High Heat Load optics optimisation for ESRF upgrade beamlines

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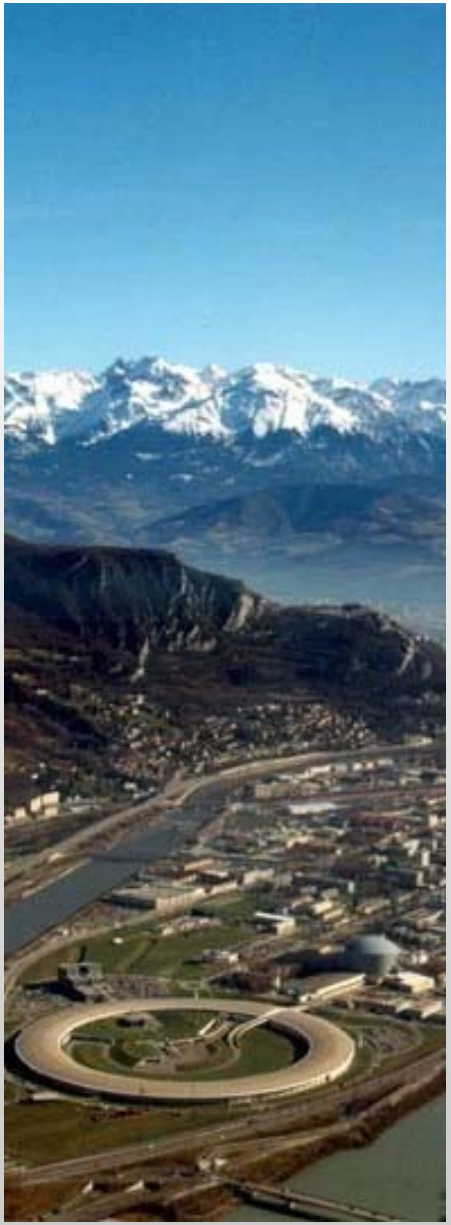
European Synchrotron Radiation Facility

The ESRF Upgrade Programme



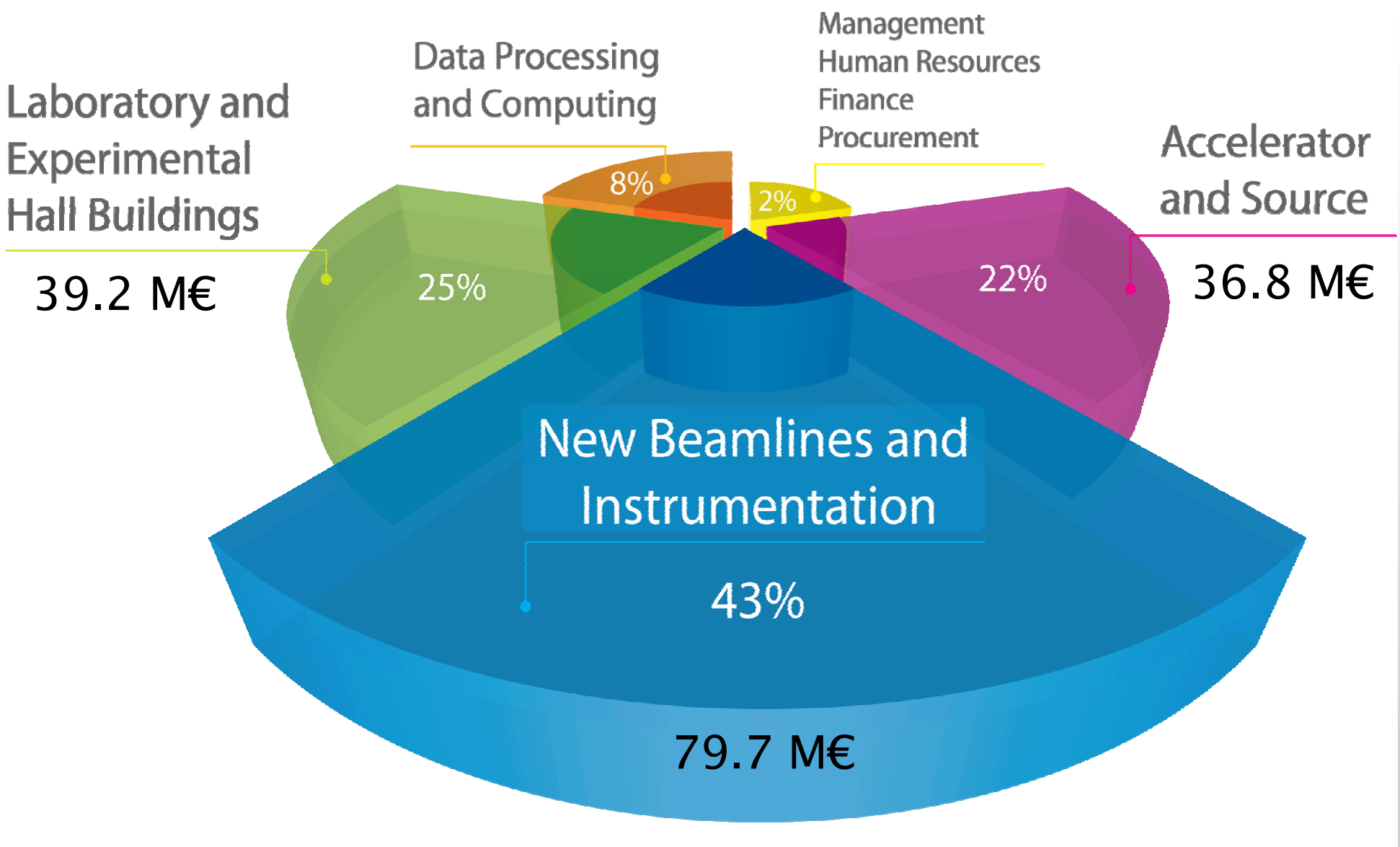
Phase I
2009-2015

2004: Long term strategy
2007: Upgrade proposal
2008: Approved by the ESRF council

Vision for 2009 to 2018 mapped out in Purple Book

- ***Science case***
- ***Enabling technology***
- ***Budget***

Upgrade Programme: 180 M€ ($240M) Budget



Implementation of UPBLs

TDR/CDR | Construction

UPBL	Old Sector	New Sector	Application
UPBL1	ID01	ID01	Diffraction imaging for nano-analysis
UPBL2	ID15	ID31	High Energies for interfaces and materials processing
UPBL4	ID22	ID16	Nano-Imaging and Nano-Analysis
UPBL6	ID16	ID20	INElastic X-ray Scattering
UPBL7	ID08	ID08	Soft X-rays/nano-magnetic & electronic spectroscopy
UPBL9a	ID02	ID02	Time-resolved ultra small angle scattering
UPBL9b	ID09TR	ID09	Pump-probe and time-resolved experiments
UPBL10	ID14	ID30	Massively Automated Sample Selection Integrated Facility
UPBL11	ID24/BM29	ID24/BM23	Time-resolved and Extreme conditions XAS

+ refurbishment beamlines

High Heat-Load Optics optimisation

High Heat-Load optics optimisation: why ?

Beamline performance depends on:

- Source properties: SR (Storage Ring), ID (Insertion Device)
- **Beamline layout**
- **Optics performance**
- Detector, and control system
- Stability, and reliability of beamline components

Optics with better performance

- Long beamline, Nanofocusing
- X-ray source properties and coherence preservation
- No wave front phase shift (due to optics deformation)

Higher heat load on optics

- In-vacuum undulator (small gap), cryo-undulator
- Longer straight section (5m → 6m, 7m)
- (higher e-beam current: 200 → 300 mA)

High Heat-Load optics optimisation → minimize the thermal deformation of the optics

High Heat-Load optics optimisation: how ?

Heat load management (on the optics)

- **Photon energy range**
  - Specified by sciences in the beamline, defined by IDs
- **X-ray source: Undulator** (Wiggler, Bending magnet)
  - Band width of photon spectrum
  - Different **period (λ_u=17 ~ 46 mm)** offers large choice for beamlines
  - Revolvers offers more choice of undulators for one beamline
  - Peak magnet field **B_0(T)**
  - Tunable by changing **gaps ($\geqslant$ 6mm)**
- **Optics (properties related to power absorption)**
  - **Crystal monochromator (Si, Ge,…)** : absorbs nearly all incident beam (Δ e/e ~ 10^{-4})
  - **White beam Mirror**: absorbs photons with energy higher than cut-off (grazing angle, coating material)
  - **Multilayer monochromator**: similar than the crystal monochromator but with large bandwidth (Δ e/e ~ 10^{-2}), reflected power ~ a few percent of the incident power
  - **White beam multilayer mirror**: reflection of higher energy photon than white beam mirror
  - (Attenuators: absorbs low energy photons, used when working with high energy photons, especially in high energy beamline)

Optical layout (optical elements, combination)

Optics optimisation

High Heat-Load optics optimisation: how ?

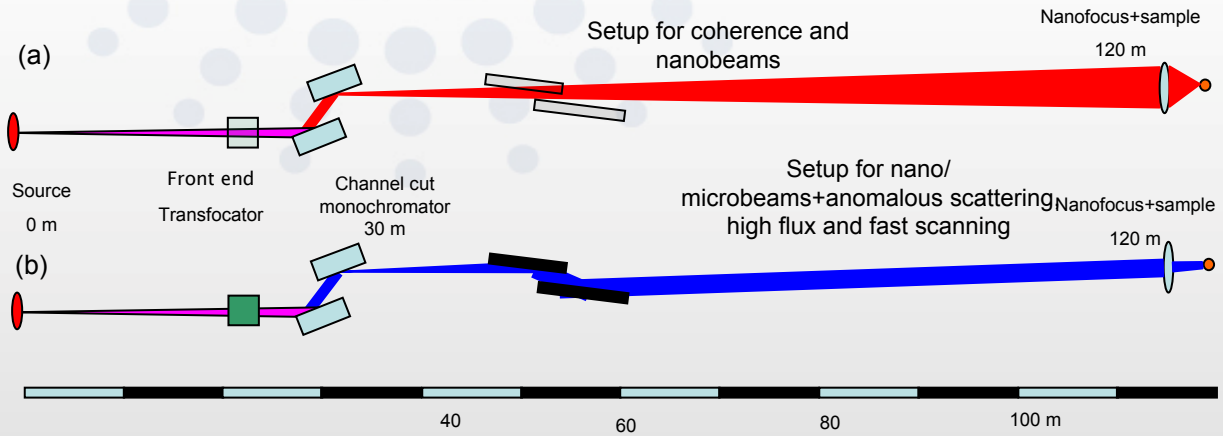
Example of UPBL01

(Diffraction imaging for nano-analysis)

Optical layout (UPBL01)

Very first version *(before heat load consideration of the optics)*

- Essentially using a channel-cut Silicon crystal monochromator as HHL optical component



(a) Optical configuration using a channel cut monochromator, all other components are inactive or removed

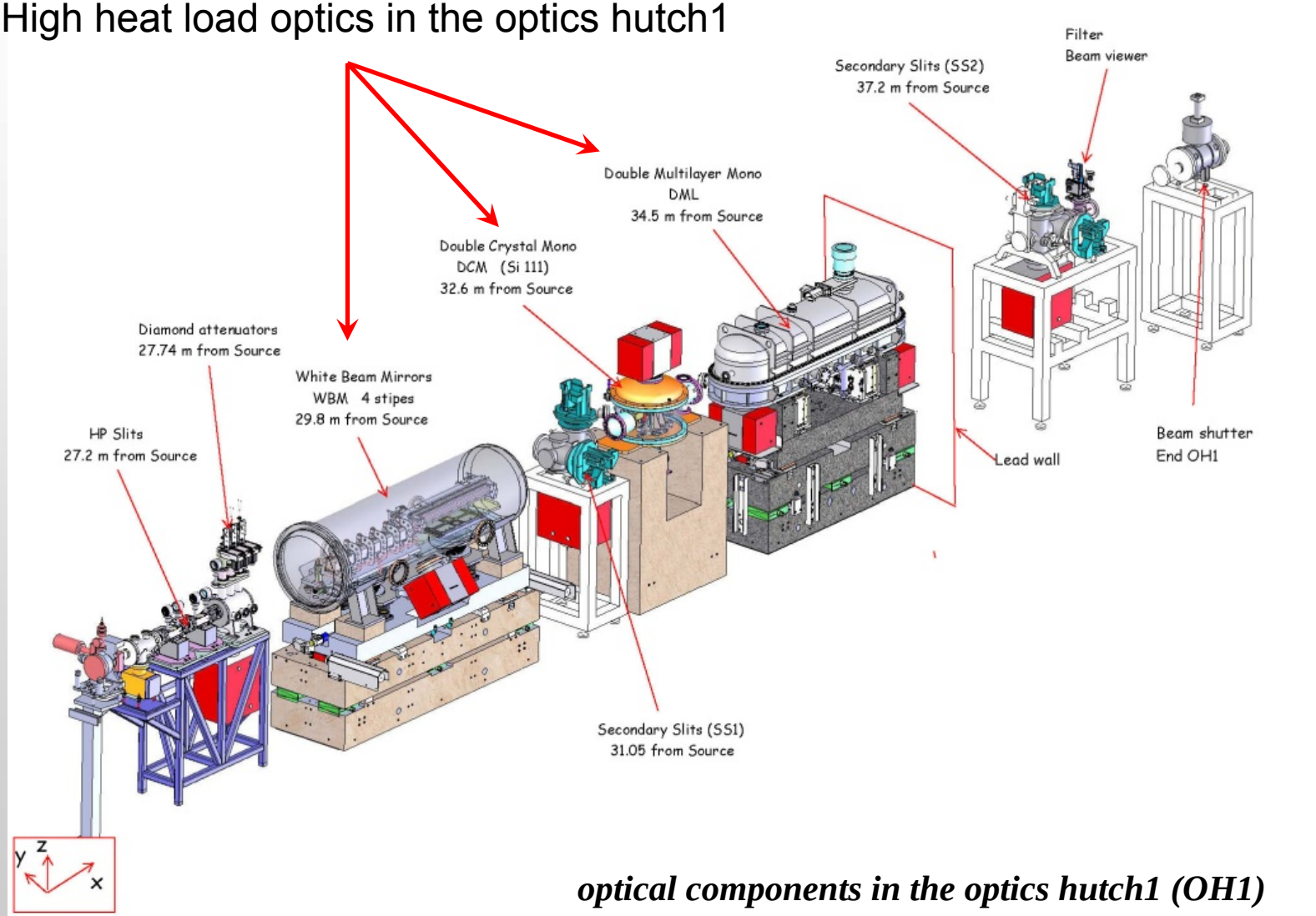
(b) Several optional elements can be inserted to allow for higher flux and/ or better harmonic rejection

- Channel-cut Silicon crystal monochromator
  - Liquid-nitrogen cooling
  - **Too much heat load → too high thermal deformation**

Optic layout (UPBL01)

Final version *(after heat load consideration and optimisation of the optics)*

- High heat load optics in the optics hutch1



optical components in the optics hutch1 (OH1)

Key optical components

White beam mirror / Multilayer

- **Water cooling**
- 4 Coatings: Si, Rh, Pt, ML-7nm ($[W/B4C]_{20}$, d=7nm)
- Grazing angle: 1.5 ~ 6 mrad
- Geometry (LxWxT): 900x**75**x80, L_{useful}=700mm
- At 30 m

Si monochromator crystal

- **Liquid nitrogen cooling**
- Bragg angle: 47 ~ 1400 mrad (θ=2.69 ~ **80.2°** , e_{ph}=42 ~ **2** keV)
- Geometry (LxWxT): 80x60x80
- At 36 m

Multilayer monochromator

- **Water cooling** (?)
- 2 Coatings: $[W/B4C]_{200}$, d=2nm , d=3.6nm
- Grazing angle: 5.7 ~ 13 (24) mrad
- Geometry (LxWxT): 350x75x80, L_{useful}=240mm
- At 38 m

Source characteristics

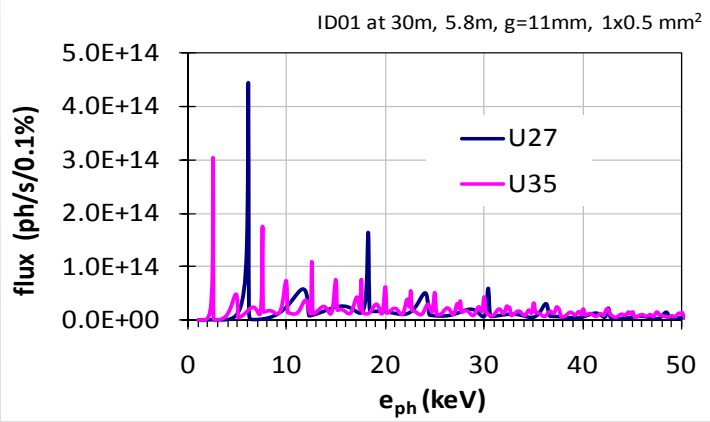
Sources parameters (Undulators)

- U27: L=5.8m, B_0=2.111 T, $K_{gap=11mm}$=1.48 , e_1=6.11 keV
- U35: L=5.8m, B_0=1.987 T, $K_{gap=11mm}$=2.420, e_1=2.51 keV

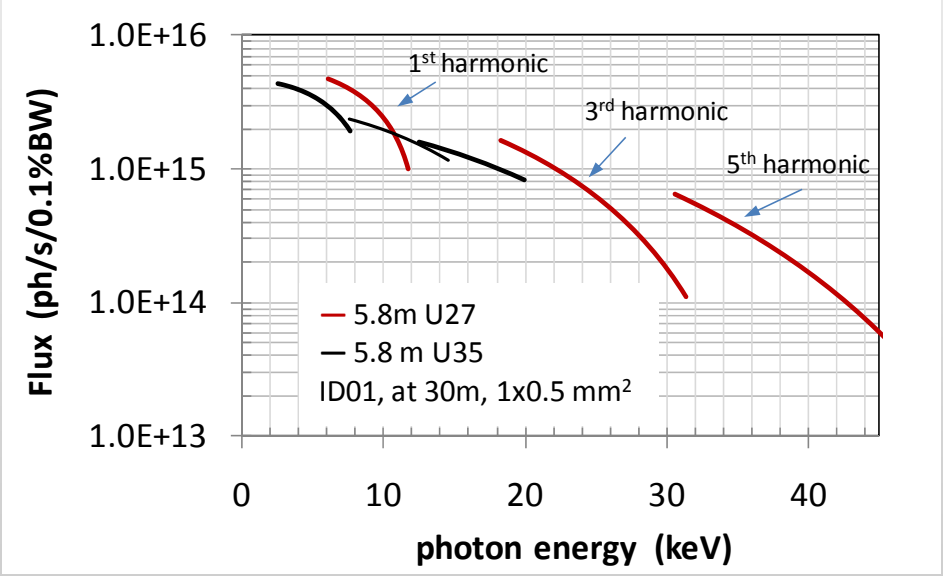
Photon energy range

- Essentially: 2.51 - 50 keV

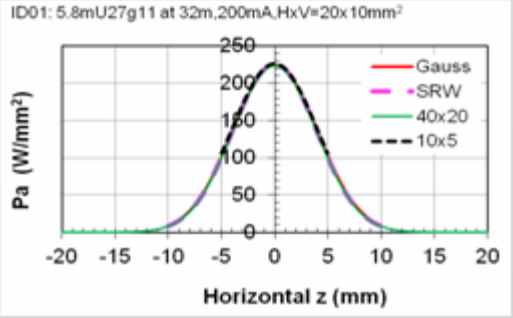
Spectral distribution

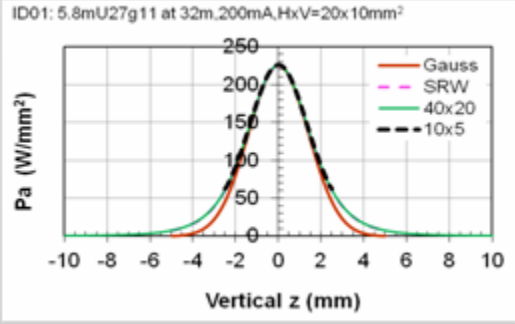


Photon flux from the undulators U27 or U35



Spatial distribution





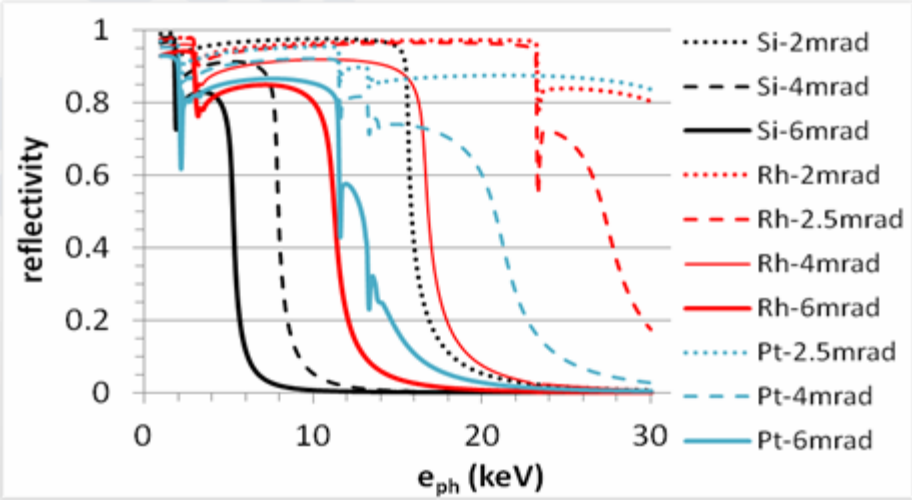
Reflectivity

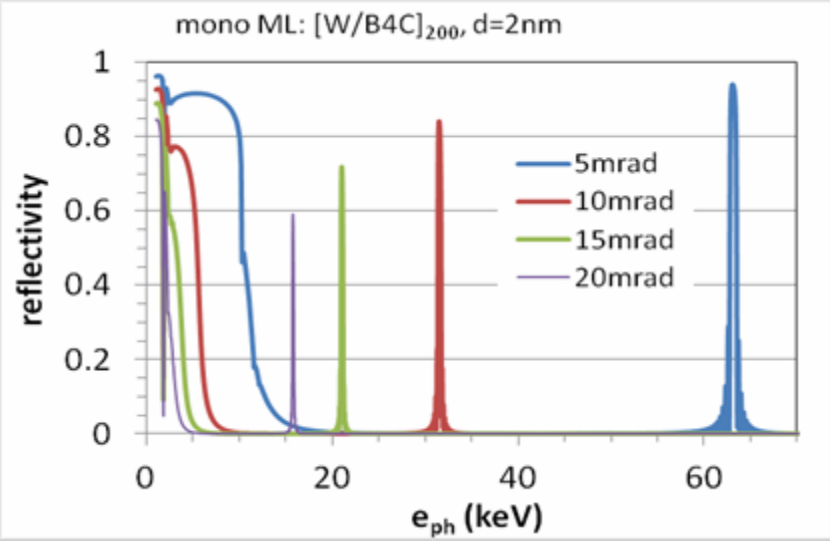
Mirror

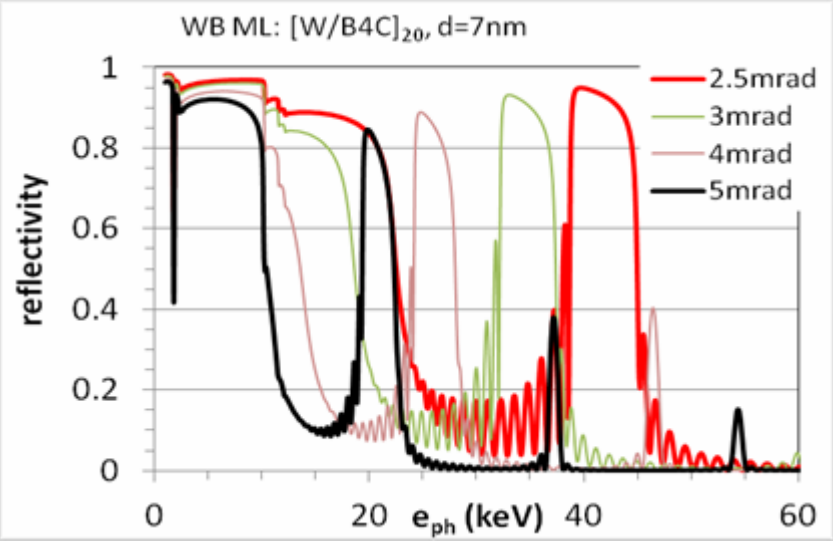
- Some overlaps
- Multi-coating/fixed angle (usually)
- Variable angle for ML mirror

Multilayers

- ML Mono
- WB ML mirror (variable angle)







Optical configuration

Example of worksheet with optical configuration

WB mirror

WB ML

Si mono

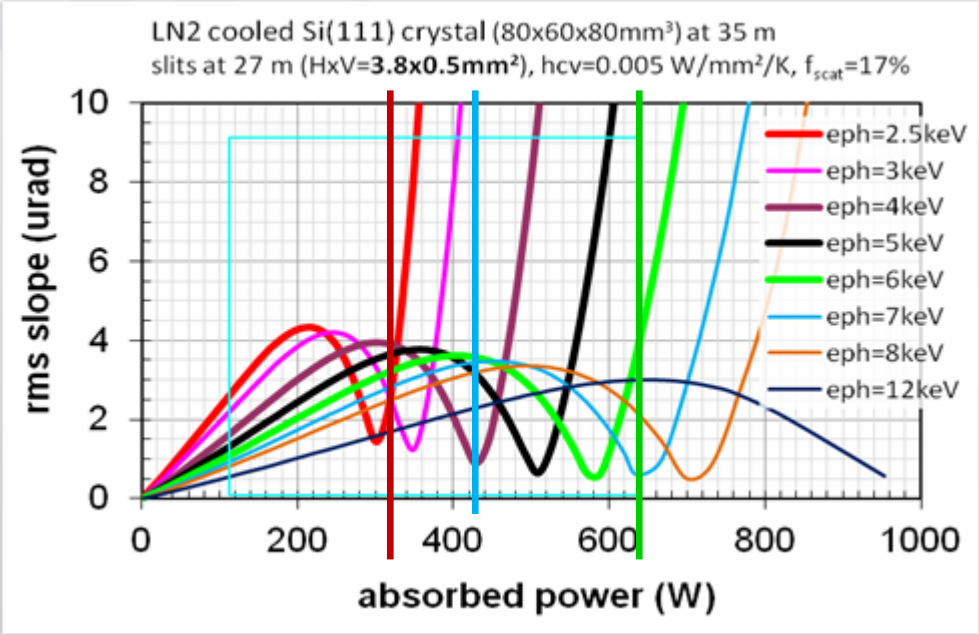
ML mono

UPBL01 Optical configuration												
								$2d_{Si(111)}$	6.271	Å		
				WB mir	WB ML		Si mono		ML mono			
Period d (nm)					7 nm ML			Si111	3.6	2	nm	
distance from src (m)				29.84	32.343			34.843	36.44	36.44		
Undulator	e_{ph}		Slits	coating		$a_{grazing}$		mono	mono	mono	? inc	? inc
	Min	Max				Min	Max				Min	Max
	keV	keV	mm^2			mrad	mrad				mrad	mrad
U27/U35	2.5	40	0.5x0.5	-	-	-	-	Si mono	-	-	49.5	912
U27/U35	11.6	23	0.5x0.5	-	-	-	-	-	ML mono		7.49	14.9
U27/U35	20.8	40	0.5x0.5	-	-	-	-	-	ML mono		7.75	14.9
U27/U35	2.5	6.2		Si	-	2	4.74	Si mono	-	-	325	912
U27/U35	6.2	15		Si	-	2	4.74	Si mono	-	-	132	325
U27/U35	5	13		Rh	-	2	4.74	Si mono	-	-	153	407
U27/U35	12	33		Rh	-	2	4.74	Si mono	-	-	60.0	166
U27/U35	5	16		Pt	-	2	4.74	Si mono	-	-	124	407
U27/U35	15	42		Pt	-	2	4.74	Si mono	-	-	47.1	132
U27/U35	2	15		Si	-	2	6	ML mono	ML mono			
U27/U35	4	33		Rh	-	2	6	ML mono	ML mono			
U27/U35	5	42		Pt	-	2	6	ML mono	ML mono			
U27/U35	15	50		-	WB ML	1.5	5	Si mono	-	-	39.6	132
U27/U35	17	30		-	WB ML	3.5	5	-	ML mono		5.74	10.1
U27/U35	25	50		-	WB ML	1.5	4.3	-	ML mono		6.2	12.4
H_{bm-max}	3.86	mm	at	27	m							
		Length (mm)		900	900				350	350		
	$H_{bm-max-optics}$ (mm)			4.27	4.62				5.21	5.21		
For overfilling,		a_{max} (mrad)		4.74	5.14				14.89	14.89		
For overfilling,		e_{ph-min} (keV)							11.57	20.83		

Silicon crystal monochromator

Si crystal monochromator (HxV=3.8x0.5 mm²)

- Size (LxWxT): 80x60x80
- Liquid nitrogen cooling
- $P_{a\text{-}abs}$= 336 W/mm²
  (Normal incidence, at 27 m)
- $P_{abs} \leqslant$ 636 W
- $\Delta\theta_{thermal}$< 5 (10) µrad



Bragg angle

FEA results

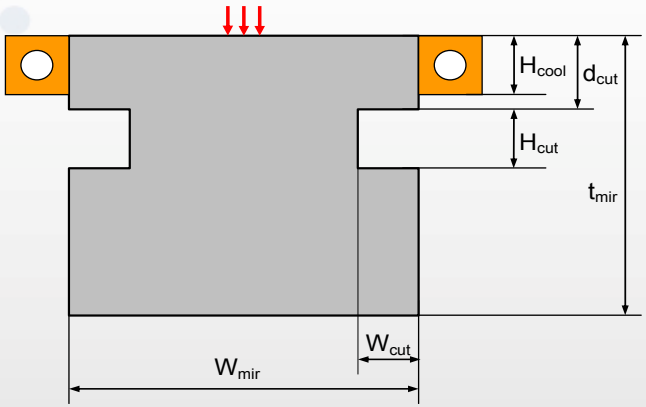
- **$e_{ph} \geqslant$ 6 keV**
  RMS slope $\leqslant$ **3.6 µrad**
- **3.7 $\leqslant e_{ph} \leqslant$ 6 keV,**
  RMS slope < **4 µrad**
  U35 gap > 14 mm, power reduction by at least 34%
- **e_{ph < 3.7 keV**, **white beam mirror or ML mirror should be used** to reduce the heat load by up to 50%

White beam mirror or Multilayer, Multilayer monochromator

Solution to limit thermal deformation

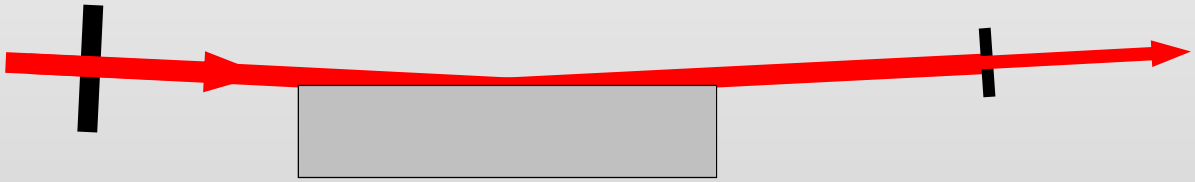
- Water cooling on top side
- Cross-section: smart cut
- Full illumination
- Secondary slits

Cross-section



L.Zhang et al., SRI2012

Side view



Primary Slits

Mirror

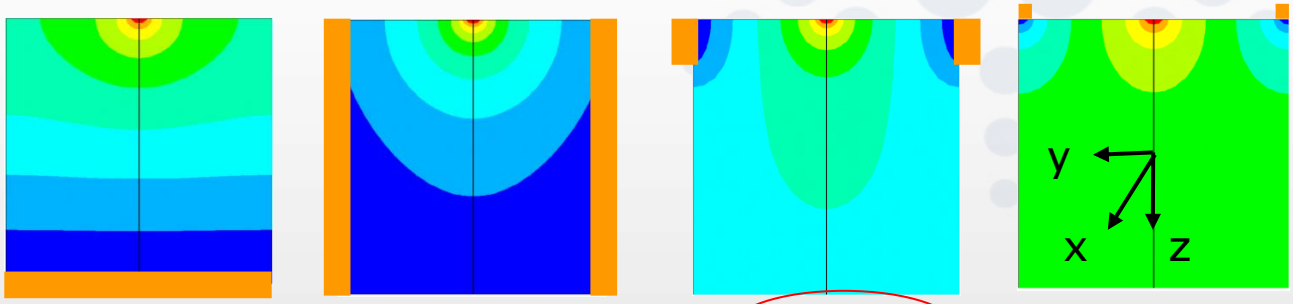
*with **fully illuminated** beam along the mirror*

2nd Slits

- *Re-define the useful beam size*
- ***remove the "end effects"***

White beam mirror or Multilayer, Multilayer monochromator

Cross section of water-cooled mirror
4 cooling schemes and their performances



Bottom **Full Side** **Top side** **Top face**

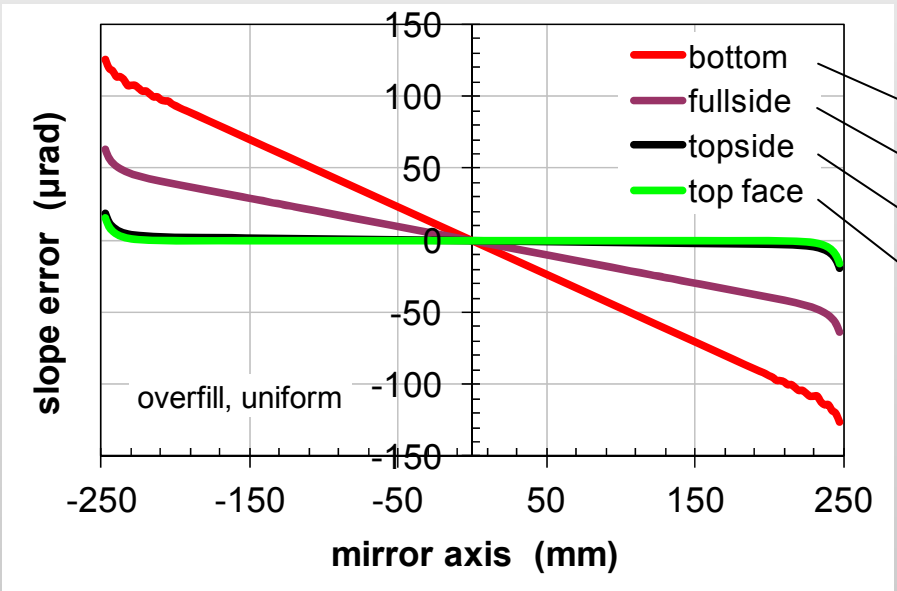
$$\theta_{slp}(x) = \frac{\alpha}{I}\int_0^x \left\{ \int_{-t/2}^{t/2} \left[\int_{-w/2}^{w/2} T(x,y,z)dy \right] zdy \right\} dx$$

for "**Top face**" cooling, the averaged temperature over the width

$$\frac{1}{w}\int_{-w/2}^{w/2} T(x,y,z)dy \equiv \overline{T}(x)$$

no gradient in depth (z)

→ $\theta_{slp}(x) = 0$



Slope$_{pp}$ (± 200 mm)

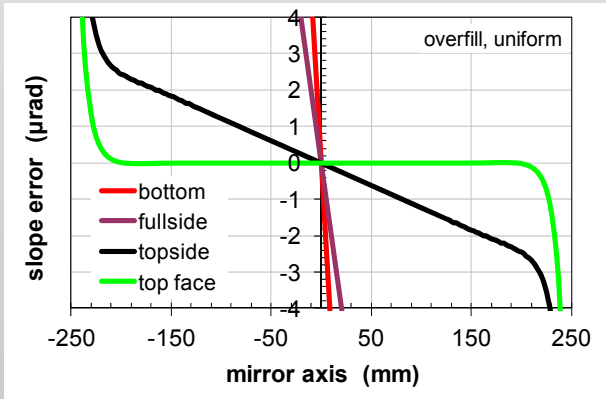
188 µ rad

78

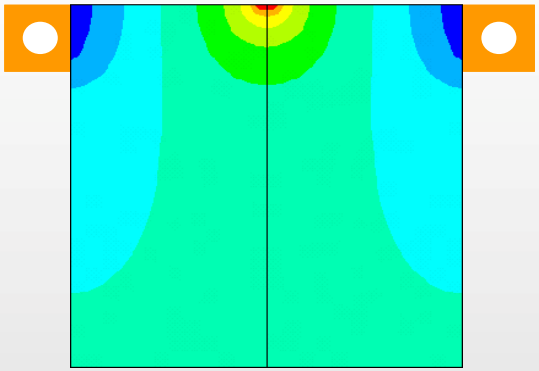
4.9

0.03

zoom

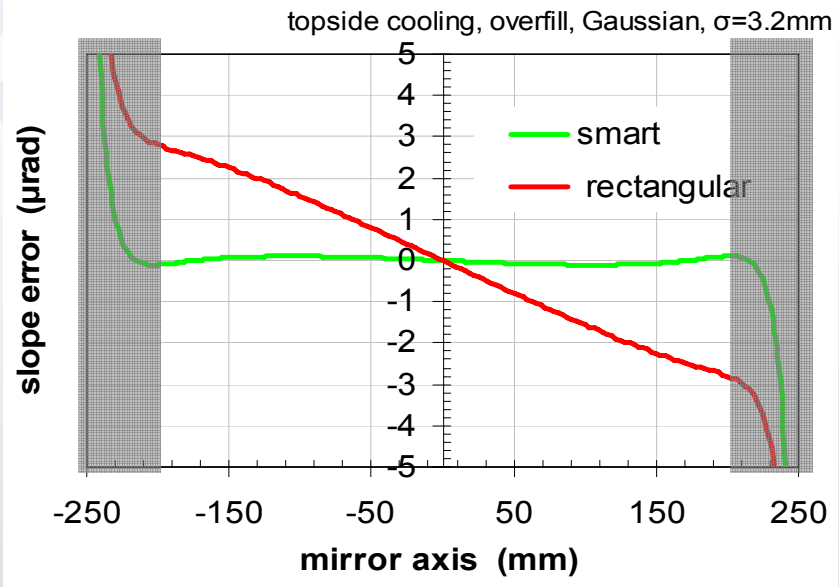


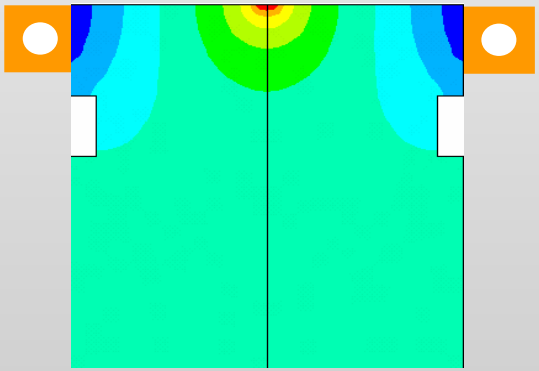
Smart cross section with notches



Top-side cooling

Still temperature gradient in the thickness





Smart cross section with notches

Notches modify temperature distribution

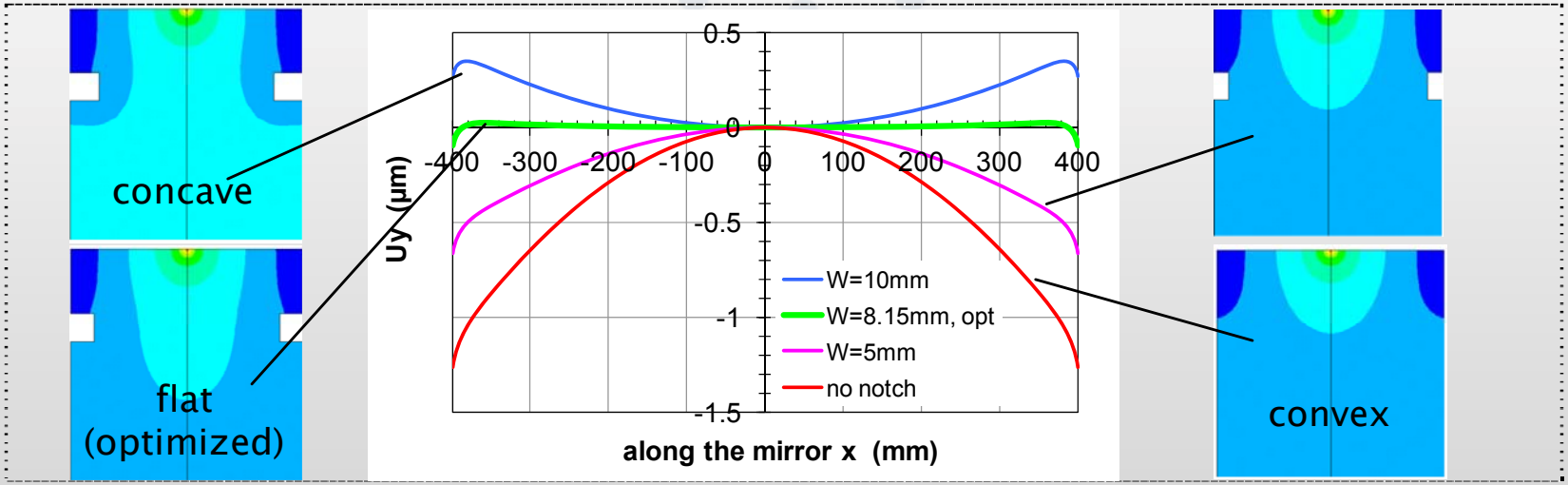
Optimised notch position and size →

- Eliminate temperature gradient in the thickness
- Minimize the thermal deformation (TD)
- Can transform convex TD to concave TD

Multilayer monochromator, White beam mirror or Multilayer

Optimisation of the cross section with notches

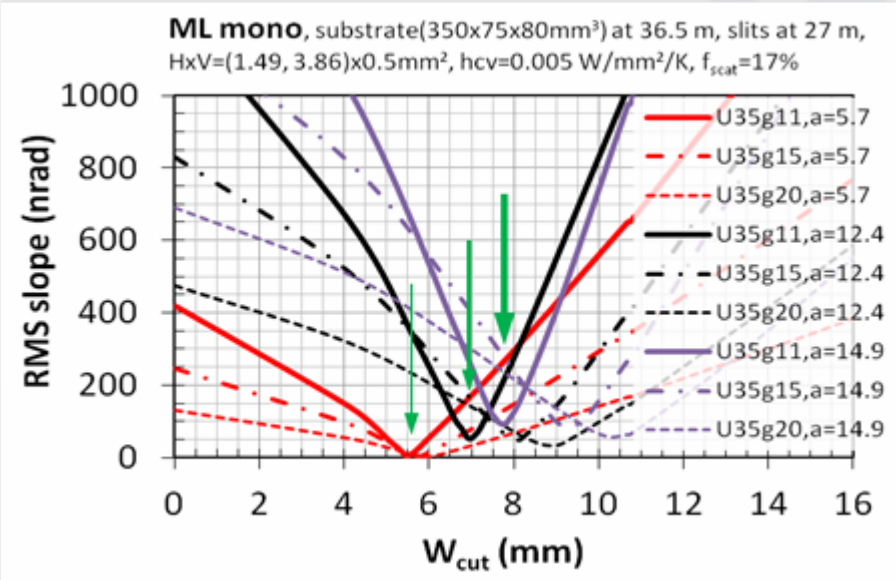
- Thermal deformation →
  - Convex shape for the cross section without cut area
  - Concave shape for the cross section with deep cut area
  - Flat shape for the cross section with optimised cut area



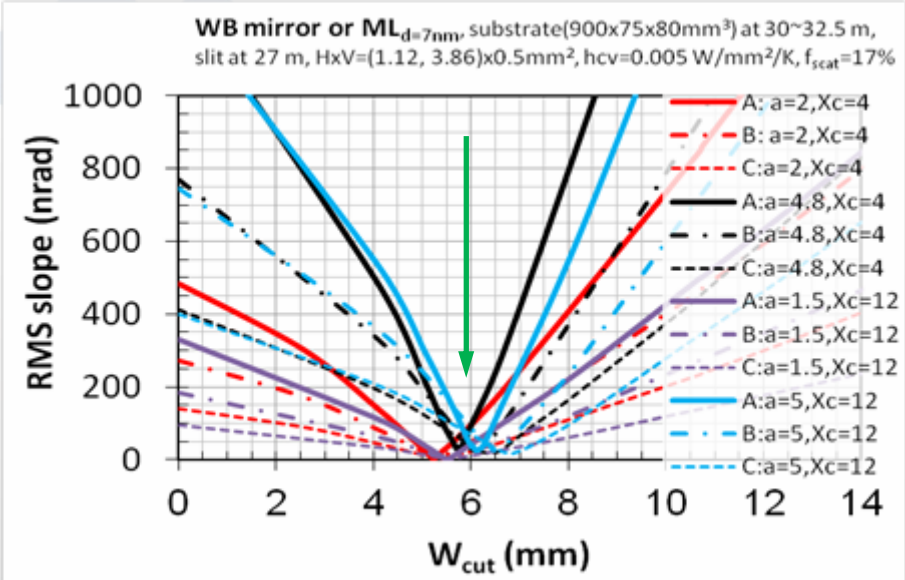
- The optimum of the notch size depends on the power distribution (undulator, gap,…), geometry of the substrate, coatings, ….
- For a particular case, the thermal slope error could be minimized to **few nrad**
- Globally, possible to reach **sub-µrad** thermal slope error

Global optimization results

Multilayer monochromator



White beam mirror or Multilayer



Globally

- For $a_{inc} \leqslant 12.4$ mrad
  - **W_{cut}=6.8 mm,** RMS_{slope} < 170 nrad
- For $a_{inc} \leqslant 14.9$ mrad
  - **W_{cut}=7.7 mm,** RMS_{slope} < 280 nrad
- *The RMS slope error could be significantly smaller when using WB mirror, WB ML or filters*

- **Individually** minimized:
  - **$RMS_{slope} \leqslant$ 1.1 nrad** for a_{inc}=1.5 mrad
- **Globally** (for different undulator gaps, grazing angle, different stripes)
  - W_{cut}=5.9 mm, **RMS_{slope} < 100 nrad**
- *The RMS slope error could be significantly smaller when taking into account the power reflection by the WB mirror or ML*

Summary

		High heat load optics		
Upgrade beamline	Application	**White beam mirror / multilayer mirror**	**Monochromator**	Other heat load optics
UPBL1	Diffraction Imaging for Nano-Analysis	multi-coating mirror and multilayer mirror	channel cut si crystal and multilayer	attenuator
UPBL2	*High Energies for interfaces and materials processing*		*bent Laue crystals*	***attenuators***
UPBL4	Nano-Imaging and Nano-Analysis	multi-coating mirror	si crystal DCM and multilayer mono	attenuators
UPBL6	INElastic X-ray Scattering	multi-coating mirror	si crystal DCM	
UPBL7	Soft X-rays/nano-magnetic & electronic spectroscopy	Si mirror	VLS grating	high performance M2
UPBL9a	Time-resolved ultra small angle scattering		channel cut si crystal	
UPBL10	Massively Automated Sample Selection Integrated Facility		channel cut si crystal	CRL
UPBL11	Time-resolved and Extreme conditions XAS	multi-coating mirror	Liquid-metal cooled bent polychromator with optimised width profiles	
ID10	Soft interfaces and coherent scattering beamline	multi-coating mirror	channel cut si crystal	CRL

cooling	indirect cooling, except liquid-metal cooled polychromator	**water cooling**, smart cross section	**LN2 cooling** for Si crystal (DCM or CCM)	
			Water cooling for multilayer mono, Laue crystals	