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Analysis of the effects of a small area magnetic field for the mitigation of the debris emitted by a laser plasma source

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Introduction

As it is known, neglecting the Coulomb explosion, a magnetic field should theoretically be able to confine the expanding plasma within a sphere with a radius R_C which represents the distance from the plasma source at which the plasma pressure equals the magnetic pressure [1] :

$$R_C = \sqrt[3]{\frac{3E_K \mu_0}{2\pi B^2}}$$

where E_K is the total kinetic energy in the plasma (typically it is about half of the laser pulse or of the electric discharge energy), B is the magnetic field and μ_0 is the vacuum magnetic permeability. For example, for B= 1 T and E_K=100 mJ, the plasma should be confined in a space size R_C~ 4 mm.

So, even small area intense magnetic fields are theoretically effective for mitigating the ionic debris emitted by EUV sources [2].

In practice, magnetic fields can not fully stop the debris emitted by plasma sources; anyway, a small area (few cm^2) magnetic field can reduce the number of ionic debris and also significantly modify their spatial and velocity distribution.

This effect can be exploited to improve the efficiency of other debris mitigation systems so that the total mitigation factor can result to be much bigger than the simple product of each component of the chain. We have designed a magnet suitable for a large cone of collectable EUV radiation from the source.

Faraday cup measurements of the ionic debris speed distribution at different angles and for different values of a small size magnetic field applied in proximity of a laser plasma source are here presented. Preliminary results showing an interplay between the magnetic field and the particulates formation in the buffer gas are also presented.

References:

[1] G. DIMONTE and L.G. WILEY, "*Dynamics of Exploding Plasmas in a Magnetic Field*," Phys. Rev. Lett. Vol. 67**,** 1755-1758 (1991).

[2] S.S. Harilal et al.: "*Extreme-ultraviolet spectral purity and magnetic ion debris mitigation by use of low-density tin targets*", Optics Lett., Vol. 31, p. 1549, (2006)

The ENEA laser plasma source

Laser: excimer XeCl, λ=308 nm

-Hercules (developed by ENEA Frascati and El.En) E_L=6J, τ_L=120 ns, p.r.r. 1-5 Hz

-Commercial E_L=0.5 J, τ_L =30 ns, p.r.r. up to 50Hz

Target: Ta, Cu, Sn and In tape,

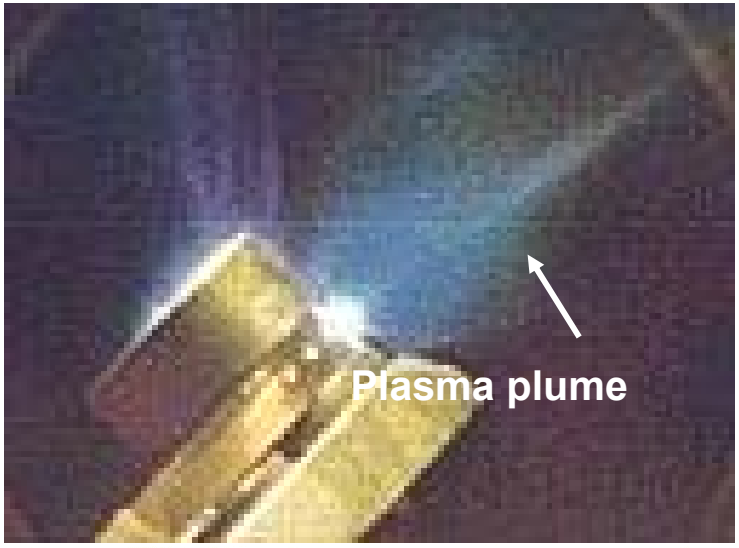
I_L (on target)= 10^{10} W/cm^2, out of focus to optmise EUV emission

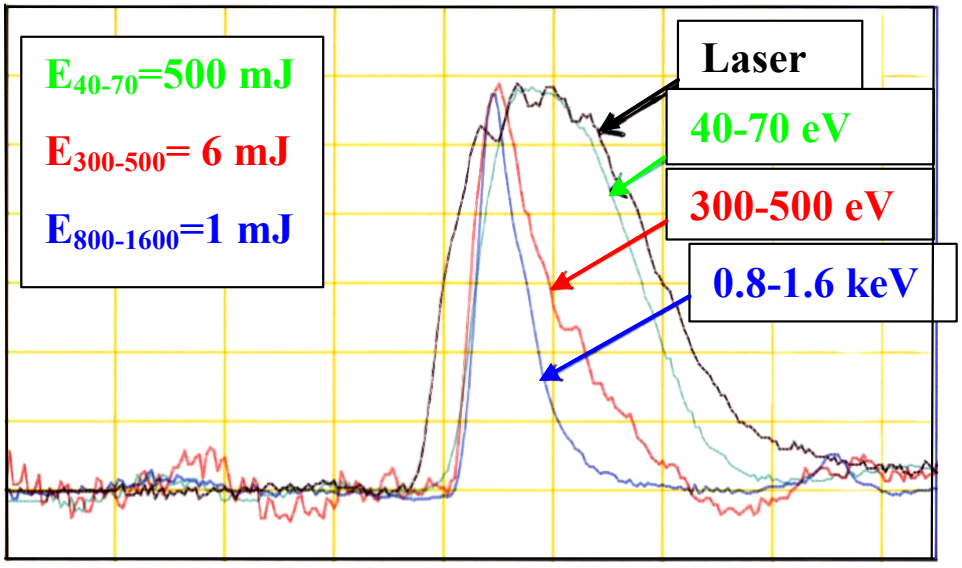
Optimised EUV radiation:

Φ= 500 μm, τ = 100 ns

angular distribution: ~cos(θ)

E_{out}= 20 mJ/shot in 1 sr and 2.5% B.W.

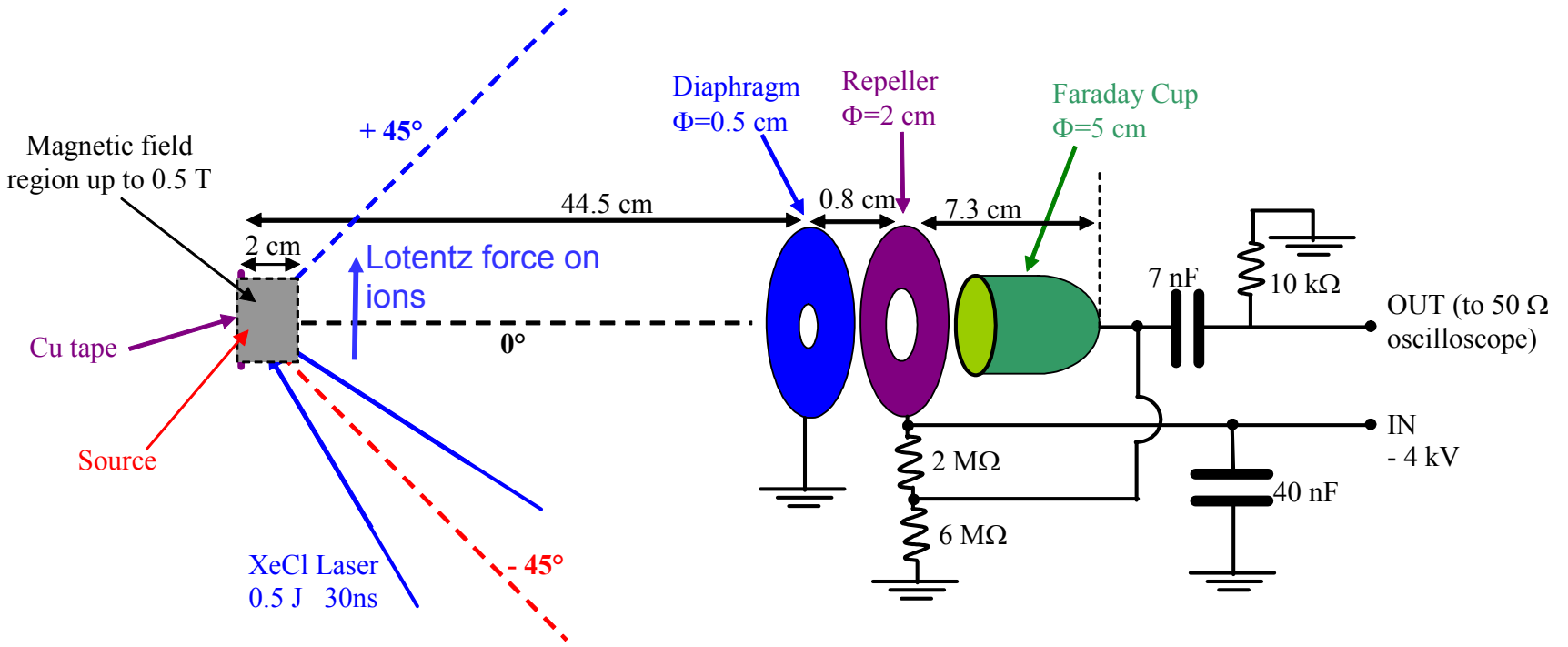




Time (60 ns/div)

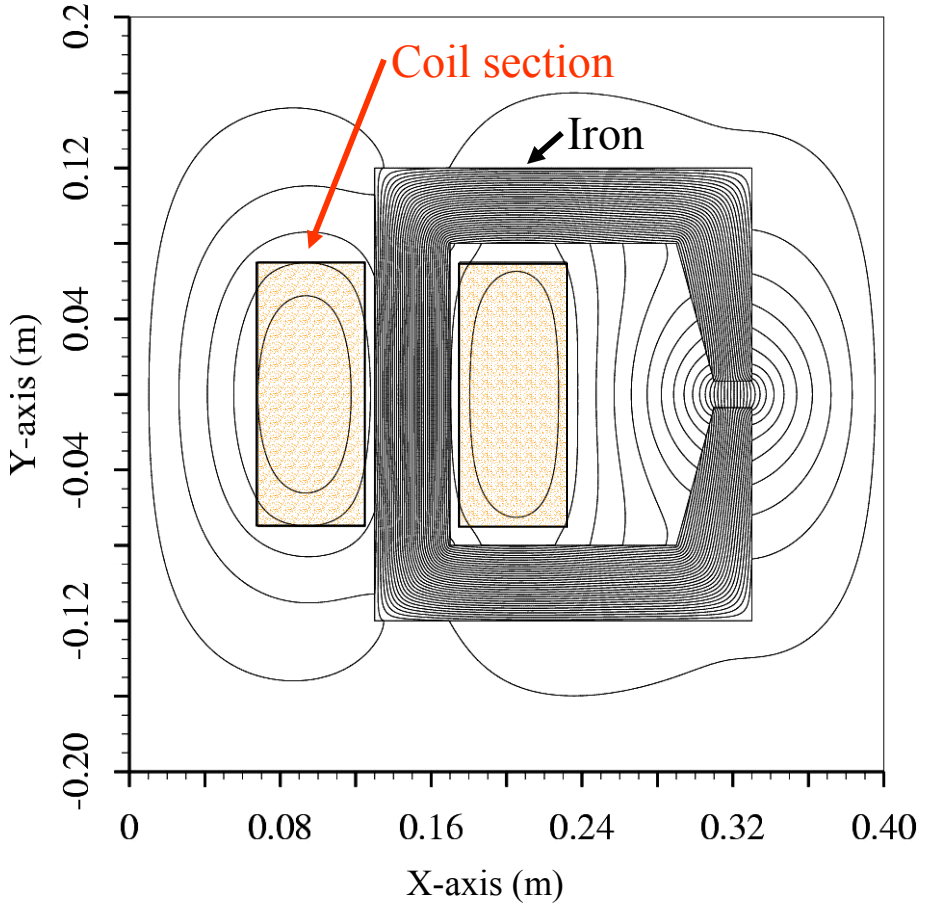
X-ray from on focus Cu target (Hercules, I_L= 10^{12} W/cm^2)

Faraday cup measurements setup

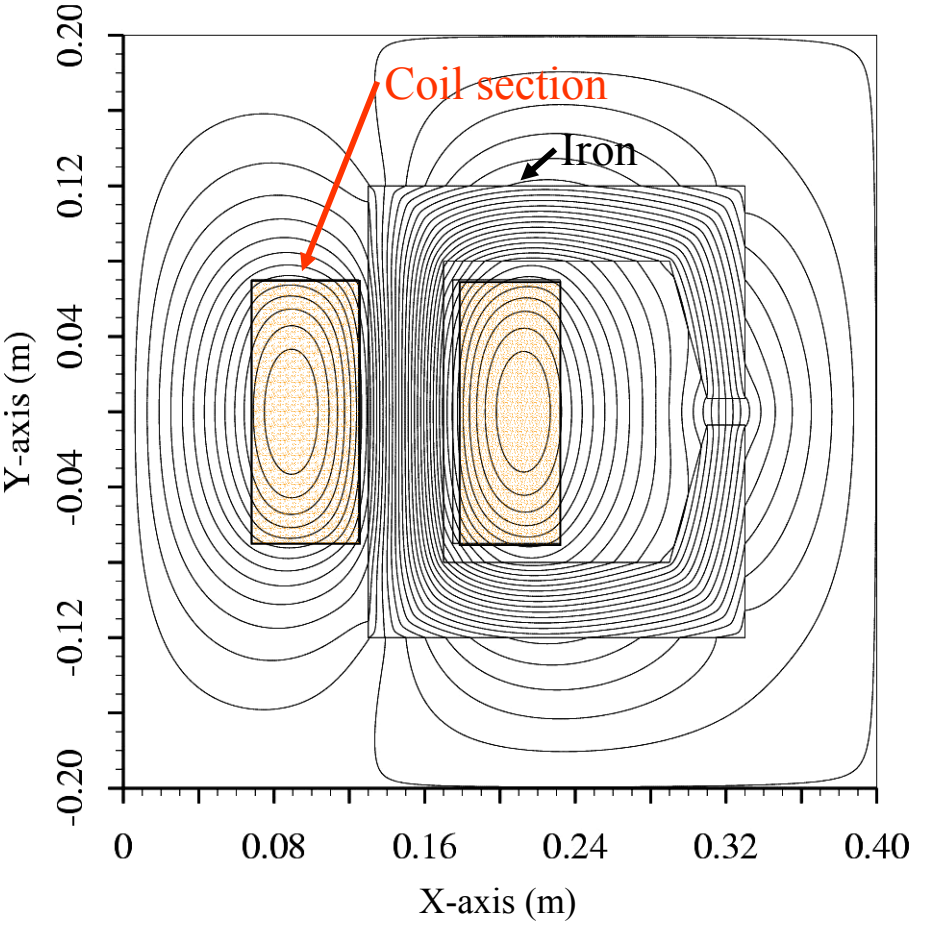


The -45° collection direction has been obtained by inverting the magnetic field orientation

Modeling of the electromagnet field lines

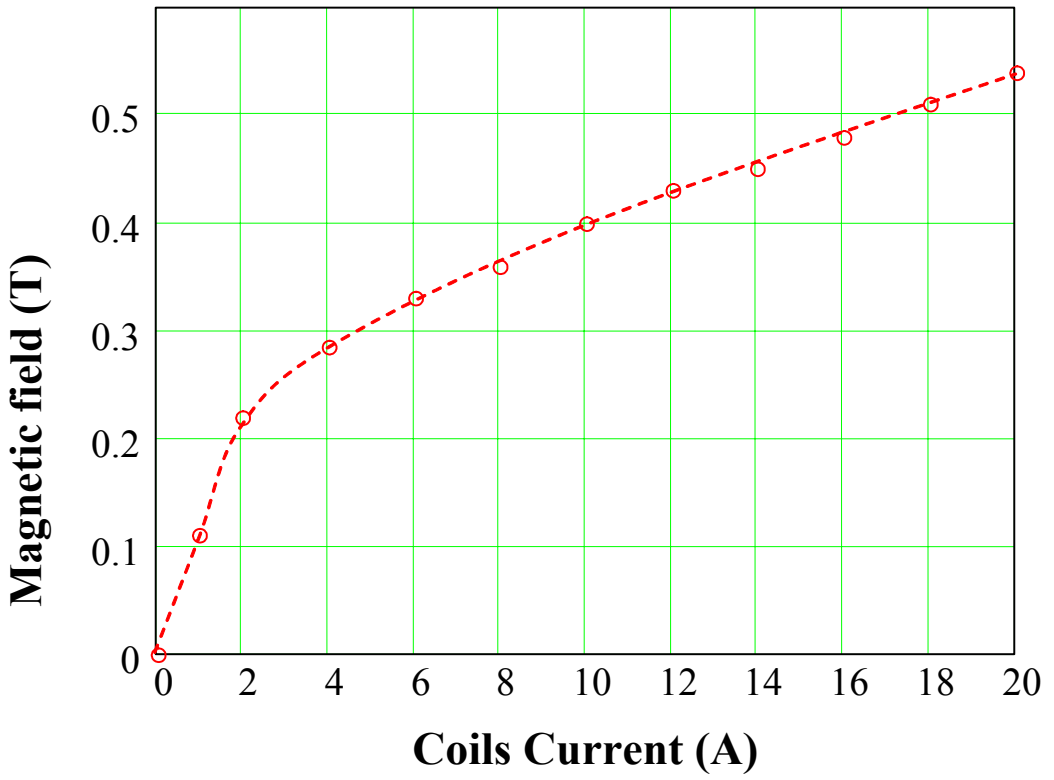


For low current values: non-saturated iron



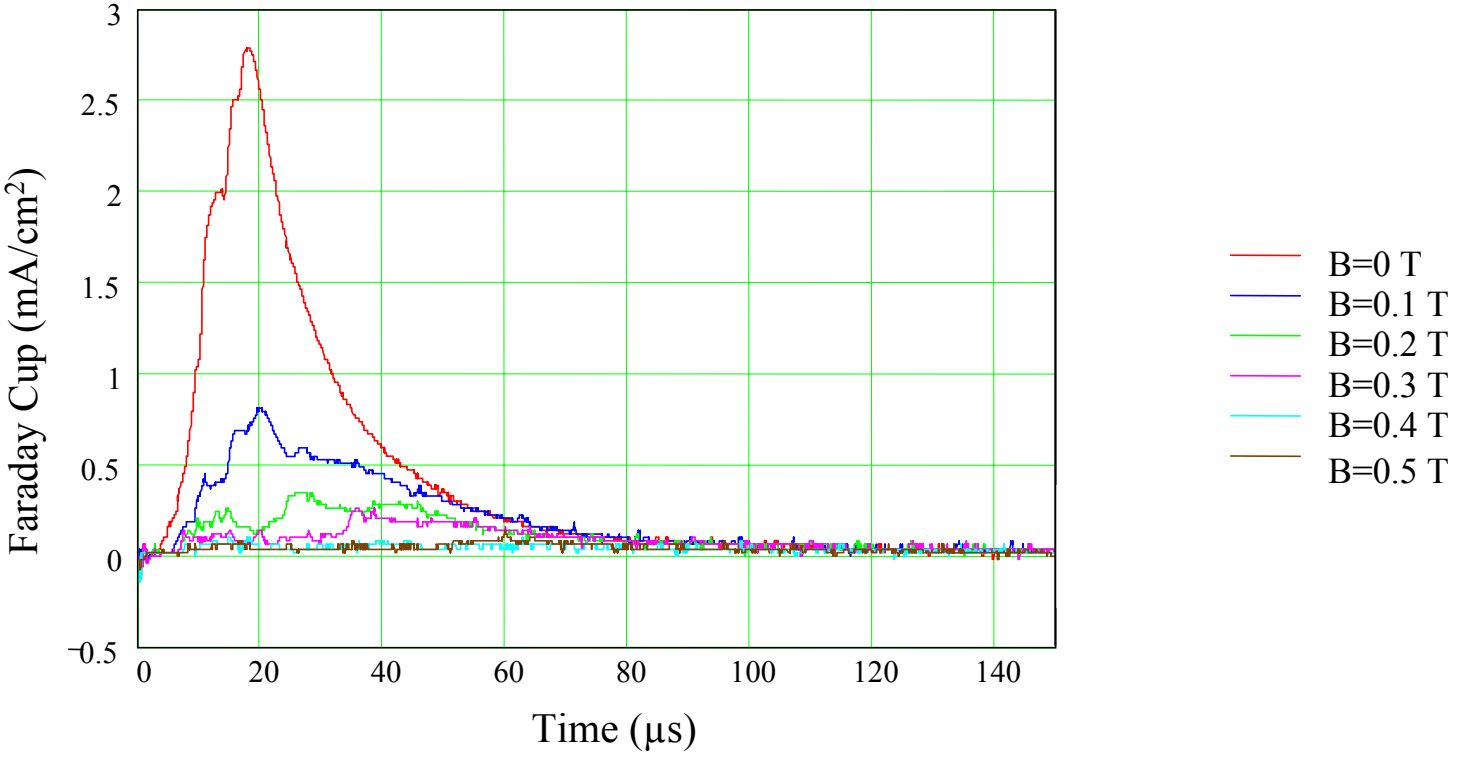
For high current values: saturated iron

Measured magnetic field vs current



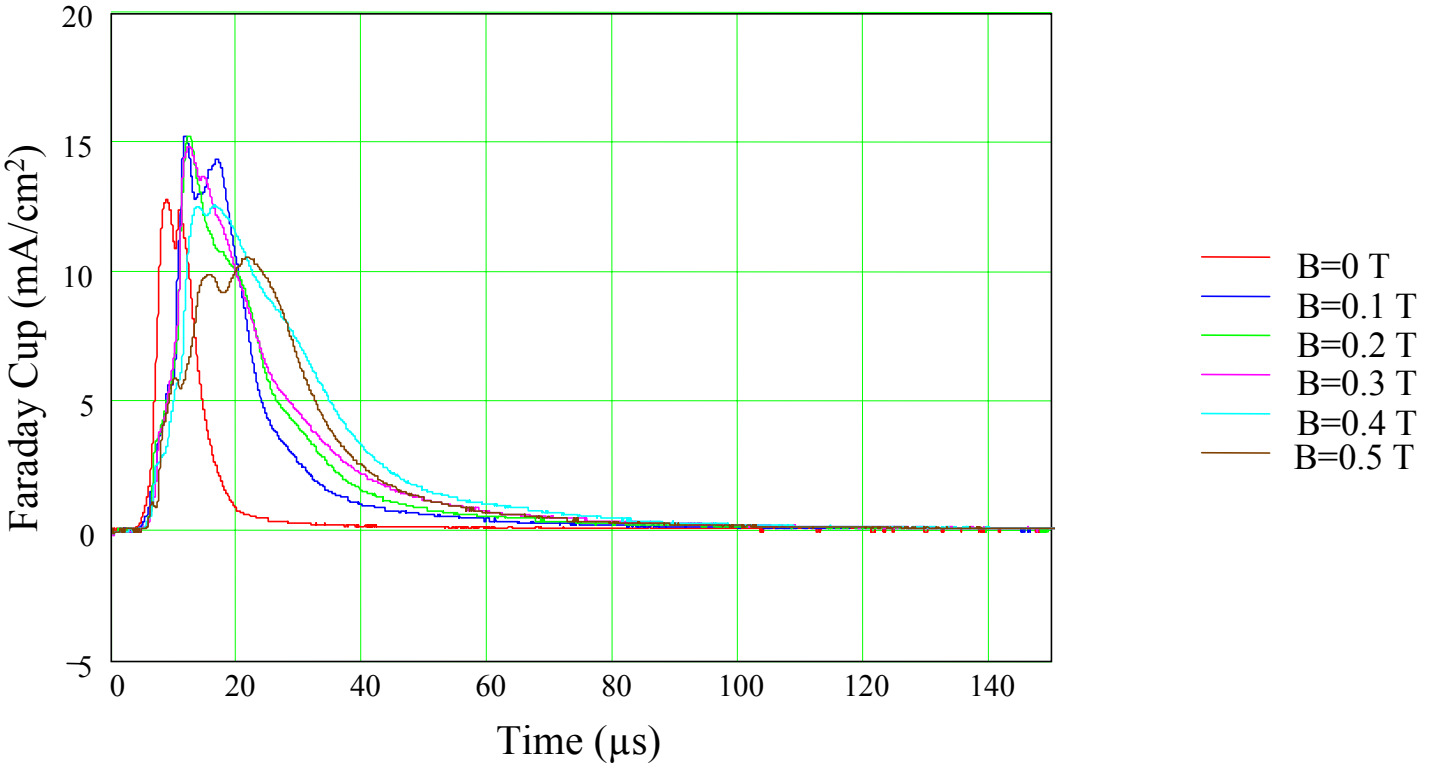
Two small coils have been added near the magnet gap in order to reduce the flux dispersion.

Faraday cup signal at -45° for different magnetic field values



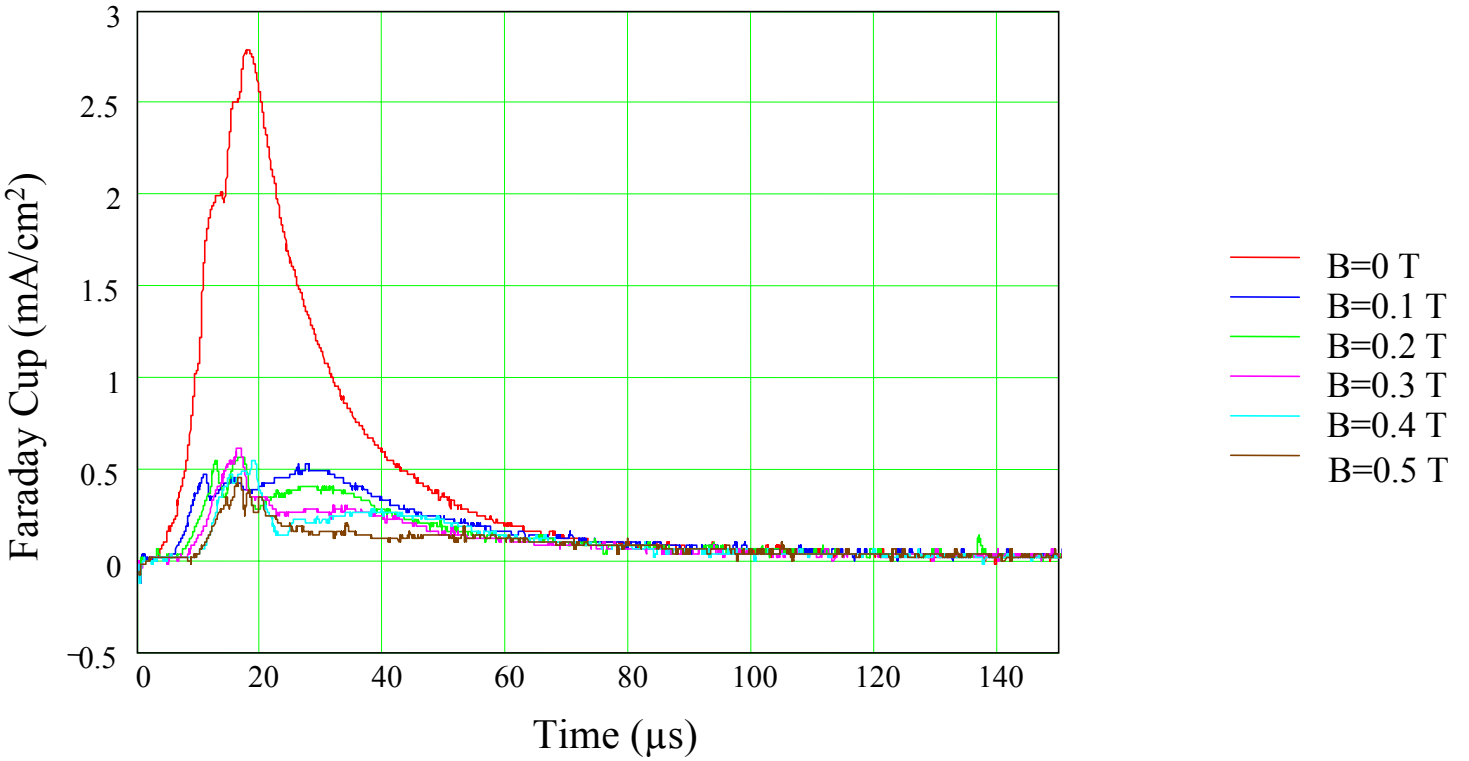
Laser intensity optimized for EUV emission ($I_L \sim 10^{10}$ W/cm^2)

Faraday cup signal at 0° for different magnetic field values



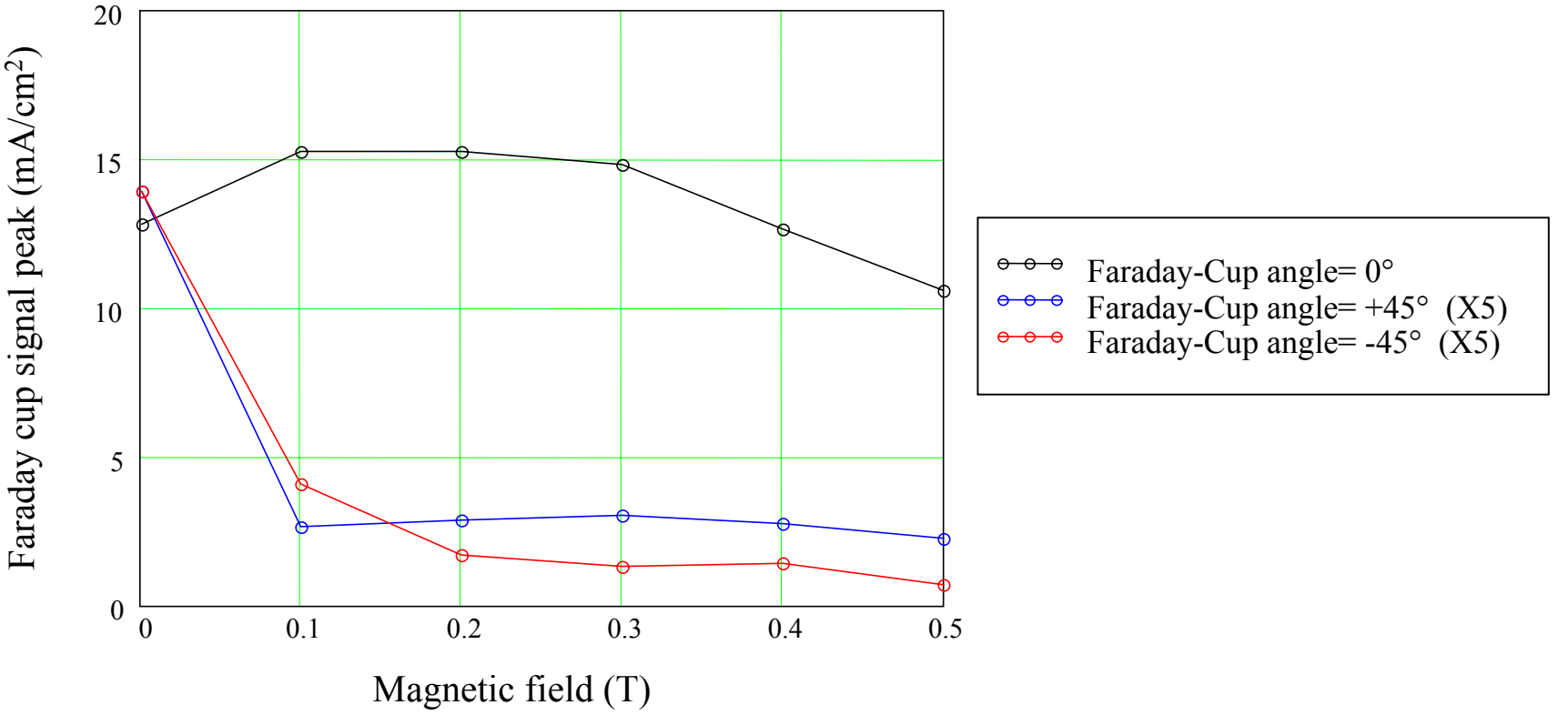
Laser intensity optimized for EUV emission (I_L~10^{10} W/cm^2)

Faraday cup signal at 45° for different magnetic field values

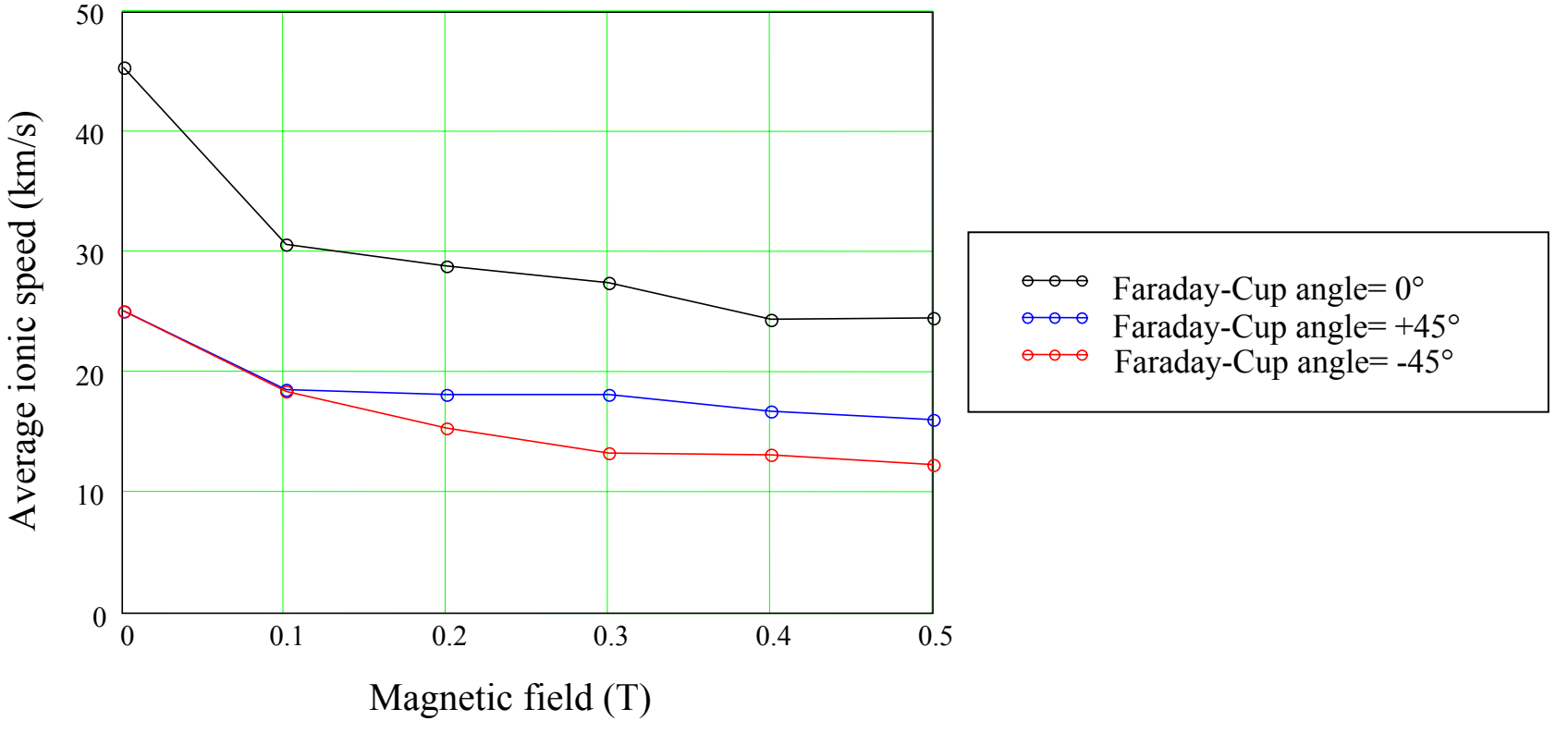


Laser intensity optimized for EUV emission (I_L~10^{10} W/cm^2)

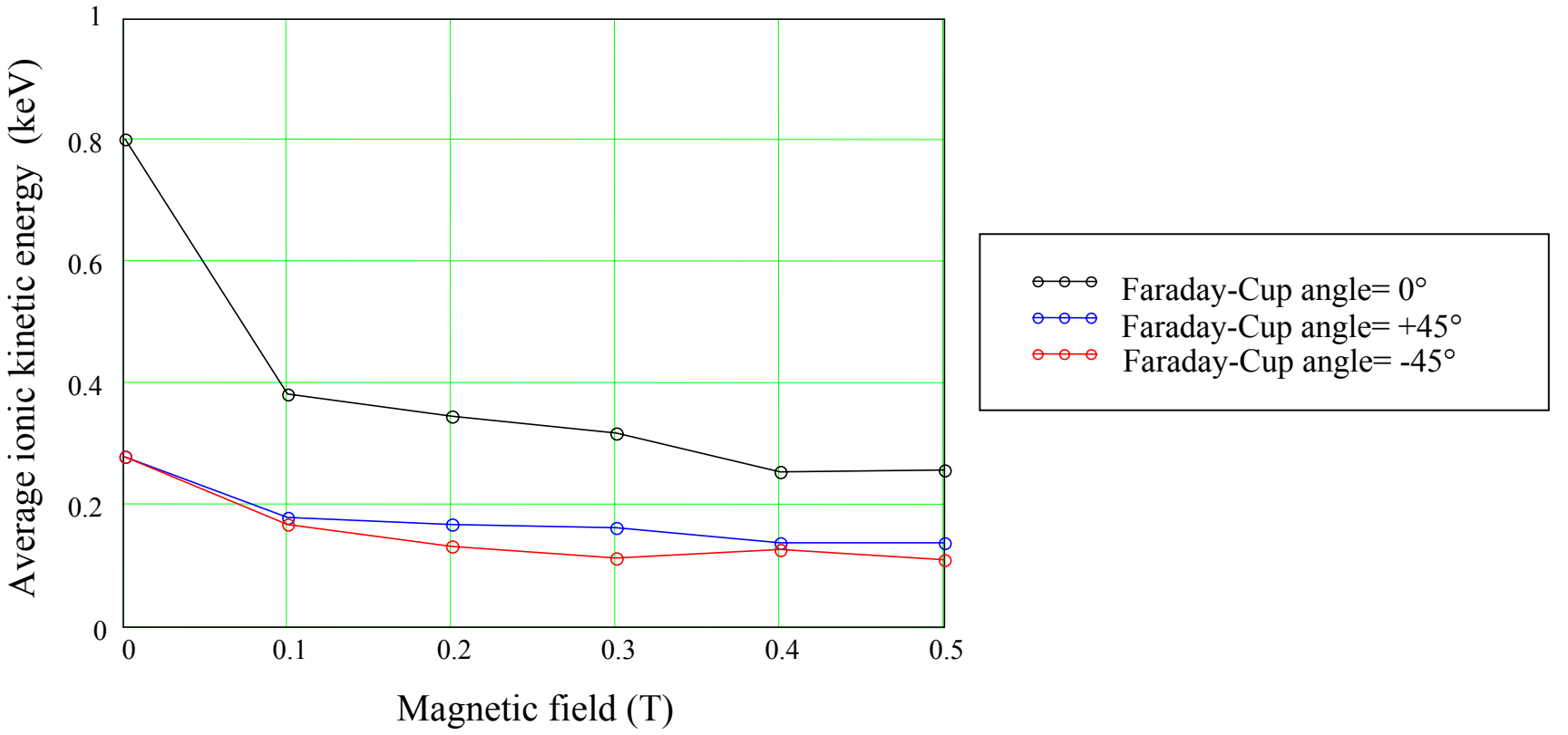
Faraday cup peak signal vs magnetic field for different collection angles



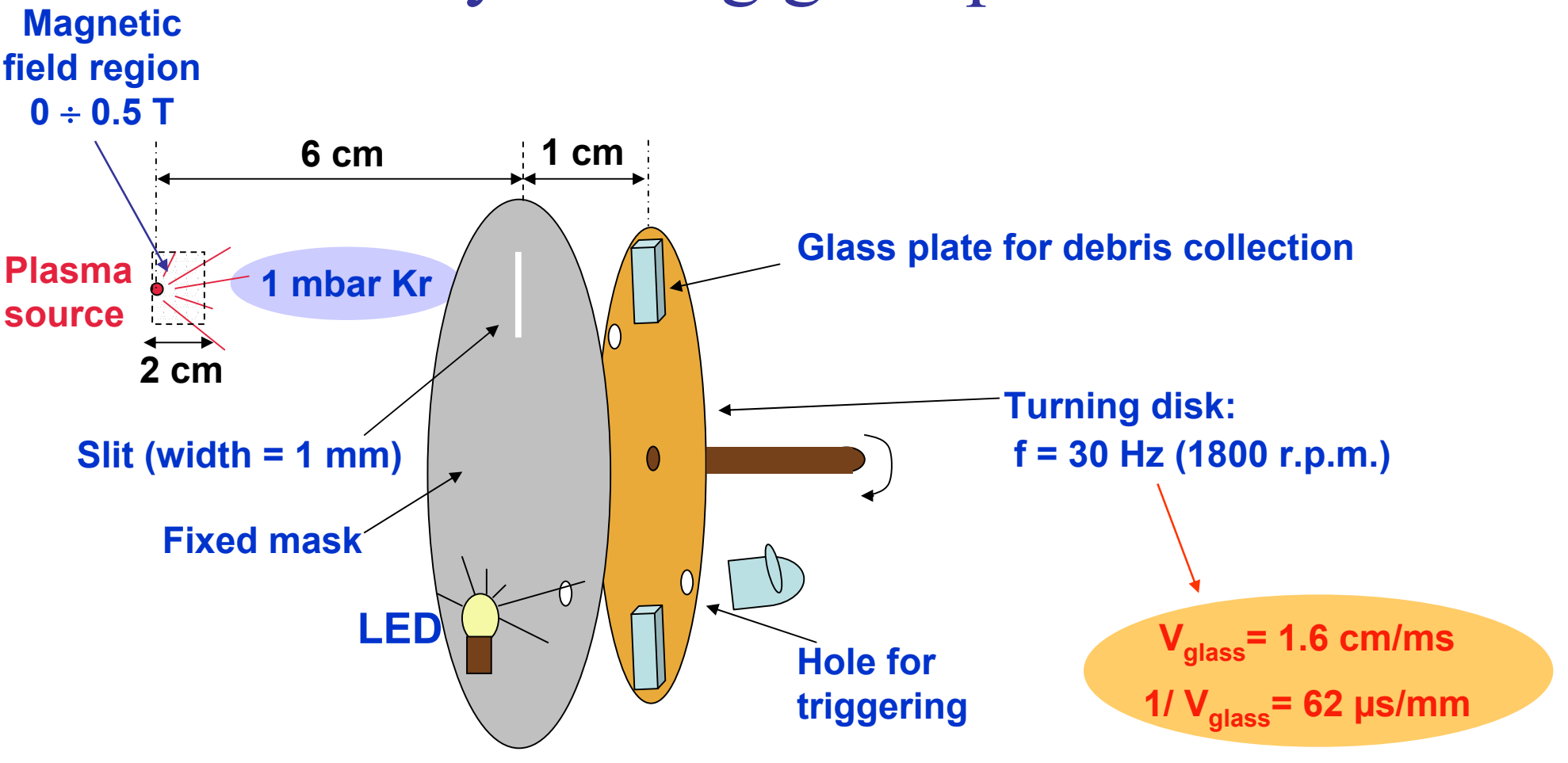
Average ionic speed vs magnetic field for different collection angles



Average ionic kinetic energy vs magnetic field for different collection angles



Characterization of Cu debris by turning glass plates (See Poster 18-SO-88)

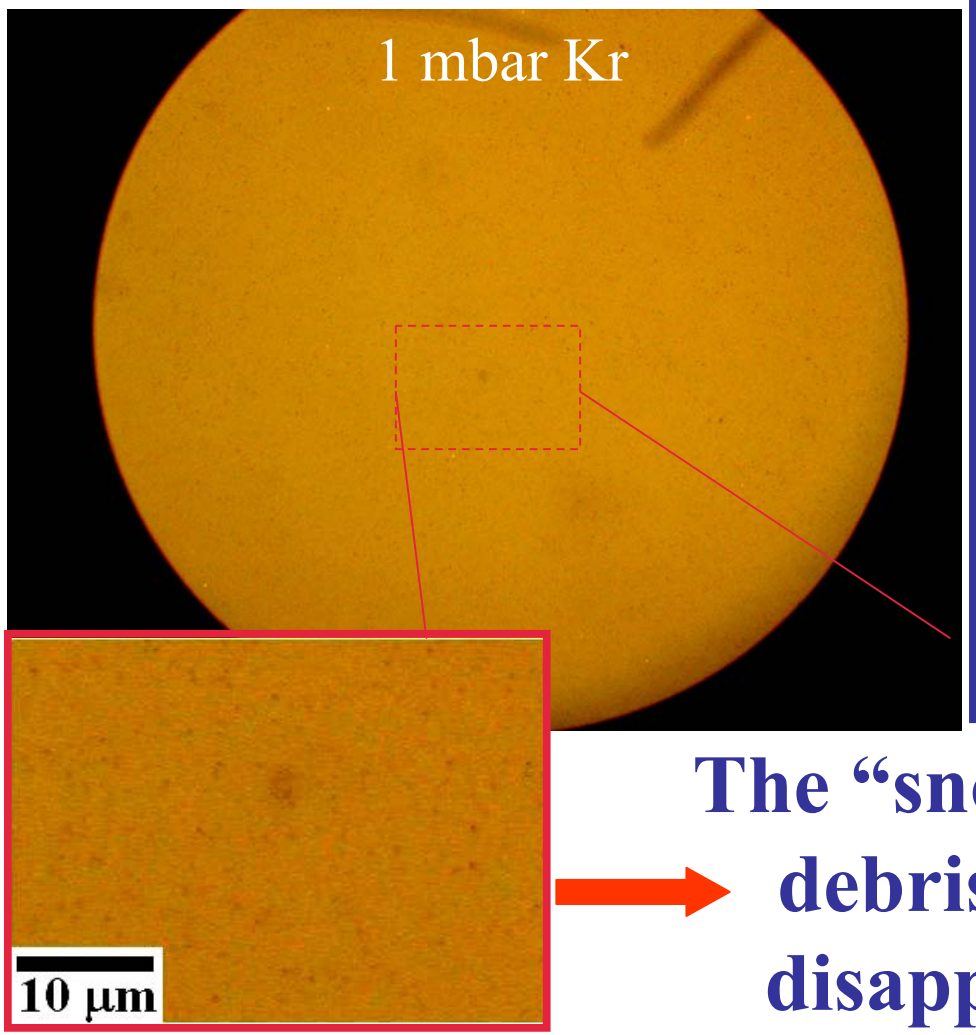


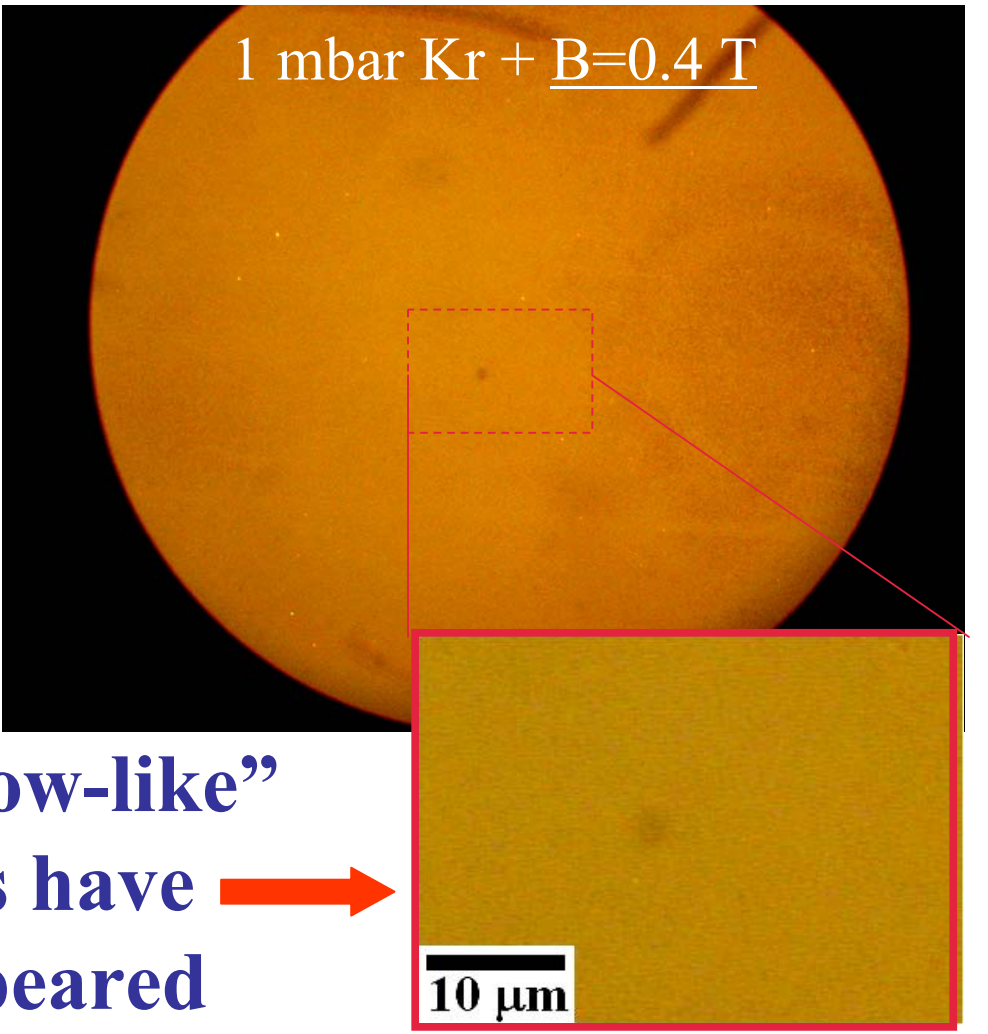
Debris exposure conditions for glass plate: 10^4 shots in Kr @ 1 mbar

Comparison between Kr and Kr+B exposures

Pictures of exposed glasses in the region corresponding to <v>=750 m/s

This is the average velocity of the observed "snow-like" particles in krypton





The "snow-like" debris have disappeared

Conclusions

- A DC current electromagnet, suitable for a large cone of collectable EUV radiation from the source, has been designed and developed. Saturation effects have limited the field to 0.5 T.
- An improved version of the magnet is under development to reach 1 T.
- A significant reduction of the ionic debris speed has been observed even at 0.5 T, especially for large angles (45°) with respect to the target normal.
- The observed strong asymmetry on debris slowing between +45° and -45° demonstrates a plasma plume deflection effect.
- The magnetic field seems also to influence the interaction of the plasma with a buffer gas reducing the formation of microparticles.
- The small size magnet (2 cm) is compatible to be combined with other debris mitigation systems to enhance their mitigation efficiency.