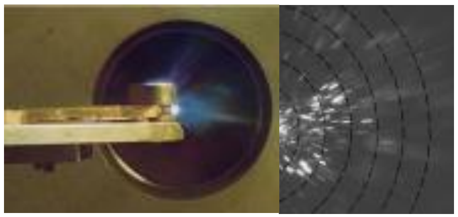
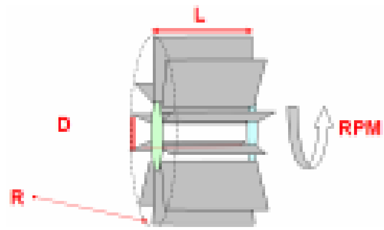
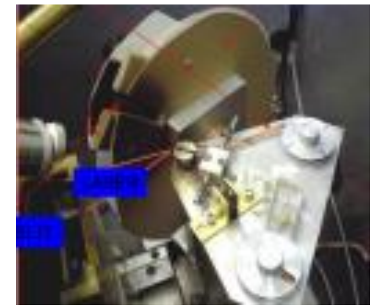
# Mitigation and selection of ion and particulate emission from Laser-produced plasmas used for Extreme UltraViolet Lithography





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# OUTLINE

- Motivation
- Measurement of debris characteristics
- Thermalization and suppression of debris
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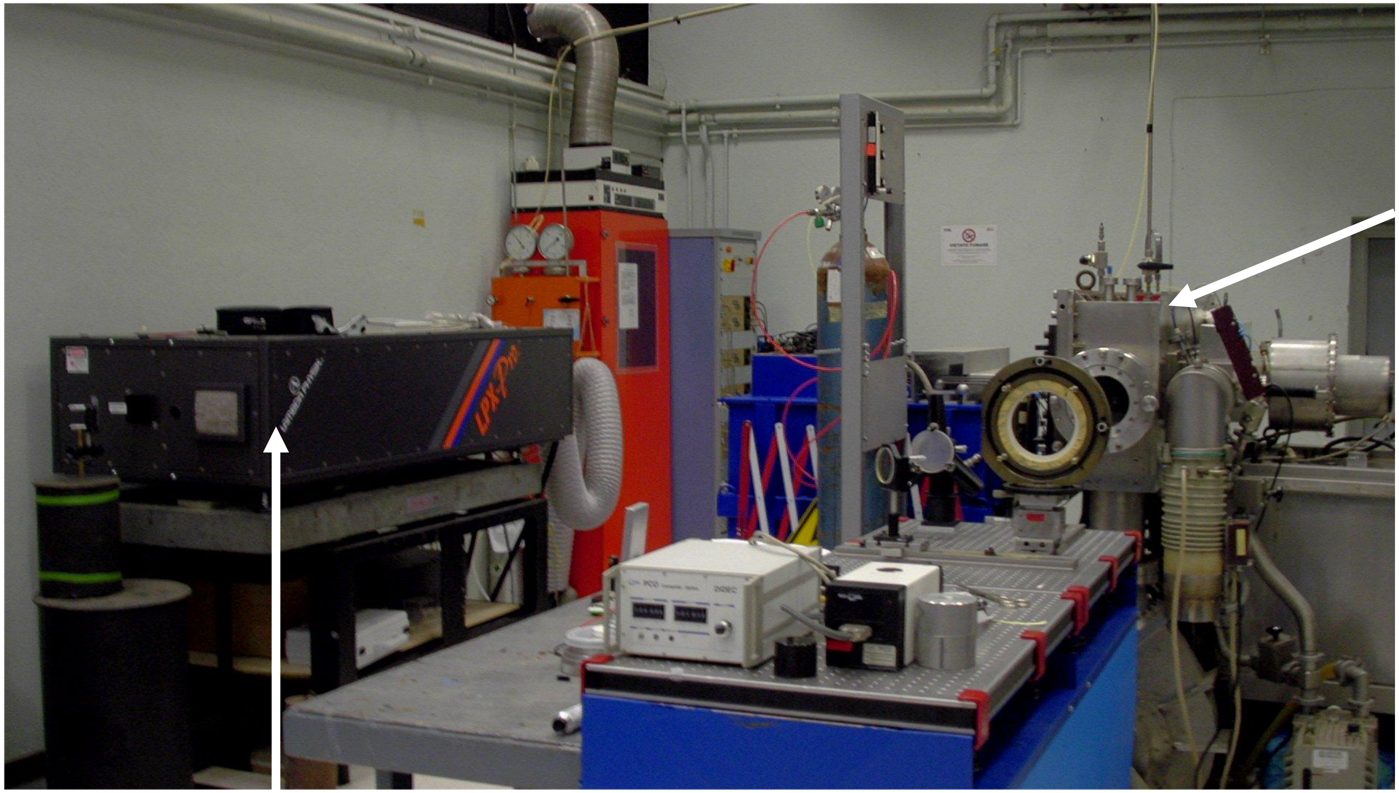
# XeCl excimer lasers as plasma-driver




**HERCULES**

**PBUR**

**5 J, 120 ns, 5 Hz**

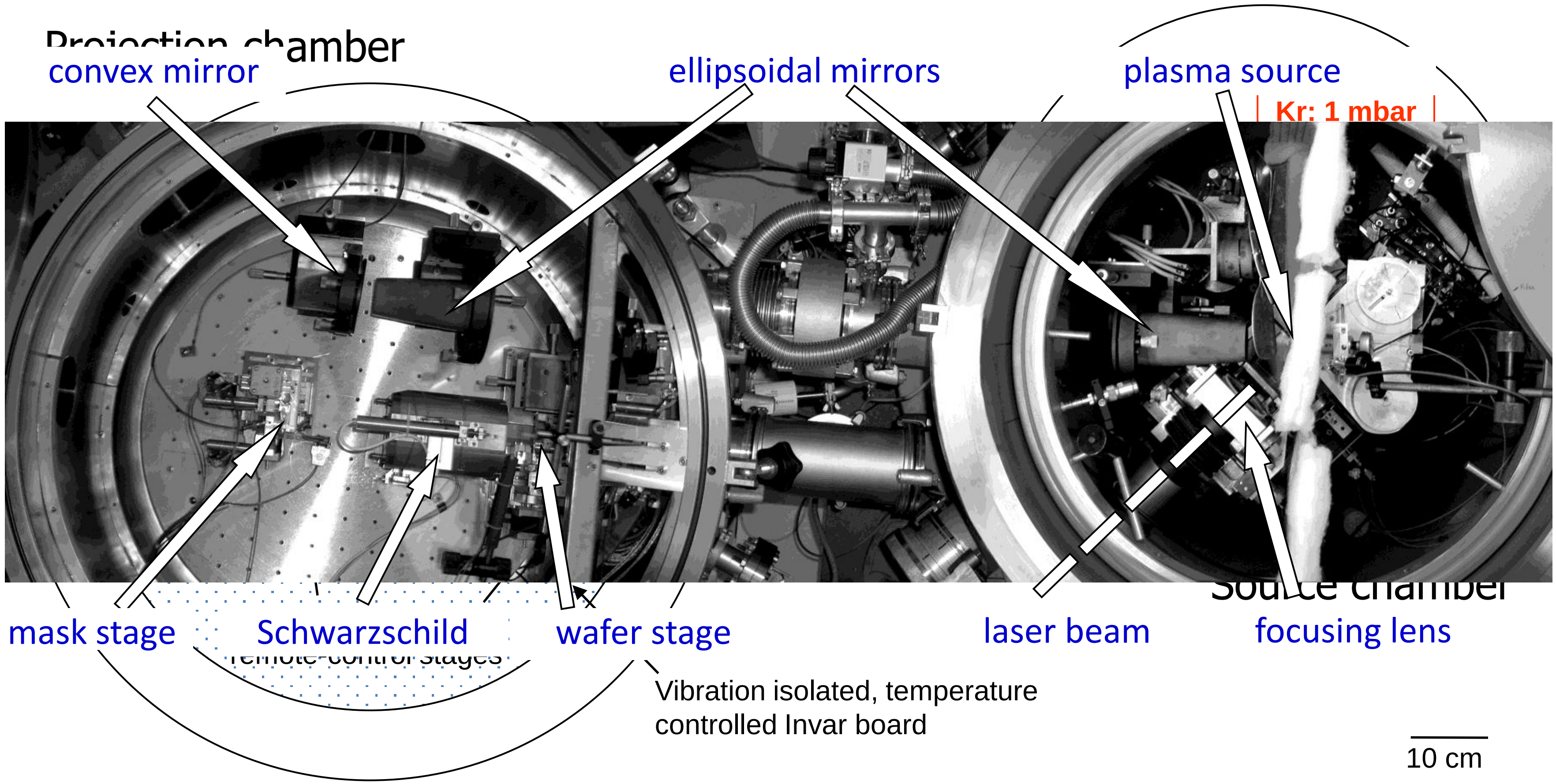
***Oscillator or Amplifier***

**LPX-305, PBUR 0.5 J, 25 ns, 50 Hz**

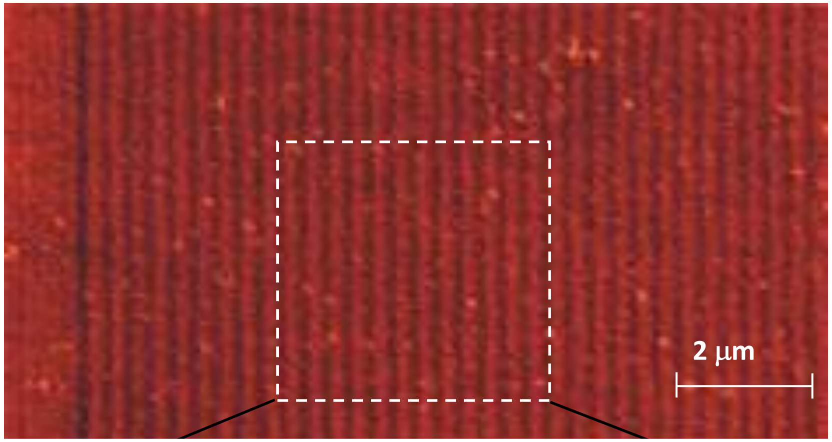
***Oscillator***

# The ENEA laser-driven plasma source

# EGERIA: the first Italian MET for EUVL



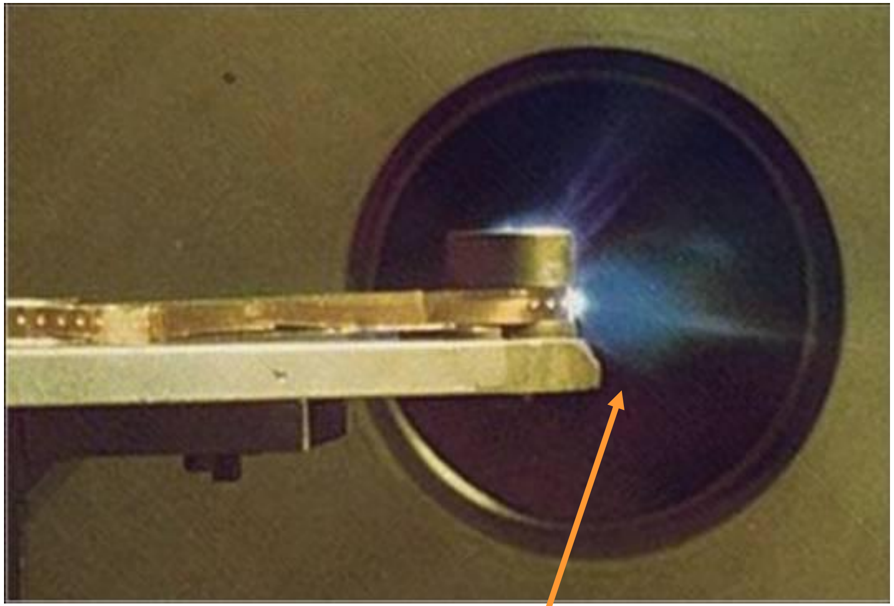
# Line space printing on PMMA: 90 nm resolution

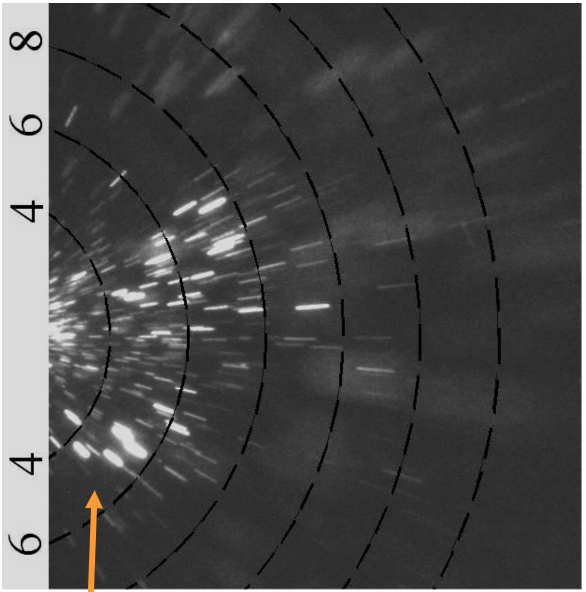



2-D pattern of 160-nm and 110-nm lines (left) observed by atomic force microscope.

**European Physics Letters 84**, 58003 p1 (2008)

# Laser-plasmas emit debris, too







**Visible light emission from atomic debris**

**Particulate debris 0.5 ms after laser pulse**

**Glass plate put 5-cm from plasma in vacuum, after $10^4$ pulses**

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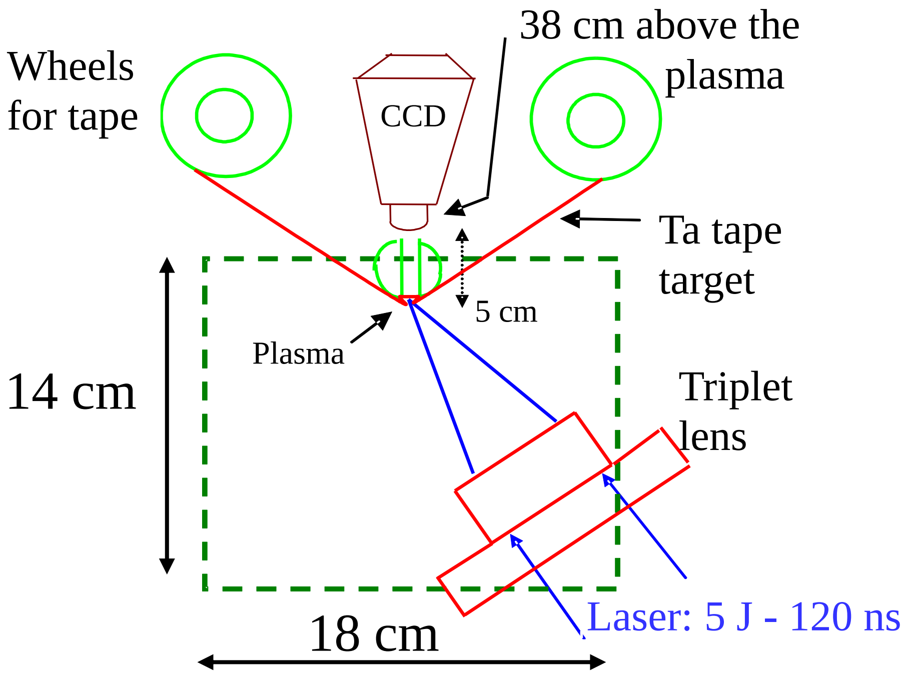
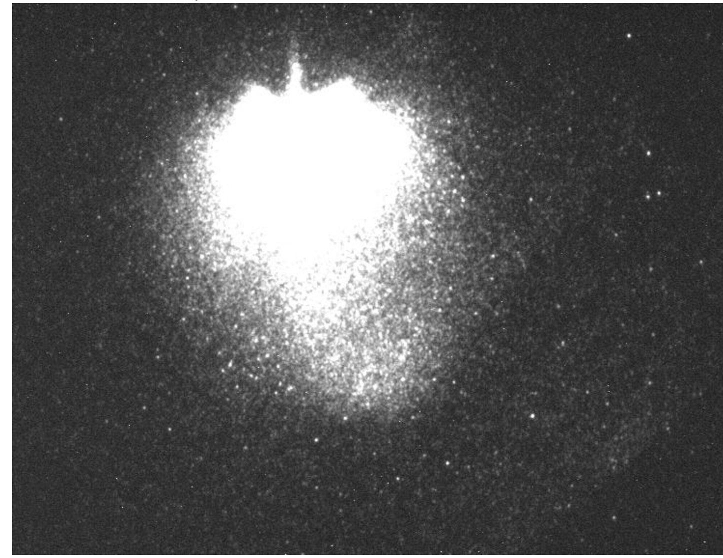
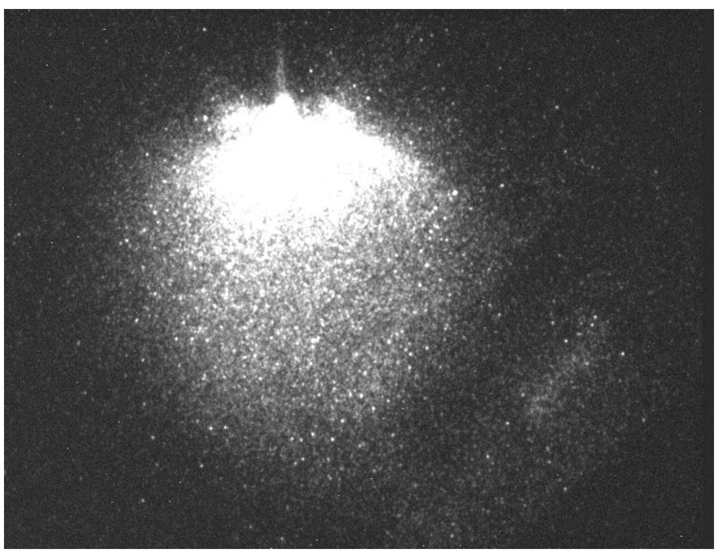
# CCD Detection of ions debris



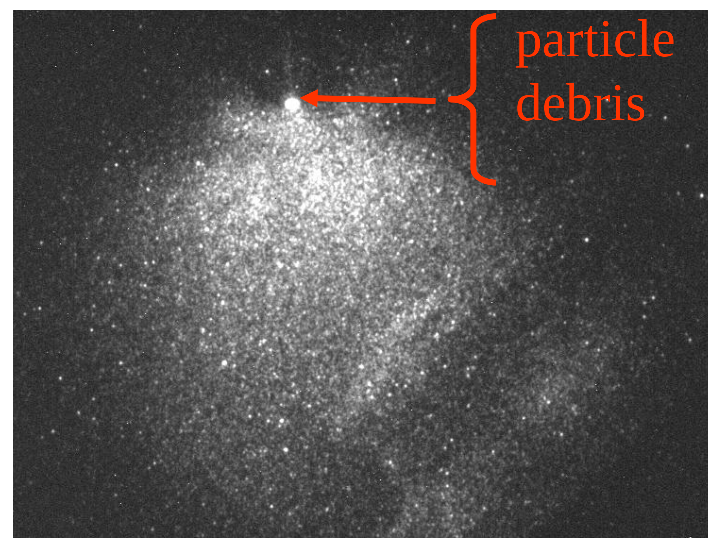

2 μs after laser shot



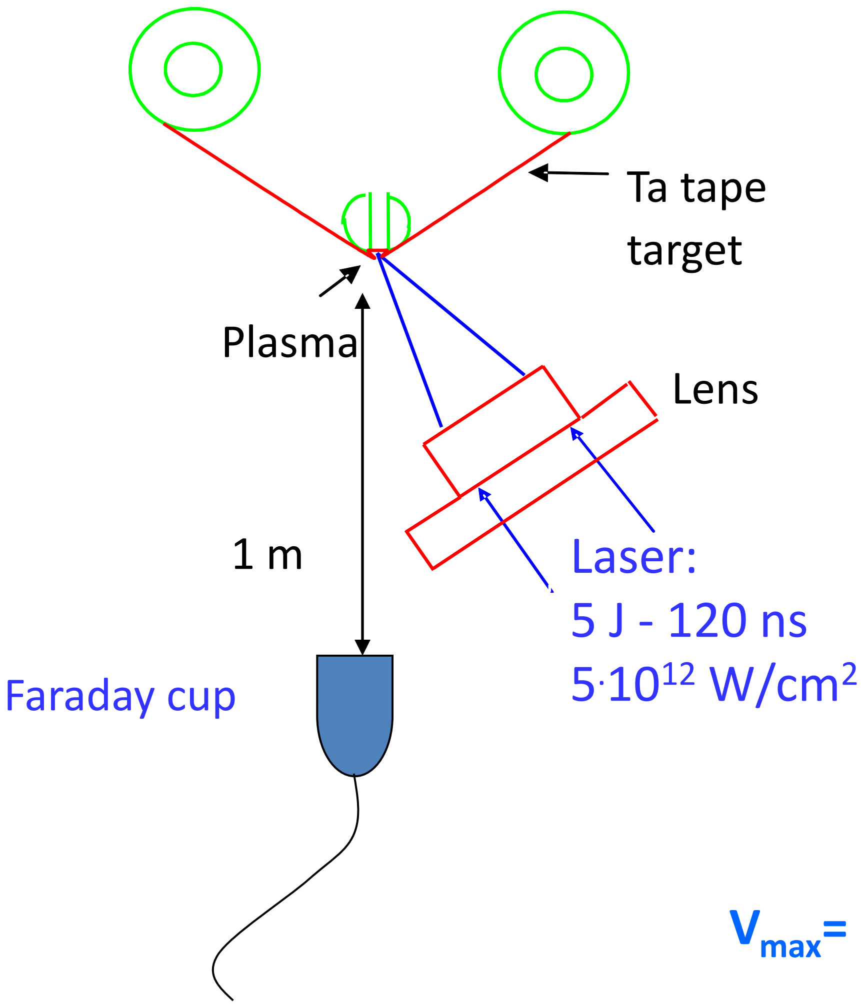
3 μs

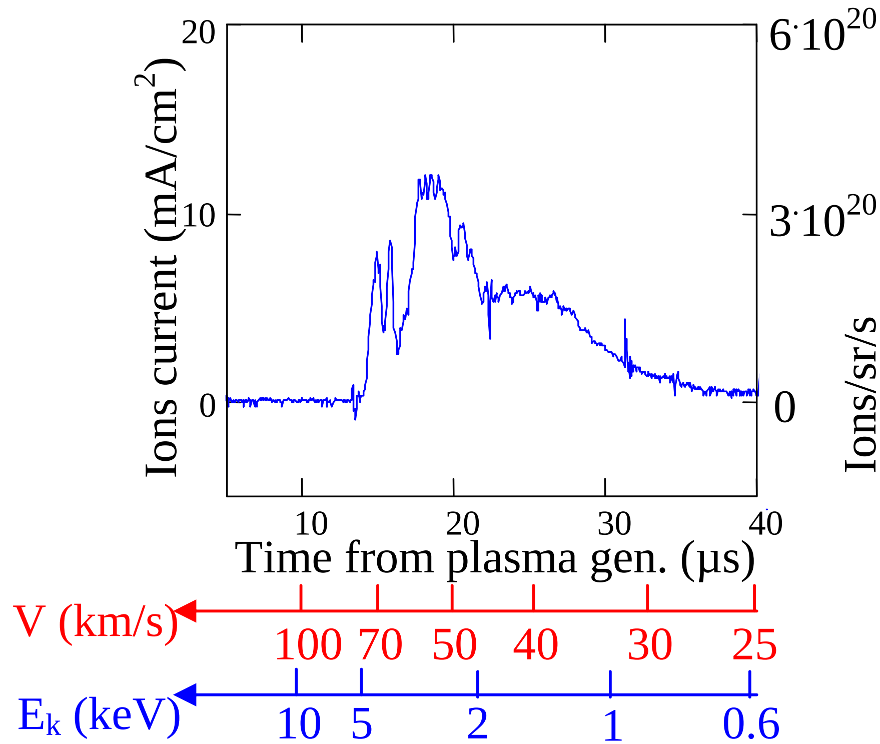


4 μs



# Velocity of ions emitted by Laser-plasmas



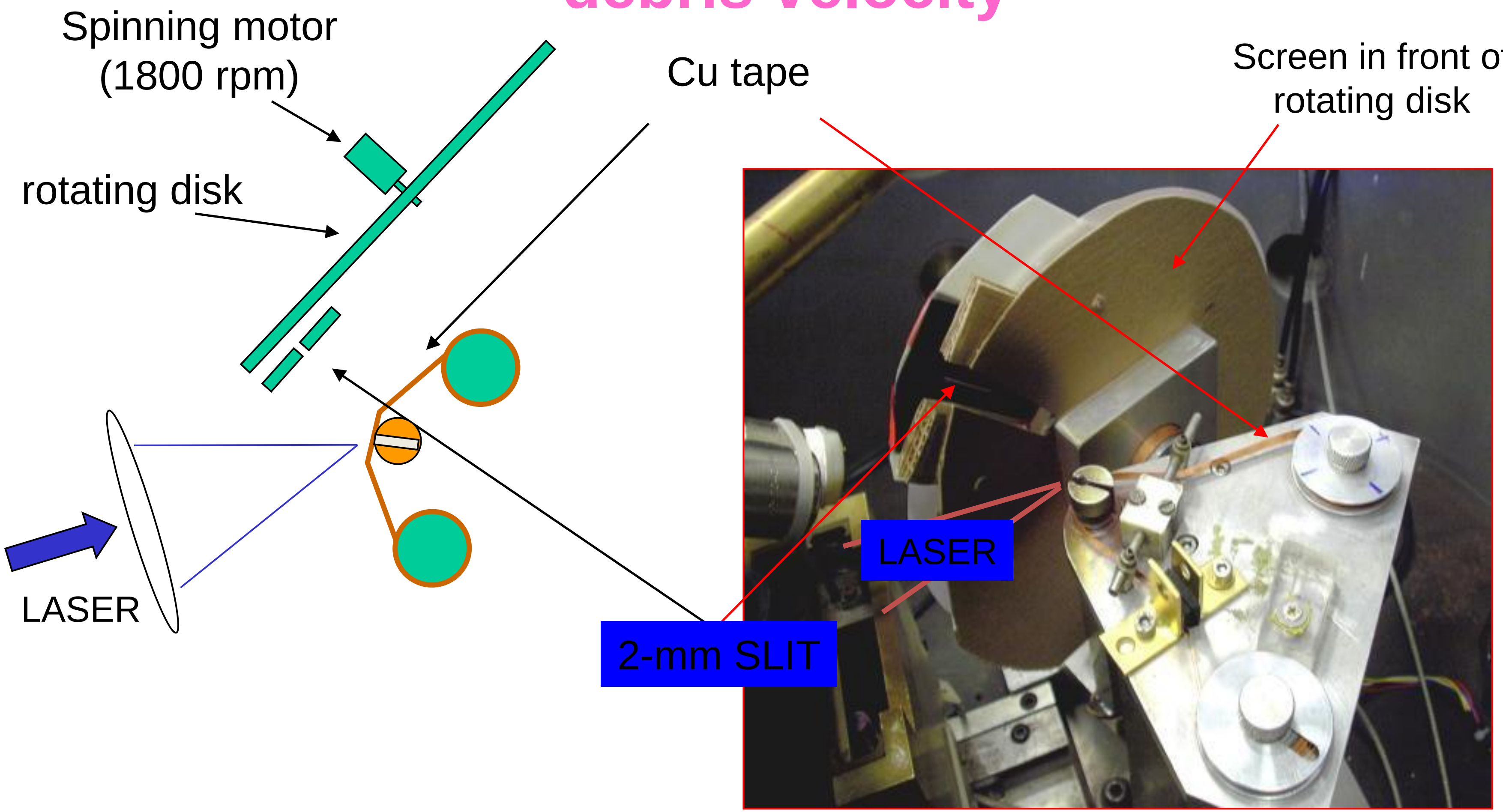

$V_{max}$ = **83 km/s**

$V_{min}$ = **26 km/s**

For Z = 2, ions flux ~ $2 \times 10^{20}$ ions/sr/s in 15 μs. → $3 \times 10^{15}$ ions/sr

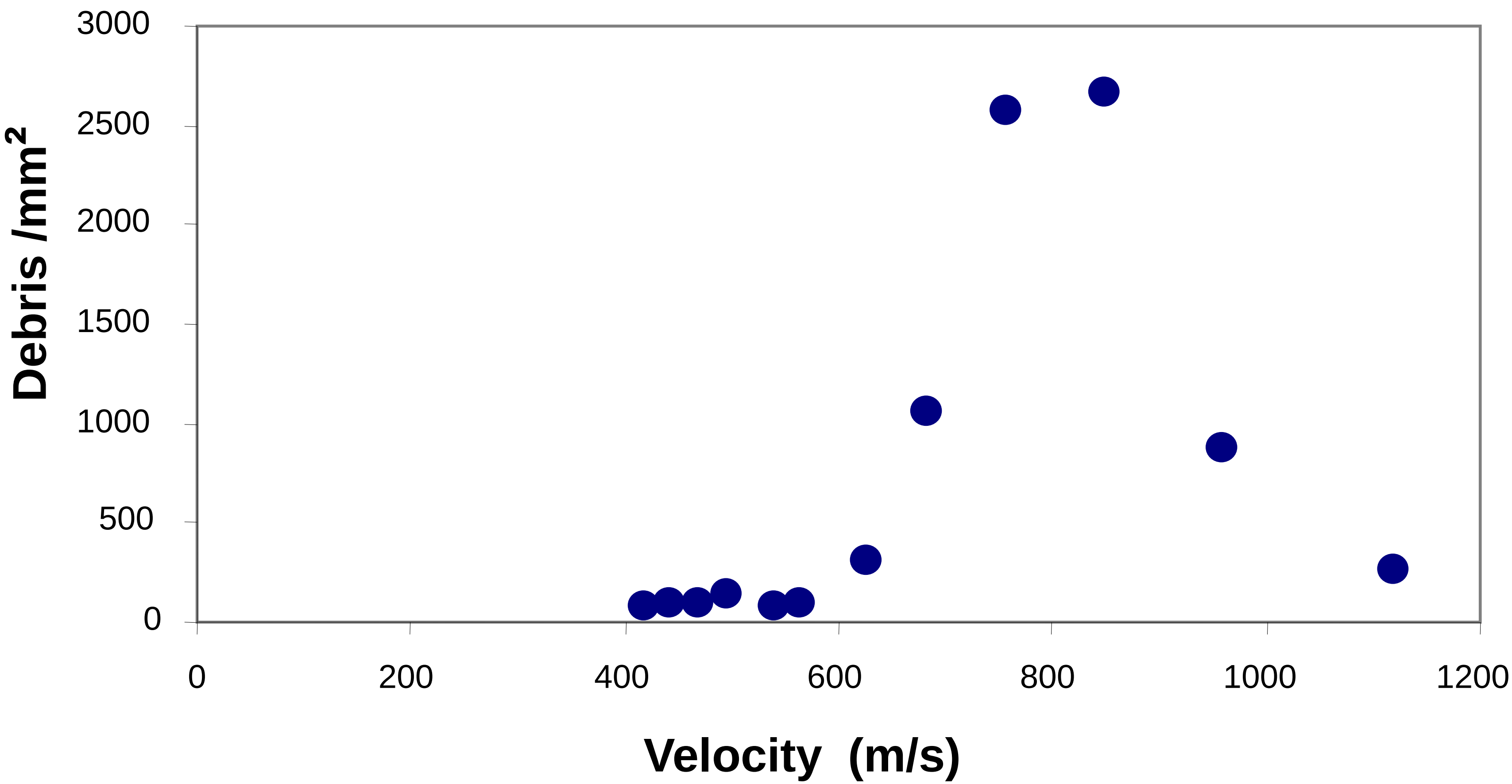
Rev. Sci. Instrum. **71**, 1405 (2000)

# Turning glass to measure the cluster-droplets debris velocity



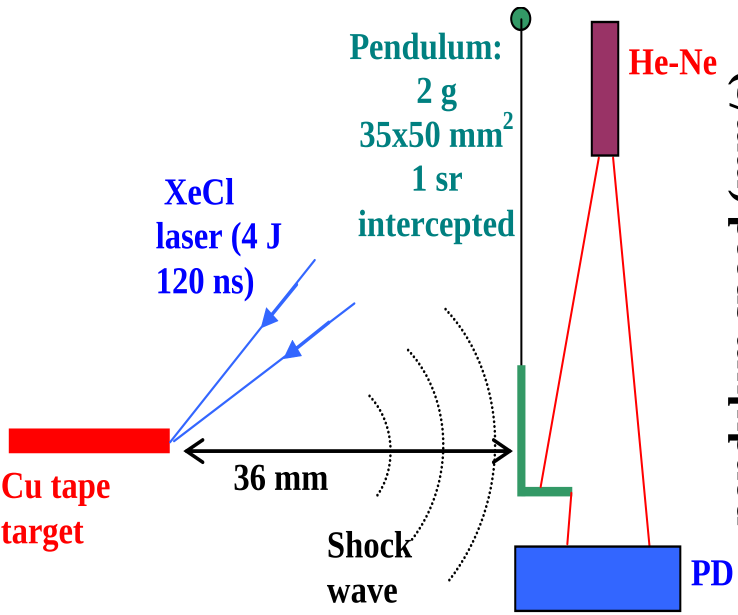

Debris with different velocities hit the rotating glass behind the slit in different times, leaving a “coma”-shaped trace on the glass. Each point of trace corresponds to a given velocity.

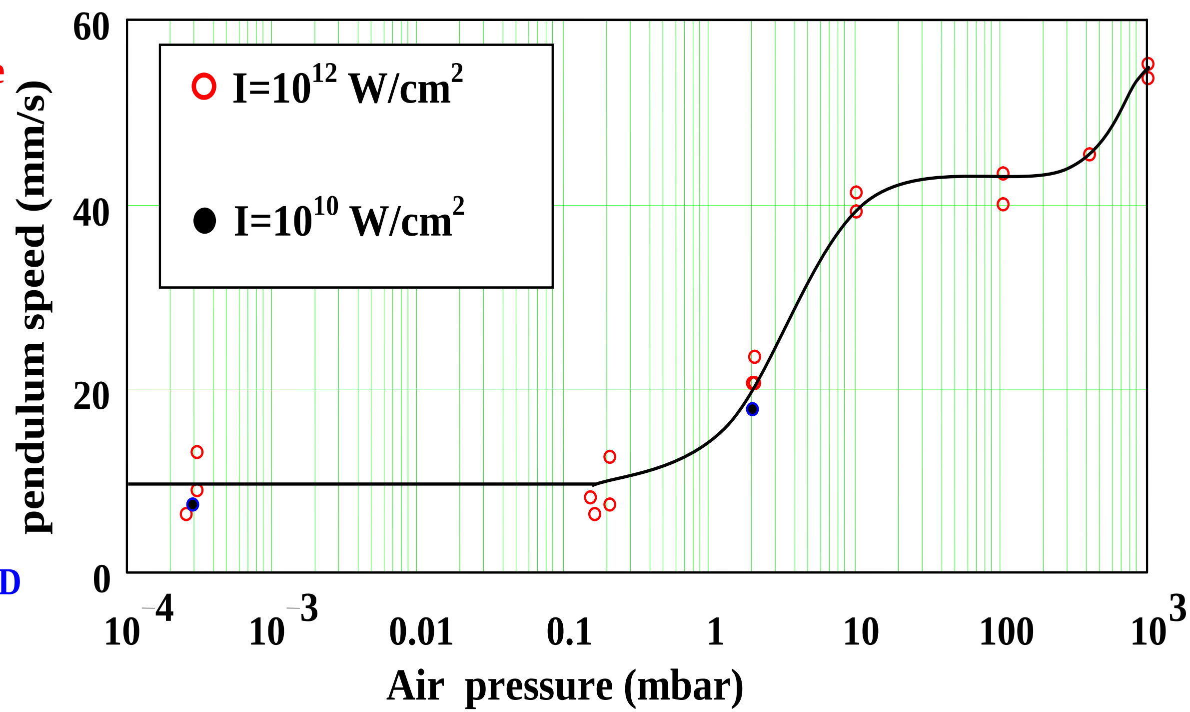
# Droplets debris velocity measured in 9 mbar*cm Kr




Debris on glass are framed at the optical microscope, and then identified and computed by a dedicated software. Most debris sizes are sub-μm.

# A pendulum to measure the momentum of debris




**When P > 0,1 mbar the speed of pendulum is due to debris + shock wave.**

**When P < 0,1 mbar the speed of pendulum is independent of pressure, and it is only caused by debris.** **The measured momentum is $2\times10^{-5}$ Kg m/s in 1 sr.**

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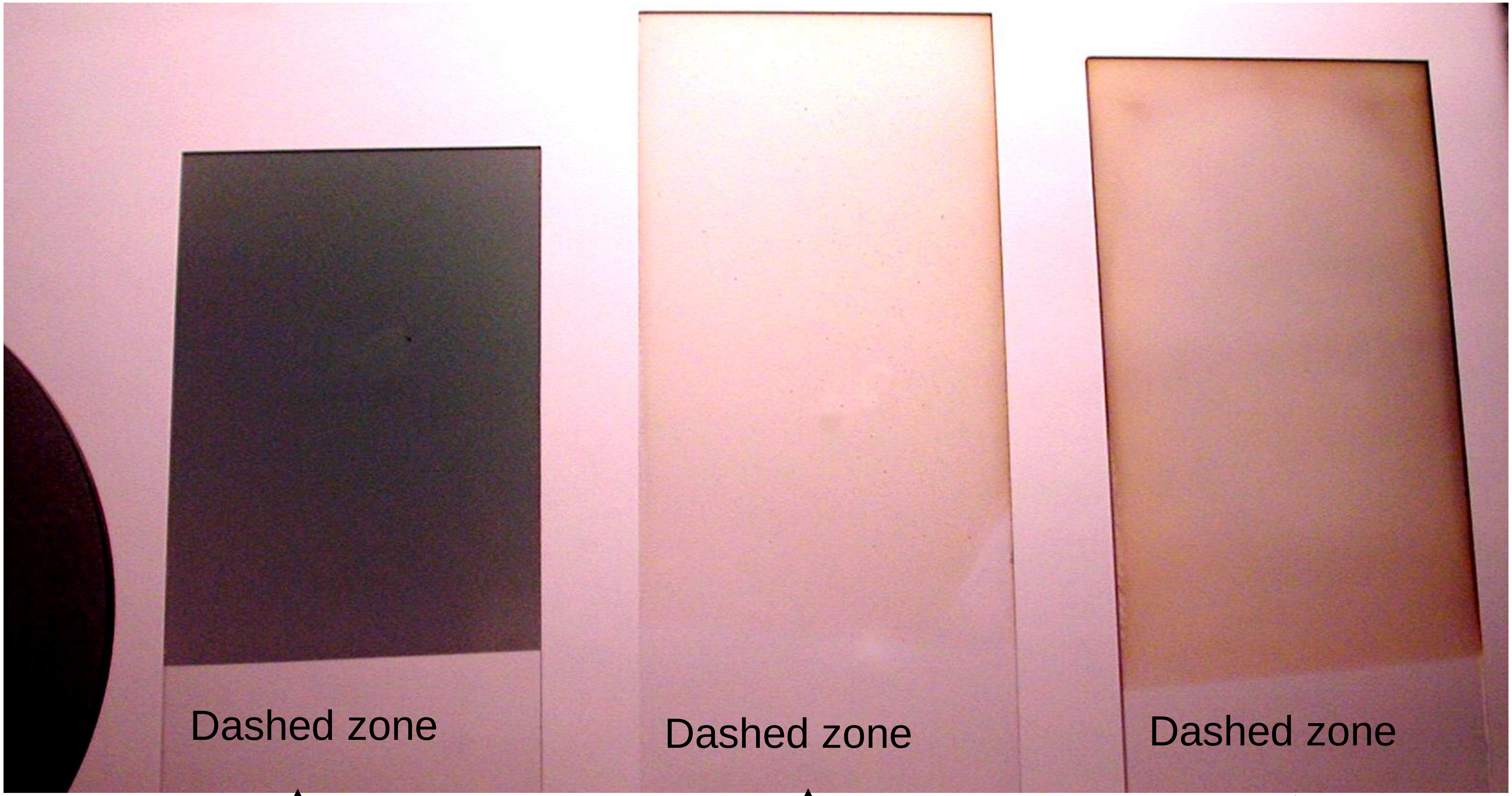
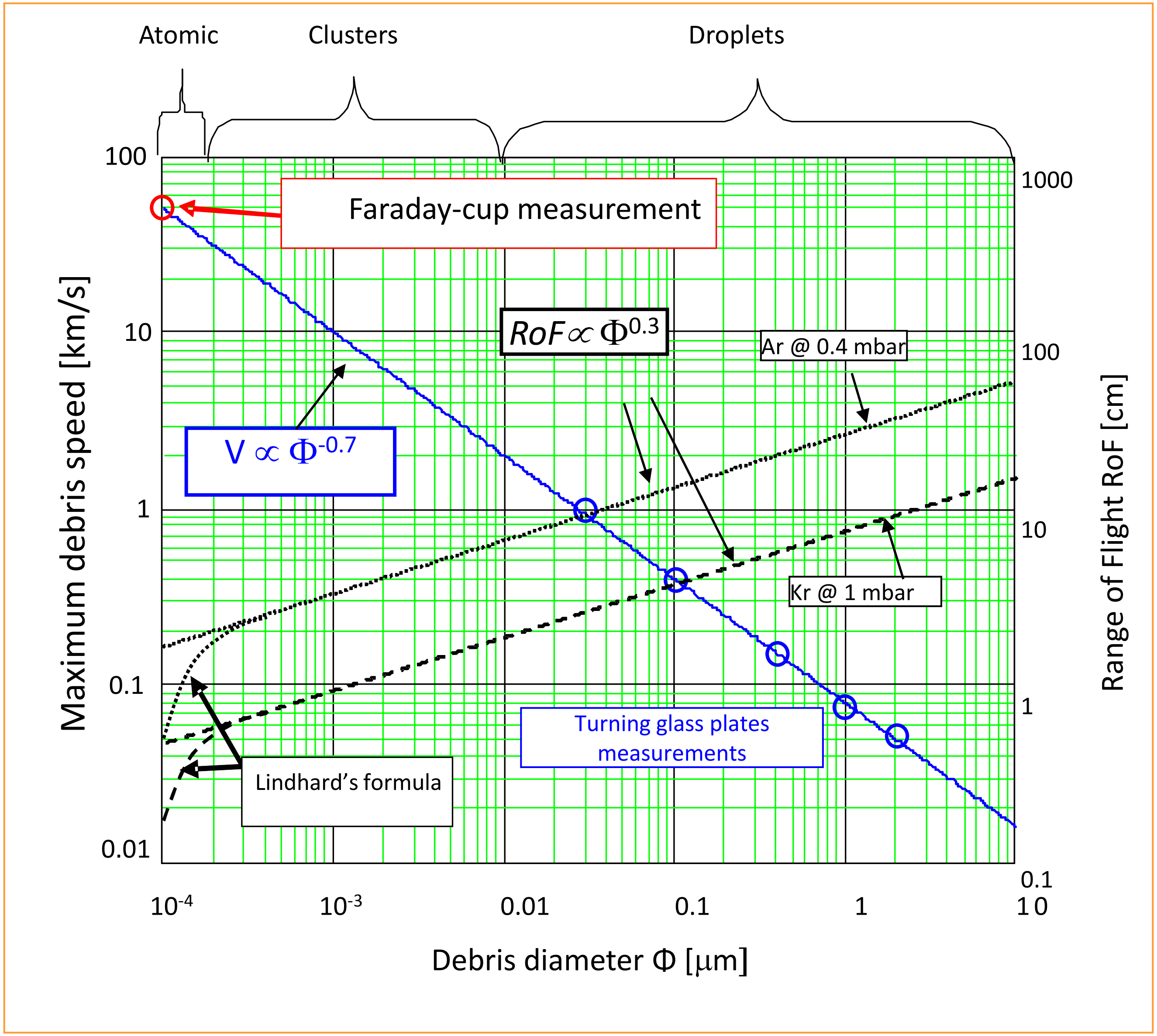
# Gas mitigation, after $10^4$ shots Cu target (red!)



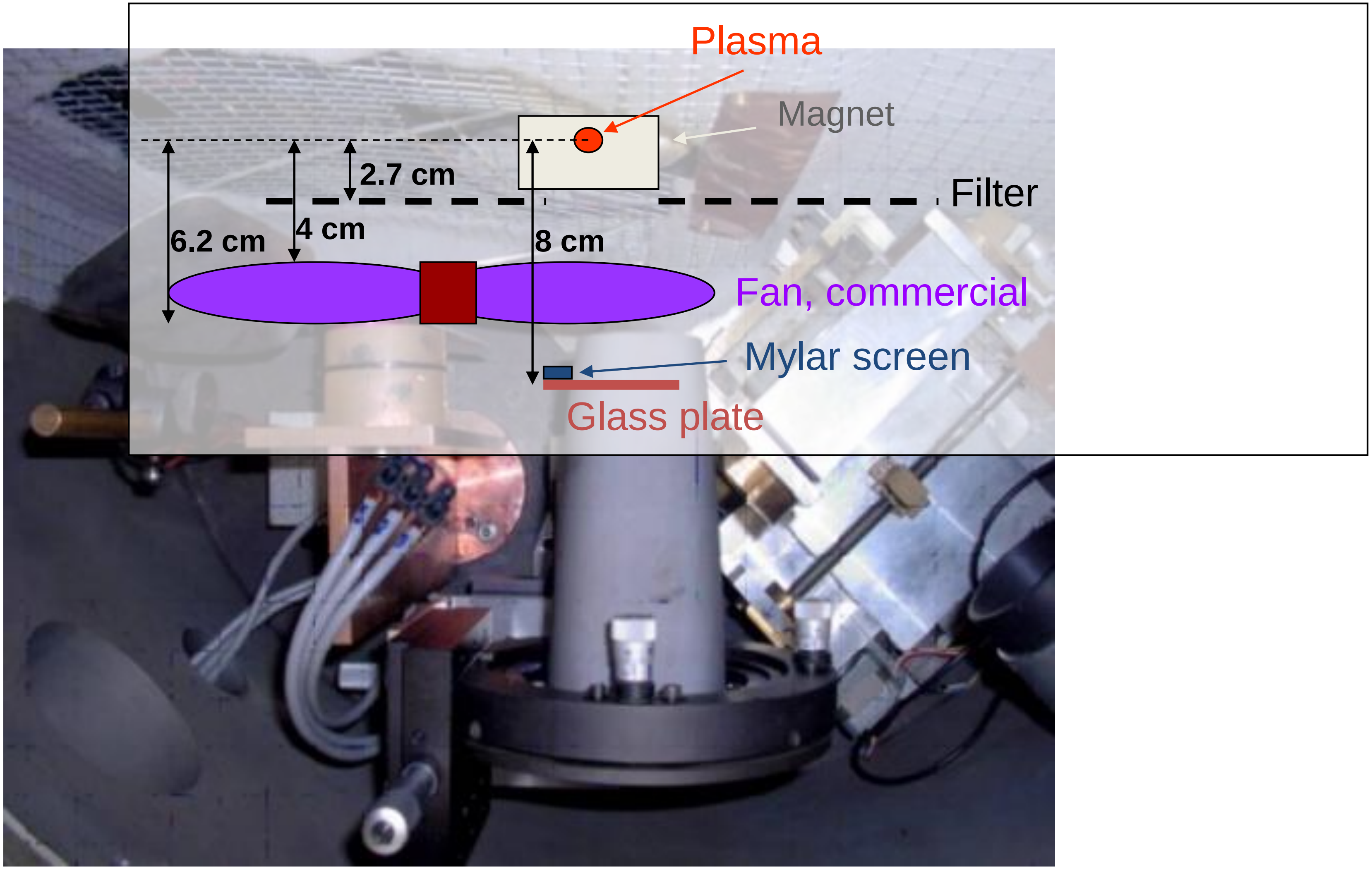

VACUUM KRYPTON ARGON

# The buffer gas stops the smaller and faster debris




**Europhysics Letters 56,** 676 (2001).

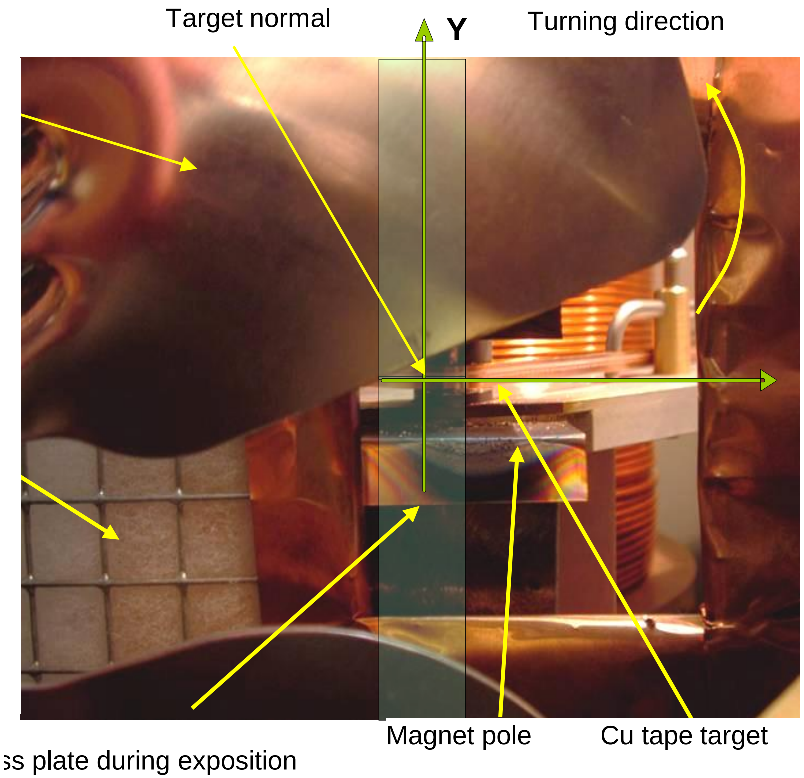
# Our DMS, reduced to practice…




**Two patents: EP 1211918 A1 and UIBM 0001372004**

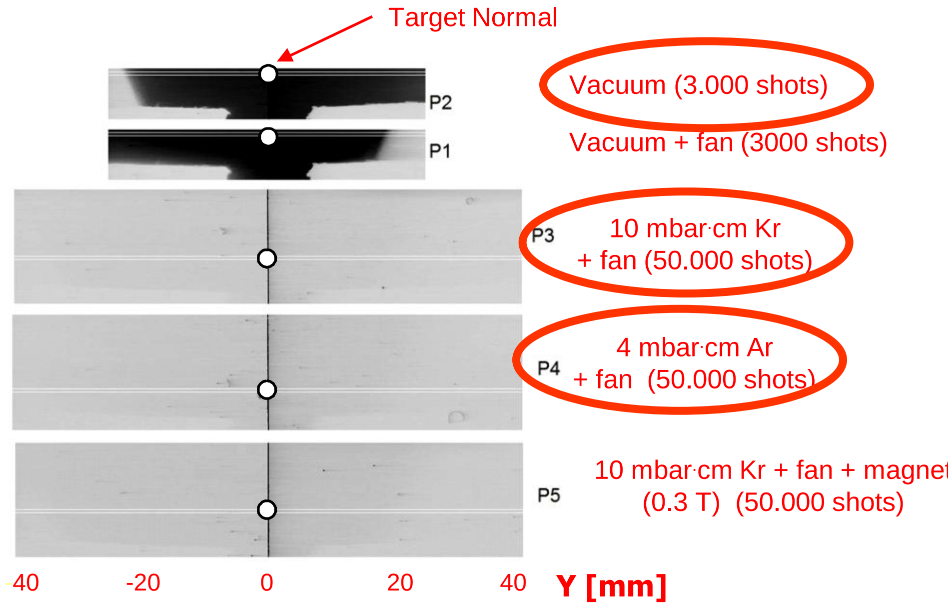
# DMS frame definition

The debris cutting speed, that is the maximum debris speed for which debris are stopped by the blade, varies with the vertical position (Y) along the plate. Since the fan was operated at 6000 r.p.m., rotating upwards, the cutting speed turns out to range from a minimum of ~ 90 m/s at Y = 20 mm to a maximum of ~ 500 m/s at Y = -25 mm.



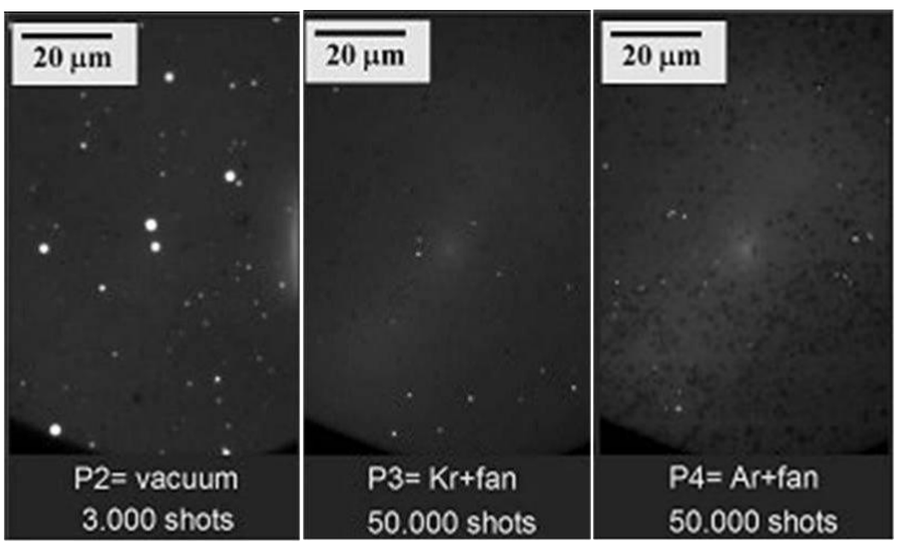
# Measurement of debris mitigation factors

**Densitometry analysis for atoms and clusters:**




**Atomic debris mitigation factor (DMf)**

**At Y = -25 mm …… DMf = 800**



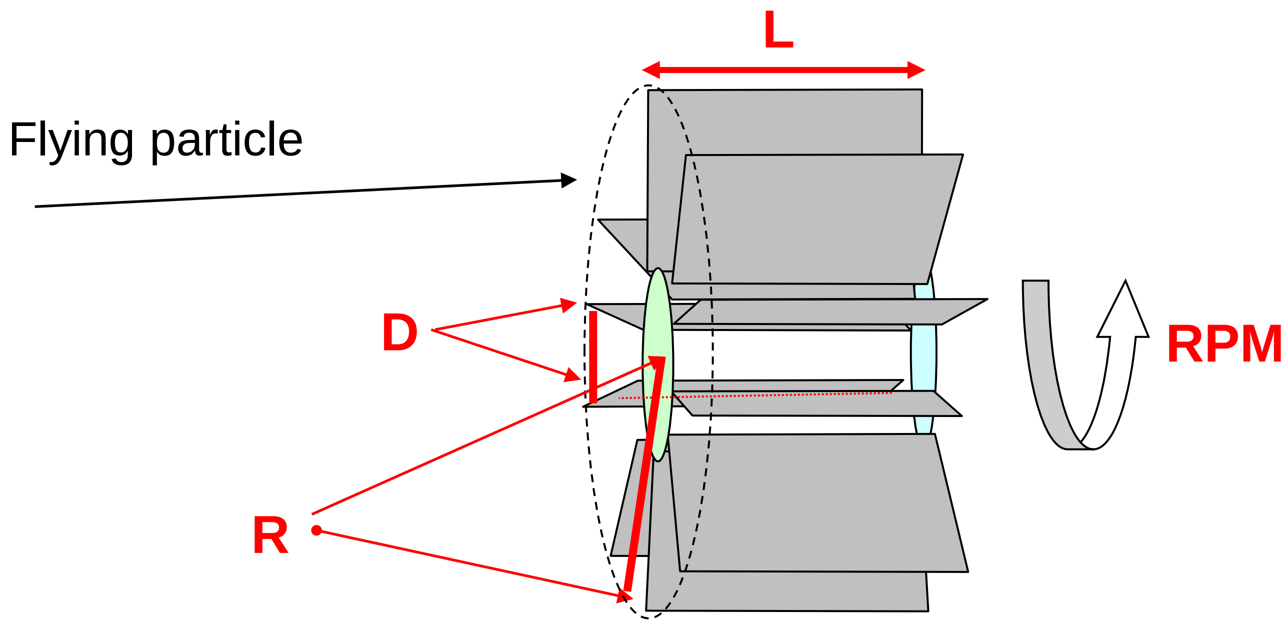

**Microscope analysis for droplets**

**Droplets mitigation factor**

| | |
|---|---|
| **Using Kr** | **DMf = 1600** |
| **Using Ar** | **DMf = 1200** |

Applied Physics **B 76**, 277 (2003) ; Applied Physics **B 96**, 479 (2009)

# A new proposal: a fan to select the velocity of emitted particles (cluster and droplets)

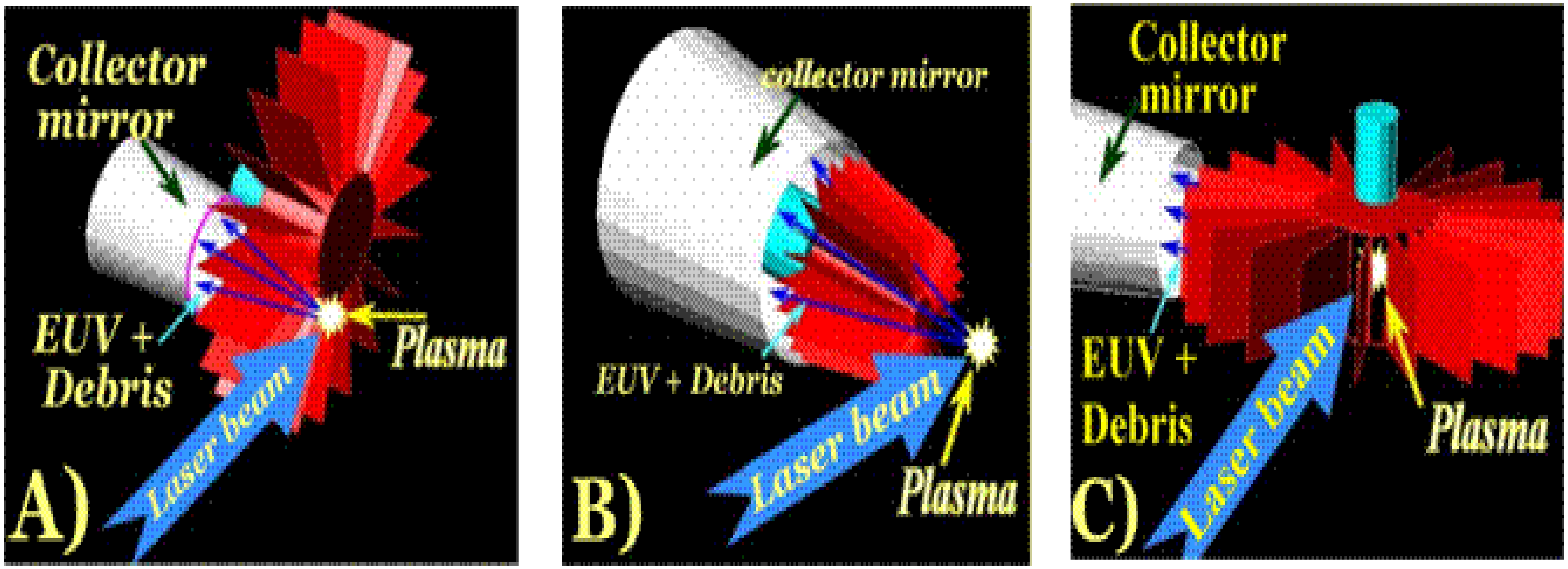



$$VmA = \frac{L}{D} \cdot \frac{2\pi R \cdot RPM}{60}$$

**VmA is the minimum velocity of a particle to pass through the fan.**

**Then, VmA is the maximum velocity of debris stopped by the fan.**

# Possible schemes of the new fans




**Ufficio Italiano Brevetti e Marchi n. 0001372004 22 Marzo 2010**

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# Ut breviter dicam

- We have used a “dirty” Laser-plasma source to measure the characteristics of ion, cluster and particulate debris.
- According with the measured velocity ranges, spatial distribution and energy spectrum of each kind of debris, we have designed and tested a debris mitigation systems (DMS) able to thermalize and suppress both ionic and particulate debris.
- The effectiveness of our DMS was estimated by different methods, including a microscope analysis of exposed glasses performed by a dedicated code for the image processing.
- The values of DMf obtained (~ 800 for atomic debris and ~ 1200 for debris > 0,5μm) are to our knowledge among the best achieved ever. Further improvements are expected in the near future, when the prototype of the high-speed-fan DMS patented by ENEA will be tested in our Lab.

# Laboratorio Laser Eccimeri, ENEA Frascati

## Award of Excellence ENEA for the first Italian Micro exposure tool for EUV lithography

# Selected references


S. Bollanti, et al.: **"Flight range of the particulate in a laser-plasma generated soft X-ray chamber", Appl. Phys. A 71,** 255 (2000).

K. Fournier, et al.: "**Novel laser ion sources**" **Rev. Sci. Instrum. 71**, 1405 (2000).

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S. Bollanti, et al.: "**High efficiency, clean EUV plasma source at 10-30 nm, driven by a long pulsewidth excimer laser**" **Appl. Phys. B 76**, 277 (2003).

K. Fournier, et al.: "**Analysis of high-n dielectronic Rydberg satellites in the spectra of Na-like Zn XX and Mg-like Zn XIX**", **Phys. Rev. E 70**, 016406, 1 (2004).

P. Di Lazzaro, F. Flora, N. Lisi, C.E. Zheng: "**Discussion for plasma evolution on laser target**" **ENEA Technical Report 41/FIS** (2006).

S. Bollanti, P. Di Lazzaro, F. Flora, L. Mezi, D. Murra and A. Torre: "**First results of high-resolution patterning by the ENEA laboratory-scale extreme ultraviolet projection lithography system**", **European Physics Letters 84**, 58003 p1 (2008).

P. Di Lazzaro, C.E. Zheng: "**A note on the use of refitted photo-multiplier to measure laser-plasma ion flow rates**" **ENEA Technical Report 9/FIM** (2009).

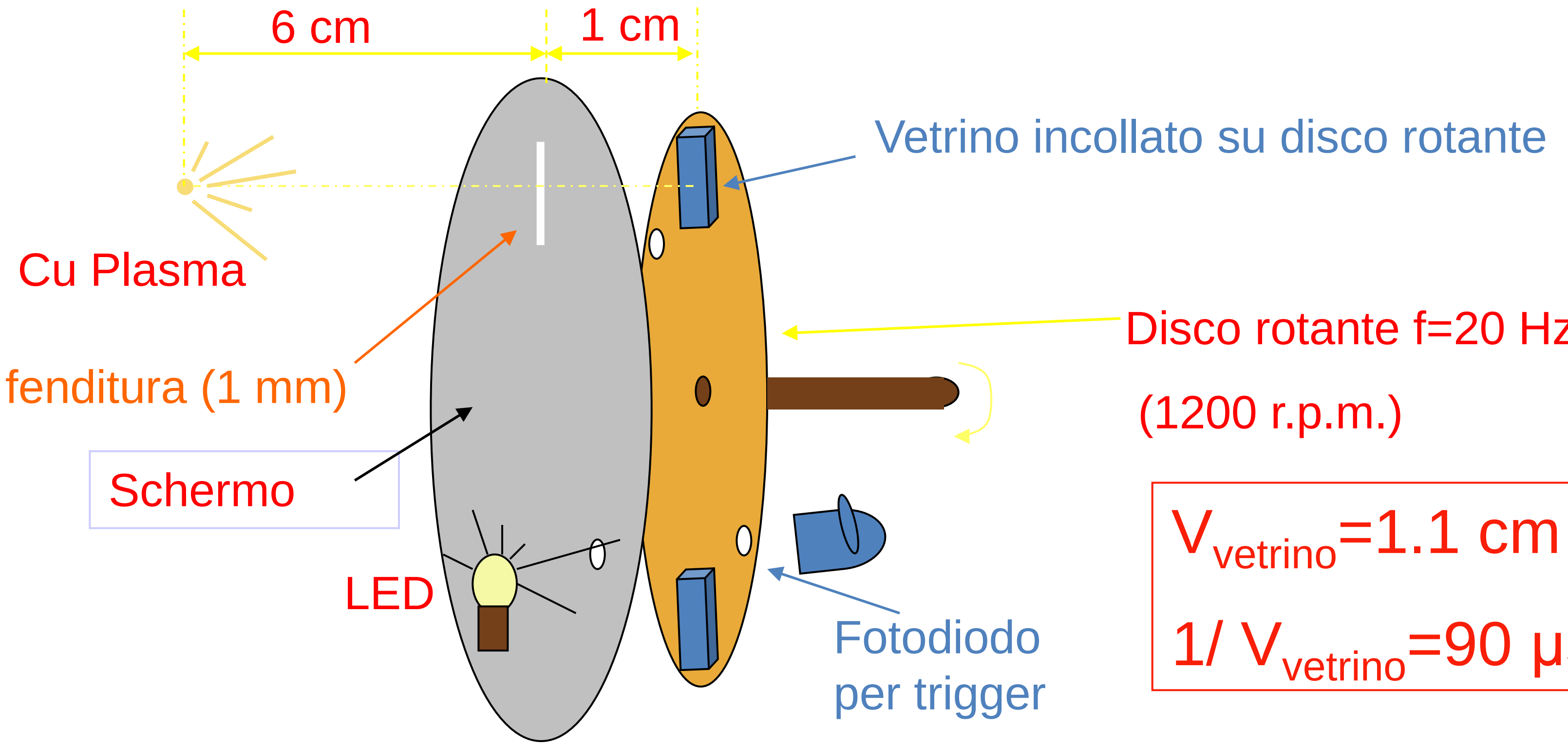
S. Bollanti, P. Di Lazzaro, F. Flora, L. Mezi, D. Murra and A. Torre: "**Laser-plasma-source debris-related investigation: an aspect of the ENEA micro-exposure tool", Appl. Phys. B 96**, 4797 (2009).

# I risultati del DMS sugli specchi

| | $R_{peak}$ before the exposure (%) | $R_{peak}$ after the exposure (%) | Corresponding DMf |
|---|---|---|---|
| M2 (Vacuum, 900 shots) | $66.0 \pm 1$ | $56.0 \pm 2.6$ | - |
| M3 (Kr + far, 60000 shots) | $66.0 \pm 1$ | $63.8 \pm 1.4$ | $300^{+1000}_{-130}$ |
| M4 (Ar + far, 60000 shots) | $68.3 \pm 1$ | $66.0 \pm 1.4$ | $290^{+820}_{-120}$ |
| M5 (Kr + fan + magne, 60000 shots) | $68.3 \pm 1$ | $65.2 \pm 1.4$ | $220^{+260}_{-80}$ |

- **Nel caso degli specchi, la valutazione dell'efficacia del DMS è stata fatta rapportando il calo di riflettività dello specchio esposto in vuoto a quello dello specchio esposto con il DMS, normalizzati al numero di colpi. I multilayer e le misure di riflettività sono stati a cura dell'INFN-LNL e del DEI-Università di Padova.**
- **In tutti i casi il calo di riflettività è confrontabile con l'errore della singola misura. Questo comporta un grande errore sul DMf.**
- **Ciononostante, risulta evidente una similarità con il DMf atomico: il degrado è dovuto principalmente ad atomi e clusters.**

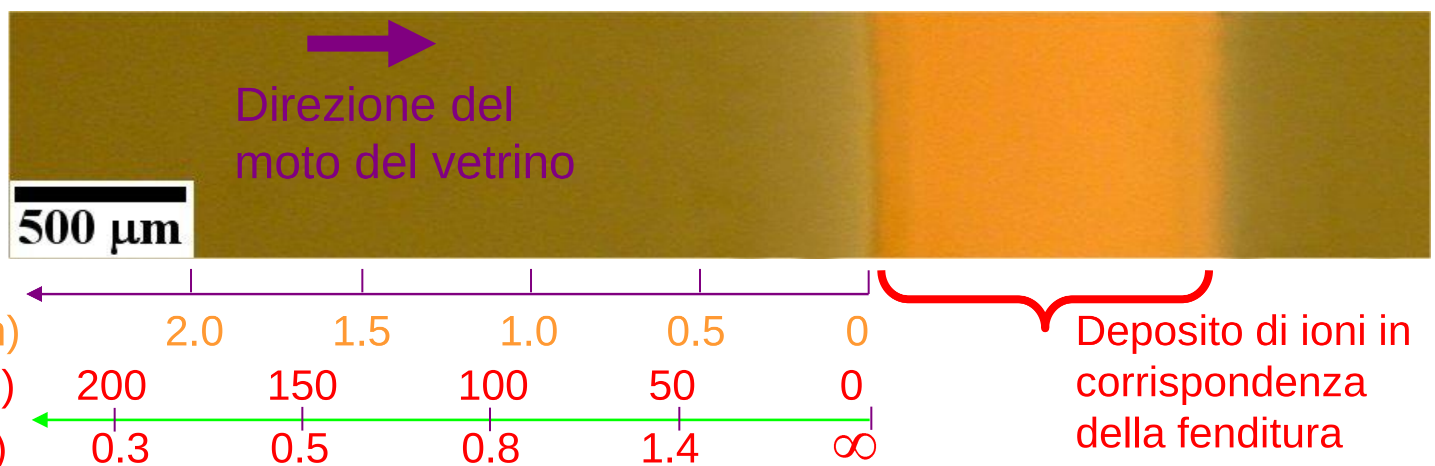
# Misura della velocità del particolato tramite deposizione su vetrini rotanti



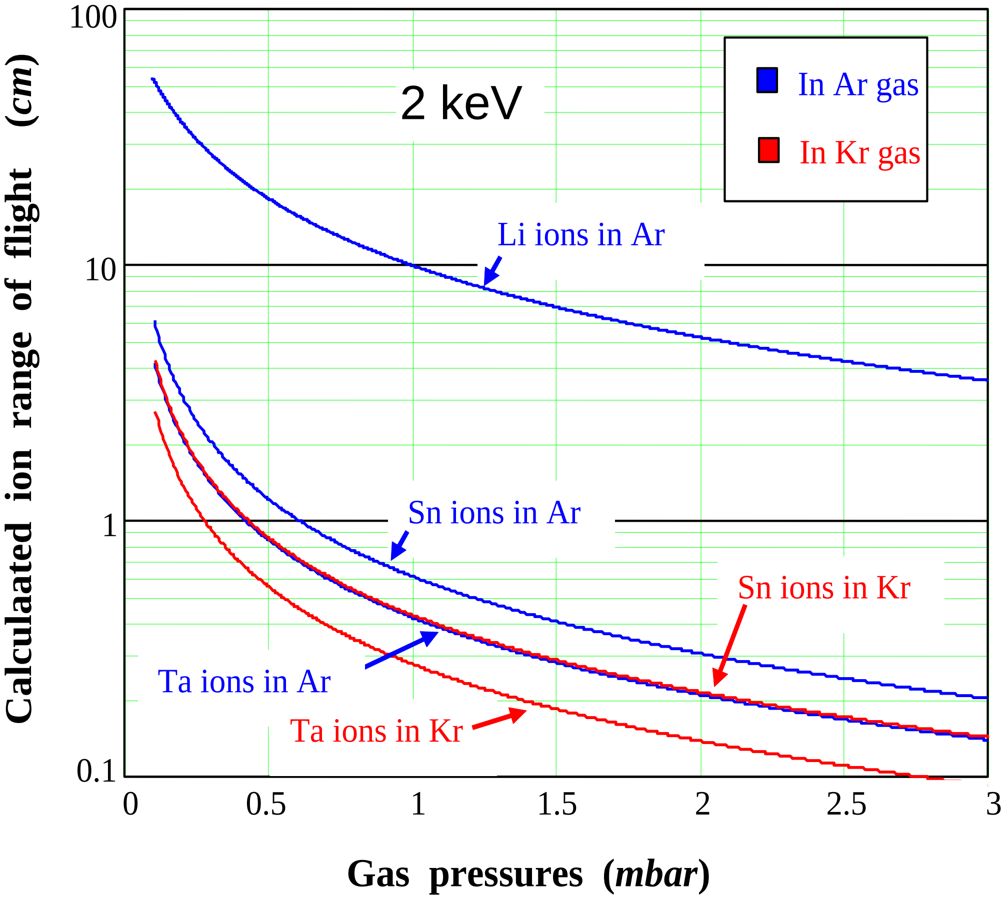

$V_{vetrino}$=1.1 cm / ms

$1/ V_{vetrino}$=90 µs / mm

Vetrino esposto a 40.000 colpi <u>visto in riflessione</u>



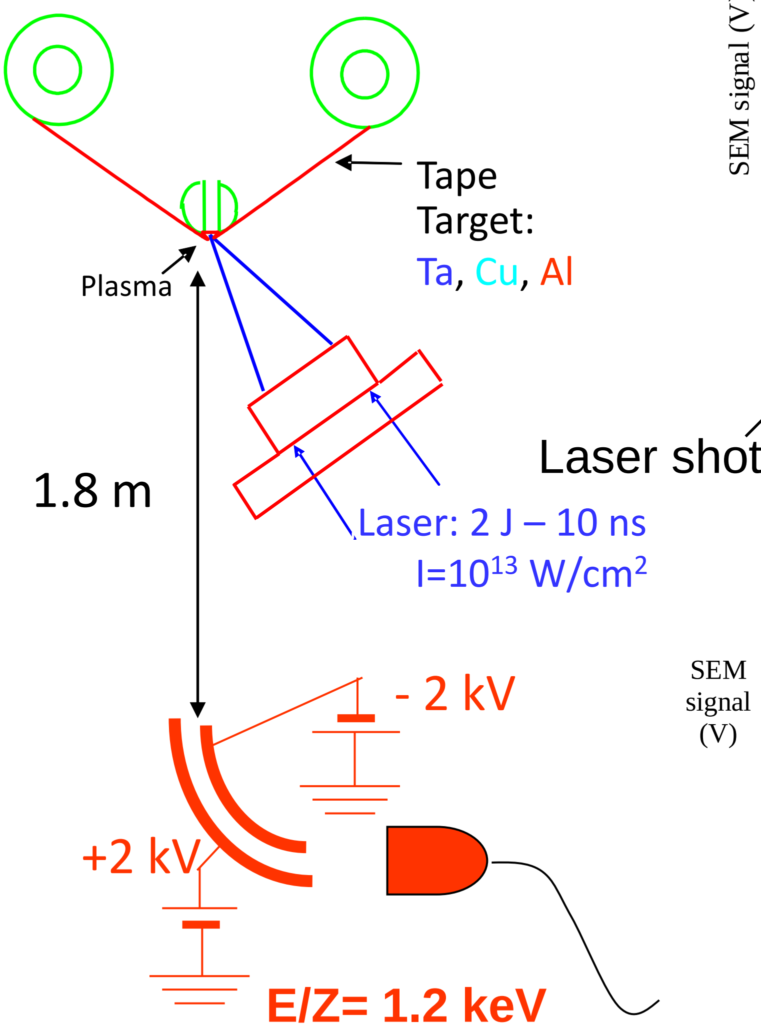
# Atomic debris mitigation: choosing the gas, range of flight issue

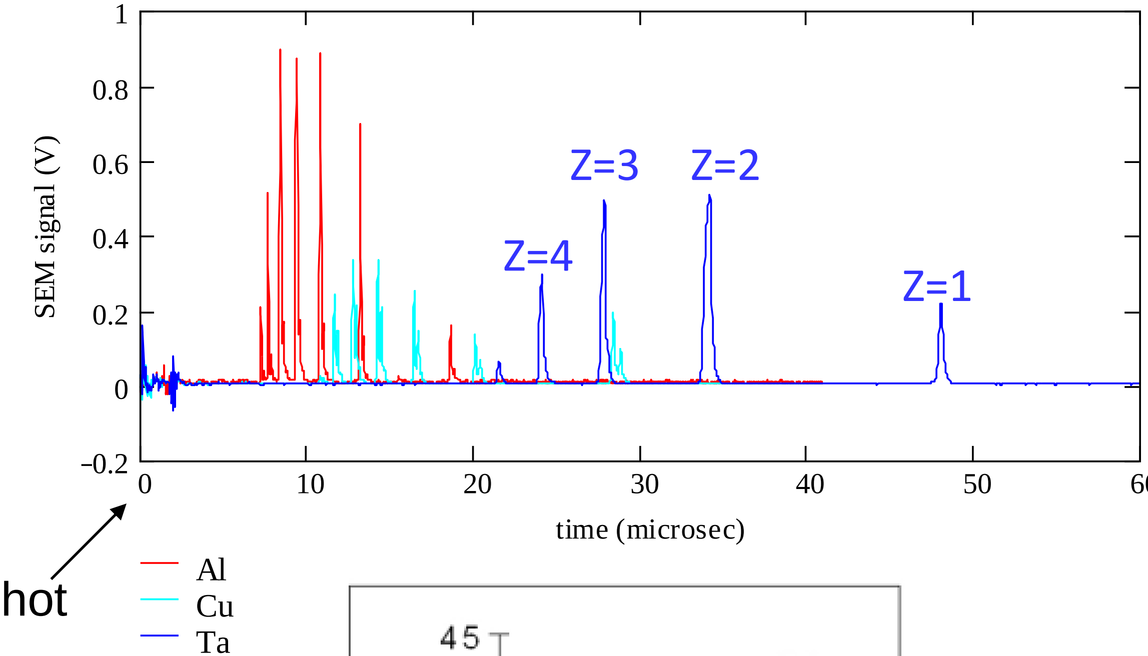


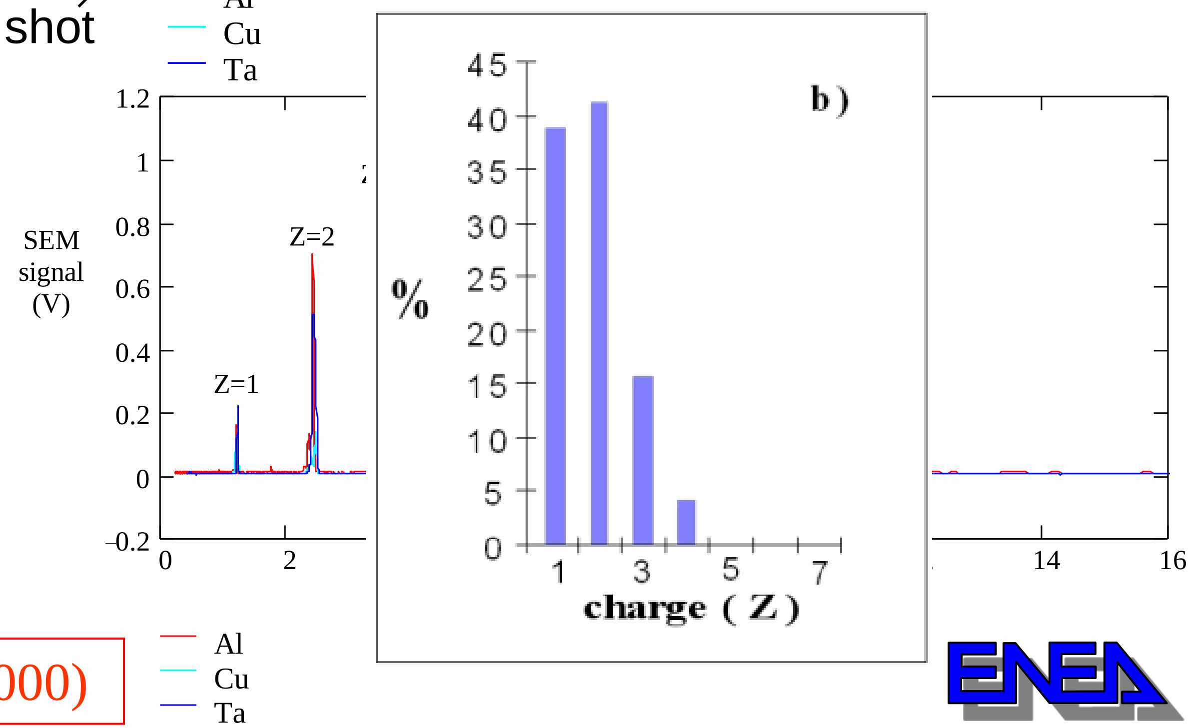

**Applied Physics A 71,** 255 (2000).

- The range of flight of heavy debris ions (Sn, Ta) is shorter than for light target (Li), for the same kinetic energy.
- Apparently, tin and tantalum ions can be stopped in a range much shorter than the path length for a reasonable EUV transmission (10 cm, T = 86%), both in Ar at 0.4 mbar and in Kr at 1 mbar. **It is'nt, due to momentum transferred to gas (the dirty cloud moves).**
- Kr is ~ 4 times better than Ar at a fixed transmission factor.

# Ion charge state measured by energy analyzer




Rev. Sci. Instrum. **71**, 1405 (2000)