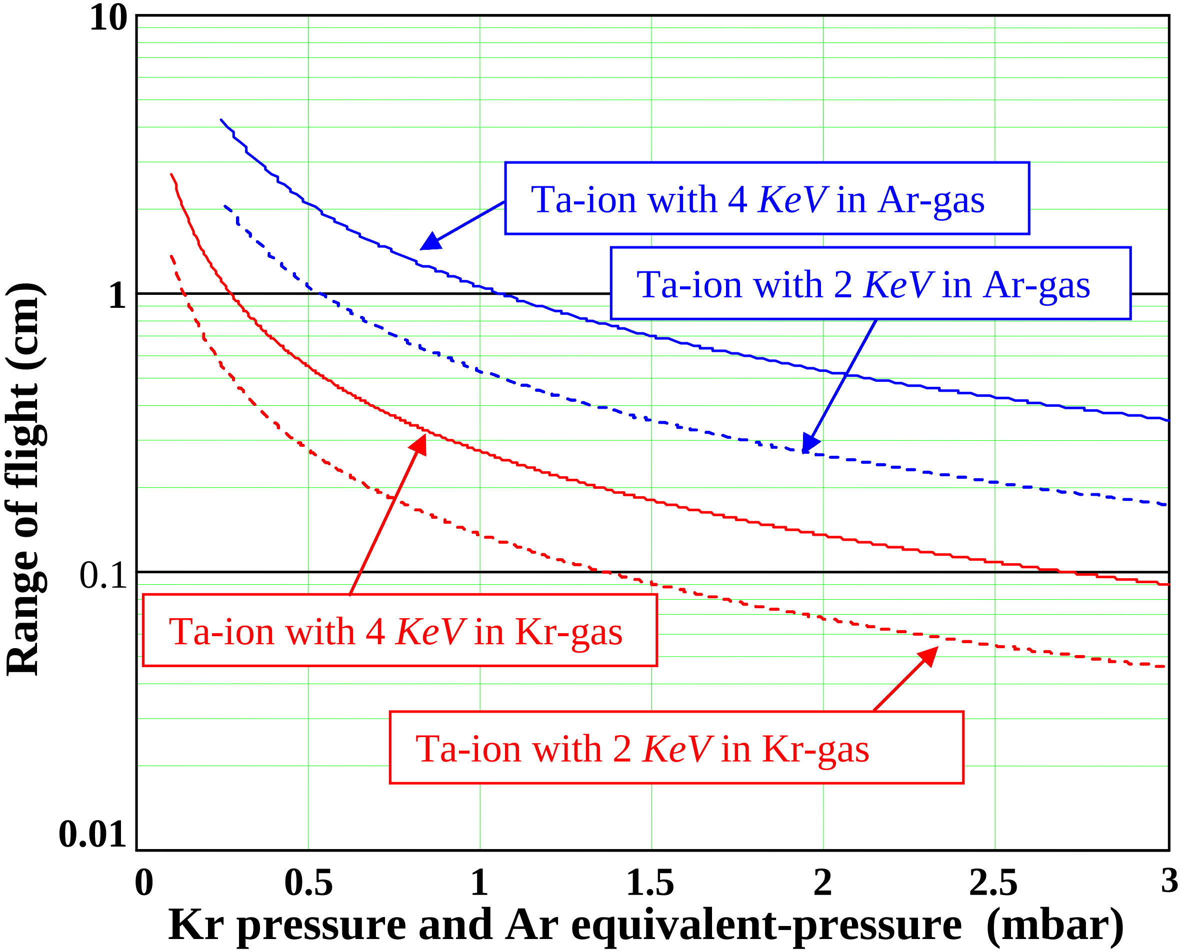
$\langle T_{OUT\ 10\text{-}300\ eV} \rangle$= 36%

For Kr:

T_{IN}(@14.2nm)= 58%

$\langle T_{OUT\ 10\text{-}300\ eV} \rangle$= 11%

Fundamental advantage of Kr compared with Ar: a much shorter Range of flight of debris (at the same transparency in the in-band range)

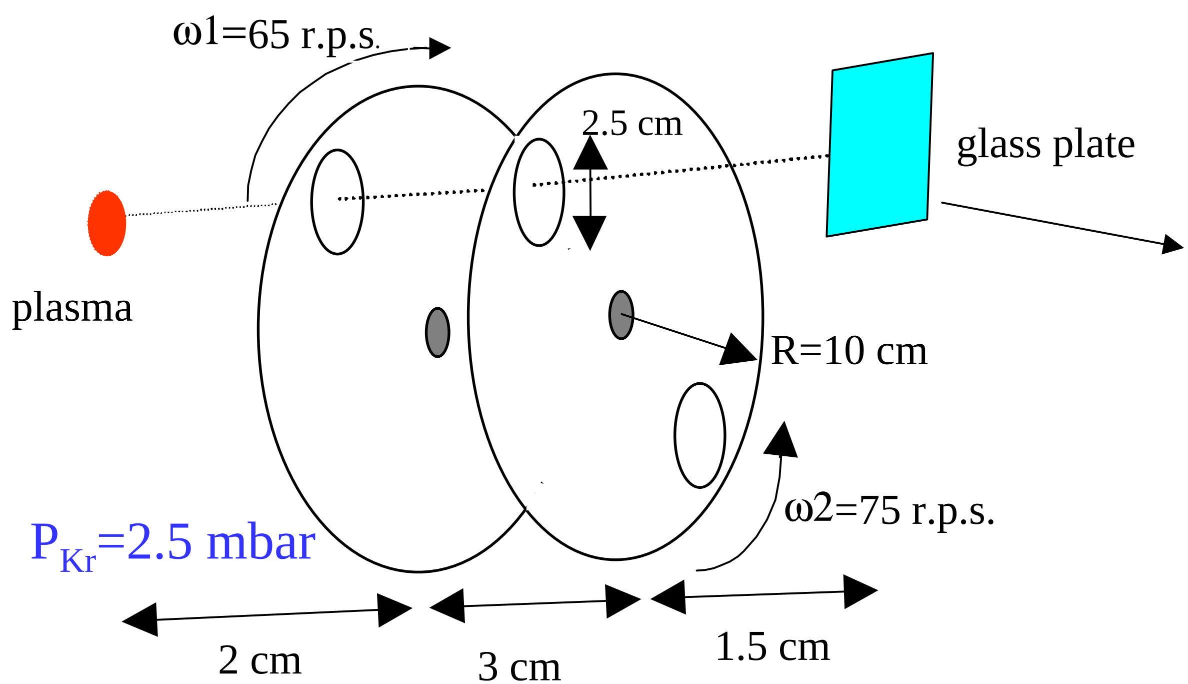


Ar quivalent-pressure is defined as the pressure for which Kr would have @ 14.2 nm the same transparency of Ar @ 13.5 nm.

Ar equival.-pressure is 2.48 times larger than the real argon pressure.

The ions flight range in Kr gas is 4 times shorter than in Ar!

The results with the ENEA DMS (Kr + disks) @ P·d= 16 mbar·cm



The plate after 1000 shots:

OD=0.0017

Mitigation on particulate: > 200

Mitigation on ions + neutrals = 250

$$T_{open} = \frac{1}{\pi \cdot (\omega_1 + \omega_2)} \cdot \frac{D_{aperture}}{D_{disks}} = 0.3ms$$

$$T_{closed} = \frac{1}{(\omega_1 - \omega_2)} = 50ms$$

Conclusions

- For 13.8<λ<20 nm Kr is more transparent than He or Ar, and it is much more efficient on stopping debris.
- The ions range of flight, in Kr case, is 4 times shorter than for Ar case, at the same in-band transmission.
- The out-of-band radiation load on the collector can be, in Kr case, 7 times lower than for Ar case, at the same in-band transmission.
- The ENEA-type DMS has proved a mitigation factor, for copper ions, larger than 200.