Beam containment system to protect radiation protection components

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Outline

- Why protect radiation protection systems from the XFEL beam?
  - Characteristics of the XFEL beam
  - Focussing optics at XFEL
  - Constraints on beam line operation before beam containment system

- Scheme to contain XFEL beam allowing operation at currently achieved maximum beam parameters – The Safety Equipment Protection System - SEPS

- Observations after 2 years of successful operation with SEPS

- Summary and outlook

Why SEPS?

Safety Equipment Protection System

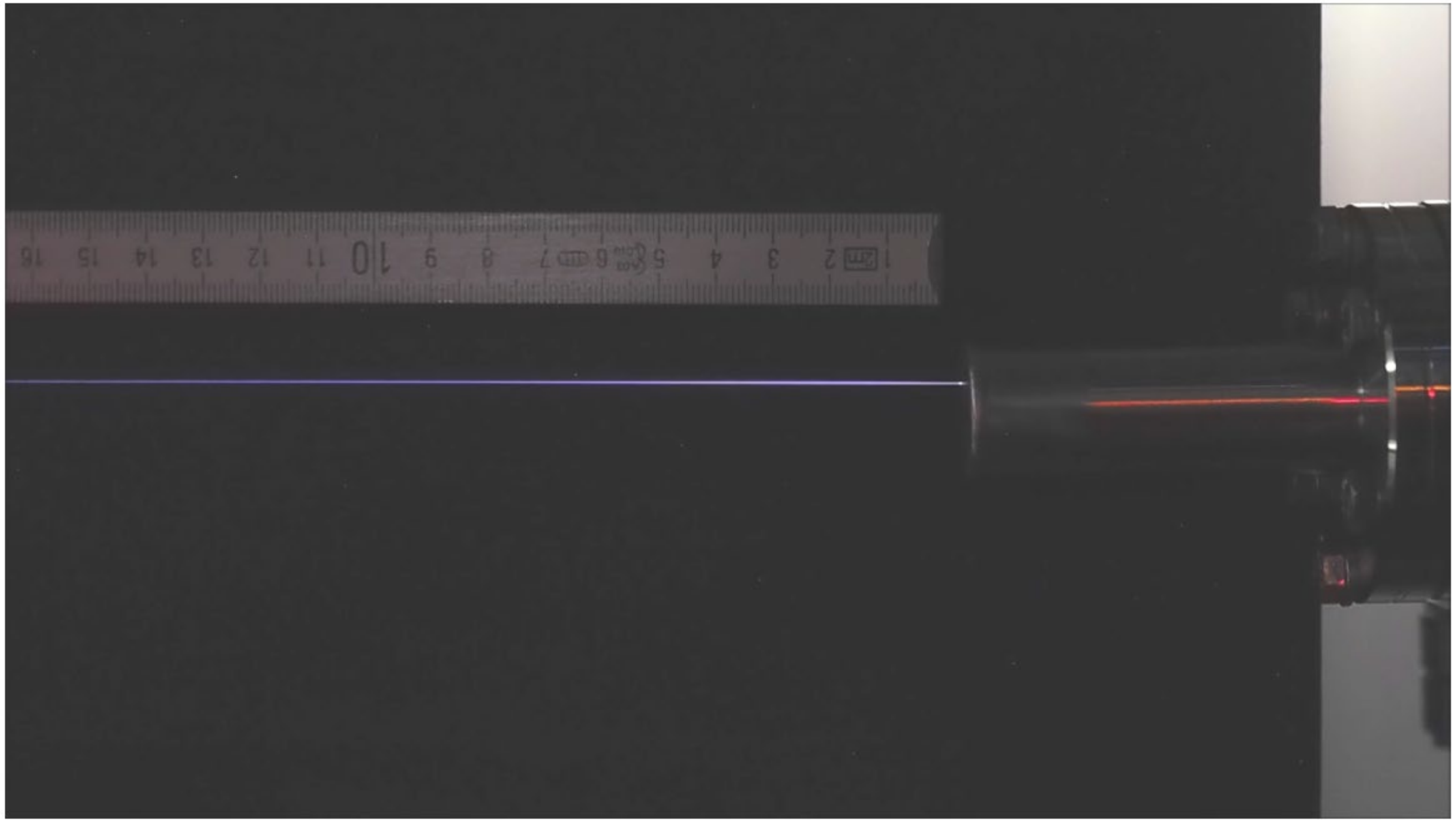
European XFEL beam characteristics

SASE	Photon energy range (keV)	Pulse Energy (mJ)	Average Power (Watts)
1 and 2	4.7 - 30	3.3	89
3	0.25 – 3	10.7	290
The pulse duration is 8 – 20 femtoseconds.			

- Intensity of XFEL beam with 3.3 mJ, 10 micrometer focal spot size and 8 fsec ≈ 10^{17} W/cm^2
- Damage threshold of tungsten is 1.46 eV/atom and that of graphite is 0.44 eV/atom
- The intensity of 10^{17} W/cm^2 is orders of magnitude greater than that required to ionize tungsten or graphite (materials for blocking XFEL beam)

Talk by Taiee Liang on 31st May at 15:00

European XFEL beam at 2.6 keV coupled out in air



European XFEL pulse structure

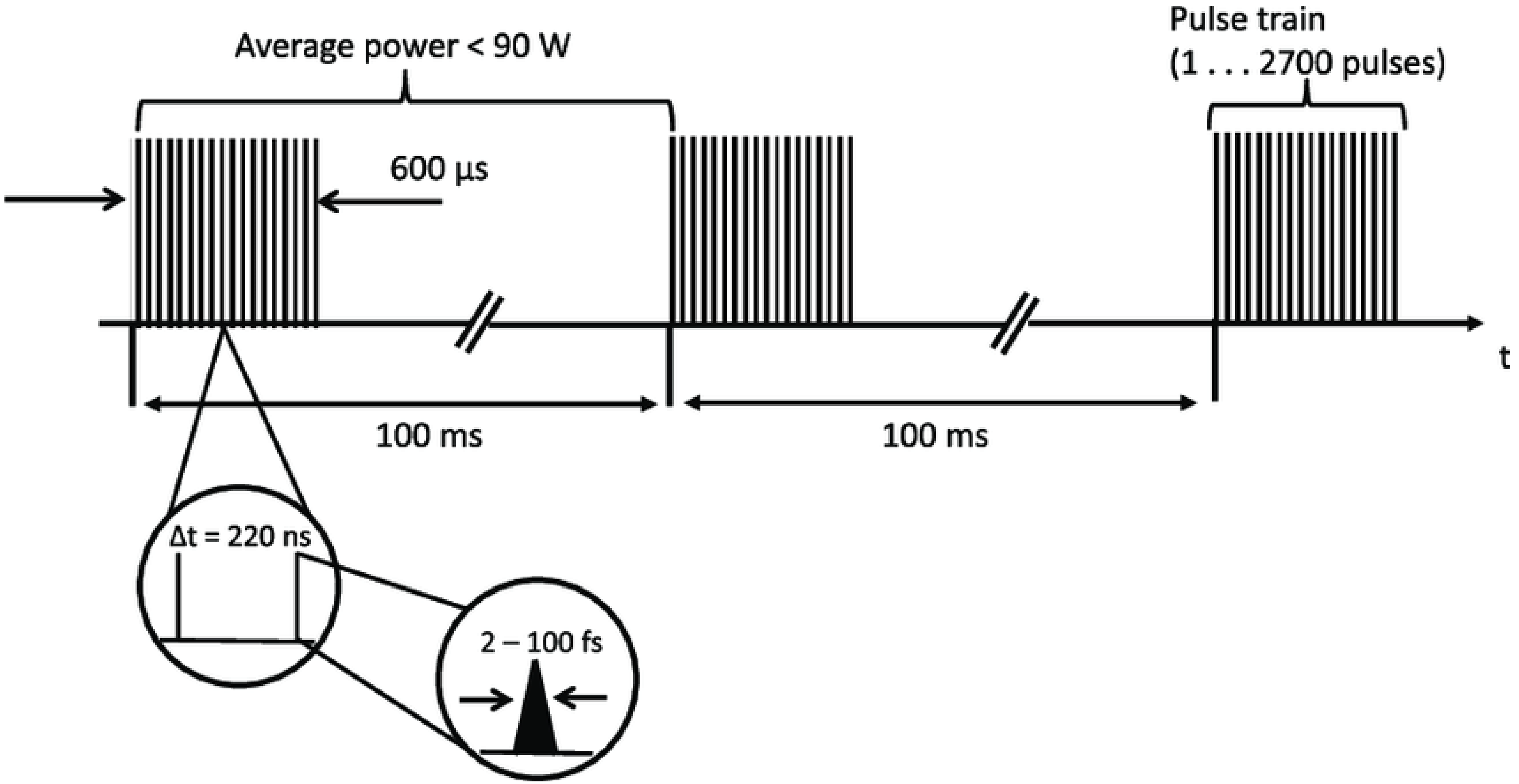
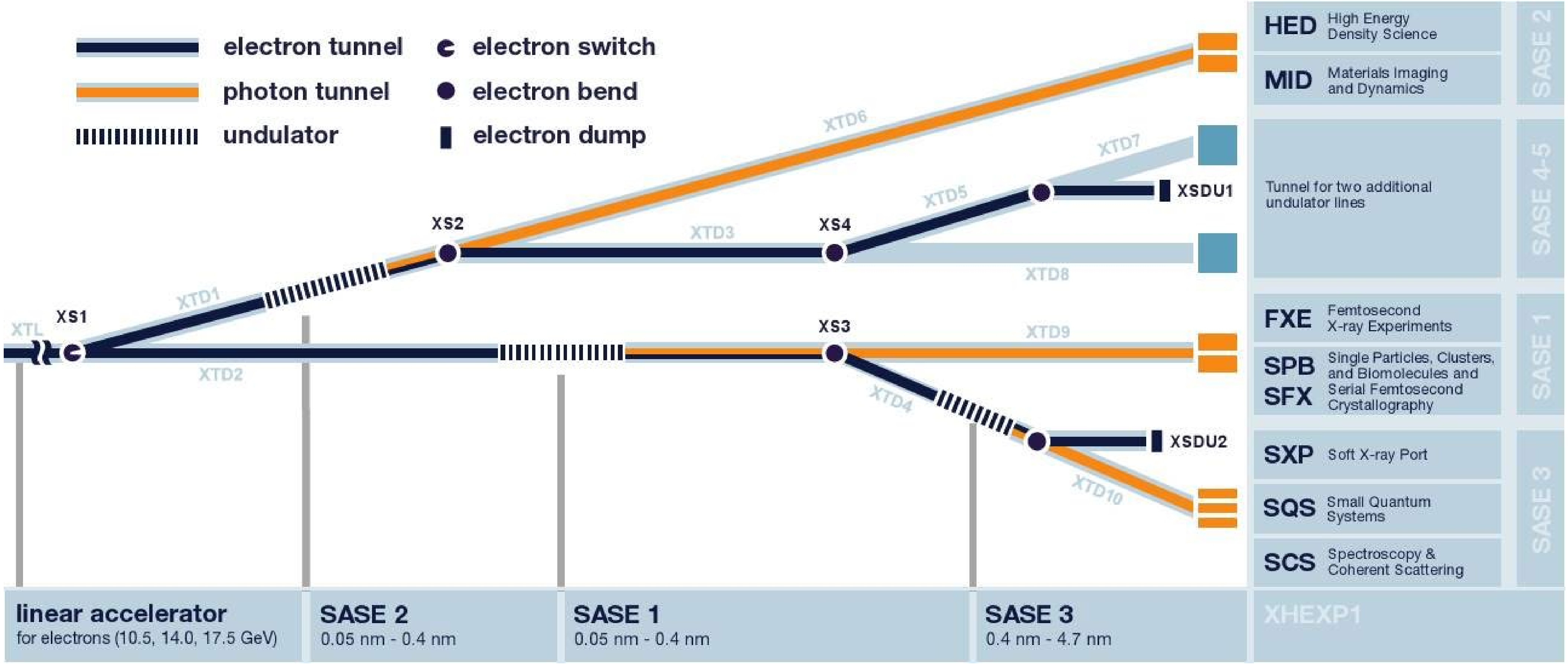


Figure credit: Joakim Laksman

Schematic showing location of European XFEL tunnels and beam lines



SASE: Self amplified spontaneous emission

Properties of focussing optics at European XFEL

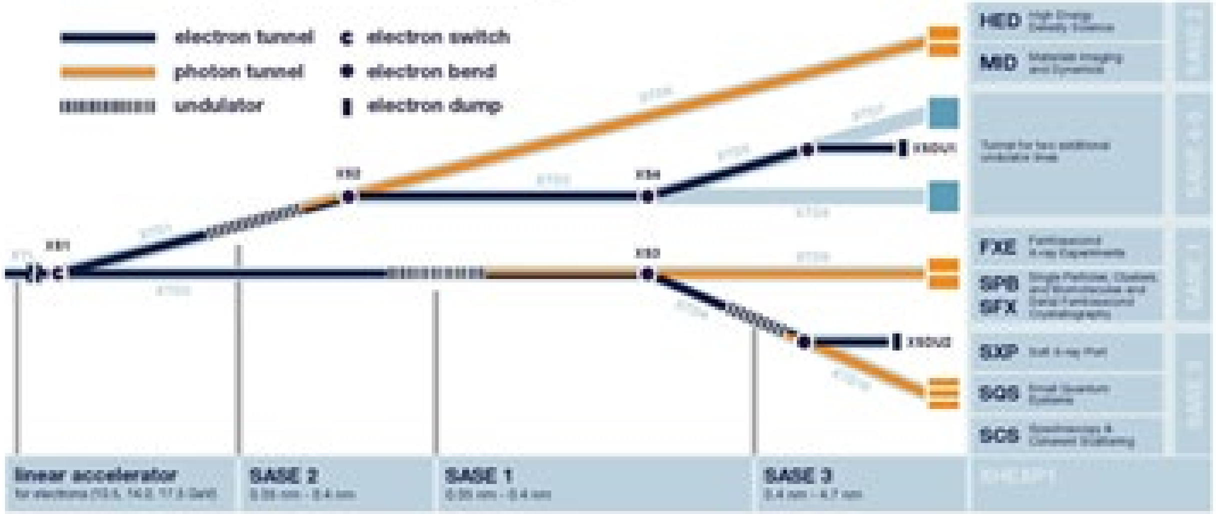
- Kirkpatrick-Baez geometry mirrors (KB mirrors)
  - Silicon, bendable mirrors that are about 1m in length;
  - Accept XFEL beam at grazing incidence and can focus the XFEL beam to spot sizes on the order of 200 nm with minimal losses;
  - Due to being bendable, the focus is not stationary and can be shifted over a wide range of distances
  - Good news for radiation protection: require cooling and heat up and start outgassing if the pulse rate exceeds (200 – 300) pulses/ pulse train. This decreases the vacuum in the beam line (10^{-8} mbar) by orders of magnitude (down to 10^{-2} mbar with 1000 pulses /pulse train).

- Compound refractive lenses (Beryllium), CRLs
  - Utilize the negative refractive index of X-rays to focus, and can focus over a wide range of distances
  - Can only accept limited power and not used for soft X-rays due to high absorption
  - Acceptable power is further limited for pulsed radiation otherwise the lens breaks due to stress. A maximum of 10W of power is foreseen for XFEL operation, but diamond CRLs are being developed.

Focussing optics in SASE 1, 2 and 3

- SASE 1, 2 and 3 at European XFEL contain KB mirrors
- SASE 1 and SASE 2 contain CRLs in addition to KB mirrors
- The CRLs do not break instantly if incident XFEL power is high, but it may take a few pulses to many before the lenses break due to stress induced by thermal heating and cooling cycles
  - There is not one CRL, but many compound refractive lenses used simultaneously to focus the XFEL beam

Schematic showing location of European XFEL tunnels and beam lines



SASE: Self amplified spontaneous emission

Distribution of focussing optics in SASE 2 – an example

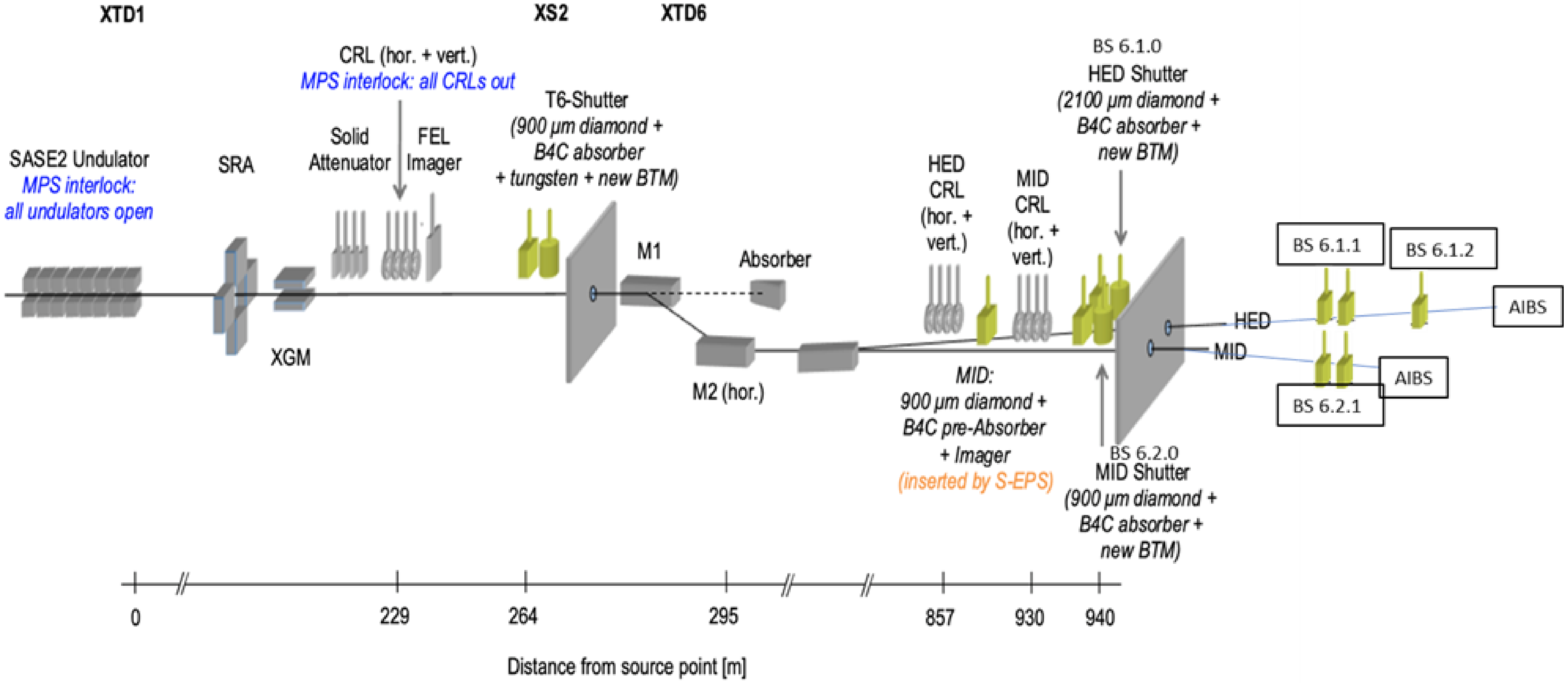
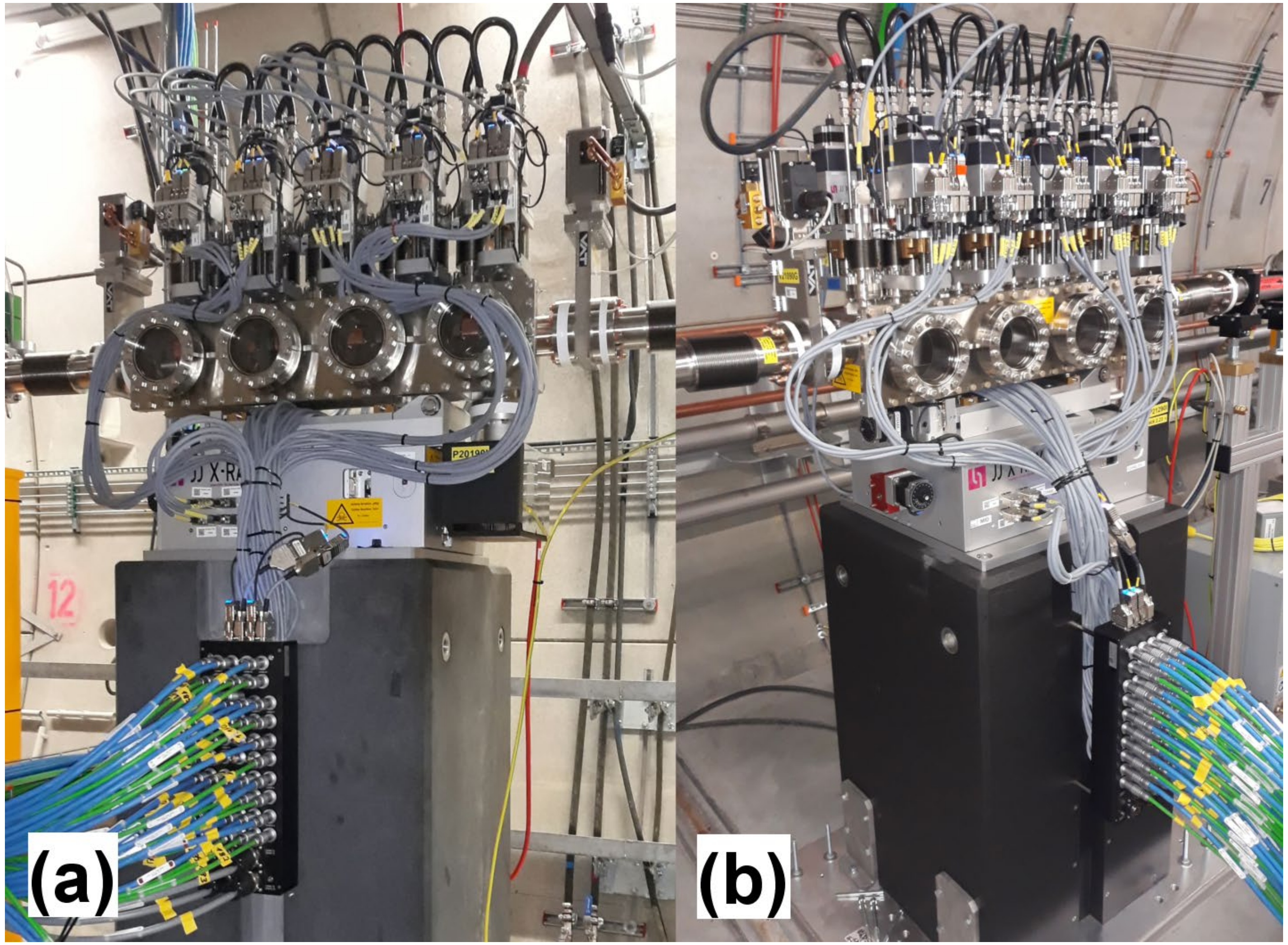


Figure credit: Harald Sinn

CRLs in SASE2



- The arms of the CRLs are fitted with induction sensors (SIL 2 sensors)

- CRLs contain 10 arms, and each arm contains a stack with several lenses;
- The KB mirror switches range does not allow to accurately predict the position of the beam in hard X-ray beamlines

Photo credit Alexey Zozulya, MID

Constraints due to radiation protection on SASE 2 beam lines

- Technical measures
  - Several arms of each CRL were physically disabled by plugging them out
  - This led to severe focussing constraints on experiments and optimal intensities were difficult to reach

- Organizational measures
  - Power and pulse number limitations on the beamlines
    - ► The maximum pulse energy may not exceed 3 mJ
    - ► Maximum number of bunches per pulse train may not exceed 400
    - ► Maximum permitted power being photon energy dependent and limited to:
      - E_{photon} (5.8 - <8.8) keV, Power $_{max} \leq$ 0.8 Watts
      - E_{photon} > 8.8 keV, Power $_{max} \leq$ 3 Watts

Organizational measures lack reliability, and put an enormous strain on Radiation Protection Officers

Summary of issues

- Wide range of foci for all X-ray optics along the X-ray beam propagation direction at XFEL
- Focussing at radiation protection beam shutters possible
- Intensities above the damage threshold of all materials tested so far
- This means that the XFEL beam cannot be stopped using standard concepts and materials – a new concept is required
- How to protect the end of the beam line in case the XFEL beam drills through the beam line at the end of the experimental hutch

Photo: Credit Alexey Zozulya, MID

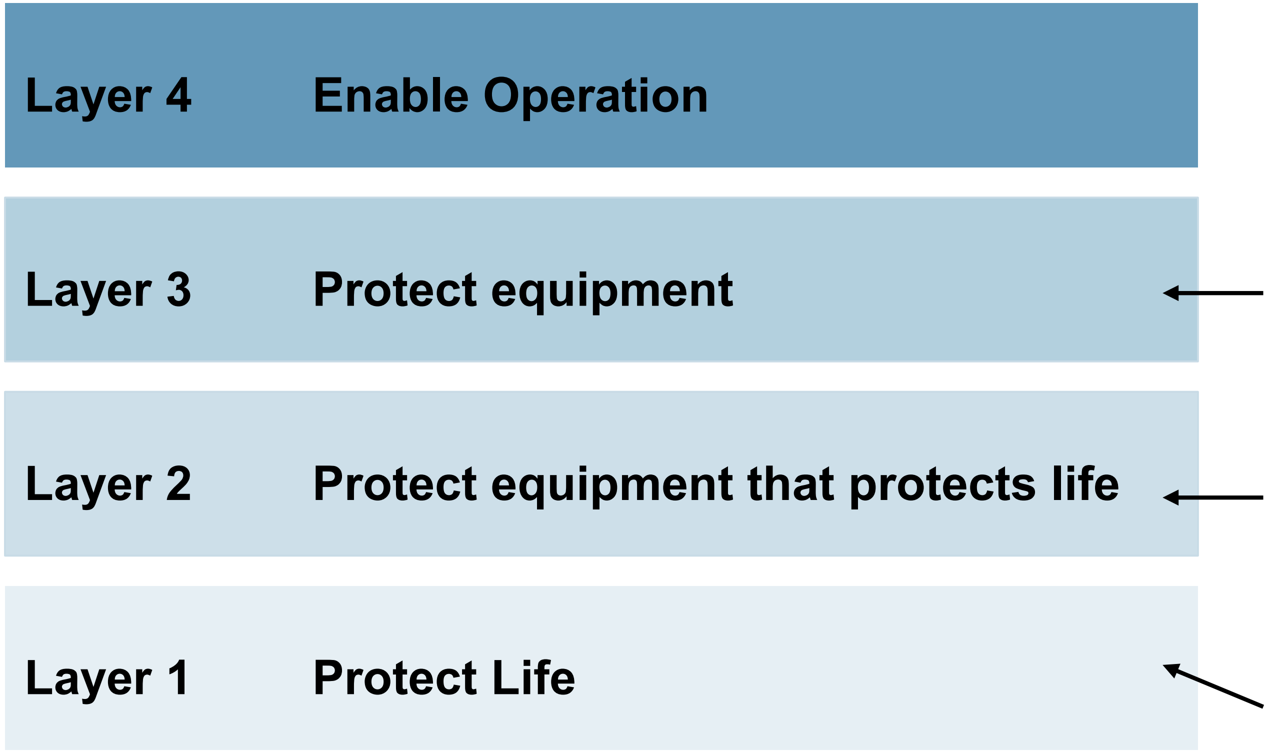
SEPS?

Safety Equipment Protection System

Concept of *Safety Layers* in Radiation Protection

Layer 4	**Enable Operation**
Layer 3	**Protect equipment**
Layer 2	**Protect equipment that protects life**
Layer 1	**Protect Life**

Assignment of components to *Safety Layers*



Layer 4 **Enable Operation**

Layer 3 **Protect equipment**

Systems that protect equipment: Machine Protection System for the accelerator; Karabo software for experiments and components in the Photon tunnels.

Layer 2 **Protect equipment that protects life**

System that protects equipment directly exposed to beam: beam shutters, burn through monitors and air boxes. *System could use software used to control experiments*.

Layer 1 **Protect Life**

Personal protection systems – interlocks, beam shutters, burn through monitors, air boxes, PANDORA detectors. *Systems should have no dependency on software used to run the accelerator and control experiments*.

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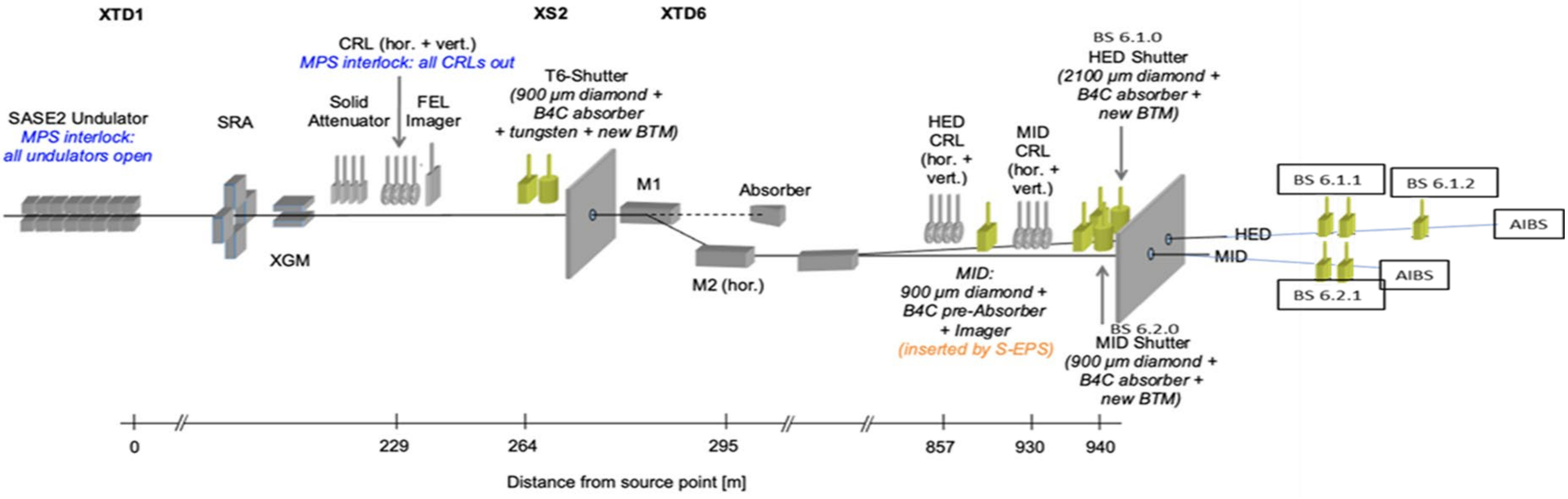
SEPS Interlock complications between MID and HED instruments

In SASE 2, both the MID and the HED instruments are coupled from a radiation protection perspective – there is no technical means to know which instrument is receiving beam



Material tests – some good news!

- Material tests on **Boron Carbide** and **Graphite** with hard and soft X-rays have yielded the result that a spot size of 100 micrometers will not drill through 4 cm of these materials at an average power of about 40 Watts for at least 10 minutes
- This means that spot sizes of about 100 micrometers incident on the absorber up to 40 Watts of average power are considered safe to stop the XFEL beam
- This helps simplify the SEPS interlocks – the steering mirrors need not be a part of the SEPS interlocks in SASE 2

Talk by Taiee Liang on 31st May at 15:00

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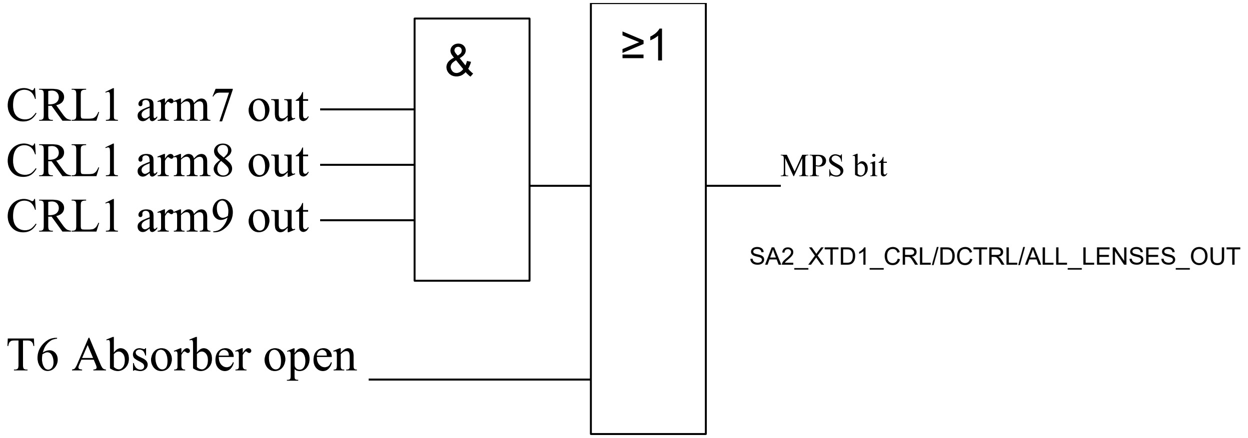
SEPS Interlock Logic of SASE 2 CRLs in XTD1 (electron tunnel)



CRL1 arm7 out

CRL1 arm8 out

CRL1 arm9 out

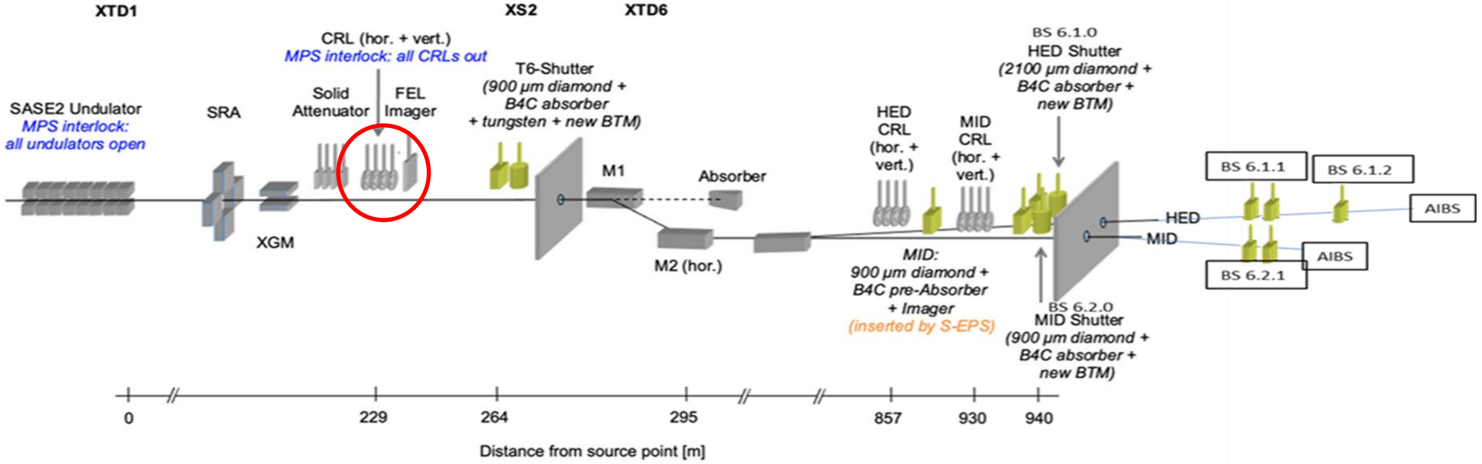
T6 Absorber open

&

≥1

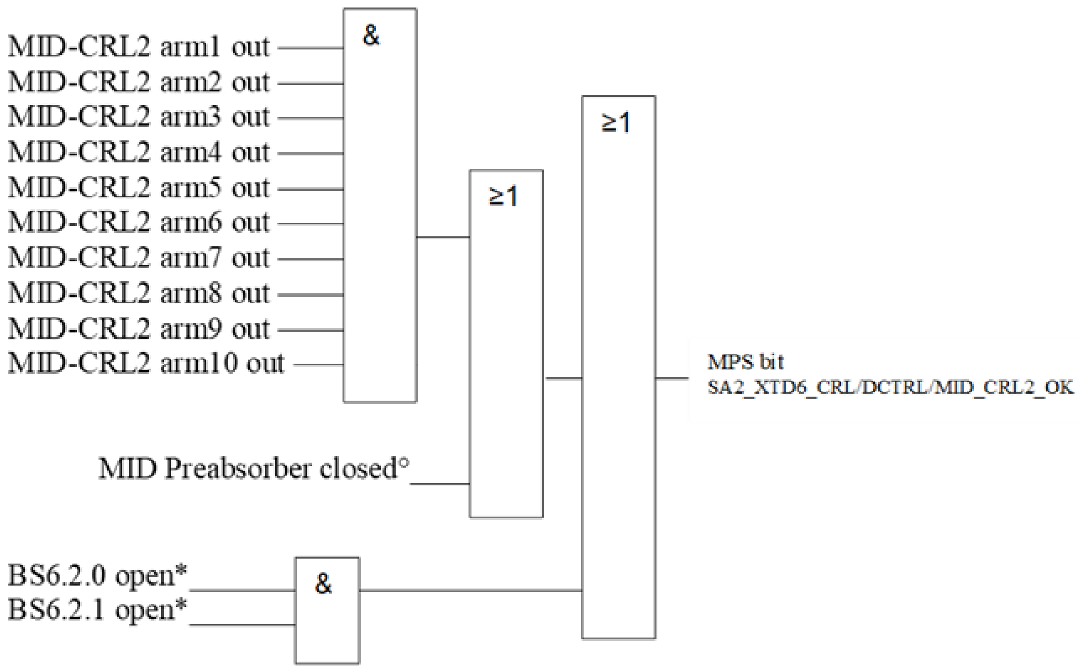
MPS bit

SA2_XTD1_CRL/DCTRL/ALL_LENSES_OUT



SEPS Interlock Logic of SASE 2 CRLs in XTD6 (photon tunnel)

MID



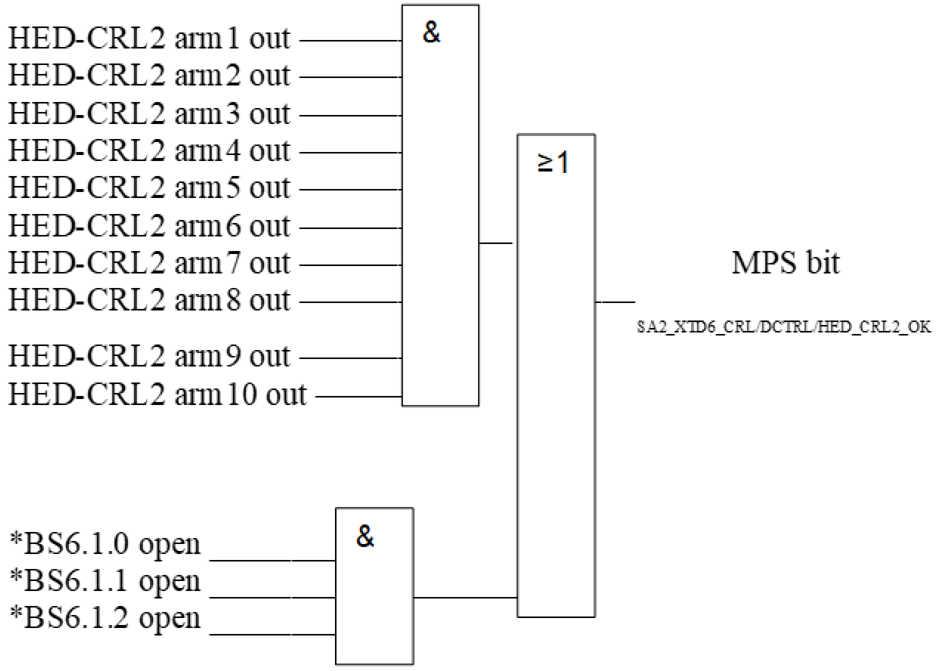
MID-CRL2 arm1 out
MID-CRL2 arm2 out
MID-CRL2 arm3 out
MID-CRL2 arm4 out
MID-CRL2 arm5 out
MID-CRL2 arm6 out
MID-CRL2 arm7 out
MID-CRL2 arm8 out
MID-CRL2 arm9 out
MID-CRL2 arm10 out

MID Preabsorber closed°

BS6.2.0 open*
BS6.2.1 open*

MPS bit
SA2_XTD6_CRL/DCTRL/MID_CRL2_OK

HED

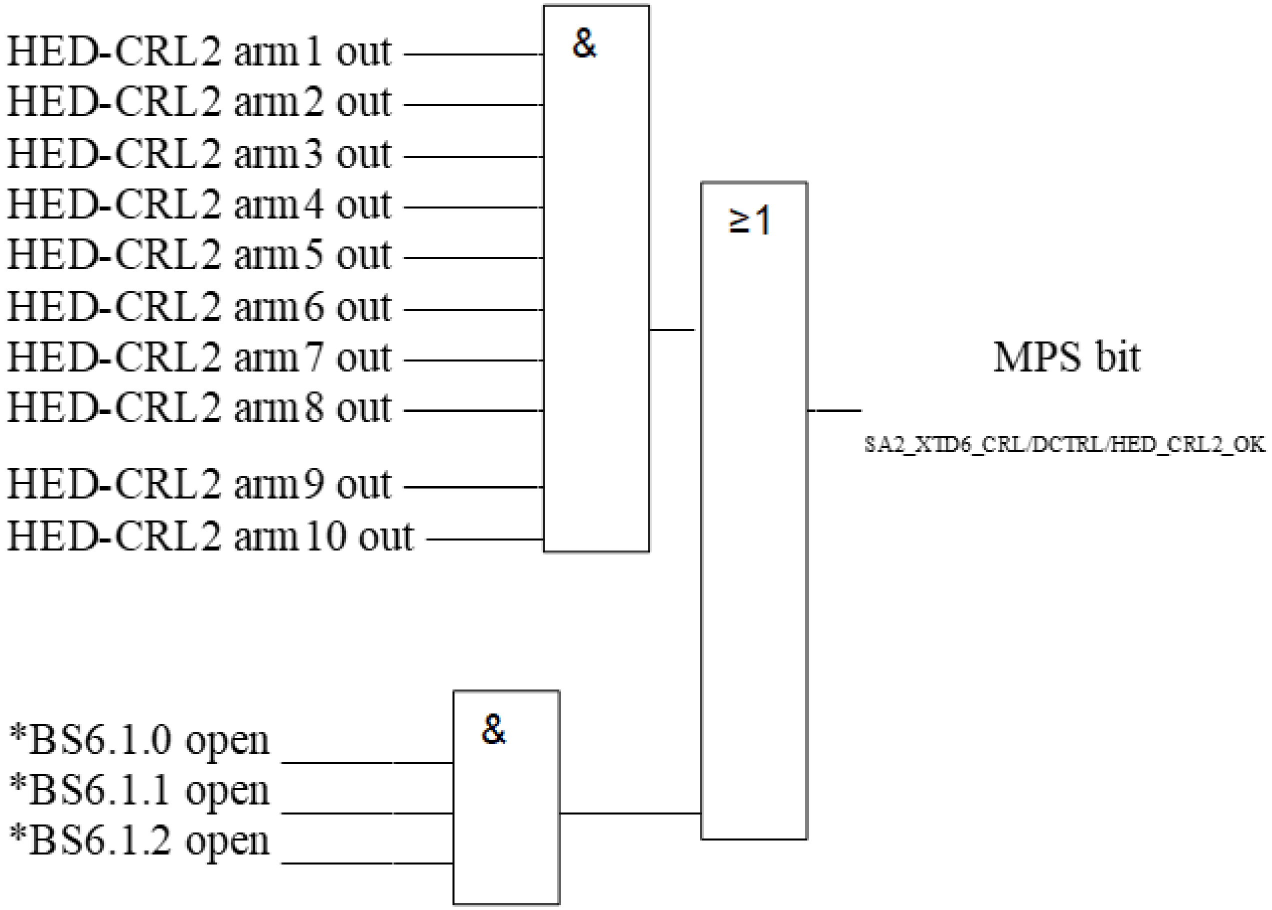


HED-CRL2 arm1 out
HED-CRL2 arm2 out
HED-CRL2 arm3 out
HED-CRL2 arm4 out
HED-CRL2 arm5 out
HED-CRL2 arm6 out
HED-CRL2 arm7 out
HED-CRL2 arm8 out
HED-CRL2 arm9 out
HED-CRL2 arm10 out

*BS6.1.0 open
*BS6.1.1 open
*BS6.1.2 open

MPS bit
SA2_XTD6_CRL/DCTRL/HED_CRL2_OK

SEPS Interlock Logic of SASE 2 CRLs in HED optics hutch



Are SEPS interlocks secure?

- Signals generated in instrument PLCs – system of PLCs connected to each other by ethernet
  - Signals in Karabo (software) can be set to True or False state
  - Copies of signals created and fed to the next PLC
  - Staff is able to activate and deactivate signals in Karabo by changing the state – prevented for the SEPS signals, but these signals must be checked regularly

- Machine RPOs able to deactivate the SEPS interlock in the MPS system – an eye must be kept on both systems

Protecting the end of instruments – Absorber, Air Box and AIBS devices

- In order to stop the beam from drilling into the air box placed at the end of the beam lines, and connected to the PPS system, the **Active Instrument Beam Stop** is placed before the air box

- It contains the same hardware as the air box. However, it is connected to a different PLC and instead of acting on the accelerator, it acts on the number of pulses. If triggered the number of pulses is reduced to zero in the particular SASE.

Lessons learnt and future outlook

- Good and regular communication between all RPOs is needed – RPOs at DESY and at XFEL
- SEPS interlocks should be implemented on a stand alone safety PLC that is not connected to any other PLC, and duplication of signals must be avoided
- The SEPS interlocks add to the complexity of operating a beam line (not relevant for Radiation Protection), but without these the instruments would be handicapped
- In general, good experience with the SEPS interlocks and planned to continue with these
- Coupling of SEPS between MID and HED has not been a problem
- Next project – development of a safety PLC for/at XFEL

Thank you for your attention!