2nd workshop on X-ray and XUV active optics

# The FERMI@Elettra beamlines: From diagnostics to microfocusing


**M. Zangrando**

On behalf of the FERMI@Elettra Photon Beam Transport System:

A. Abrami, D. Bacescu, D. Cocco (project leader), I. Cudin, C. Fava, D. Giuressi, R. Godnig, D. Lonza, F. Parmigiani, L. Rumiz, R. Sergo, C. Svetina

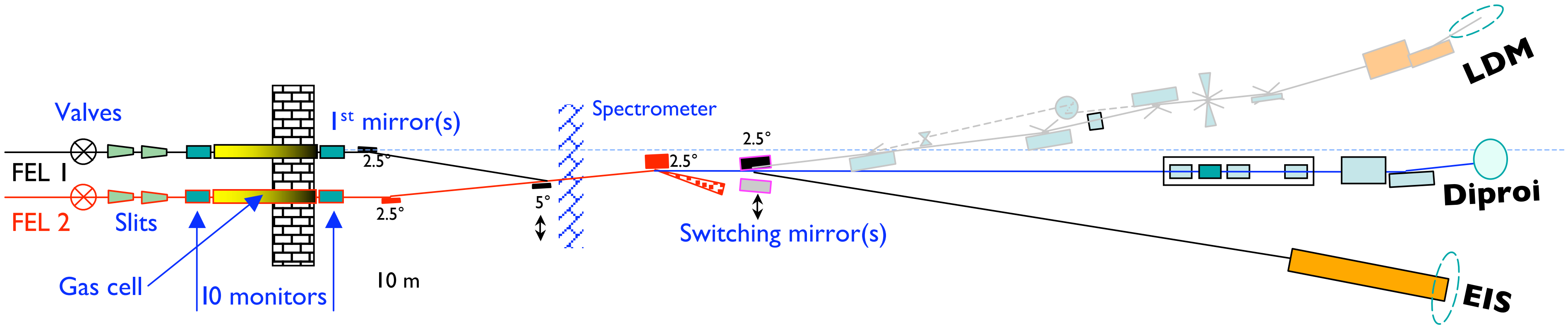

**Trieste, October 9th 2008**


PICTURES FROM THE TRIESTE TOURIST ATTRACTION SITE

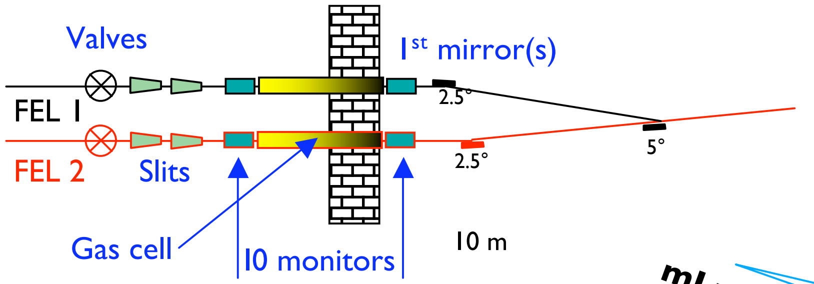
# FERMI@Elettra parameters

| Parameter | FEL 1 | FEL 2 |
|---|---|---|
| Wavelength (nm) | 100 - 20 | 40 - 10 |
| Pulse length FWHM (fs) | 50 - 100 | 100 - 200 |
| Bandwidth rms (meV) | ~20 | ~5 |
| Polarization | Variable | Variable |
| Peak power (GW) | 1-5 | ~0.4 |
| Photons per pulse | ~2 $10^{14}$ (100 nm) | ~1 $10^{13}$ (10 nm) |
| Brightness (Ph/s/mm$^2$/mrad$^2$/0.1%BW) | ~6 $10^{32}$ | ~$10^{32}$ |
| Power fluctuation (%) | ~25 | > 50 |
| Central wavelength fluctuation | Within BW | Within BW |
| Pointing fluctuation (μrad) | < 5 | < 5 |
| Source size FWHM (μm) | 290 | 140 |
| Divergence rms (μrad) | 50 | 15 |
| Repetition rate (Hz) | 10 - 50 | 10 - 50 |

# Photon beam transport system

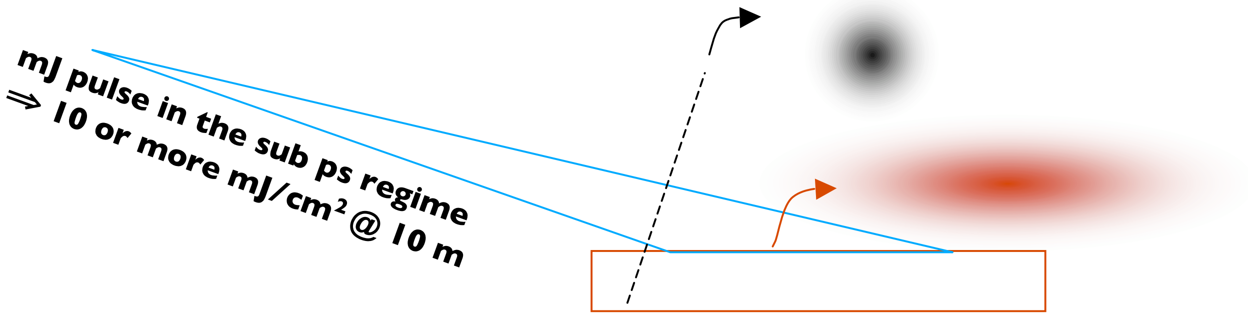


# Damage threshold



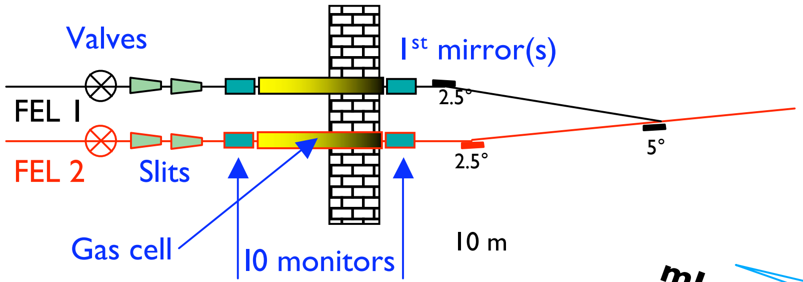

**FEL 1:**
**100 fs; 5 GW ⇒ ~ 0.5 mJ**

**FEL 2:**
**200 fs; 1 GW ⇒ ~ 0.2 mJ**




**A. Andrejczuk et al. *DESY annual report 2001***
**D. Von der Linde et al. *Appl. Surf. Science 154 (2000)***
**Y. Hirayama et al. *Appl. Surf. Science 197 (2002)***
**H. Jeschke et al. *Appl. Surf. Science 197 (2002) (2 articles)***
**J. Kuba et al. *NIM A 507 (2003)***
**L. Juha et al. *NIM A 507 (2003)***
**V. Schmidt et al. *Appl. Surf. Science 197 (2002)***
**K. Venkatakrishnan at al. *Optics & laser technology 34 (2002)***
**Y. Dong et al. *Appl. Surf. Science 252 (2005)***

# Damage threshold

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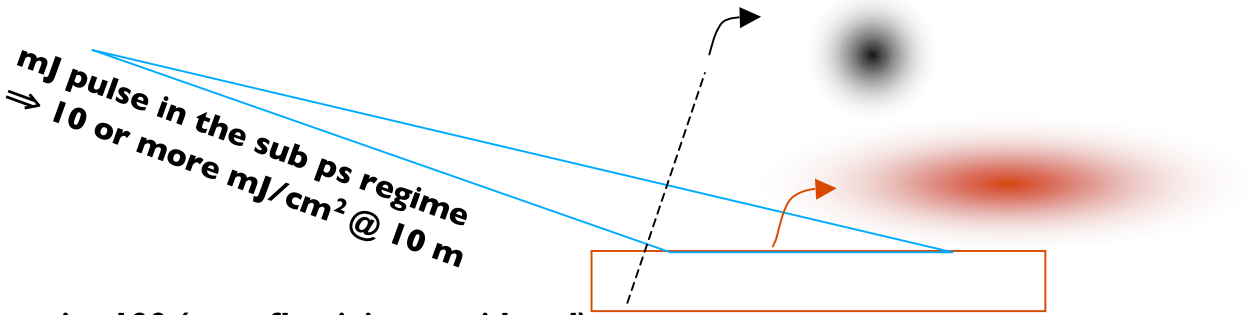
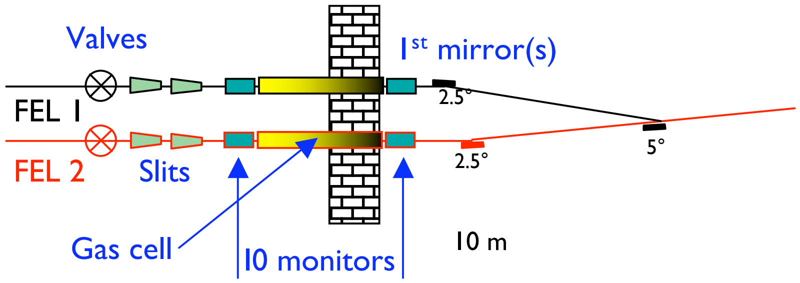


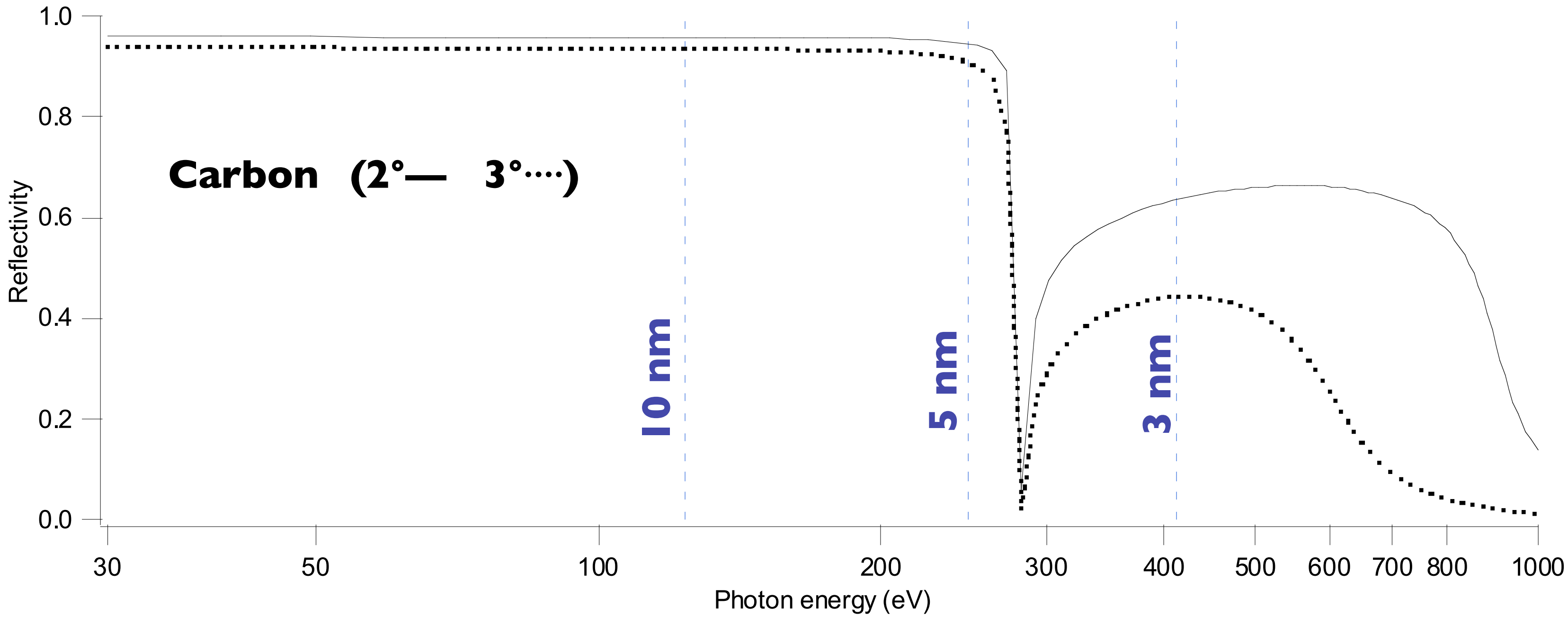

***Safety margin=100 (no reflectivity considered)***

| ***Material*** | ***Damage threshold @ 90 nm*** | ***Safety angle 100 nm (10 /20/40 m)*** | ***Estimated damage threshold @ 40 nm*** | ***Safety angle 40 nm (10 /20/40 m)*** |
|---|---|---|---|---|
| Cu/Glidcop bilk | ~ 500 mJ/cm² | 24° / 90°/ 90° | ~ 1000 mJ/cm² | 41° / 90°/ 90° |
| Au coating | 40 mJ/cm² | 1.9° / 7.6°/ 32° | 50 mJ/cm² | 4.8° / 20°/ 77° |
| Silicon bulk | 30 mJ/cm² | 1.5° / 6°/ 23° | | |
| Graphite coating | 60 mJ/cm² | 2.9° / 11.5°/ 53° | 240 mJ/cm² | 9° / 40°/ 90° |
| YAG bulk | 70 mJ/cm² | 3.3° / 13.4°/ 68° | | |

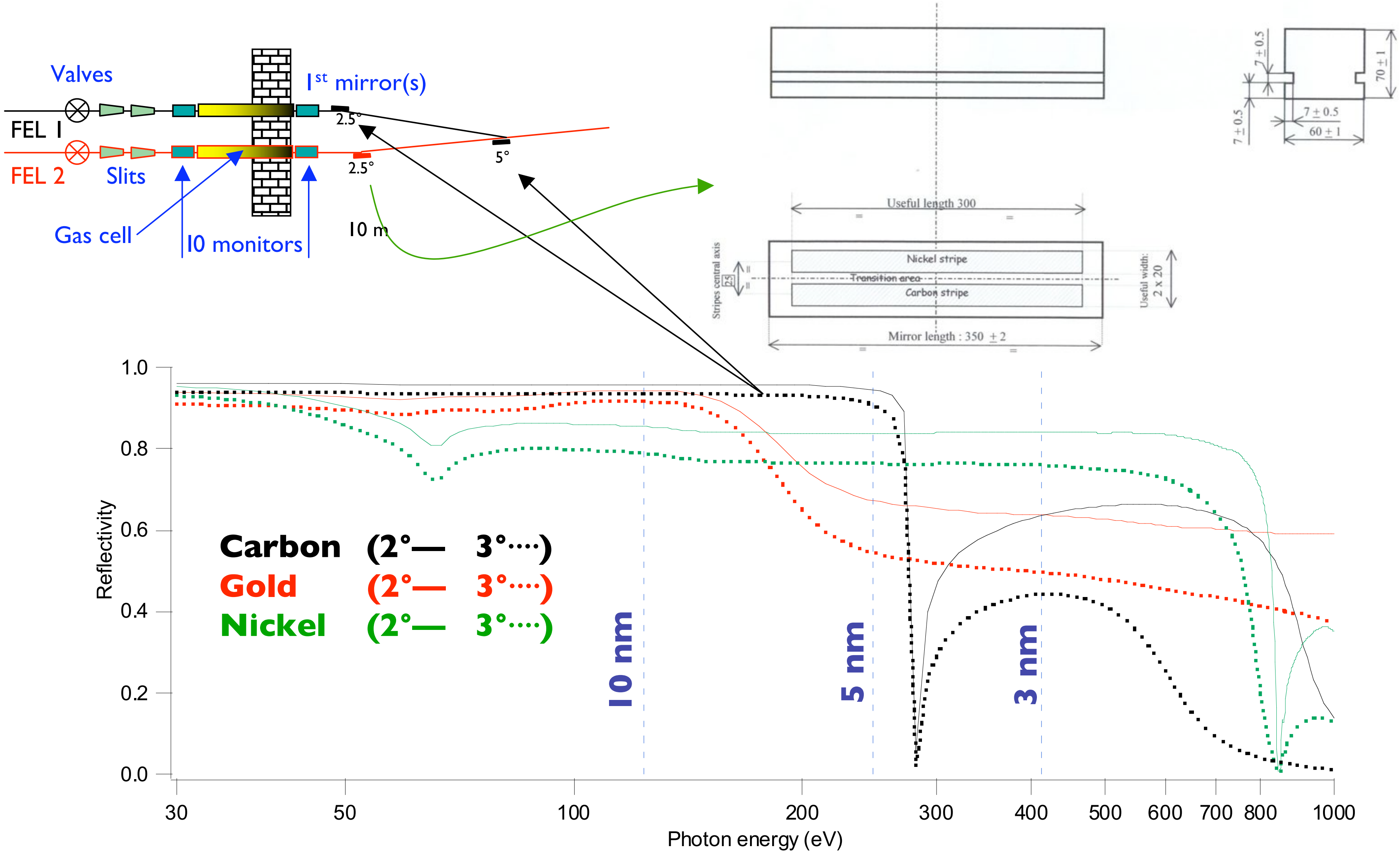
**Fel 1** (damage threshold @ 90 nm; safety angle 100 nm) — **Fel 2** (estimated damage threshold @ 40 nm; safety angle 40 nm)

# Damage threshold

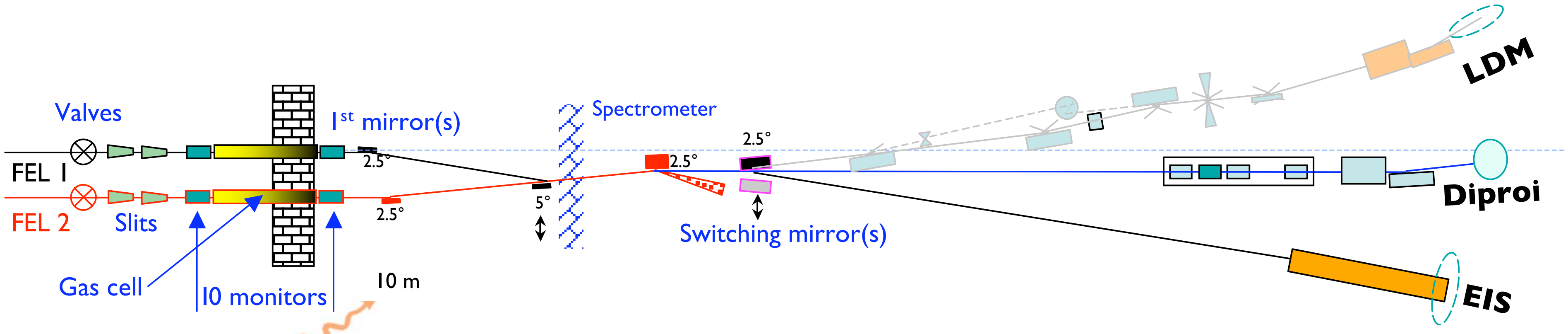


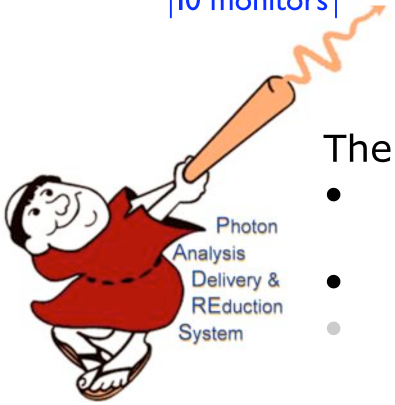



# Mirrors coating



# Photon diagnostics




There will be the possibility to measure the following characteristics:

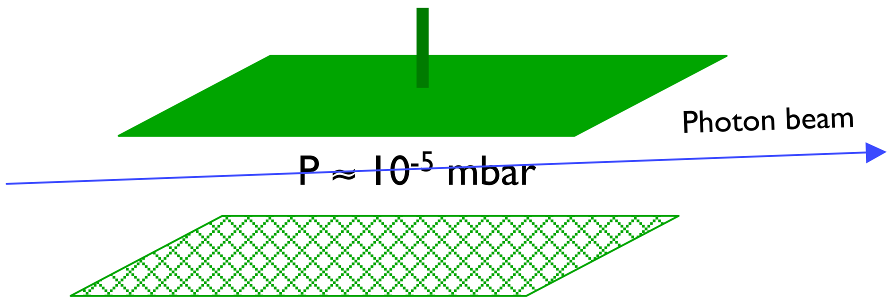
- Intensity: On line; Shot by shot; 1% repeatability, 2-3% precision (calibration dependent)
- Angular position: On line; Shot by shot; $\sim 2$ μrad sensibility
- Divergence: NOT On line; NOT Shot by shot; based on YAG crystal measurements
- Photon energy distribution: On line; Shot by shot; Single spectrometer, 12-360 eV sub mV resolution.
- Arrival time: On line; Shot by shot; Visible streak camera (Timing and Synchronization Area) ps resolution
- Wavefront: Hartmann sensor (Imagine Optic), Precision λ/50 at 20-5 nm range or CCD
- Pulse length measurement: NOT On line; NOT Shot by shot;

# BPMs and I0 monitors

## On line I0 monitor

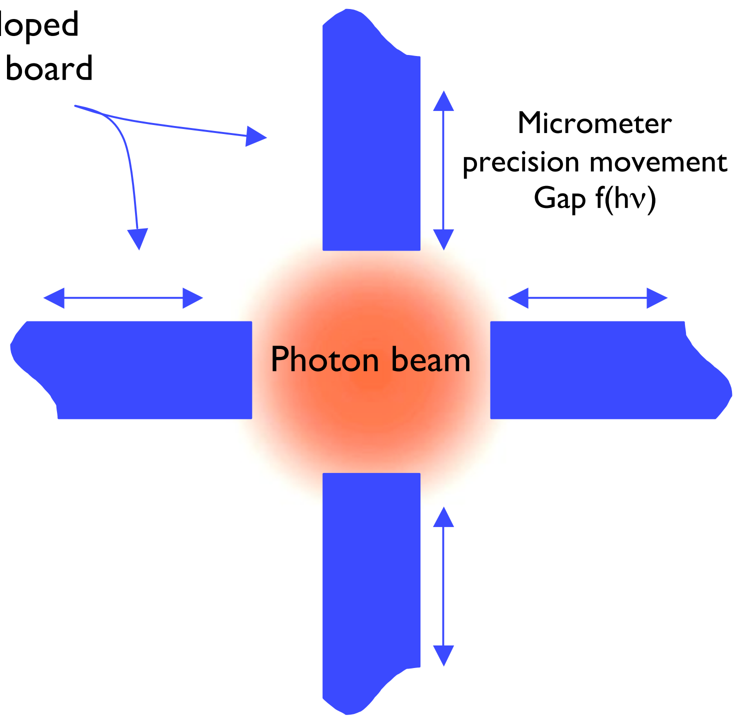
## Beam Position Monitor

Collect nA/pA signals using an
already internally-developed
fA precision acquisition board
(ref. D. Giuressi)




Applied Voltage (Bias)
+ or - depending on tests/noise

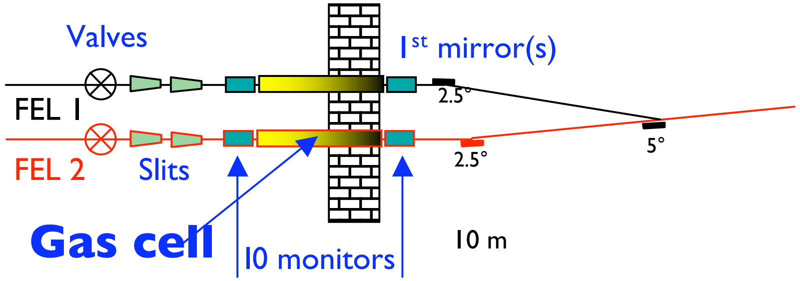
Calibrated with High precision IRD photodiodes
(4% absolute calibration, <0.1% repeatability)

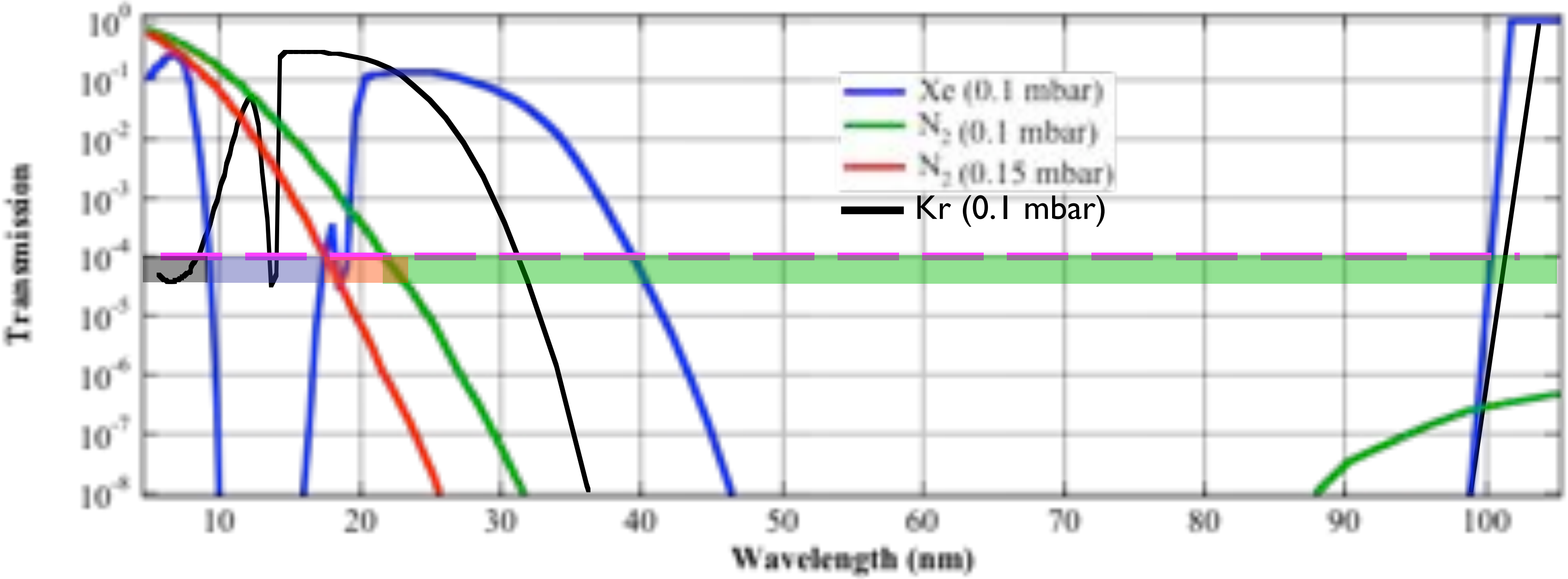



*In collaboration with the Instrumentation Group and T-REX lab for prototyping the systems*

# Gas reduction cell



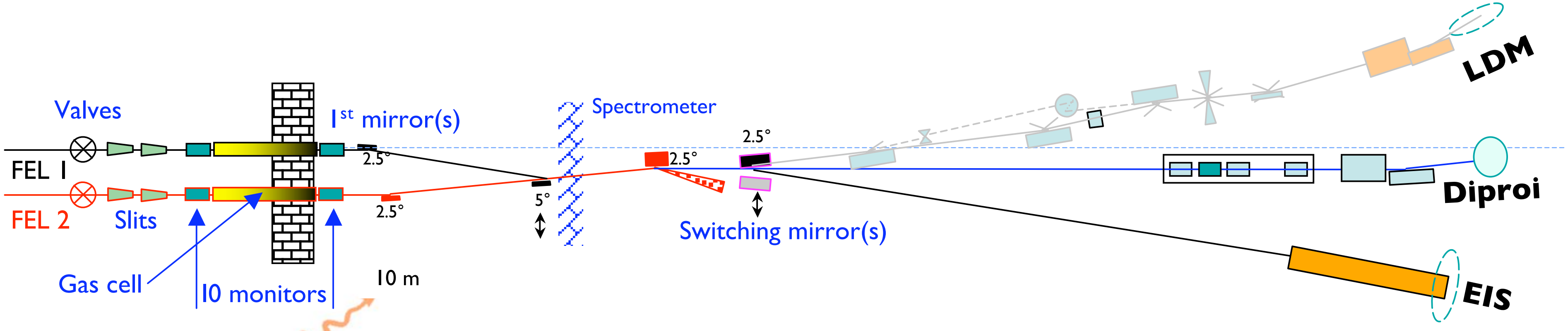


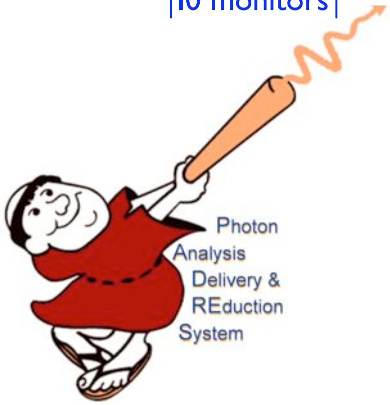




Gas Absorber Cell:
length = 6 m

- **Maximum attenuation on the whole photon energy range = $10^{-4}$**
- **Use of different gases at different pressures**
- **Preservation of coherence, statistics, spectrum, etc.**

# Photon diagnostics




: will be the possibility to measure the following characteristics:

- Intensity: On line; Shot by shot; 1% repeatability, 2-3% precision (calibration dependent)
- Angular position: On line; Shot by shot; ~2 μrad sensibility
- Divergence: NOT On line; NOT Shot by shot; based on YAG crystal measurements
- Photon energy distribution: On line; Shot by shot; Single spectrometer, 12-360 eV sub mV resolution.
- Arrival time: On line; Shot by shot; Visible streak camera (Timing and Synchronization Area) ps resolution
- Wavefront: Hartmann sensor (Imagine Optic), Precision λ/50 at 20-5 nm range or CCD
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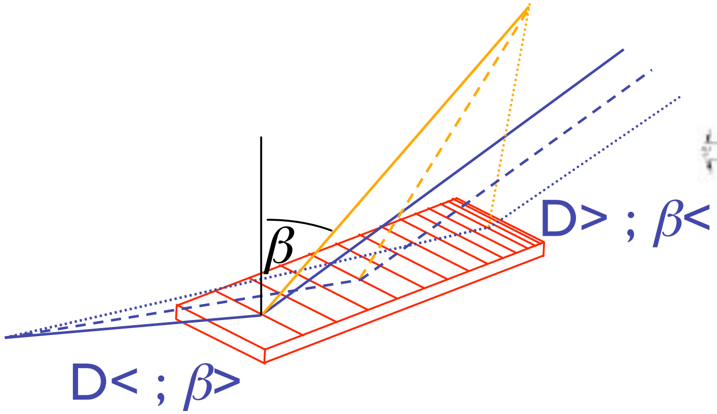
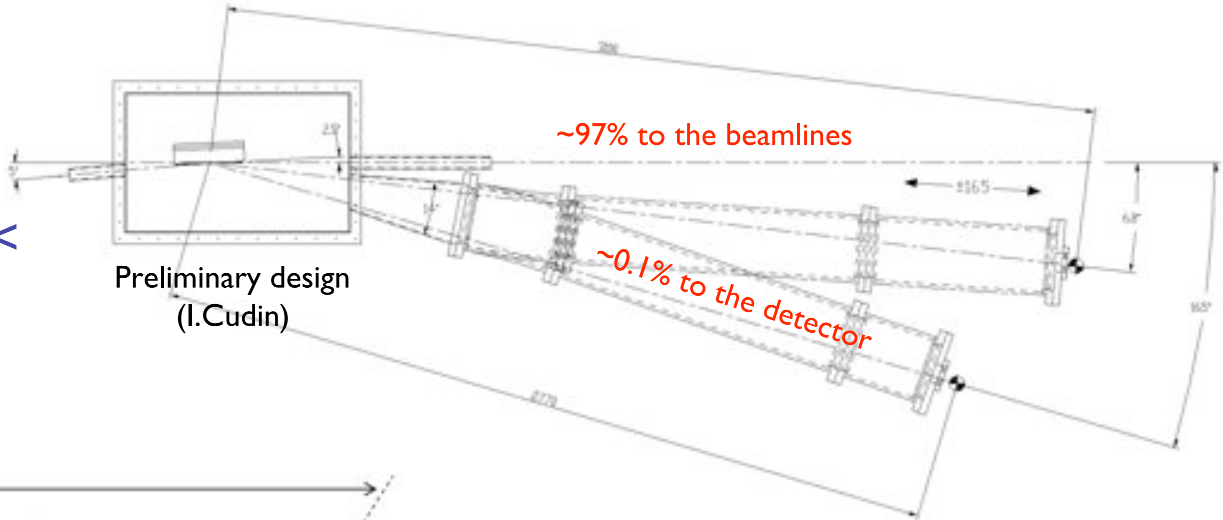
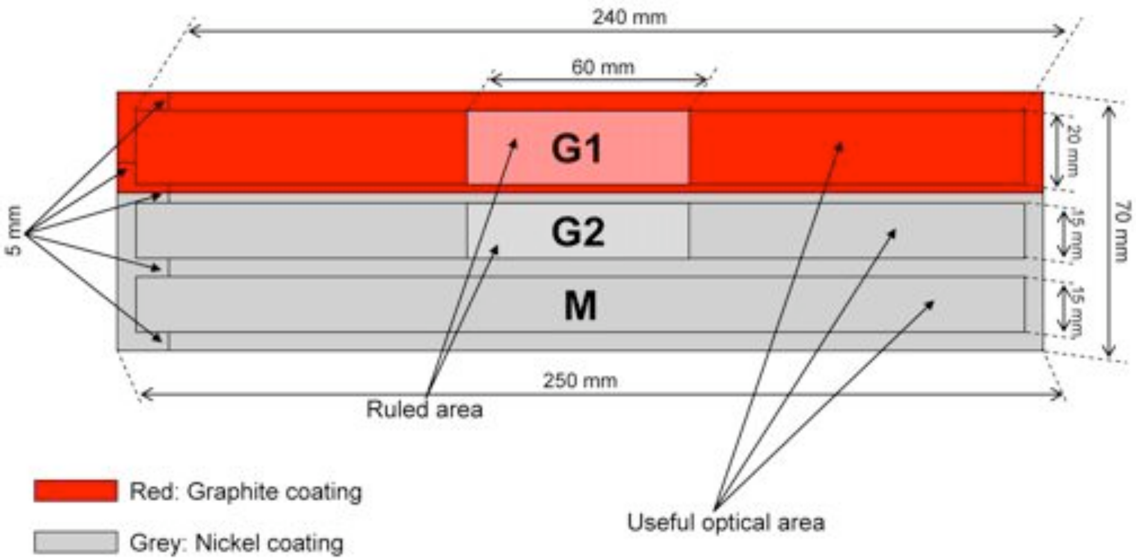
# Energy spectrometer

## Variable Line Spacing grating



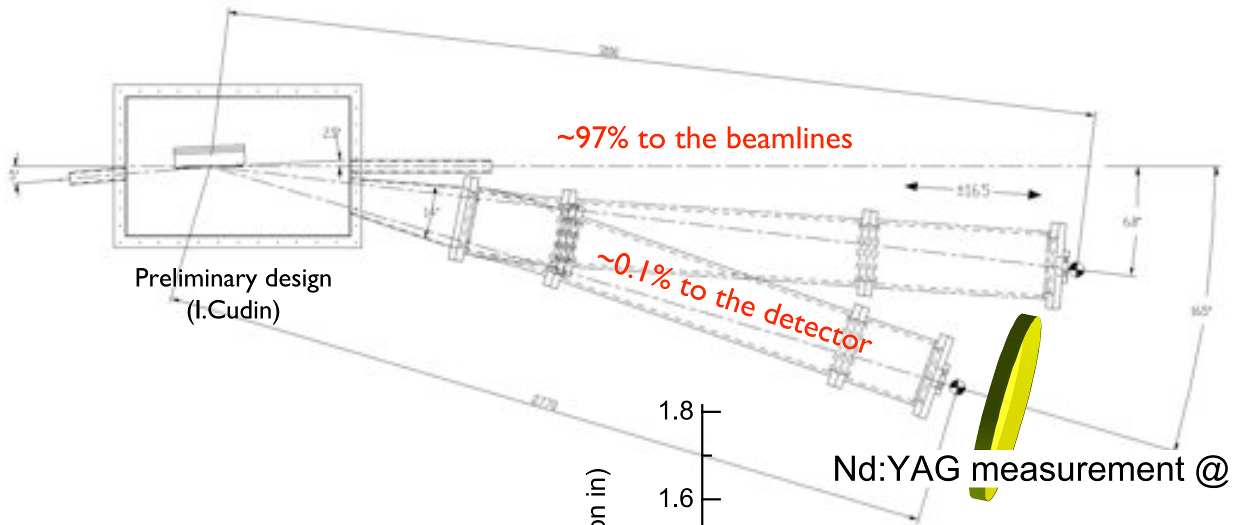




G1 ⇒ $N_0$=500 l/mm, $N_1$=0.35 l/mm$^2$,
$N_2$=1.7x10$^{-4}$ l/mm$^3$
Graphite coated
12-90 eV in 1st and 2nd order
ΔE: 0.2 meV to 3 meV

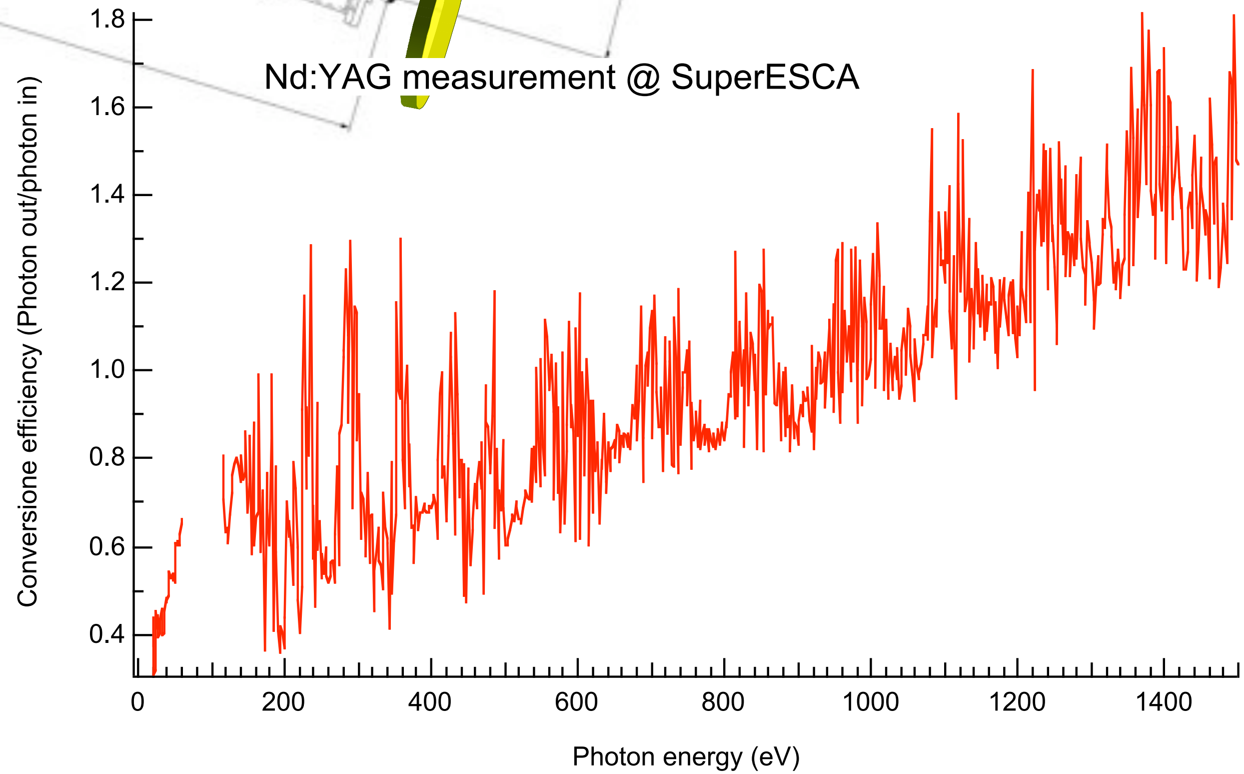
G2 ⇒ $N_0$=1800 l/mm, $N_1$=1.26 l/mm$^2$,
$N_2$=6.3x10$^{-4}$ l/mm$^3$
Ni coated
30-360 eV in 1st and 2nd order
ΔE: 0.3 meV to 3-4 meV

# Energy spectrometer




Preliminary design
(I.Cudin)

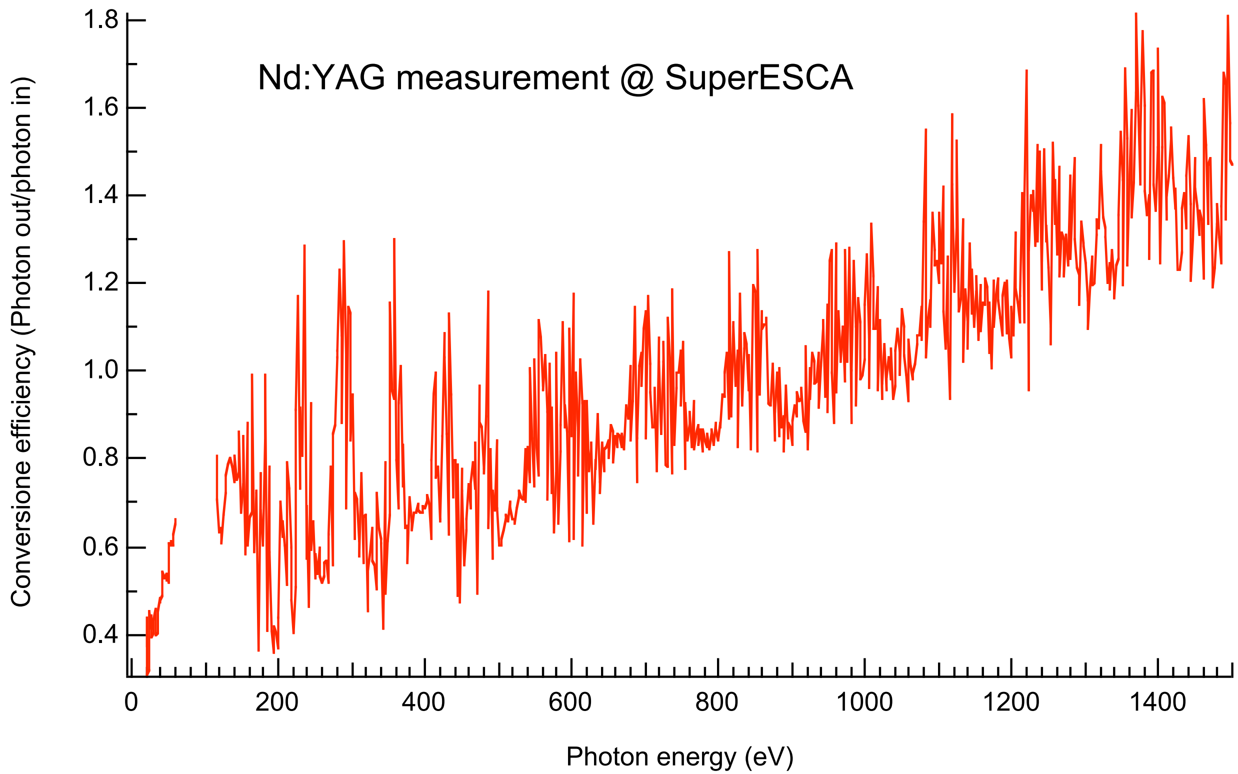
YAG Crystal to convert
XUV into Visible



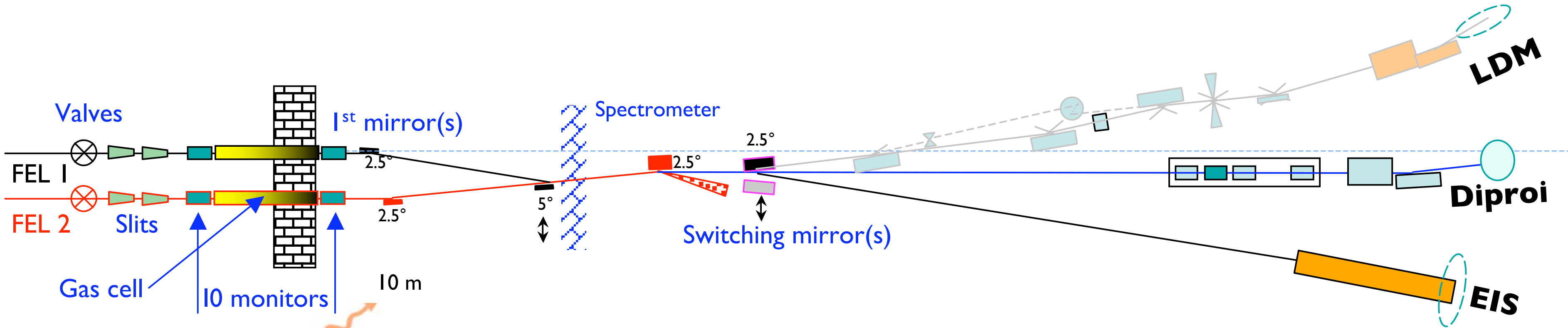
# Energy spectrometer

| Photon energy (eV) | Photon per pulse | Bandwidth (meV) | Grating efficiency | Screen efficiency (Vis ph out/XUV ph in) | CCD efficiency | Spot dimension (μm) | Energy resolution (meV) | Expected photon per pixel ($10x10\mu m^2$) with demagnification 2:1 |
|---|---|---|---|---|---|---|---|---|
| 12 | ~ 2 $10^{14}$ | 20 | 0.1% | 0.25 | ~ 85% | 4.5 μm X13mm | 0.3 | ~ 250,000 |
| 31 | ~ 4 $10^{13}$ | 20 | 0.25% | 0.4 | ~ 85% | 5.9 μm X5.2mm | 1.0 | ~ 1,200,000 |
| 124 | ~ 1 $10^{13}$ | 10 | 0.2% | 1 | ~ 85% | 4.8 μm X1.6mm | 2.4 | ~ 125,000 |

Use of a set of visible filters



# Photon diagnostics





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- Pulse length measurement: NOT On line; NOT Shot by shot;

# Pulse length measurement

VUV pulse lengths can be measured by:

- Cross-correlation, …, with a short-pulse laser.
Can be applied to many systems (Above Threshold Ionization of noble gases, pump-probe of molecules, etc.) BUT time resolution is determined by jitter

- Streak camera type techniques: collaboration ST-Hamamatsu for a sub-ps EUV-SXR streak camera (Ref. F. Parmigiani, M. Zangrando)

- Autocorrelation (beam splitting). Precision depends entirely on mechanical design of optics. Requires non-linear phenomena.

*Courtesy by K. Prince*

# Pulse length measurement

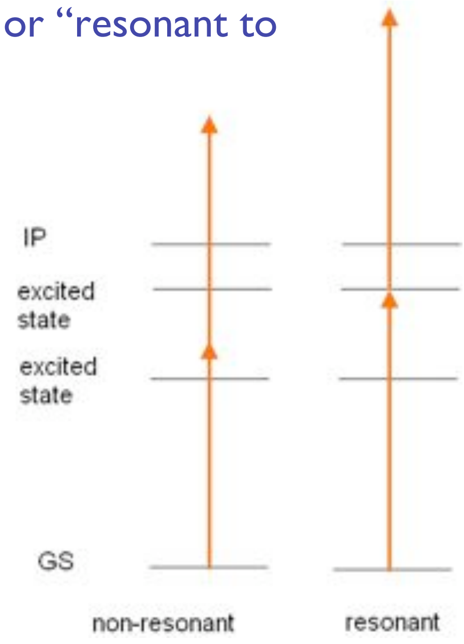
Autocorrelation by using Helium!

- first ionization potential is high, 24.6 eV, second is 79.004 eV,
- calculations exist, laser harmonic results exist,
- “canonical” three body system.

For FEL1, we can choose energies below 24.6 for “non-resonant to continuum” or “resonant to continuum” two photon ionization.

For FEL2, we can choose two-photon, double ionization (above 79 eV).

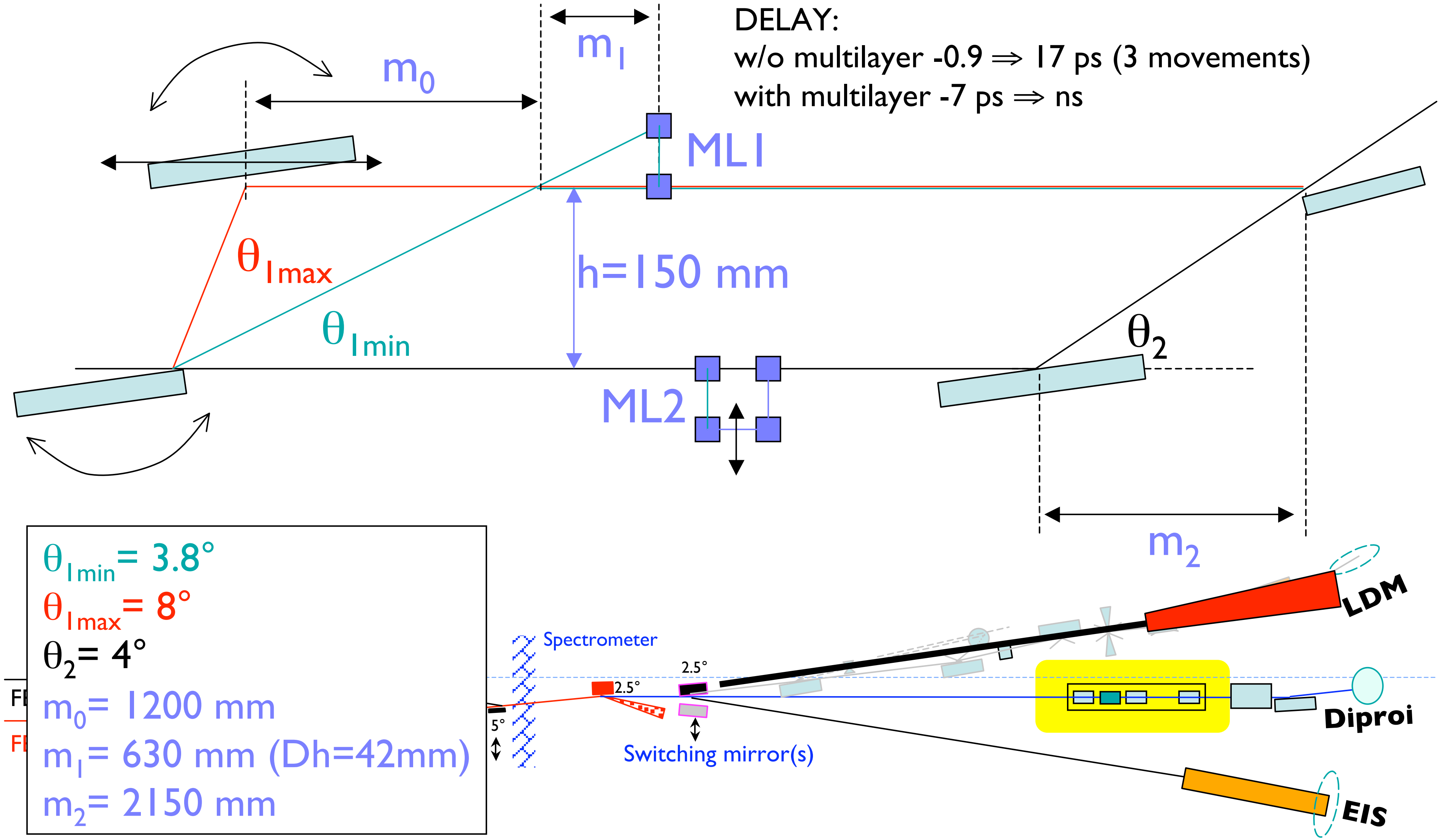
Feasibility
Cross-section is $10^{-50}$-$10^{-53}$ $cm^4$ s.
We estimate count rates of 1 to 100 counts/sec, for a 20x20 micron spot.




*Courtesy by K. Prince*

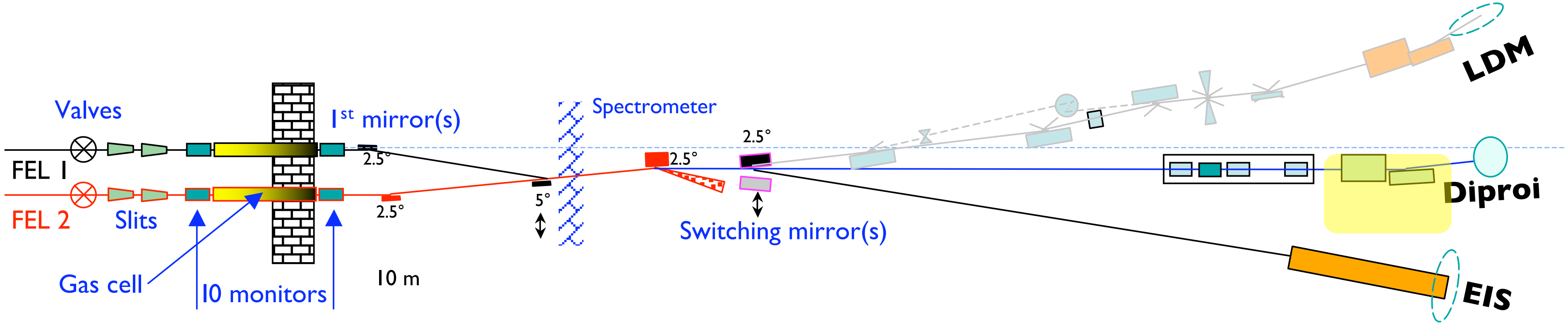
# Pulse length measurement

DELAY:
w/o multilayer -0.9 ⇒ 17 ps (3 movements)
with multilayer -7 ps ⇒ ns




$\theta_{I\,min}$= 3.8°
$\theta_{I\,max}$= 8°
$\theta_2$= 4°
$m_0$= 1200 mm
$m_I$= 630 mm (Dh=42mm)
$m_2$= 2150 mm

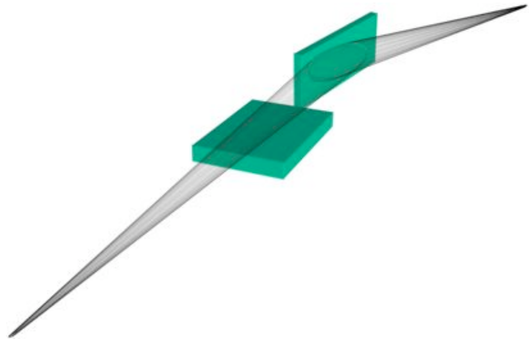
# Refocusing section




**"Focus" on:**

- Very high fluence
- Wavefront/coherence preservation
- Decoupled focusing (H vs. V)
- Variable source position

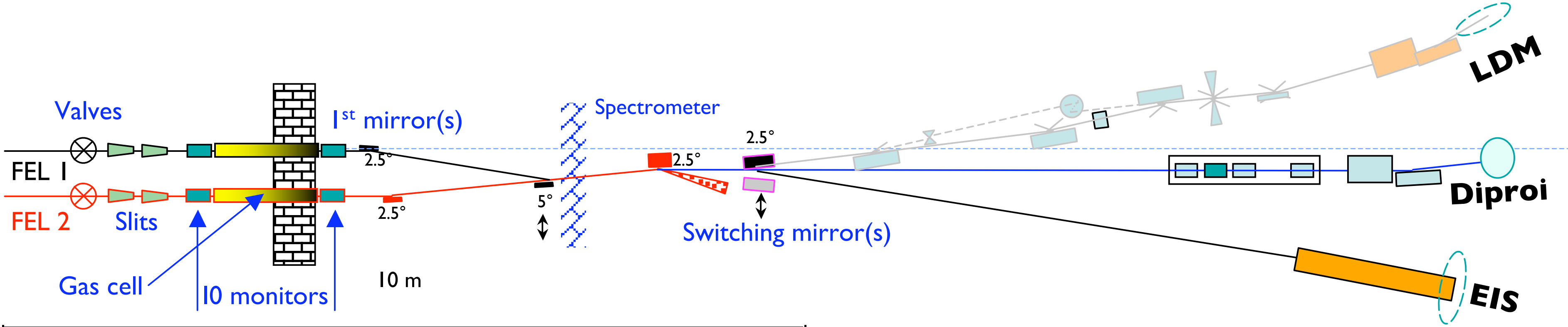
→ **Kirpatrick-Baez system with two "variable shape" plane-elliptical mirrors**



*Source–M1 ~ 75 m;   M2–Exp. chamber ~ 0.8 m*

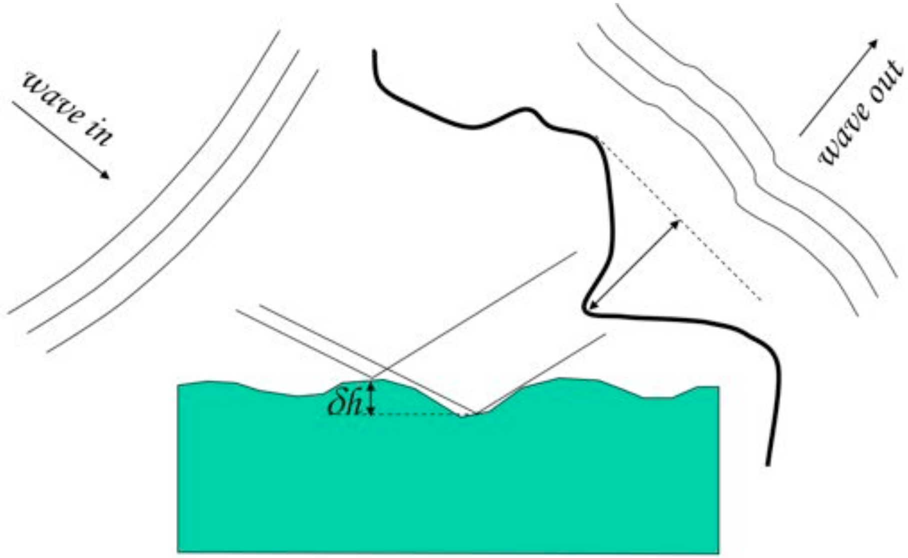
**Spot FEL 1**: on focus 4x2.5 μm$^2$ (~ 3x10$^{16}$ W/cm$^2$)
**Spot FEL 2**: on focus 3.5x2 μm$^2$ (~ 7x10$^{15}$ W/cm$^2$)

# Wavefront preservation




| Fermi@elettra case | | | |
|---|---|---|---|
| Wavelength | Angle of incidence | shape error p -v φ =0.25 | shape error p -v φ =0.1 |
| 40 nm | 6° | 47 | 18 |
| 40 nm | 3° | 95 | 38 |
| 40 nm | 1.5° | 191 | 76 |
| 10 nm | 3° | 23 | 9 |
| 10 nm | 2° | 35 | 14 |
| 10 nm | 1° | 71 | 28 |
| 5 nm | 3° | 12 | 5 |
| 5 nm | 2° | 18 | 7.2 |
| 5 nm | 1° | 36 | 14 |

**Ok for plane and spherical surfaces.**
**Almost impossible for toroidal, elliptical…**



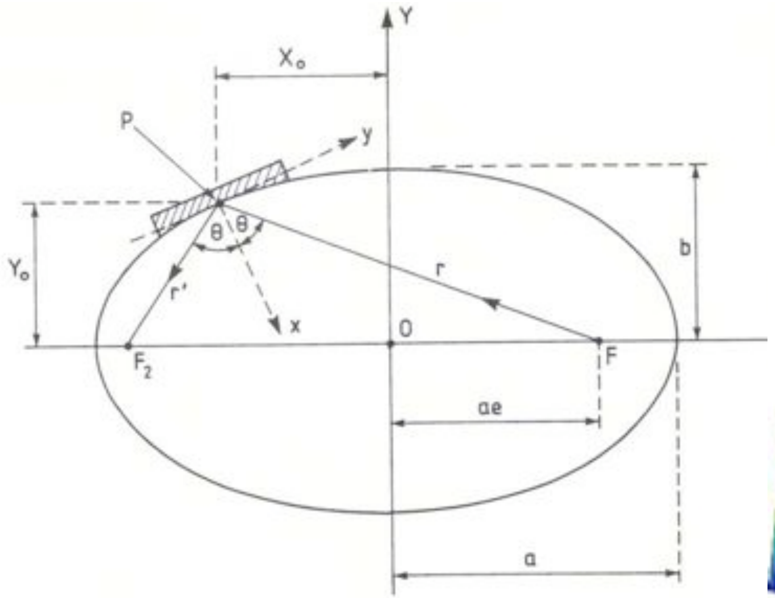

$$\varphi = \frac{2\delta h \cdot \sin\vartheta}{\lambda}$$

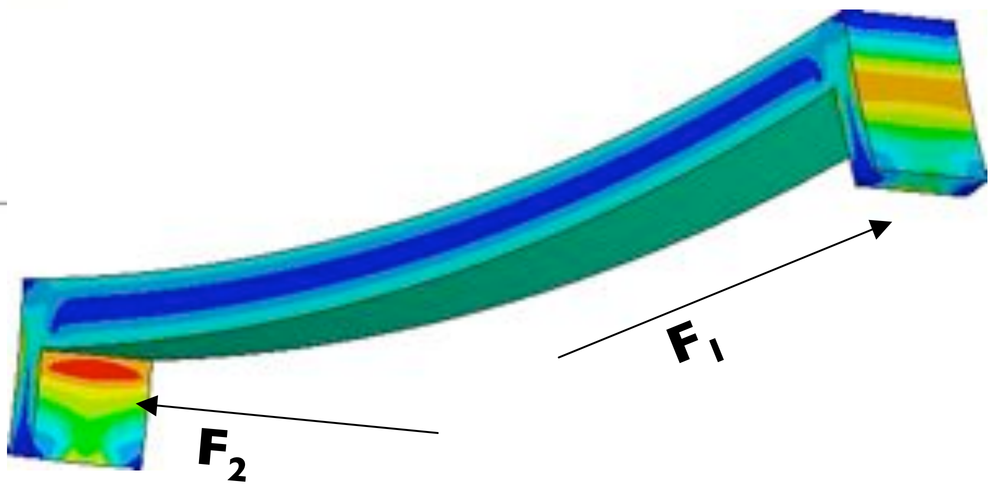
# Active optics project

$$x^2\left(\frac{\sin^2\vartheta}{b^2}+\frac{1}{a^2}\right)+y^2\left(\frac{\cos^2\vartheta}{b^2}\right)-x\left(\frac{4f\cos\vartheta}{b^2}\right)-xy\left[\frac{2\sin\vartheta\sqrt{e^2-\sin^2\vartheta}}{b^2}\right]=0$$

where: $f=\left(\frac{1}{r}+\frac{1}{r'}\right)^{-1}$

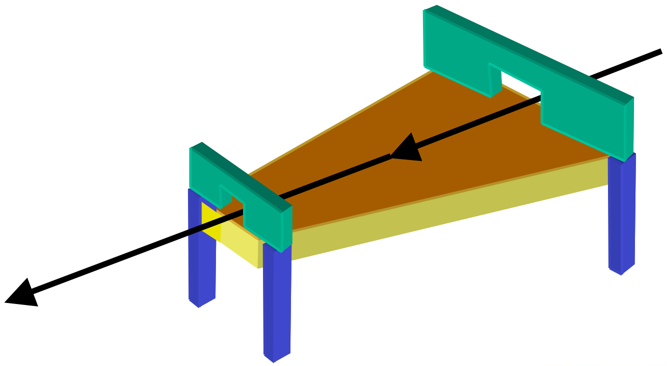
**Need for a 3rd order approximation in shape**




**Two unequal moments applied at the edges**

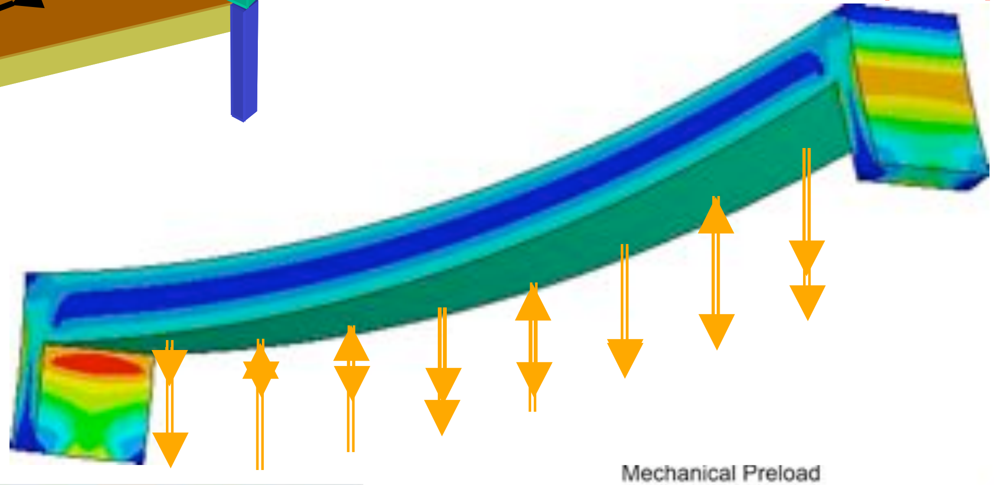
# Active optics project

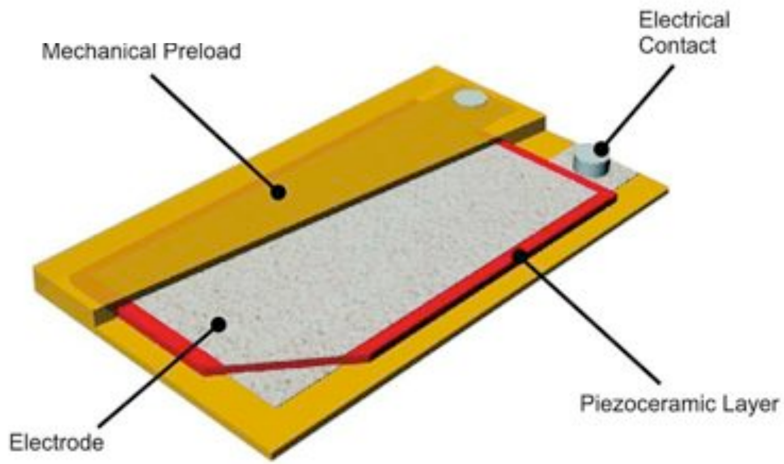


**Higher orders corrected by:**

Dynamic variation of the moment of Inertia

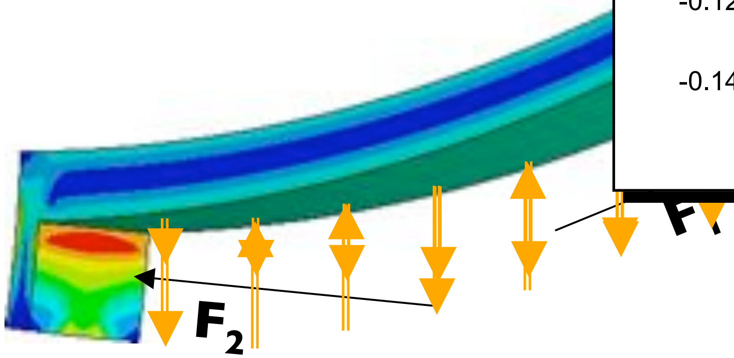
Correction of low frequency shape errors

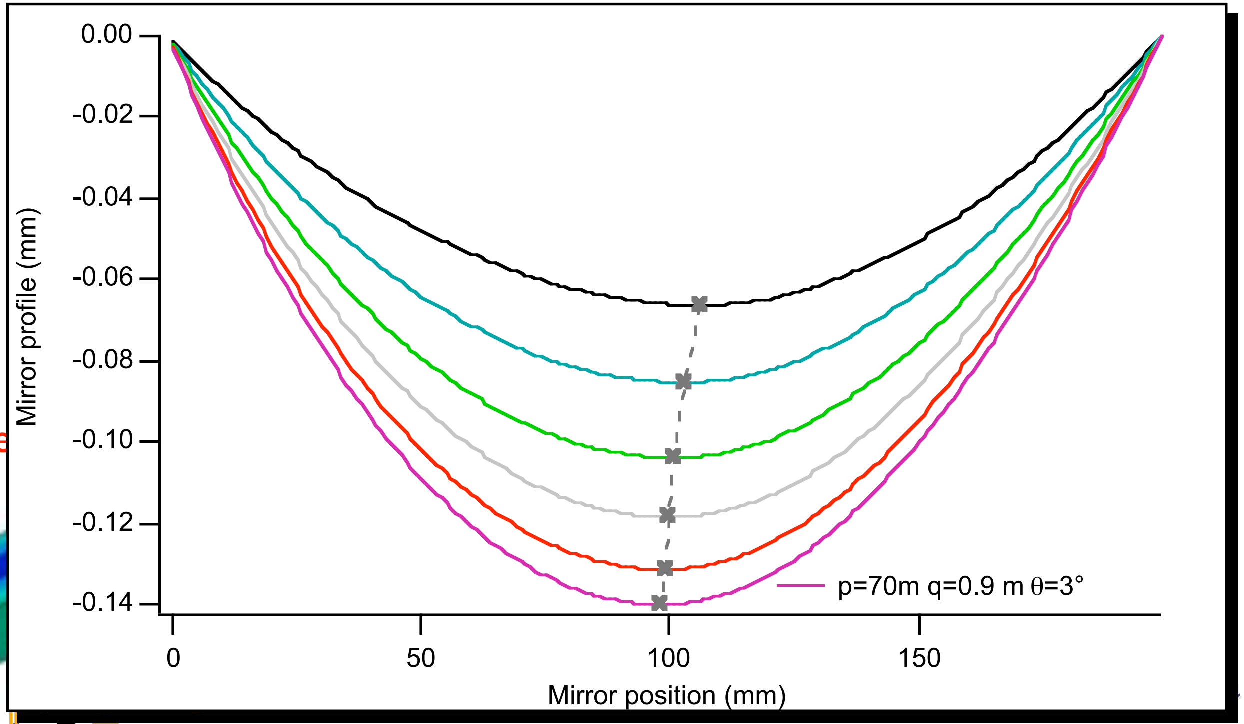


# Active optics project

Correction of low frequency shape



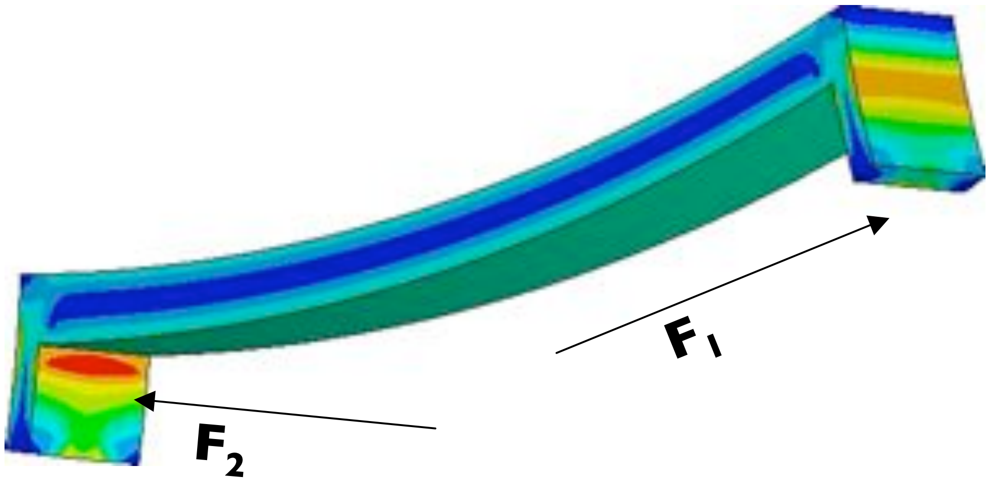

Obtained without 3rd order compensation

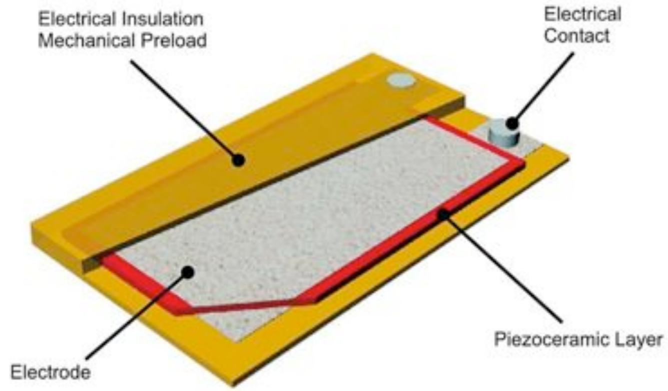
Source – M1 ~ 75 m; M2 - exp cham. ~ 0.8 m,

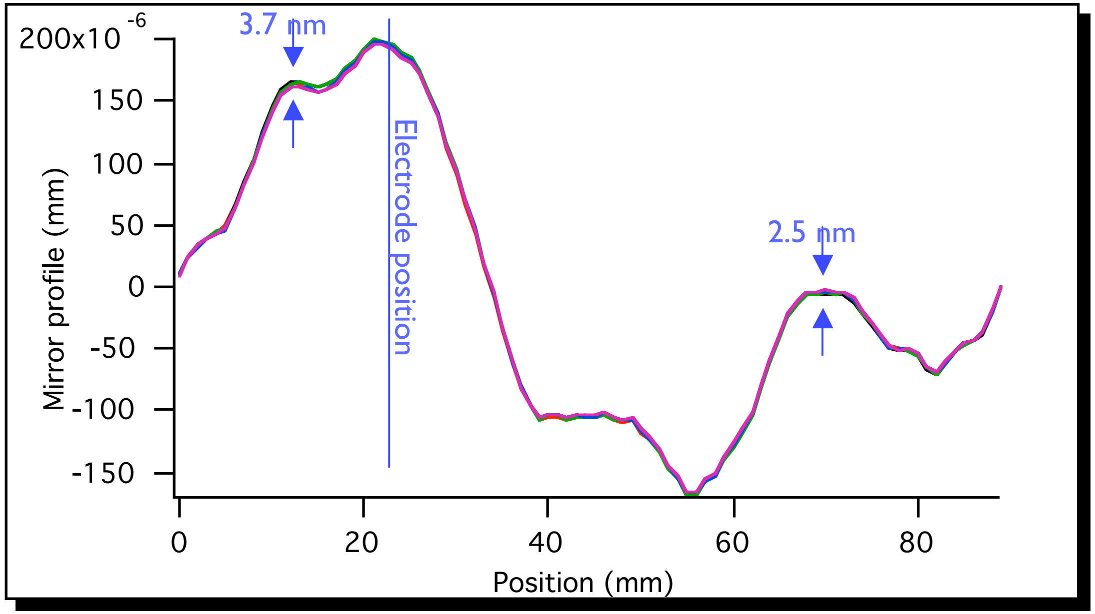
Spot FEL 1: on focus 4X2.5 μm² (~ 3x10¹⁶ W/cm²)

Spot FEL 2: on focus 3.5X2 μm² (~ 7x10¹⁵ W/cm²)

# Active optics project

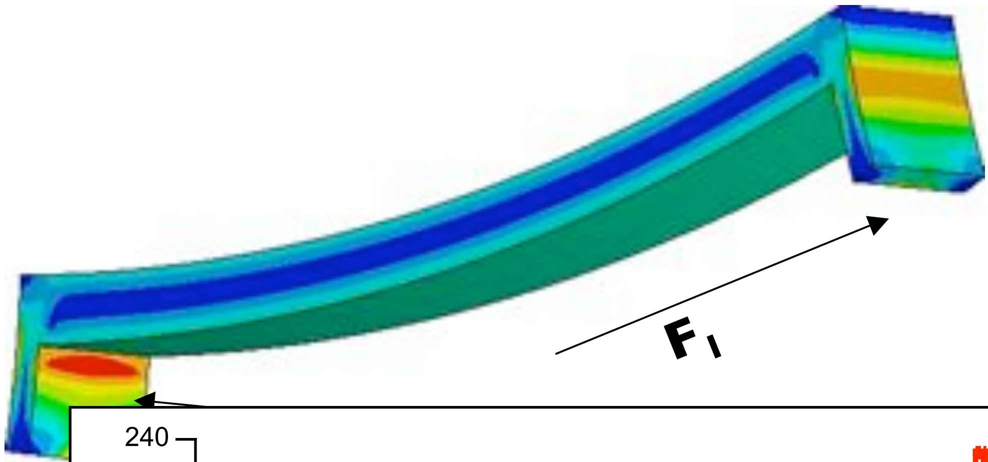


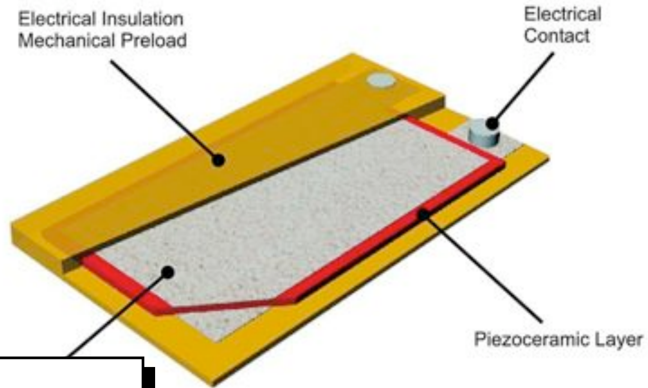



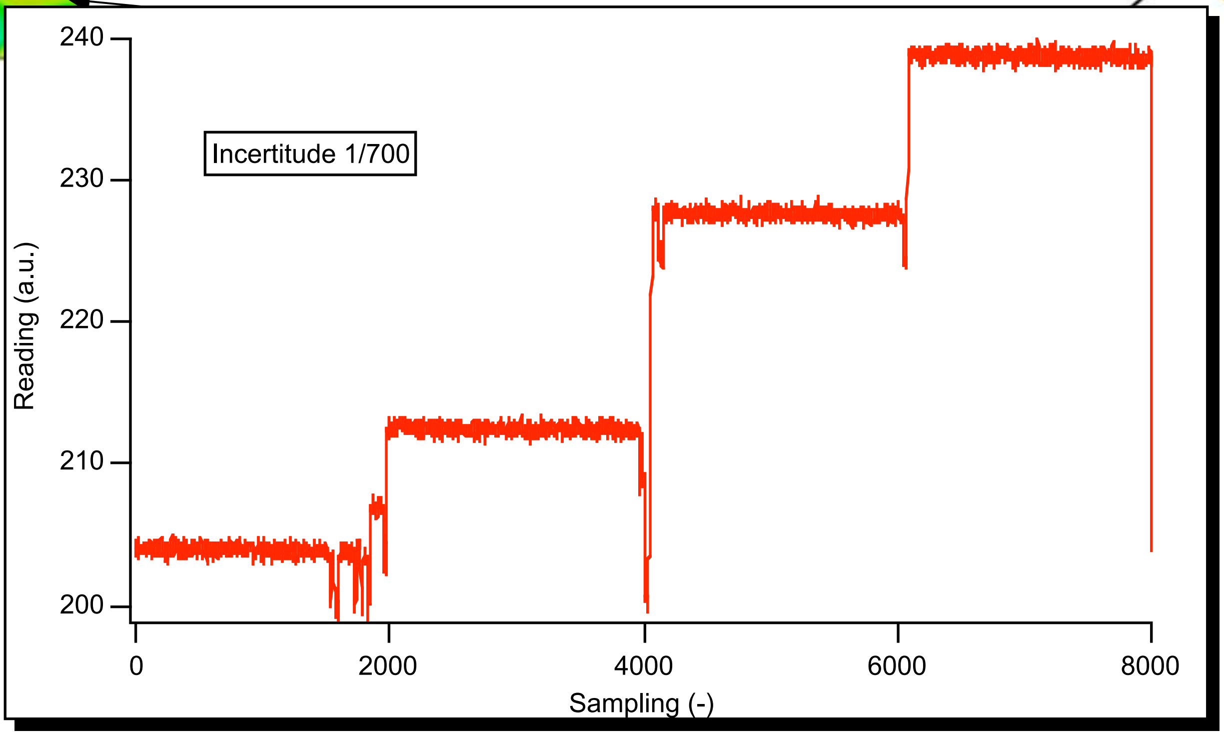




Mirror profile measurement over days with electrode in operation (30V)

# Active optics project

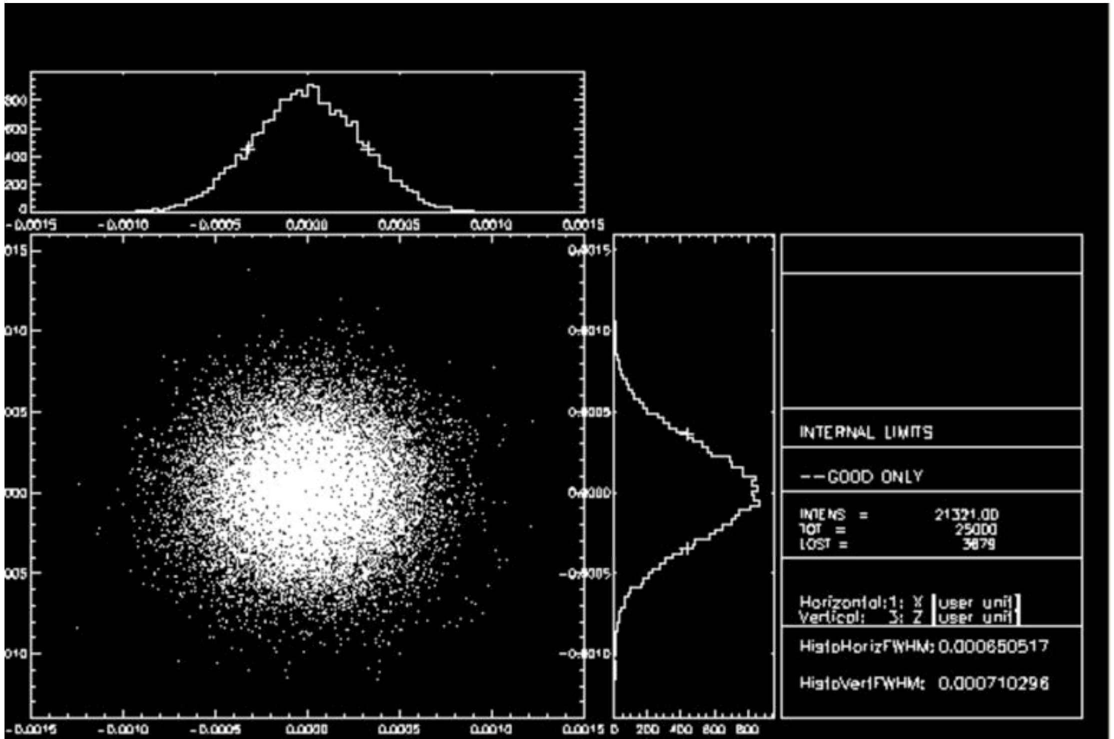



Measurement of the local radius of curvature using strain gauges glued on the back of the mirror

# Focusing systems comparison



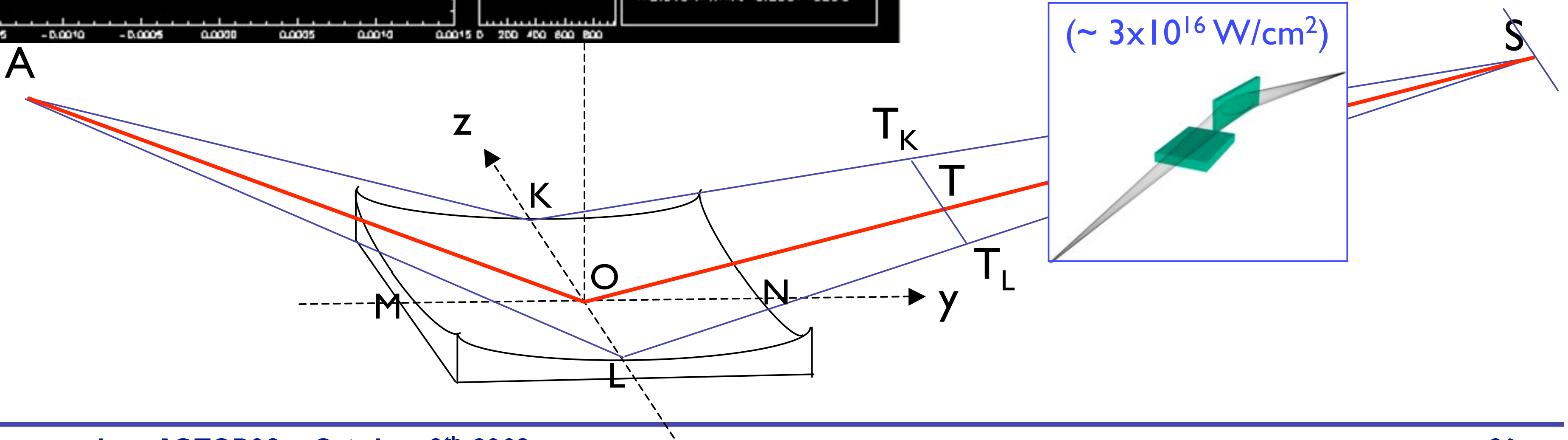

Spot at focus

| H Spot FWHM (μm) | V Spot FWHM (μm) |
|---|---|
| 6.5 | 7.1 |

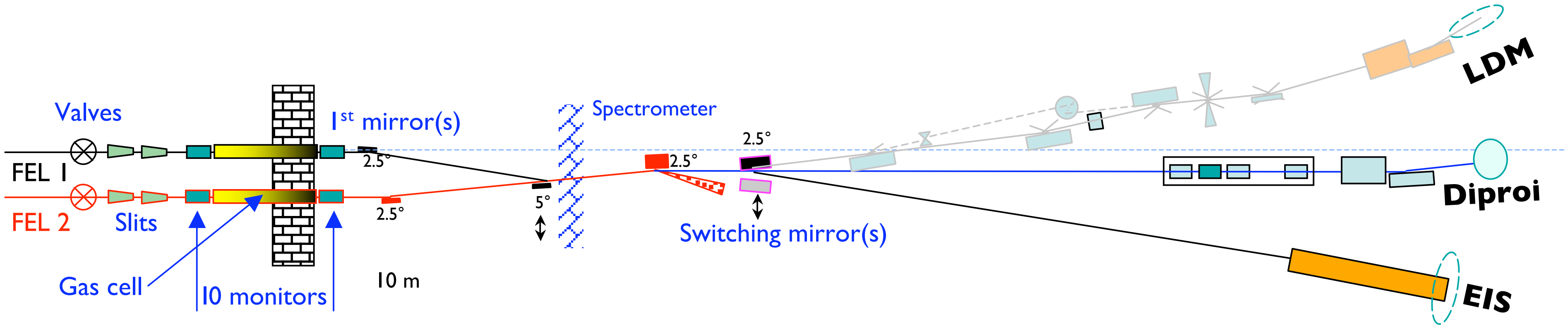
Spot at focus with 1μrad slope errors

| H Spot FWHM (μm) | V Spot FWHM (μm) |
|---|---|
| 6.5 | 12.7 |

(~ $4\times10^{15}$ W/cm$^2$)

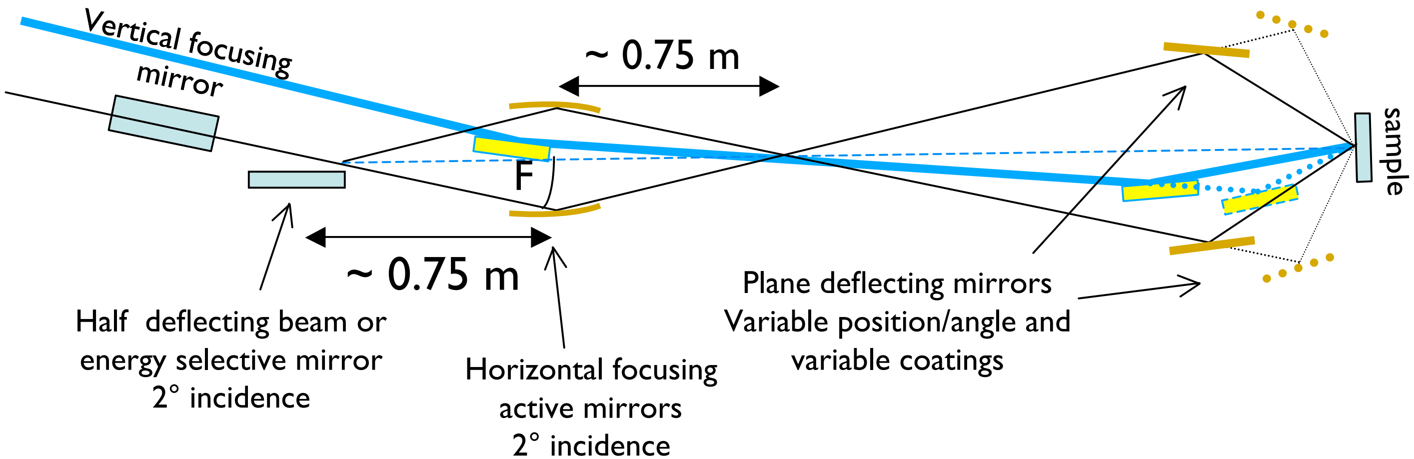


# EIS focusing system

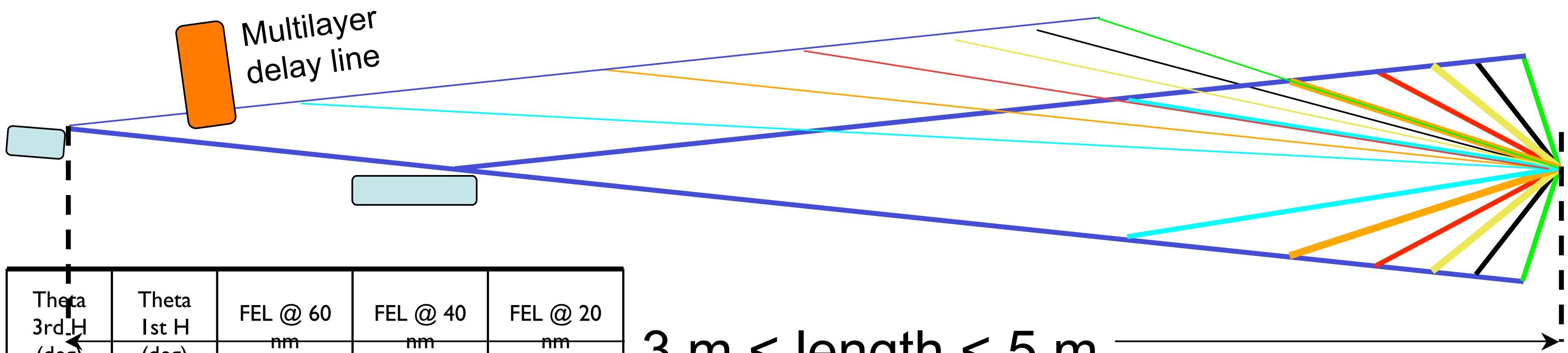



**Simplified to have**
**"just" 4 angles and 3 wavelength**

**Higher/lower orders contamination < 1%**



# EIS focusing system

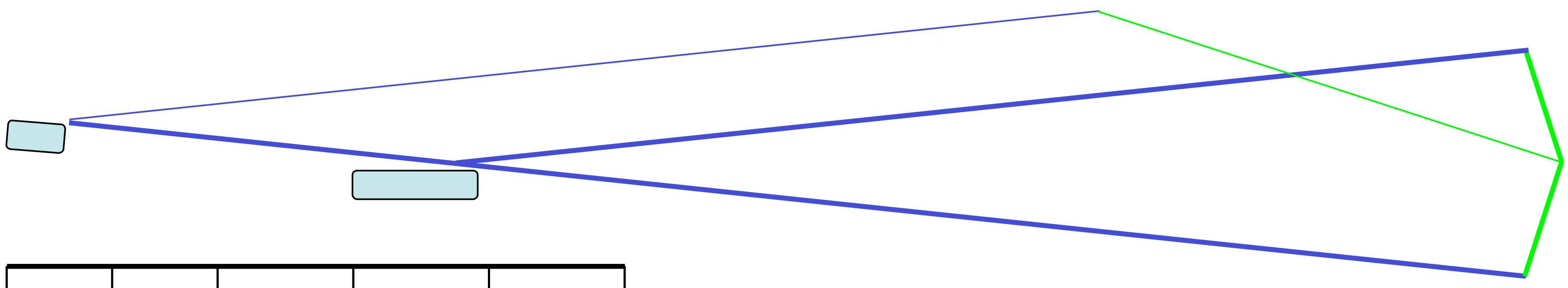



| Theta 3rd H (deg) | Theta 1st H (deg) | FEL @ 60 nm | FEL @ 40 nm | FEL @ 20 nm |
|---|---|---|---|---|
| **1.53** | **4.6** | **0.017** | **0.025** | **0.05** |
| **3.05** | **9.2** | **0.033** | **0.05** | **0.1** |
| **4.56** | **13.8** | **0.05** | **0.075** | **0.15** |
| **6.1** | **18.6** | **0.067** | **0.1** | **0.2** |
| **7.6** | **23.4** | **0.083** | **0.125** | **0.25** |
| **9.1** | **28.5** | **0.1** | **0.15** | **0.3** |
| **10.7** | **33.9** | **0.117** | **0.175** | **0.35** |
| **12.2** | **39.5** | **0.133** | **0.2** | **0.4** |
| **13.8** | **45.7** | **0.015** | **0.225** | **0.45** |
| **15.4** | **52.7** | **0.167** | **0.25** | **0.5** |
| **17** | **61.1** | **0.183** | **0.275** | **0.55** |
| **18.6** | **72.7** | **0.2** | **0.3** | **0.6** |

Delay required:
-10 ps < Δt < 5 ns
-3 mm < Δt < 1.5 m
Precision: 10 fs (3μm)

# EIS focusing system

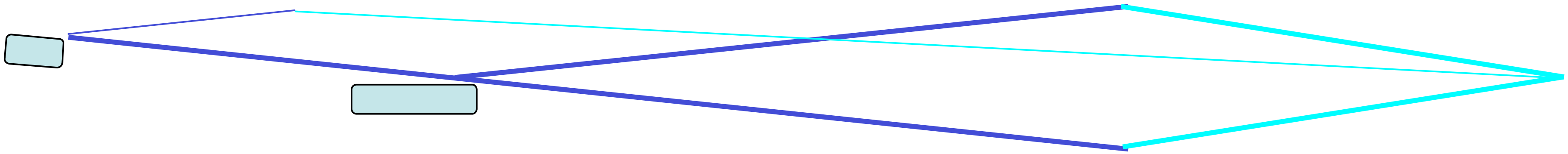




| Theta 3rd H (deg) | Theta 1st H (deg) | FEL @ 60 nm | FEL @ 40 nm | FEL @ 20 nm |
|---|---|---|---|---|
| 1.53 | 4.6 | 0.017 | 0.025 | 0.05 |
| 3.05 | 9.2 | 0.033 | 0.05 | 0.1 |
| 4.56 | 13.8 | 0.05 | 0.075 | 0.15 |
| 6.1 | 18.6 | 0.067 | 0.1 | 0.2 |
| 7.6 | 23.4 | 0.083 | 0.125 | 0.25 |
| 9.1 | 28.5 | 0.1 | 0.15 | 0.3 |
| 10.7 | 33.9 | 0.117 | 0.175 | 0.35 |
| 12.2 | 39.5 | 0.133 | 0.2 | 0.4 |
| 13.8 | 45.7 | 0.015 | 0.225 | 0.45 |
| 15.4 | 52.7 | 0.167 | 0.25 | 0.5 |
| 17 | 61.1 | 0.183 | 0.275 | 0.55 |
| 18.6 | 72.7 | 0.2 | 0.3 | 0.6 |

Delay required:
-10 ps < $\Delta t$ < 5 ns
-3 mm < $\Delta t$ < 1.5 m
Precision: 10 fs (3µm)

# EIS focusing system

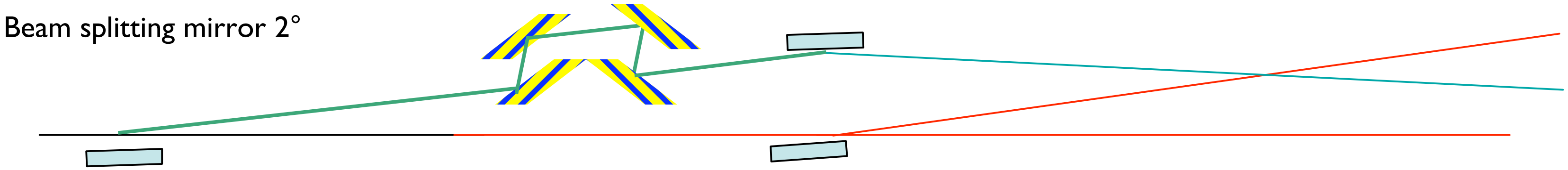


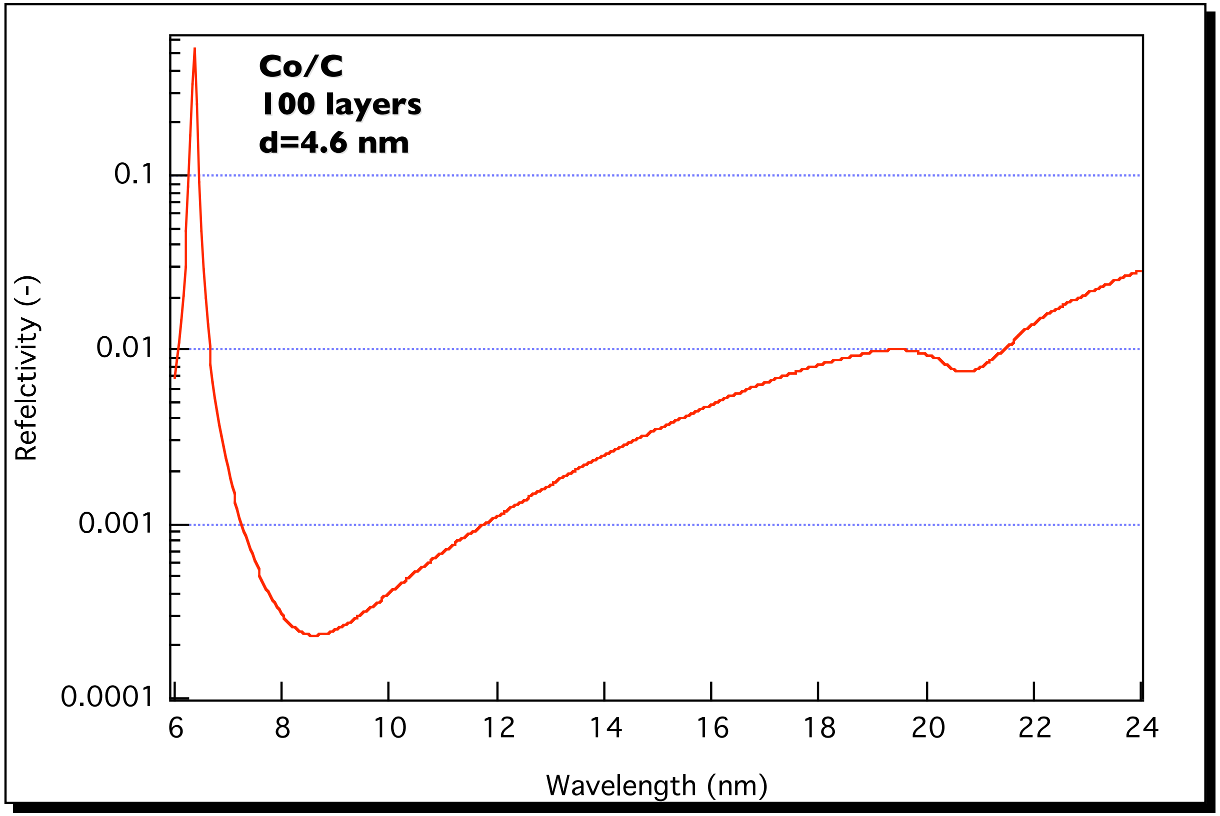
| Theta 3rd H (deg) | Theta 1st H (deg) | FEL @ 60 nm | FEL @ 40 nm | FEL @ 20 nm |
|---|---|---|---|---|
| **1.53** | **4.6** | **0.017** | **0.025** | **0.05** |
| **3.05** | **9.2** | **0.033** | **0.05** | **0.1** |
| **4.56** | **13.8** | **0.05** | **0.075** | **0.15** |
| **6.1** | **18.6** | **0.067** | **0.1** | **0.2** |
| **7.6** | **23.4** | **0.083** | **0.125** | **0.25** |
| **9.1** | **28.5** | **0.1** | **0.15** | **0.3** |
| **10.7** | **33.9** | **0.117** | **0.175** | **0.35** |
| **12.2** | **39.5** | **0.133** | **0.2** | **0.4** |
| **13.8** | **45.7** | **0.015** | **0.225** | **0.45** |
| **15.4** | **52.7** | **0.167** | **0.25** | **0.5** |
| **17** | **61.1** | **0.183** | **0.275** | **0.55** |
| **18.6** | **72.7** | **0.2** | **0.3** | **0.6** |

Delay required:
-10 ps < Δt < 5 ns
-3 mm < Δt < 1.5 m
Precision: 10 fs (3μm)

# EIS focusing system

Higher/lower orders contamination < 1%



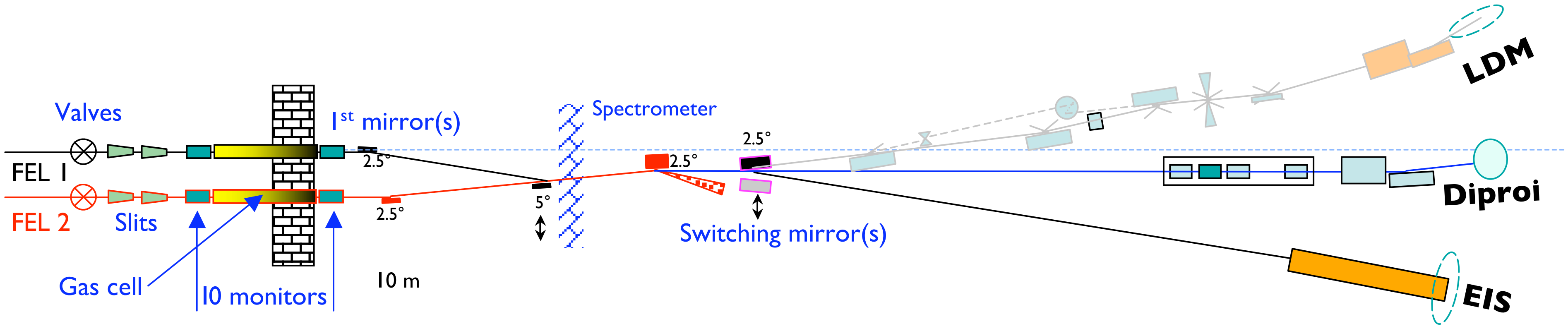

**Ratio eff. 6.33nm/eff. 20nm**
**1 mirror ⇒ 57**
**2 mirrors ⇒ 3300**
**4 mirrors ⇒ $10^7$**

**Source:**

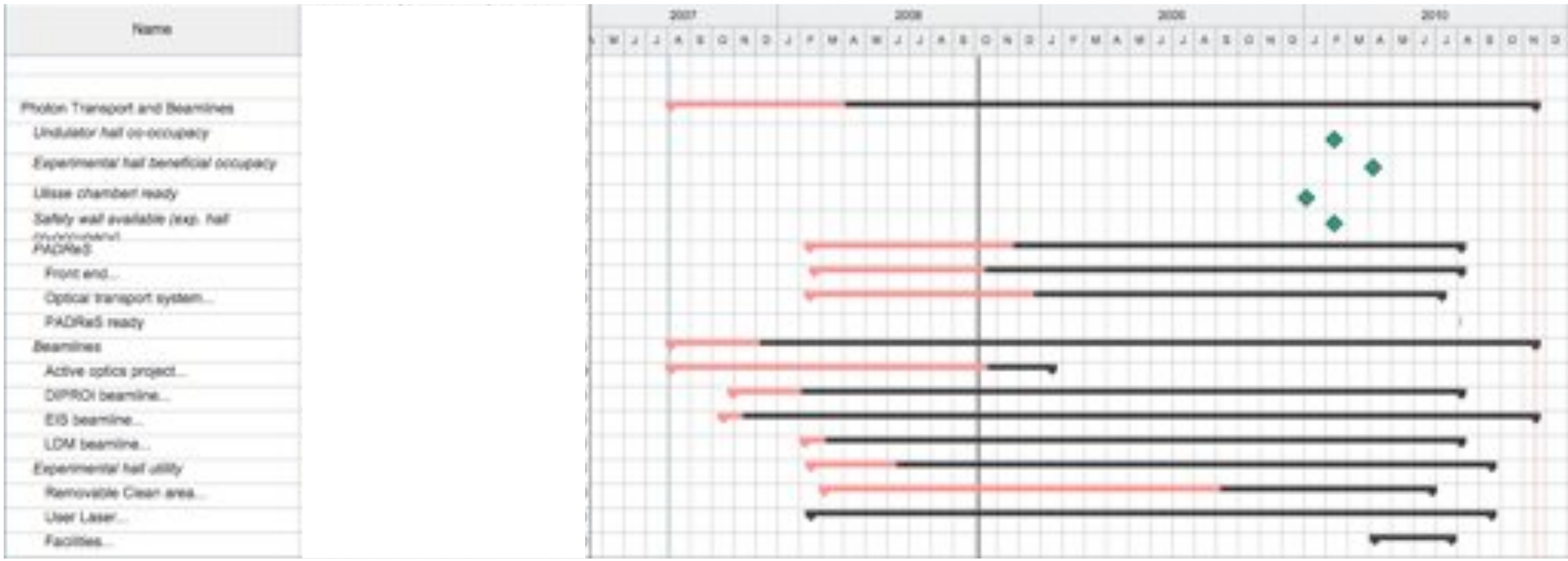
$$\frac{Intensity\ \ 20nm\ \left(1^{st}\ harm\right)}{Intensity\ \ 6.33nm\ \left(3^{rd}\ harm\right)} \geq 100$$

| | Material | Efficiency |
|---|---|---|
| **40 m** | Sc/Si | 70% |
| **20 m** | Mo/Si | 70% |
| **13.3nm** | Mo/Si | 75% |
| **6.33nm** | Co/C | 50% |

# Schedule



Valves
FEL 1
FEL 2
Slits
Gas cell
I0 monitors
1st mirror(s)
2.5°
2.5°
5°
10 m
Spectrometer
2.5°
2.5°
Switching mirror(s)
LDM
Diproi
EIS

Name
2007
2008
2009
2010
Photon Transport and Beamlines
Undulator hall co-occupacy
Experimental hall beneficial occupacy
Ulisse chamber ready
Safety wall available (exp. hall
PADReS
Front end...
Optical transport system...
PADReS ready
Beamlines
Active optics project...
DIPROI beamline...
EIS beamline...
LDM beamline...
Experimental hall utility
Removable Clean area...
User Laser...
Facilities...

**THANK YOU**
**FOR YOUR ATTENTION**