EUROPEAN UNION

Competitiveness Operational Programme (COP)

Structural Instruments
2014-2020

nuclear physics

Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase II
Project Co-financed by the European Regional Development Fund

IFIN-HH

Wavefront Metrology Developments

Using Adaptive Optics And Debris Shield Wavefront Measurements

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- Extreme Light Infrastructure – Nuclear Physics
- Adaptive Optics
- Experimental Set-up
- Debris Shields Metrology
- Results & Conclusions

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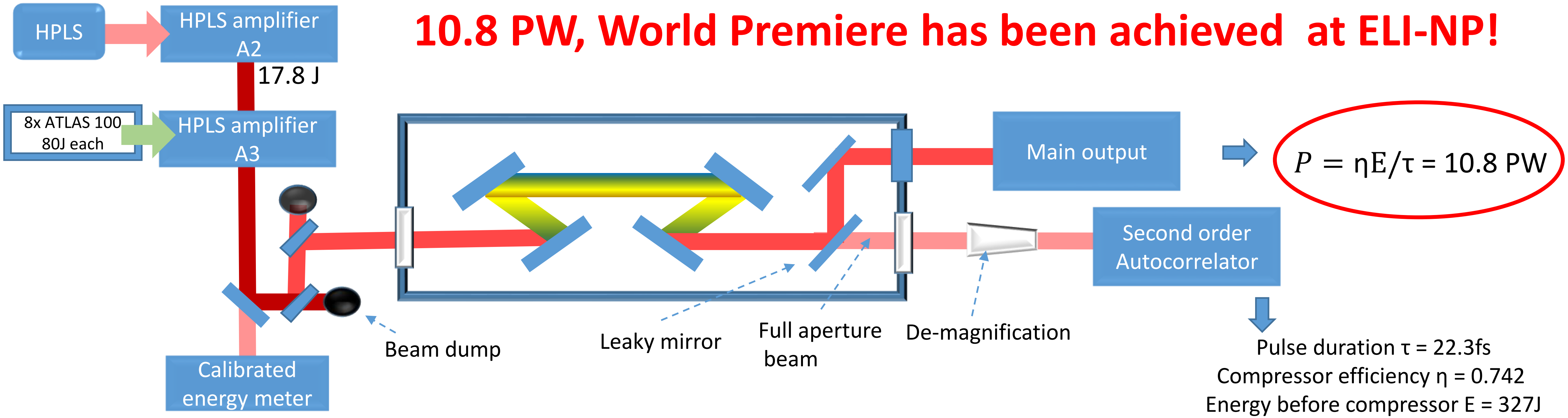
10.8 PW, World Premiere has been achieved at ELI-NP!



$P = \eta E/\tau = 10.8$ PW

Pulse duration $\tau = 22.3$fs
Compressor efficiency $\eta = 0.742$
Energy before compressor $E = 327$J


ELI-NP

BREAKING NEWS!

10 PW, World Premiere at ELI-NP

On Wednesday, March 13, 2019, the 10PW (ten millions of billions of Watts) performance of ELI-NP's High Power Laser System was officially released and a demonstrative test was presented.

Reaching 10 PW at ELI-NP is a reference point for scientific research worldwide, Europe making available, in premiere, via Romania, the most powerful laser in the world. The completion of this unique scientific equipment at the assumed parameters confirms that ELI-NP is a successful project, a landmark in the history of Science, and paves the way to top-level international experiments in Magurele.

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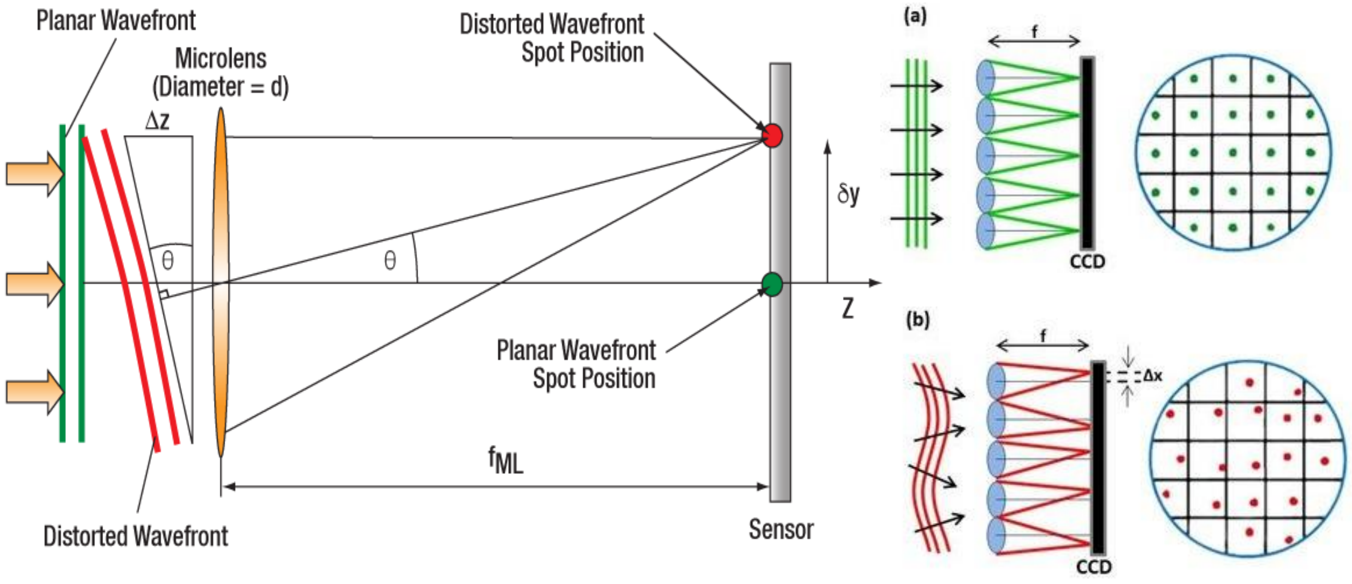
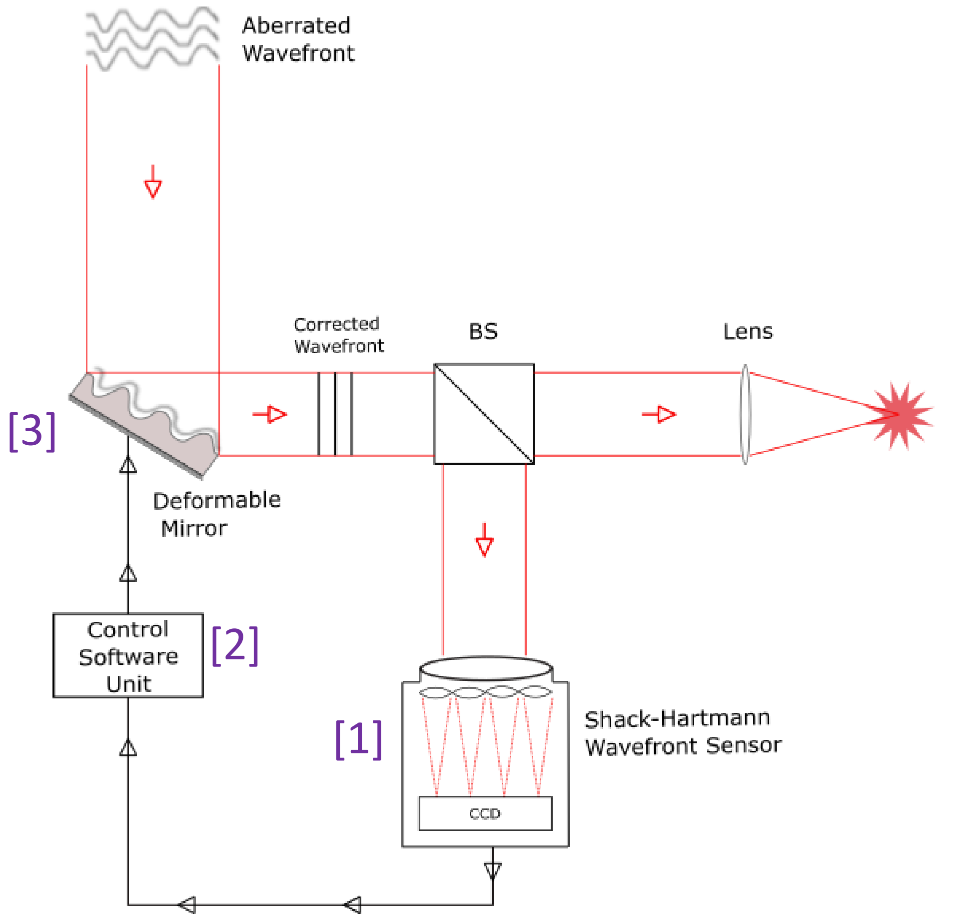
Adaptive Optics Principle



Shack-Hartmann wave front sensor operation principle. Planar wave fronts are normally incident on the lens and focus to the reference position (green spot) lens , while distorted wave fronts focus to a displaced location (red spot). *Picture taken from ThorLabs.*



Basic layout and operation principle of an AO system comprising the 3 steps of the process: [1] WF sensing, [2] feedback control and [3] deformable mirror correction.

Duffner, Robert W., and Robert Q. Fugate. The Adaptive Optics Revolution: A History (University of New Mexico Press, 2009)

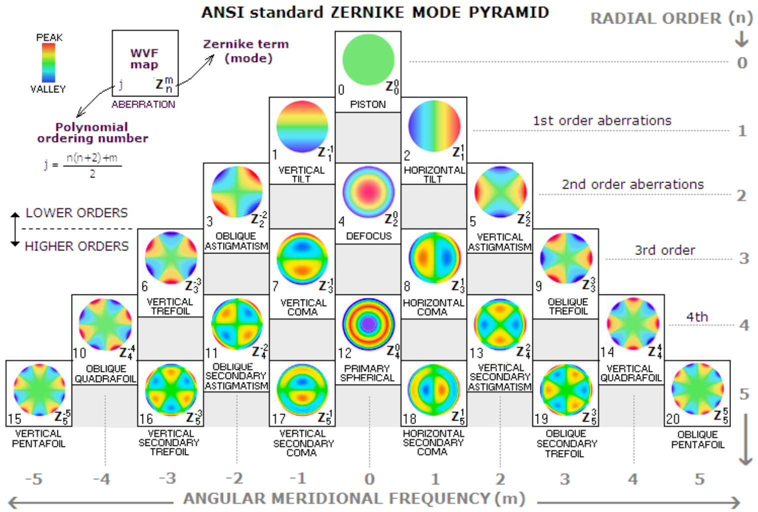
Tyson, Robert (2010). Principles of Adaptive Optics (Third ed.). Taylor & Francis

Deformable mirror coupled with a wavefront sensor through a feedback loop conpensates wavefront distorsions.

Generation of high quality flat reference wavefront achieved.

Wavefront reconstruction

Zernike polynomials formalism



$$Z_n^m(\rho,\varphi) = N_n^m \cdot R_n^m(\rho) \cdot A^m(\varphi) \cdot z_n^m$$

Normalization term

Radial polynomial

Angular term

Zernike coefficient

$$R_n^m(\rho) = \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k (n-k)!}{k!\left(\frac{n+m}{2}-k\right)!\left(\frac{n-m}{2}-k\right)!}\rho^{n-2k}$$

$$N_n^m = \sqrt{\frac{2(n+1)}{1+\delta_{m0}}} \qquad A^m(\varphi) = \begin{cases} \cos(m\varphi)\,; for\ m \geq 0 \\ \sin(m\varphi)\,; for\ m < 0 \end{cases}$$

Lakshminarayanan, V.; A. Fleck (2011). "Zernike polynomials: a guide". J. Mod. Opt. 58 (7)

M. Born, E. Wolf, Principles of Optics, 7th ed. (Cambridge University, 1991).

Zonal Southwell reconstruction model

First Neighbors

2	3	2
3	4	3
2	3	2

$$S_{ij}^x = \frac{\varphi_{i+1,j} - \varphi_{i,j}}{h}$$

$$S_{ij}^y = \frac{\varphi_{i,j+1} - \varphi_{i,j}}{h}$$

$$S_{i-1,j}^x = \frac{\varphi_{i,j} - \varphi_{i-1,j}}{h}$$

$$S_{i,j-1}^y = \frac{\varphi_{i,j} - \varphi_{i,j-1}}{h}$$

Number of first neighbors for an inner square ij.

$$\boxed{\begin{aligned} 4 * \varphi_{ij} &- \left(\varphi_{i+1,j} + \varphi_{i,j+1} + \varphi_{i-1,j} + \varphi_{i,j-1}\right) = \\ &= \left(S_{i-1,j}^x + S_{i,j-1}^y - S_{i,j}^x - S_{i,j}^y\right) * h \end{aligned}}$$

$4*\widetilde{\varphi_{ij}}$

b_{ij}

For a square at the frontier of the surface, the first neighbors are less than 4 and the equation has to be rearranged accordingly.

Finally we obtain: $$\boxed{\varphi_{ij}^{m+1} = \widetilde{\varphi}_{ij}^{\,m} + \frac{b_{ij}}{g_{ij}}}$$

Where: $\boldsymbol{\varphi_{ij}}$: the averaged phase in the element (ij) to be estimated. *(Takes a new value at each step)* **(INITIALIZED at 0)**

$\widetilde{\varphi}_{ij}$: the average of the averaged phase in the first neighbors of the element (ij). *(Takes a new value at each step)*

$\boldsymbol{b_{ij}}$: the averaged slope around the element (ij). *(This is given by the Data and is a CONSTANT)*

$\boldsymbol{g_{ij}}$: the number of the nearest neighbors of the element (ij). *(Depends on the geometry of the surface and it is a CONSTANT)*

W. H. Southwell, J. Opt. Soc. Am., Vol. 70, No. 8, August 1980

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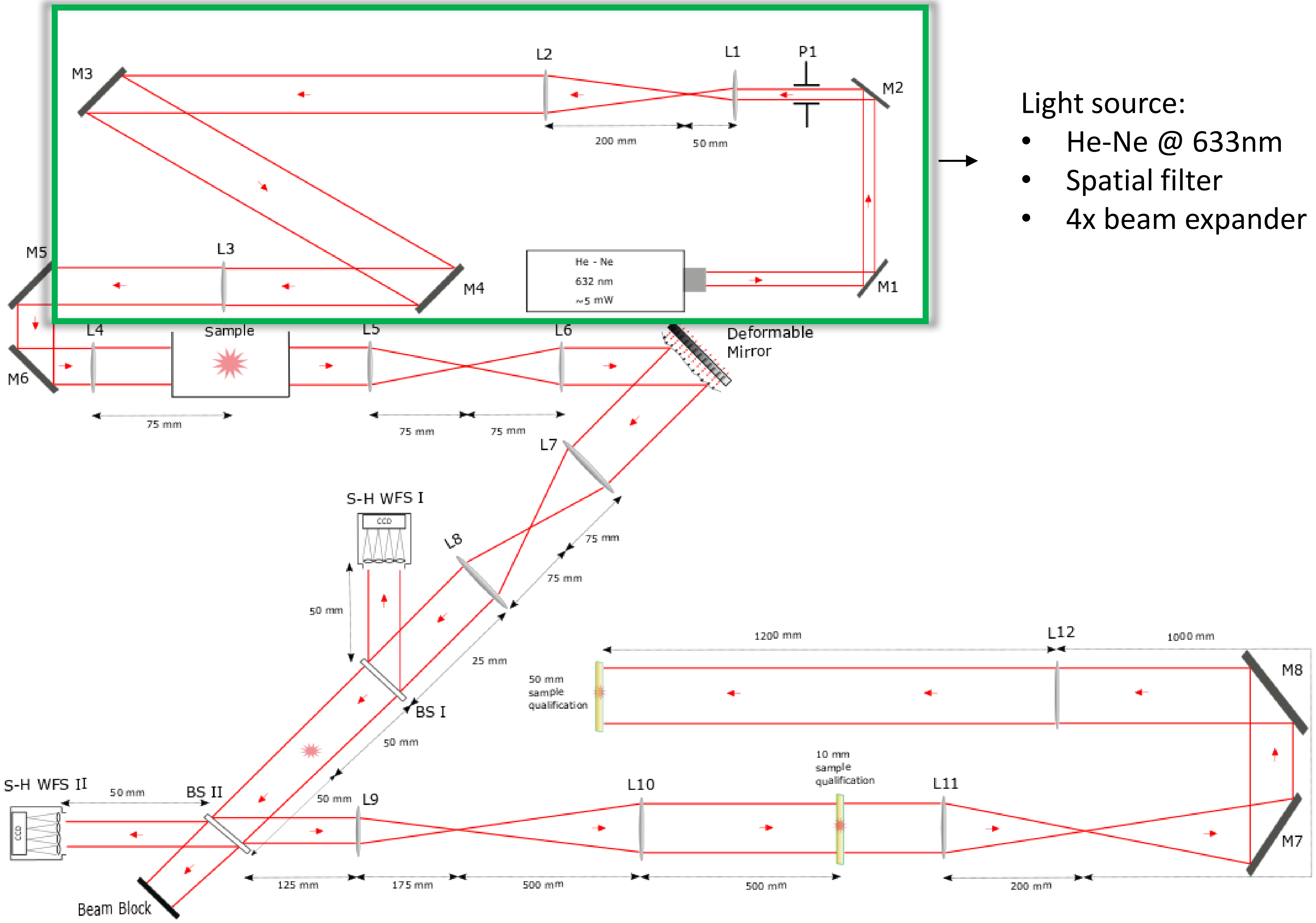
Experimental set-up



Light source:

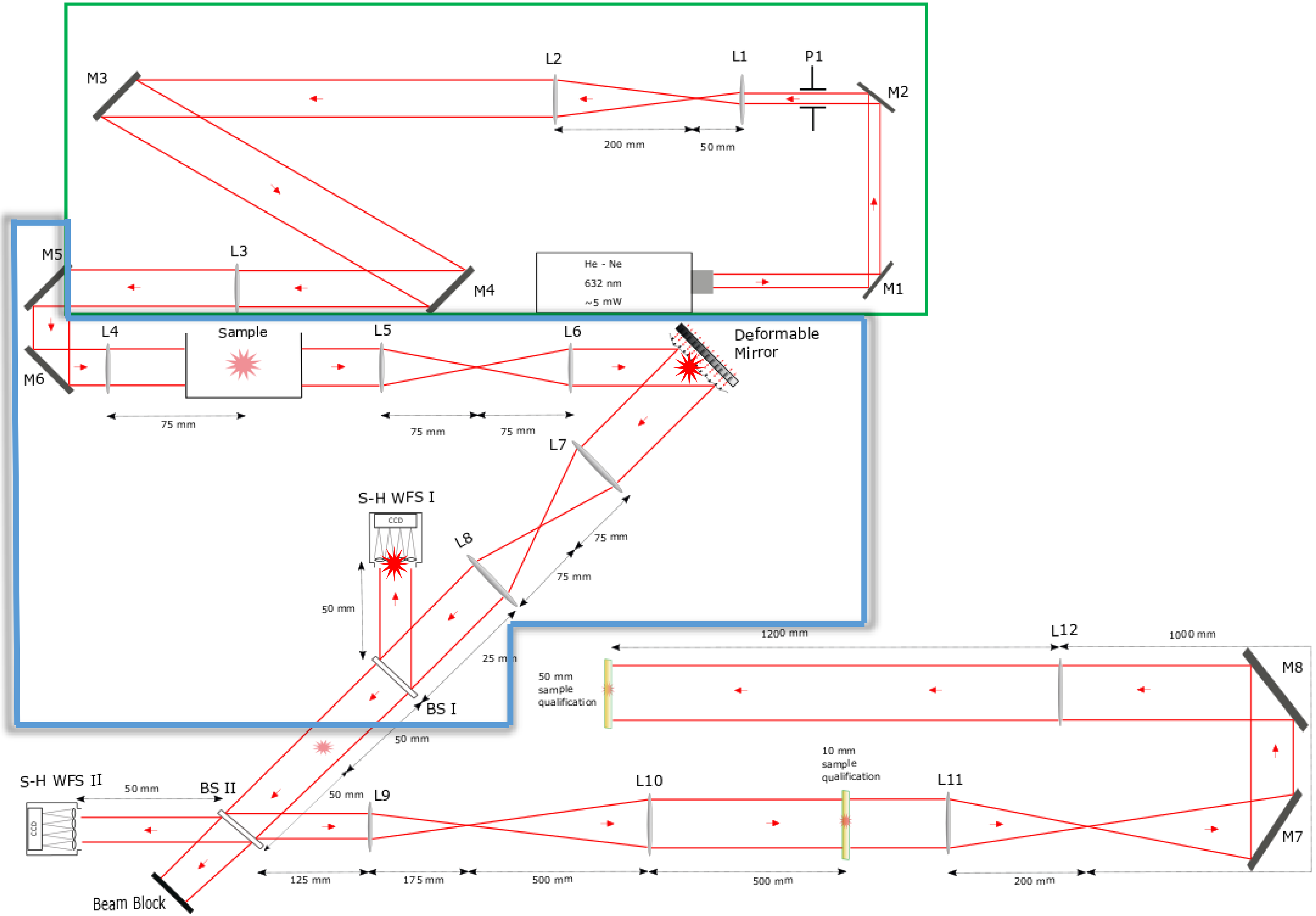
- He-Ne @ 633nm
- Spatial filter
- 4x beam expander

Experimental set-up

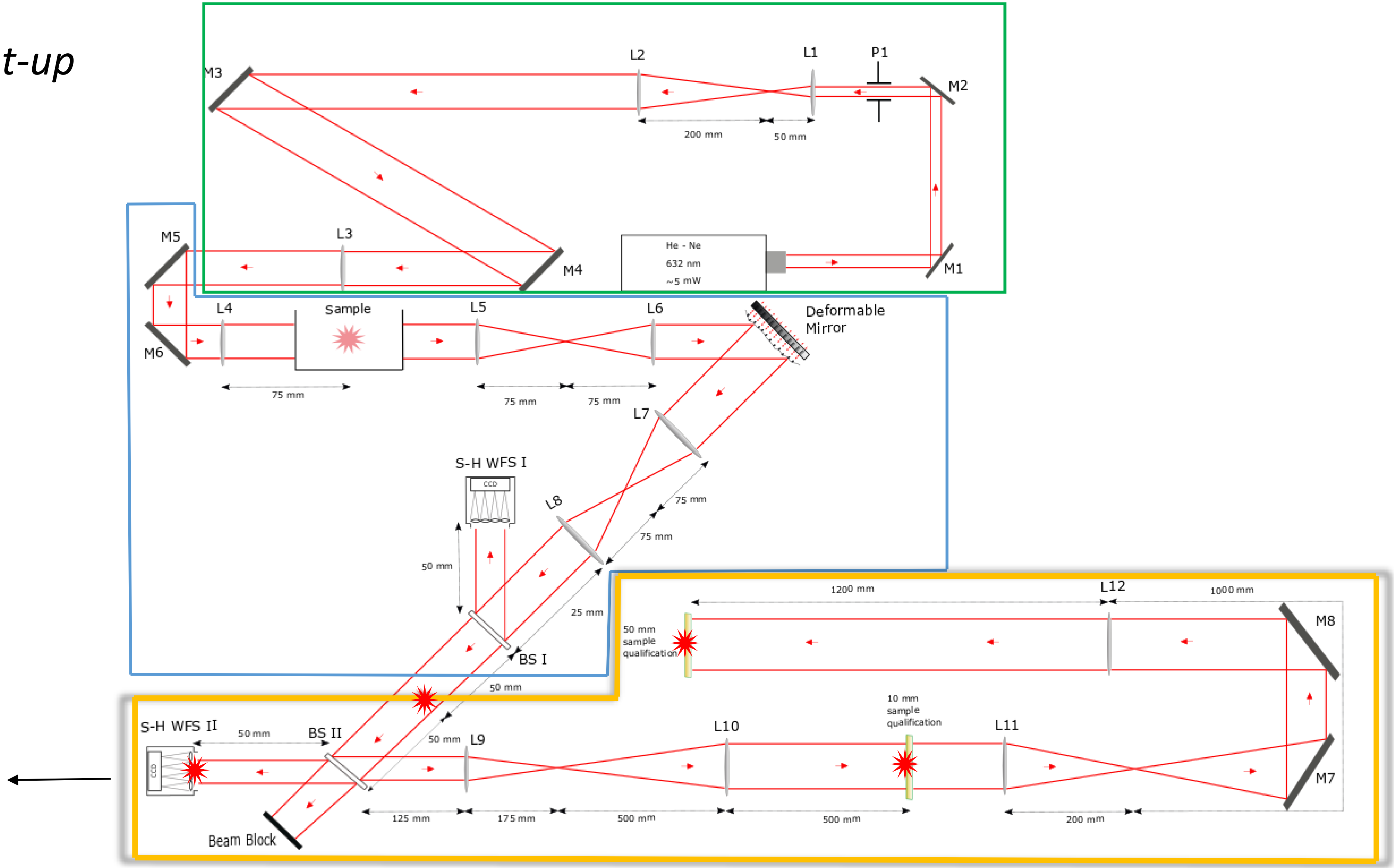
Reference wavefront generation:

- Deformable mirror
- Relay imaging: ✸
- Wavefront sensor

←



Experimental set-up



Wavefront measurement:

- Relay imaging: ✷
- Beam expander
  - 10mm
  - 50mm
- Wavefront sensor

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Debris shields for High Power Laser Systems

B qualifies the nonlinear wavefront distortion:

$$B = \frac{2\pi}{\lambda}\int \frac{\Delta n}{n}\,dl = \frac{2\pi}{\lambda} n_2 \int_0^L I(z)\,dz \sim \frac{2\pi}{\lambda} n_2\, IL < 1 \;\Rightarrow\; \mathrm{L} < 300\ \mu m$$

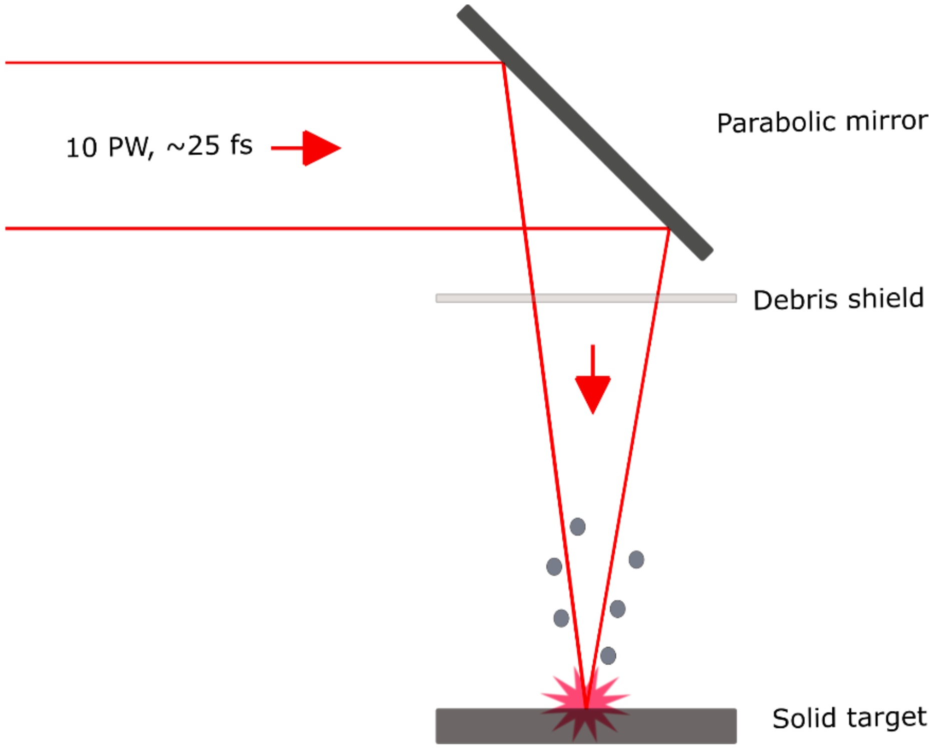
λ – incident wave length (@ 800 nm)

n_2 – nonlinear refractive index (e.g.: $4\text{x}10^{-16}\ \mathrm{cm}^2/_{\mathrm{W}}$ for Fused Silica)

I(z) – laser beam irradiance

L – path length (material thickness)

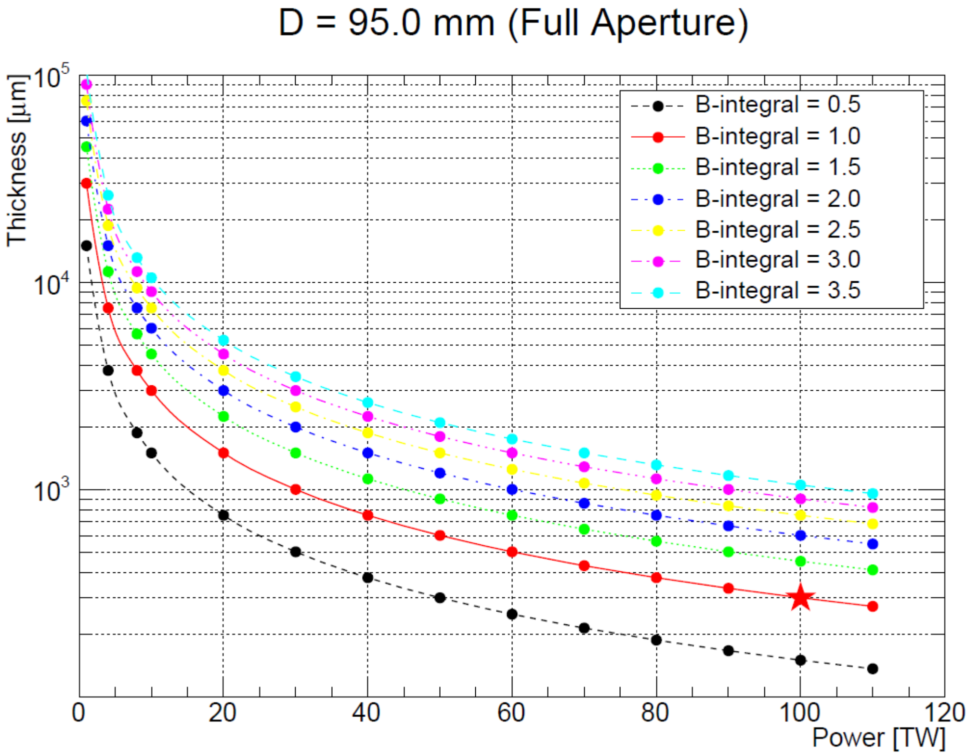
If B ~ π ⟶ risk of self focusing inside the material !

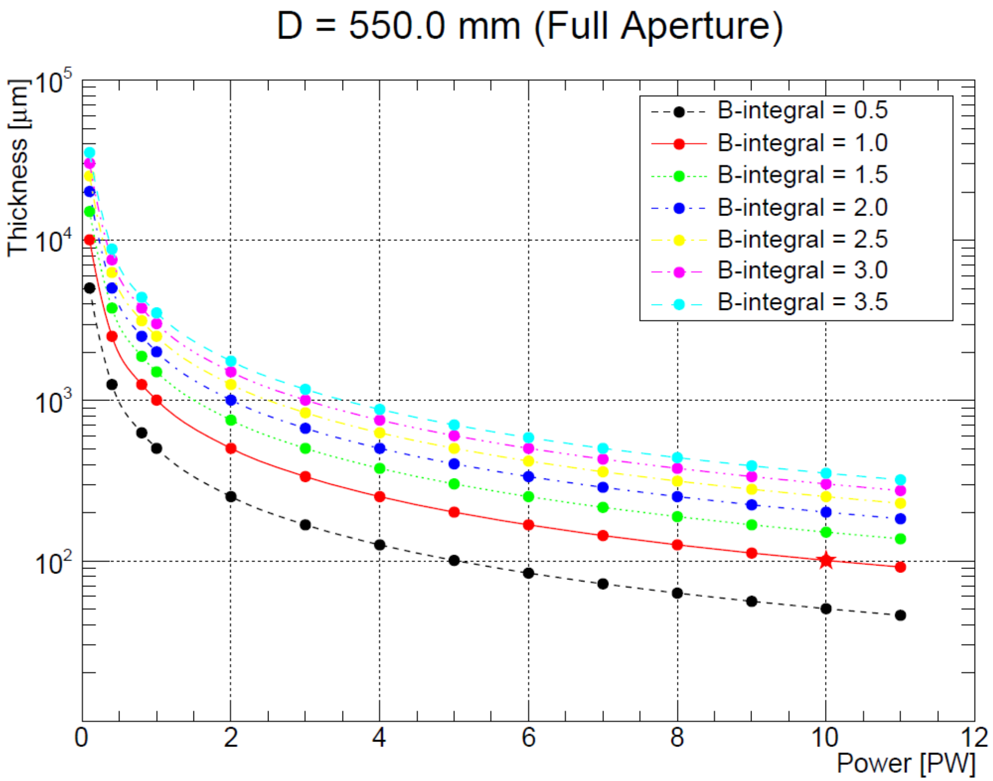


Proposed debris shield schematics positioning within the Large Beam Transport Systems (LBTS)

Debris shields are thin (L <300 μm) and high quality transmitted wavefront might be difficult to obtain !

Debris shields thickness for 100 TW & 10 PW

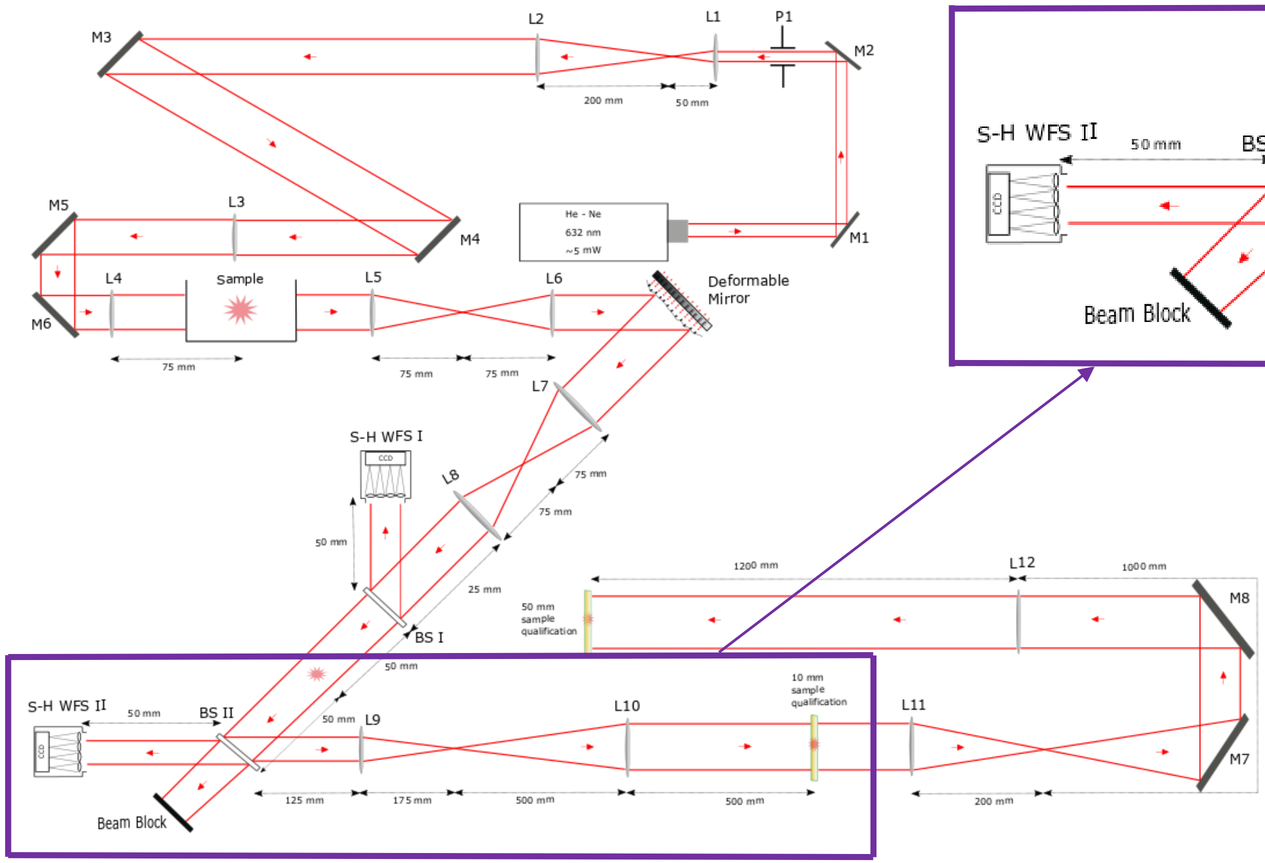


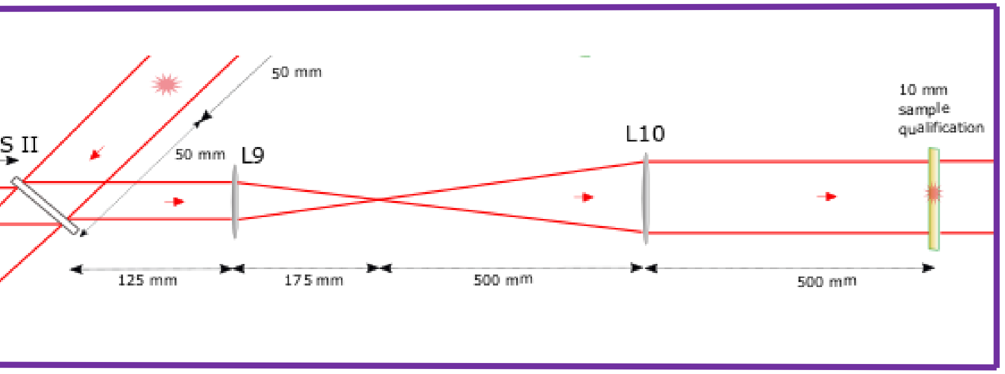


For 100 TW → 300 µm is maximal thickness
(when B-integral = 1 defined as critical).

For 10 PW → 100 µm is maximal thickness
(when B-integral = 1 defined as critical.)

Thin debris shields qualification





Position of the sample within the experimental set-up

Sample holder with two docking locations

Measurement configuration: 10 mm aperture, double pass and different stress applied on sample.

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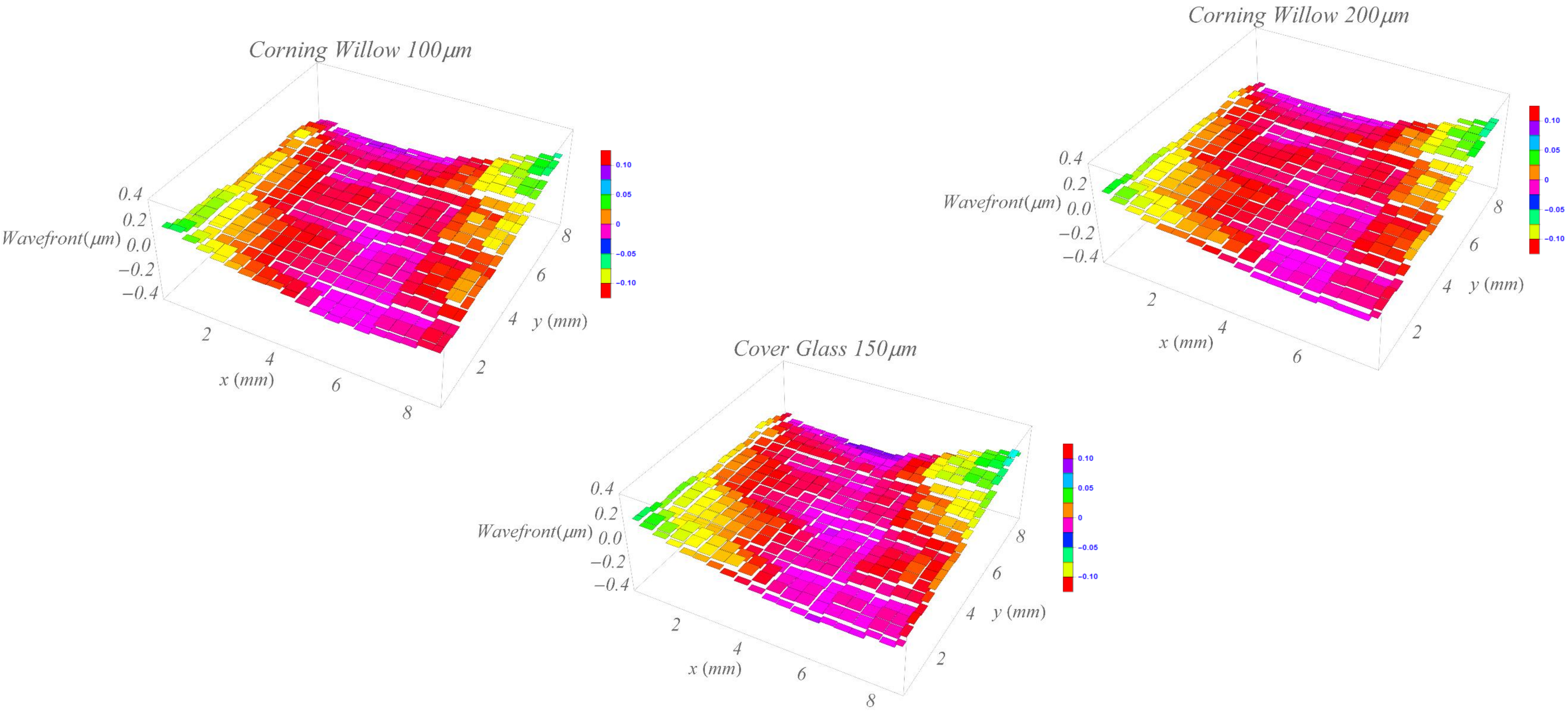
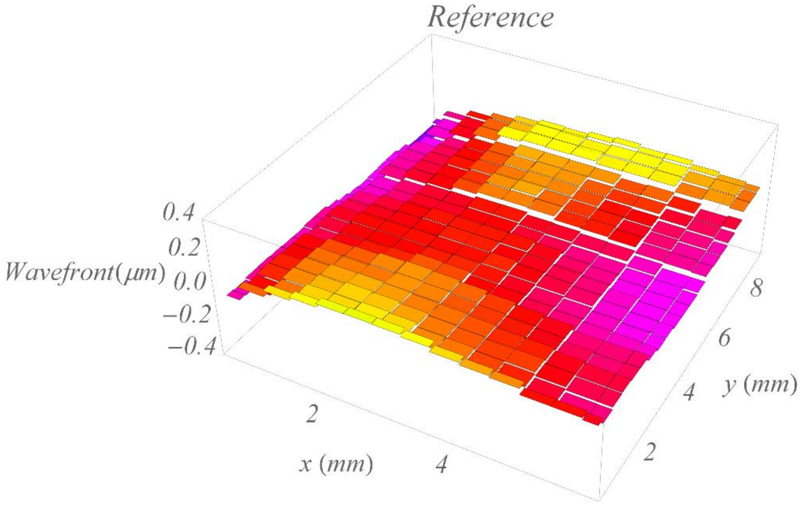
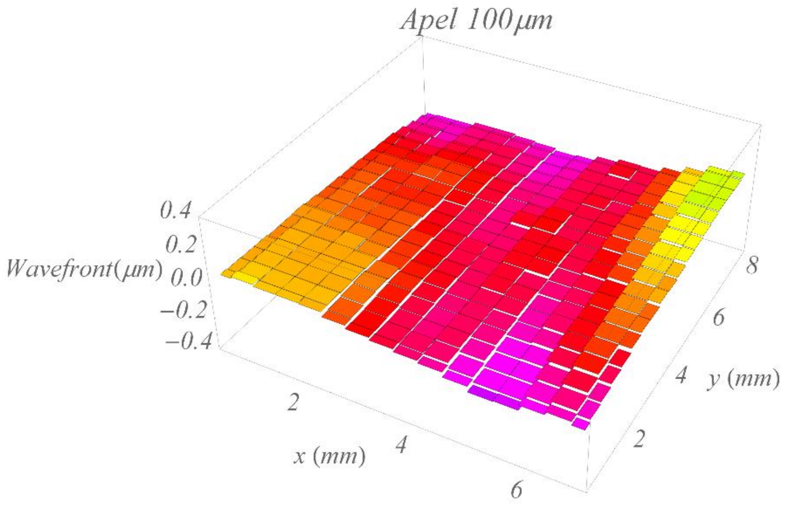
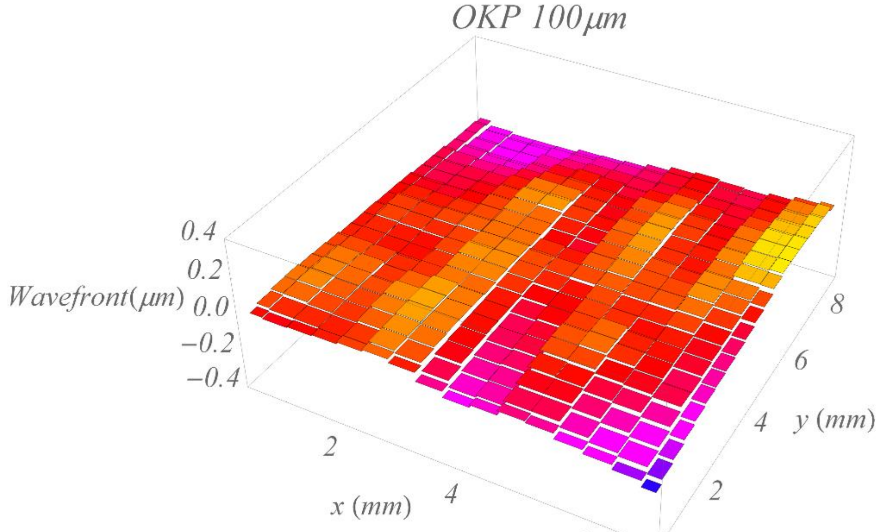
Glass based debris shield samples (100µm, 150µm and 200µm)

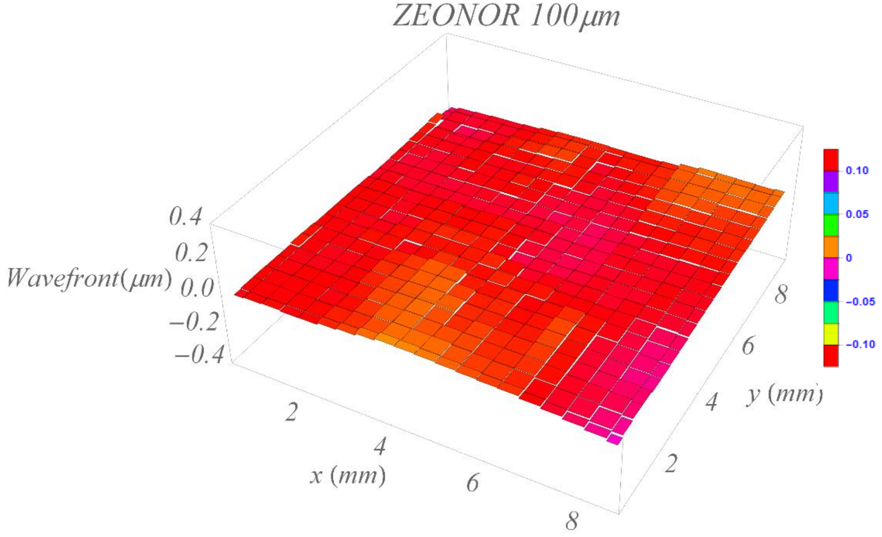


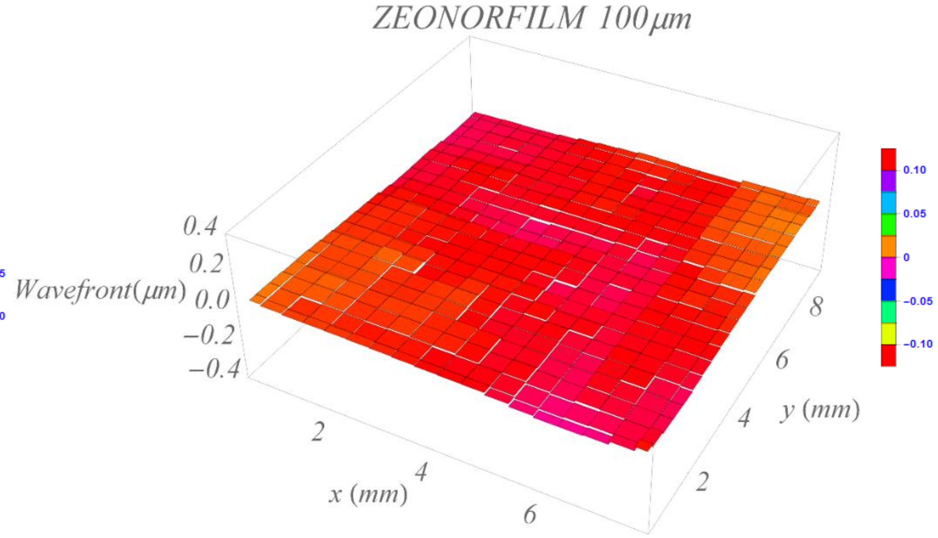
Alternative shield debris samples (100μm)







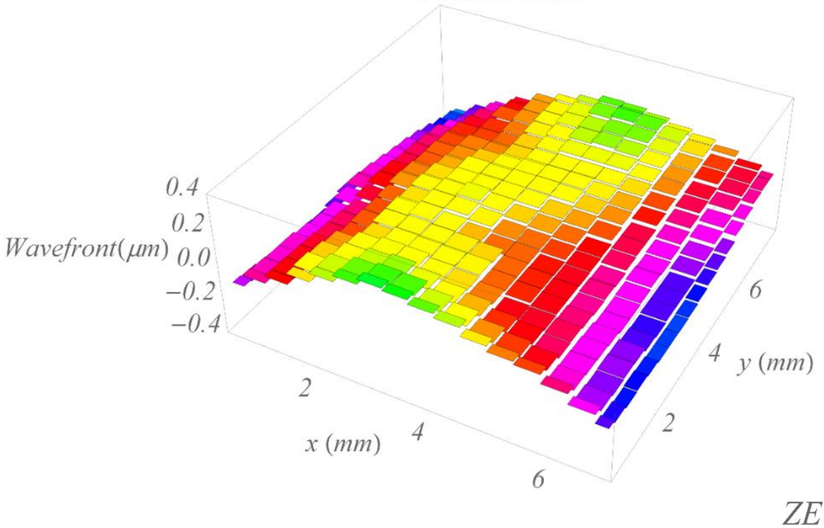




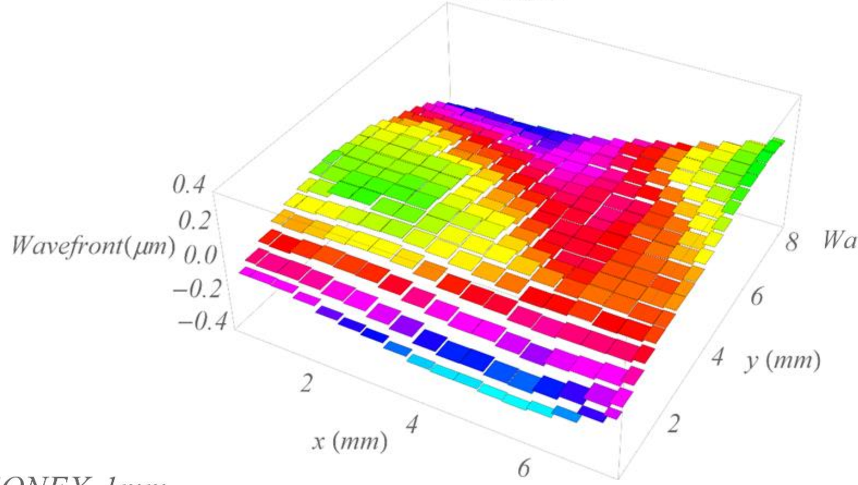
Materials: Courtesy of J. Wheeler and G. Bleotu

Alternative shield debris samples (1 mm)

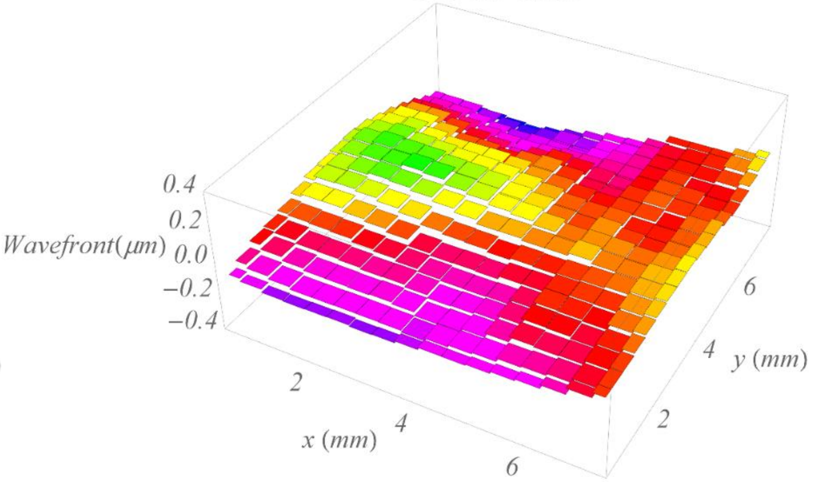
PMMA 1mm



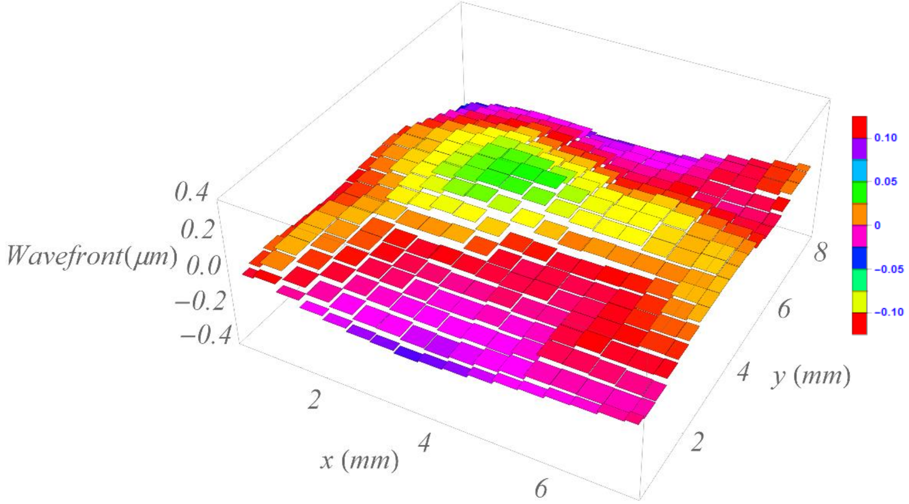
PC 1mm



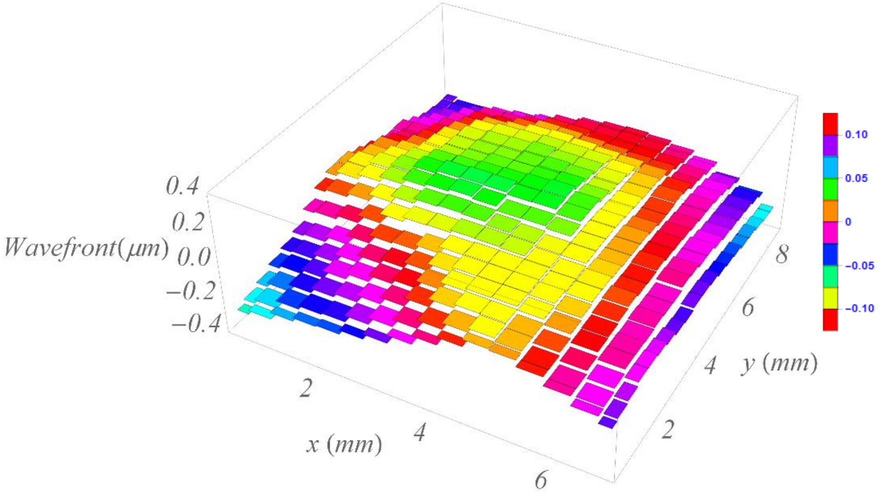
TOPAS 1mm



ZEONEX 1mm



ZEONOR 1mm



Materials: Courtesy of J. Wheeler and G. Bleotu

Shield debris samples (Summary)

Material	RMS (um)	P-to-V (um)
Reference	$0.0454296 \rightarrow \approx \lambda / 13$	$0.22808 \rightarrow \ > \lambda / 3$
Corning Willow 100µm	$0.061 \ \mu m \rightarrow \approx \lambda / 10$	$0.320 \ \mu m \rightarrow \ > \ \lambda / 2$
Cover Glass 150µm	$0\ .070 \ \mu m \rightarrow \approx \lambda / 9$	$0.369 \ \mu m \rightarrow > \lambda / 2$
Corning Willow 200µm	$0.0605 \ \mu m \rightarrow \approx \lambda / 10$	$0.319 \ \mu m \rightarrow > \lambda / 2$
Apel 100µm	$0.0418016 \rightarrow \approx \lambda / 13$	$0.221005 \rightarrow \ > \lambda / 3$
OKP 100µm	$0.0354816 \rightarrow \approx \lambda / 18$	$0.219698 \rightarrow > \lambda / 3$
PC 1 mm	$0.0962373 \rightarrow \approx \lambda / 6$	$0.420039 \rightarrow \ > \lambda / 2$
PMMA 1 mm	$0.0934852 \rightarrow \approx \lambda / 6$	$0.454621 \rightarrow > \lambda / 2$
Zeonex 1mm	$0.0678375 \rightarrow \approx \lambda / 10$	$0.343005 \rightarrow \ > \lambda / 2$
Zeonor 1mm	$0.105165 \rightarrow \approx \lambda / 6$	$0.461723 \rightarrow > \lambda / 2$
Zeonor 100µm	$0.0144826 \rightarrow \approx \lambda / 45$	$0.0950715 \rightarrow \approx \lambda / 6$
ZeonorFilm 100µm	$0.0149006 \rightarrow \approx \lambda / 45$	$0.0769832 \rightarrow \approx \lambda / 8$
TOPAS 1mm	$0.072012 \rightarrow \approx \lambda / 9$	$0.338402 \rightarrow \ > \lambda / 2$

Most suitable for debris shields and ultra-short pulse compression.

Conclusions & Outlooks

- Lasers systems such as HPLS **require** debris shielding.
- WF measurement set-up based on deformable mirror and wavefront sensor has been developed.
- Glass samples: WF in the range of $\frac{\lambda}{10}\ (RMS)\ and\ \frac{\lambda}{3}$ (P-to-V).
- Plastics samples show be better .
- LIDT and n_2 to be tested.

Perspectives:

AO bench implementation within a CPA system (> 10 mJ; < 40 fs @ 10 Hz, 800 nm)

Preliminary results show debris shields glass materials under 200 μm thickness as acceptable to be utilized within the Large Beam Transport System (LBTS) @ ELI-NP.

References

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- J.P. Zou and B. Wattellier in, *Topics in Adaptive Optics*, Dr. Bob Tyson ed. (IntechOpen Limited, London, 2012), “Adaptive Optics for High-Peak-Power Lasers – An Optical Adaptive Closed-Loop Used for High-Energy Short-Pulse Laser Facilities: Laser Wave-Front Correction and Focal-Spot Shaping”.

Acknowledgments

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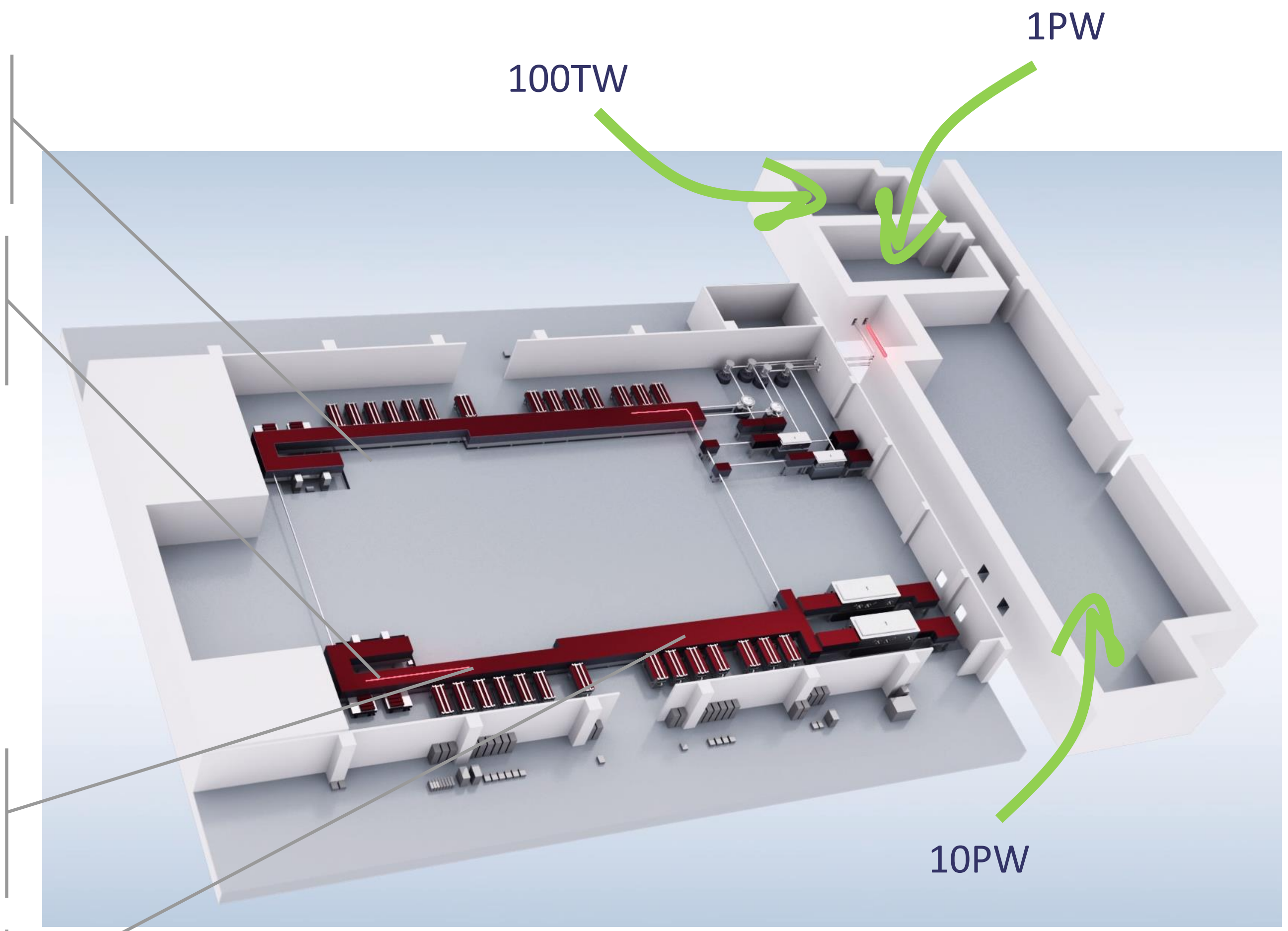
http://www.eli-np.ro/jobs.php

Thanks for your time !

Annexes

Extreme Light Infrastructure – Nuclear Physics



CPA 1 – Ti-Sa regenerativ amplifier
XPW - contrast and spectrum enhancement
OPCPA - contrast enhancement

CPA 2 - energy stability
Ti-Sa multipass amplifiers
100 TW @10Hz

- Both Front ends operational: remotely controlled
- All 48 pump lasers, in final position, operational, tested;
  - 2x AMP1, 4J@10Hz operational;
  - 2xAMP2, 39J@1Hz operational;
  - 2xAmp 3.1, 80J+1xAmp3.2, 209 J @1 shot/minute
- 6x Compressors aligned, inclusive the output diagnostics benches

CPA 2 -energy stability
Ti-Sa multipass amplifiers
1PW @1Hz

CPA 2 -energy stability
Ti-Sa multipass amplifiers
10 PW @ 1 shot/min

High Power Laser System (HPLS) architecture. Based on hybrid double Chirped Pulse Amplification (CPA) configuration

2019, February 5th

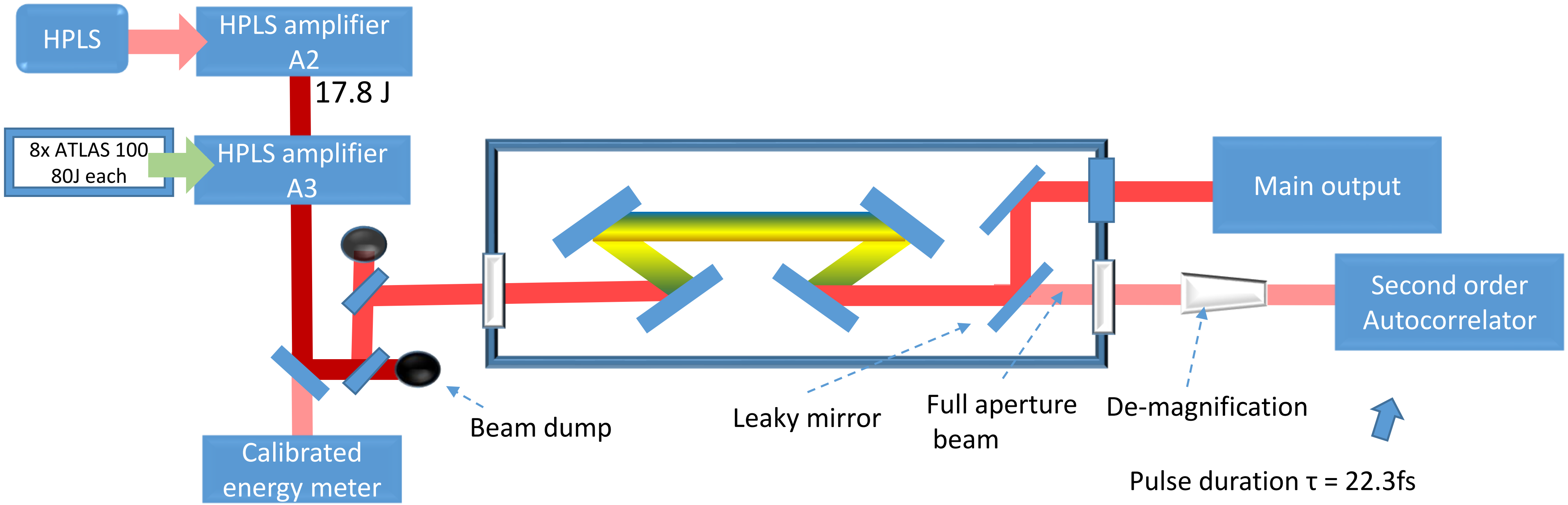
Both Front ends operational: remotely controlled

All 48 pump lasers, in final position, operational, tested;

2x AMP1, 4J@10Hz operational; 2xAMP2, 39J@1Hz operational; 2xAmp 3.1, 80J+1xAmp3.2, 209 J @1 shot/minute

6x Compressors aligned, inclusive the output diagnostics benches

Extreme Light Infrastructure – Nuclear Physics


HPLS

HPLS amplifier A2

17.8 J

8x ATLAS 100
80J each

HPLS amplifier A3

Main output

Second order Autocorrelator

Calibrated energy meter

Beam dump

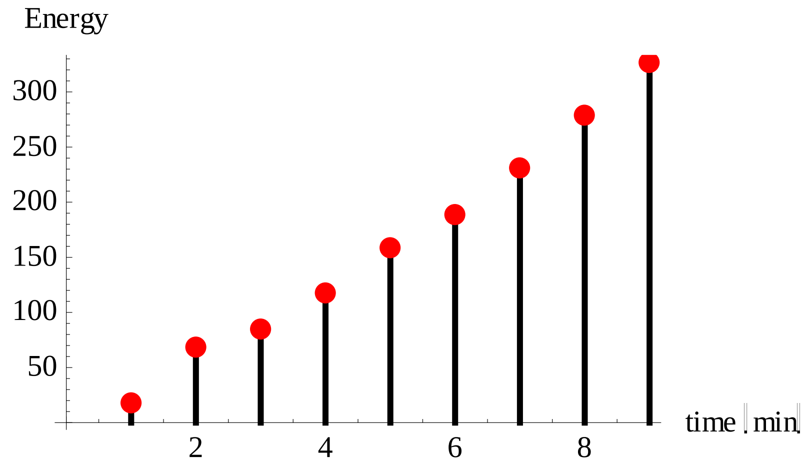
Leaky mirror

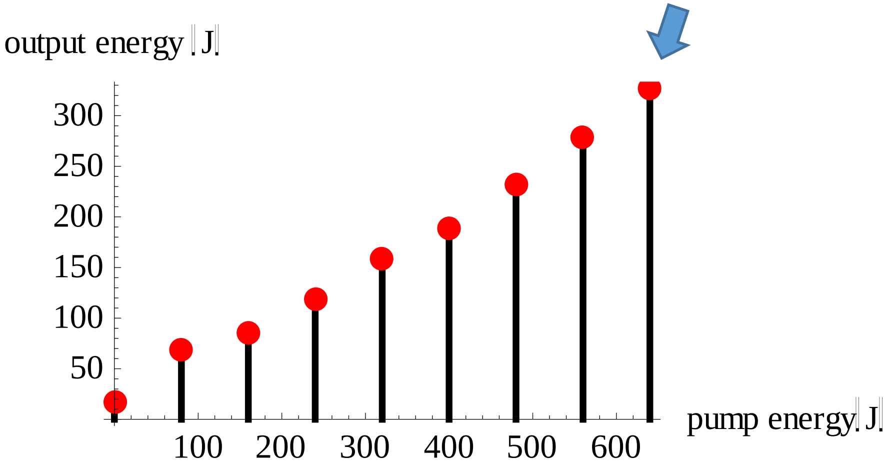
Full aperture beam

De-magnification

Pulse duration τ = 22.3fs
Compressor efficiency η = 0.742
Energy before compressor E = 327J

$P = \eta E/\tau$ = 10.8 PW





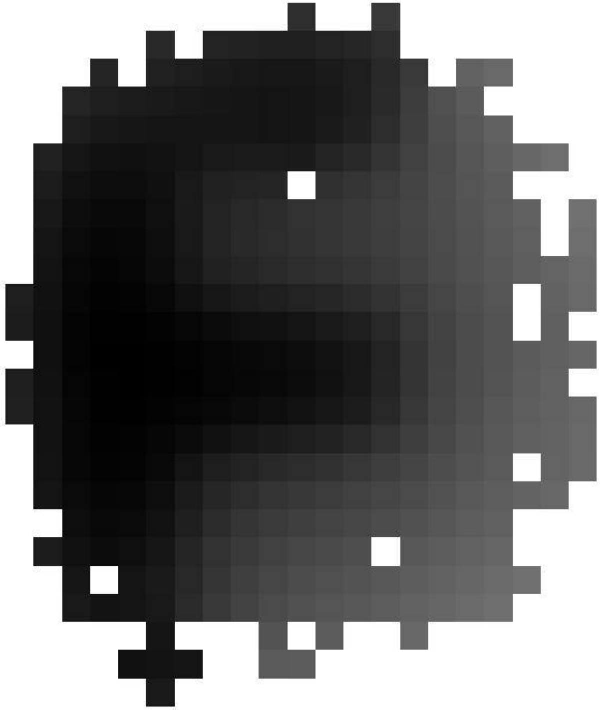
High Power Laser System expectations at 10PW

	min	max	unit
Energy/pulse	150	225	J
Central wavelength	814	825	nm
Spectral bandwidth (FWHM)	55	65	nm
Spectral bandwidth (at nearly zero level of intensity)	120	130	nm
Pulse duration (FWHM)	15	22.5	fs
FWHM beam diameter/Full aperture beam diameter	450/550		mm
Repetition rate	1		pulse /min
Strehl ratio	0.8	0.95	
Pointing stability	2	5	µrad
Beam height to the floor	1500	1510	mm

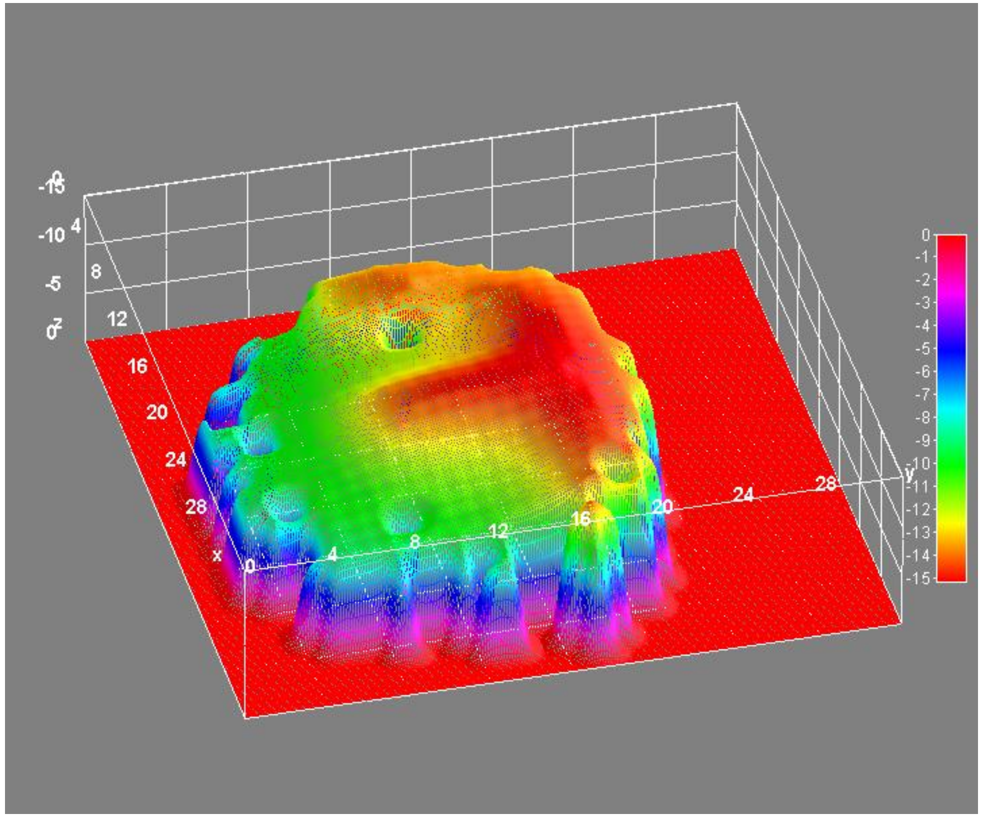
High Power Laser System preliminary tests on ELI-NP site

ARM #1	100TW	1PW	unit	comments
Energy/pulse	2.31	24.2	J	70.5% compressors transmission
Central wavelength	805	807	nm	(~80nm bandwidth FWHM)
Ns contrast	10^-9	10^-9		Regen to be tuned.
Ps contrast	10^-11	10^-11		Device limited. 1PW to be optimised
Pulse duration (FWHM)	23.1	23.6	fs	Full aperture, full amplification, 1%
FWHM beam diameter	55	180	mm	
Repetition rate	10	1	Hz	
Strehl ratio	0.84	0.86		
Pointing stability	3.3	1.9	µrad	
Energy stability	2.6%	4%		Rms, for 300 shots. Down to 1% for 100 consecutive 1PW shots

Shack-Hartmann calibration



@ μm scale



@ μm scale