Material Burn-through Tests at the European XFEL

Subtitle of Presentation

T. Liang, Z. Ansari, W. Clement, S.L. Gerdt, A. Leuschner, N. Tesch, S. Zander

RadSynch 2023, ESRF, Grenoble, 31 May 2023

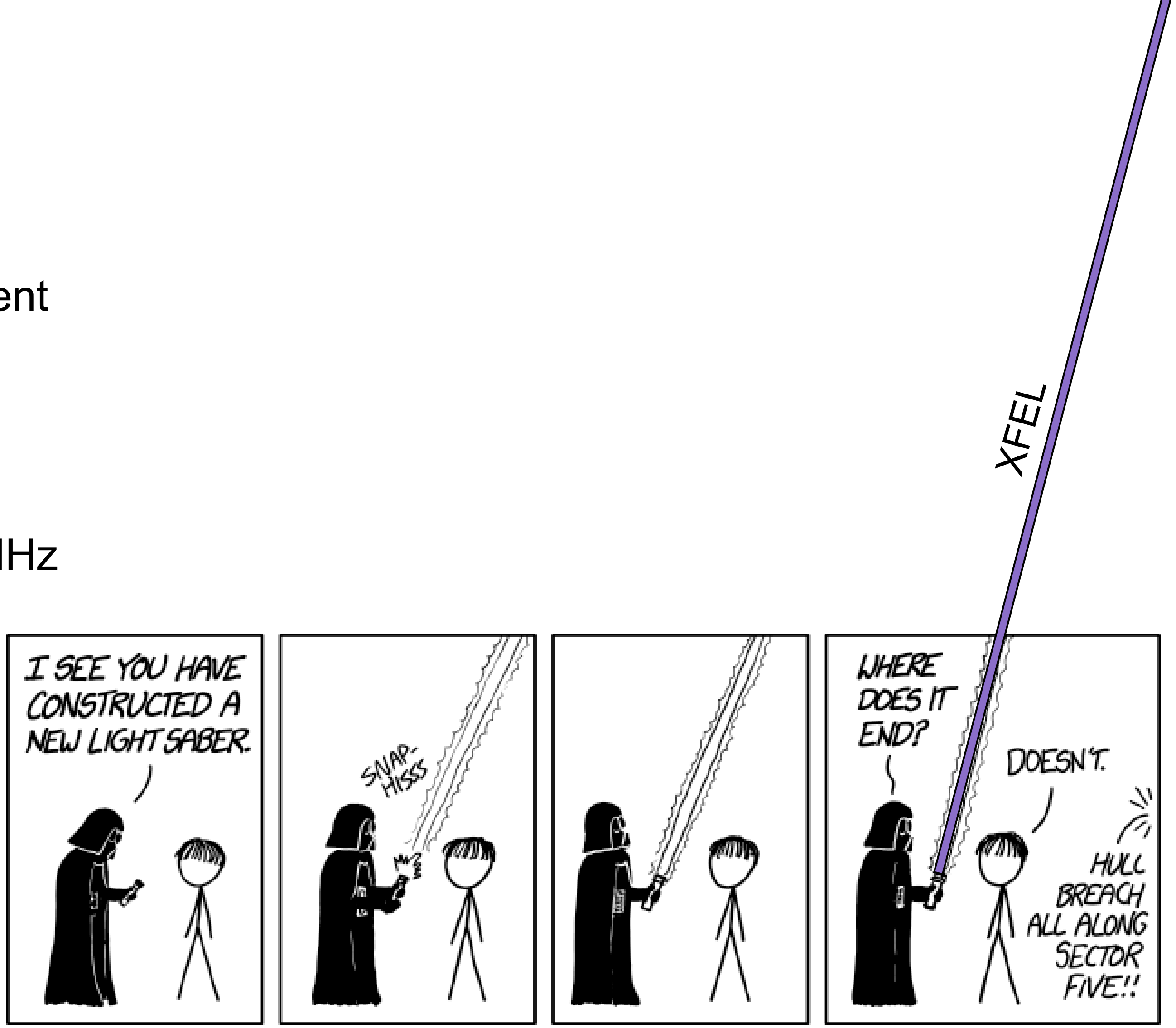
HELMHOLTZ

DESY.

European XFEL

Material tests @ FXE (SASE1)

- Femtosecond X-ray Experiments (FXE) instrument
- X-ray energy: 9.3 keV
- Inter-train repetition rate: 10 Hz
- Intra-train repetition rate: 1.125 MHz, 0.45-4.5 MHz
- Bunches per train: single bunch to 400 bunches
- Bunch energy at undulator hall: 1-2 mJ
- Transmission to FXE hutch: ~60%
- Spotsizes: 10-30 µm FWHM
- Materials tested:
  Cu, W, SiC, B4C, graphite, granite, diamond



Experimental test setup

FXE @ 9.3 keV

- X-ray beam traverses from the right-to-left
- X-rays interact with the **sample material**, generating a dose rate signal at the radiation monitor (**Pandora**)
- While still burning-through the sample material, NO light is detected at airbox/chamber, which house the photomultipliers (**PMT**) and multi pixel photon counters (**MPPC**)
- Upon successful burn-through of sample material, X-rays generate fluorescence light, which is detected by PMT and MPPC
- Timestamps determine burn-through time

light-tight airbox/chambers housing **PMT** and **MPPC** to detect light after successful burn-through

stand for holding **sample material**

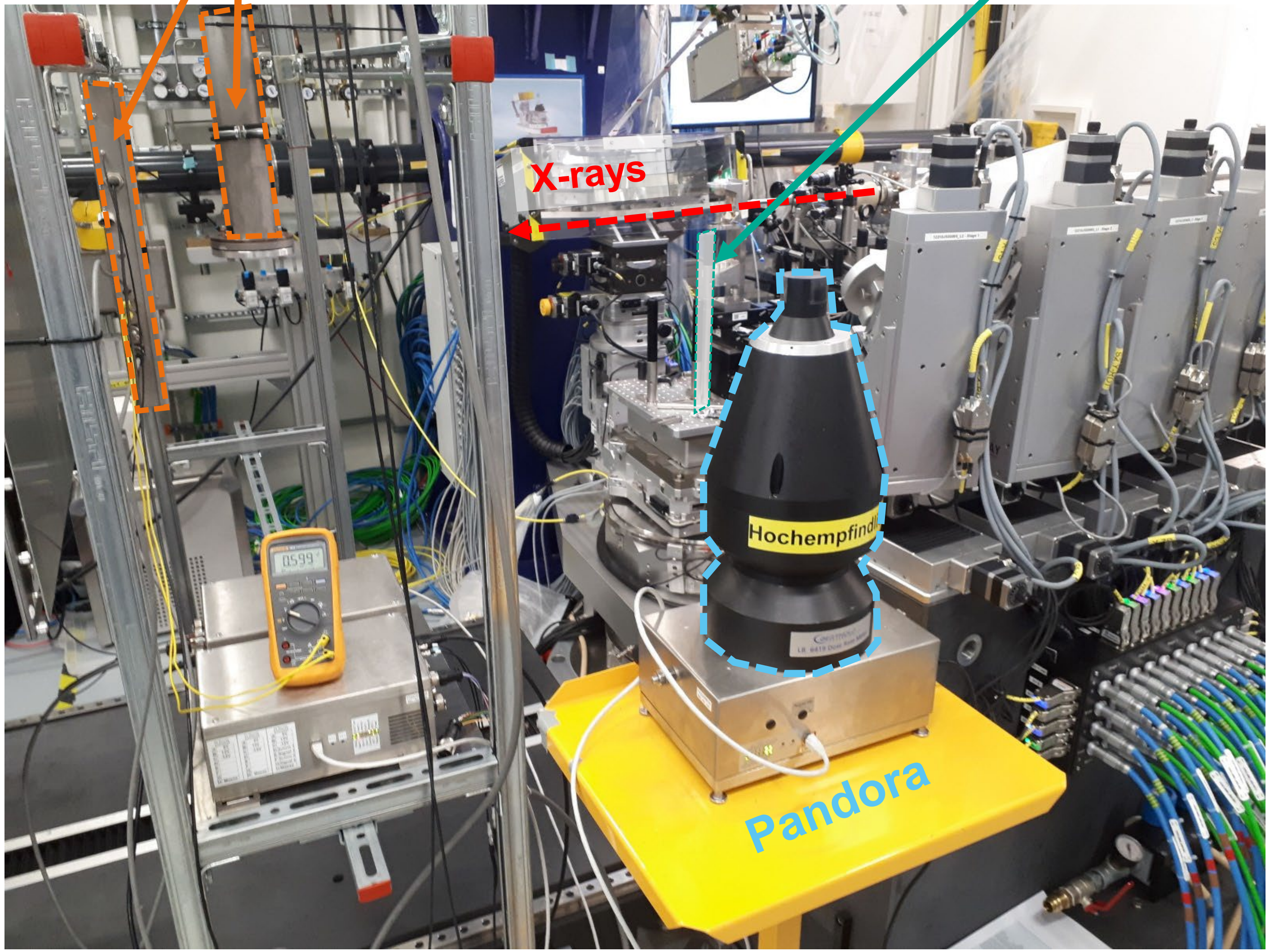
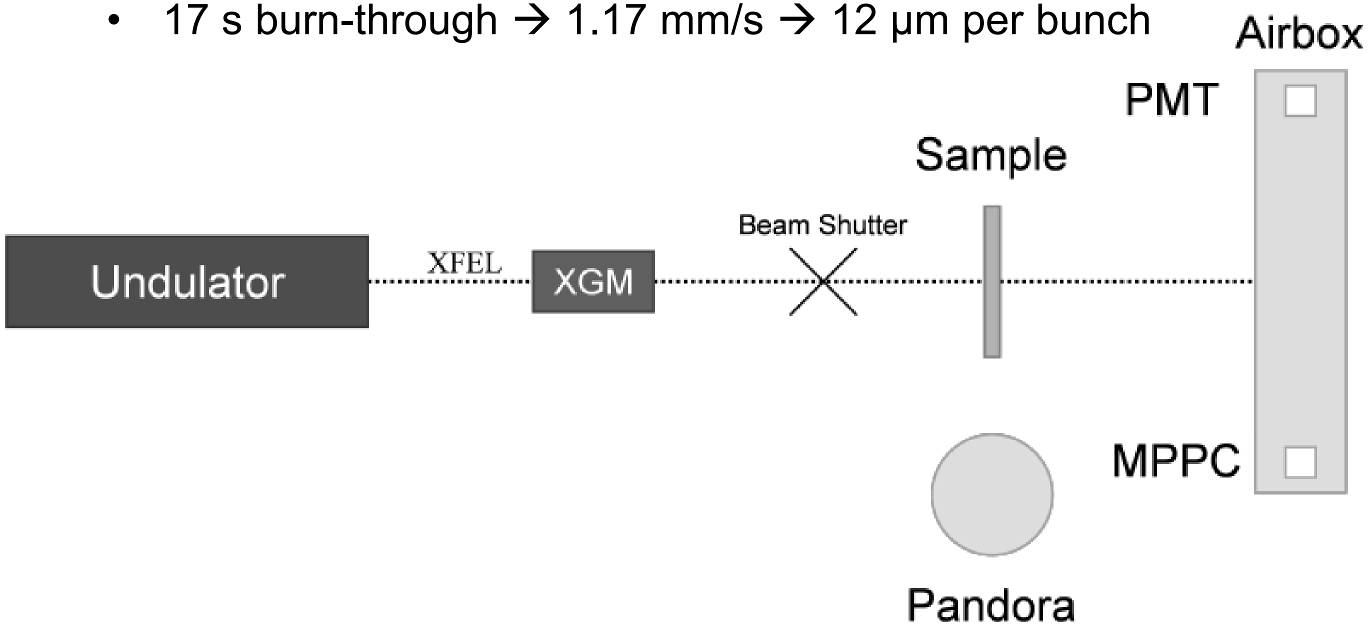
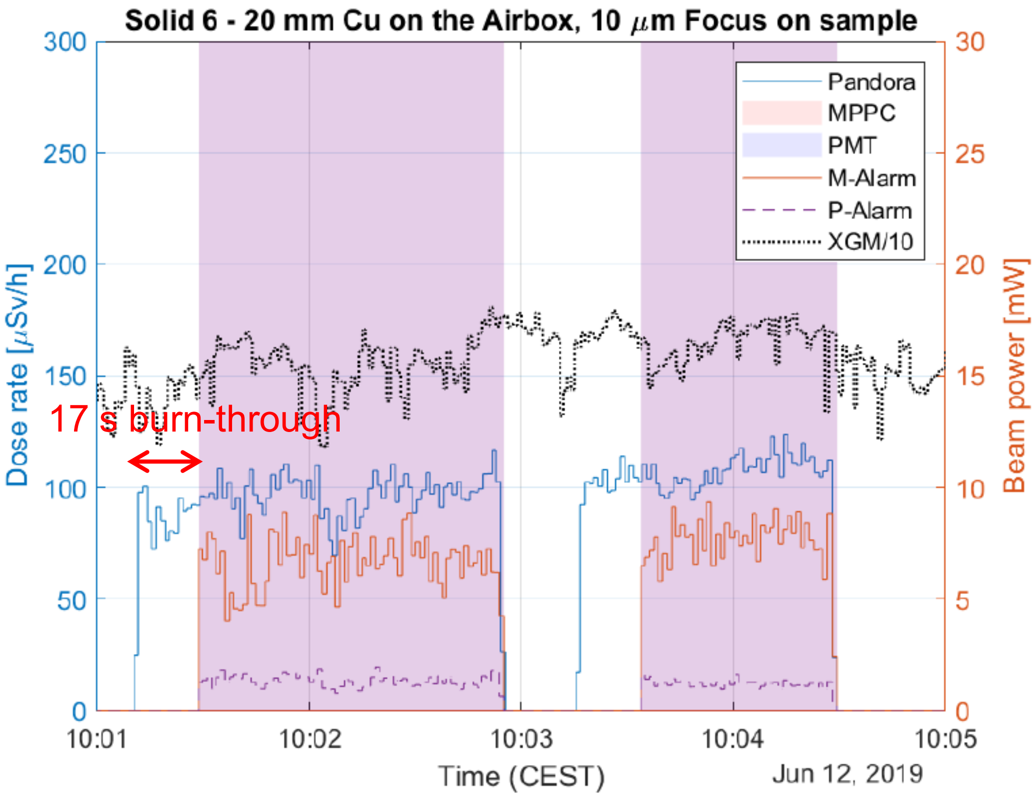


Diagram of test setup

FXE @ 9.3 keV

- Radiation monitor (Pandora) detects when XFEL beam is on the sample
- Photomultiplier (PMT) and Multi Pixel Photon Counter (MPPC) detect light when there is burn-through
- All instruments are active and difference between signal “start” determines burn-through time
- Example with 20 mm Copper:
  - 10 bunches per train, ~1.6 mJ/bunch @ 10 Hz → ~160 mW
  - 17 s burn-through → 1.17 mm/s → 12 μm per bunch





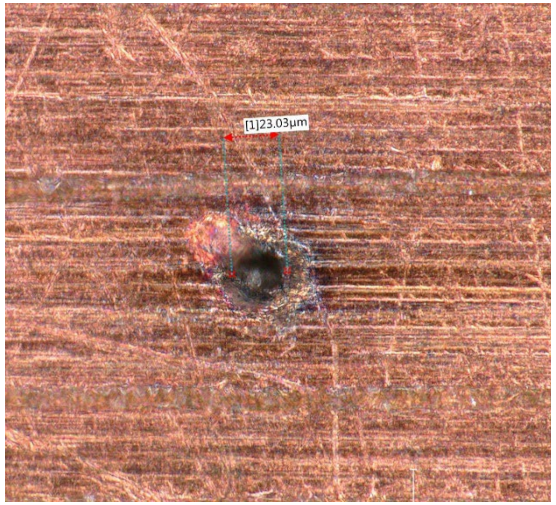
Burn-through data

Pure copper

- Copper samples of varying thicknesses @ 1.125 MHz bunch spacing and 10 Hz train rate

Cu 20 mm	176 bunches	1.3 sec	8.7 μm per bunch
Cu 20 mm	10 bunches	17 and 17 sec	12 μm per bunch
Cu 30 mm	299 bunches	$<$ 1 sec	10 μm per bunch
Cu 100 mm	299 bunches	3 sec	11 μm per bunch
Cu 150 mm	299 bunches	5, 6.2, and 4 sec	avg: 10 μm per bunch
Cu 254 mm	299 bunches	flickering signal after 3 min, but no burn-through	

Microscope image:
23 µm diameter hole



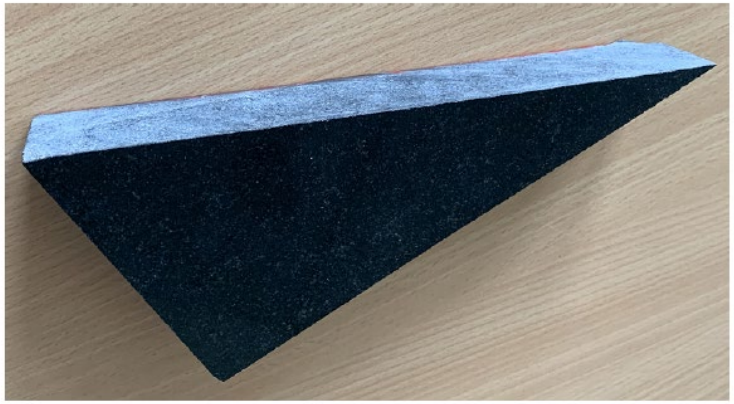
- Feed motion for Cu is consistently ~10 µm per bunch (even with varying thicknesses and bunch numbers)
- No burn-through achieved with 254 mm Cu

Burn-through data

Granite (Nero Assoluto)

- This wedge-shaped granite block was mounted onto a remote-controlled platform, such that many different thicknesses could be tested by laterally shifting platform
- Granite @ 1.125 MHz bunch spacing and 10 Hz train rate

Granite 1 mm	290 bunches	< 1 sec	0.35 μm per bunch
Granite 2 mm	290 bunches	2 sec	0.35 μm per bunch
Granite 3 mm	290 bunches	20 sec	0.052 μm per bunch
Granite 4 mm	290 bunches	13 sec	0.11 μm per bunch
Granite 5 mm	290 bunches	15 sec	0.12 μm per bunch
Granite 6 mm	290 bunches	58 sec	0.036 μm per bunch
Granite 7 mm	290 bunches	66 sec	0.037 μm per bunch
Granite 8 mm	290 bunches	112 sec	0.025 μm per bunch
Granite 9 mm	290 bunches	325 sec	0.010 μm per bunch
Granite 10 mm	290 bunches	288 sec	0.012 μm per bunch
Granite 11 mm	290 bunches	no burn-through after 20 min	



Feed motion [µm per bunch] generally decreases with increasing granite thickness until no burn-through at 11 mm granite

3 mm test took 20 sec…possible inconsistency in granite due to being a composite?

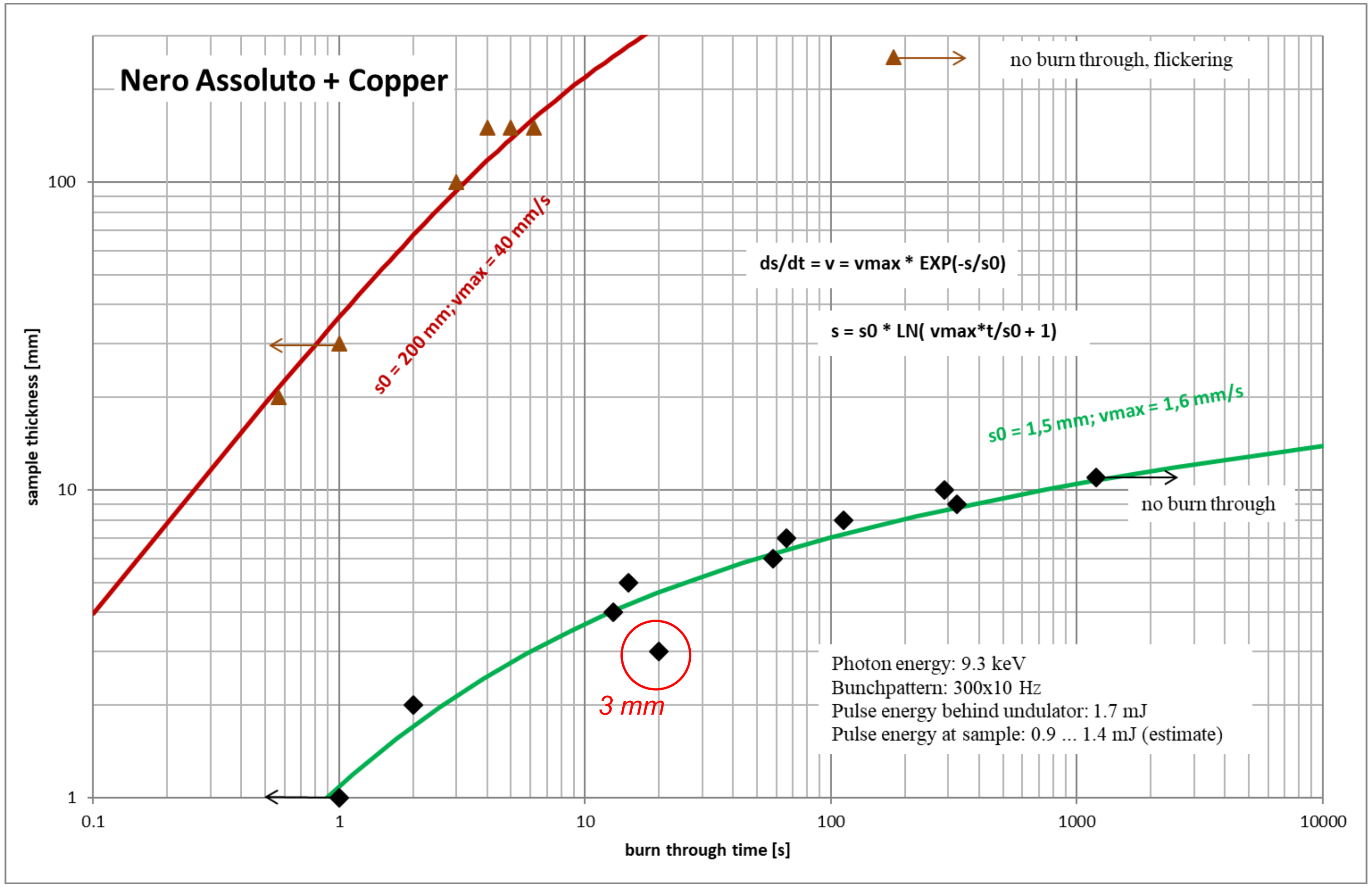
Burn-through times

Copper and Granite (Nero Assoluto) @ 1.125 MHz

- Copper and granite data plotted as burn-through time [s] and sample thickness [mm]

- Curve fitting with logarithmic function and parameters s_0 and v_{max}
  - Copper v_{max} = 40 mm/s = 13 µm/b
  - Granite v_{max} = 1.6 mm/s = 0.53 µm/b

- As sample thickness increases, burn-through time increases exponentially



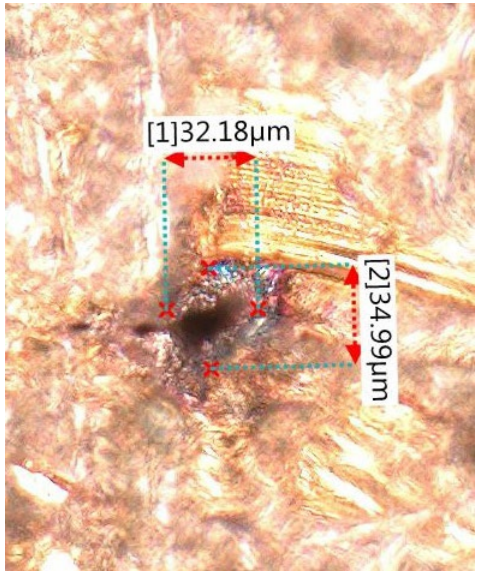
Burn-through data

Pure copper

- 60 mm copper @ varying bunch frequency (spacing as μs in parentheses)

10 bunches	4.5 MHz (0.22 μs)	55 sec	11 μm per bunch
5 bunches	4.5 MHz (0.22 μs)	94 sec	13 μm per bunch
10 bunches	2.25 MHz (0.44 μs)	43 sec	14 μm per bunch
10 bunches	1.5 MHz (0.67 μs)	40 sec	15 μm per bunch
10 bunches	1.125 MHz (0.89 μs)	40 sec	15 μm per bunch
10 bunches	0.45 MHz (2.2 μs)	38 sec	16 μm per bunch
1 bunch	10 Hz (10^5 μs)	400 sec	15 μm per bunch

Microscope image:
32 μm x 34 μm hole

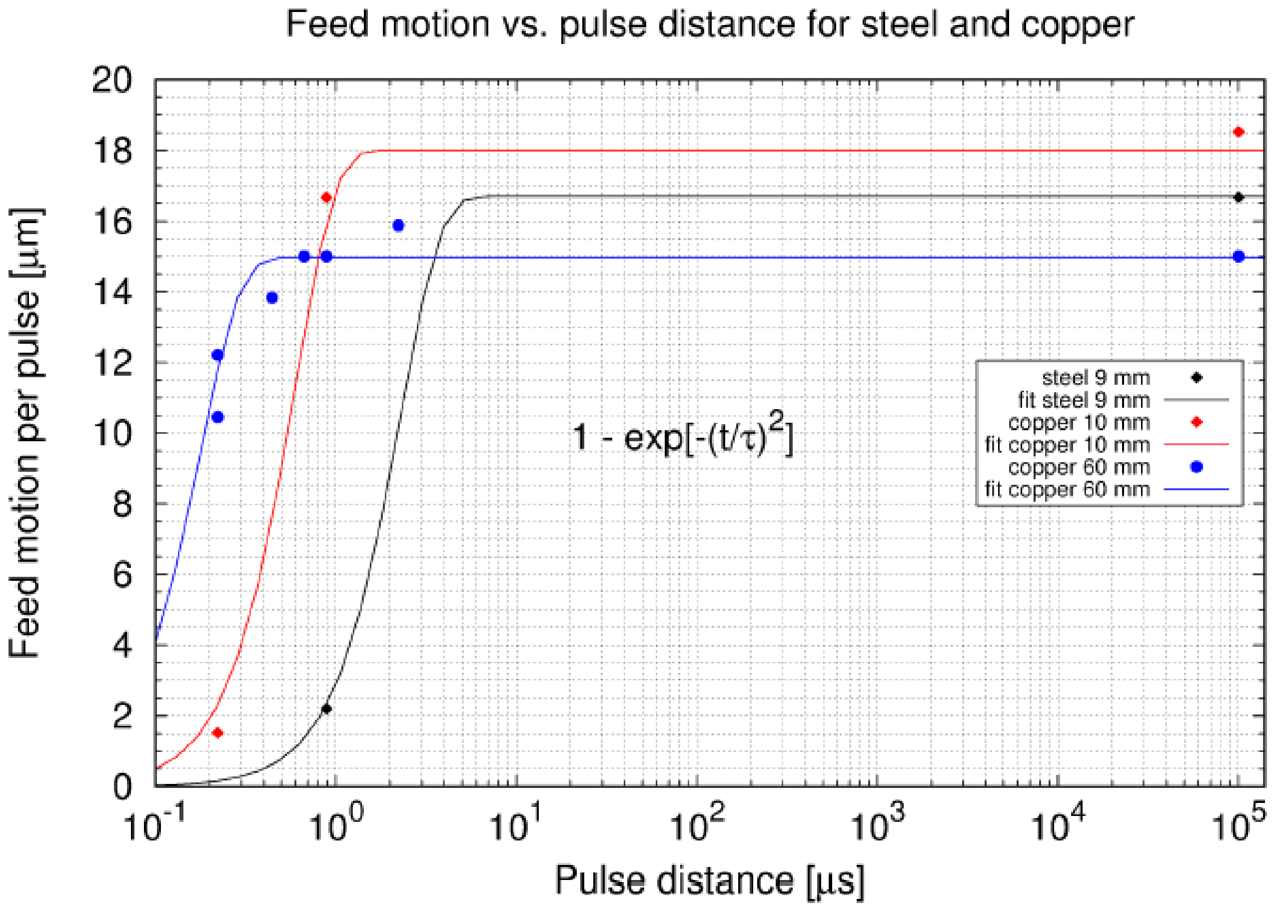


- Bunch spacing achieved with bunch selector (kick-out every N bunch in a train)
- Increase in bunch spacing increases feed motion of 60 mm copper
    - Is vaporized copper within drilled hole absorbing some % of the energy of the incoming X-rays?
    - Is more bunch spacing allowing time for vaporized material to escape?

Dependency on bunch spacing

Samples: copper (10 and 60 mm) and steel (9 mm)

- 0.22 µs corresponds to 4.5 MHz mode
  0.9 µs corresponds to 1.25 MHz mode
  2.2 µs corresponds to 0.45 MHz mode
  10^5 µs corresponds to single bunch mode
- Increase in bunch spacing increases feed motion for both the copper and steel samples
- Data fitting with exponential that plateaus as pulse distance increases
- Same questions as before:
  - Is vaporized copper within drilled hole absorbing some % of the energy of the incoming X-rays?
  - Is more bunch spacing allowing time for vaporized material to escape?



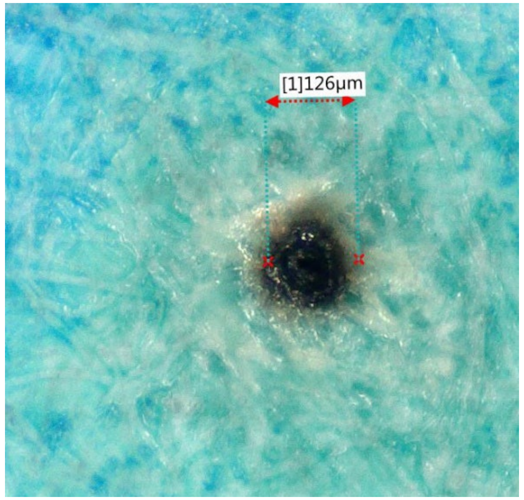
Burn-through data

Pure tungsten

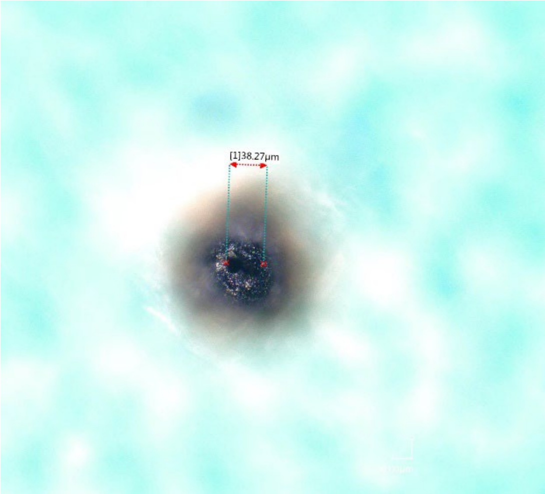
- Tungsten samples of varying thicknesses @ 1.125 MHz bunch spacing and 10 Hz train rate

W 2 mm	299 bunches	< 1 sec	0.7 µm per bunch
W 30 mm	299 bunches	14 sec	0.7 µm per bunch
W 40 mm	299 bunches	85 sec	0.2 µm per bunch
W 40 mm	299 bunches	3.5 sec	3.8 µm per bunch
W 50 mm	299 bunches	3.3, 1.4, and 3.5 sec	avg: 7.3 µm per bunch

Microscope image:
126 µm burn mark



- Feed motion for W increases with sample thickness (What happened with 40 mm W? Closer look next slide)
  - Why is it easier to burn-through W as thickness increases?
- Burn-through achieved with even 50 mm W plate (three attempts to confirm result)



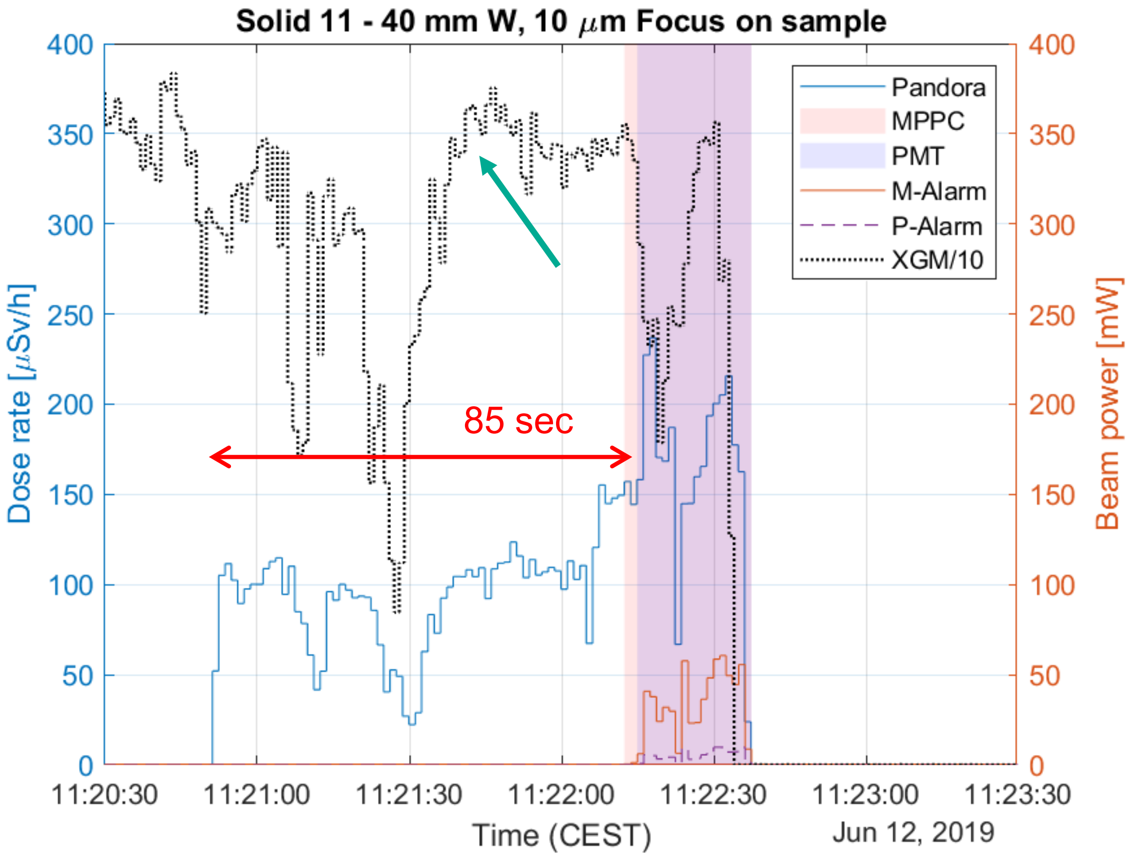
Microscope image:
38 µm diameter hole

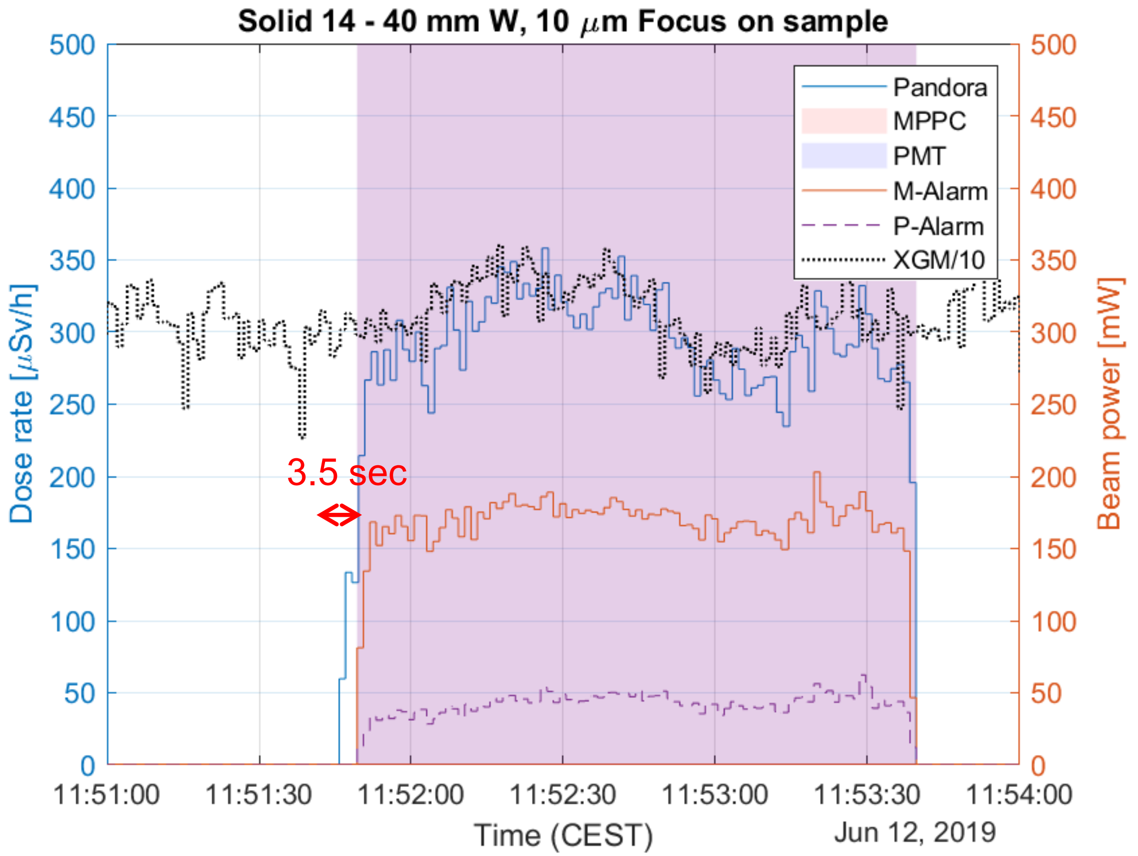
Closer look at 40 mm W tests

Stability of XFEL beam points to possible reason for large difference in burn-through time: 85 vs. 3.5 sec

Stability of XFEL beam monitored with X-ray Gas Monitor (XGM):

- Run 11 (L) shows "up-and-down" XFEL beam power → inefficient drilling of W by XFEL beam (85 sec)
- Run 14 (R) shows increased stability in XFEL beam → very fast burn-through of 40 mm W (3.5 sec)





However, here the beam becomes stable for longer than 30 sec, yet there is no burn-through!

Burn-through data

Carbon-based samples: graphite and diamond

- Carbon-based samples @ 1.125 MHz bunch spacing and 10 Hz train rate

Graphite 25 mm	176 bunches	no burn-through after 9 min
Graphite 25 mm	299 bunches	no burn-through after 84 sec
Diamond 0.15 mm	299 bunches	90% transmission (9.3 keV X-rays), no burn-through or hole

- Carbon-based samples @ 2.25 MHz bunch spacing and 10 Hz train rate

Graphite 1 mm, 400 bunches	59% transmission, no burn-through
Graphite 5 mm, 400 bunches	7% transmission, no burn-through
Graphite 10 mm, 400 bunches	0.5% transmission, no burn-through
Graphite 25 mm, 400 bunches	no burn-through after 23 minutes

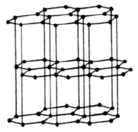
No microscope images; extremely difficult to find hole or burn mark on rough surface of graphite

THIELMANN GRAPHITE GmbH & Co. KG
Präzisions-Graphite

Graphit CS36

Physikalische Daten / Physical Datas

Dichte / Bulk Density g/cm³ 1,75



Thin pieces of graphite (and diamond) are thin enough to transmit 9.3 keV beam but no burn-through achieved

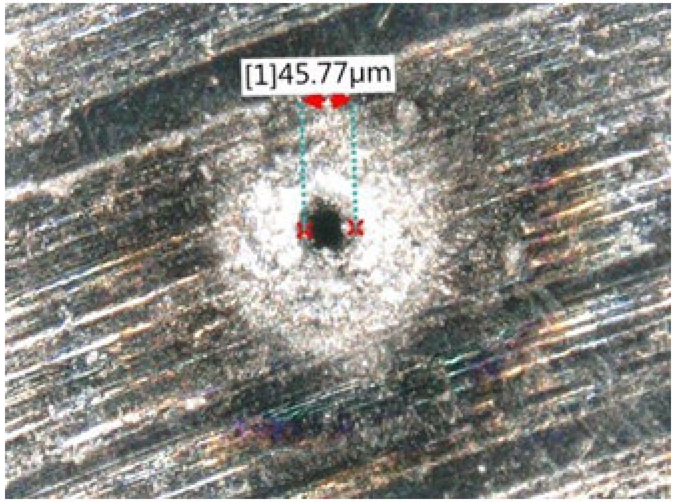
No transmitted signal seen at PMT or MPPC with 25 mm graphite but also no burn-through

Burn-through data

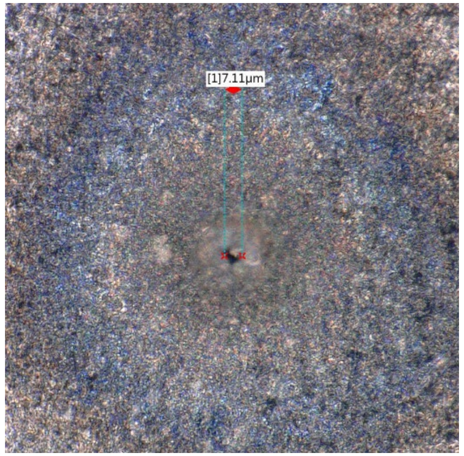
Other sample materials (with sometimes strange results)

- Tungsten heavy alloy from SLAC (WHA)
  - 10 mm WHA: 10 b, 293 s → 2 µm per bunch
  - Recall successful burn-through of up to 50 mm pure W
- Silicon Carbide (SiC)
  - 10 mm SiC: 299 b, no burn-through after 5.5 min
- Boron Carbide (B4C)
  - 14 mm B4C: 400 b, 75 s → 0.05 µm per bunch
  - 30 mm B4C: 400 b, no burn-through after 13.3 min
- Molybdenum (Mo)
  - 3 mm Mo: 100 b, no burn-through after 20 min, but multiple attempts after showed a flickering signal at the Airbox's MPPC
  - Why is there no burn-through for so little Mo even when there is a visible hole on the surface? (More on next slide)

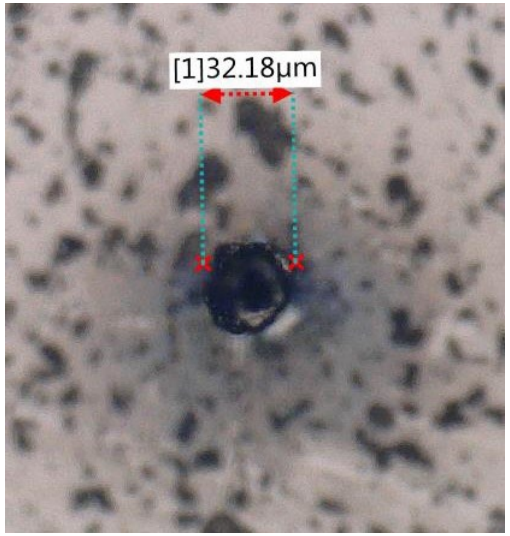
WHA with 46 µm hole



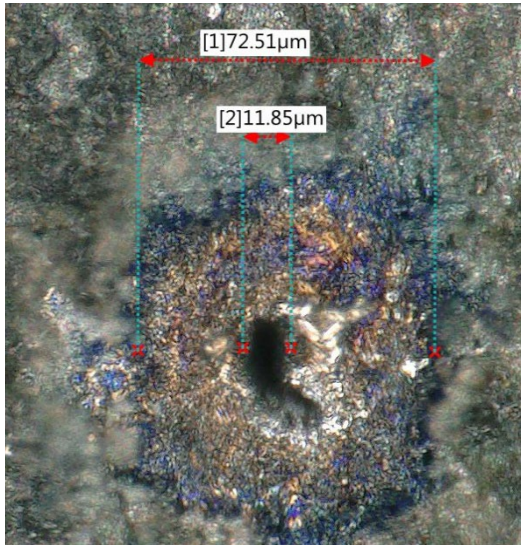
SiC with 7 µm hole



B4C with 32 µm hole



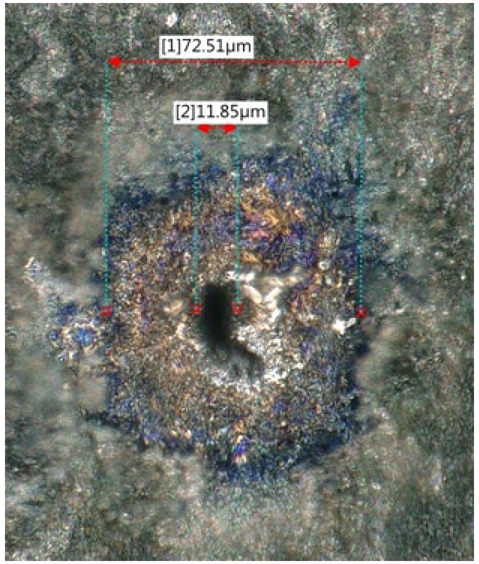
Mo with 12 µm hole (but not burned-through)



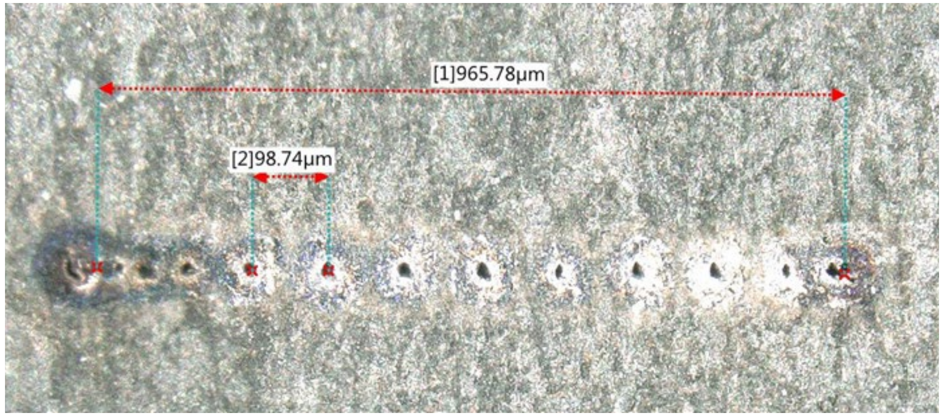
Closer look at 3 mm Mo tests

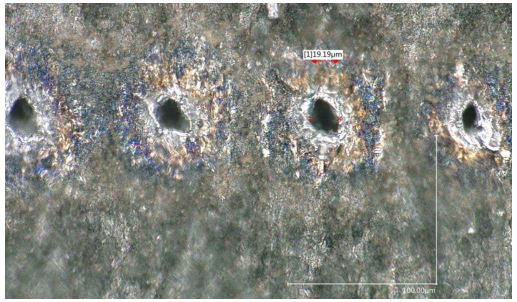
No burn-through due to poor beam spatial stability; partial burn-through with improvement

- Non-circular oblong shape of entrance hole indicates fluctuations in XFEL beam's spatial position on sample
- Beam stability improved, and mechanical rastering allows for “fresh” material (beam moves left-to-right)
- With improved stability, partial burn-through of 3 mm Mo achieved; flickering signal detected

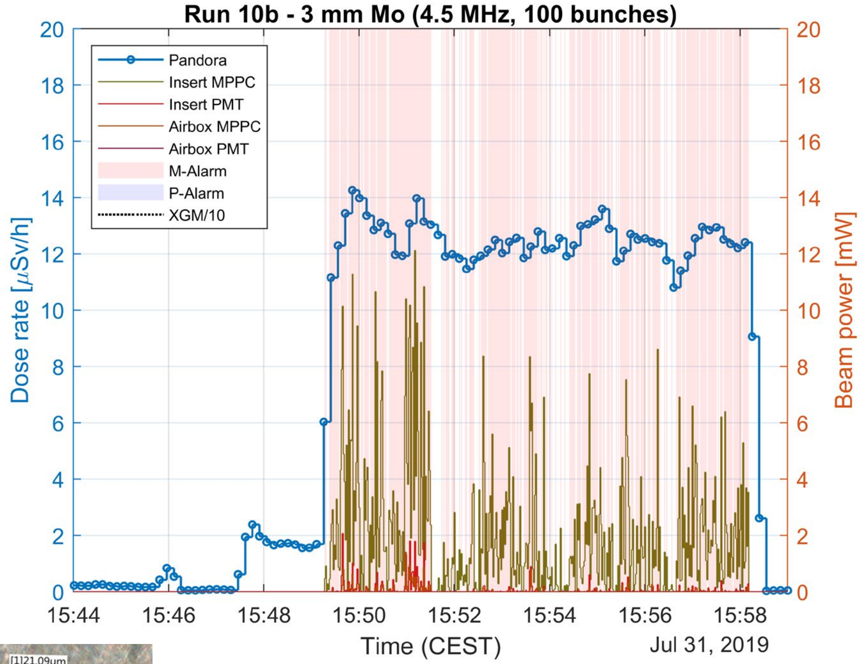


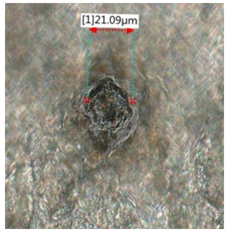
1st run with oblong hole; No signal at Airbox and no burn-through





Improved beam stability leads to more circular entrance holes with diameters on the order of 20 µm and partial burn-through of sample





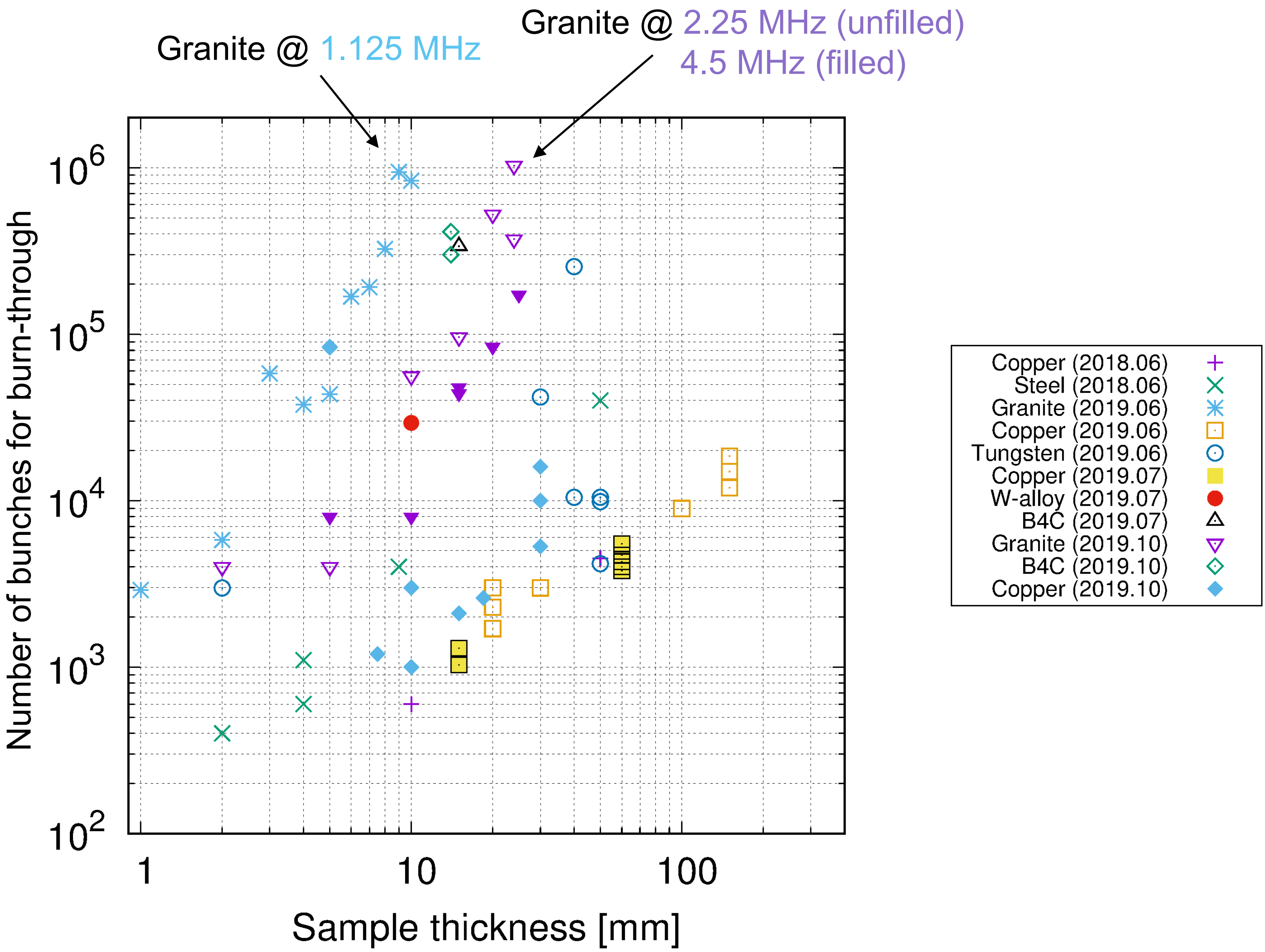
Exit hole after improved beam spatial stability; partial flickering signal observed by **MPPC** and **PMT**

Collection of data from FXE material tests

XFEL-FXE @ 9.3 keV

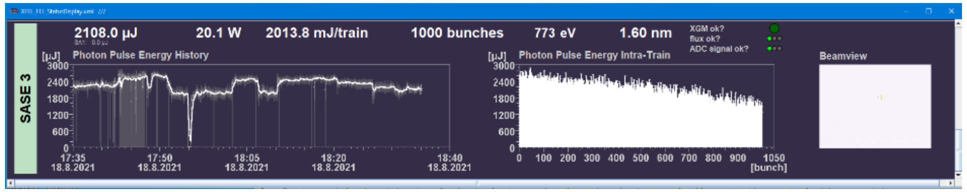
- Number of XFEL X-ray bunches to burn-through various pure metals and composites clearly trends upwards as the sample material's thickness increases

- Bunch spacing has important effect on number of bunches for burn-through as seen by graphite and also by copper

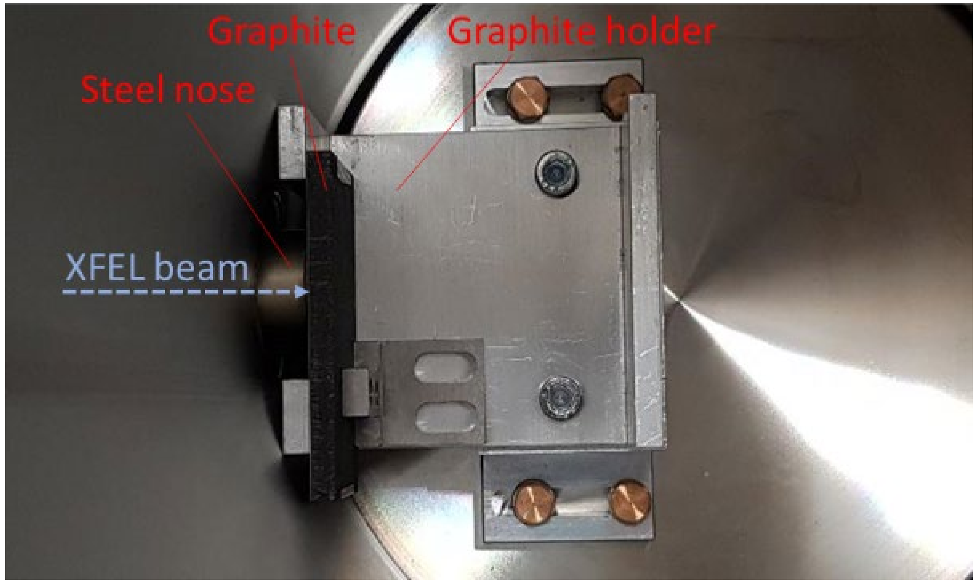


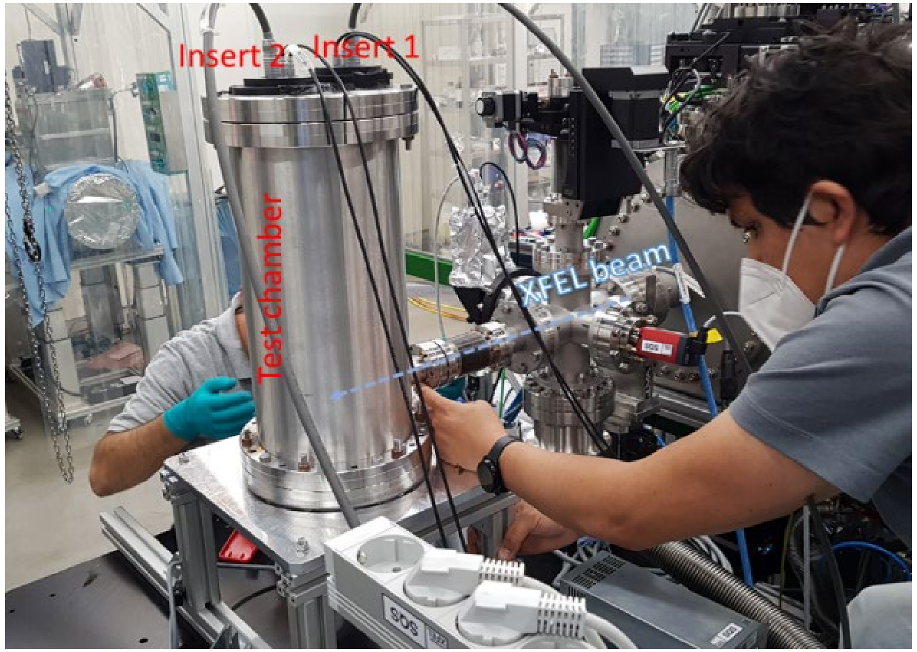
Tests at XFEL-SQS

Graphite tests @ 0.773 and 2.66 keV



- Up to 1000 bunches per train through SASE3 (first time at XFEL!)
- 10 Hz train repetition rate and 1.125 and 2.25 MHZ intra-train rate
- Bunch energy from SASE3 was 2-5 mJ with stable transmission to SQS (45% @ 0.77 keV, 75% @ 2.66 keV)
- XFEL first burns-through 150-200 µm steel nose (separates vacuum from air); pumps maintain vacuum… then beam reaches graphite; Insert 1 detects beam-on-sample and Insert 2 detects burn-through of graphite





Graphite burn-through data

Tests @ 0.773 keV (left) and @ 2.66 keV (right)

Run #	Configuration	Bunches per train	Intra-train rate	XGM SQS	Burn-through time
16	0.5 cm graphite	100 b	1.125 MHz	1.3 W	5 sec
17	1 cm graphite	100 b	1.125 MHz	1.3 W	NO after 3 min
18	1 cm graphite	300 b	1.125 MHz	3.6 W	20 sec
19a	2 cm graphite	300 b	1.125 MHz	3.7 W	NO after 5.75 min
19b	2 cm graphite	401 b	1.125 MHz	4.5 W	NO after 10.7 min
20	1 cm graphite	300 b	2.25 MHz	3.6 W	4-5 sec
21	2 cm graphite	401 b	2.25 MHz	4.9 W	NO after 5 min
22	2 cm graphite	600 b	2.25 MHz	7.1 W	NO after 1.7 min
25	2 cm graphite	1 000 b	2.25 MHz	11 W	NO after 3.5 min
26	4 cm air + 0.5 cm graphite	1 000 b	2.25 MHz	11 W	Immediate signal on Insert 1
27	8 cm air + little Al and steel between Insert 1&2	1 000 b	2.25 MHz	11 W	Signal on Insert 2 after 110 sec
28	4 cm air + 1 cm graphite	1 000 b	2.25 MHz	11 W	Immediate signal on Insert 1

2.25 MHz has faster burn-through time than 1.125 MHz → less time between bunches for heat dissipation

Run #	Configuration	Bunches per train	Intra-train rate	SASE3 power	Burn-through time
43	1 cm graphite	600 b	2.25 MHz	8.7 W	50 sec
44	2 cm graphite	600 b	2.25 MHz	9.2 W	4 min
45	4 cm graphite	600 b	2.25 MHz	9.1 W	NO after 10 min
46	4 cm air + 2 cm graphite	600 b	2.25 MHz	9.9 W	NO after 10 min

Attenuation for 1 cm of air:

- 2.66 keV: 0.66
- 0.773 keV: ***0.001***

- Decision to use 5 cm graphite as absorber material
- Extrapolate times for 100 b per train @ 10 Hz
  - 0.773 keV: ~12 000 sec (3.33 h)
  - 2.66 keV: ~36 000 (10 h)

Summary

Materials tests @ XFEL-FXE and XFEL-SQS

- XFEL beam at 9.3 keV used for material tests at FXE
  - 1-400 bunches per train @ 10 Hz; 1-2 mJ per bunch with bunch frequency from 0.45-4.5 MHz; spotsizes of 10-30 µm
- XFEL beam at 0.773 and 2.66 keV for graphite tests at SQS
  - 100-1000 bunches per train @ 10 Hz; 2-5 mJ per bunch (variation due different X-ray keV energies) with frequency of 1.125 and 2.25 MHz; spotsizes of 5-20 µm

- Material tests performed for a variety of metals and composites
  - Copper, tungsten, graphite, diamond, WHA, B4C and SiC were burned-through with XFEL beam
  - Graphite samples survived burn-through and 5 cm recommended as absorber material thickness

- Observations, remaining questions and further investigations
  - Large effect on burn-through time with regards to beam stability - both power and spatial
  - Dependency of feed motion (µm per pulse) on bunch spacing (time between bunches arriving to sample)
  - Modeling burn-through as function of XFEL beam parameters and material type

Contact

Deutsches Elektronen-
Synchrotron DESY

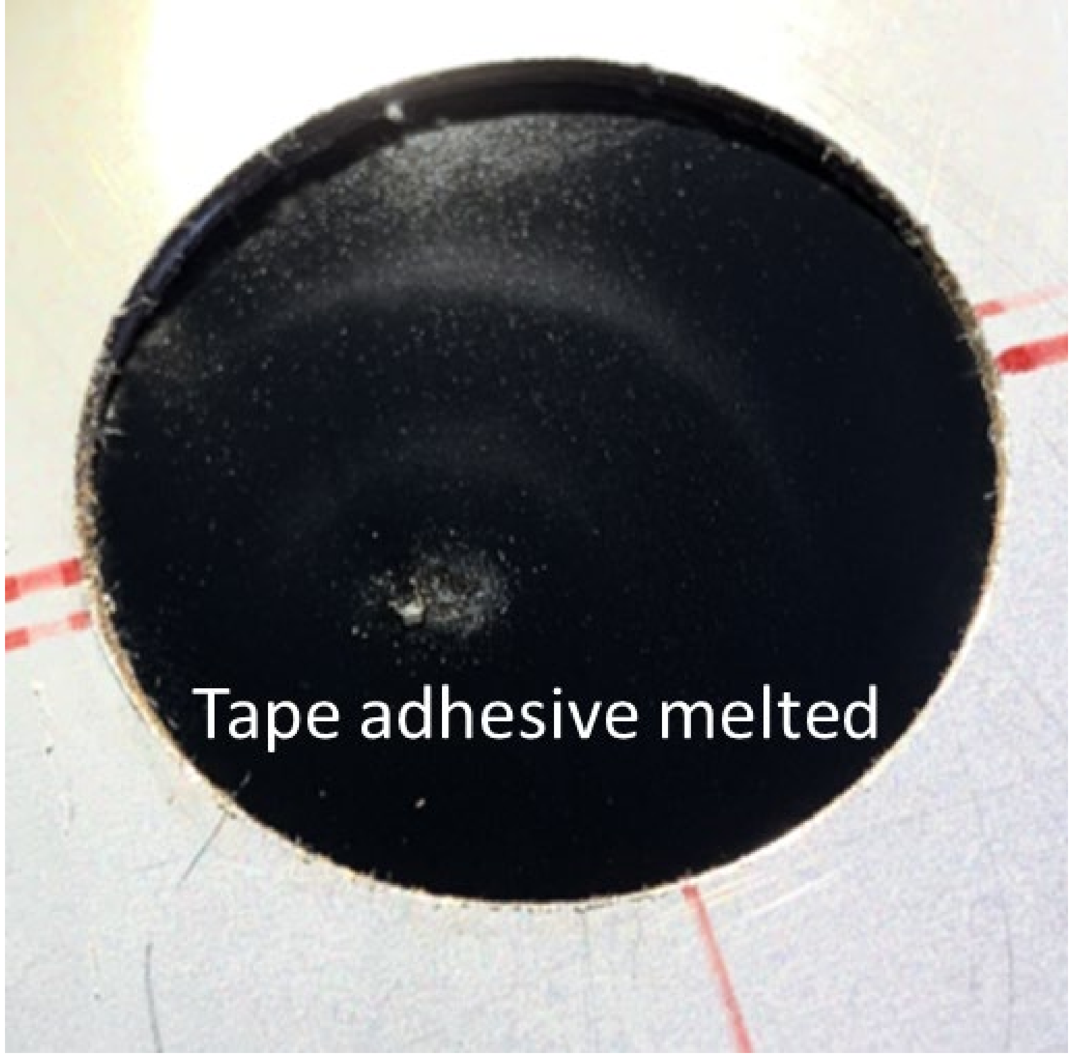
www.desy.de

Ted Liang
Radiation Protection Group D3
ted.liang@desy.de

Extra slides

Damage to polyvinyl tape

Used to make airbox/chamber with PMT and MPPC light-tight



XFEL-SQS beamline stability

XFEL beam power stability good for 0.773 keV and 2.66 keV (with a few outliers)