Wavefront preserving optics development for high power FELs

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Physics & Applications
of High Efficiency
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California NanoSystem Institute*

U.S. DEPARTMENT OF ENERGY
Office of Science

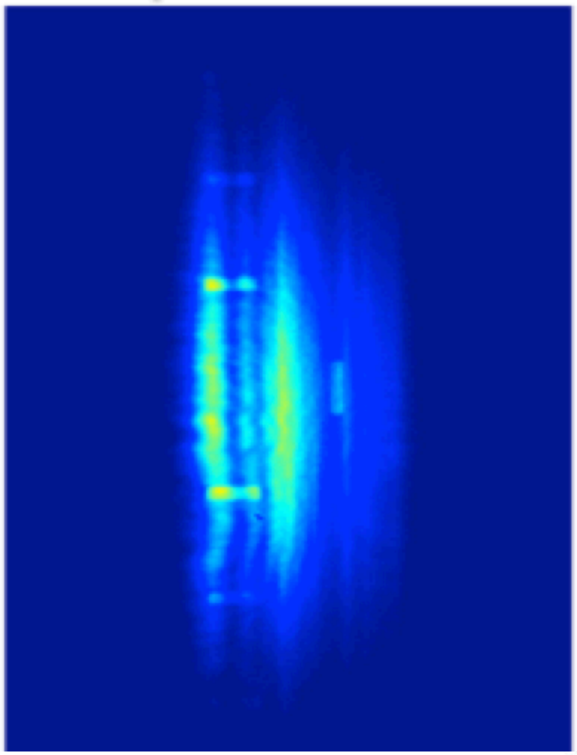
Stanford University

Wavefront preserving optics development for high power FELs

subtitle: how to go from

this **to this**

…and preserve it with an high power source

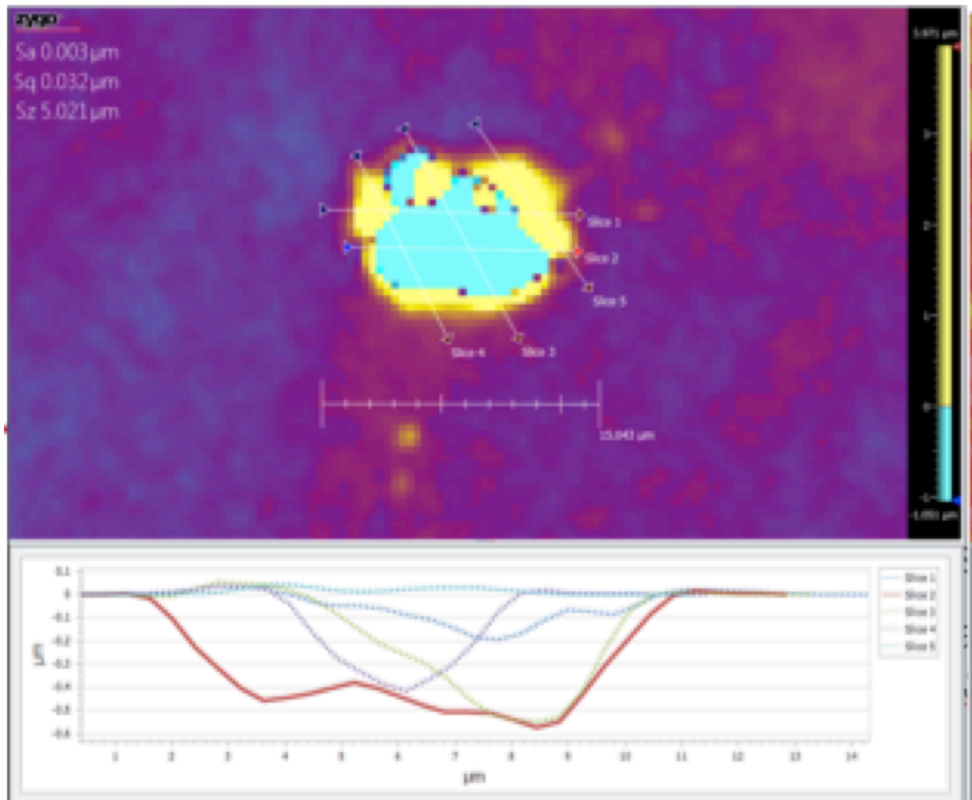


Out of focus LCLS photon beam profile in late 2016

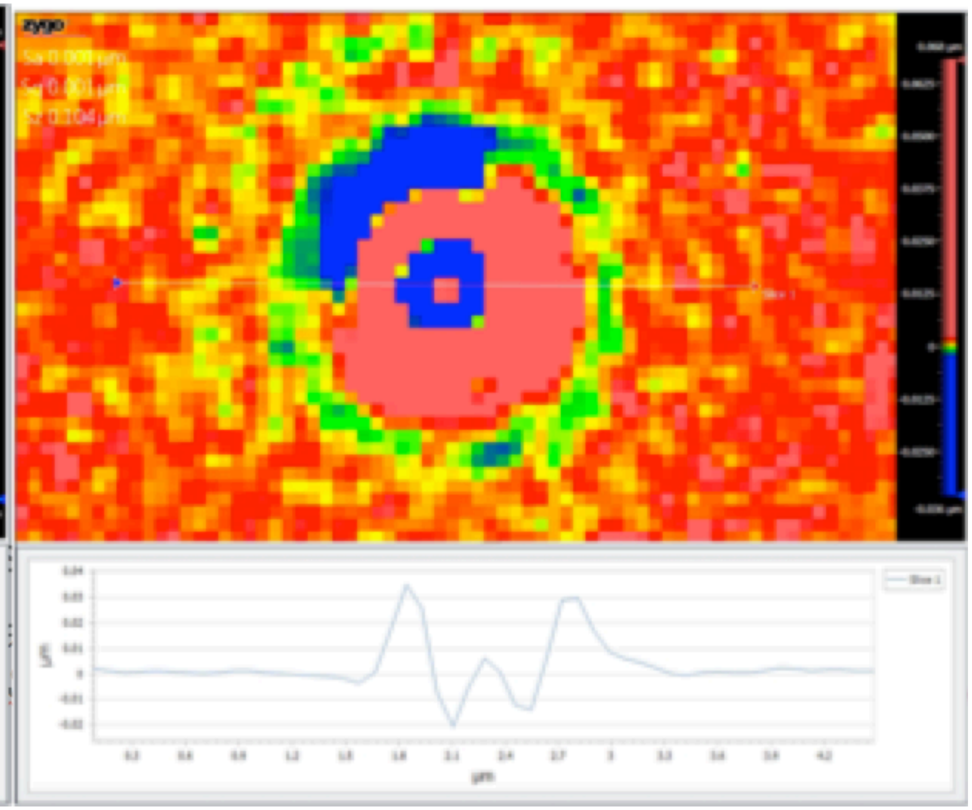
Out of focus LCLS photon beam June 2017
(images taken in the very first days of operation with the machine not perfectly tuned)

Wavefront preserving optics development for high power FELs

subtitle: and create a very small spot without destroying the mirrors

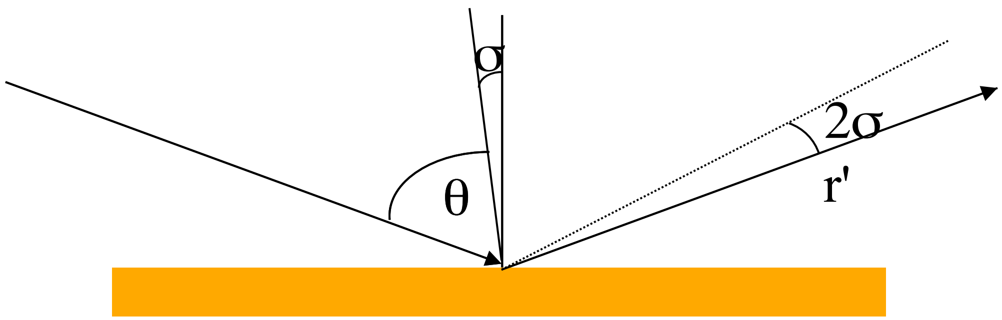


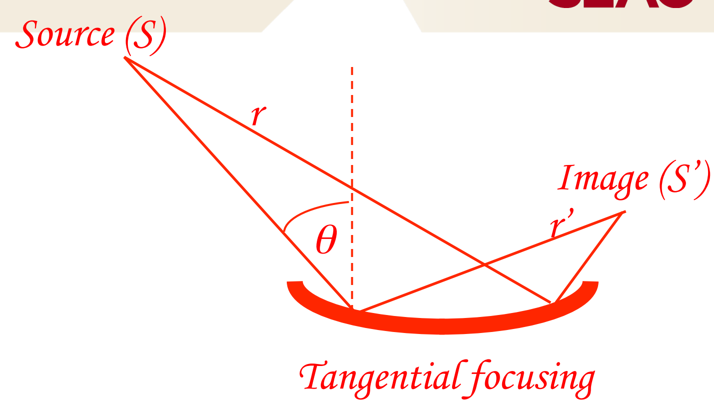
Best spot before cleaning (and wavefront sensor alignment) ≈ 3 µm



Measured spot after cleaning (and wavefront sensor alignment) ≈ 1 µm

Grazing incidence optics defect - SLOPE ERRORS





Spot enlargement $\Delta s' = 2\, r'\sigma$

M (magnification) = r'/r

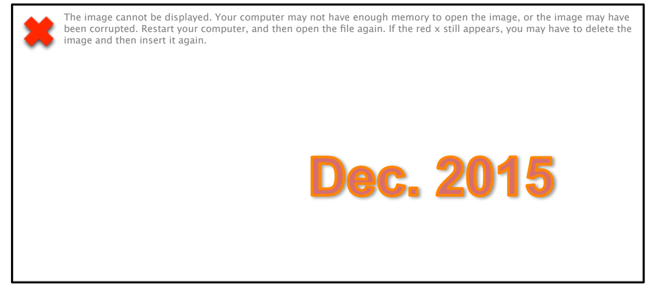
Need a 1 μm spot
➔ r' ≈ 1 m
Needed σ ≈ 0.5 μrad

$\Delta s'\ (0.1\ \mu m) = 2\ r'\ (1\ m)\ \sigma\ (\underline{0.05\ \mu rad})$

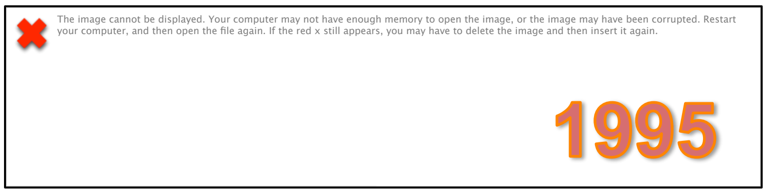
Understand what you really need

Optical designer in SR are use to specify mirrors in slope. This modus operandi has been transferred to the FELs

Only recently, it has been demonstrated that SHAPE is important, not slope



It was, actually, embedded into a 20 years old precursor article (it was just too advanced, at that time, for the SR needs)

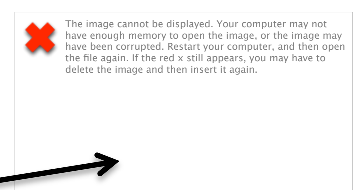


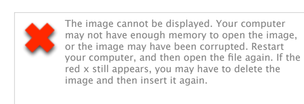
In a **diffraction-limited optic**, with W > L (classical FEL cases), only shape errors are important and slope errors, in principle, does not play any role in spot enlargement or beam inhomogeneity

System coherence length (W)

$$W = \frac{\sqrt{2}\lambda}{\Theta \sin \vartheta}$$

Angular radius ($1/e^2$) → Θ



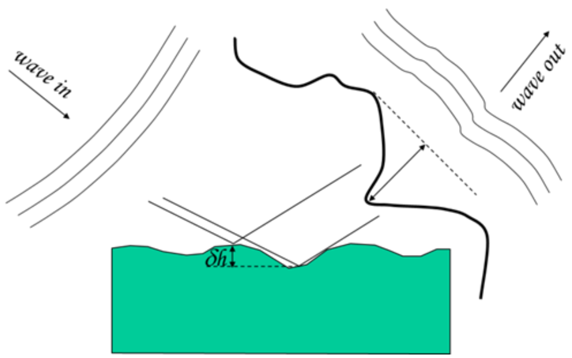


Illuminated part of the mirror →

Shape errors effect

$$\text{Strehl Ratio} \approx e^{-(2\pi\varphi)^2} \approx 1-(2\pi\varphi)^2$$

The Strehl Ratio (SR) is defined as a ratio of the maximum intensity in the focus, with and without wave front distortions which are introduced by the optics

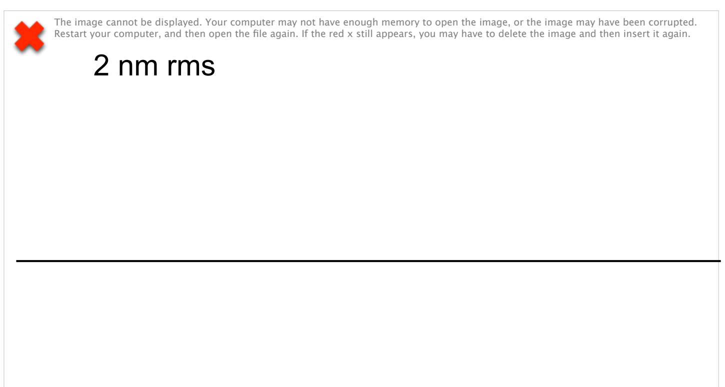


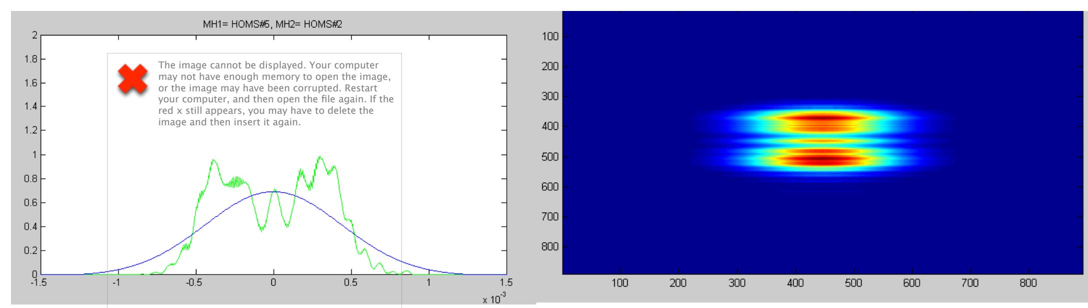
$$\varphi = \frac{2\delta h \sin\vartheta}{\lambda}$$

φ is the wave distortion (phase)

$$\delta h = \lambda \frac{\sqrt{1 - Strehl \quad Ratio}}{4\pi \sin\vartheta}$$

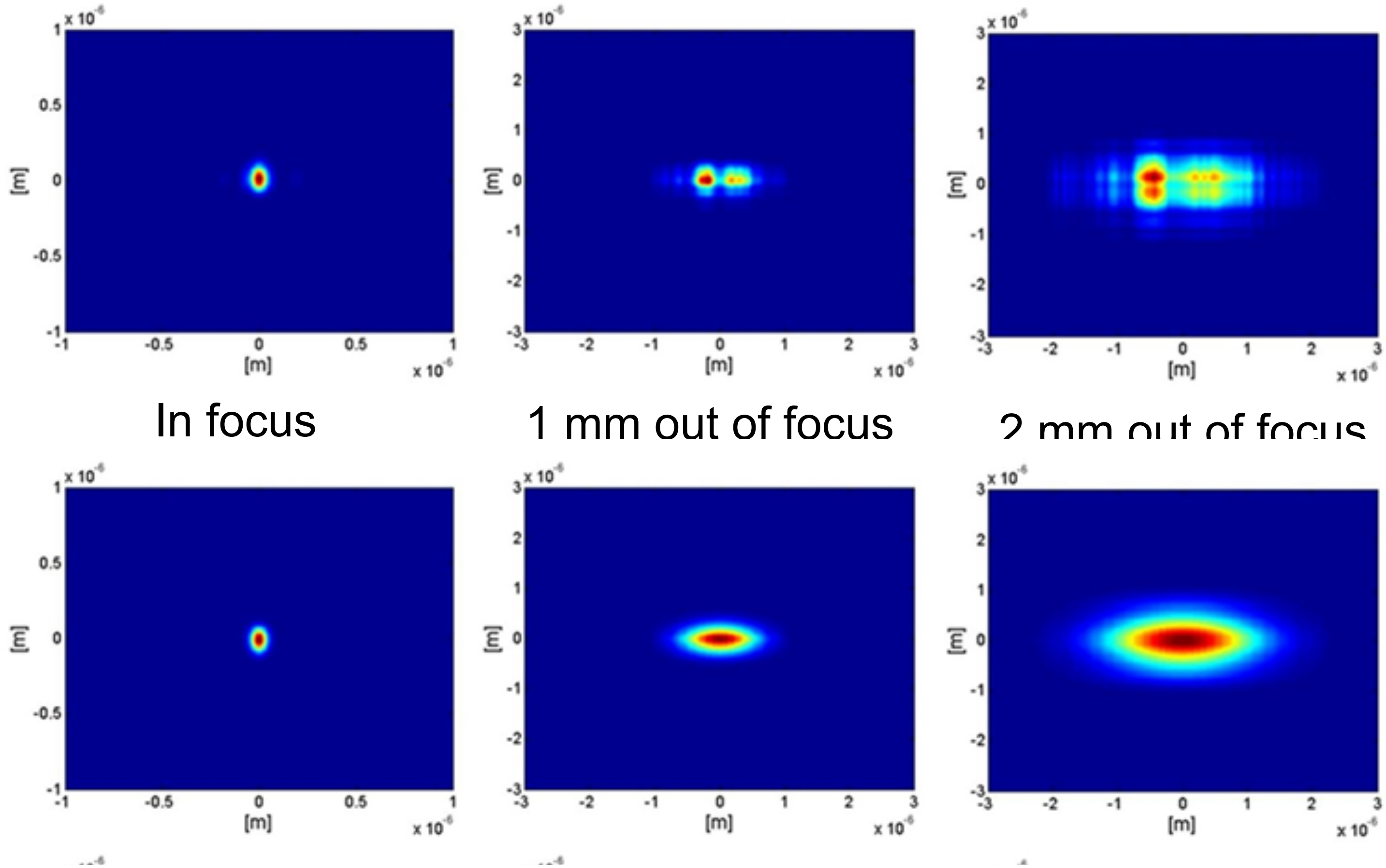
SR ≥ 0.8 (according to the Marechal Criterion) is necessary to have "good" optical system





Shape errors effect

The Marechal Criterion states that a good optical system has a SR ≥ 0.8; e.g.
In focus: the *Gaussian* spot intensity is ≥ 0.8 of the unperturbed *Gaussian* spot intensity



SR≈0.8⁺

SR≈0.97*

⁺Simulations of 3 mirrors in one direction and 1 in the other for a global SR of 0.8
* Simulation made with state of the art CXI mirrors

Shape errors effect

$$\text{Strehl Ratio} \approx e^{-(2\pi\varphi)^2} \approx 1-(2\pi\varphi)^2$$

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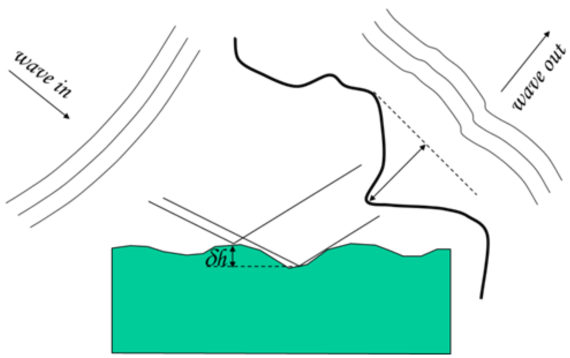

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SR ≥ 0.8 (according to the Marechal Criterion) is necessary to have "good" optical system

Examples for a SR=0.97:
(current LCLS configuration)

HXR; 1.35 mrad, 13 keV → **0.56 nm rms**

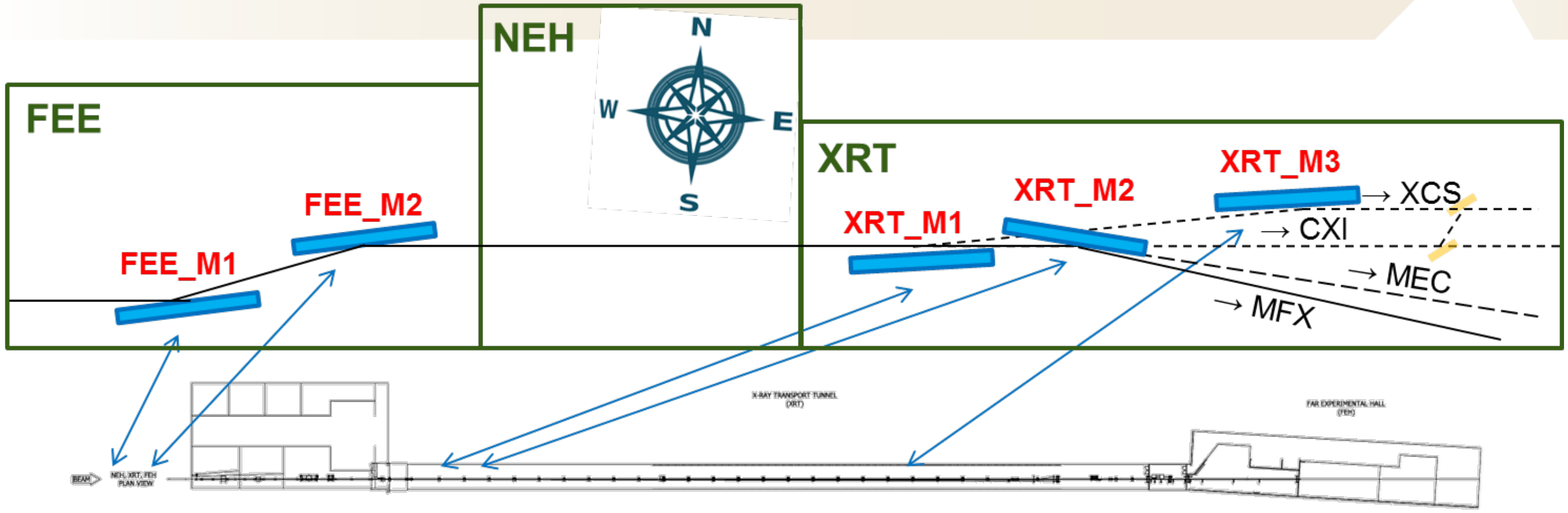
SXR; 12.0 mrad, 1.3 keV → **0.63 nm rms**

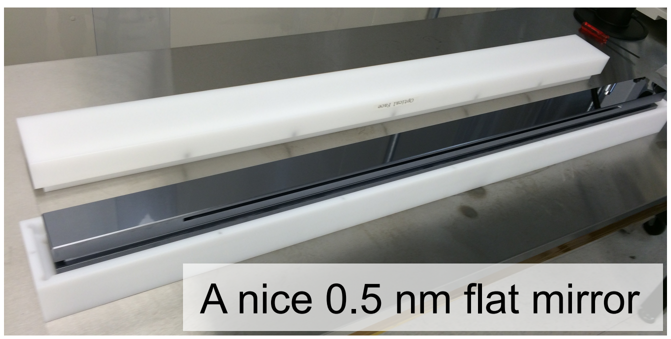
(after 3 mirrors)

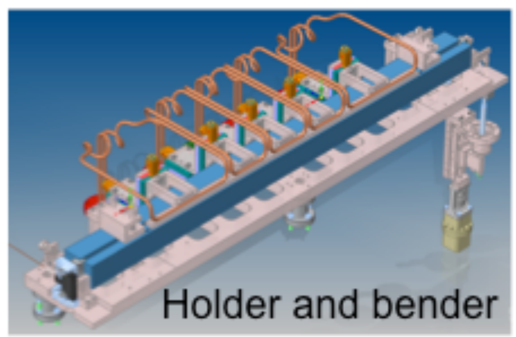
***30 times** better than a very good X-ray mirror*

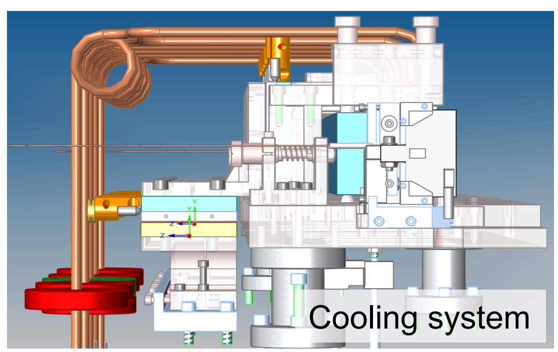
NOTE: with the mirror installed and under the beam!

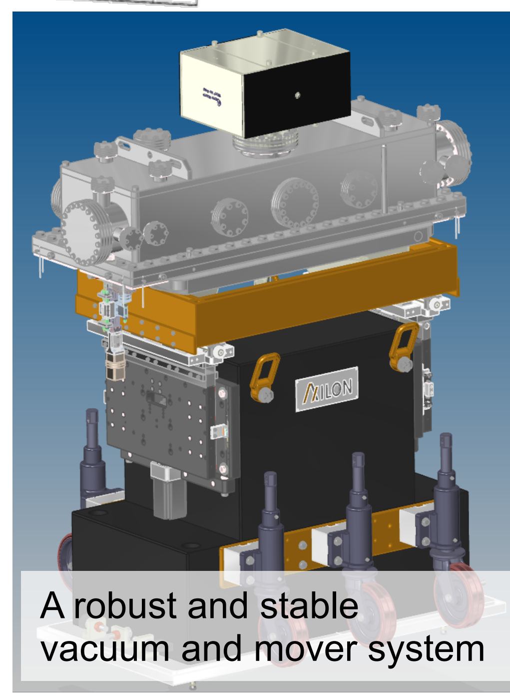
HOMS (HXR mirror system) upgrade




A nice 0.5 nm flat mirror

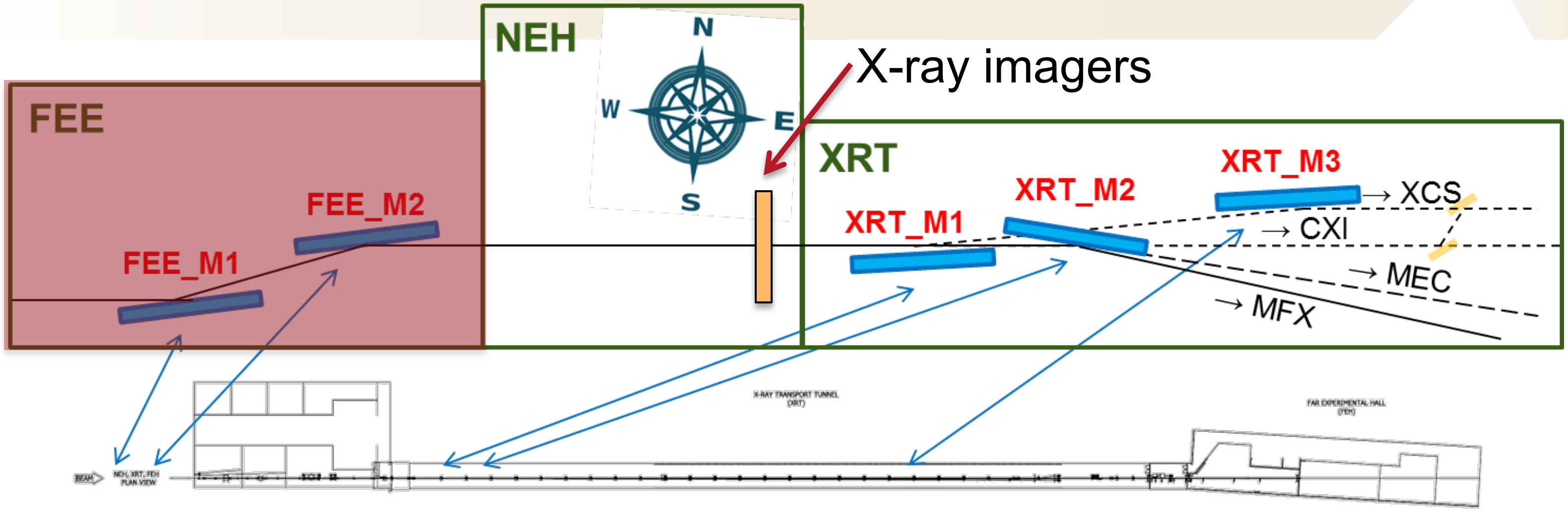

Holder and bender

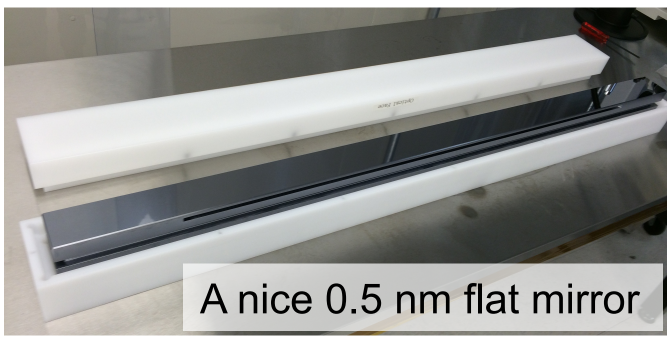

Cooling system


A robust and stable vacuum and mover system

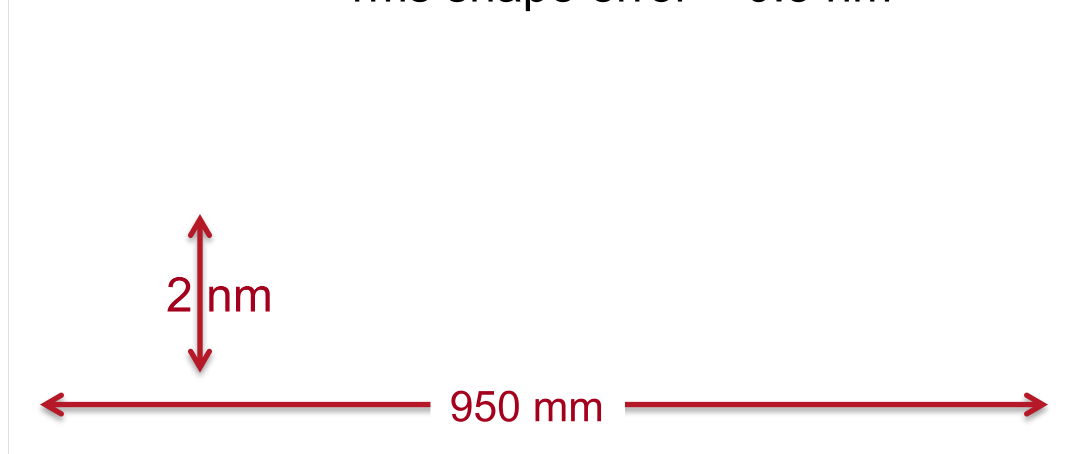
..to what we need to have (< 0.5 nm rms, 2 FWHM acceptance)
with up to 200 W on the mirror

Does it work?





Mirrors profile
rms shape error < 0.5 nm



ϑ=1.35 mrad
λ=0.13 nm (9500 eV)
SR expected (after 2 mirrors) > 0.98

Measured spot (out of focus 9.5 keV)

SLAC

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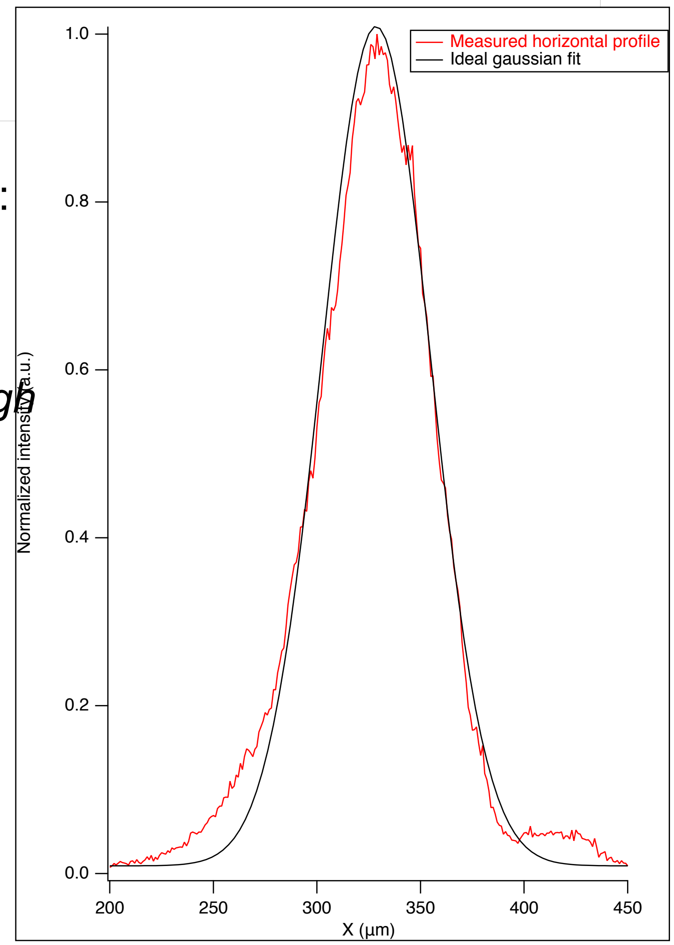
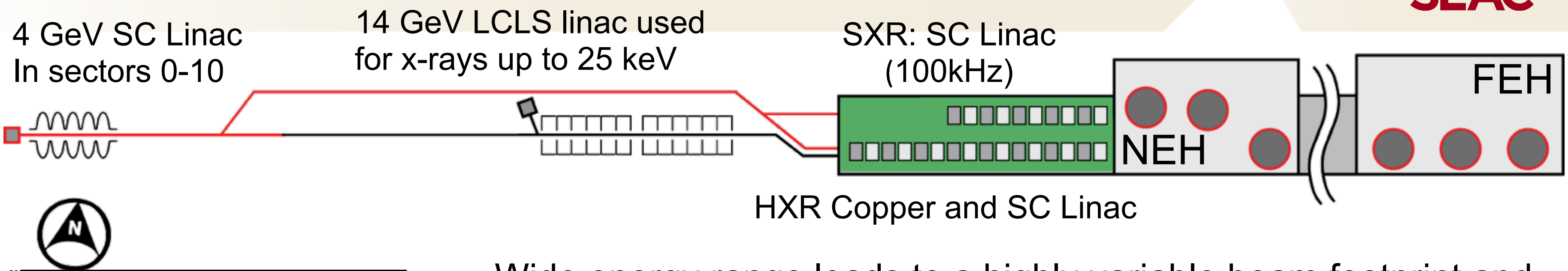
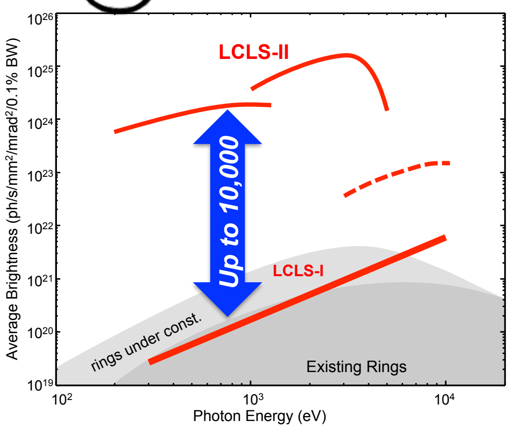
Potential source of errors:
Source inhomogeneity?
Maybe (not measured)
Mirror clamping?
Maybe (unlikely at this high frequency)
Mirror deterioration?
Coating inhomogeneity?



SR expected (after 2 mirrors) > 0.98
SR measured ≈ 0.965
1 nm rms shape errors needed to have a SR of 0.965

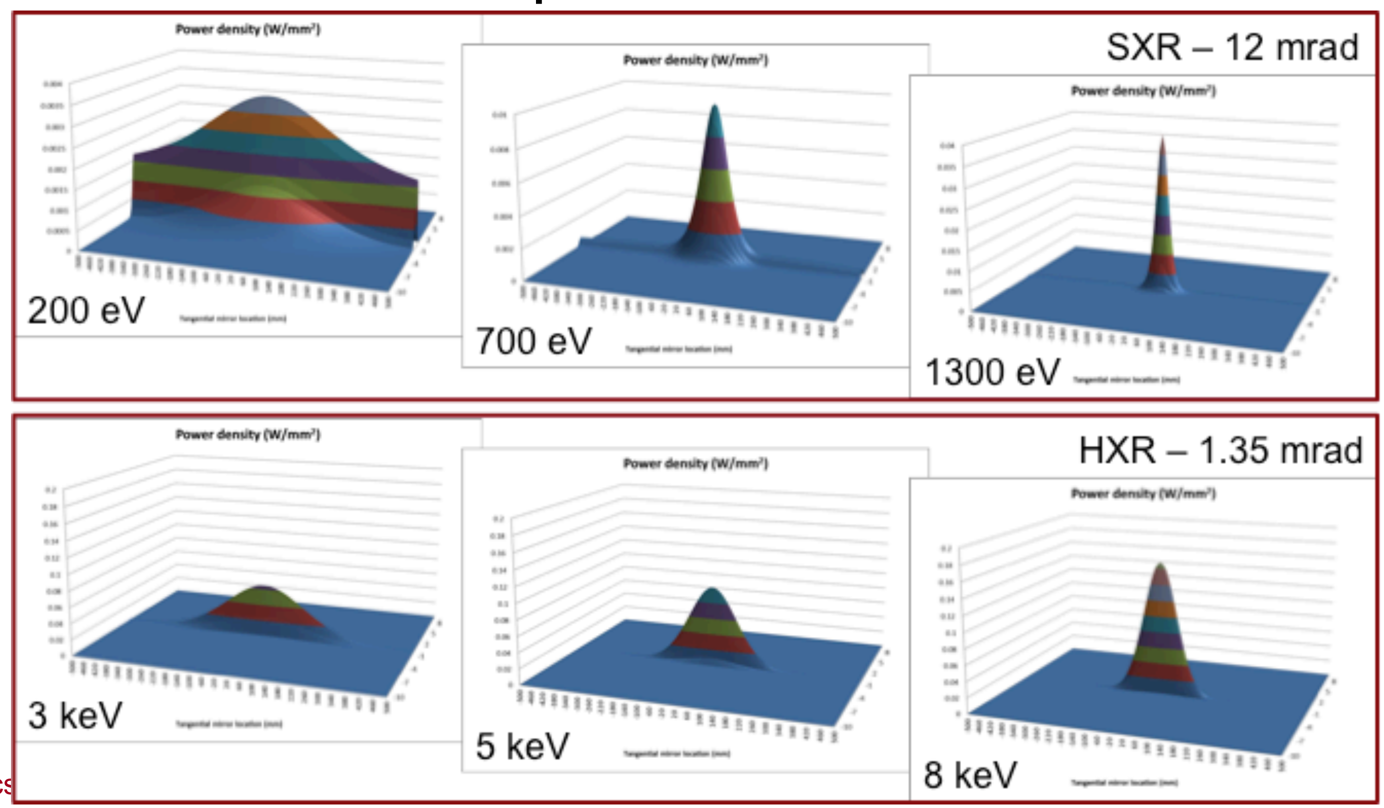
LCLS - II



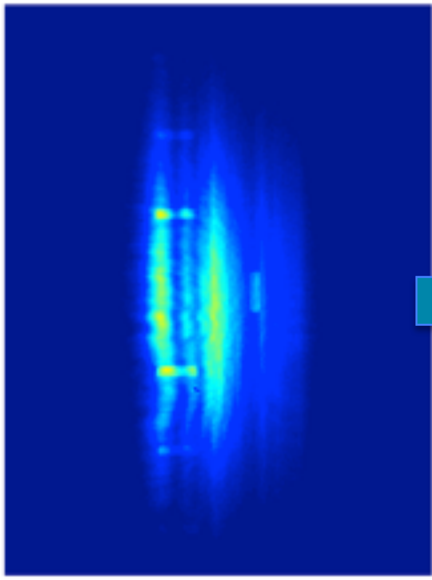


From the current 2-300 mW to up to 600 W on the optics

Wide energy range leads to a highly variable beam footprint and **power absorbed**



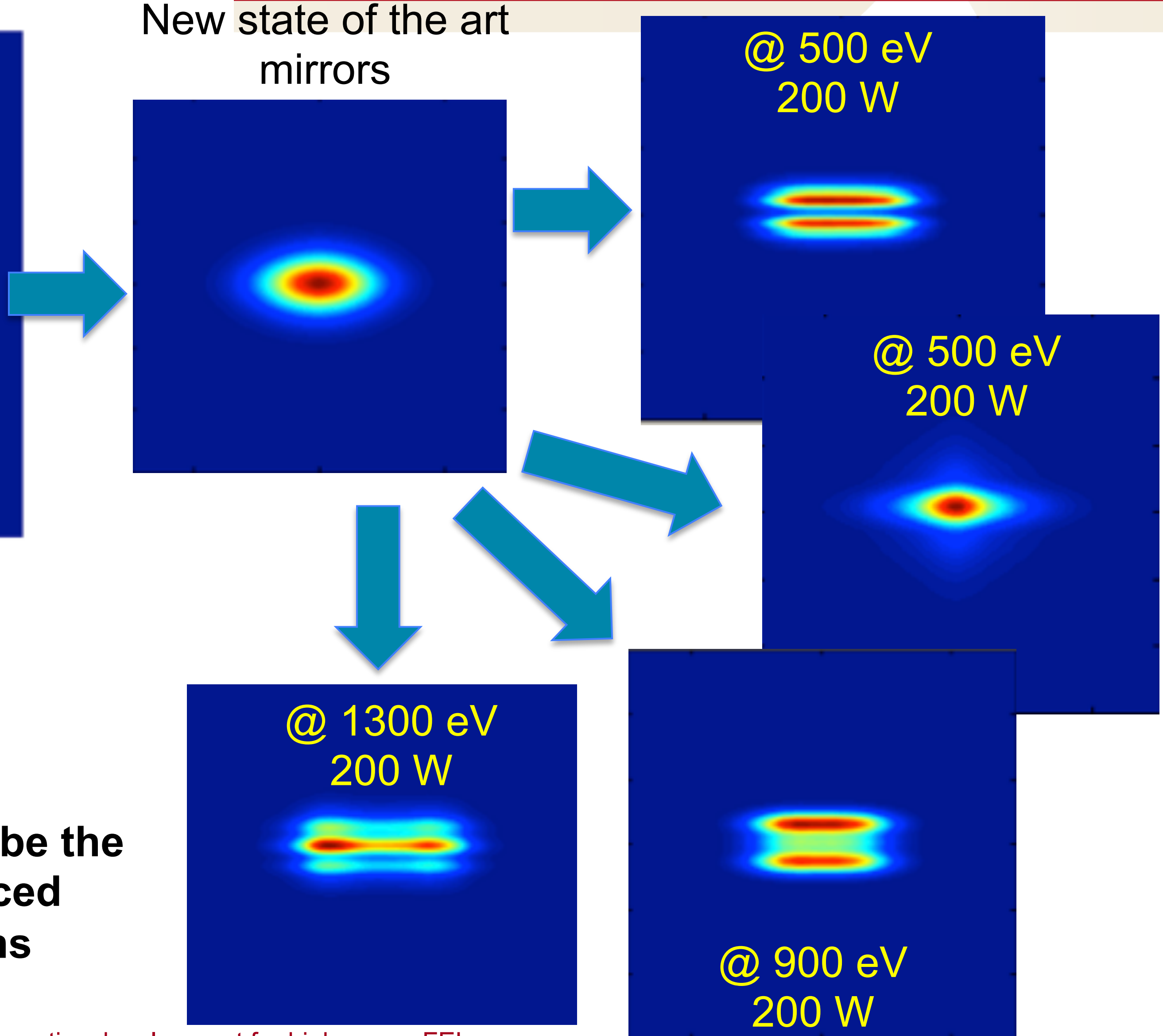
Out of focus beam profile



Old Mirror limit
shape errors

Next limit could be the thermal induced deformations

New state of the art mirrors



Wavefront preserving mirrors – DOE/BES ADR project

SLAC

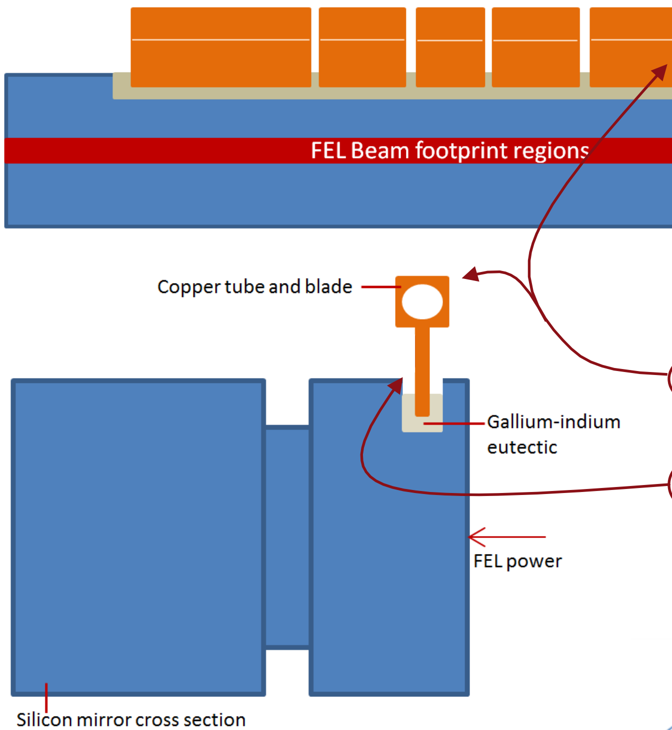
WAVEFRONT PRESERVING MIRRORS – ABSTRACT

Daniele Cocco, SLAC National Accelerator Laboratory (Principal Investigator)
Lahsen Assoufid, Argonne National Laboratory (Co-Investigator)
Kenneth Goldberg, Lawrence Berkeley National Laboratory (Co-Investigator)
Mourad Idir, Brookhaven National Laboratory (Co-Investigator)

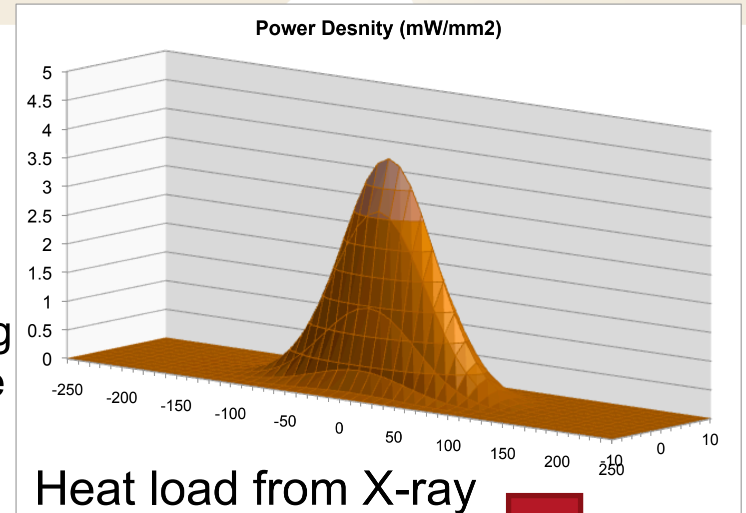
Abstract
This proposal brings together teams from the four major, large scale facilities operated under the auspices of the Department of Energy, Basic Energy Science; …................. The development of a novel room-temperature mirror cooling system with in-situ, at-wavelength testing, and the study of non-invasive wavefront sensing are aimed at preserving the wavefront and the beam quality of Free Electron Lasers (FELs) and Diffraction Limited Storage Rings (DLSR).

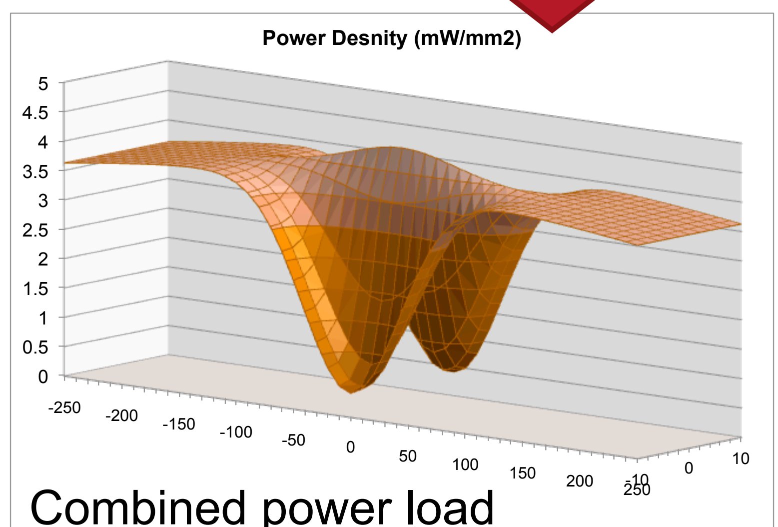
- 2 years project:
- Deliverables:
  - ***SLAC:*** Development and demonstration of the novel cooling scheme
  - ***BNL:*** Implementation of an "invasive" wavefront sensor to test REAL sustaining 50-100 W
  - ***LBNL:*** Study of "non invasive" beam diagnostics (WS) for SXR
  - ***ANL:*** Study of "non invasive" beam diagnostics (WS) for HXR

REAL (Resistive Element Adjustable Length) Cooled Optics

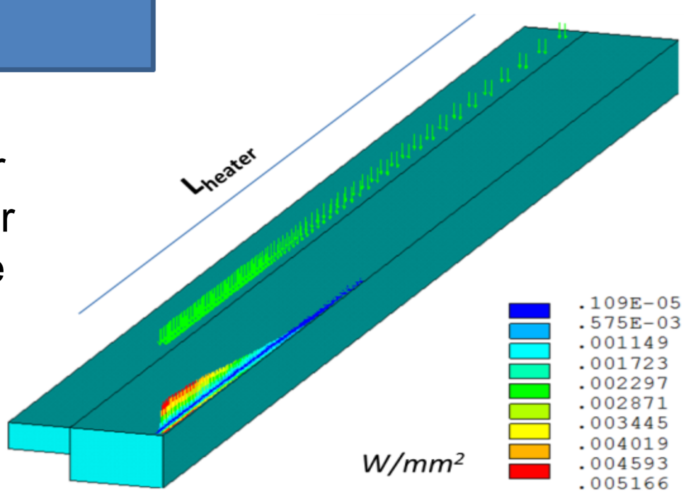


1) Add to the existing fins, used to cool the mirror, some resistive heaters



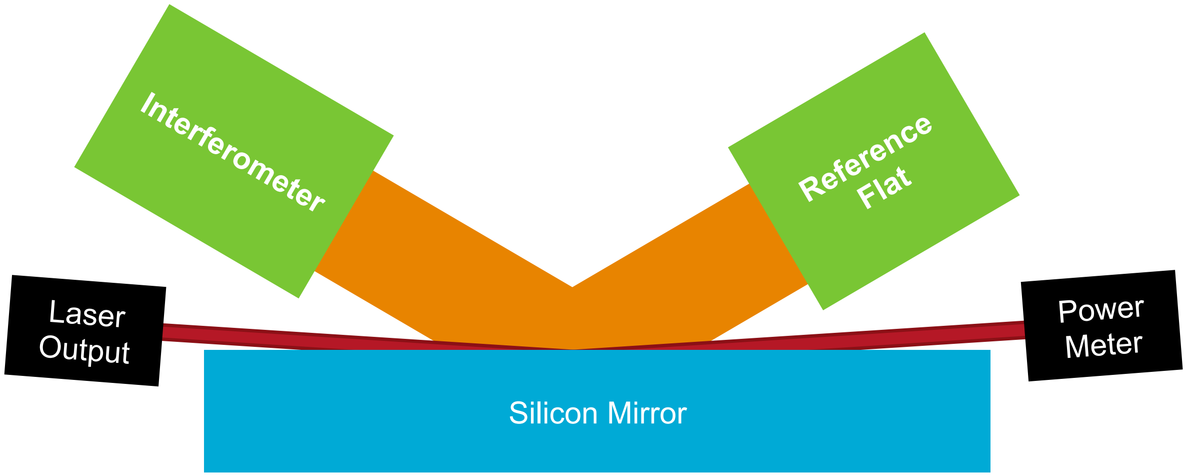


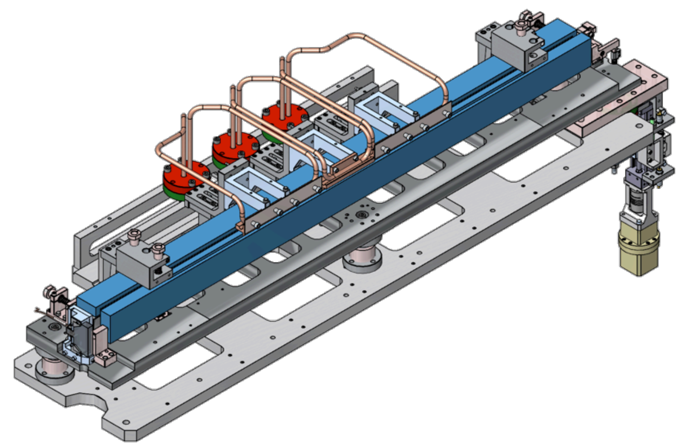
2) Apply the proper power to the proper heaters to equalize deformation on the mirror

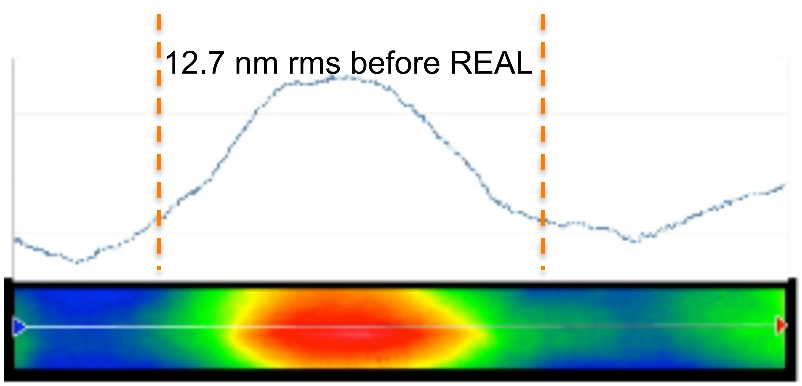


REAL test

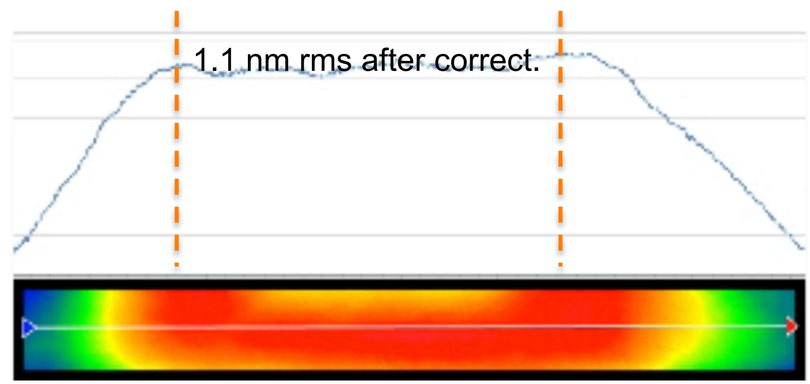
Metrology measurements - 2D map and central line profile (≈ 12 W absorbed)





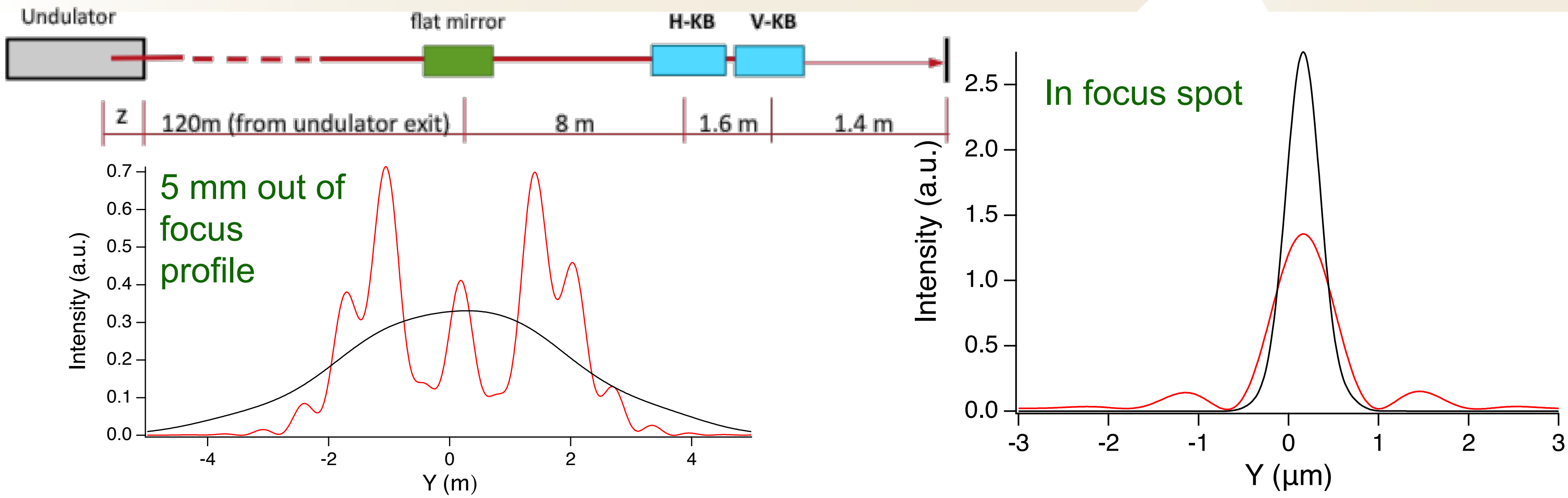


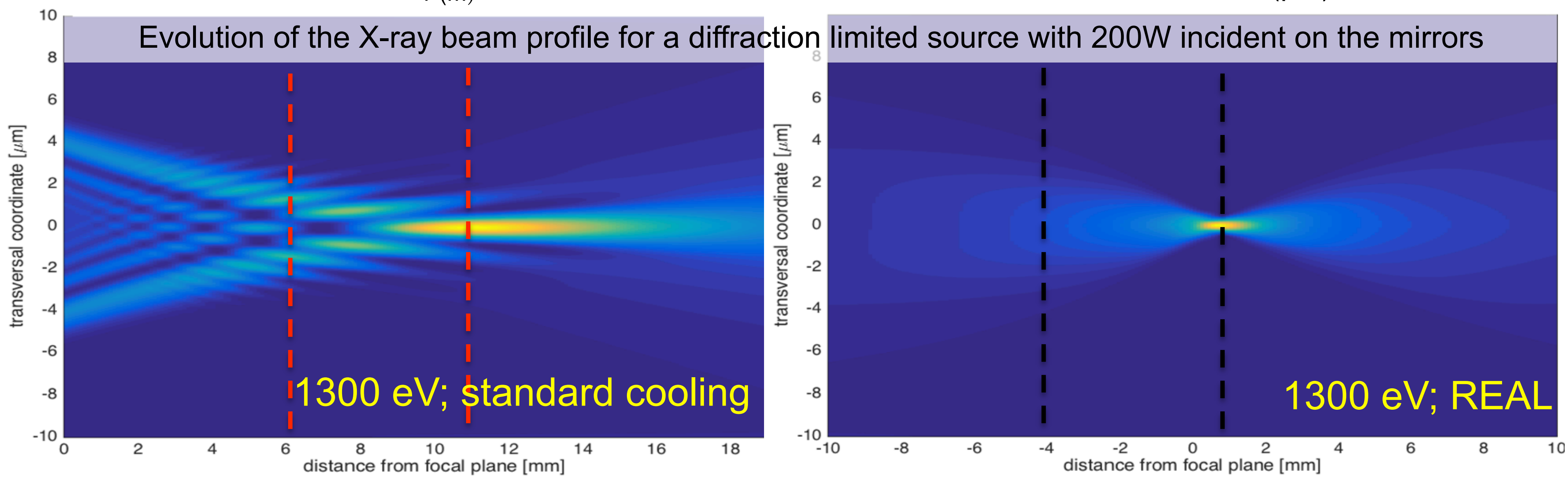
Heat Load induced by an IR laser (15W)



Combined effect (REAL + heat Load)

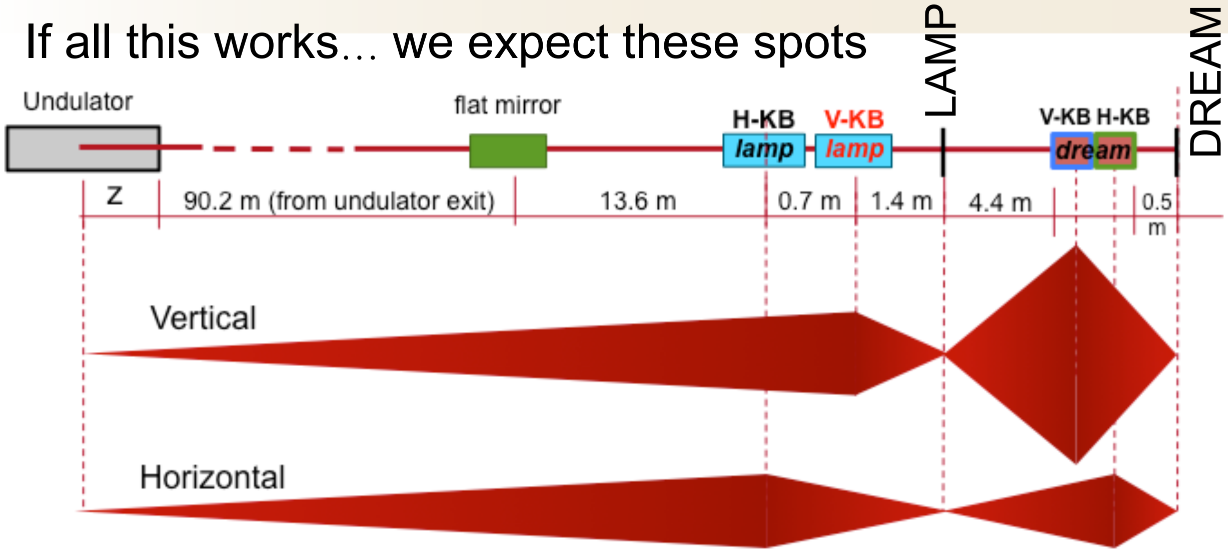
Expected performance improvement - a REAL example



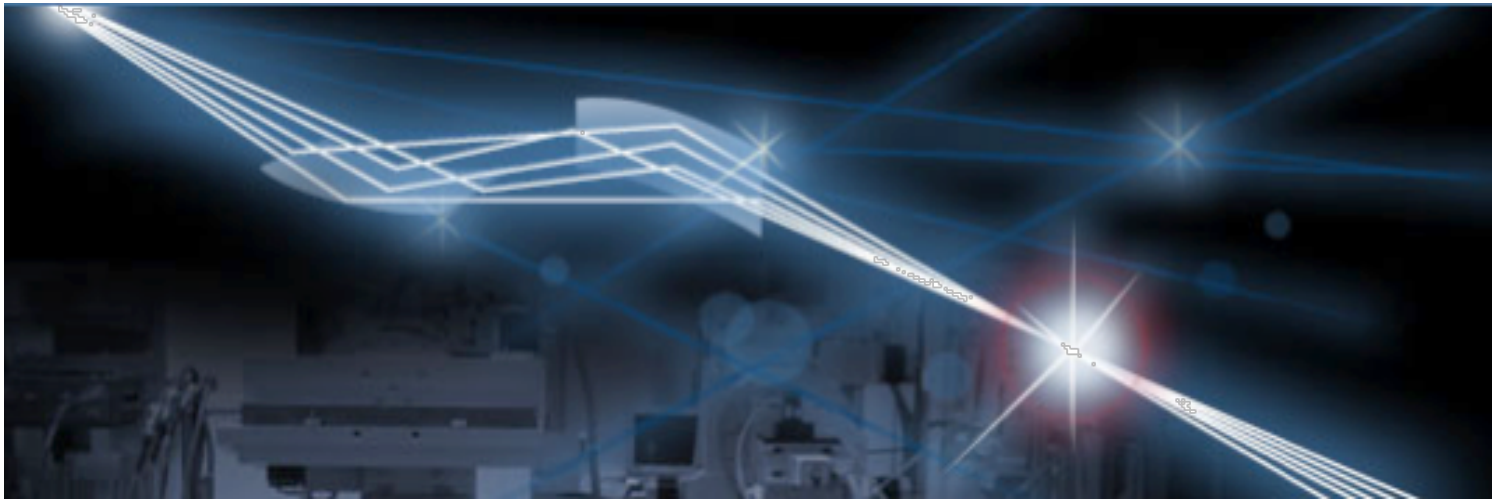


DREAM and LAMP

If all this works… we expect these spots

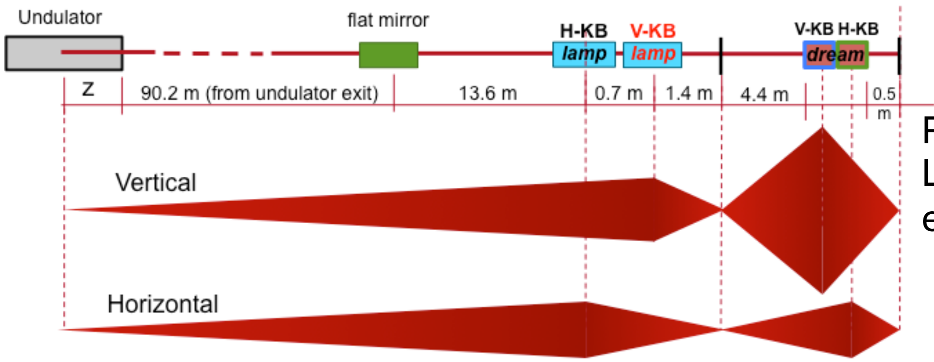


Possibility to run 2 experiments in series
LAMP mirrors – bendable to optimize the focal spot in both experimental chambers



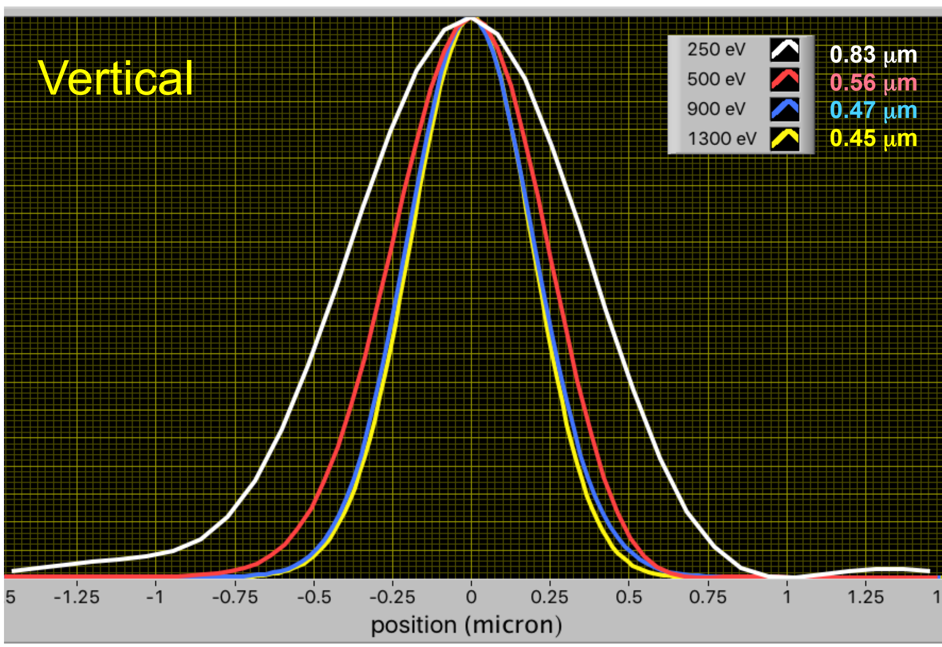
DREAM and LAMP (expected performance)

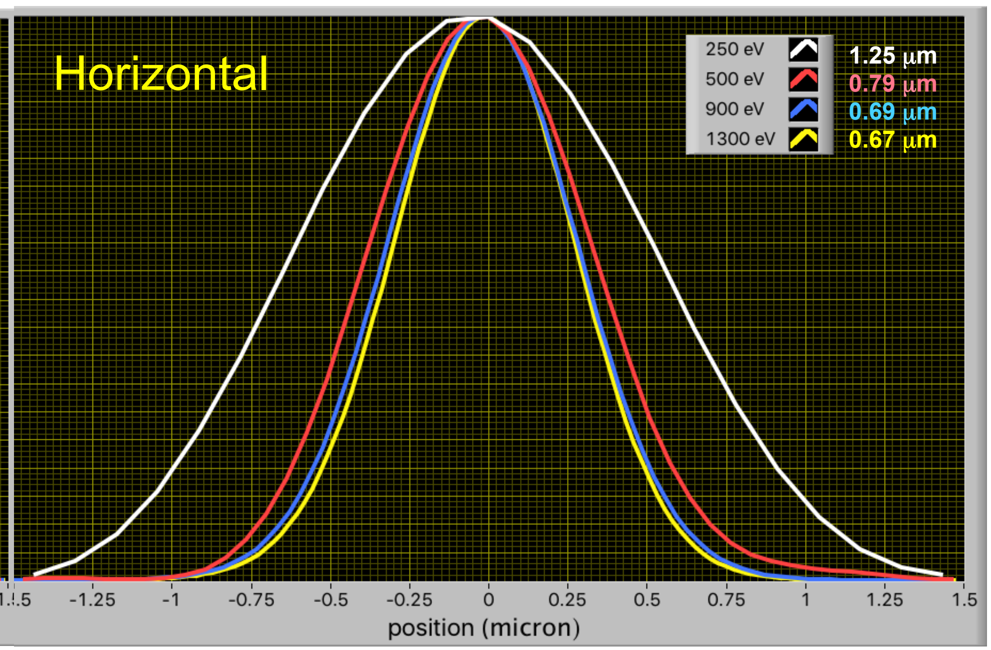
If all this works… we expect these spots



Possibility to run 2 experiments in series
LAMP mirrors – bendable to optimize the focal spot in both experimental chambers

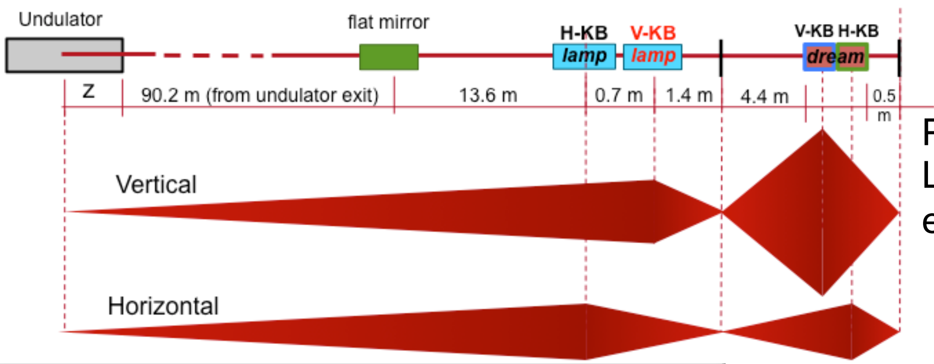
6×10^{19} W/cm^2 @ 900 eV with 2 mJ pulse





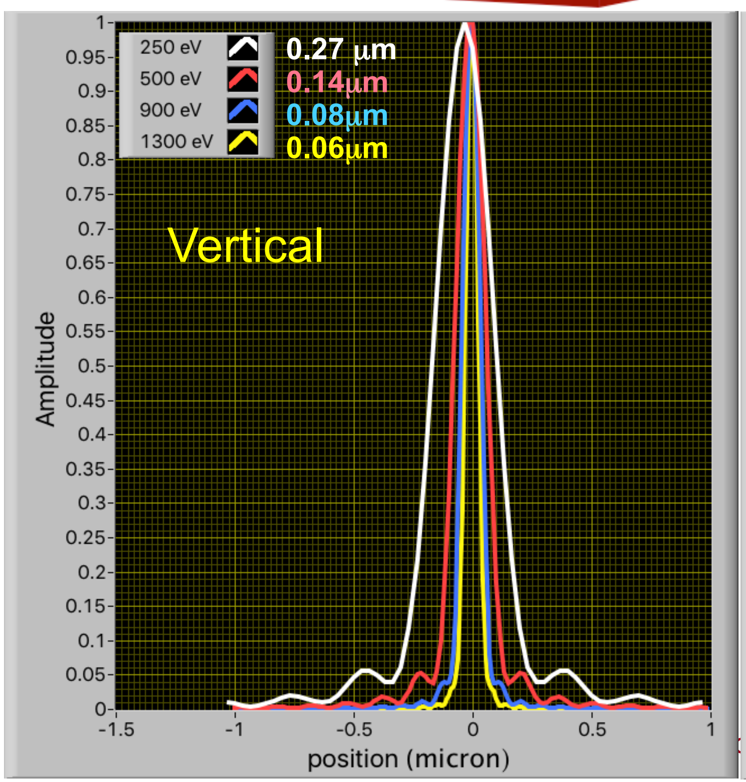
DREAM and LAMP (expected performance)

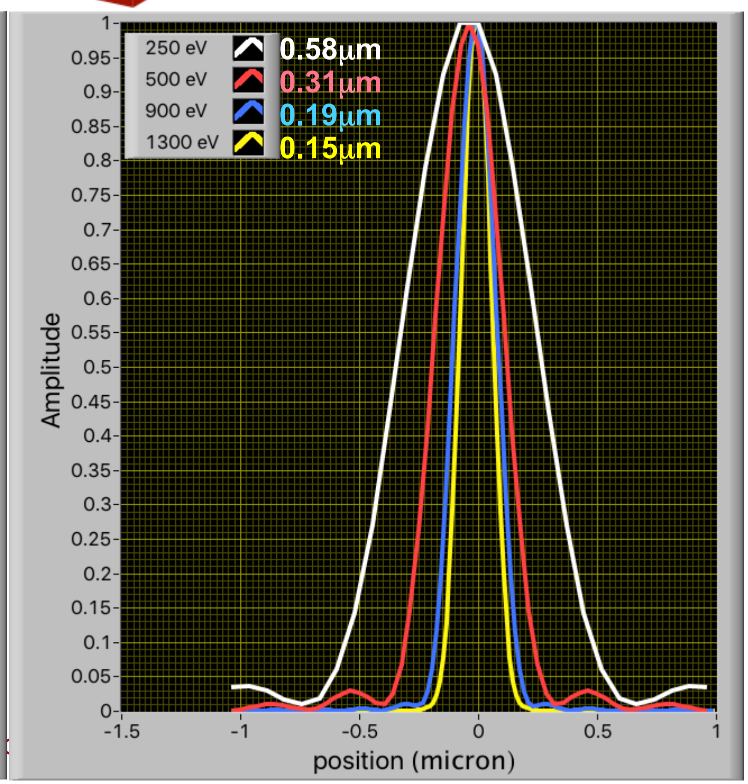
If all this works… we expect these spots



Possibility to run 2 experiments in series
LAMP mirrors – bendable to optimize the focal spot in both experimental chambers

1.5x10^{21} W/cm^2 @ 1300 eV with 2 mJ pulse



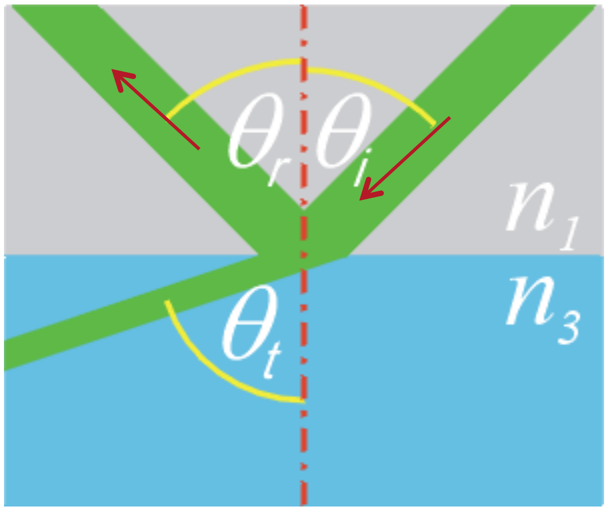


> 10^{22} W/cm^2
1300 eV
12 mJ pulse
(possible with LCLS II)
Sub 10 fsec pulse

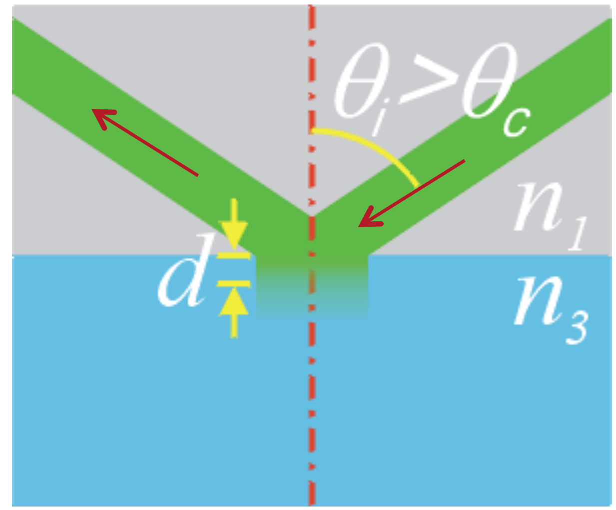
CAN WE?

Optical surface damage

Above the grazing critical angle



Below the grazing critical angle



The non reflected energy is absorbed (1/e) in d ↘

$$d = \frac{\lambda \xi}{4\pi\beta}$$

$$\xi = \sqrt{\frac{\sin^2\theta - 2\delta + \sqrt{(\sin^2\theta - 2\delta)^2 + 4\beta^2}}{2}}$$

$$n = 1 - \delta - i\beta$$

$$\delta = \frac{Ne^2\lambda^2}{2\pi mc^2}$$

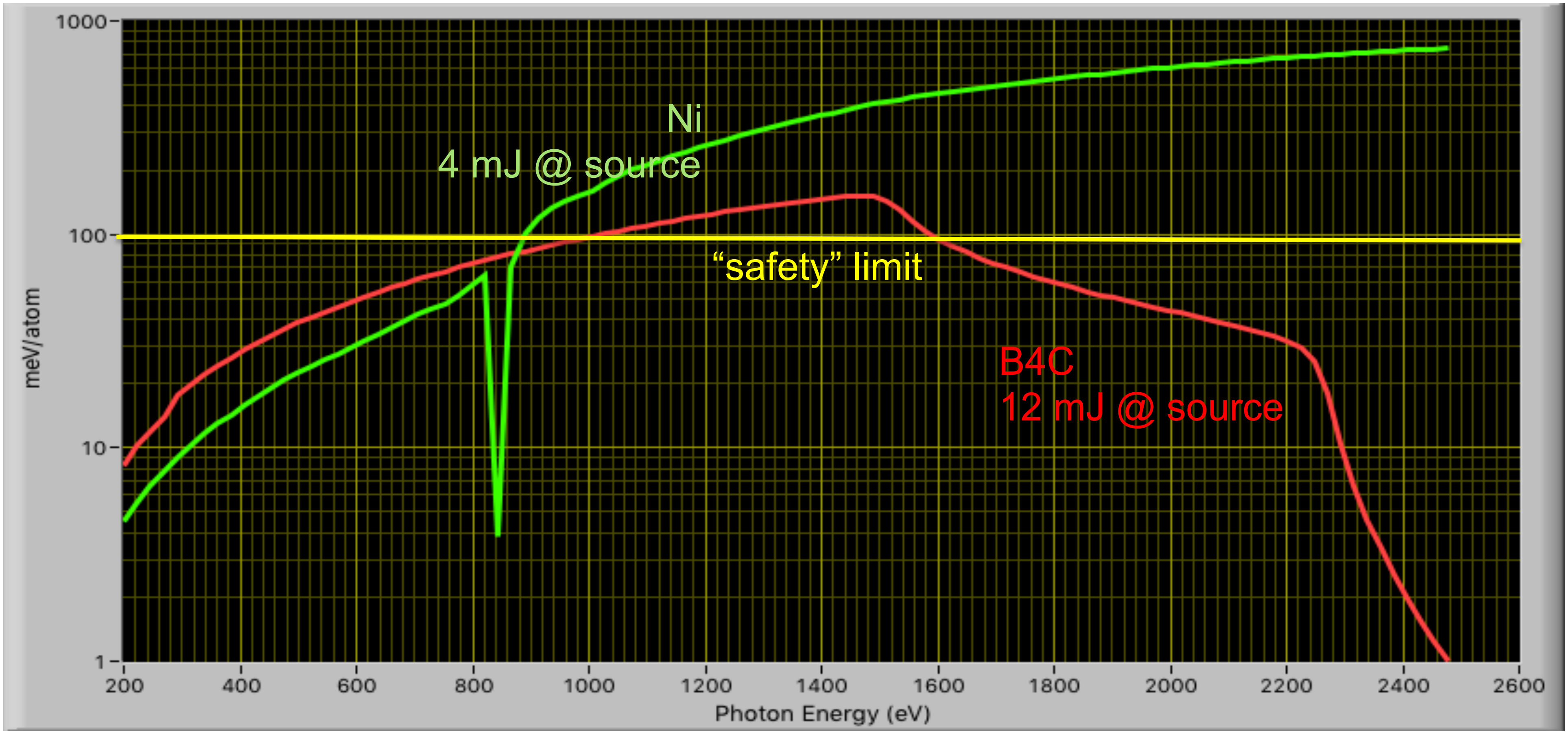
R=reflectivity
P=pulse power
θ=angle of incidence
r=source distance
σ=source divergence
ρ=atomic density

$$Aborbed \quad Energy_{ATOM} = \frac{(1-R)P\sin\vartheta}{r\sigma_x\sigma_y d\rho}$$

Ideal coating should have a large penetration depth (light materials) and good reflectivity (usually associated with heavy materials)

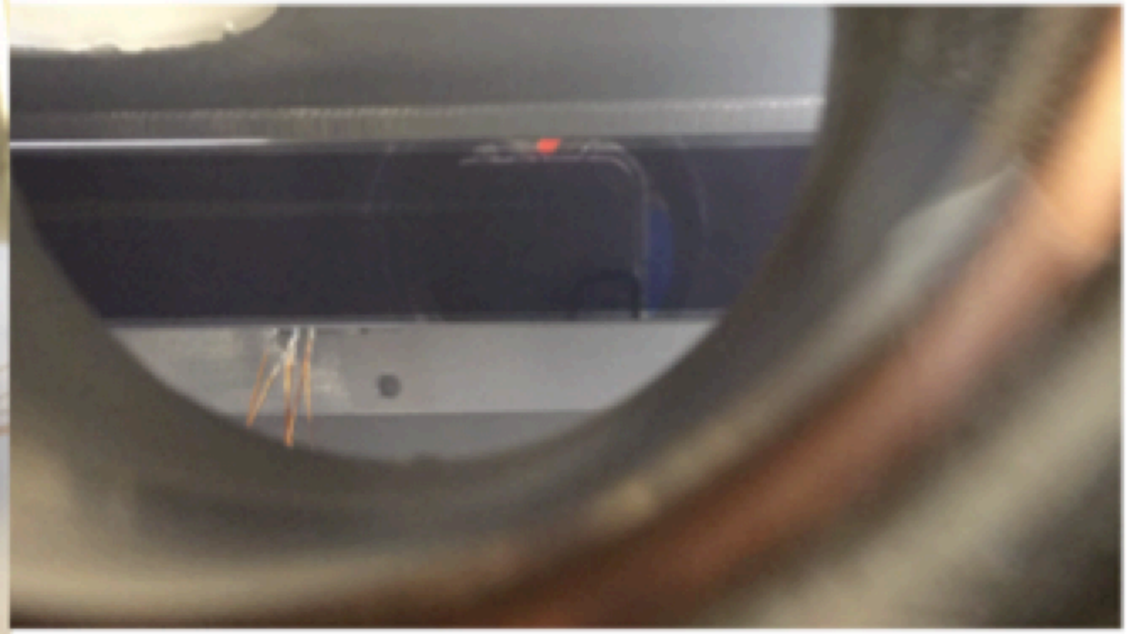
DREAM (21 mrad) – damage threshold

- **Need to work at 21 mrad to collect the entire beam**
- **B_4C** as the reflective coatings works from 5-600 to 1600 eV up to 12 mJ pulse energy
- **Ni** works up to 700 eV and up to 4 mJ pulse energy



Let's use B4C… not so quickly

There is a problem…..



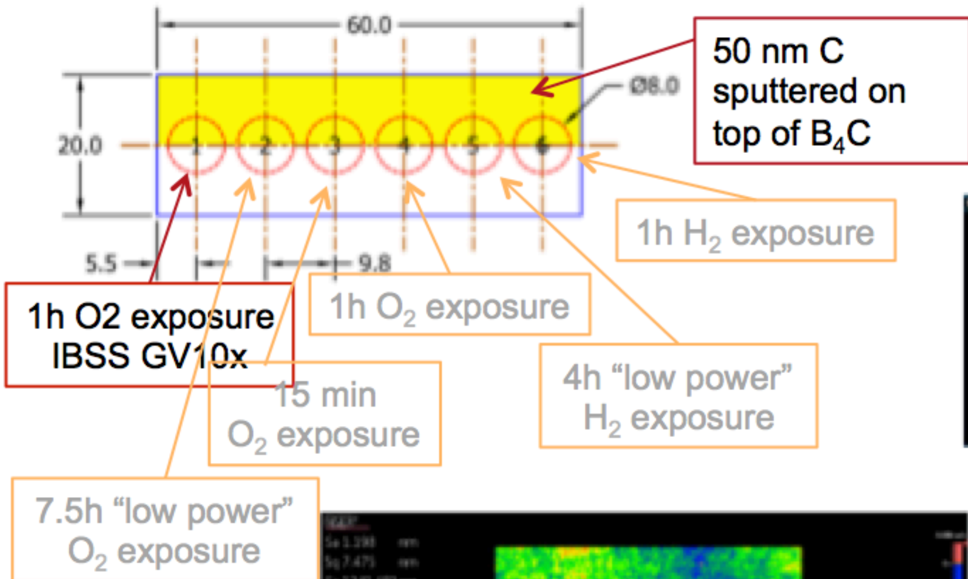
The X-ray radiation cracks the residual hydrocarbons present in the UHV
The surface of the mirror become "active" and adsorb carbon atoms. A carbonaceous layer growth on the mirror surface
The carbon contamination results in

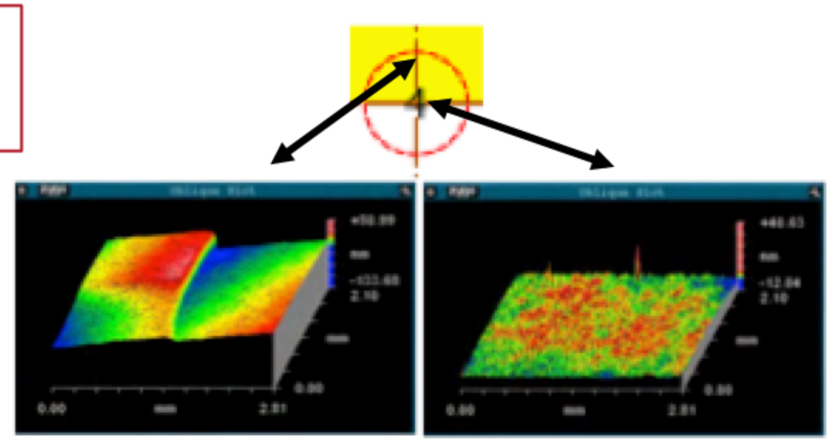
- **Flux reduction**
- **Wavefront distortion**
- **Change of focal properties**

Carbon can be removed by oxygen plasma cleaning….but this remove the B4C too… till now

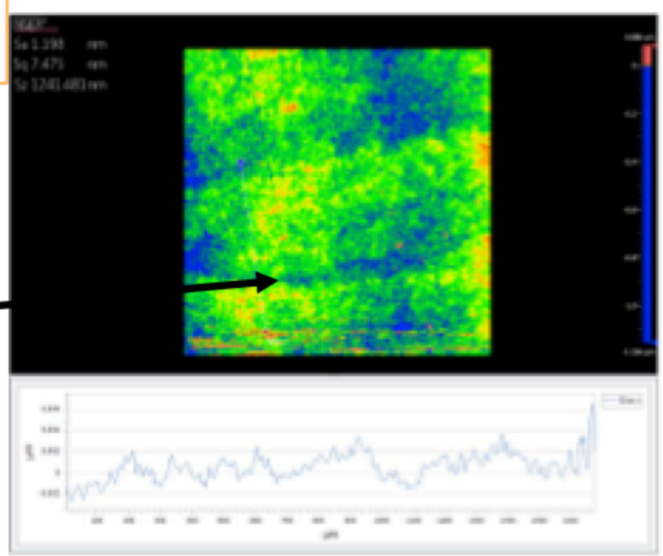
B_4C cleaning

Test sample: 50 nm B4C coating on Silicon





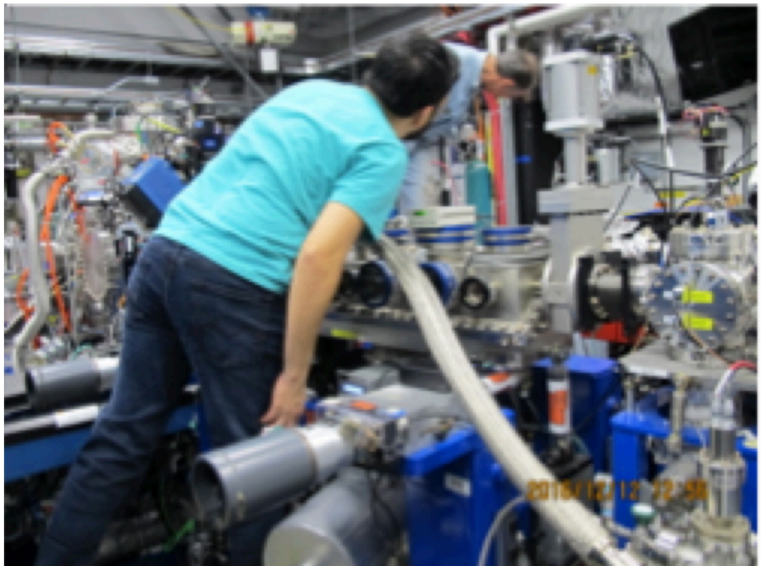
On zone 4 there is an apparent full removal of Carbon contamination with no apparent increase of roughens

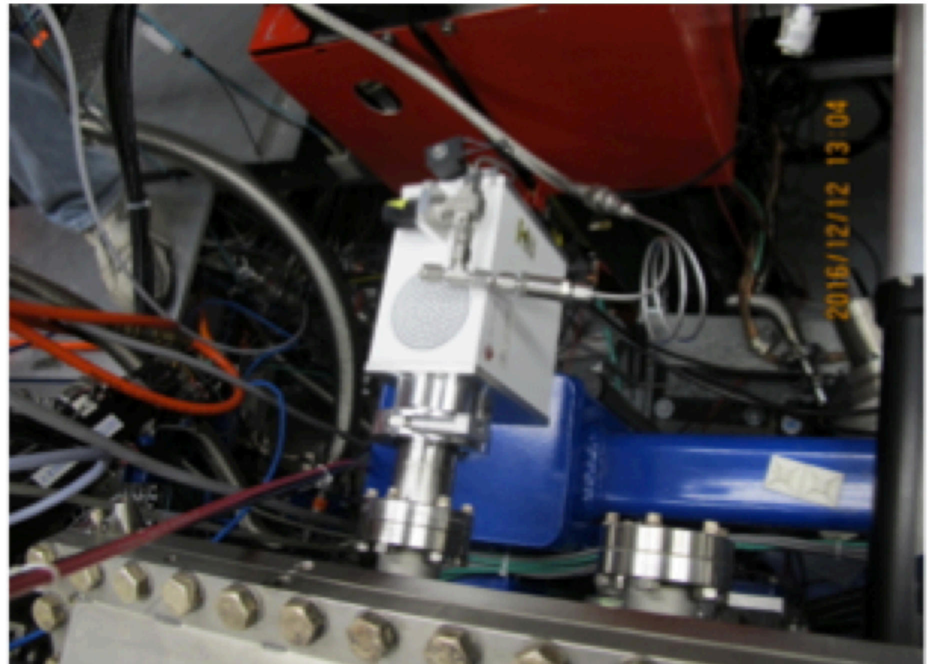


Some B4C removal has been observed!

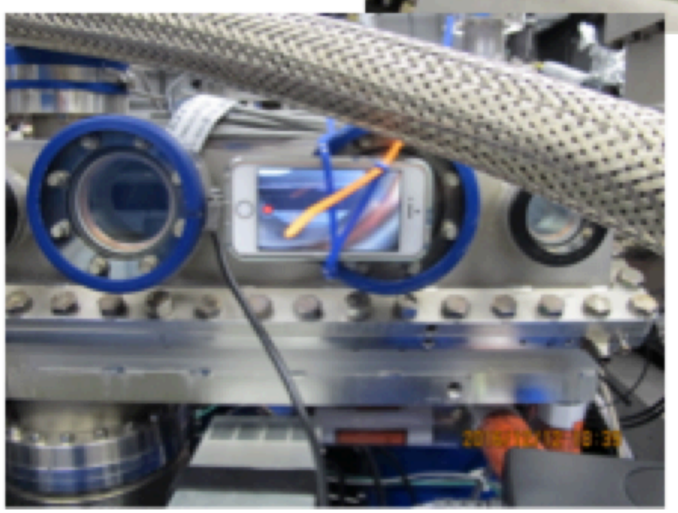
B4C coated KBs cleaning

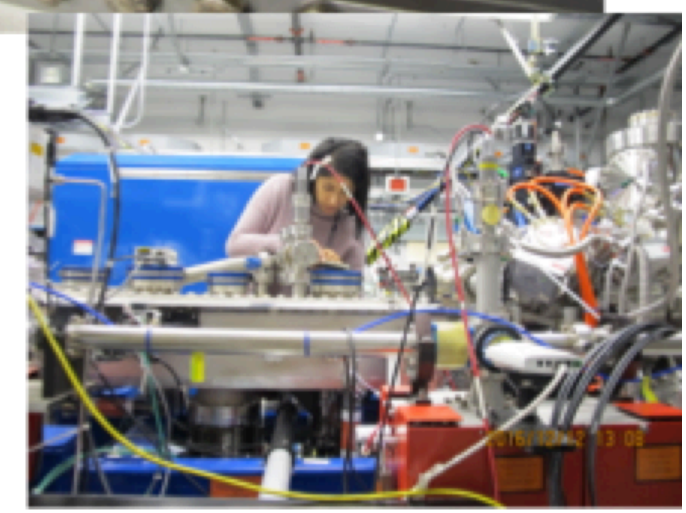
SLAC



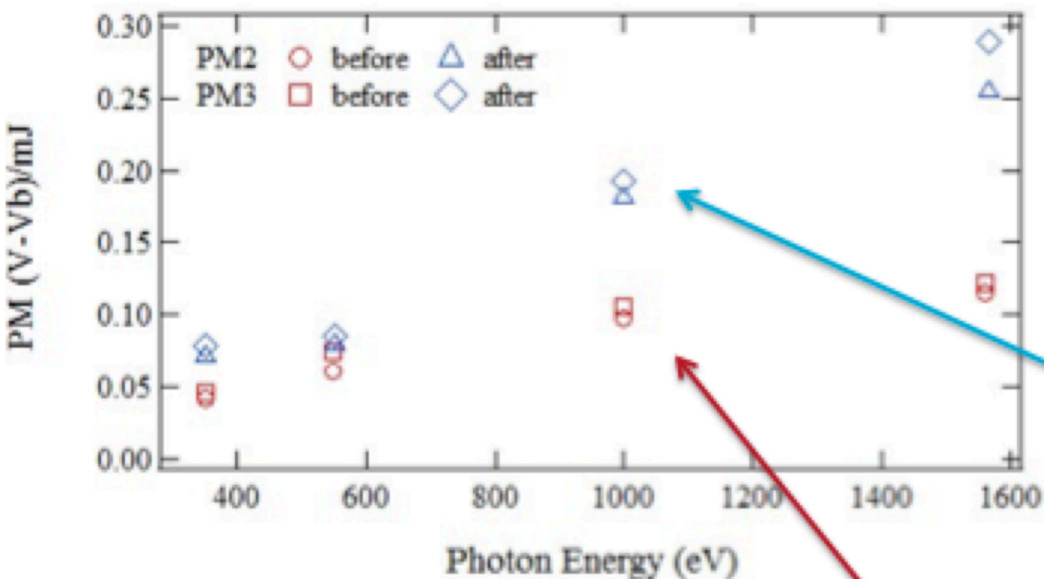


Despite some risk we decided to proceed with the cleaning using an IPhone to track the cleaning evolution and visual inspection to decide when we are done





B4C coated KBs cleaning



GAIN

350 eV: 1.51 → Contamination footprint narrower than the beam

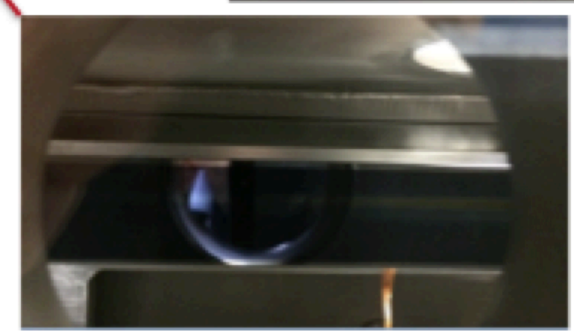
550 eV: 1.19 → Some residual Oxygen contamination

1000 eV: 1.77 }
1560 eV: 2.67 } Imply a very rough contamination layer

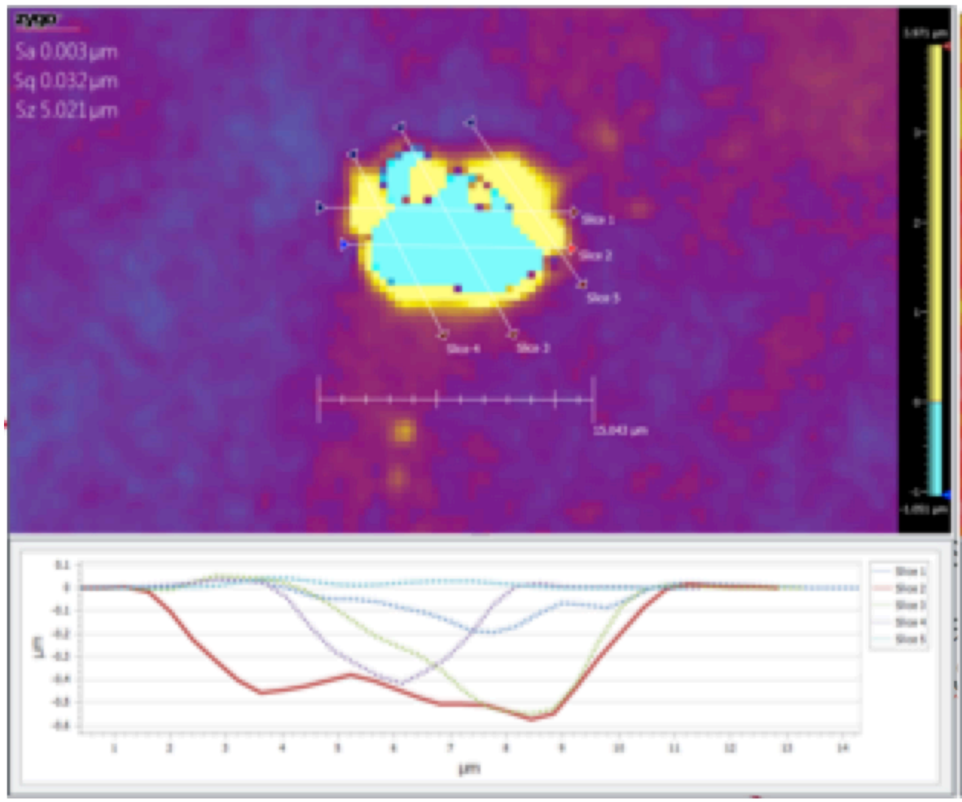
900 eV has been the most used photon energy and 500 the lowest

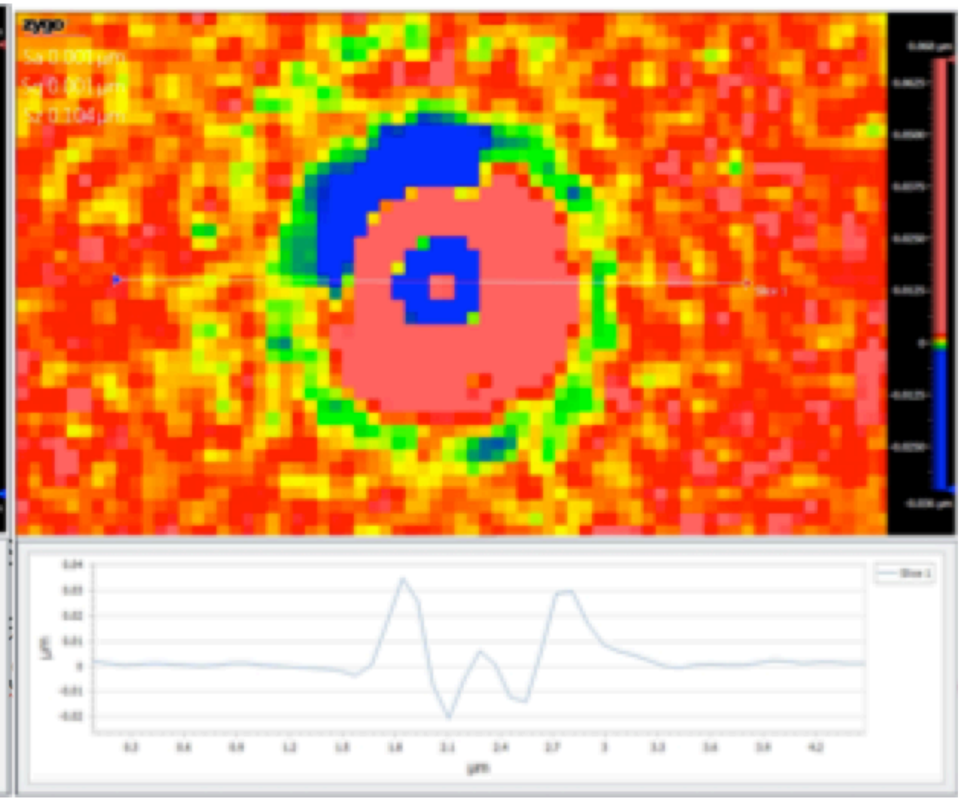
Most of the 300 eV beam sees a "clean mirror"

(a donat-like profile has been observed out of focus at low energy)



Improvement in spot profile





Best spot before cleaning (and wavefront sensor alignment) ≈ 3 μm

Measured spot after cleaning (and wavefront sensor alignment) ≈ 1 μm

With High Rep Rate Machine…

Growth:

HXR 2 nm *measured* in 6 years @120 Hz

Maximum tolerable thickness: 5-10 nm

@ 100 kHz one should have 10 nm in 2 weeks!

SXR 40-50 nm estimated from cleaning in 6 years @120 Hz

Maximum tolerable < 5 nm

@ 100 kHz one should have 5 nm in 6 hours!

Luckily the process is slow so, high rep rate will not act so drastically but, will help the growth. It is expect needing a cleaning process every 6 months

Mitigation: Procure large mirrors and use a fresh part of the coating

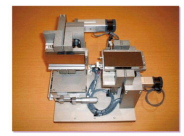
Improve of one order of magnitude the vacuum level

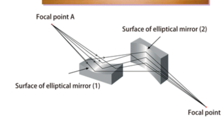
7 nm spot @ SPRING 8 - Japan

Step to reach such a small focus (Yamauchi; Ishikawa)

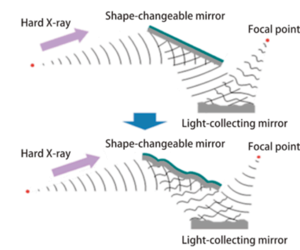
1) Have a 1 Km beamline on a stable synchrotron

2) Make a 2 steps process with very small mirrors



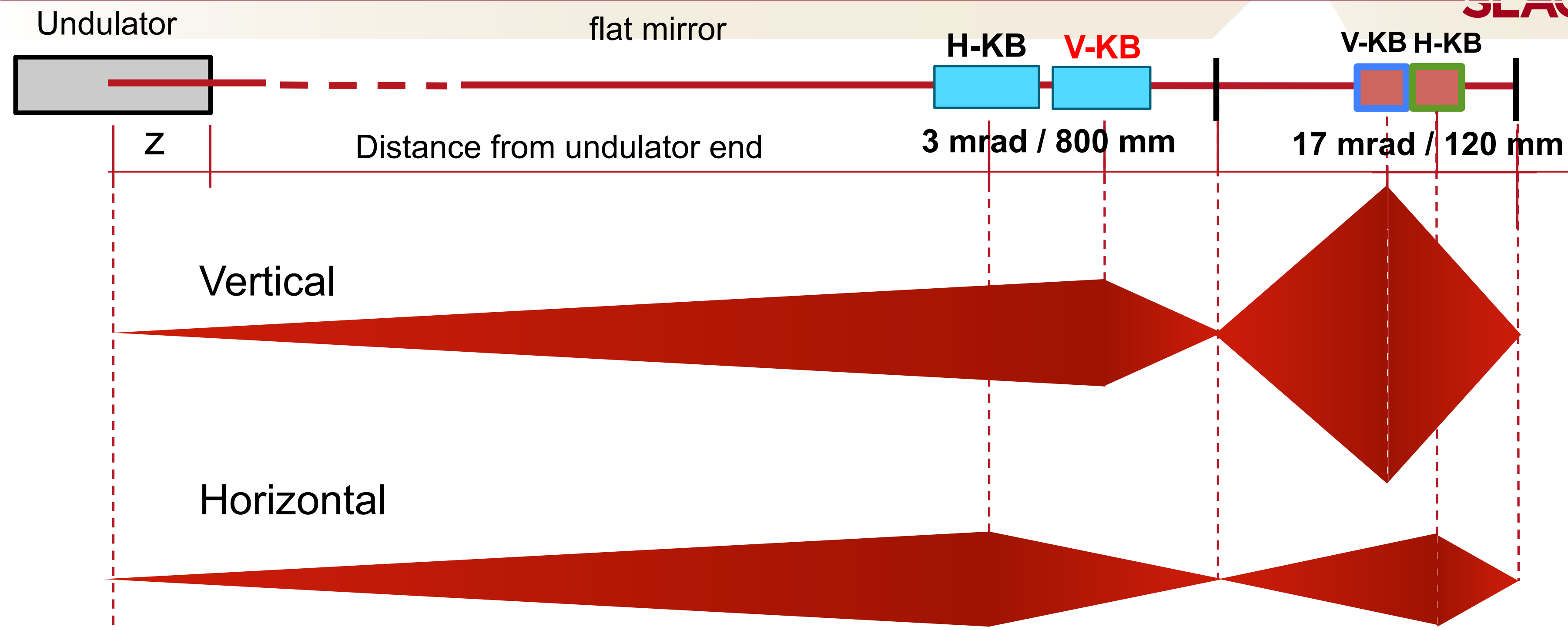


3) Use of large angle of incidence multilayer mirrors and correcting optics



Not al these options are compatible with the length of the experimental halls and high power FEL beam

TW beamline Layout 4 mirrors @ 8 keV



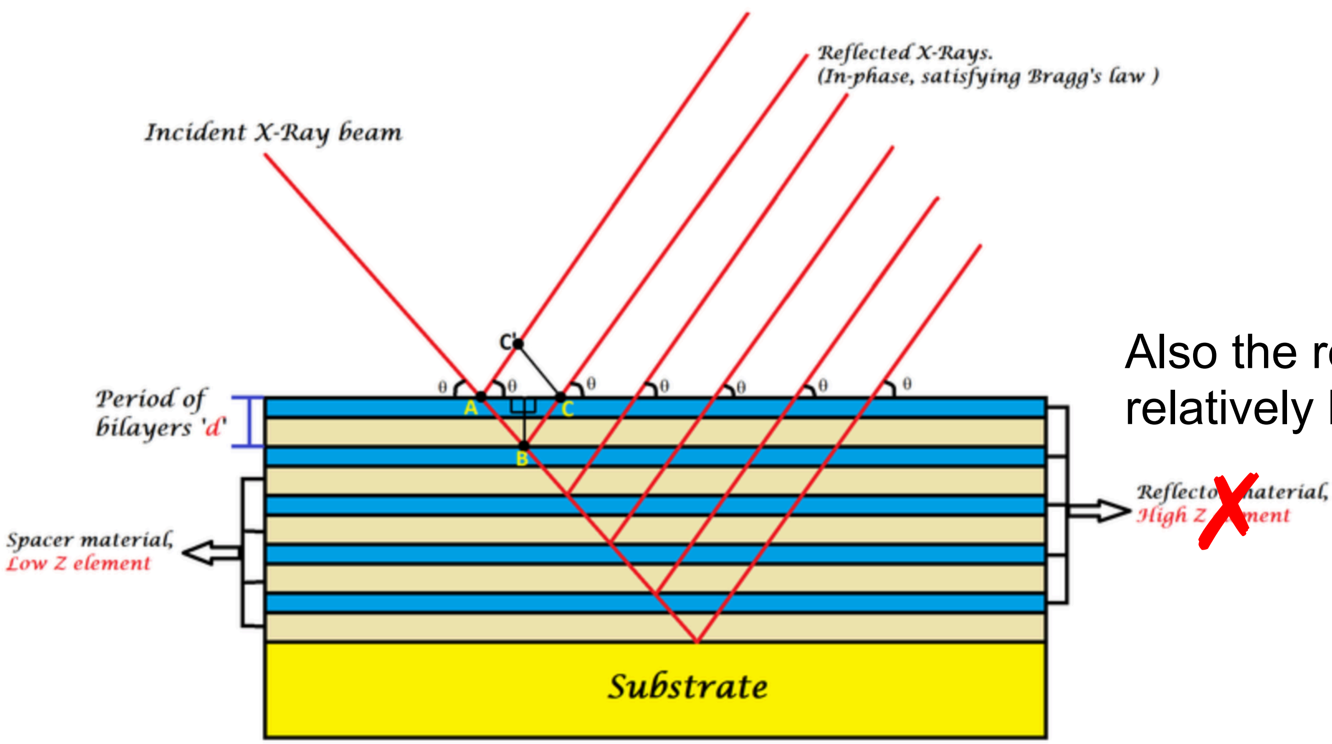
	Horizontal	Vertical
Source-IP (m)	**360**	**360**
Demag 2nd set	**20**	**10**
q1=	**3.540**	**1.777**
Demag 1st set	**100**	**200**
p1=	**354.045**	**355.363**
p2=	**2.3**	**2.6**
q2=	**0.115**	**0.26**
Absolute M1 position	**354.045**	**355.363**
focus 1 position	**357.585**	**357.14**
M2 position	**359.885**	**359.74**

Need of short mirrors to go close to the focus; Need of steep angle to collect the entire beam

Multilayer option to go to 17 mrad @ 8-12 keV

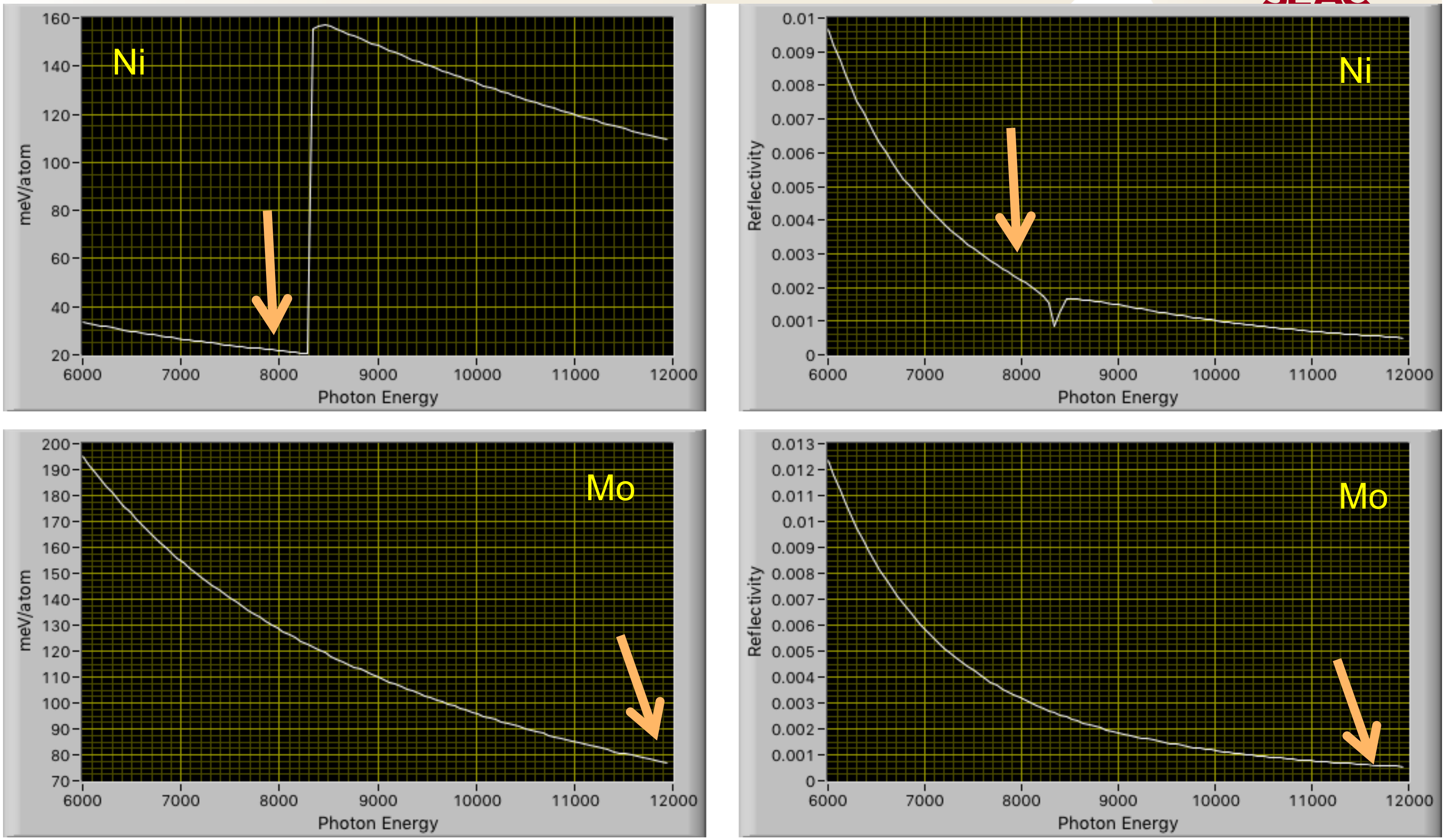
Use of a reflector (ideally a low Z metal) and a low absorption spacer
Damage threshold for metal must be low enough
Each layer reflect a small amount
Total reflectivity may be large
Use of a maximum of 60 layers to prevent beam elongation

With 17 mrad incidence, focal distances can be reduced

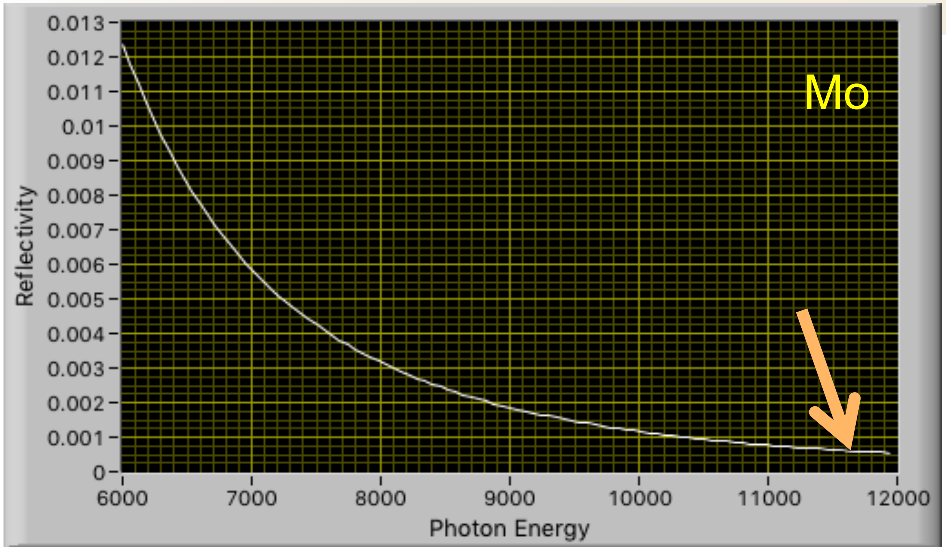


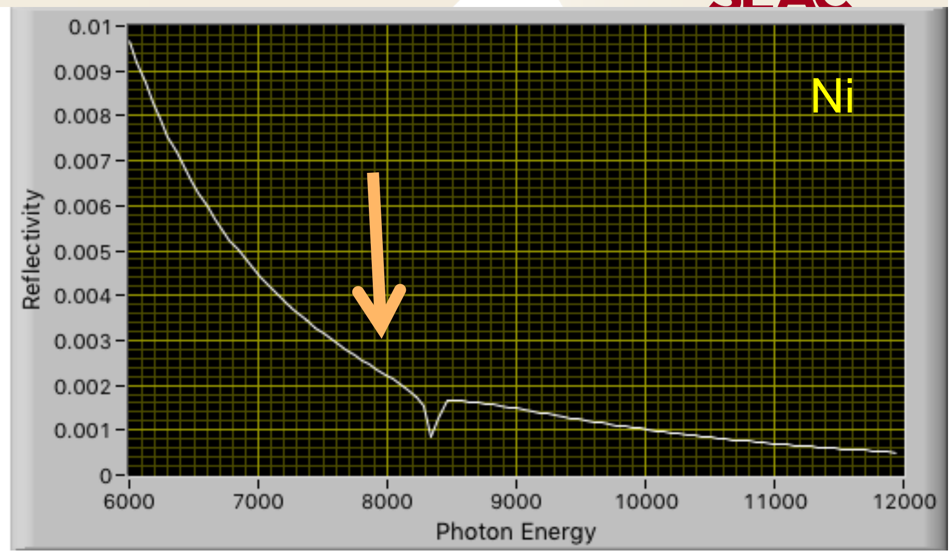
Also the reflector shall be a relatively low Z material

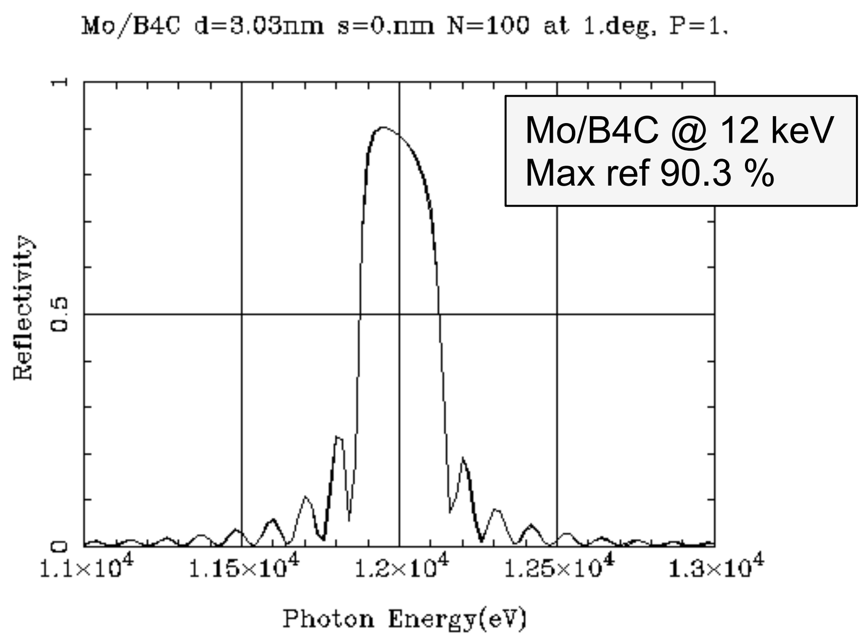
Possible Multilayer meterials @ 17 mrad

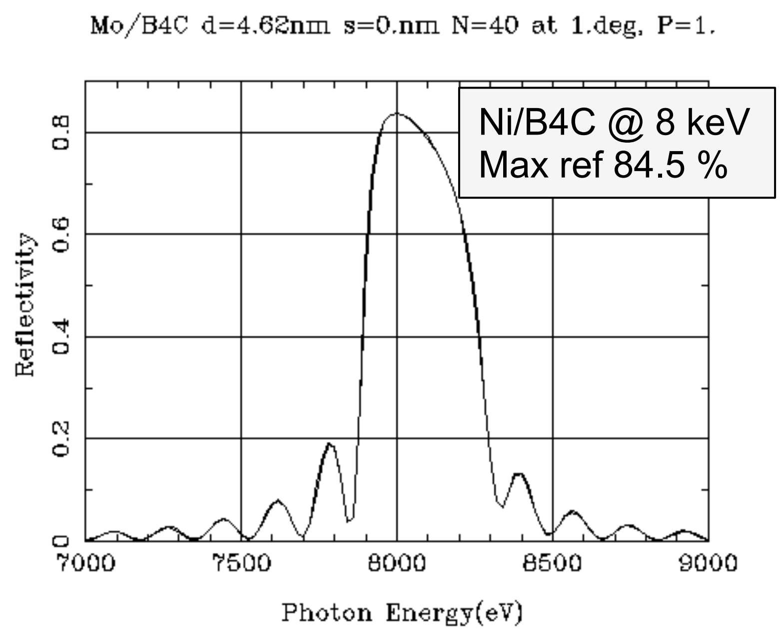


Possible Multilayer meterials @ 17 mrad

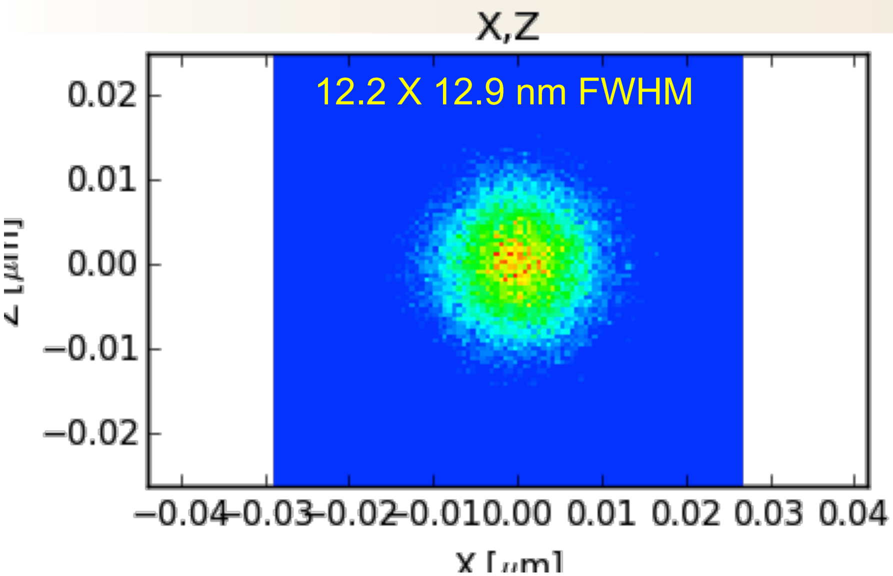




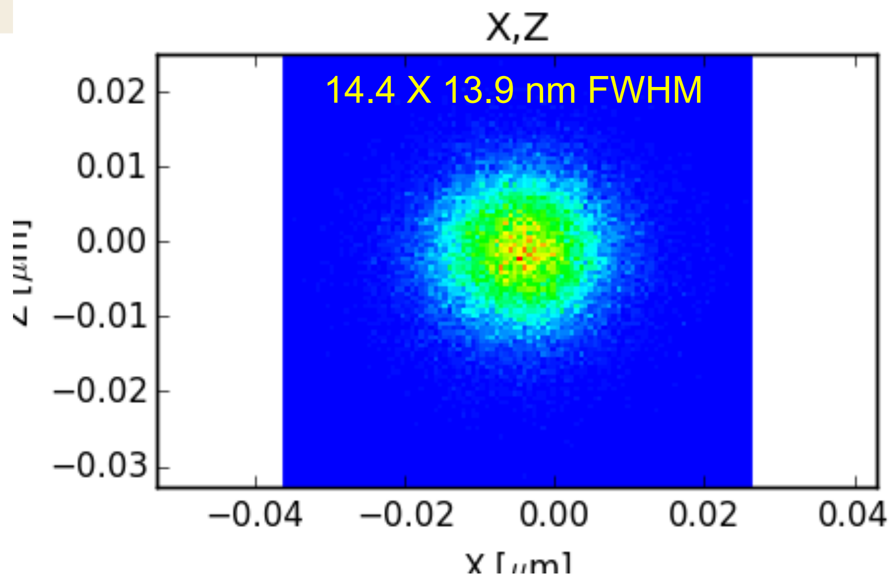




Spot properties @ 8 keV



Ideal spot / no slope/shape errors



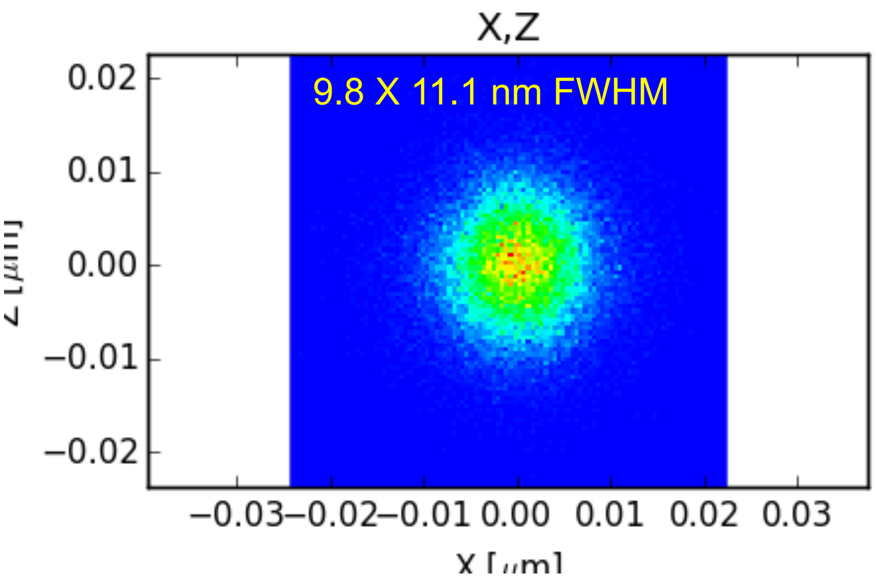
Using 0.3 nm rms on the 800 mm mirror (the best value we have measured so far) and 1 nm rms on the 130 mm mirrors (estimated from polishing and metrology limits)

Peak Power density starting with 1 TW at the source (8 mJ)

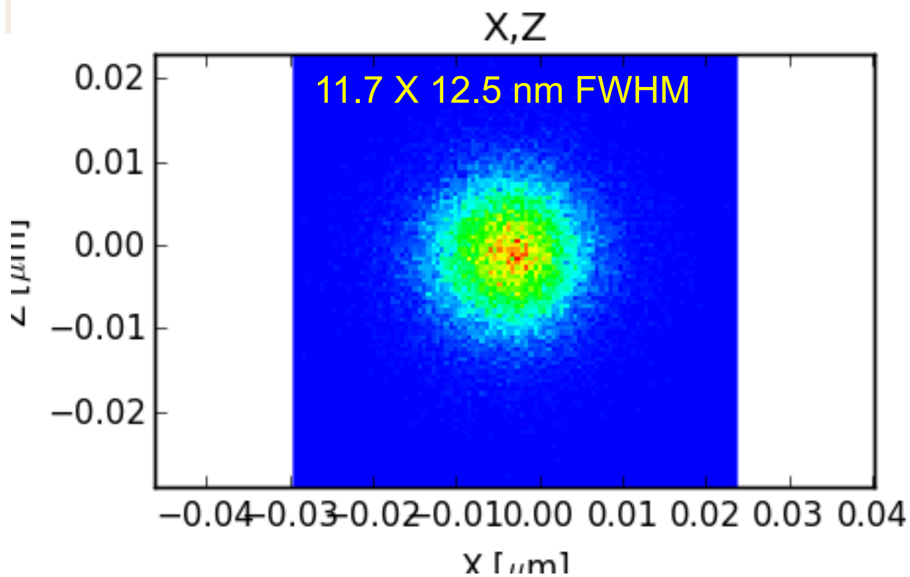
4.3 x10^{+23} W/cm^2
(including reflectivity and elongation)

3.4 x10^{+23} W/cm^2
(including reflectivity and elongation)

Spot properties @ 12 keV



Ideal spot / no slope/shape errors



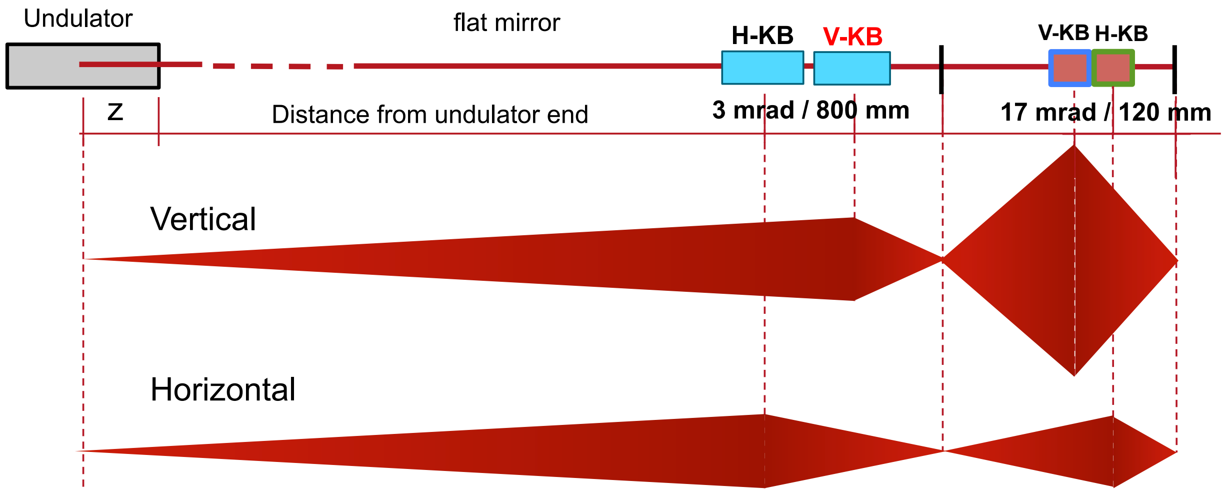
Using 0.3 nm rms on the 800 mm mirror (the best value we have measured so far) and 1 nm rms on the 100 mm mirrors (estimated from polishing and metrology limits)

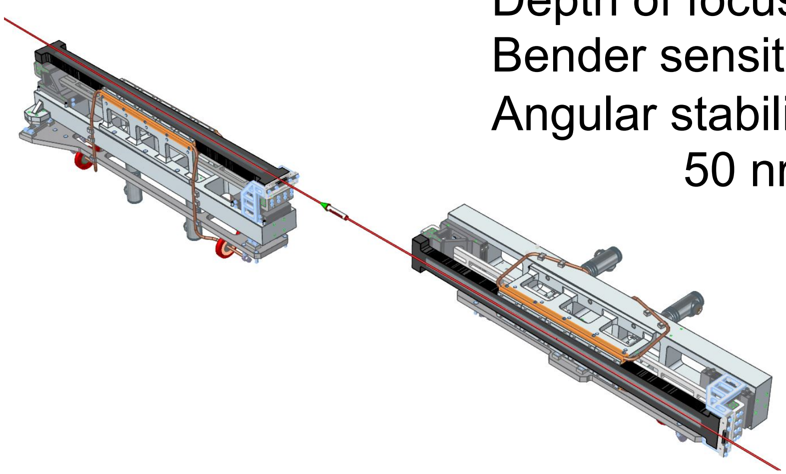
Peak Power density starting with 1 TW at the source (8 mJ)

$6.4 \times 10^{+23}$ W/cm^2
(including reflectivity and elongation)

$4.8 \times 10^{+23}$ W/cm^2
(including reflectivity and elongation)

Tolerances focus and alignment

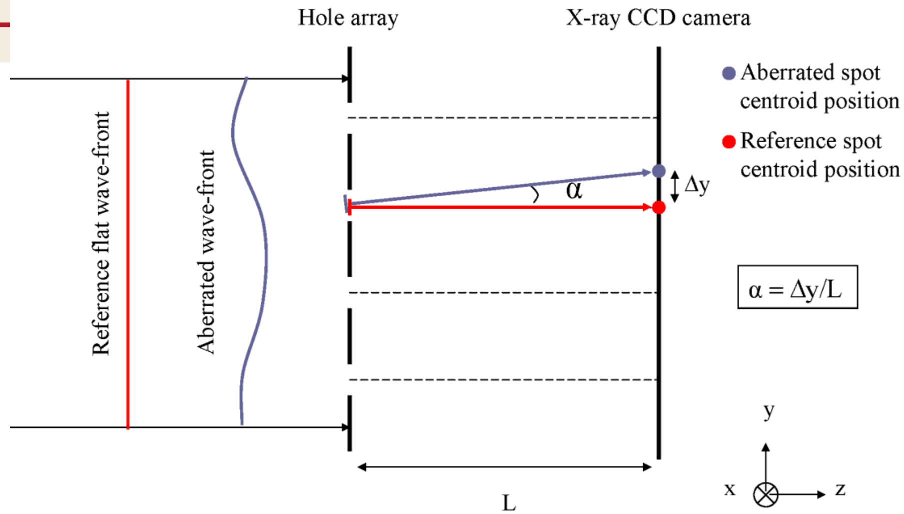


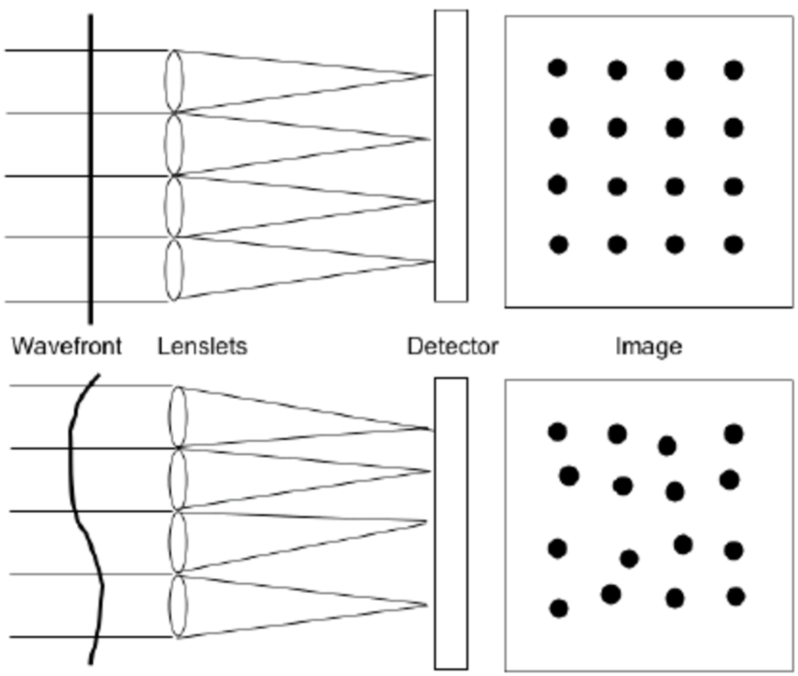


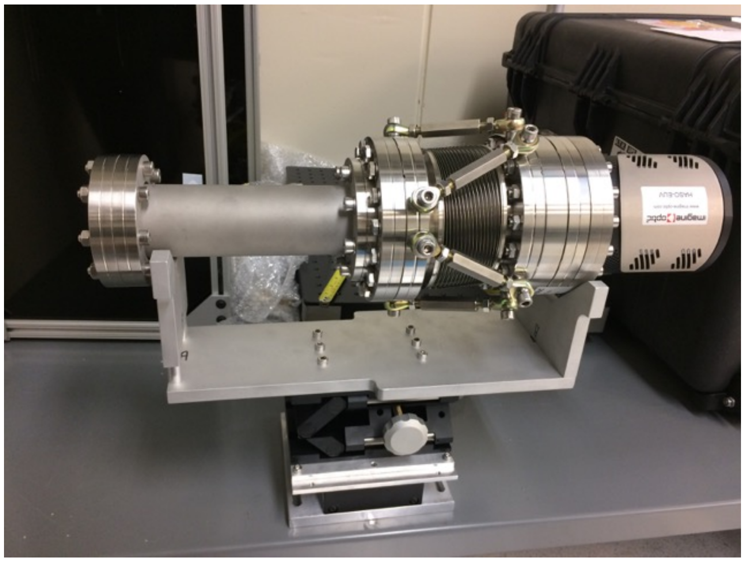
Depth of focus is 1 µm!
Bender sensitivity (mechanical stability of lever arms (0.1 µm)
Angular stability/alignment:
50 nrad first 2 mirrors
80 nrad second KB set

Hartman Sensor

The distorted wavefront hit the various pin-holes with different local angles of incidence, producing a non uniform distribution of spots on the detector.
This can be done on a single shot basis and at very low power (using filters). Power can then be "restored".

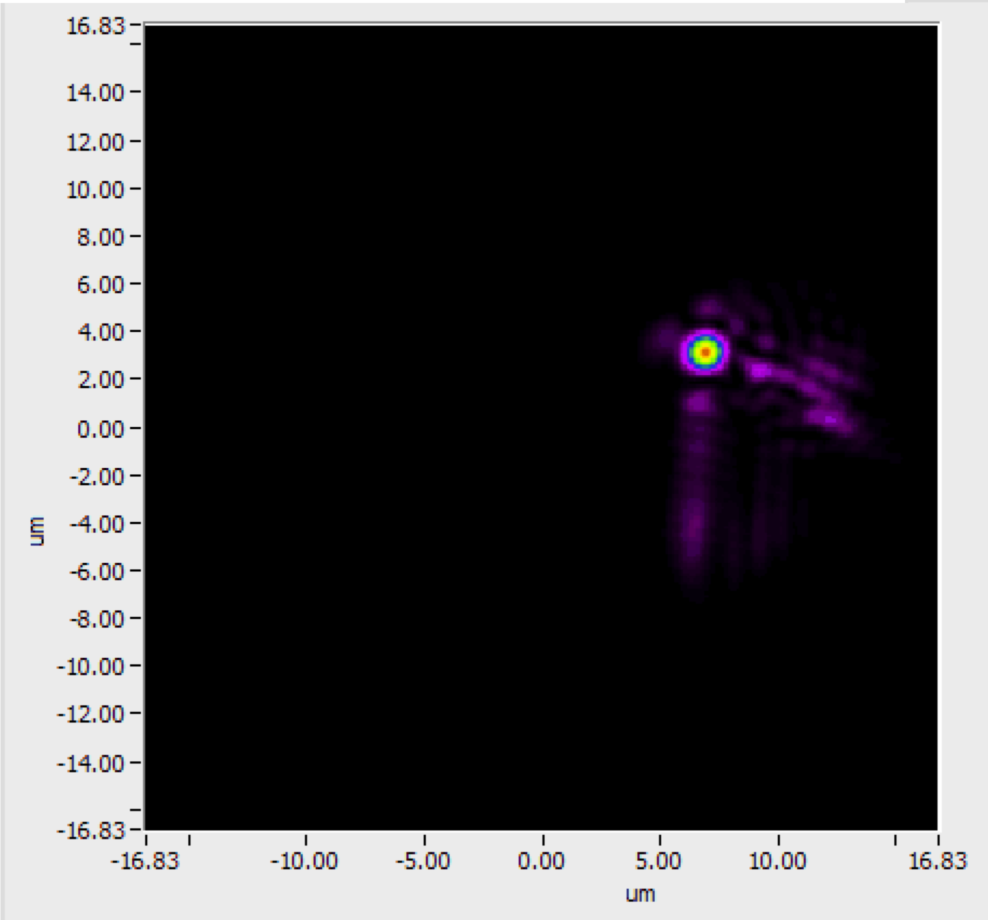




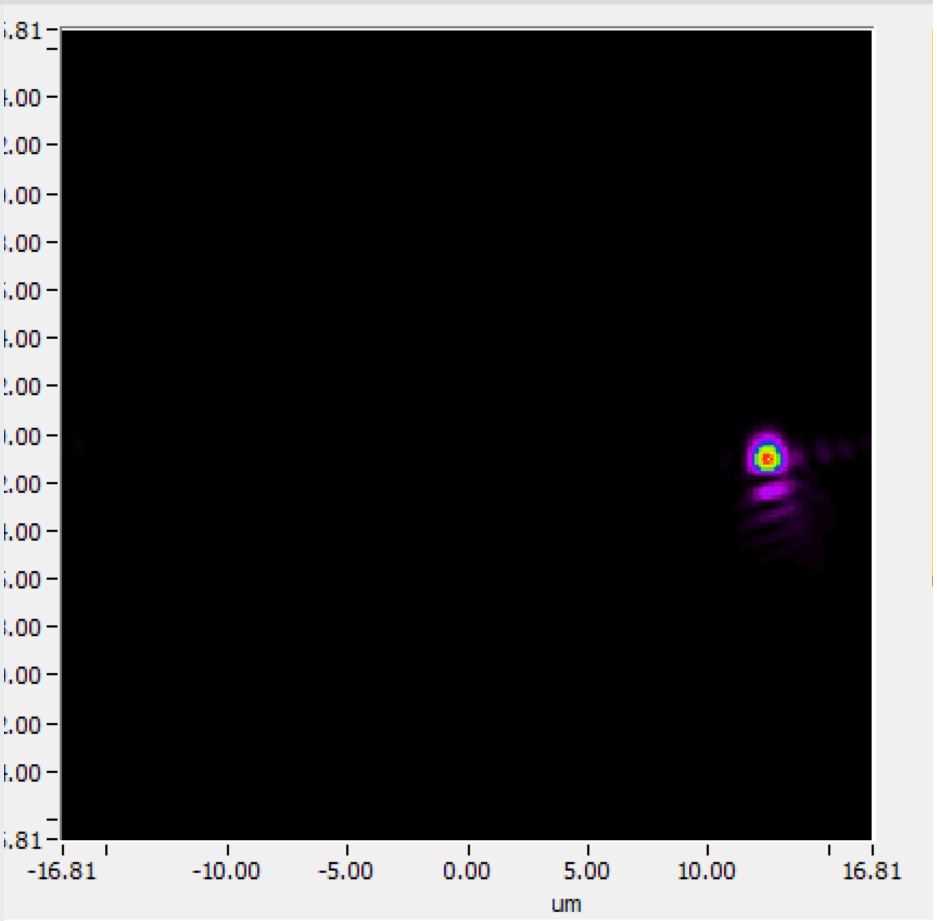


Reconstructed image around the focus position

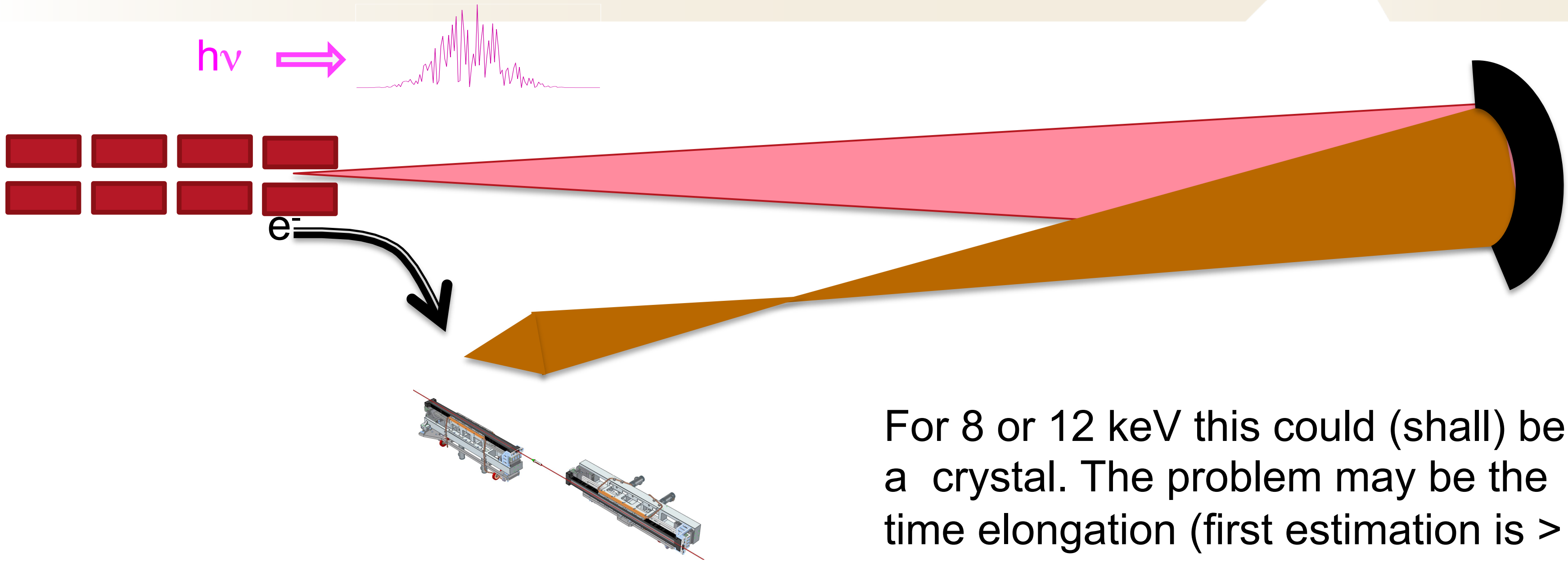
Before WFS assisted KB optimization



After WFS assisted KB optimization



Reaching the Schwinger field
presented by Claudio on Wednesday



For 8 or 12 keV this could (shall) be a crystal. The problem may be the time elongation (first estimation is > 30 fs)

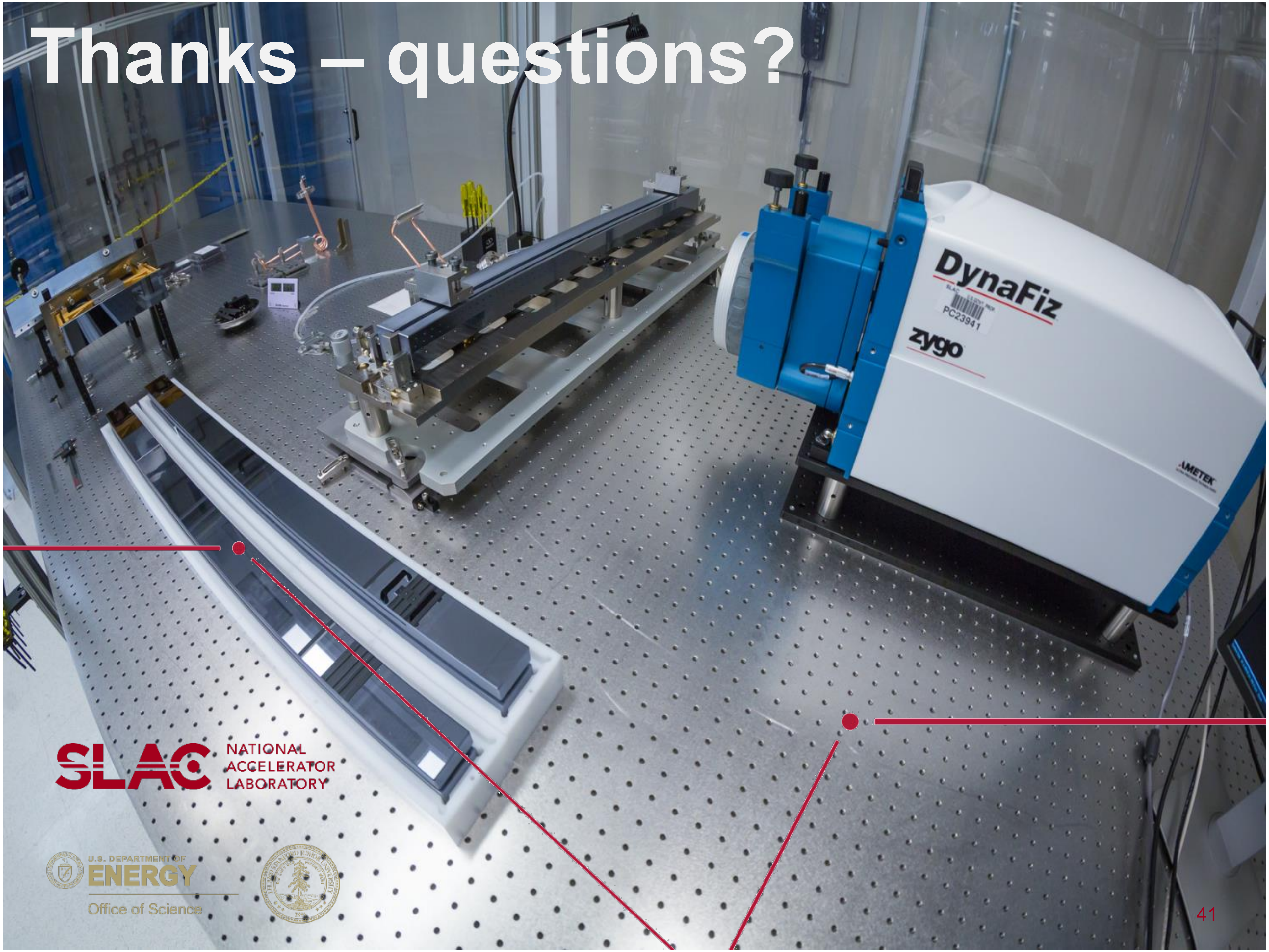
Or, at, for instance 13 nm (95 eV), one can use proven multilayer (Mo/Si, 6.7 nm d-spacing, 40 layers)

Conclusions

This talk was an "FYI"… optics can do a lot of damage
… but there are not only bad news..
TW is not out of reach… just need some more effort

- High average power source (not necessarily the main topic of this workshop) have seen R&D to face problems like:
  - Mitigation of the effect of thermal deformation
  - Mitigation/removal of the carbon contamination from optics
  - Wavefront sensing to optimize the spot (with full power *Work in Progress*)
  - Introducing the cooling scheme on adaptive optics (not discussed)
  - …….
- High peak power (pulse energy) have seen some R&D so far (after the initial boosts), mainly on damage studies. Some of the High Heat load R&D efforts are important for High Peak Power sources too. Having a beamline reaching 10^{24} w/cm^2 is not impossible!
- Left to do:
  - Having a broad(er) scientific community requiring access to TW to boost the R&D
  - Improve the beam and optic stability
  - Crystals and Multilayer in either forward or back diffraction geometry to preserve the pulse length (and survive the beam)
  - High power diagnostic (with close loop feedback with the optics)
  - …….

Thanks – questions?



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