# Radiation Damage and Characterization in the SOLEIL Storage Ring


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on behalf of the « radiation working group »:

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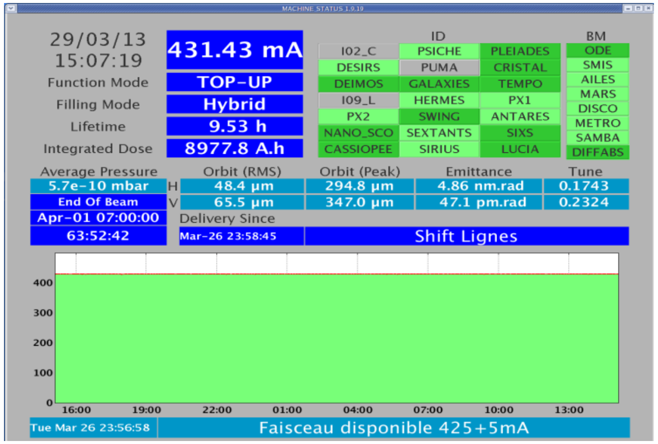
SOLEIL SYNCHROTRON

# INTRODUCTION

- **Synchrotron SOLEIL**
  - **2.75 GeV Synchrotron Light Source**, south of Paris, France
  - In operation since **2006**
  - 9800 A.h integrated current
  - **26 Beamlines** taking beam, 3 more are in construction (PUMA, ROCK and ANATOMIX)
  - Nominal mode of operation: 430 mA with hybrid filling pattern




  - SOLEIL is the first light source with **extensive use of NEG coating** (~50 % of the ring circumference) for vacuum improvement:
    - All straight sections
    - All quadrupole type vacuum chambers
  - After 6 years of operation, some equipment in the storage ring presents **unexpected damages due to radiations**

# OUTLINE

- **Equipment damage**
  - Description
  - Location
- **Dose measurement**
  - Dose spatial distribution
  - Absolute measurement
- **Radiation source**
  - Synchrotron radiation distribution
  - X Fluorescence
  - Photon spectrum measurement
- **Vacuum Chamber Material Considerations**
  - Shielding
  - Material comparison
- **Conclusion**

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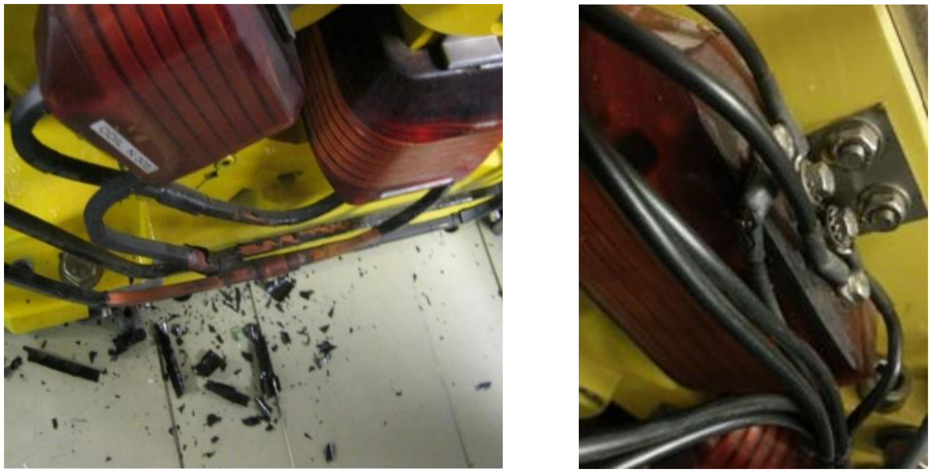
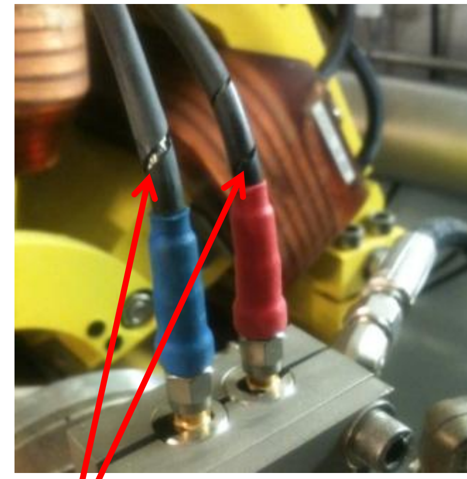
# Equipment damage due to radiations

- Fast aging of some equipment:
  - Cable insulators become rigid and brittle

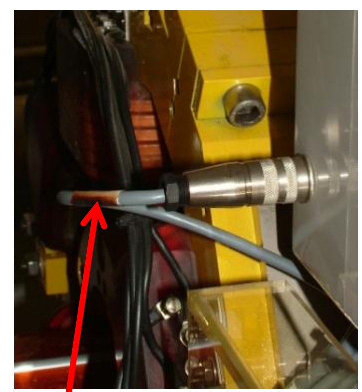


Sextupoles (downstream/upstream)



BPM cables

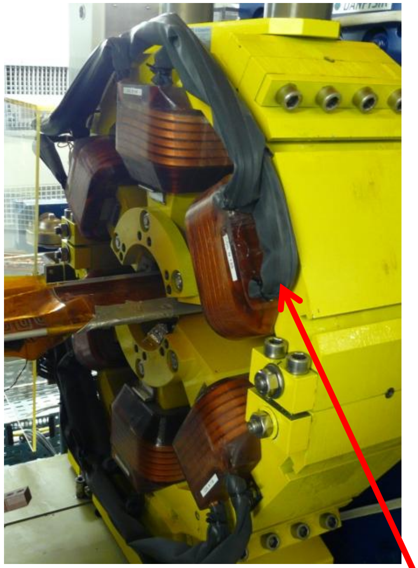
Temperature sensor boxes

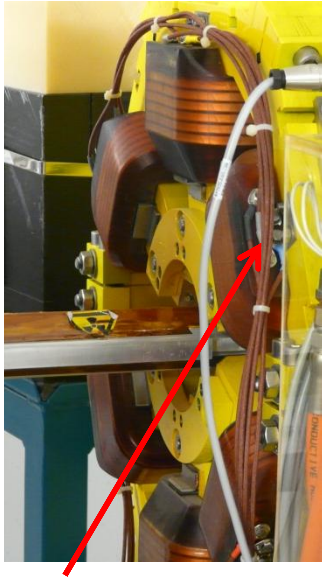


Browning of labelling

# Equipment damage due to radiations

- Insulator damage remedies:
  - Poses a risk for the machine reliability
    - → Insulator replacement (sextupole main coils conductors)
    - → Cable replacement (sextupole secondary coils)
    - → Insertion of disposable pigtails (BPMs)





Cable/insulator replacement with radiation hardened material

Disposable pigtails inserted between BPM and long original cable

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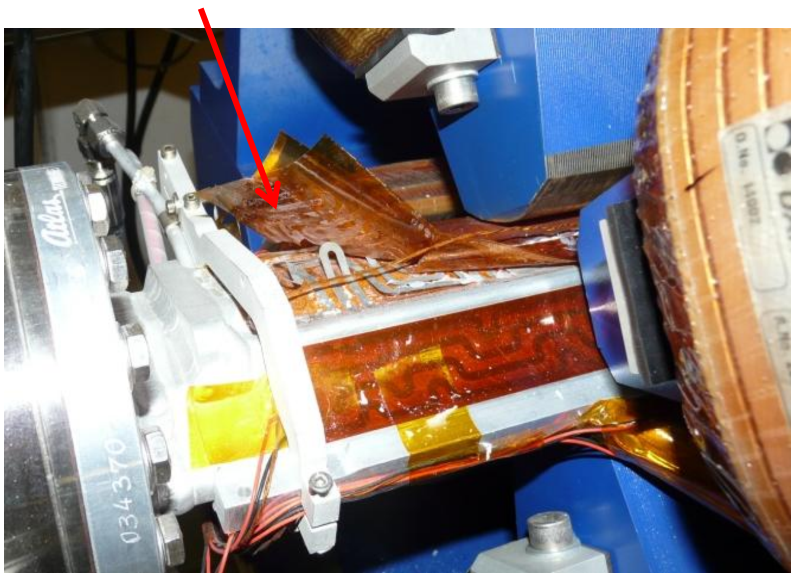
# Equipment damage due to radiations

- Fast aging of baking out film:
  - For activation (180 °C) of the Non Evaporable Getter (NEG) coating
  - made of sandwiches of conducting tracks between kapton foils and glued to the vacuum chamber
  - Make possible the baking out in-situ without removing quadrupole and sextupole yokes

**Radiation aging of the glue that sticks together baking out film kapton foils**



- Preventive replacement would be a tedious and very time demanding task:
  - Removing magnet yokes
  - Scraping residual film and installing a new one (2 days* 2 persons /1 chamber)

→ Preventive replacement is not an option, but films are replaced case by case if necessary

Study is going on to find new glue material more radiation hardened than the present one, like polyimide glue

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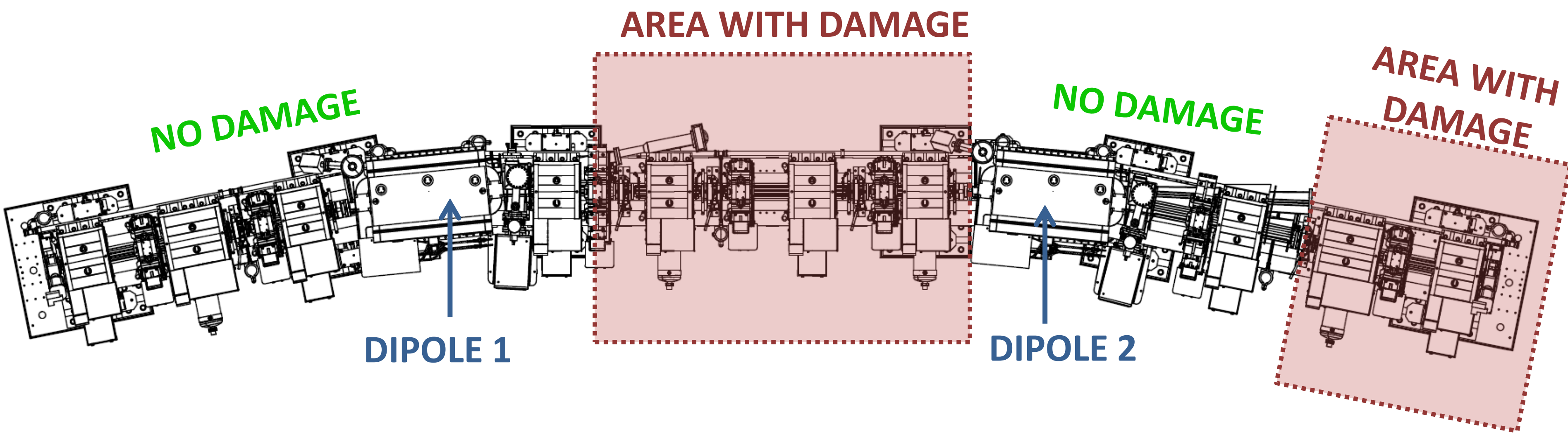
# Equipment damage locations

- Damages location:
  - In each of the 16 cells of the storage ring
  - In the arcs
  - In the vicinity of given so called "quadrupole vacuum chamber"
  - Downstream a bending magnet



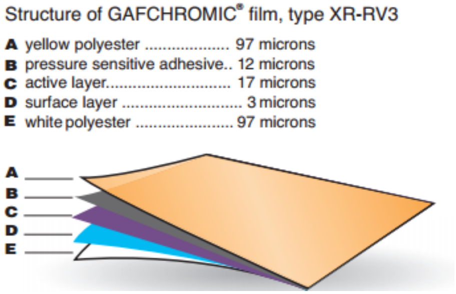

- Equipment located elsewhere are in perfect condition:
  - In the straight section
  - Before the first bending magnet
  - Around the dipole vacuum chamber

# Dose Spatial Distribution

## How localizing and characterizing radiation source?

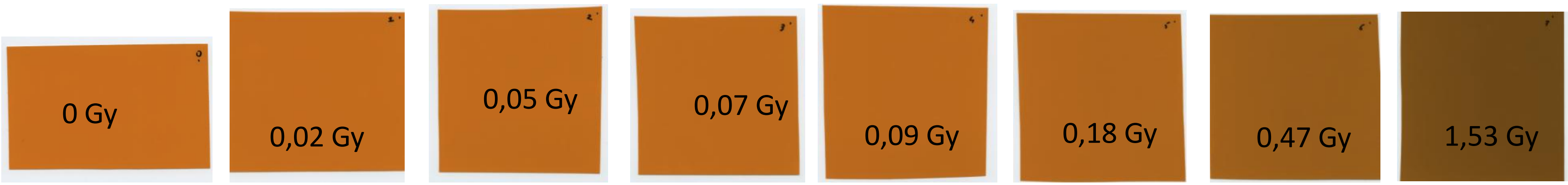
→ Use of Gafchromic XR-RV3 films

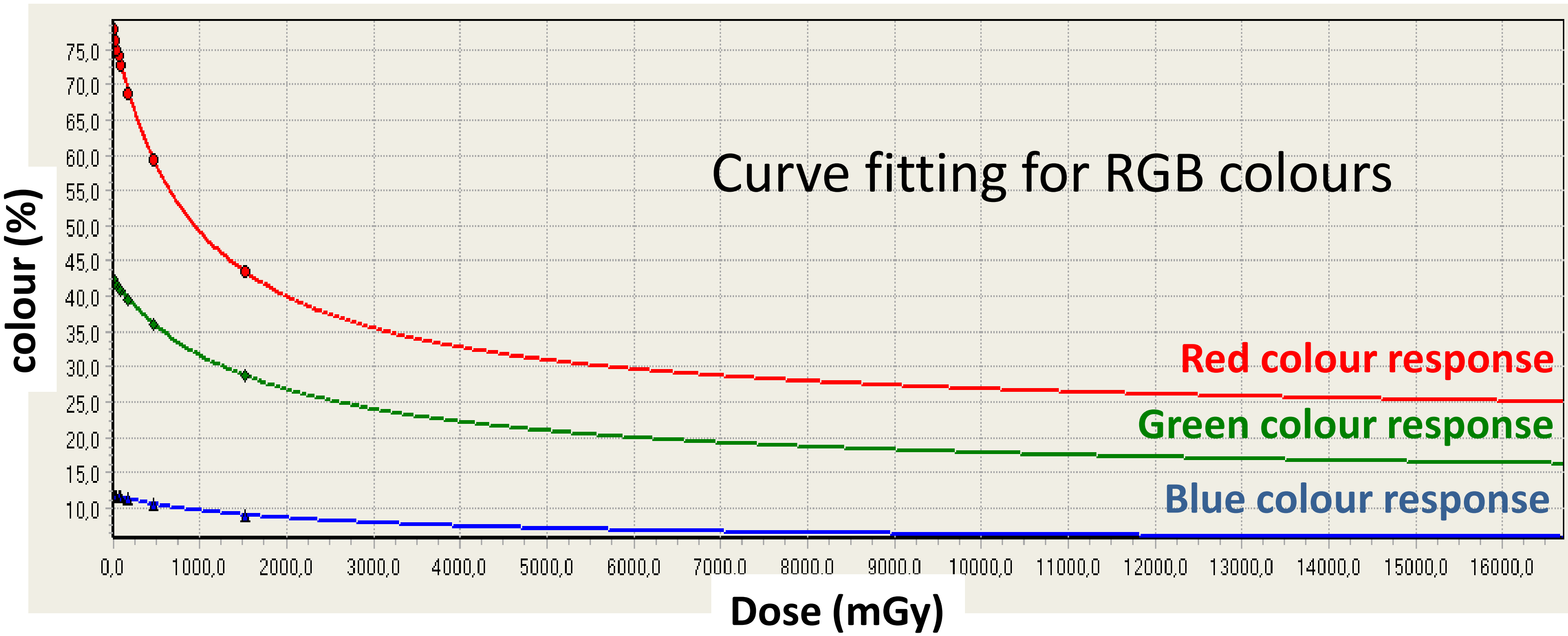
- Usually used in **medical field** for surface peak skin dose measurement
- Big enough (14”x17”) to cover a **large surface of equipment**
- Dose range 0.01 Gy to **30 Gy**
- Film **colour is modified** (browning) **depending on the dose** received during exposure time
- **No processing** but direct scan with commercially available high colour depth scanner (Epson perfection V700 Photo)
- Red, Green and Blue (RGB) colour responses can be converted into a dose value
- Calibration done with a **40 keV X-ray tube-based source** and a **solid state dose sensor** for absolute measurement (Radcal DDX6) placed behind films




# Gafchromic Film Calibration

- Calibration (film batch and scanner responses):

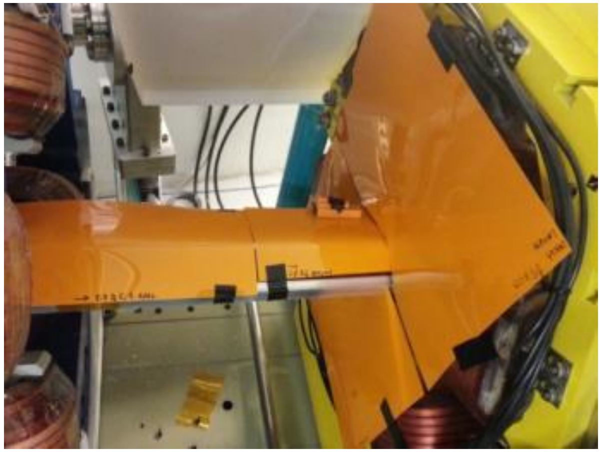



- Good sensibility to dose for the red (low dose) and the green (high dose) colours, while the blue cannot be used

# Dose Spatial Distribution

- Film installation:
  - On arcs in cells C08 and C10 of the storage ring
  - Longitudinally: complete length of vacuum chambers has been covered on both sides (up and down)
  - Transversally: most all of the quadrupole and sextupole faces covered (upstream and downstream)



**C08 S4 upstream**

**C08 S1 downstream**

**Inside C08 Q8.2 yokes**

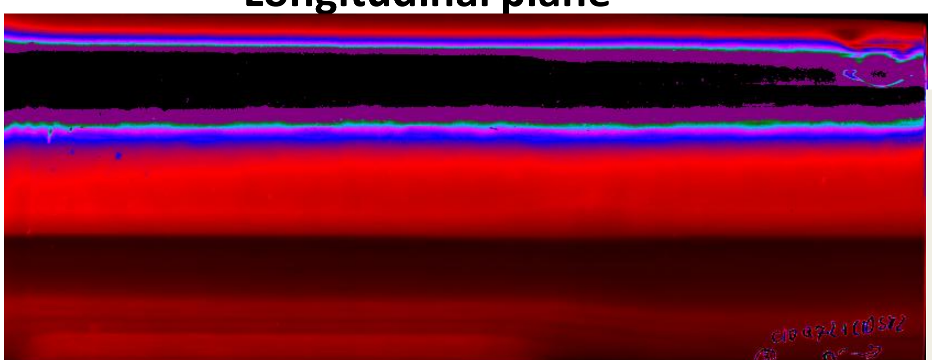
**C08 BPM5 cables**

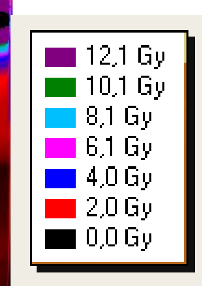
# Dose Spatial Distribution

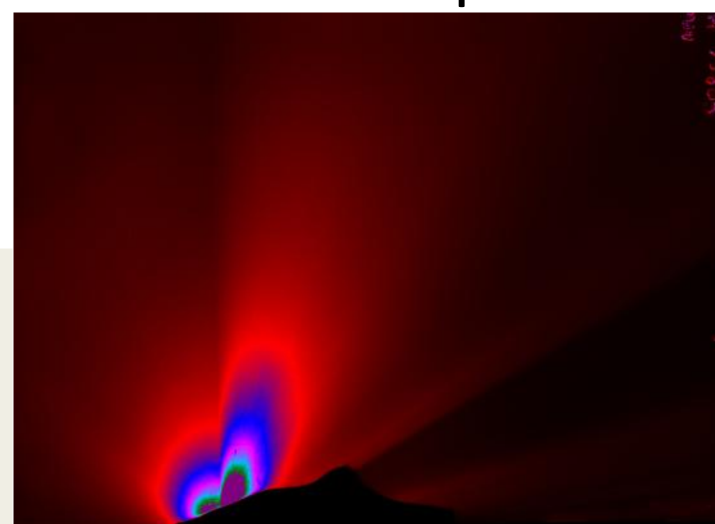
- Exposition:
  - 12 min with 16.4 mA stored in the machine
  - Equivalent to a 3.2 mA.h integrated current

Transverse plane

Longitudinal plane





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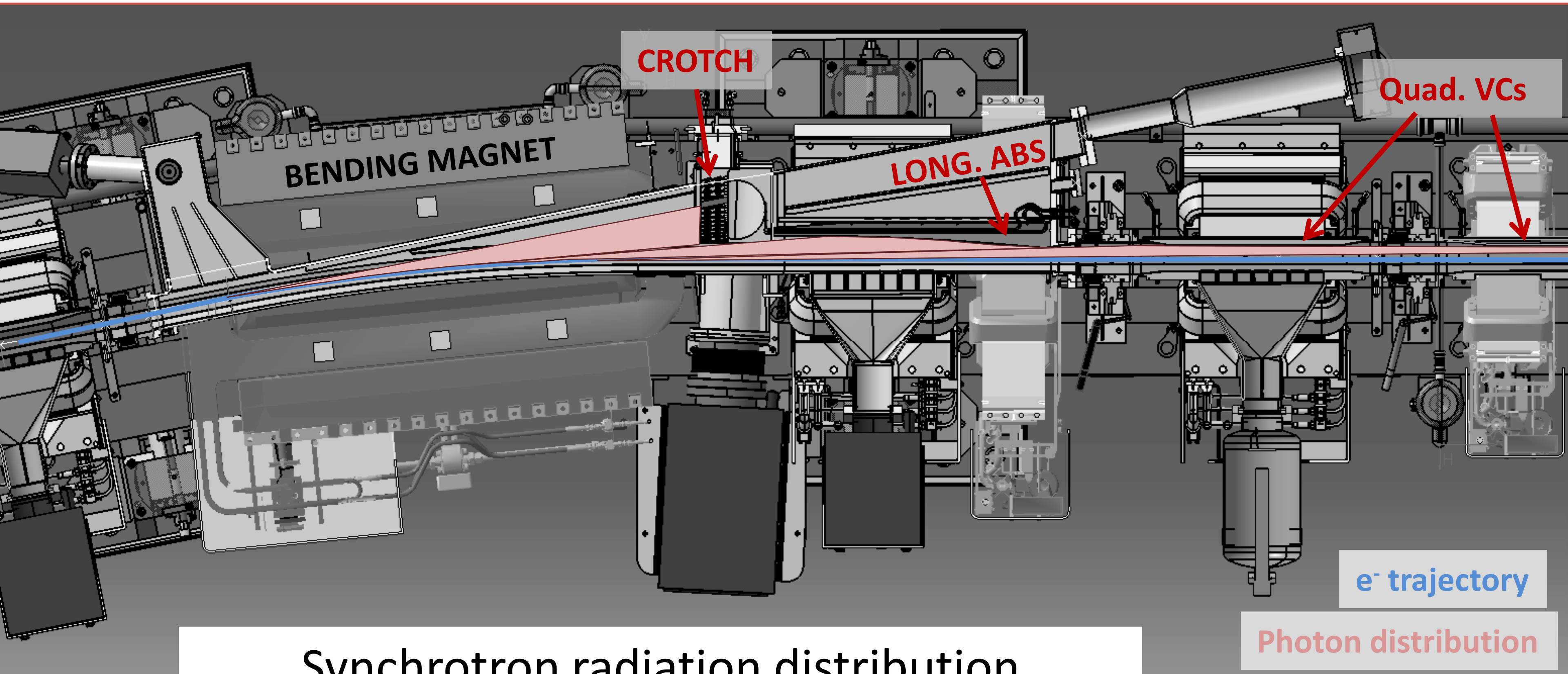
# Absolute Dose Measurement

- Absolute dose measurement at the location of equipment damage:

| Equipment | Distance to VC (cm) | Measured dose (Gy) | Dose Rate (Gy/A.h) | Total Dose since commissioning: 9800 A.h integrated current (Gy) |
|---|---|---|---|---|
| Corrector Cables | 20 | 0.5 | 156 | $1.5\ 10^6$ |
| Sextupole Insulators | 25 | 0.3 | 94 | $0.9\ 10^6$ |
| BPM Cables | 25 | 0.3 | 94 | $0.9\ 10^6$ |
| Baking out Film | **contact** | **100** | **31250** | **$300\ 10^6$** |

# Fluorescence X

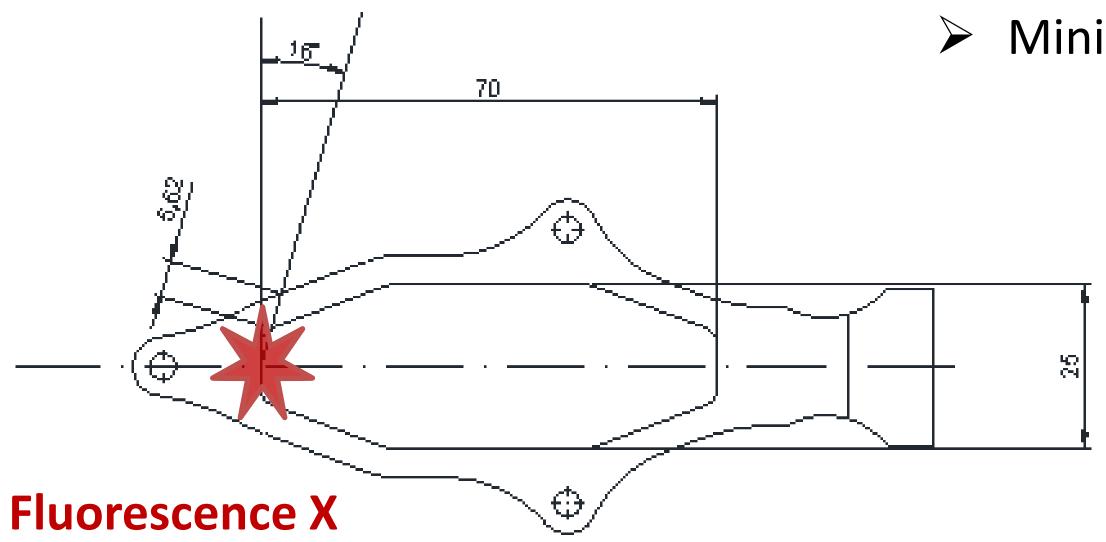
- Most of the photons emitted in the dipole are absorbed by 3 possible elements depending on the emission angle:
  - The crotch: first 102 mrad, 7.6 kW at 500 mA
  - The longitudinal absorber: next 69 mrad, 5.1 kW
  - The downstream quadrupole vacuum chambers: last 25 mrad, 1.8 kW




Synchrotron radiation distribution

# Fluorescence X

- Under the impact of synchrotron radiation, quadrupole vacuum chamber materials fluoresce, emitting X-rays isotropically

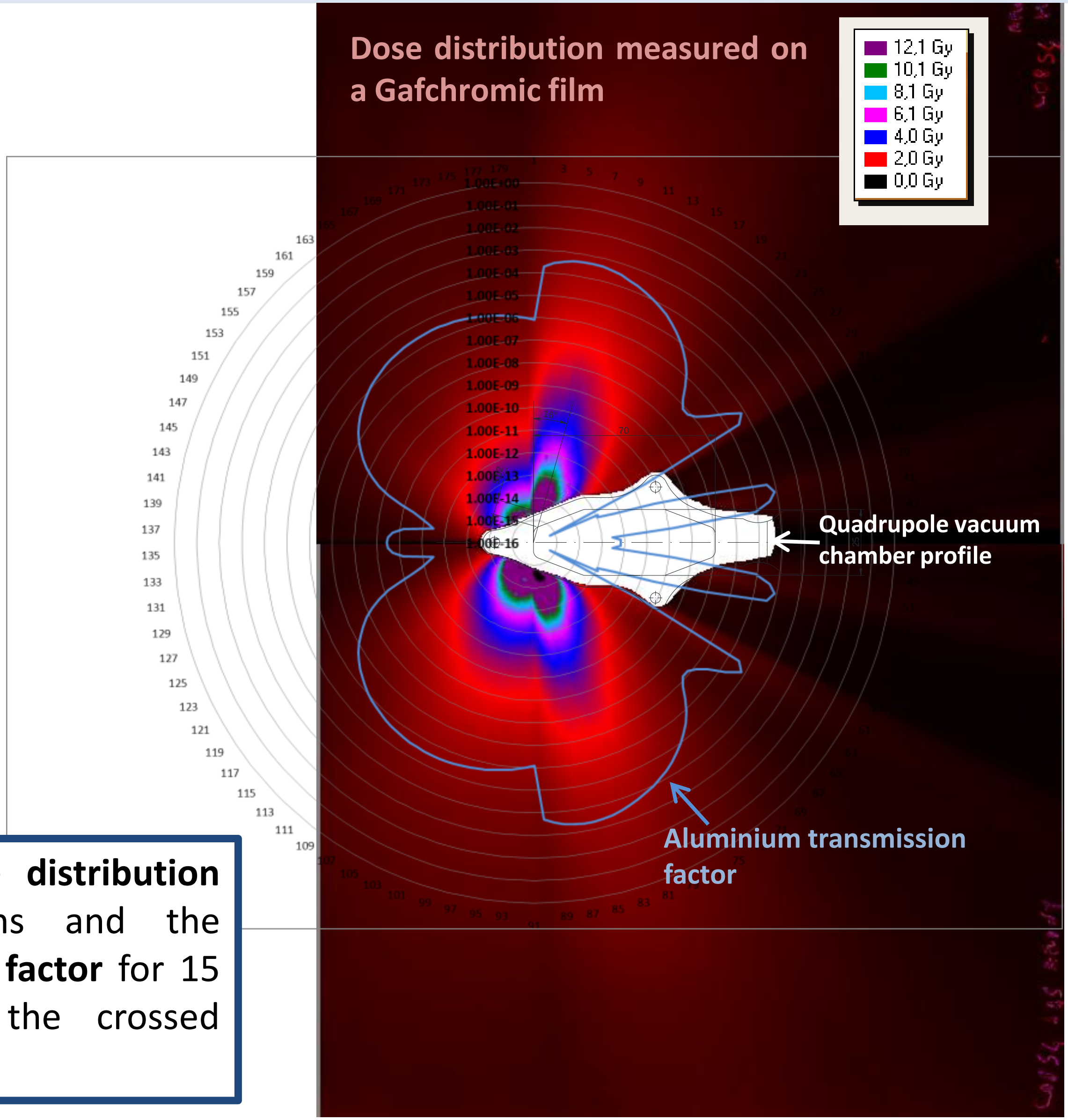



- Quadrupole vacuum chambers are made of aluminium
- Minimum thickness is 3 mm

Quadrupole vacuum chamber cross-section

# Fluorescence X

- Dose distribution in the transverse plane:




**Perfect correlation** between **dose distribution** measured with Gafchromic films and the calculated **aluminium transmission factor** for 15 keV X-rays (as a function of the crossed aluminium thickness)

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# Fluorescence X

| Vacuum chamber composition: | | | Fluorescence X spectrum lines (keV): | |
|---|---|---|---|---|
| Aluminium | (Al) | > 96 % | Kα: 1.49 | |
| Magnesium | (Mg) | 0.8-1.2 % | Kα: 1.25 | |
| Iron | (Fe) | 0.7 % | Kα: 6.40 | Kβ: 7.06 |
| Silicon | (Si) | 0.4-0.8 % | Kα: 1.74 | |
| Copper | (Cu) | 0.15-0.40 % | Kα: 8.05 | Kβ: 8.91 |
| Chromium | (Cr) | 0.04-0.35 % | Kα: 5.41 | Kβ: 5.95 |
| Zinc | (Zn) | 0.25 % | Kα: 8.64 | Kβ: 9.57 |
| Manganese | (Mn) | 0.15 % | Kα: 5.89 | Kβ: 6.49 |
| Titanium | (Ti) | 0.15 % | Kα: 4.51 | Kβ: 4.93 |
| Other | | 0.15 % | | |

- NEG Coating composition:

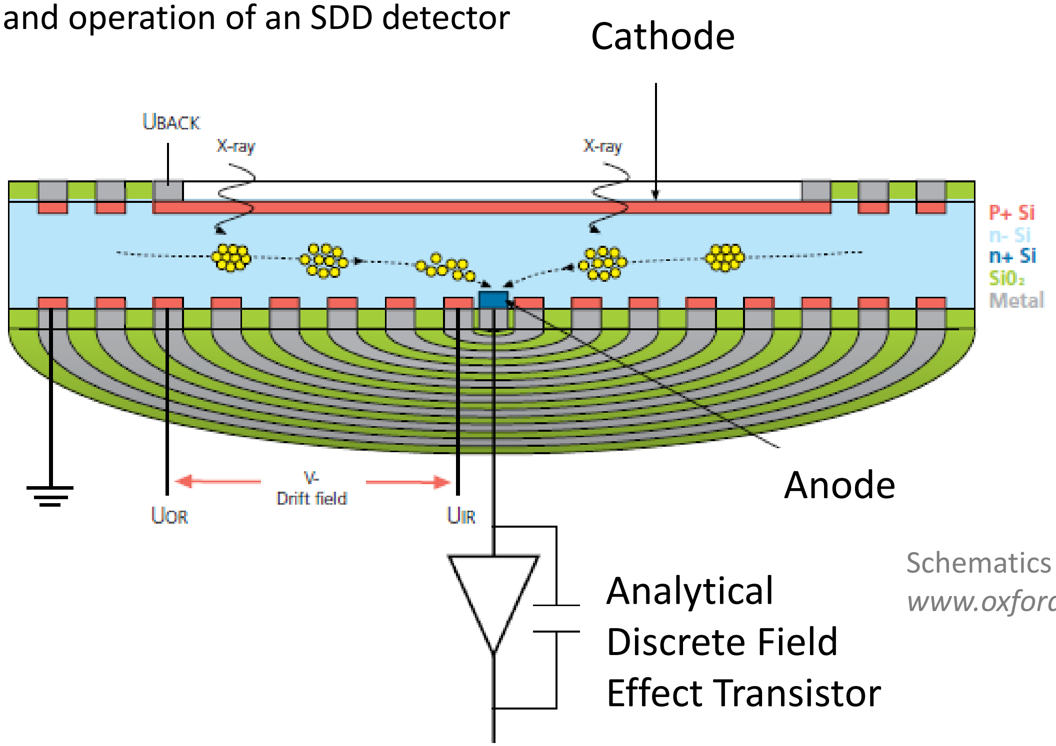
| | | | | |
|---|---|---|---|---|
| Titanium | (Ti) | 30 % | Kα: 4.51 | Kβ: 4.93 |
| Vanadium | (V) | 40 % | Kα: 4.95 | Kβ: 5.43 |
| Zirconium | (Zr) | 30 % | Kα: 15.78 | Kβ: 17.67 |

# Fluorescence X-ray measurement

- Silicon Drift Detector:
  - X-rays ionise silicon
  - Electron cloud drifted to the anode
  - Charge of each electron cloud depends on energy deposited by incoming X-rays

Röntec SDD detector

Construction and operation of an SDD detector




Schematics from
*www.oxford-intruments.com*

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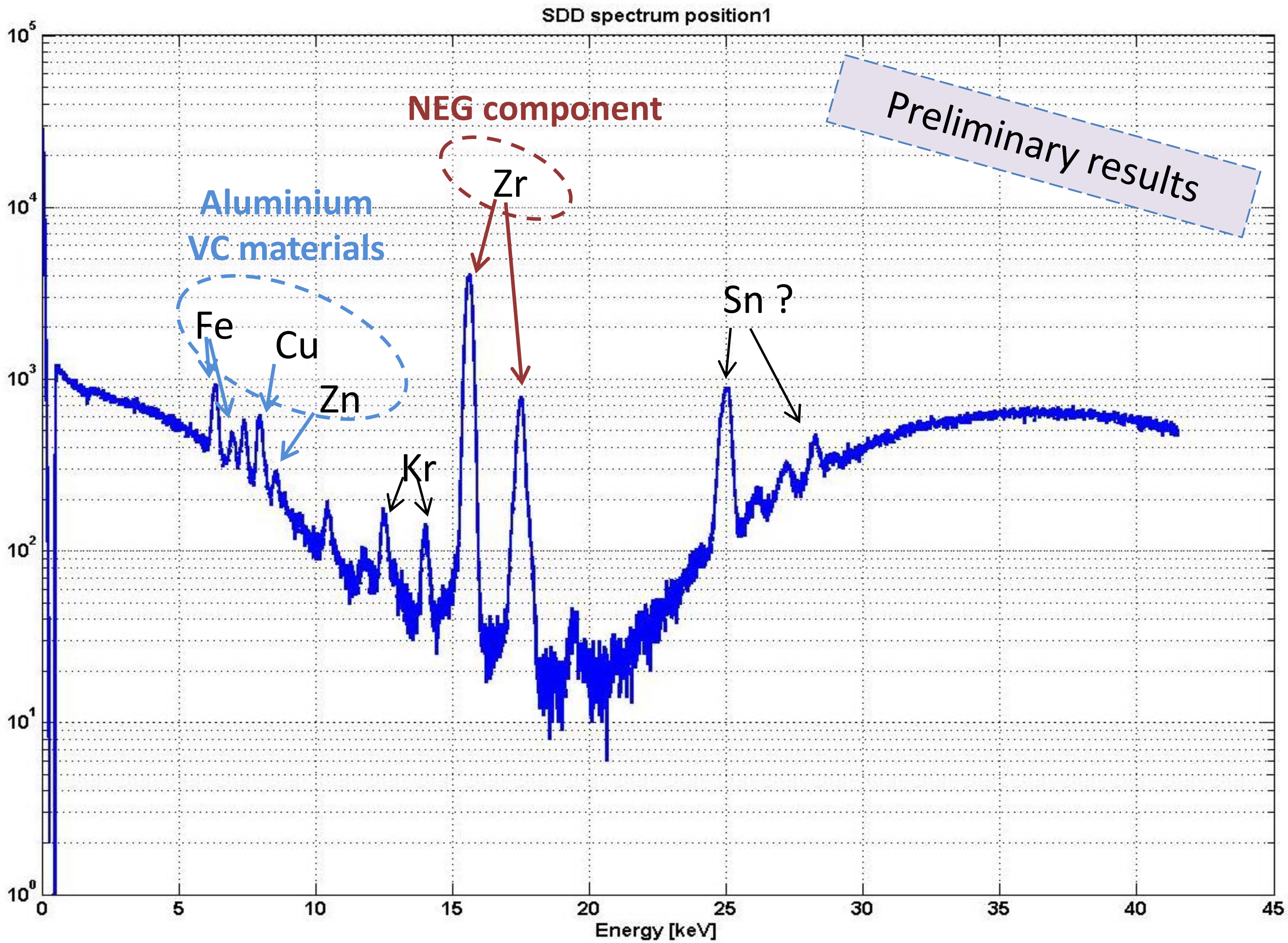
# Fluorescence X-ray measurement

- Silicon Drift Detector:



# Vacuum chamber shielding effect

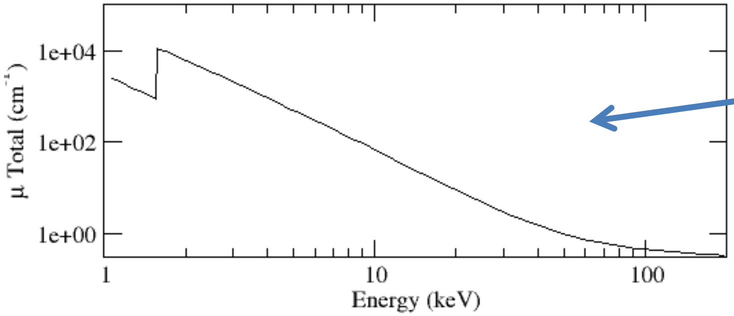
- X-rays emitted inside the vacuum chamber are attenuated by vacuum chamber itself when crossing material.

$$I(x) = I_0 * e^{-\mu * x}$$

Where:

- $I_0$ is the radiation intensity before crossing
- x is the thickness of the material
- μ is the linear attenuation coefficient of the material

- **Linear attenuation coefficient** depends on material **atomic number** and on **photon energy**

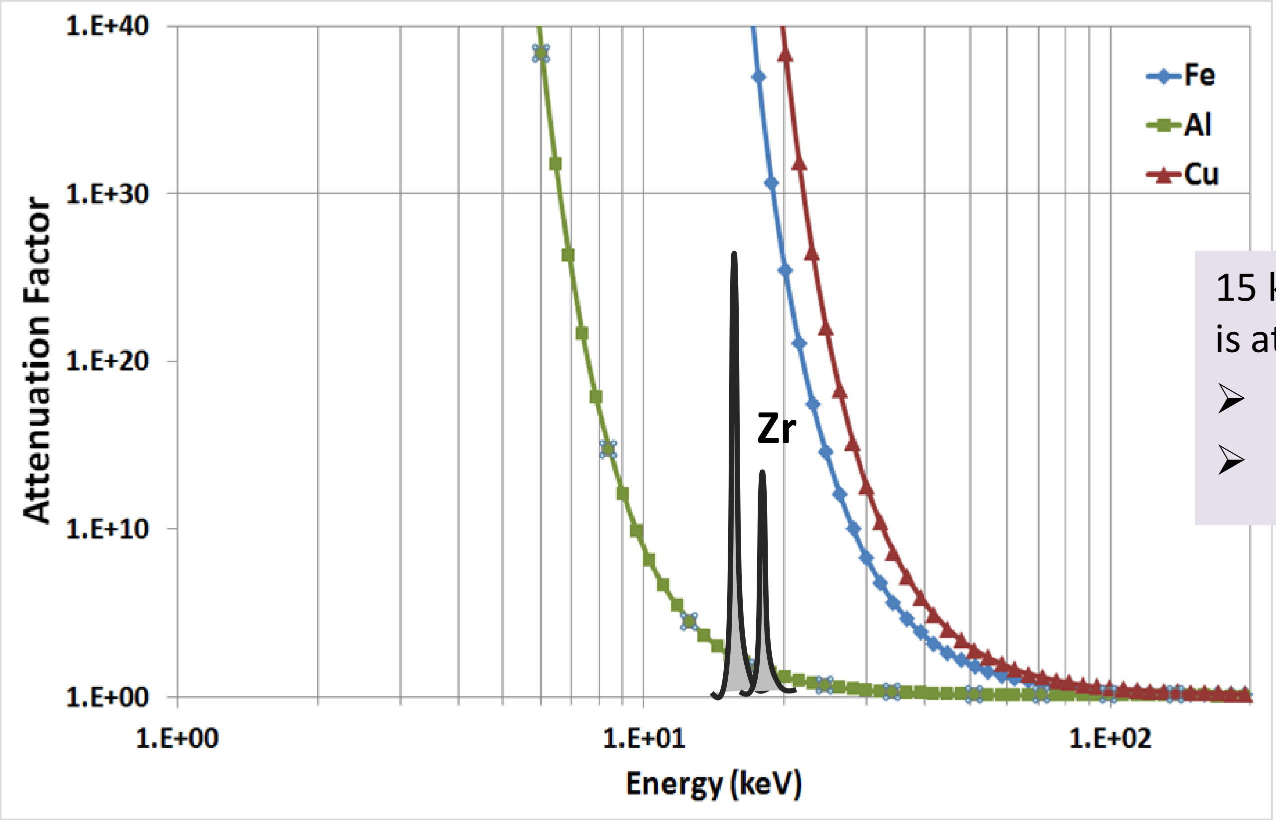



Aluminium (Z=13) linear attenuation coefficient in function of the photon energy

*Data from the National Institute of Standards and Technology (NIST)*

# Vacuum chamber shielding effect

- Shielding effect comparison between materials:




15 keV Zr Kα fluorescence X-ray is attenuated by:

- **3.10²** with 3 mm thick **Al** VC
- **6.10⁵³** with 3 mm thick **SS** VC

Attenuation factor applied to X-rays crossing 3 mm of Al, Fe or Cu depending on their energy

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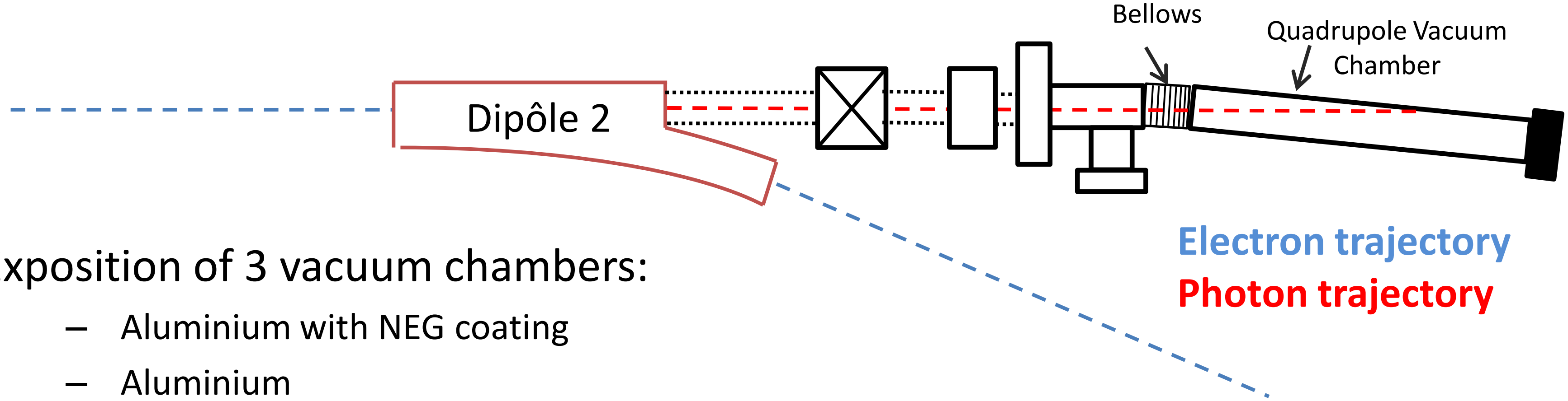
# Conclusion (1)

- Origin of radiation damages in the SOLEIL storage ring is understood and characterized:
  - Emission of **Fluorescence X-rays** when the **NEG coated** quadrupole vacuum chamber is hit by **synchrotron radiation** (upstream dipole)
  - Energy of emitted X-rays is too high to be efficiently attenuated by the 3 mm aluminium thickness of the vacuum chamber

- Test bench to be installed in C08-D2 beamline frontend:




Exposition of 3 vacuum chambers:

- Aluminium with NEG coating
- Aluminium
- Stainless steel with NEG coating

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# Conclusion (2)

- **NEG coated aluminium vacuum chamber is not a relevant solution in case this one has to intercept part of the upstream synchrotron radiation**

- This phenomenon has to be considered seriously for **the design of future light sources** (like horizontal diffracted limited light sources):
  - Extensive use of NEG coating
  - Circular small and **thin vacuum chambers**

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# Acknowledgements


- **Koji Tsumaki** from SPring-8 for useful discussion about dose distribution measurement
- **Thibault Tailleur** from the Meditest Company for its collaboration in the Gafchromic film calibration


**Thank you for your attention!**