Silicon Carbide X-ray diagnostic

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Outline

- Introduction to synchrotron beam monitoring
  - Current applications of SiC XBPMs at microXAS@SLS
- Whitebeam and cross-chromatic monitoring
  - Comparisons between hard and soft beamlines @ SLS
  - Example of 6GeV Engineering materials beamline @ HEPS
- Conclusions and outlooks
- Q&E

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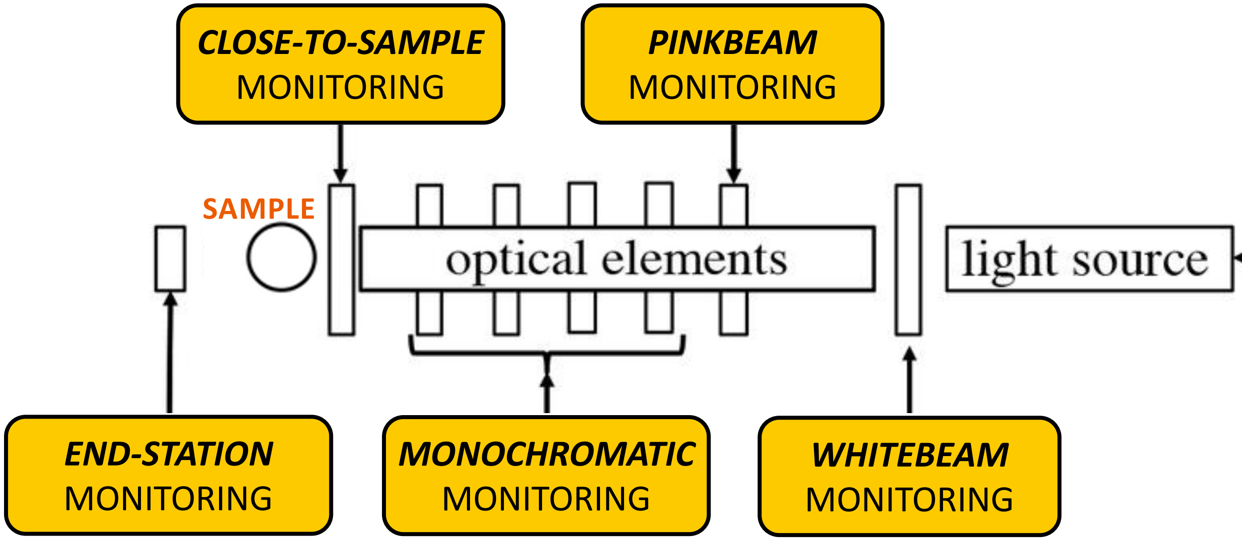
Generalities of Synchrotron Beam monitoring



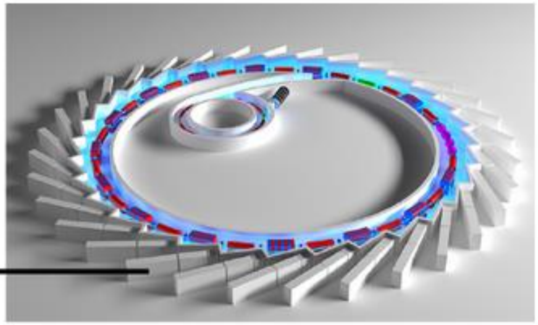
CLOSE-TO-SAMPLE MONITORING

PINKBEAM MONITORING

END-STATION MONITORING

MONOCHROMATIC MONITORING

WHITEBEAM MONITORING



Main requirements

- transparency (>98%)
- stability over time
- good lateral resolution (<um)
- fast response (<ms, <us)
- large active areas (mm^2)

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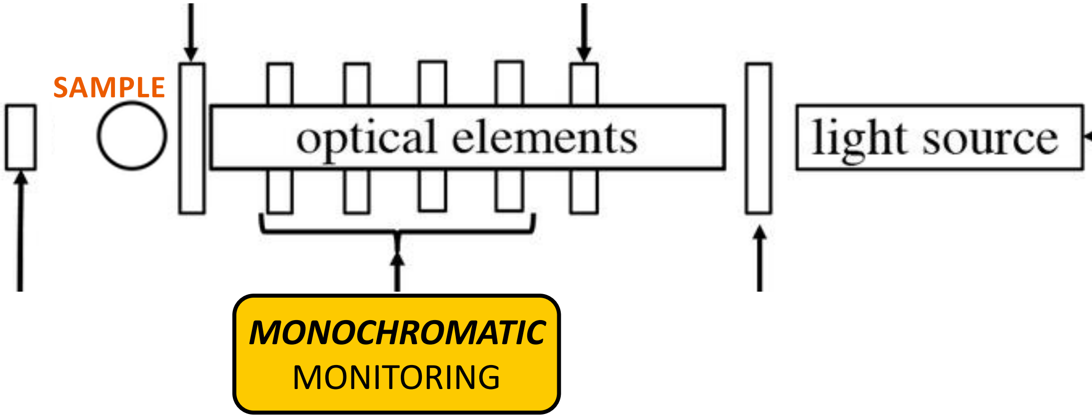
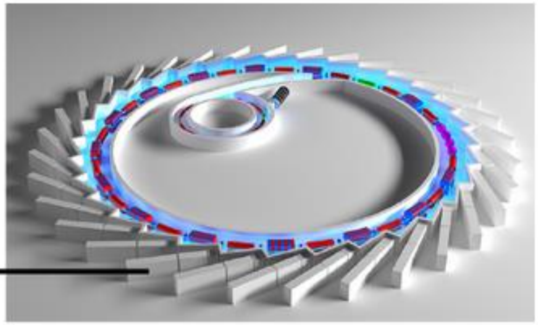
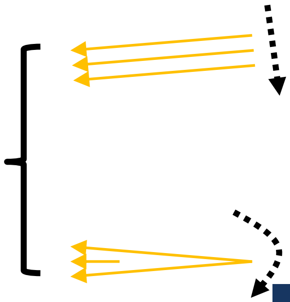
Generalities of Synchrotron Beam monitoring





Commercially available XBPM

1) **Monochromatic**
2) ***Hard-Xray***
3) ***Position***
4) **4)** Only on ***single-feedback*** schema



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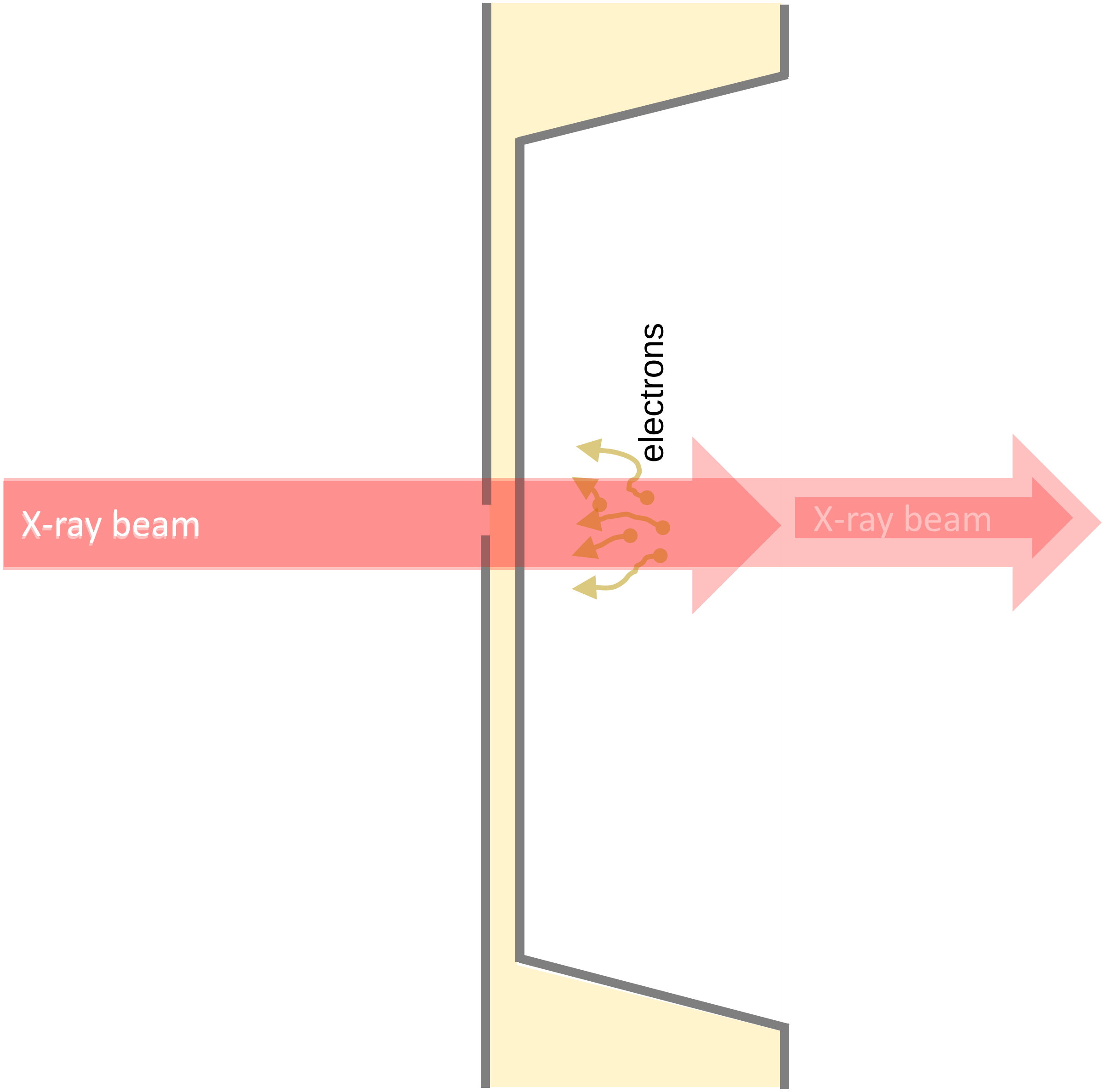
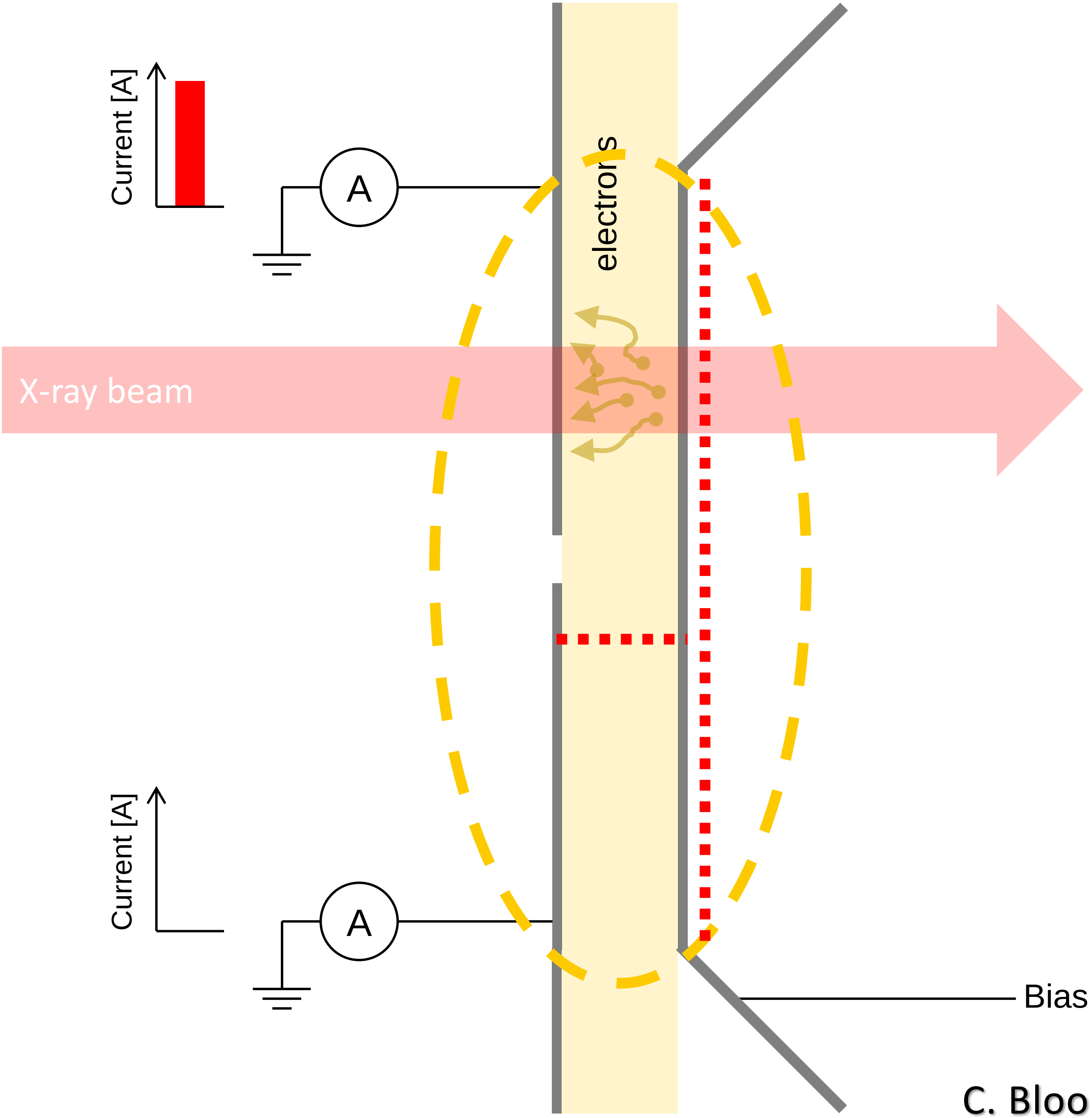
Standard "thin-membrane" solid state XBPM



<2% abs.

Standard "thin-membrane" XBPM

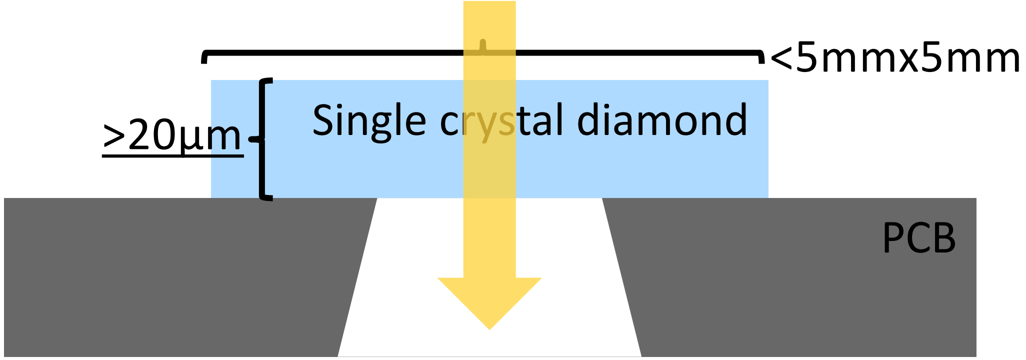


C. Bloomer

Comparison between Diamond and Silicon Carbide XBPM

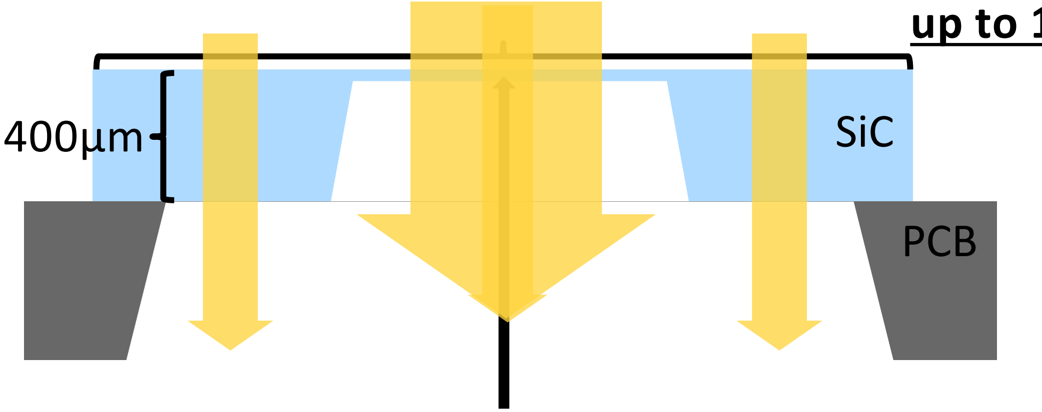
“A comparison between <u>single crystal diamond</u> and SiC X-ray beam position monitors”

HOUGHTON, Diamond Light Source, SRI/JSR



CIVIDEC

SYDOR



ultra-thin (framed) membrane!

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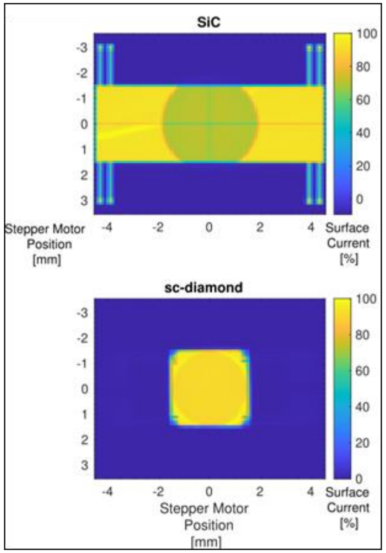

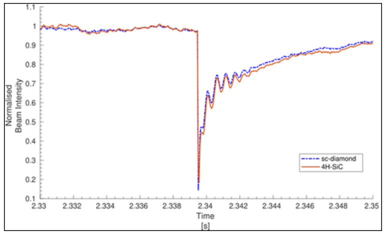

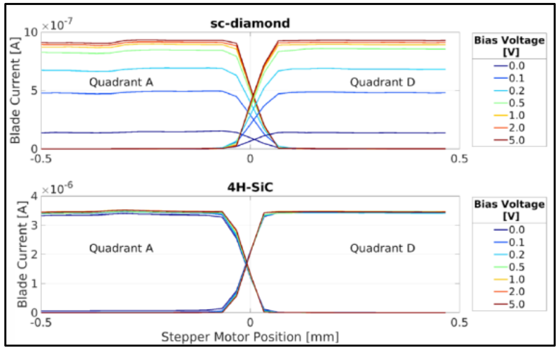

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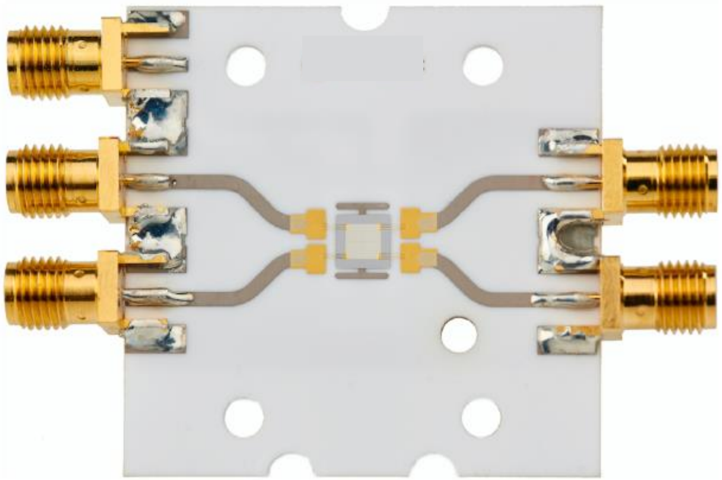
*up to instrumental limits

Why choose Silicon Carbide XBPMs?



- Lower device costs
- Larger active areas (up to x9 time higher)
- Higher current signals / higher resolutions*
- Superior transparencies (20µm, 2µm, 1µm, 0.2µm)
- easier installations:
  - zero bias operation
  - test of devices without beam
- Short delivery times
- Large number of devices quickly available

*for equivalent sensor geometries

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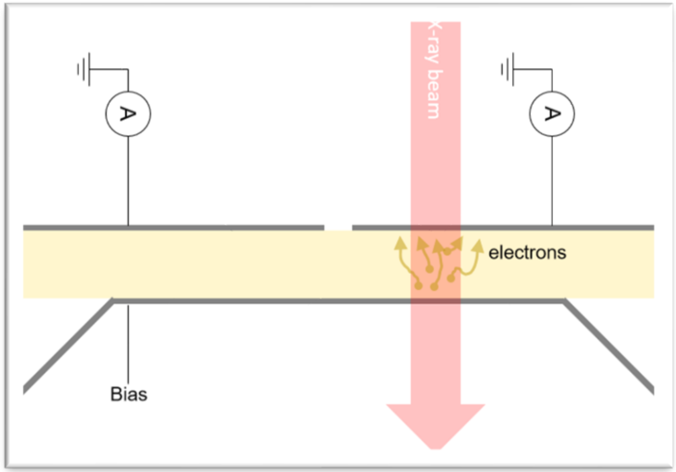
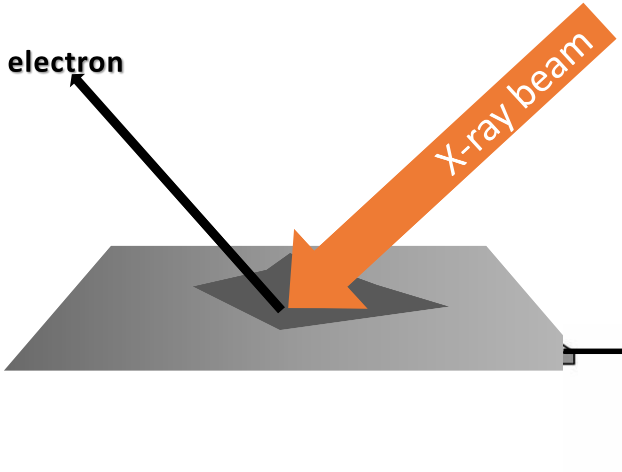
Comparison of X-ray sensors

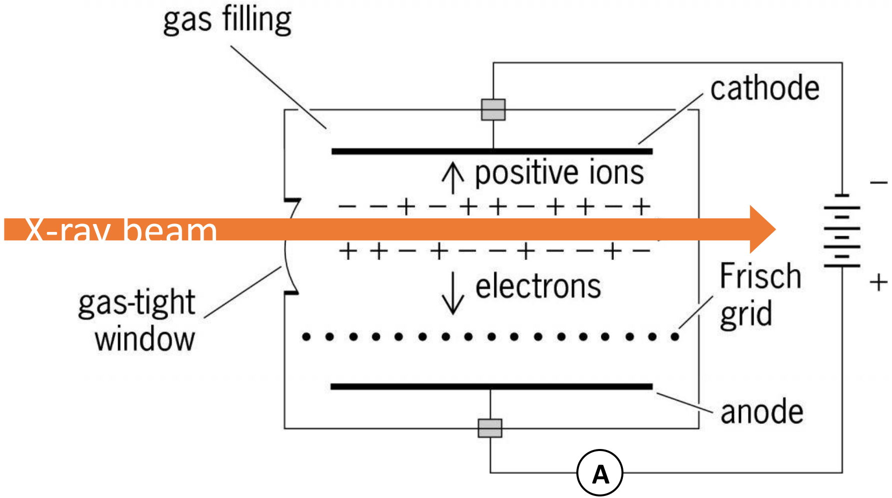
semiconductor based
internal photoemission



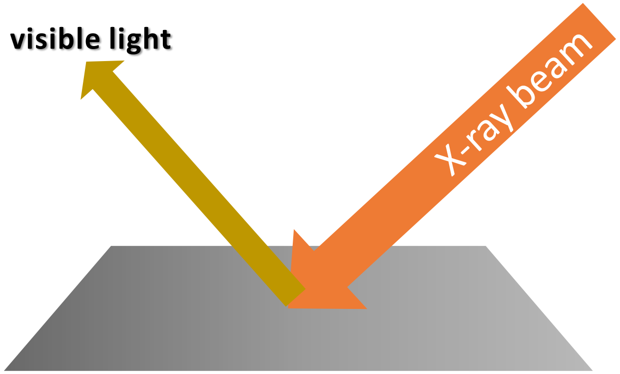
metal based
external photoemission



gas based
photoionization



fluorescence screen



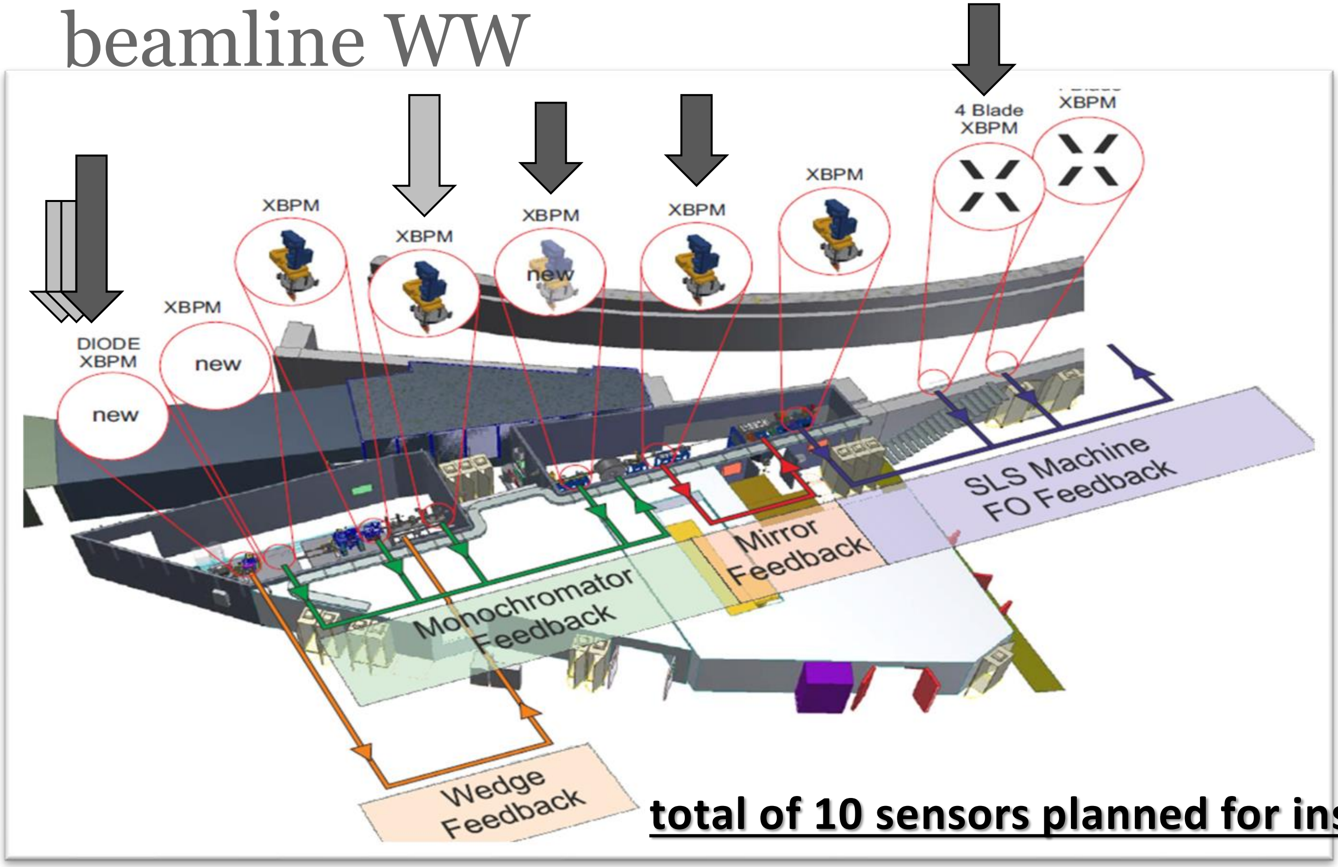
Schematic comparison of detectors

sensor type	Gas chambers	Blade monitors	Semiconductor sensors	fluorescence screen
transparency	high	very low very high	dep☺ls...	low
radiation hardness	intrinsic high	medium/high	dep☺ls...	low
foot print	medium/large	medium	extrem☺ small	large
lateral resolution	low	medium	ver☺igh	medium
time response	low	low/medium	Ver☺igh	low

- Can't we take best advantage of miniaturization
- While mitigating the transparency/Rad-Hard responses?

- If so, solid state sensors will expand their areas of applications -

microXAS@PSI currently represents the most advanced "XBPM-monitored" beamline WW



total of 10 sensors planned for installation

- **Currently installed:**

n.7 sensors (after mono, I0, nano-focus, pinkbeam and beam-stopper intensity)

- **Planned:** pixelated, before mono, whitebeam, beam-stopper *position*

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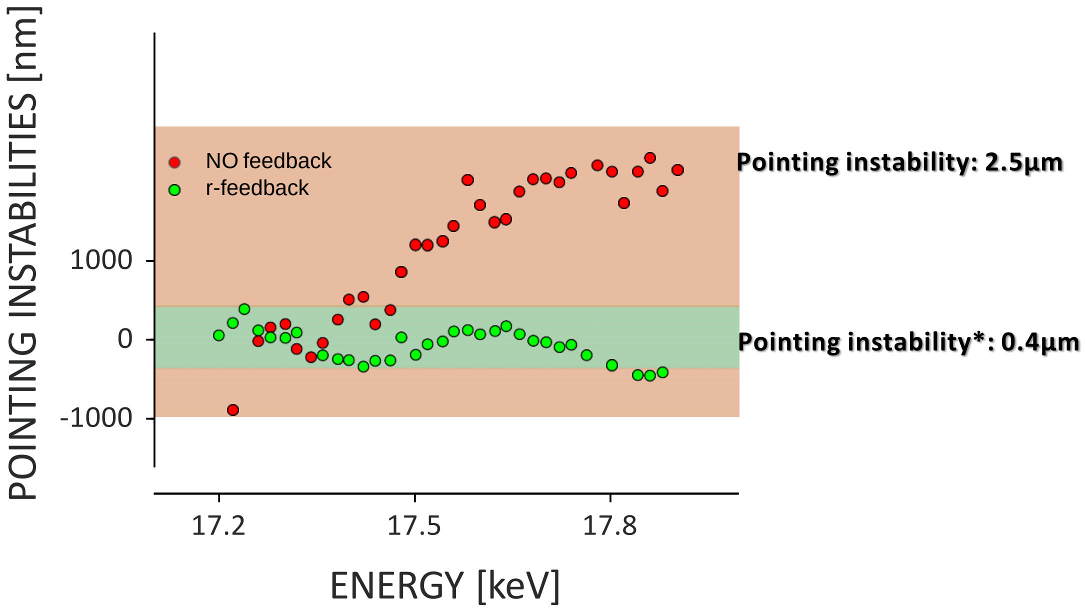
Monochromatic “standard” XBPM

-first implemented SiC XBPM base feedback-loop schema

working on further automation/improvement



Pointing instability: 2.5µm

Pointing instability*: 0.4µm

x5 Improvement using SiC XPBM based feedback system

Control/feedback important in spectroscopy measurements to compensate for energy drifts!

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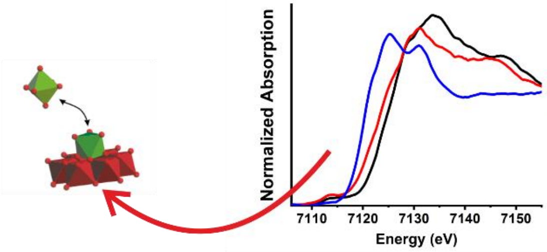
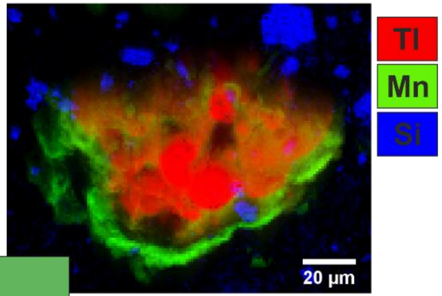
***sigma: <400nm**

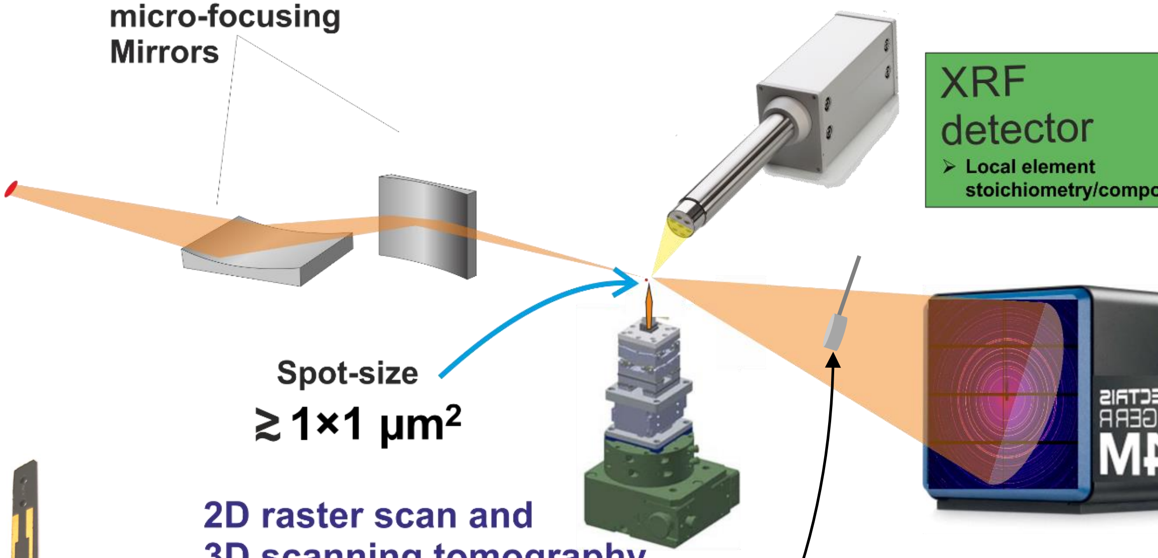
Near sample monitoring

-Beam stopper diode (no transmittance mode)



microscopic X-ray Absorption-Spectrocopies
- Oxidation state
- Chemical speciation
- Local atomic coordination





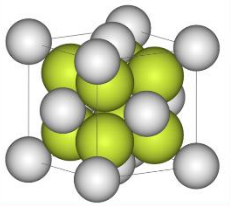
micro-focusing Mirrors

Spot-size

≳1×1 µm²

2D raster scan and 3D scanning tomography

XRF detector
- Local element stoichiometry/composition



XRD detector
- Crystalline phase identification
- Chemical speciation
- Stress

Absorption → SiC Diode on the beamstopper
- **Absorption Contrast Imaging**
- **X-Ray Absorption Spectroscopy**

Collaboration of microXAS team with Massimo Camarda, Laboratory for Micro- and Nanotechnology, PSI
- 3D Mechatronic Integrated Device

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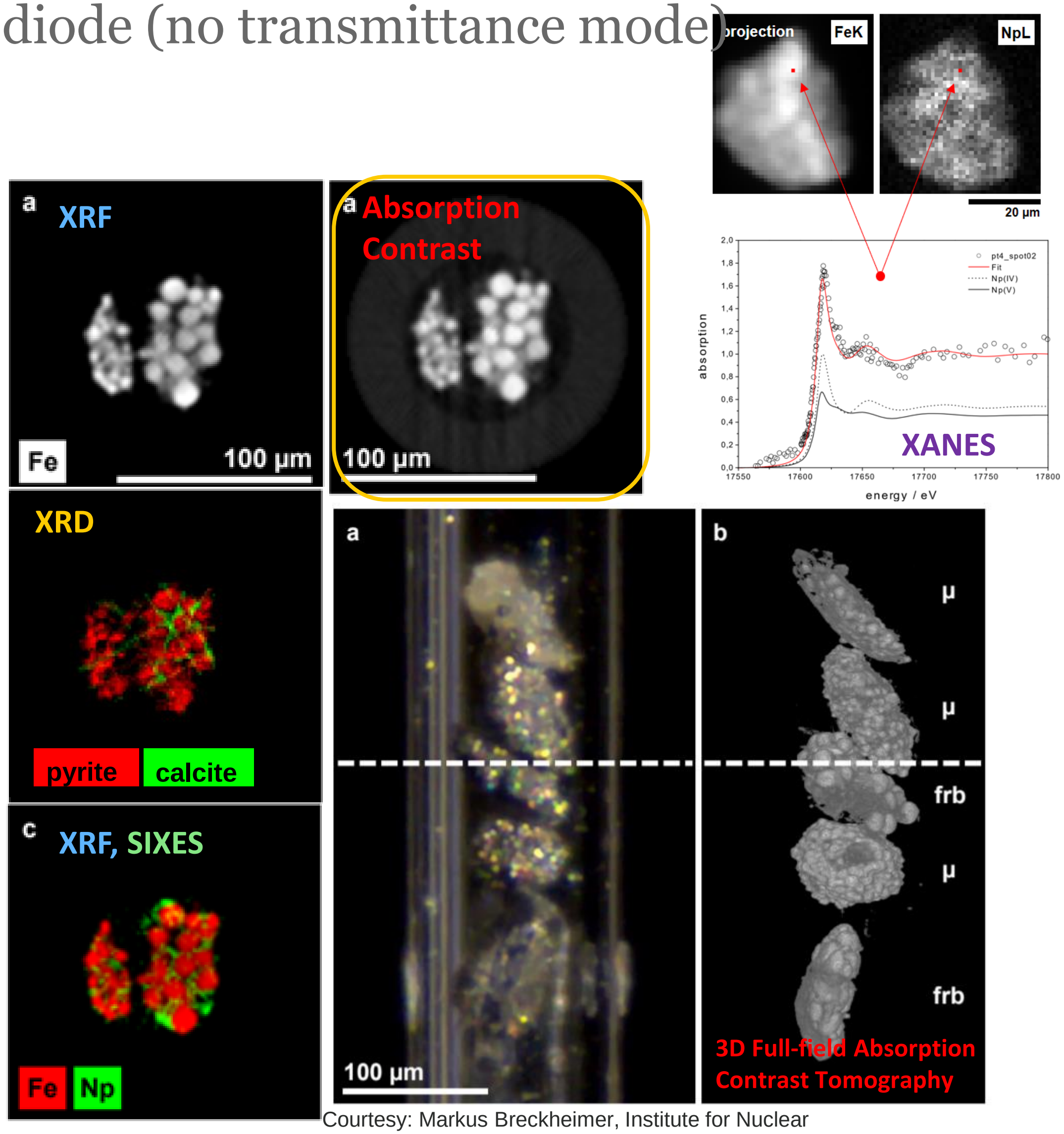
Courtesy: Dario Sanchez

Near sample monitoring

-Beam stopper diode (no transmittance mode)



Courtesy: Markus Breckheimer, Institute for Nuclear Chemistry, Johannes Gutenberg-University Mainz

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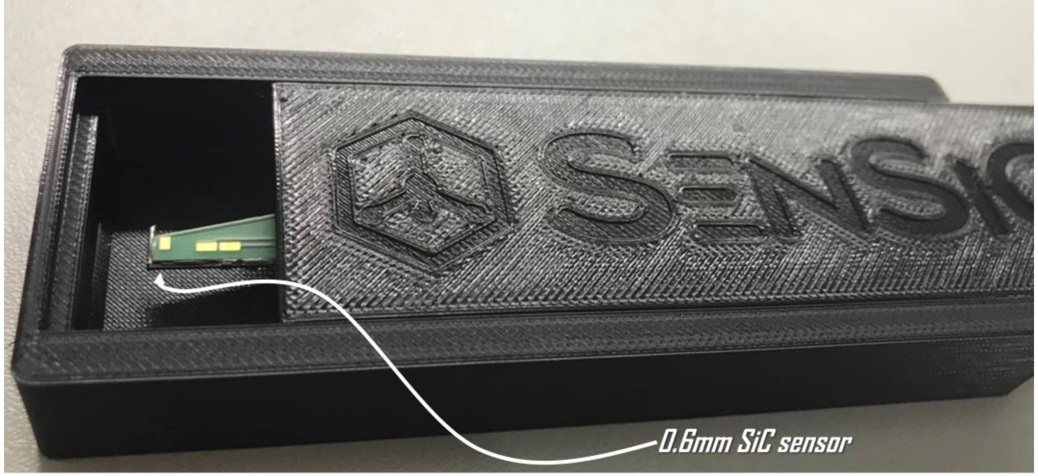
Near sample monitoring

-Beam stopper diode (no transmittance mode)



- 0.6mm (0.8mm) intensity monitor
- 1.8mm (2mm) intensity monitor
- 1.8mm (2.2mm) position monitor
- 2.8mm (3.3mm) position monitor

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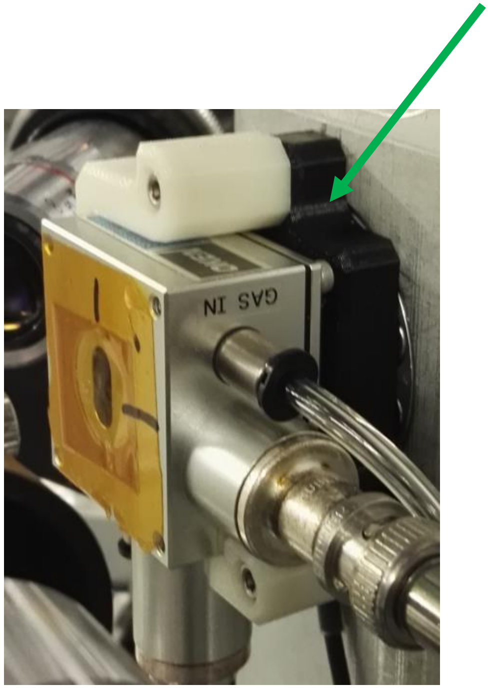
Near sample monitoring

-Fast/compact intensity sensor*



CURRENTLY WORKING ON:

1. **COMBINATION OF INTENSITY+POSITION MONITOR (TELESCOPE CONFIG.)**
2. **COMBINATION OF POSITION + PIN-HOLE**

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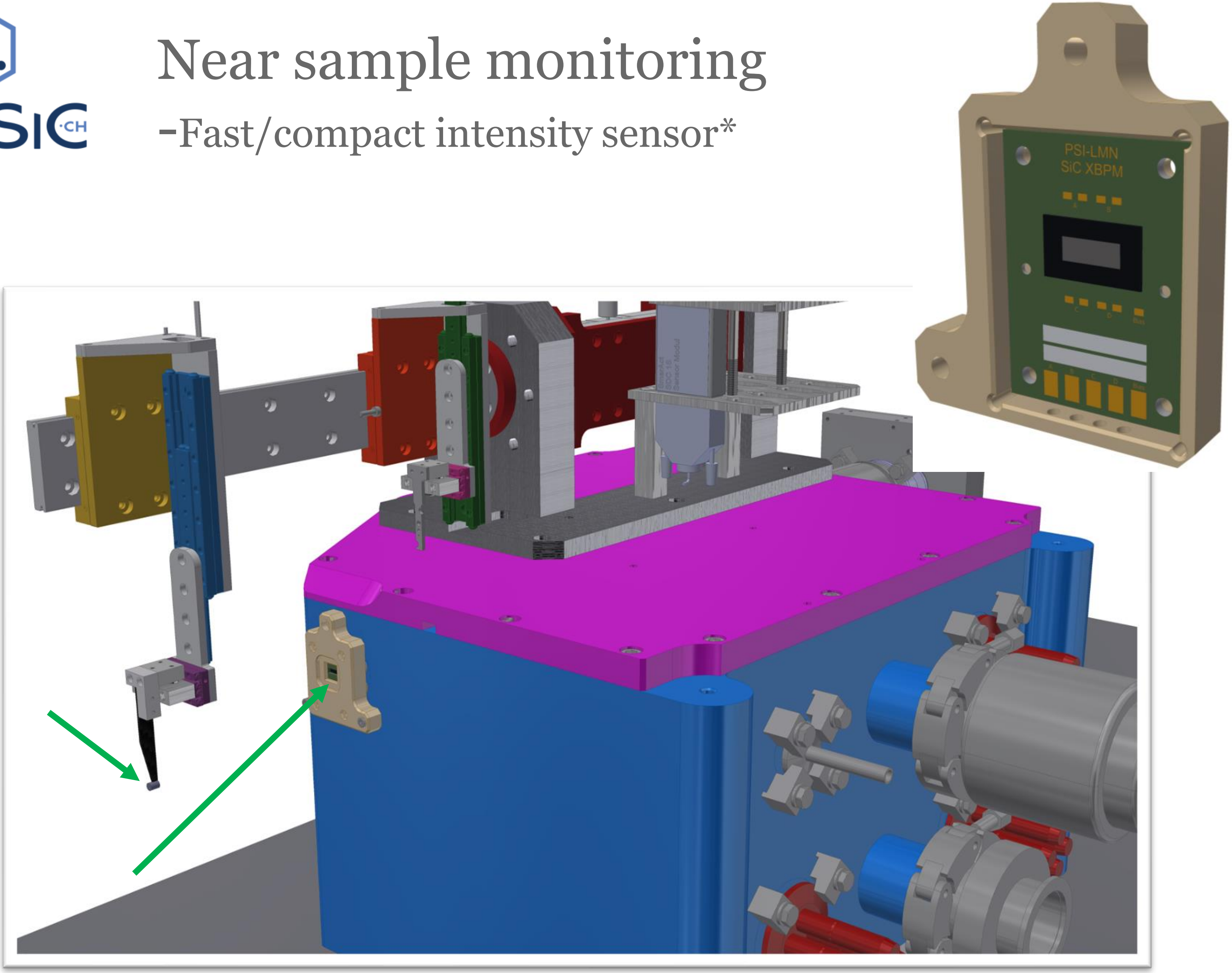
Near sample monitoring

-Fast/compact intensity sensor*



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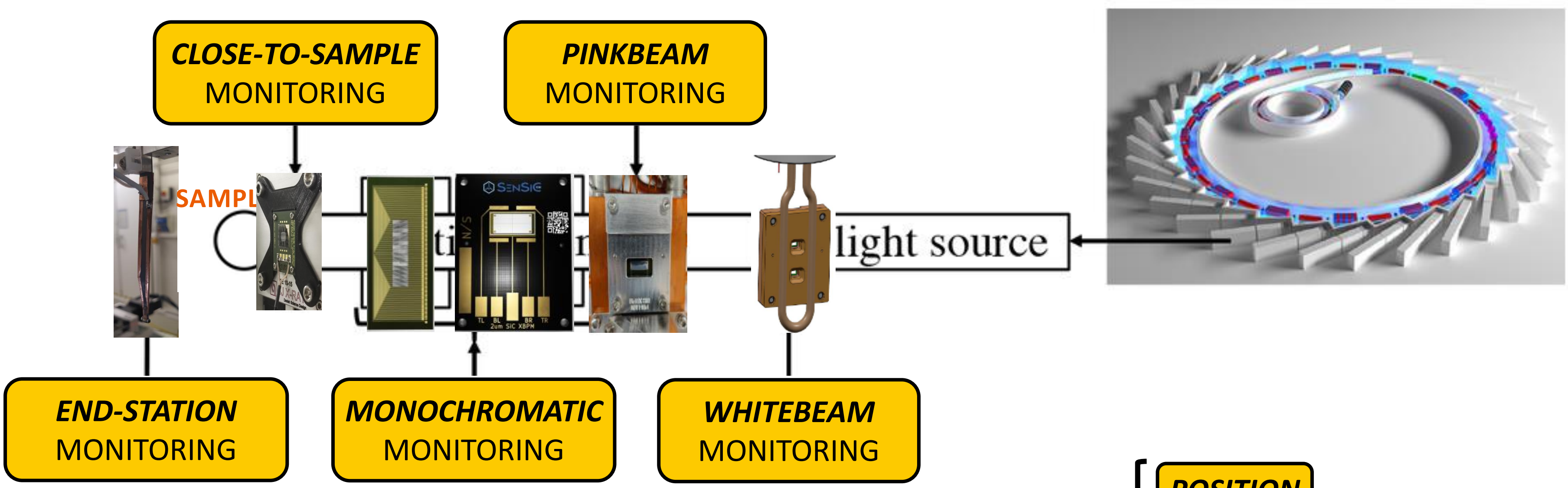
Value proposition



CLOSE-TO-SAMPLE MONITORING

PINKBEAM MONITORING

END-STATION MONITORING

MONOCHROMATIC MONITORING

WHITEBEAM MONITORING

DEVELOPMENT OF CUSTOMIZED ELECTRONICS FOR READOUT AND CONTROL (FEEDBACK)

- ***MONOCHROMATIC*** MONITORING
  - ***POSITION***
  - ***PROFILE***
- ***WHITE/PINK*** MONITORING →
  - ***HARD-XRAY***
  - ***SOFT-XRAY***
- ***CLOSE-TO-SAMPLE*** MONITORING
  - ***INTENSITY***
  - ***BEAM-STOPPER***

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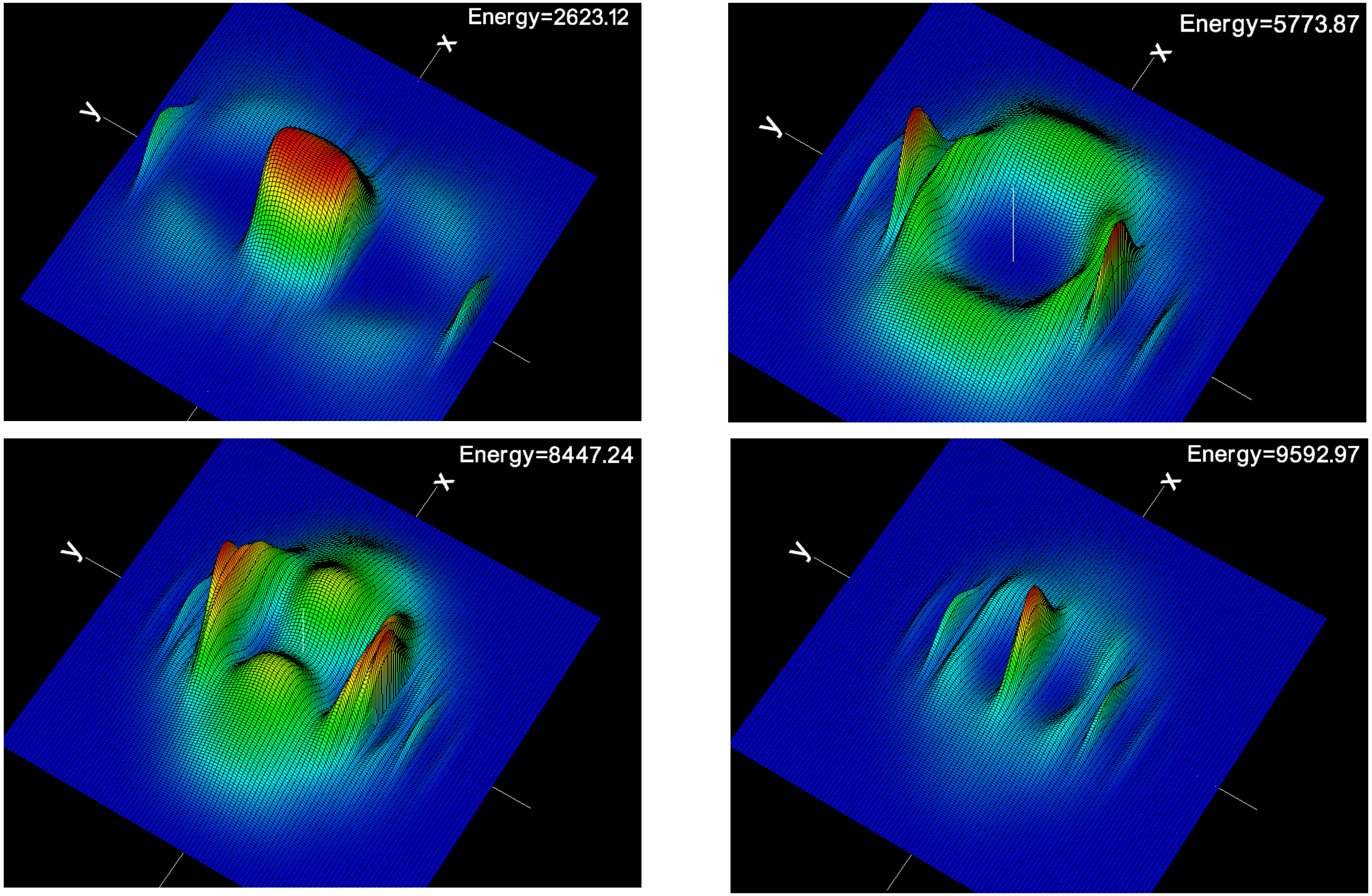
ID whitebeam, spectra

(microXAS, spectra)

1. determine flux(E,x,y,z) generated by ID (Spectra)



plots using very wide acceptance window (24x24mm^2)

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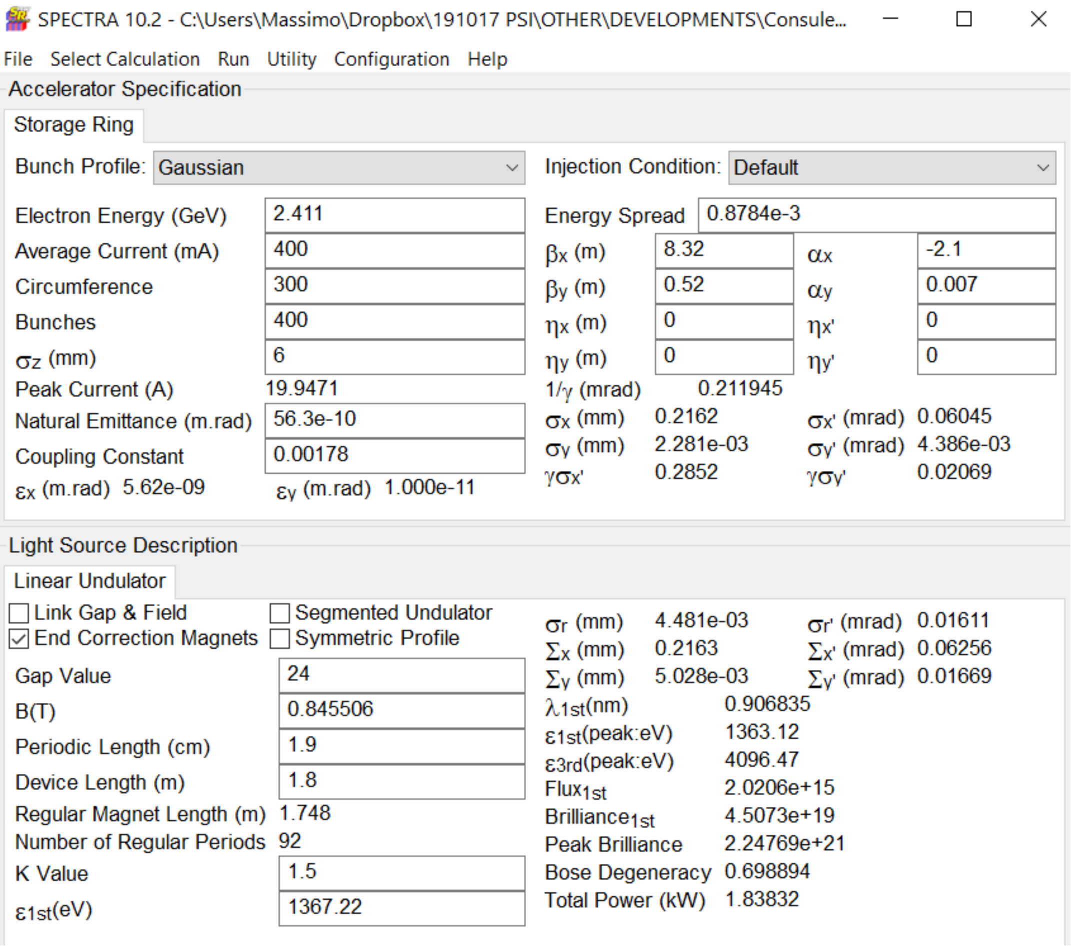
ID whitebeam, spectra

(microXAS, spectra)

1. determine flux(E,x,y,z) generated by ID (Spectra)



Accelerator Specification

Storage Ring

Bunch Profile: Gaussian
Injection Condition: Default

Electron Energy (GeV) 2.411
Average Current (mA) 400
Circumference 300
Bunches 400
σ_z (mm) 6
Peak Current (A) 19.9471
Natural Emittance (m.rad) 56.3e-10
Coupling Constant 0.00178
ε_x (m.rad) 5.62e-09
ε_y (m.rad) 1.000e-11

Energy Spread 0.8784e-3
β_x (m) 8.32
α_x -2.1
β_y (m) 0.52
α_y 0.007
η_x (m) 0
η_x' 0
η_y (m) 0
η_y' 0
$1/\gamma$ (mrad) 0.211945
σ_x (mm) 0.2162
$\sigma_{x'}$ (mrad) 0.06045
σ_y (mm) 2.281e-03
$\sigma_{y'}$ (mrad) 4.386e-03
$\gamma\sigma_{x'}$ 0.2852
$\gamma\sigma_{y'}$ 0.02069

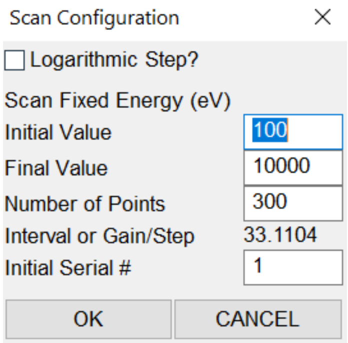
Light Source Description

Linear Undulator

☐ Link Gap & Field
☑ End Correction Magnets
☐ Segmented Undulator
☐ Symmetric Profile

Gap Value 24
B(T) 0.845506
Periodic Length (cm) 1.9
Device Length (m) 1.8
Regular Magnet Length (m) 1.748
Number of Regular Periods 92
K Value 1.5
ε_{1st}(eV) 1367.22

σ_r (mm) 4.481e-03
$\sigma_{r'}$ (mrad) 0.01611
Σ_x (mm) 0.2163
$\Sigma_{x'}$ (mrad) 0.06256
Σ_y (mm) 5.028e-03
$\Sigma_{y'}$ (mrad) 0.01669
λ_{1st}(nm) 0.906835
ε_{1st}(peak:eV) 1363.12
ε_{3rd}(peak:eV) 4096.47
Flux_{1st} 2.0206e+15
Brilliance_{1st} 4.5073e+19
Peak Brilliance 2.24769e+21
Bose Degeneracy 0.698894
Total Power (kW) 1.83832



Scan Configuration

☐ Logarithmic Step?

Scan Fixed Energy (eV)
Initial Value 100
Final Value 10000
Number of Points 300
Interval or Gain/Step 33.1104
Initial Serial # 1

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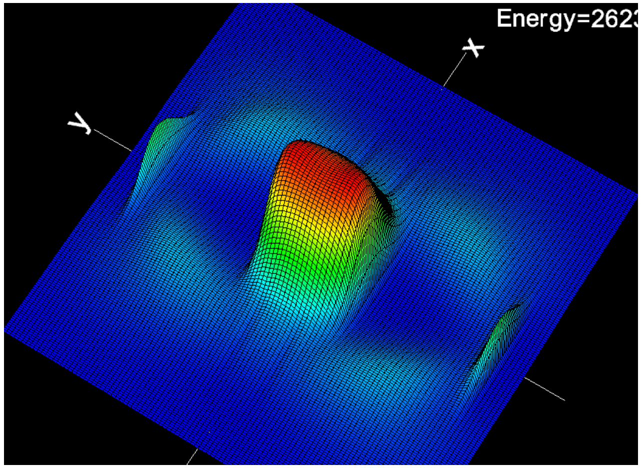
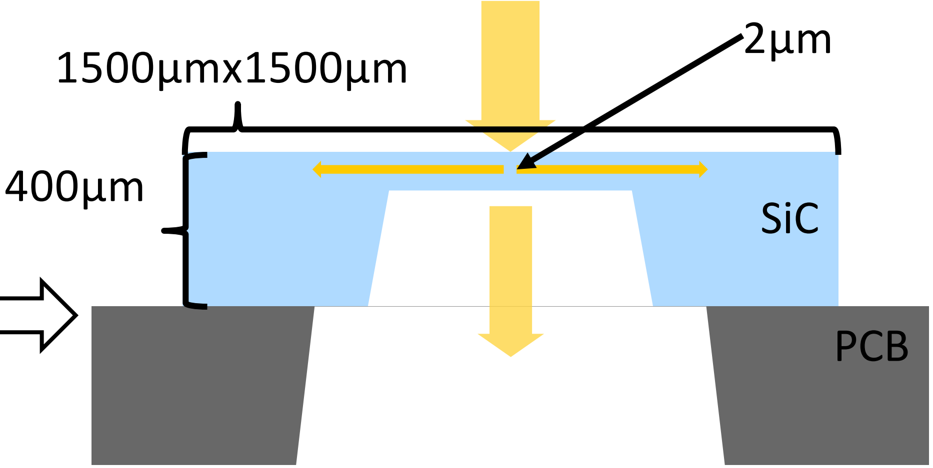
ID whitebeam, spectra

(microXAS, spectra)

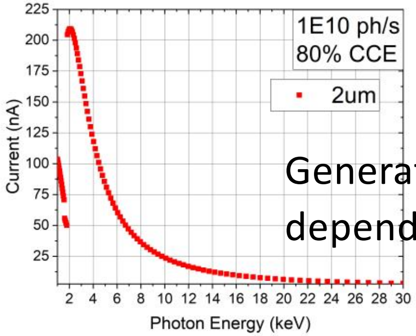
2. <u>determine current on XBPM</u>

Flux after optical elements





(X,Y,E) CURRENT MAPS



Generated current depends on E_{ph}

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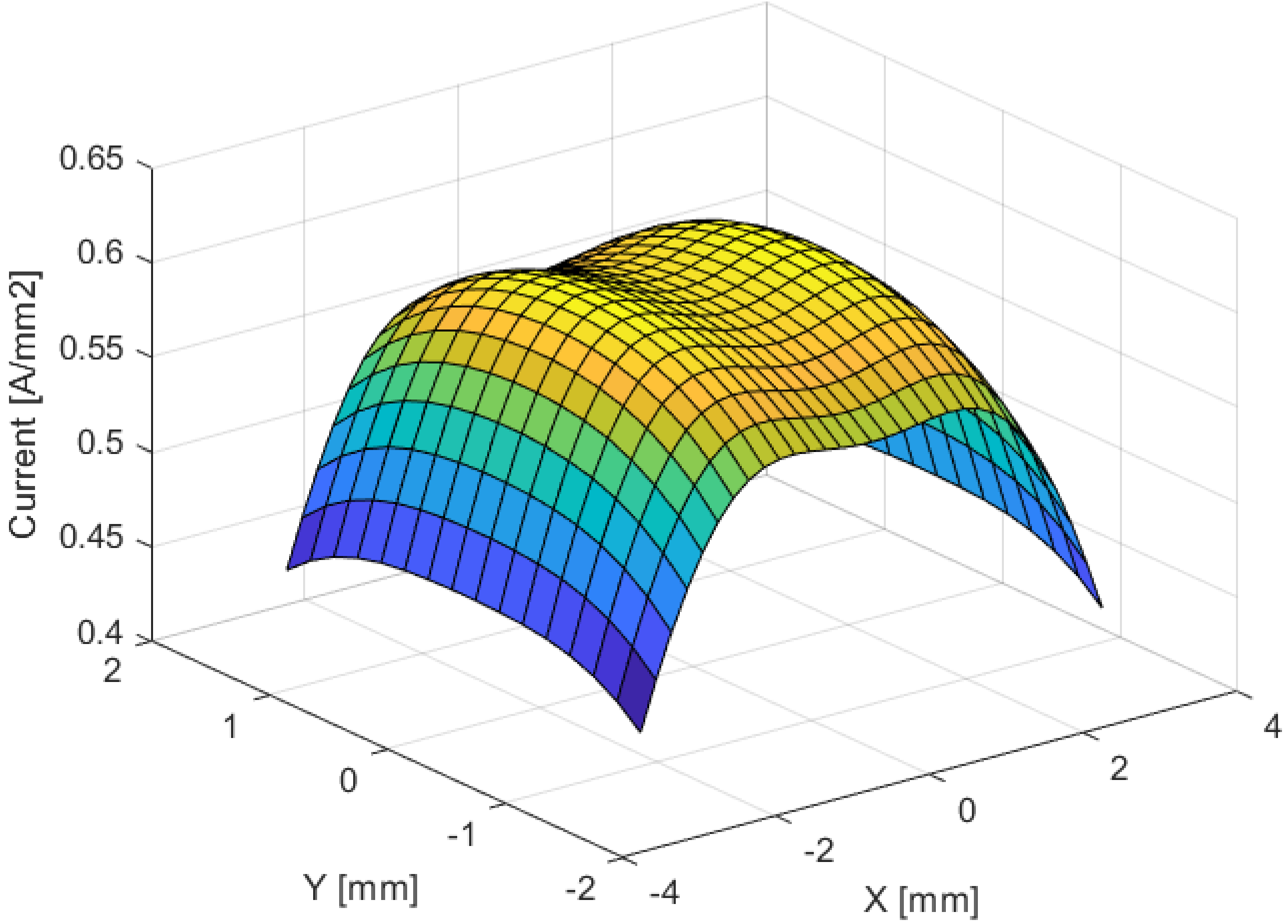
Beam to Current conversion
“Standard 2um SiC XBPM, microXAS”

Current map



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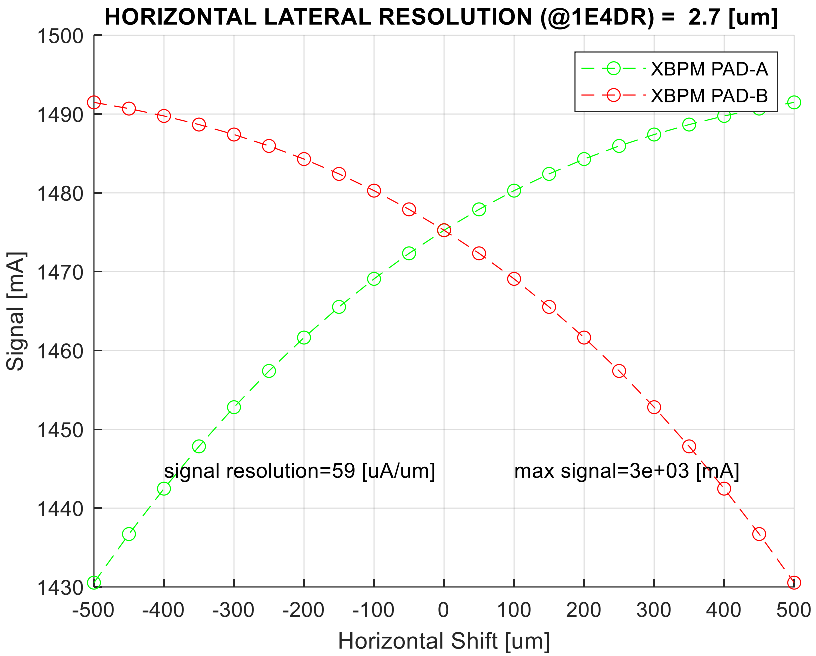
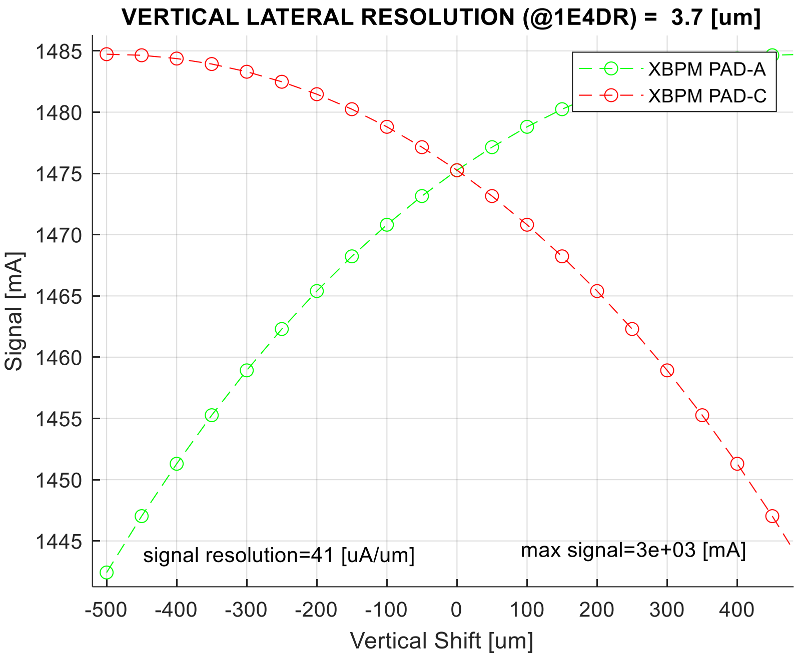
Knife-edge scan at center

Standard 2um SiC XBPM@microXAS


HORIZONTAL LATERAL RESOLUTION (@1E4DR) = 2.7 [um]


VERTICAL LATERAL RESOLUTION (@1E4DR) = 3.7 [um]

(Theoretical) lateral resolution of [2.7um,3.7um]

Max current on device (diaphram*) 3[A]

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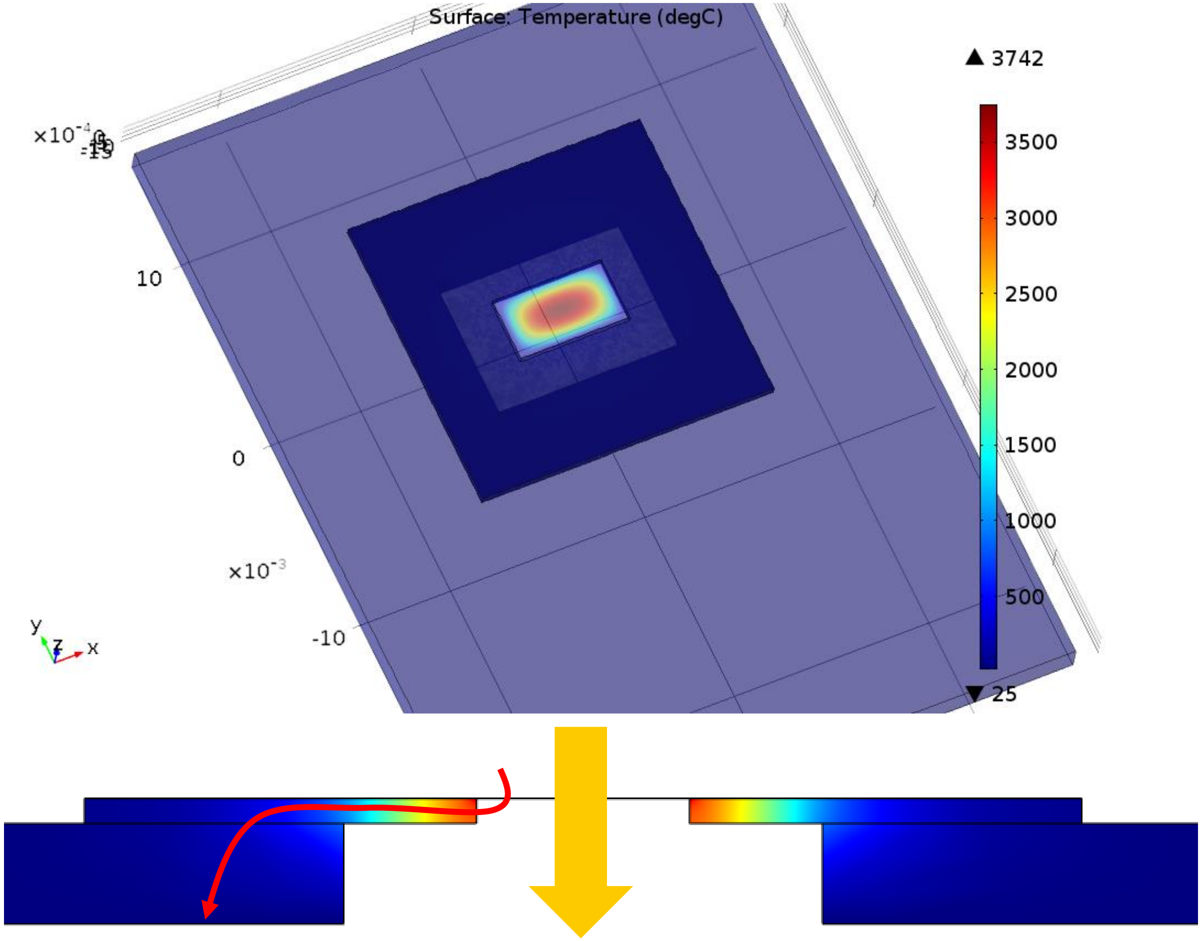
Temperature profile

Standard 2um SiC XBPM@microXAS



Expected 3500°C….

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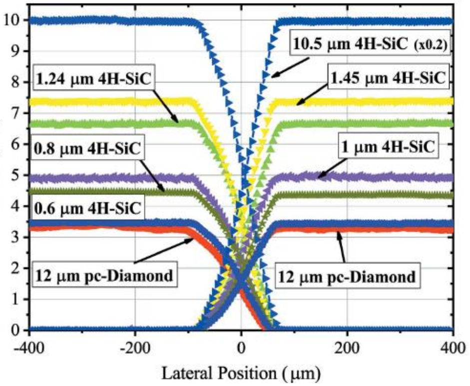
LIMITS AT THE MATERIAL LEVEL

J. Synchrotron Rad. (2019). **26**, 28–35

Silicon carbide X-ray beam position monitors for synchrotron applications

Selamnesh Nida,[a]* Alexander Tsibizov,[a] Thomas Ziemann,[a] Judith Woerle,[a,b] Andy Moesch,[c] Clemens Schulze-Briese,[c] Claude Pradervand,[b] Salvatore Tudisco,[d] Hans Sigg,[b] Oliver Bunk,[b] Ulrike Grossner[a] and Massimo Camarda[a,b]*



In this work, the performance of thin silicon carbide membranes as material for radiation hard X-ray beam position monitors (XBPMs) is investigated. Thermal and electrical behavior of XBPMs made from thin silicon carbide membranes and single-crystal diamond is compared using finite-element simulations. Fabricated silicon carbide devices are also compared with a 12 μm commercial polycrystalline diamond XBPM at the Swiss Light Source at the Paul Scherrer Institute. Results show that silicon carbide devices can reach equivalent transparencies while showing improved linearity, dynamics and signal-to-noise ratio compared with commercial polycrystalline diamond XBPMs. Given the obtained results and availability of electronic-grade epitaxies on up to 6 inch wafers, it is expected that silicon carbide can substitute for diamond in most beam monitoring applications, whereas diamond, owing to its lower absorption, could remain the material of choice in cases of extreme X-ray power densities, such as pink and white beams.

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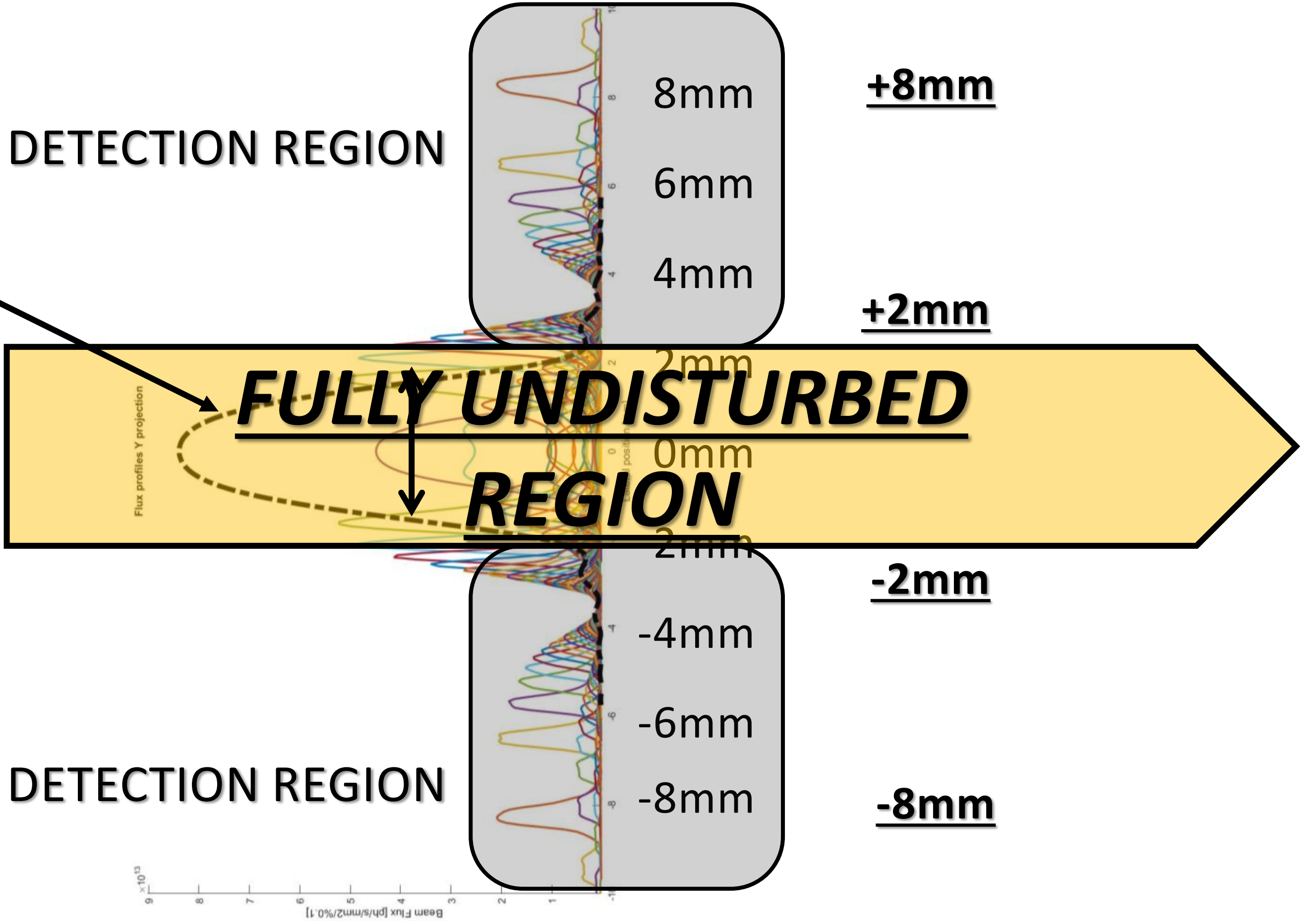
Generalities of whitebeam monitoring

Y profile



DETECTION REGION

HARMONICS

FULLY UNDISTURBED REGION

DETECTION REGION

+8mm

+2mm

-2mm

-8mm

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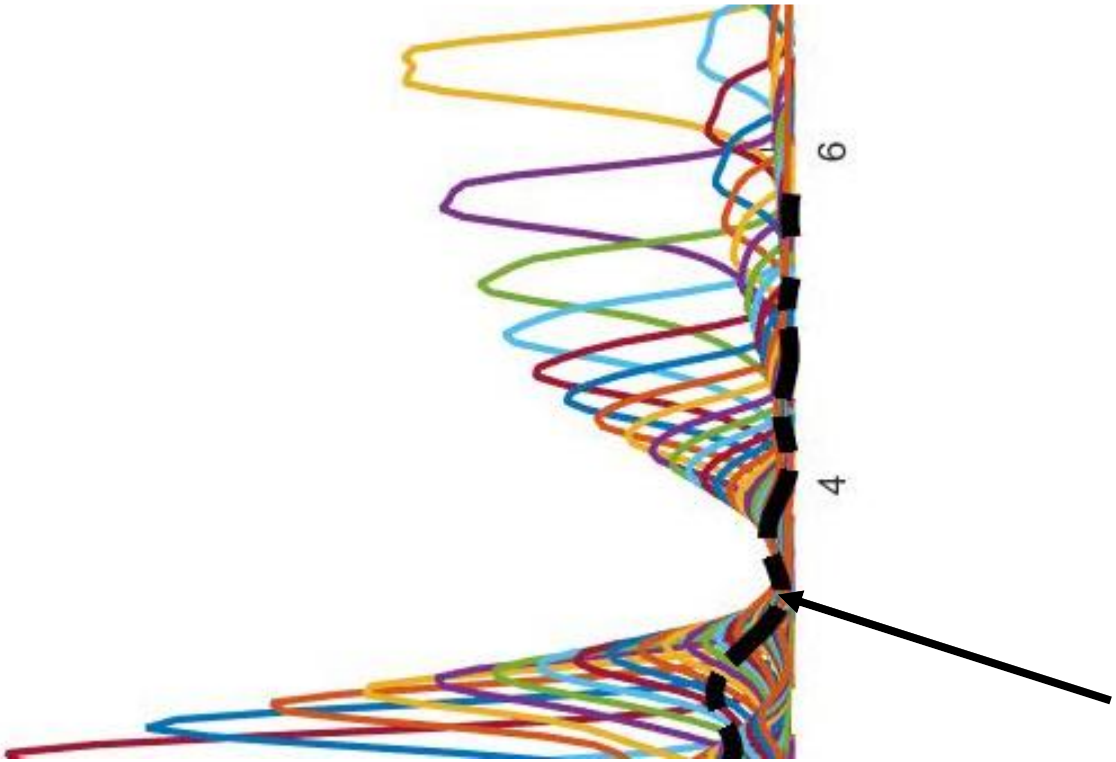
Generalities of whitebeam monitoring



WE ARE NOT MEASURING THE «TAILS» OF THE BEAM

WE ARE REALLY MEASURING THE «OFF HARMONIC» COMPONENTS!

CROSS-CHROMATIC MONITORING

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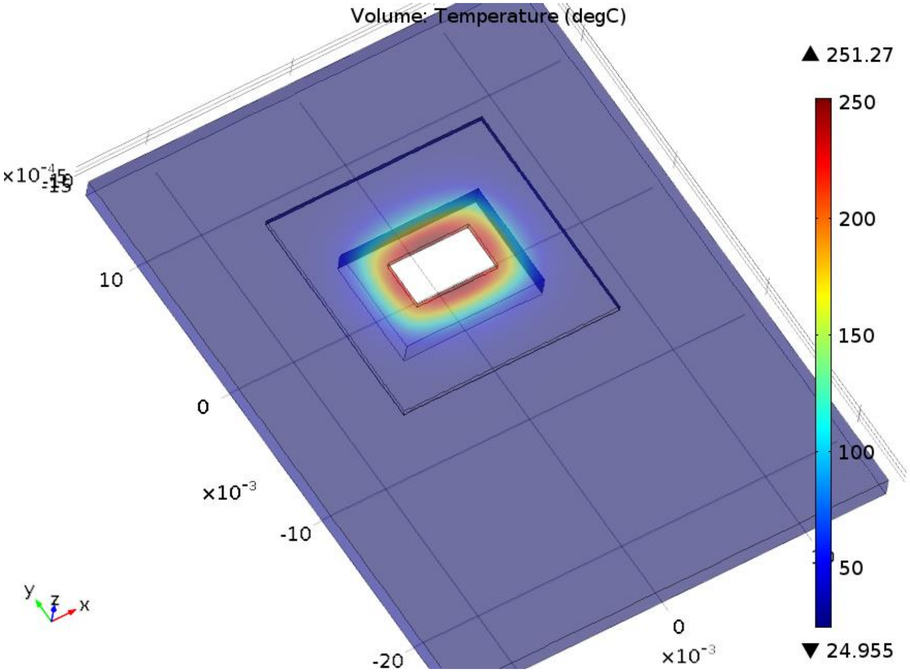
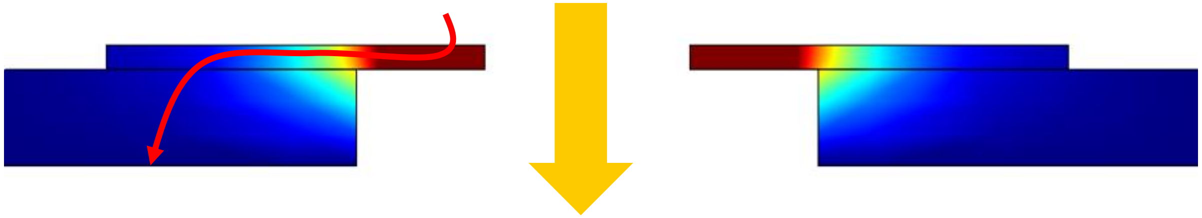
Whitebeam monitoring
"*Blade-type*" 2um SiC XBPM, microXAS





SIMULATED TEMPERATURE: 250°C (x10 reduction!)

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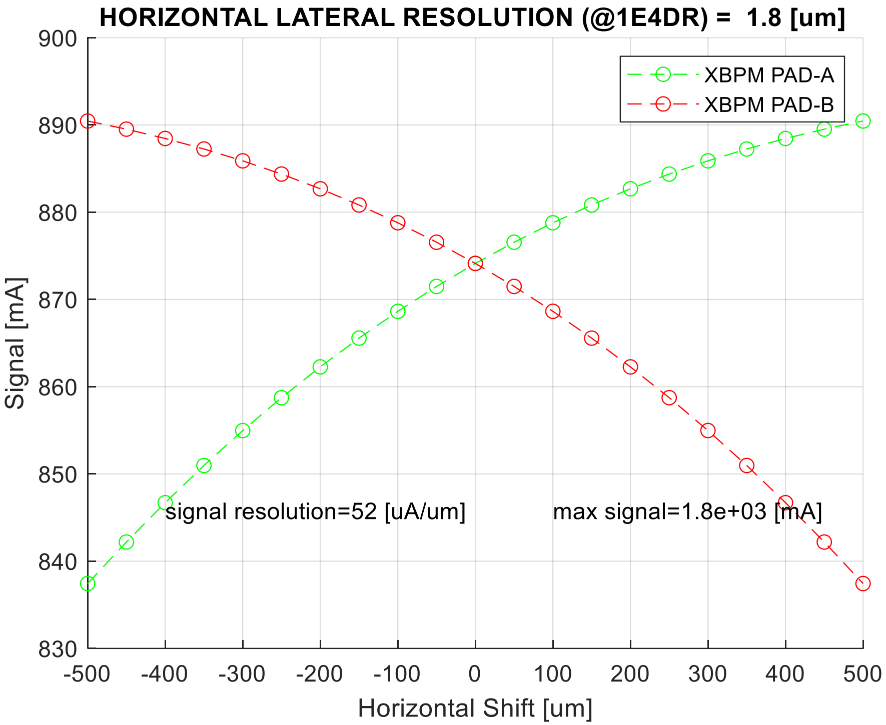
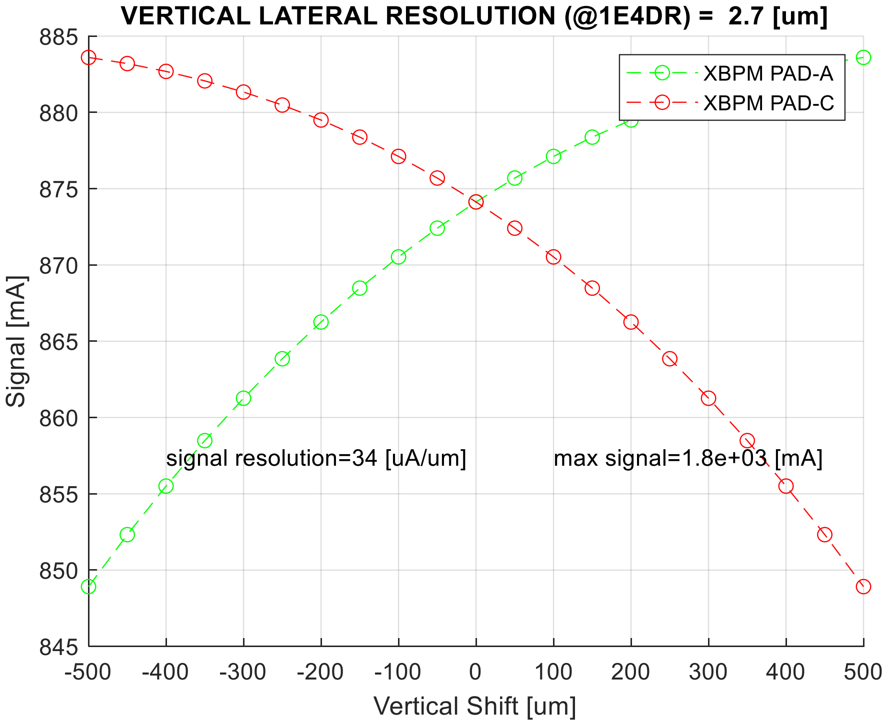
Knife-edge scan at center
“*Blade-type*” 2um SiC XBPM, microXAS





Max current on device (diaphram) 1.7[A] (x2 reduction)

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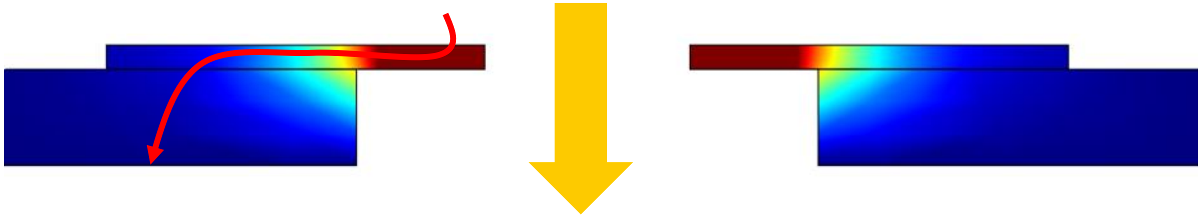
Whitebeam monitoring

“*Blade-type*” 2um SiC XBPM@microXAS

- **Max current on device (diaphram) 1.7[A] (x2 reduction)**

- **Max temperature 250°C (*x10 reduction*)**



- **Lateral resolution of [1.8um,2.7um] (≈x2 improvement)**

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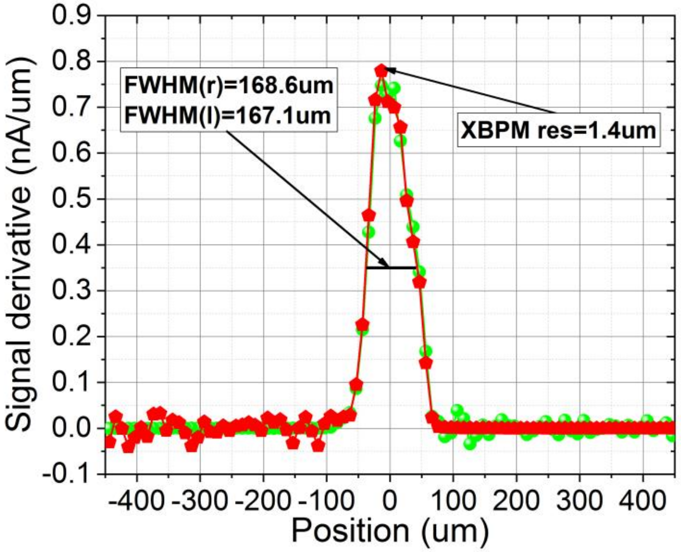
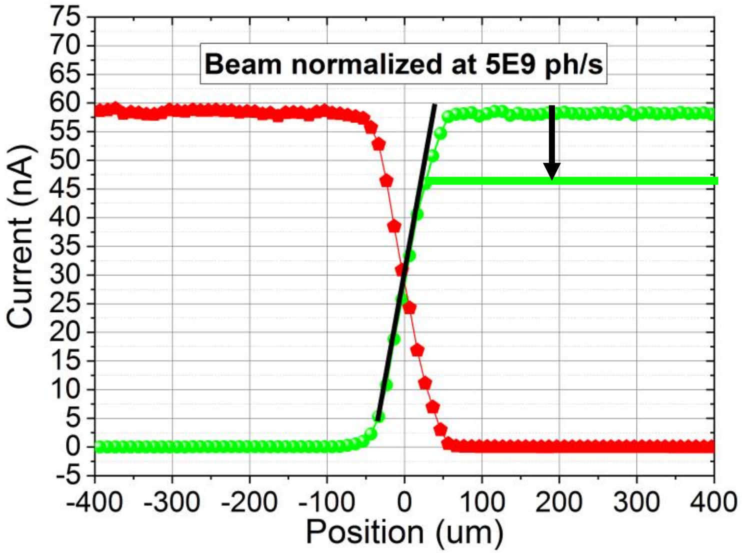
Whitebeam monitoring

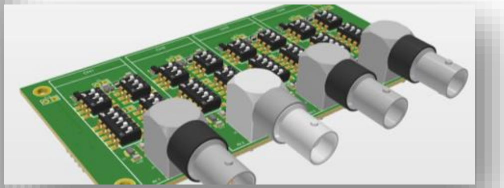
"*Blade-type*" 2um SiC XBPM@microXAS





LATERAL RESOLUTION

$$\frac{Max\ current}{\nabla current(x,y)/\nabla x} \times \frac{1}{SNR(electronics)}$$



$$SNR(electronics) \approx 1E4$$

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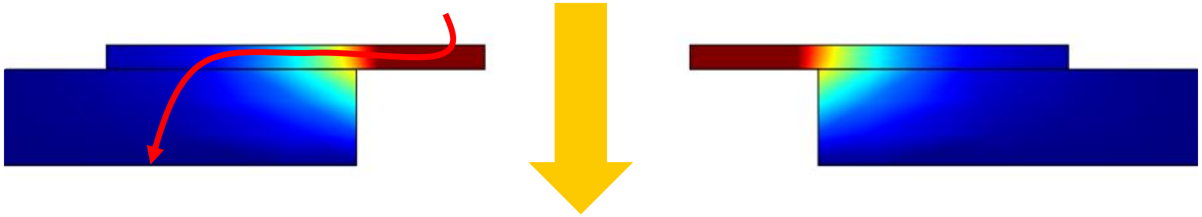
Whitebeam monitoring

"*Blade-type*" 2um SiC XBPM@microXAS

- **Max current on device (diaphram) 1.7[A] (x2 reduction)**

- **Max temperature 250°C (*x10 reduction*)**



- **Lateral resolution of [1.8um,2.7um] (≈x2 improvement)**

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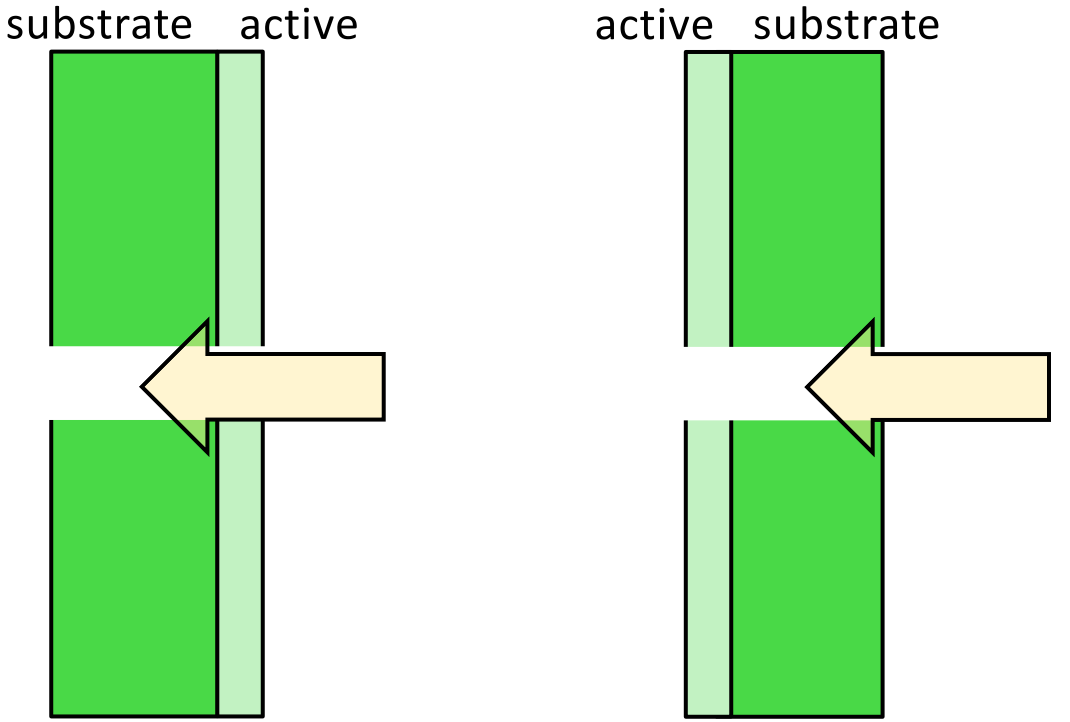
Response of SiCBlades:
FILTERED CONFIGURATION



- we are using an "*integrated/monolitic/local filter*"
- quite strong filter (*equivalent to 3.6mm diamond window*)
- a filter present only on the tails, not at beam center
  - applicable for all Xray beamlines (soft-hard)

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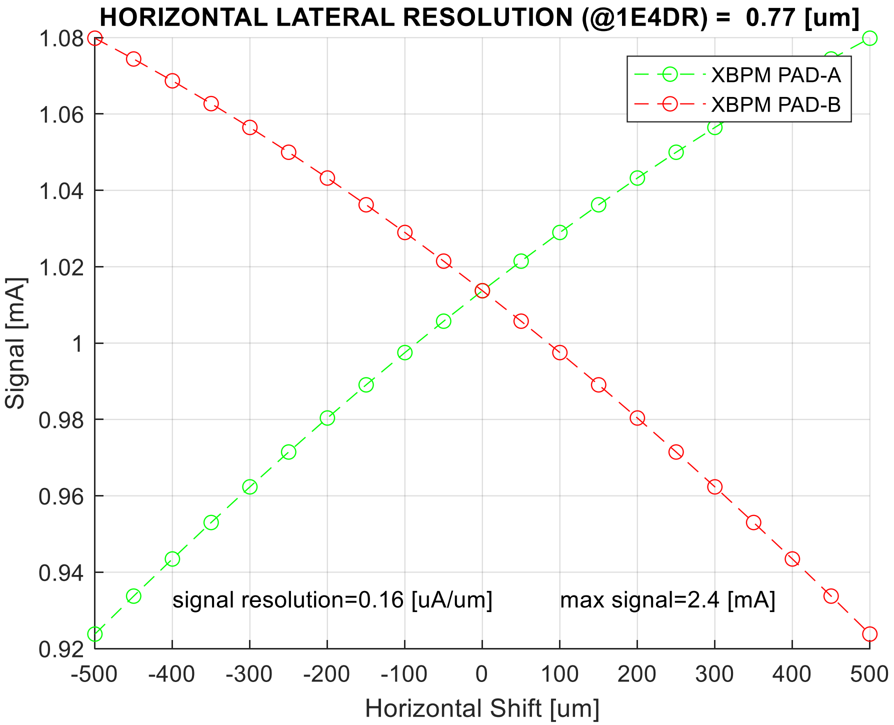
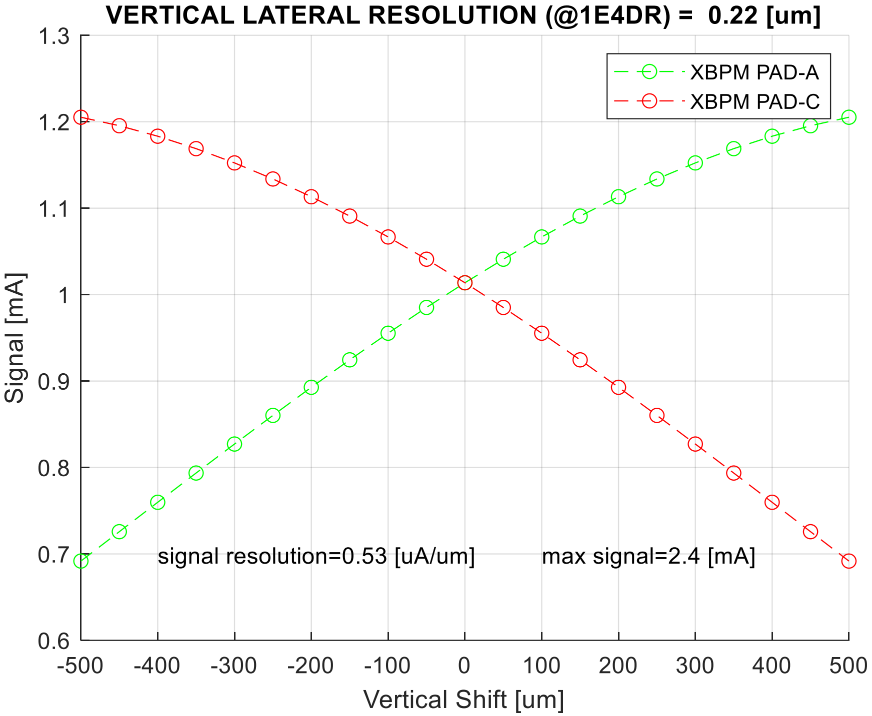
Whitebeam monitoring “OPTIMIZED Blade-type” 2um SiC XBPM, microXAS


HORIZONTAL LATERAL RESOLUTION (@1E4DR) = 0.77 [um]


VERTICAL LATERAL RESOLUTION (@1E4DR) = 0.22 [um]

Max temperature same of before (250°C)…

Max current on device (diaphram) 2 [mA] *(>x1000 reduction)*

Lateral resolution of [0.7um,0.22um] *(>x3-10 improvement*)*

WHY???

2um mem= [2.7um,3.7um]
blade=[1.8um,2.7um]

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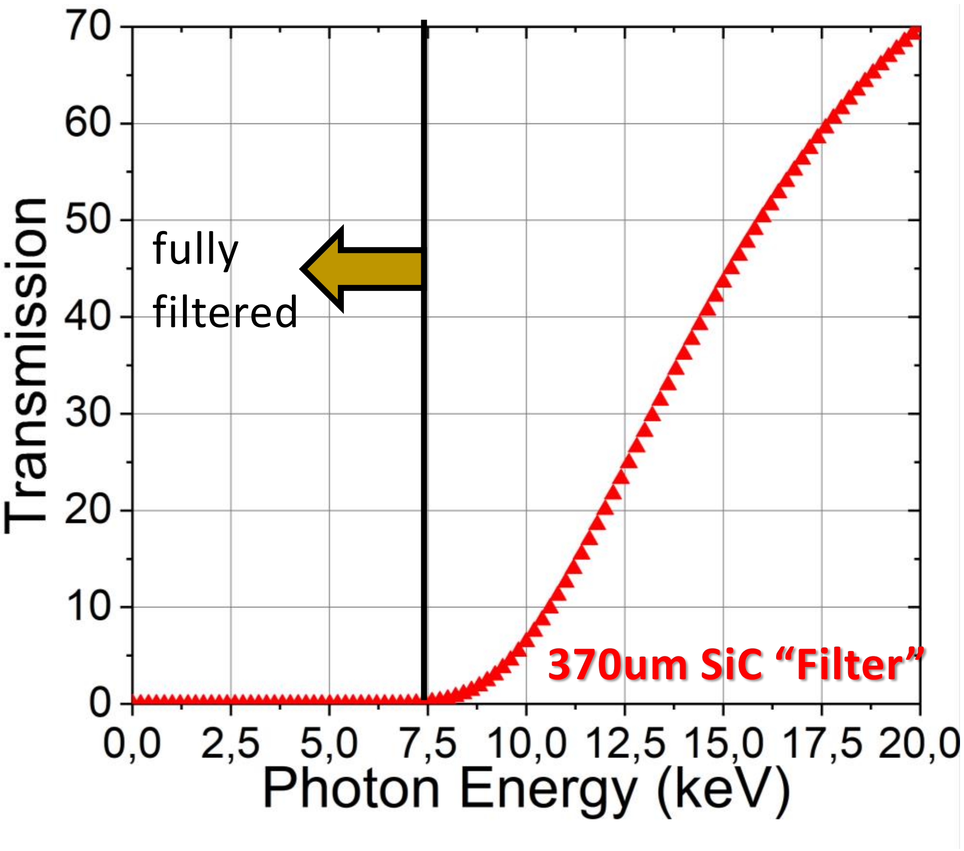
Blade-type sensors: *OPTIMIZED*



filtering everything below 7.5keV → *cross-chromatic* monitoring

filtering everything below 7.5keV → can filter bendig magnet radiation

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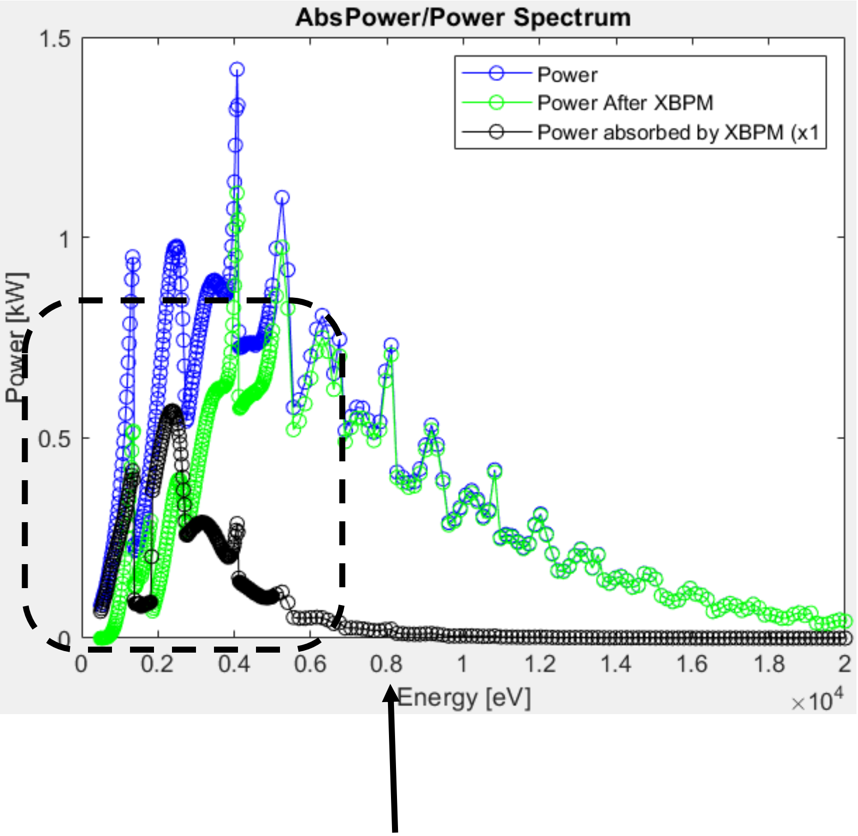
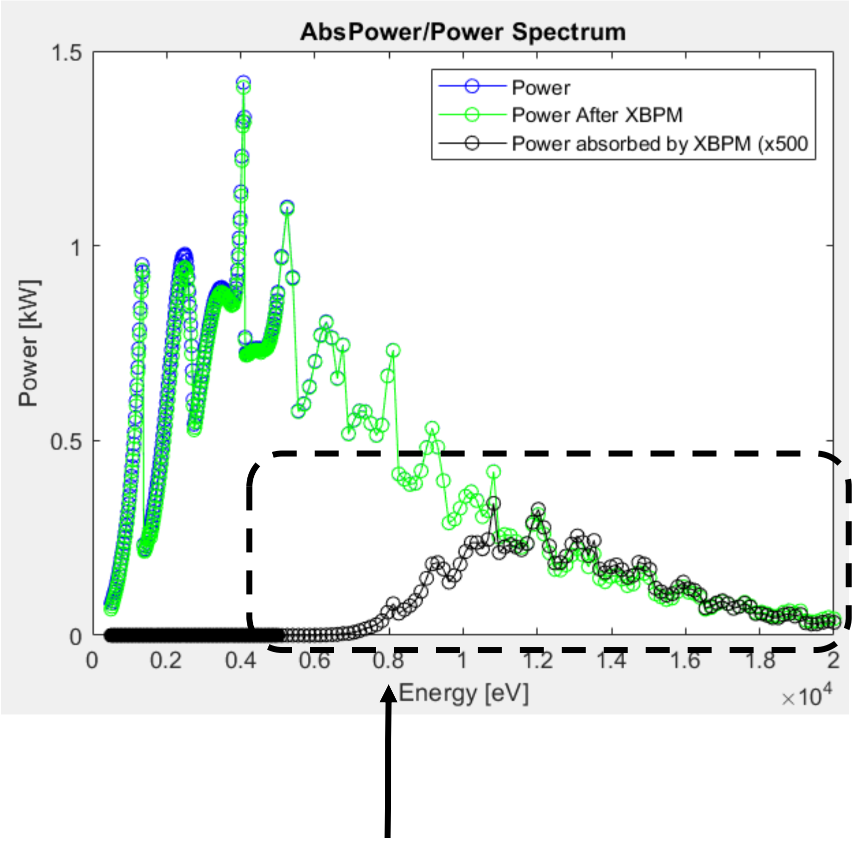
Blade-type sensors: *OPTIMIZED*

STANDARD SiC XBPM



main signal contribution coming from <8keV photons

OPTIMIZED SiC XBPM



main signal contribution coming from <8keV photons

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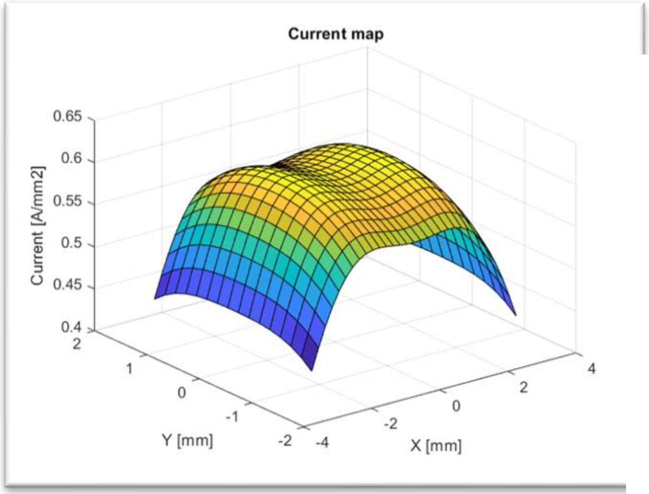
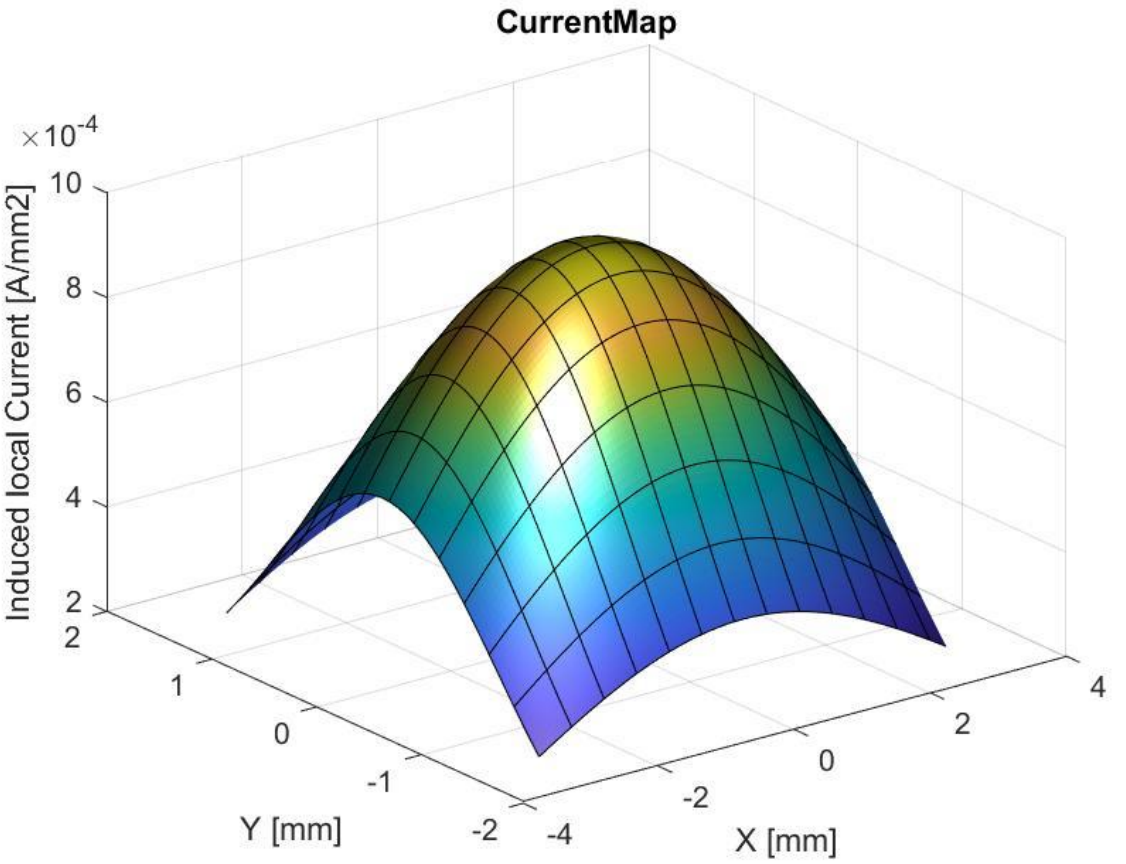
STD vs. FLIPPED





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Knife-edge scan at center

comparison of XBPM types@ SIM beamline

“Standard” 2um SiC XBPM

- **Lateral resolution of [116um(!)– 1.3um]**
- **Max current on device 4.8[A]**
- **Max temperature 3000°C**

“BLADE” SiC XBPM

- **Lateral resolution of [138um– 0.86um]**
- **Max current on device 1.4[A]**
- **Max temperature 130°C!**

“OPTIMIZED BLADE” SiC XBPM

- **Lateral resolution of [4.6um(!)– 0.18um]**
- **Max current on device 1[mA]**
- **Max temperature 130°C**

[x25(!)–x7]

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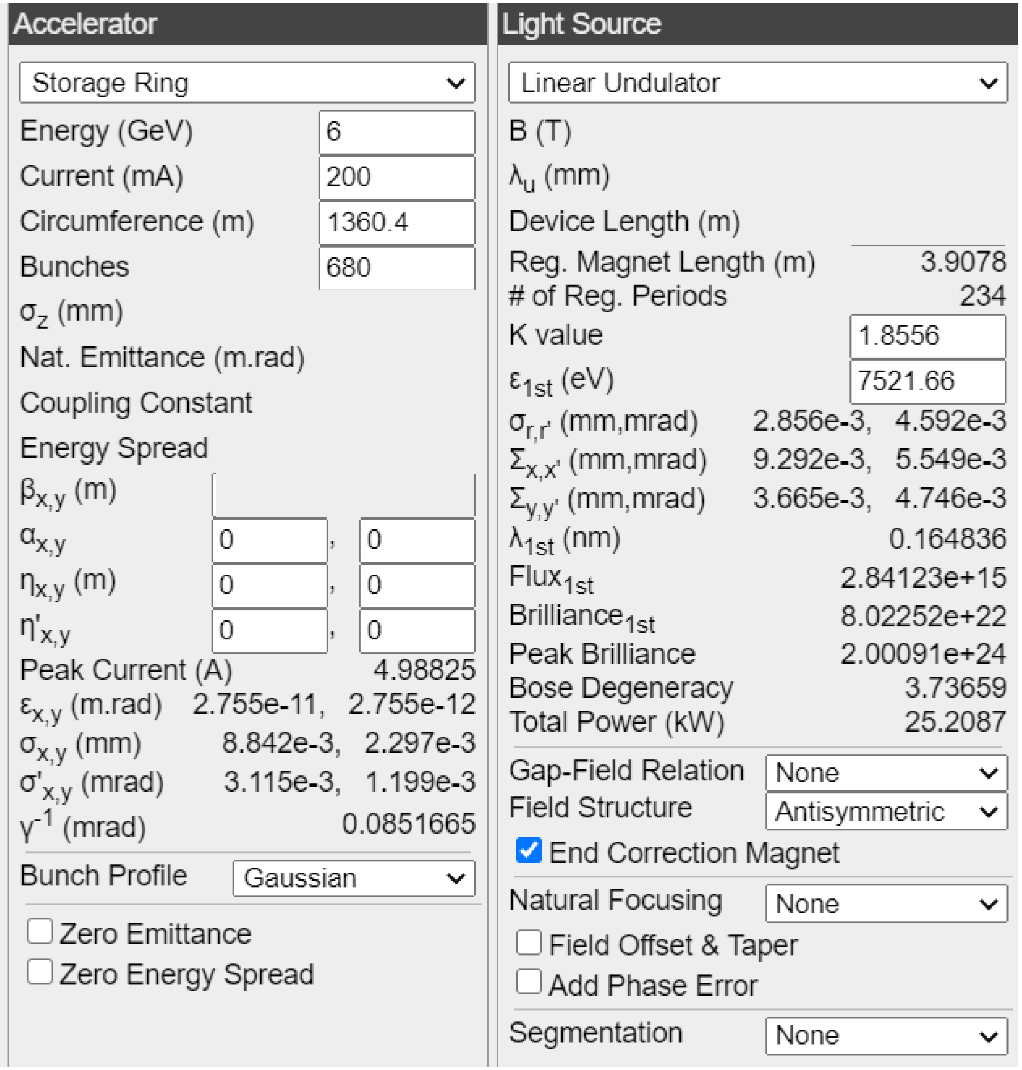
SPECTRA parameters/calculations

B1 Engineering materials beamline@**HEPS**



Accelerator

Storage Ring

Energy (GeV)	6	
Current (mA)	200	
Circumference (m)	1360.4	
Bunches	680	
σ_z (mm)		
Nat. Emittance (m.rad)		
Coupling Constant		
Energy Spread		
$\beta_{x,y}$ (m)		
$\alpha_{x,y}$	0	0
$\eta_{x,y}$ (m)	0	0
$\eta'_{x,y}$	0	0
Peak Current (A)	4.98825	
$\varepsilon_{x,y}$ (m.rad)	2.755e-11	2.755e-12
$\sigma_{x,y}$ (mm)	8.842e-3	2.297e-3
$\sigma'_{x,y}$ (mrad)	3.115e-3	1.199e-3
γ^{-1} (mrad)	0.0851665	
Bunch Profile	Gaussian	

☐ Zero Emittance

☐ Zero Energy Spread

Light Source

Linear Undulator

B (T)		
λ_u (mm)		
Device Length (m)		
Reg. Magnet Length (m)	3.9078	
# of Reg. Periods	234	
K value	1.8556	
ε_{1st} (eV)	7521.66	
$\sigma_{r,r'}$ (mm,mrad)	2.856e-3	4.592e-3
$\Sigma_{x,x'}$ (mm,mrad)	9.292e-3	5.549e-3
$\Sigma_{y,y'}$ (mm,mrad)	3.665e-3	4.746e-3
λ_{1st} (nm)	0.164836	
Flux_{1st}	2.84123e+15	
$\mathrm{Brilliance}_{1st}$	8.02252e+22	
Peak Brilliance	2.00091e+24	
Bose Degeneracy	3.73659	
Total Power (kW)	25.2087	
Gap-Field Relation	None	
Field Structure	Antisymmetric	

☑ End Correction Magnet

Natural Focusing: None

☐ Field Offset & Taper

☐ Add Phase Error

Segmentation: None

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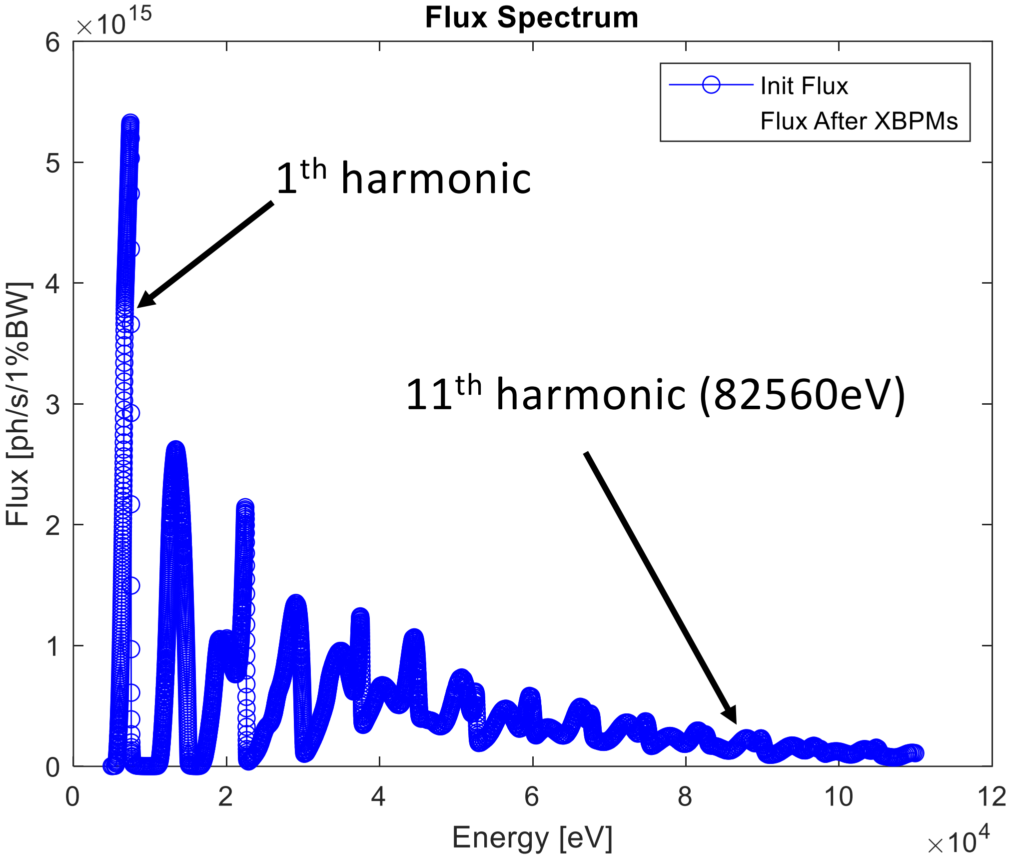
Integrated (over *space*, assuming 0.1%BW) FLUX



flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)
3000 steps between 50keV-110keV (20eV steps)

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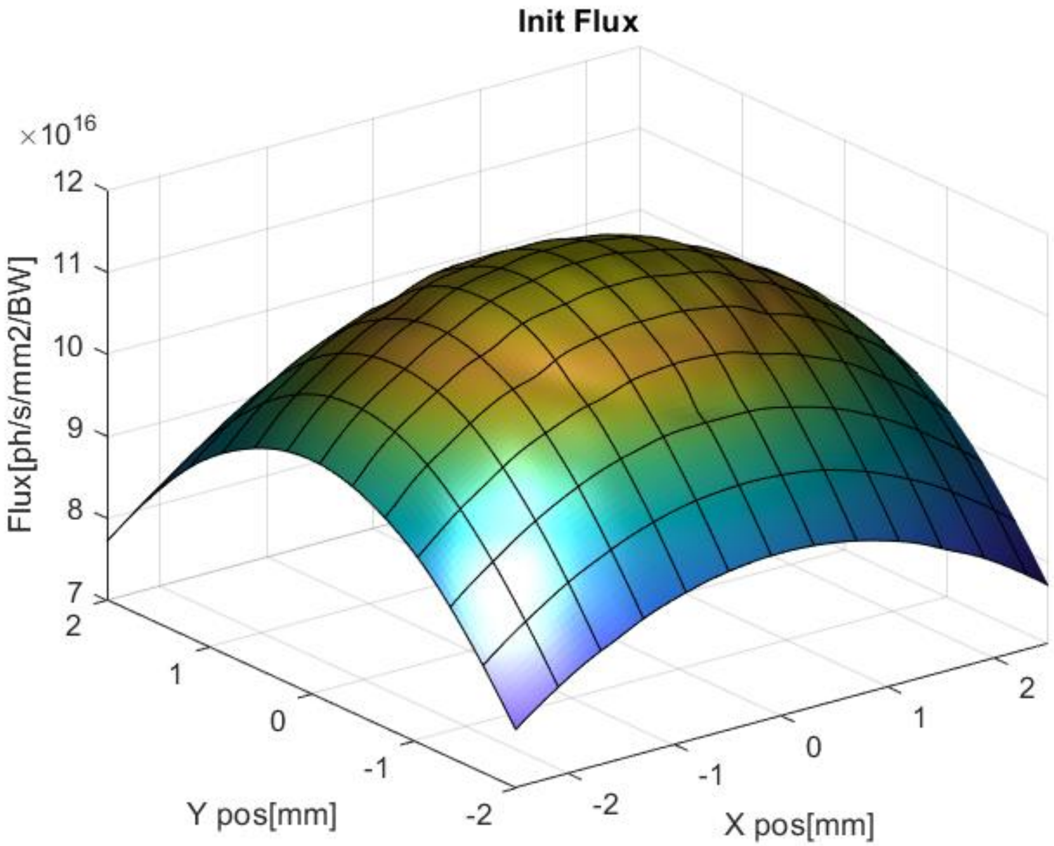
Integrated (over energy, assuming 0.1%BW) FLUX



NOTICE:
simmetric profile

flux maps energy calculations:	6000 steps between 500-50000eV (7eV steps)
	3000 steps between 50keV-110keV (20eV steps)

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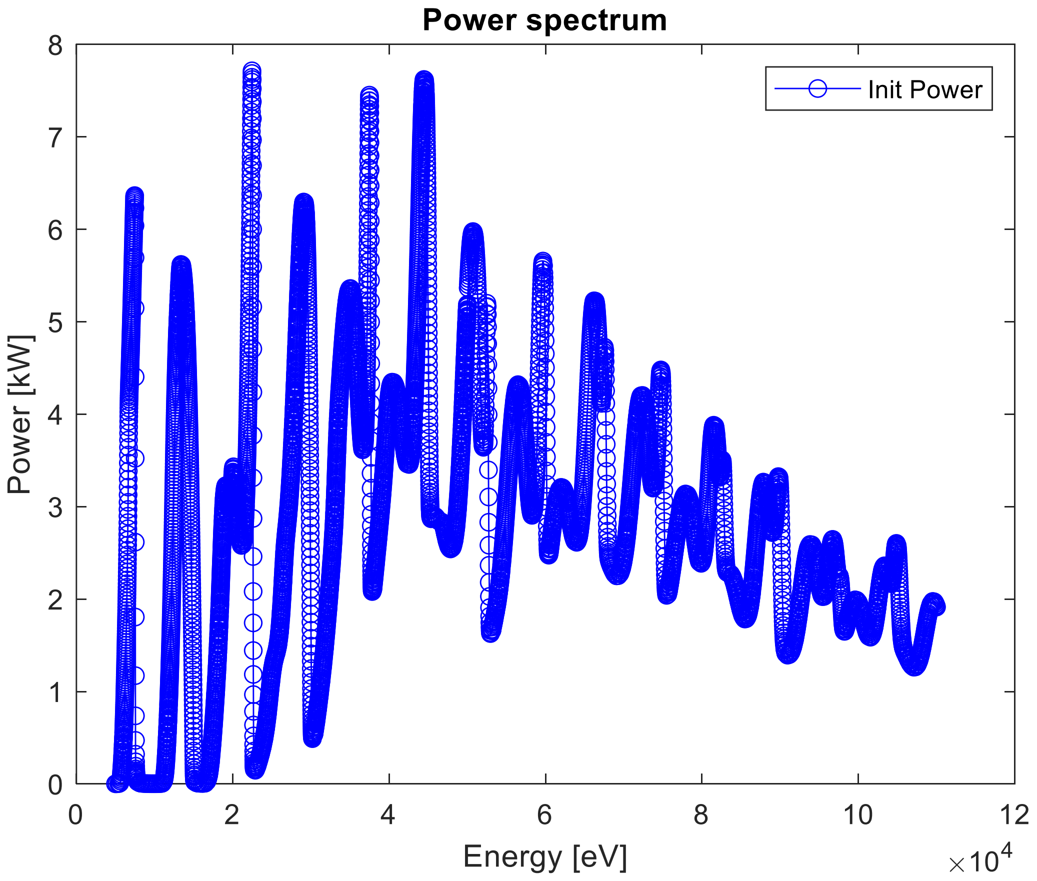
Integrated (over *space*, assuming 0.1%BW) POWER



flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)

3000 steps between 50keV-110keV (20eV steps)

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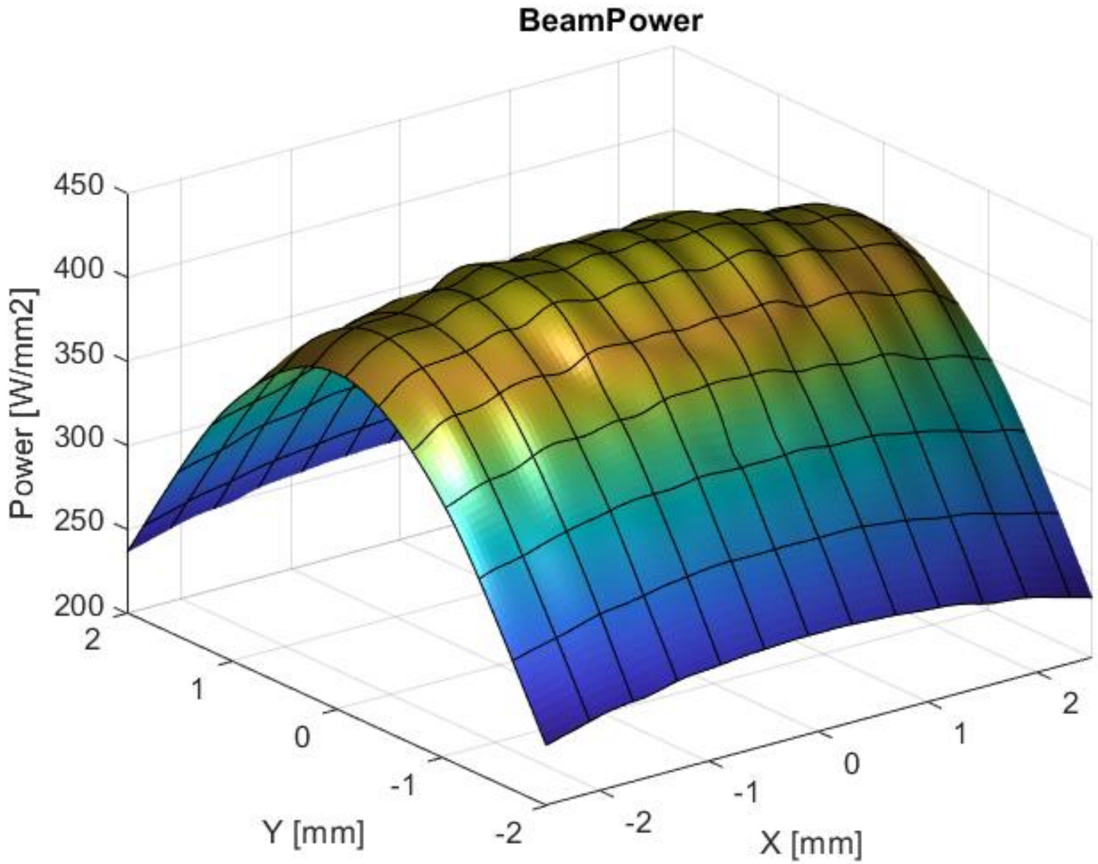
Integrated (over energy, assuming 0.1%BW) POWER



NOTICE:

elongation ***<u>along X</u>***

flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)
3000 steps between 50keV-110keV (20eV steps)

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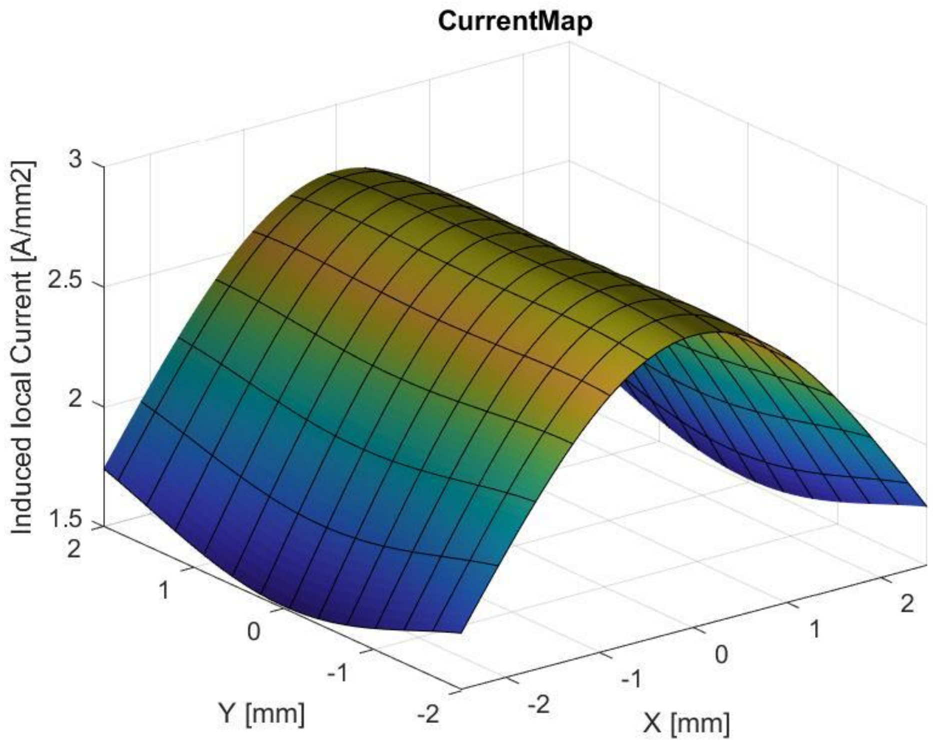
Integrated (over energy, assuming 0.1%BW) *ABSORBED* POWER (2um SiC XBPM)



NOTICE:
elongation ***along Y!!***

Lateral resolution

[1.12um,36.3um]

Max current on device

1.4[A]

flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)
3000 steps between 50keV-110keV (20eV steps)

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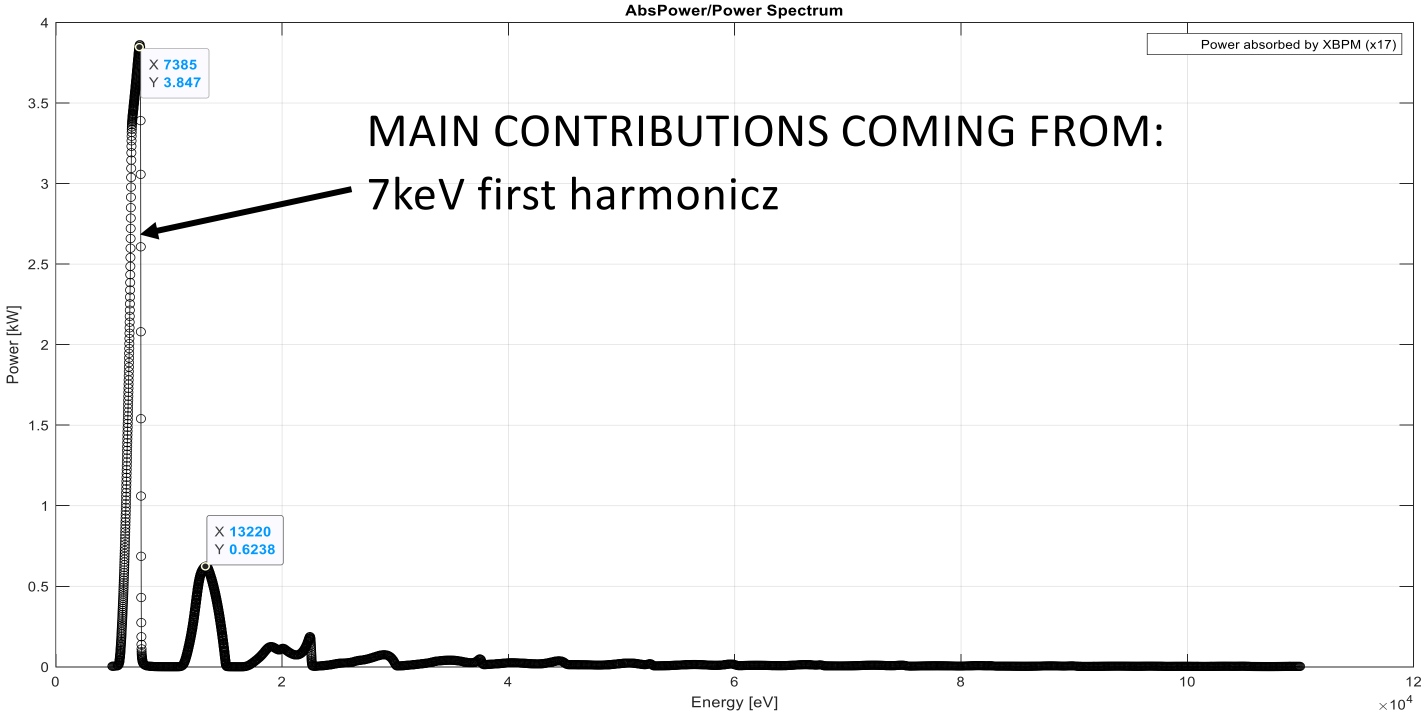
Integrated (over *space*, assuming 0.1%BW) *ABSORBED* POWER (2um SiC XBPM)



MAIN CONTRIBUTIONS COMING FROM:

7keV first harmonicz

flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)

3000 steps between 50keV-110keV (20eV steps)

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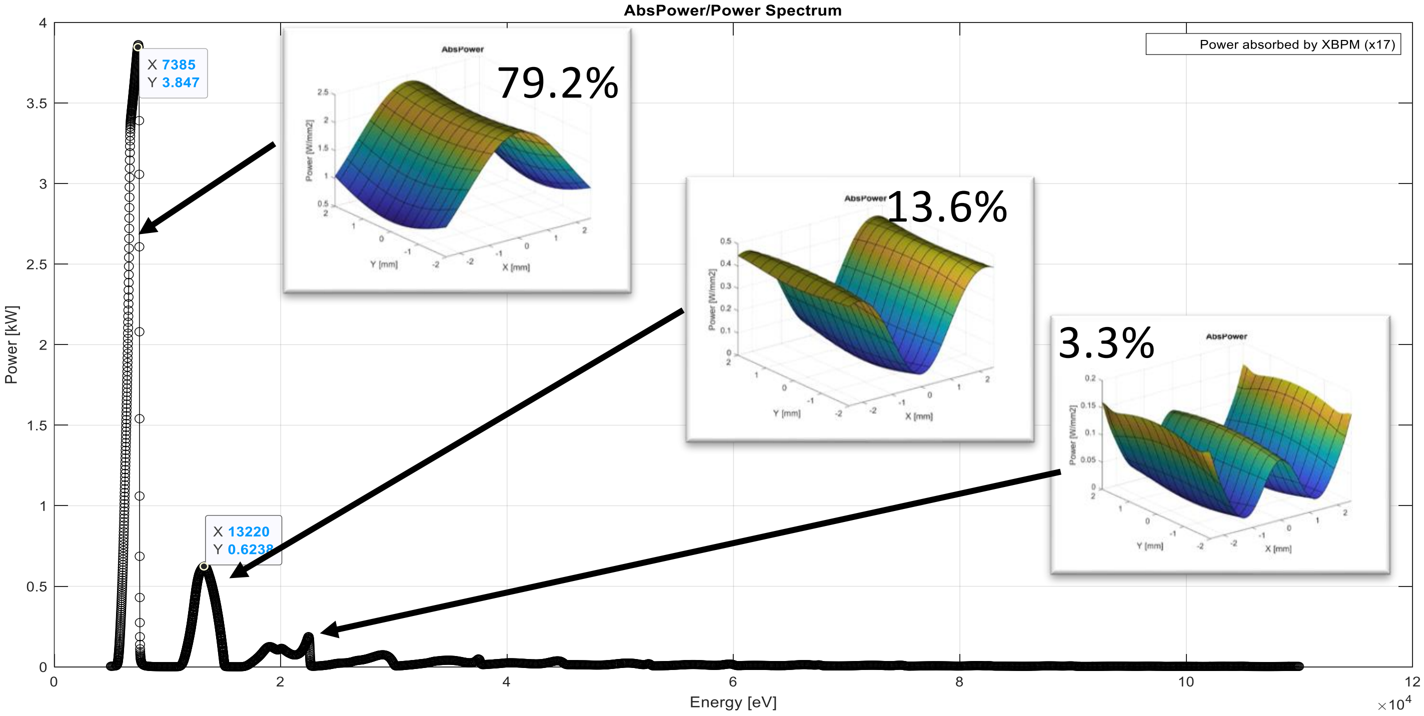
Integrated (over *space*, assuming 0.1%BW) POWER ABSORBED BY DEVICE (STD, 2um)



flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)

3000 steps between 50keV-110keV (20eV steps)

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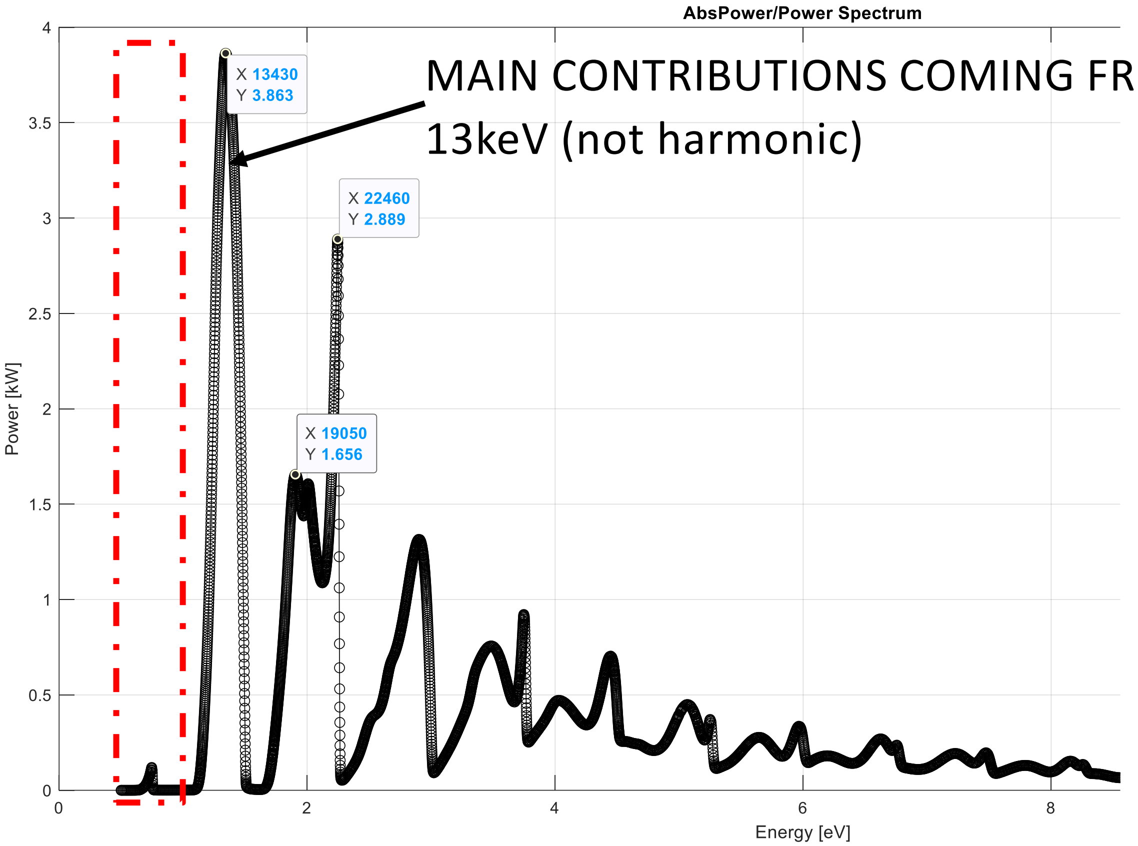
Integrated (over *space*, assuming 0.1%BW) POWER ABSORBED BY DEVICE (*FILTERED BLADE*, 2um)



MAIN CONTRIBUTIONS COMING FROM:
13keV (not harmonic)

flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)
3000 steps between 50keV-110keV (20eV steps)

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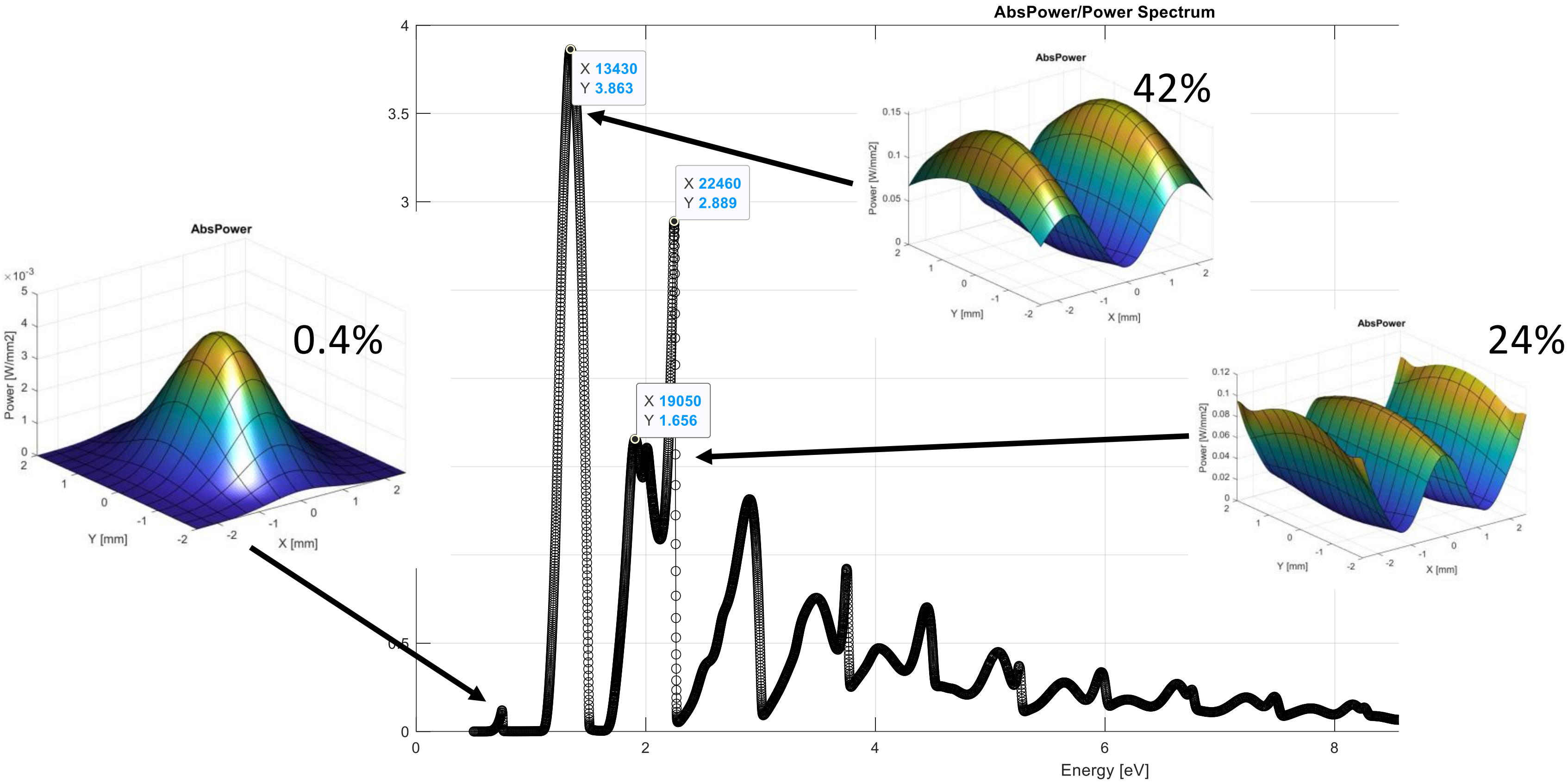
Integrated (over *space*, assuming 0.1%BW) POWER ABSORBED BY DEVICE (FILTERED BLADE, 2um)



flux maps energy calculations: 6000 steps between 500-50000eV (7eV steps)

3000 steps between 50keV-110keV (20eV steps)

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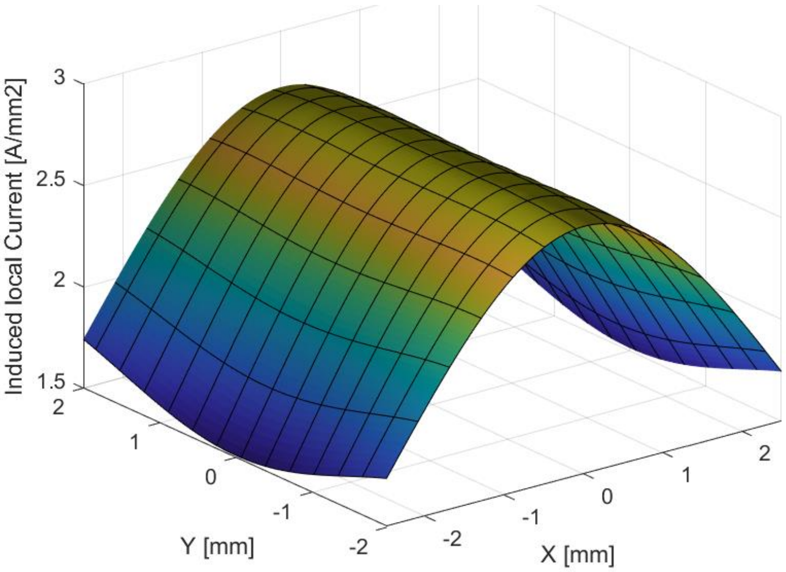
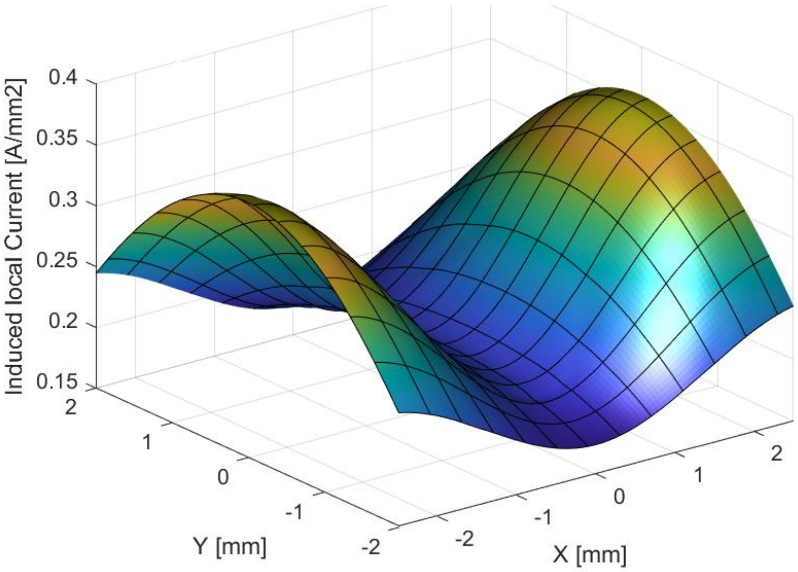
DEVICE CURRENT MAPs comparison

STD “blade”

FILTERED “blade”





Very different profiles

related to different shape of 1th and 2th harmonics

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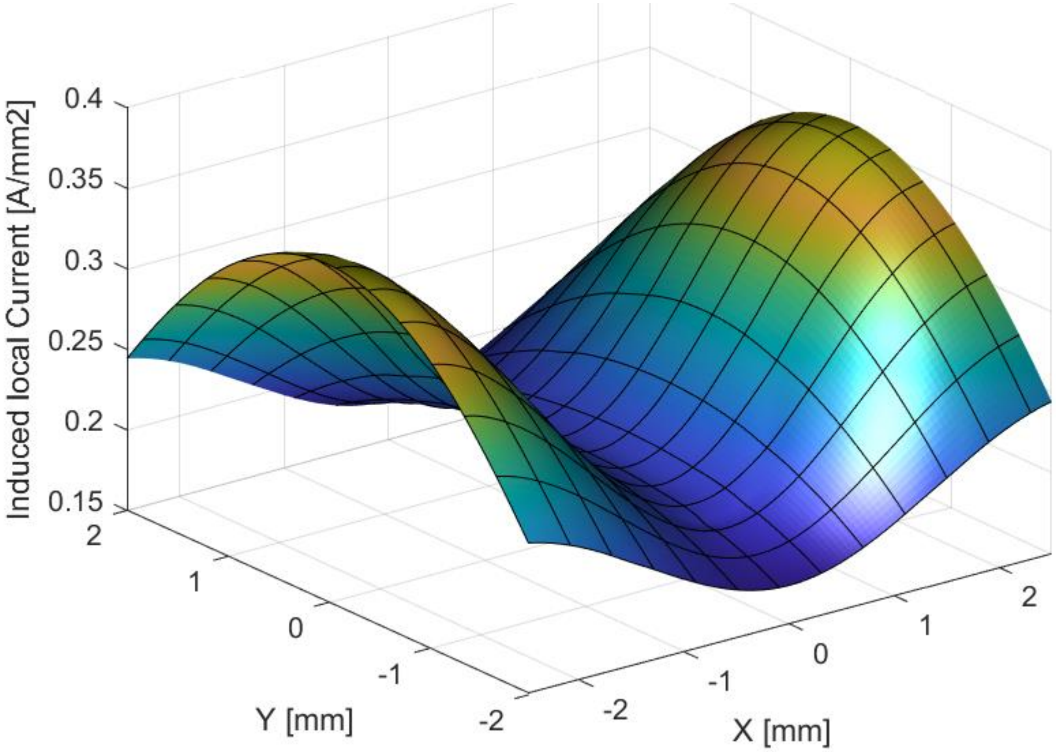
Integrated (over energy, assuming 0.1%BW) *ABSORBED* POWER (2um SiC OPT XBPM)



Lateral resolution

[0.46um,**2.7um**] **x10**

Max current on device

90[mA]

flux maps energy calculations:

6000 steps between 500-50000eV (7eV steps)
3000 steps between 50keV-110keV (20eV steps)

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conclusions and outlook

Goal of SenSiC is to develop X-ray diagnostic *at all levels*, using a novel material and *customized* technologies

What is now (installed):

1. Standard SiC XBPM with better characteristics than diamond
2. SiC sensors alternative to gas chambers (I0)
3. SiC sensors for absorption measurements (beam-stopper)
4. “Ultra-compact” SiC sensors alternative to xray eyes (nano-focusing)
5. Feedback system for (slow) shift during spectral measurements

What we are currently working on:

1. Fast and complete readout and feedback control loops
2. Monitors for small angles scattering measurements (XBPM beam-stopper)
3. Monitors for profile monitors (X-ray imaging)
4. Resistive Xray position monitors (single pixes sensors)
5. Whitebeam and crosschromatic monitoring

SiCblades™ detectors *can*:

- widthstand (easily) extreme high powers
- be used for both soft- and hard-Xray beamlines
- be optimized to yield very high lateral resolutions
- be optimized to avoid bending magnet background radiation
- have multiple “pixels” to reconstruct asymmetric distributions

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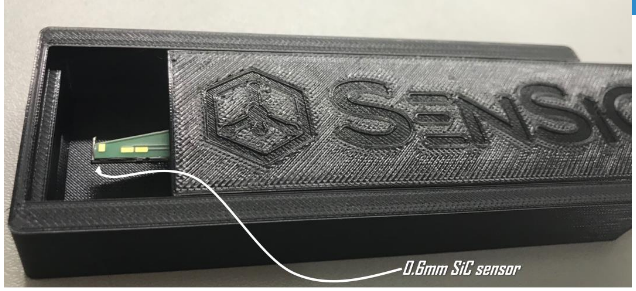
THANKS FOR YOUR ATTENTION!



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