The Photon Beamline Vacuum System of the European XFEL.

European XFEL

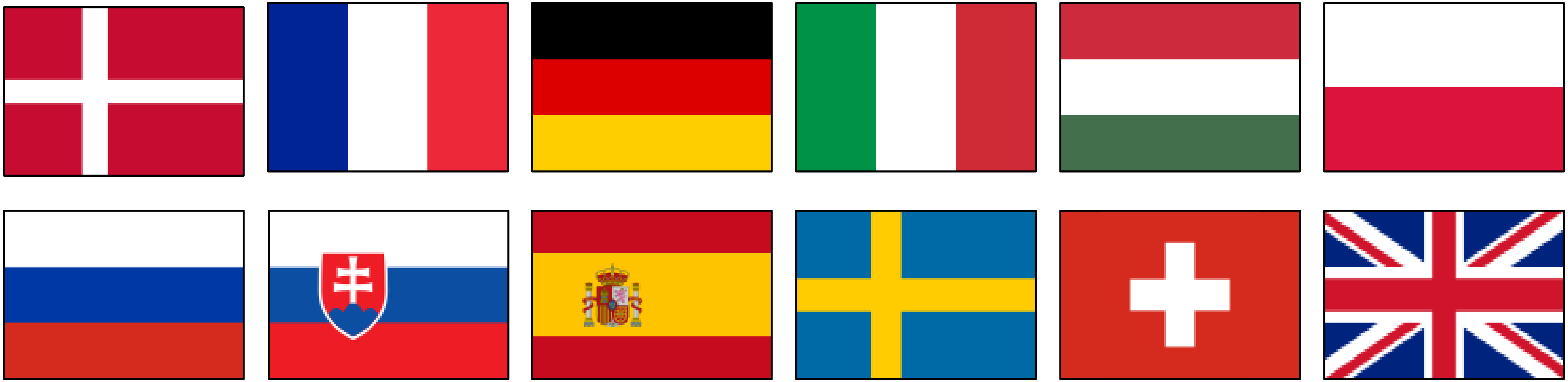
First years of operation (2017-2023). An overview.

Raúl Villanueva
Senior Vacuum Engineer,
on behalf of the European XFEL Vacuum Group.

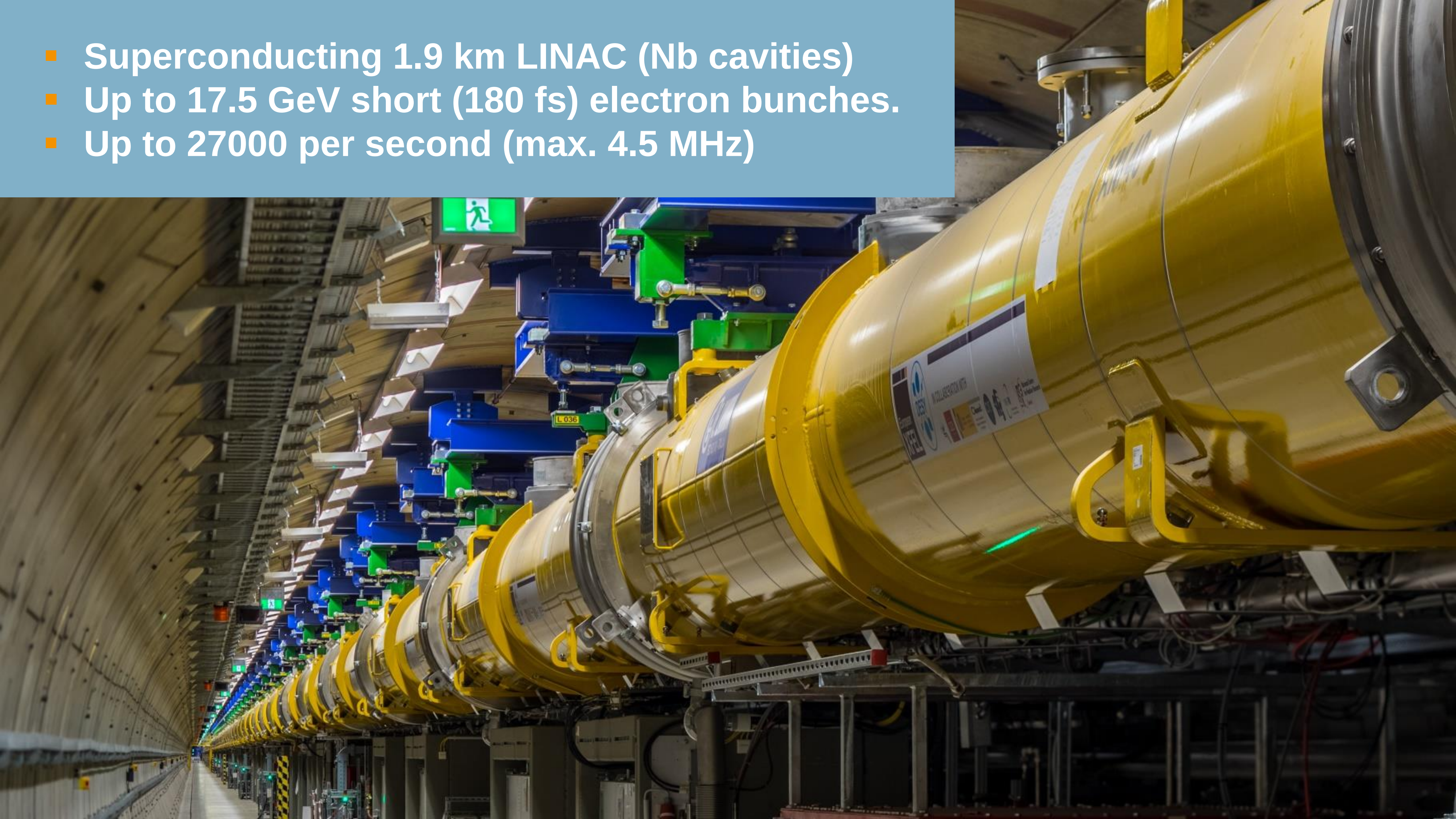
Fermilab 18th April, 2024
6th Workshop on the Operation of Large Vacuum Systems [OLAV-VI]

The Facility

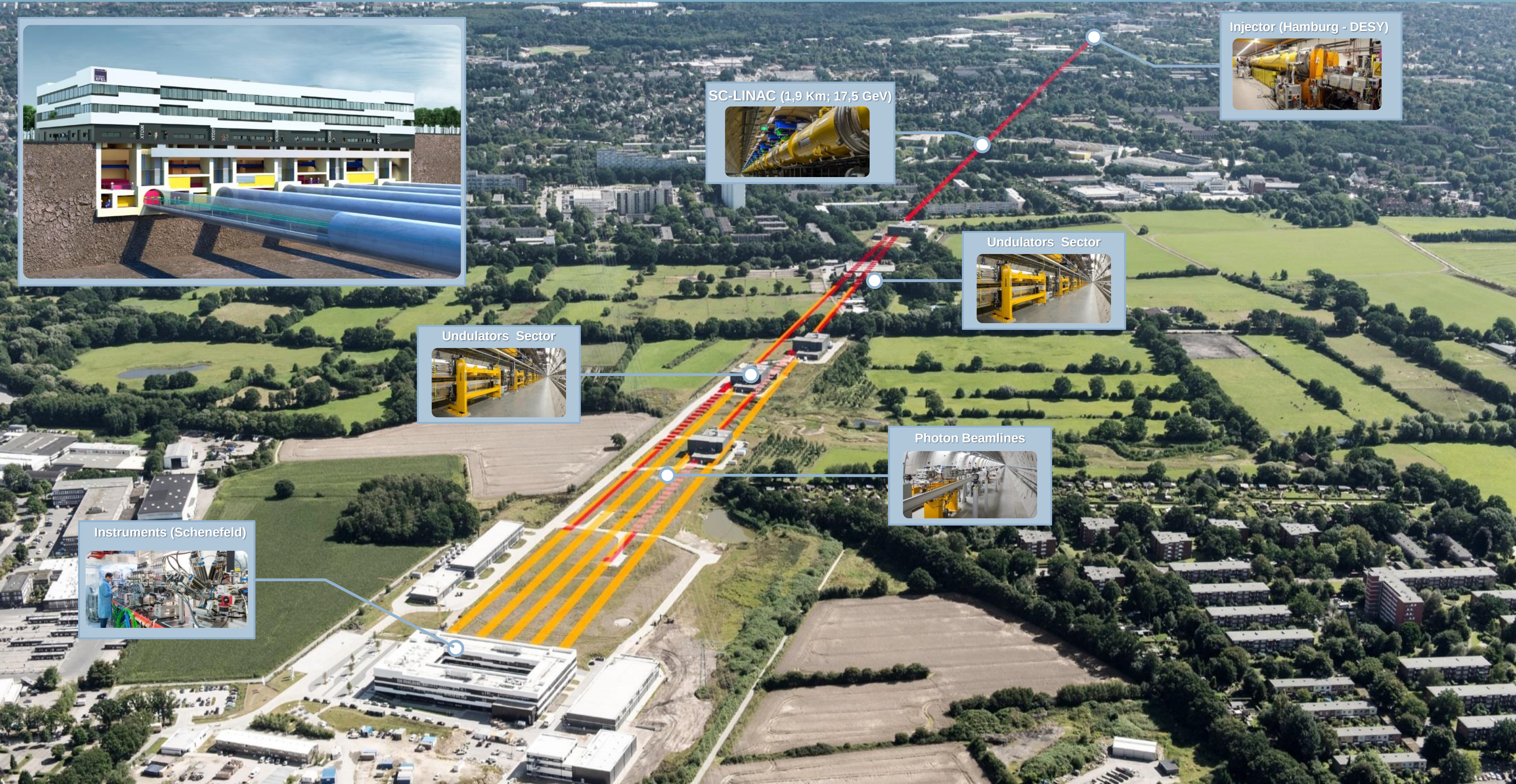
12 Participating Countries



- Superconducting 1.9 km LINAC (Nb cavities)
- Up to 17.5 GeV short (180 fs) electron bunches.
- Up to 27000 per second (max. 4.5 MHz)

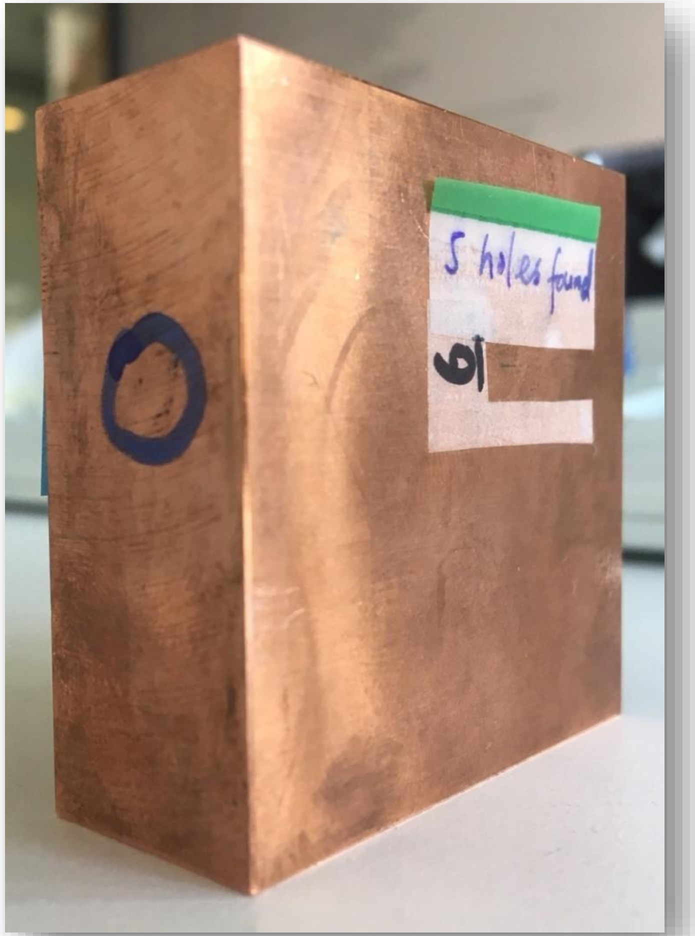


3,4 Km from Injector to Experimental Hall.

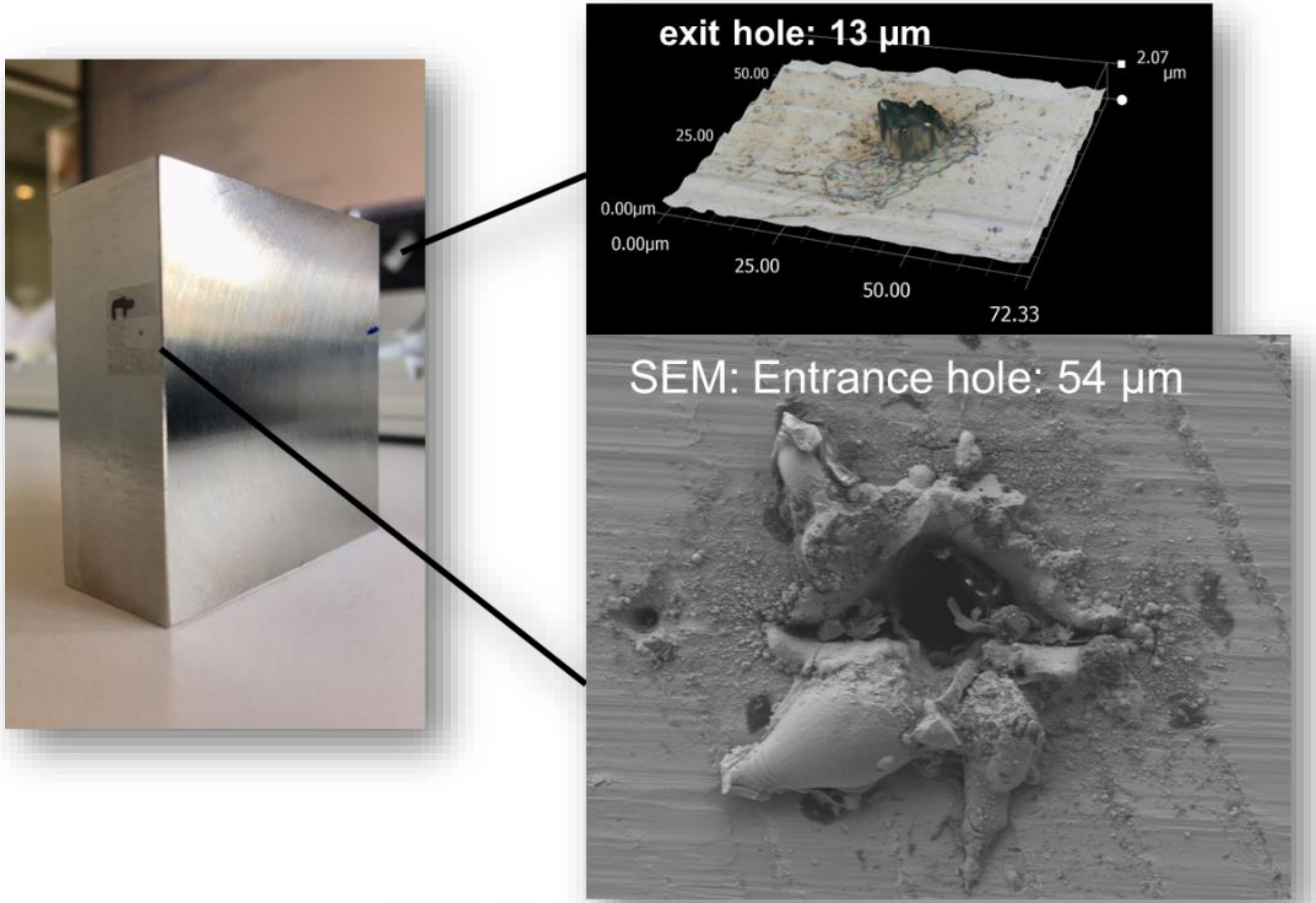


Fact #1: A Powerful X-Ray Laser Machine.

50 mm copper: 3 seconds

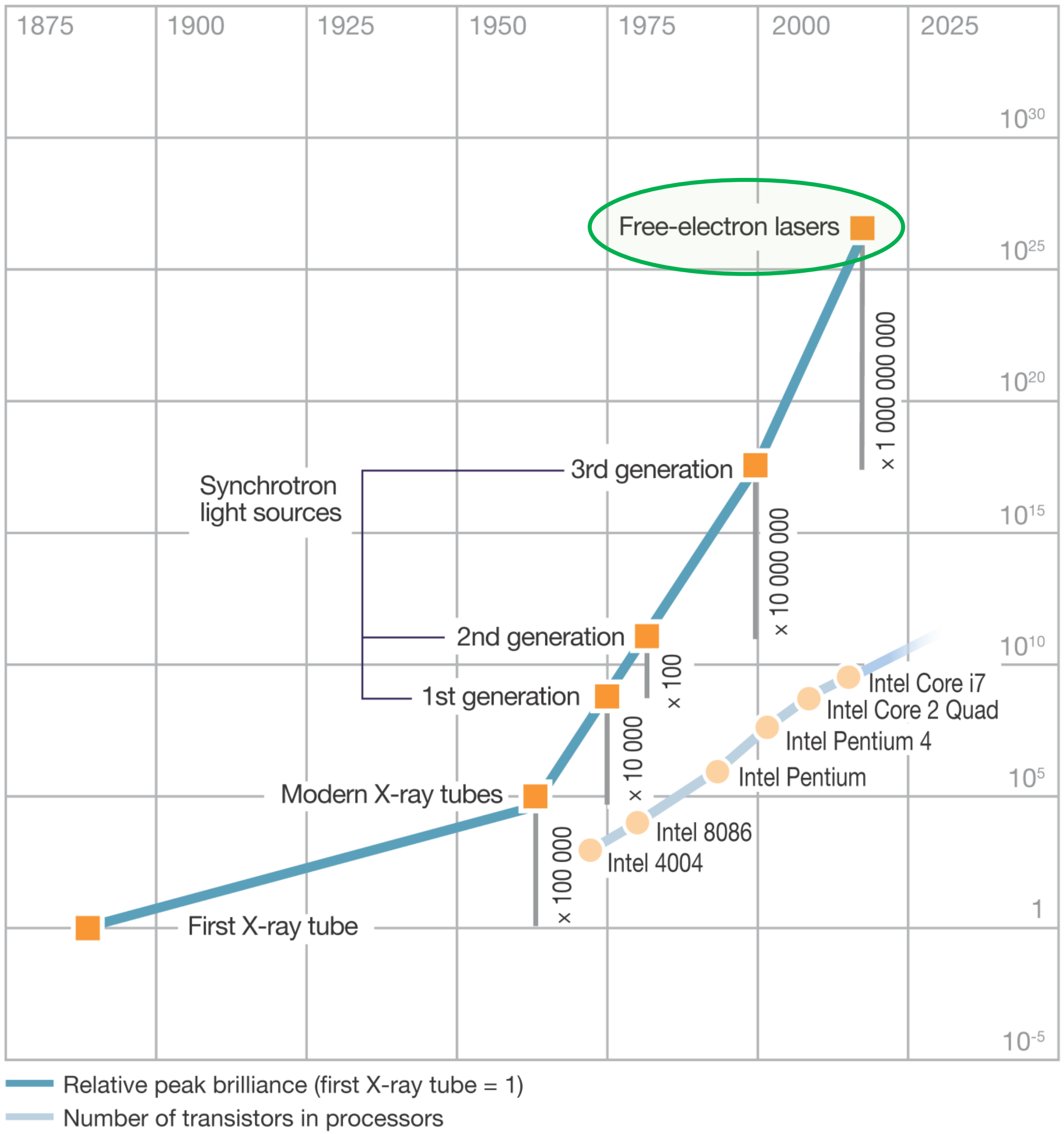


50 mm steel in 26 seconds (9.1 keV, beam size 20 µm)



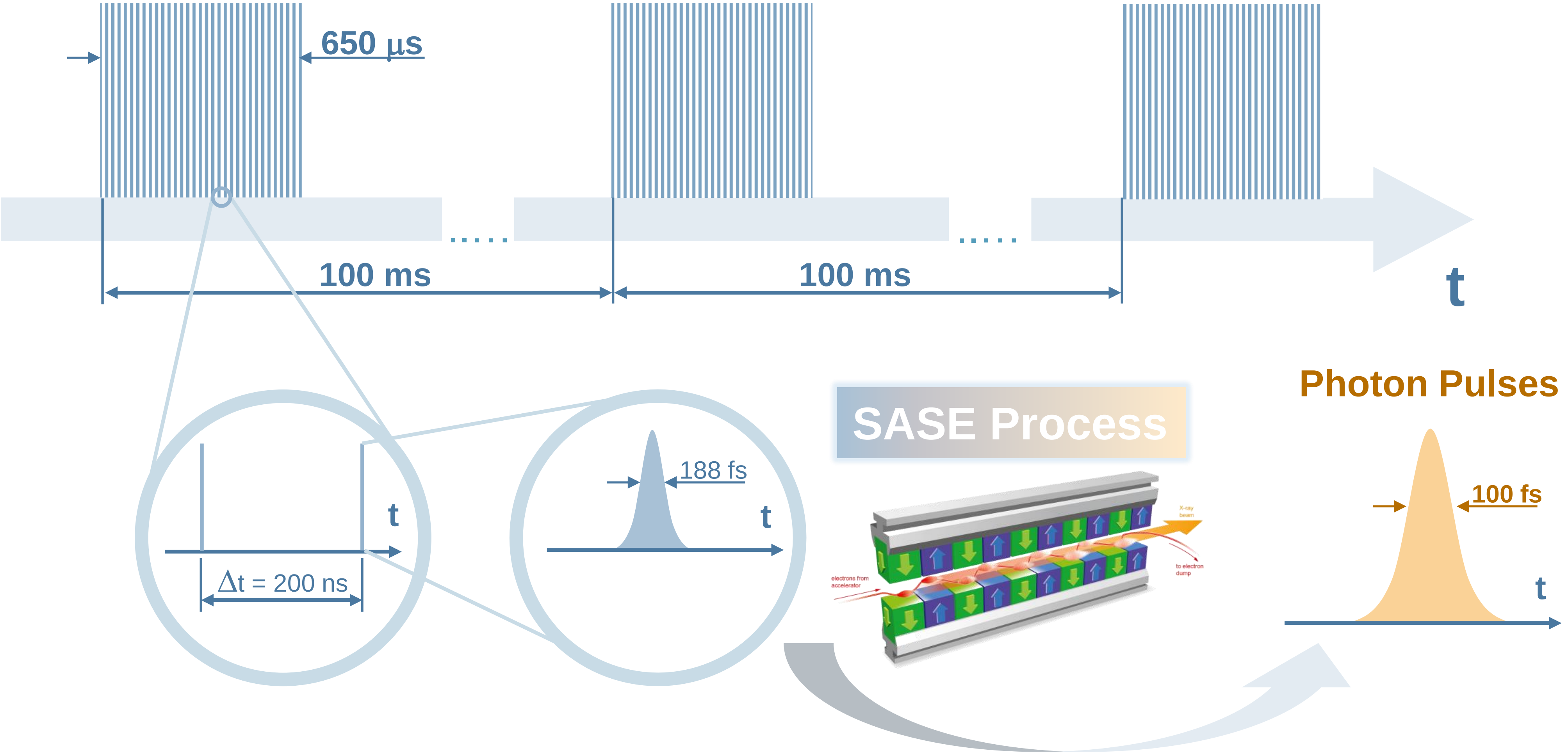
H. Sinn, A. Leuschner, F. Yang et al., European XFEL & DESY 2018

FEL´s are incredibly BRIGHT X-RAY light SOURCES

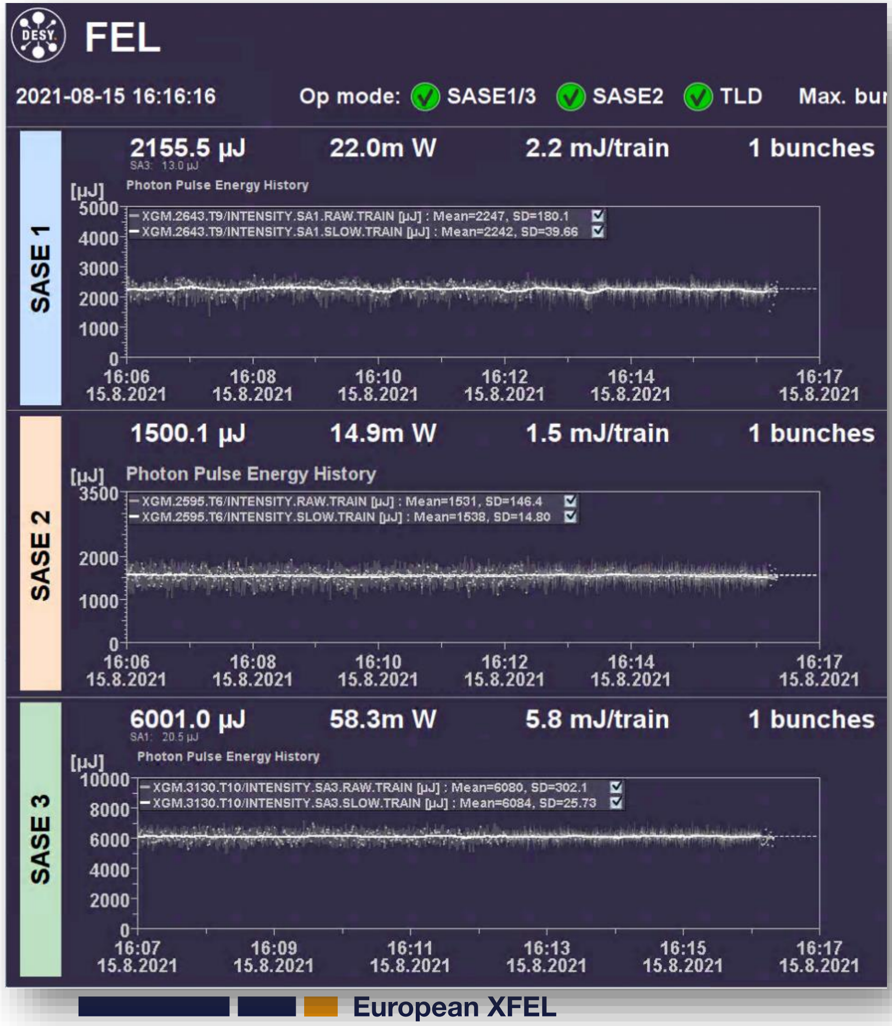


PEAK BRILLIANCE *[photons / s / mrad² /mm² / 0,1% bandwith]*

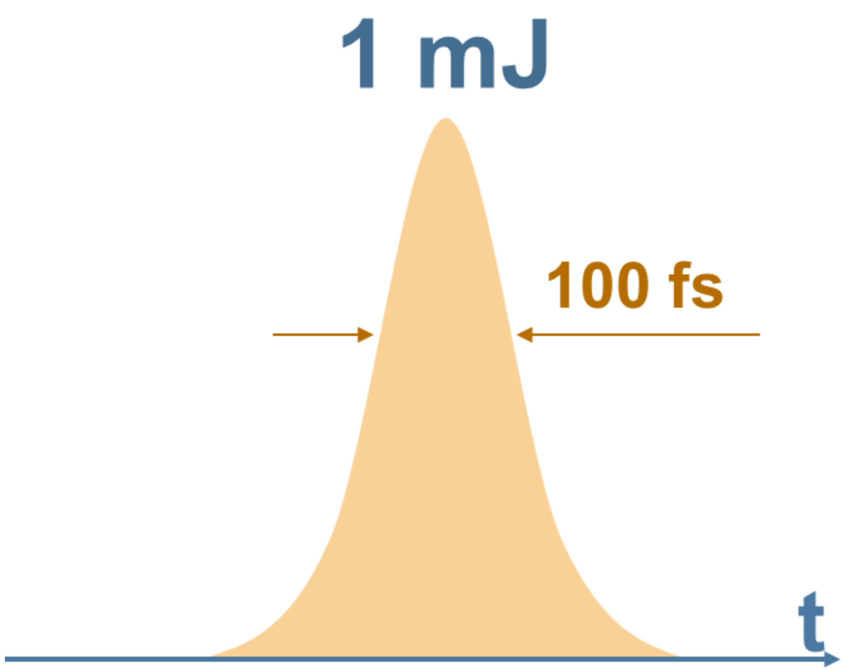
European XFEL Temporal Structure.



….that means a lot of pulse instant power available on a regular day…



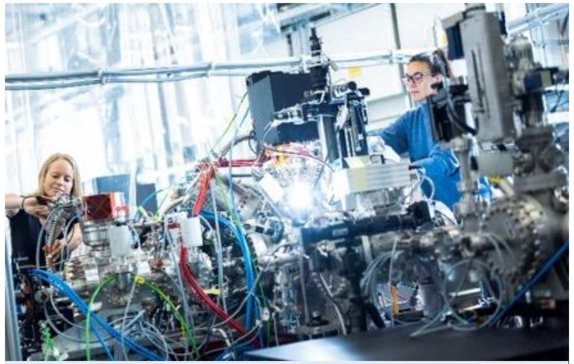
10 GW / pulse!



Fact #2: An user-oriented research facility

Currently delivering photons to seven scientific instruments

FXE (Sept. 2017)

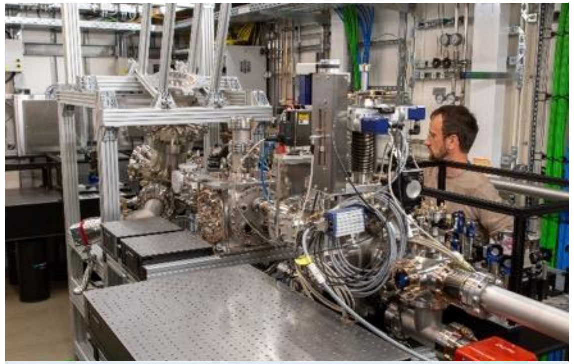


SQS (Nov. 2018)

SCS (Nov. 2018)

HED (May 2019)

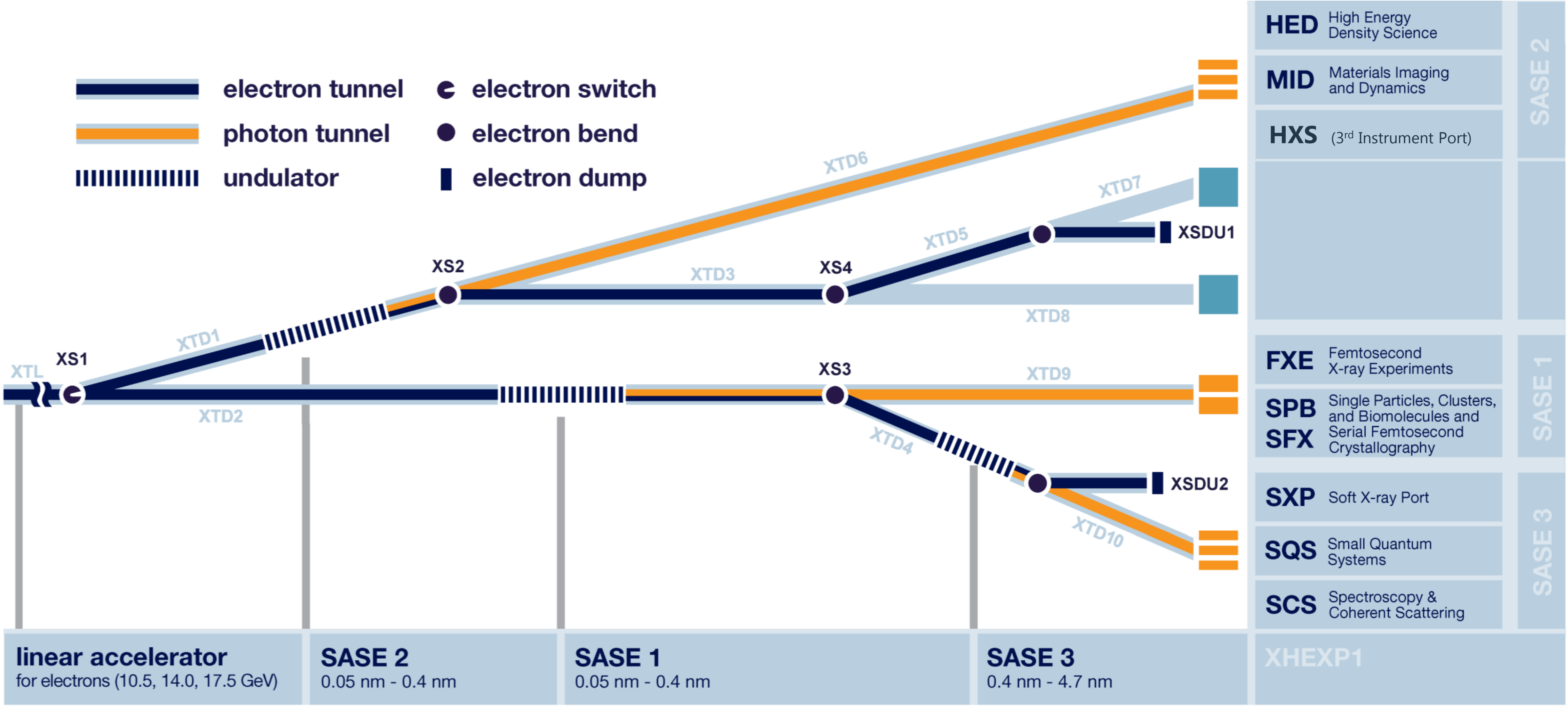
SPB/SFX (Sept. 2017)



SXP (August 2023)

MID (April 2019)

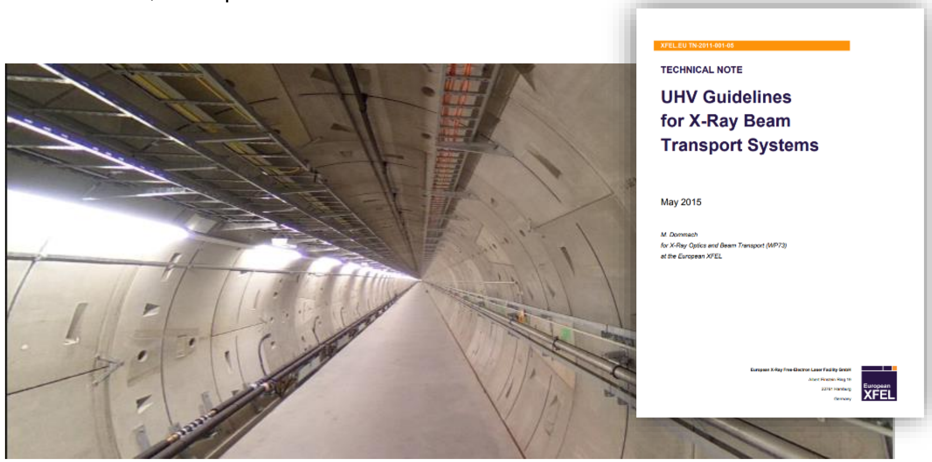
Next decade: SASE 4 & 5 Beamlines



Photon Beam Vacuum System

The Photon Beam Vacuum System …in a nutshell.

- According to XFEL UHV Guidelines.
- 304L or 316L piping and 316LN ESU CF flanging.
- Outsourced manufacturing and cleaning.
- “Particle free“ specifications (ISO Class 5/6).
- Sectorization & mobile clean tents.
- Average base pressure < $9 \cdot 10^{-9}$ mbar (unbaked system!)
- Standard vacuum components (or slighlty customised…):
  - Pumping Stations
  - Beamline Pumping equipment (mechanical, SIP’s, NEG’s)
  - Gauges, RGA‘s, controllers.
- Facility harmonized PLC based control system. (Beckhoff)


TECHNICAL NOTE

UHV Guidelines for X-Ray Beam Transport Systems

May 2015

The Photon Beam Vacuum System …in numbers.

- Three beamlines with more than 3km total length of photon beam pipes
  - Mostly “particle-free”.
  - Around 90 sectors
- Installed pumping capacity:
  - 300 Sputter Ion Pumps
  - 50 Turbo Pumps
  - 30 NEG Pumps (and increasing…)
  - 23 permanently operated roughing pumps
- 150 gate valves

SASE2 offset mirror chambers in XTD6

beamlines

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The photon beamline vacuum system of the European XFEL

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Keywords: photon beamlines; vacuum; beam transport system; XFEL.

The photon beamline vacuum system of the European X-ray Free-Electron Laser Facility (European XFEL) is described. The ultra-large, in total more than 3 km-long, fan-like vacuum system, consisting of three photon beamlines is an essential part of the photon beam transport. It is located between the accelerator vacuum system and the scientific instruments. The main focus of the design was on the efficiency, reliability and robustness of the entire system to ensure the retention of beam properties and the operation of the X-ray optics and X-ray photon diagnostics components. Installation started in late 2014, the first of the three beamline vacuum systems was commissioned in spring 2017, and the last one was operational in mid-2018. The present state and experience from the first years of operation are outlined.

1. Introduction

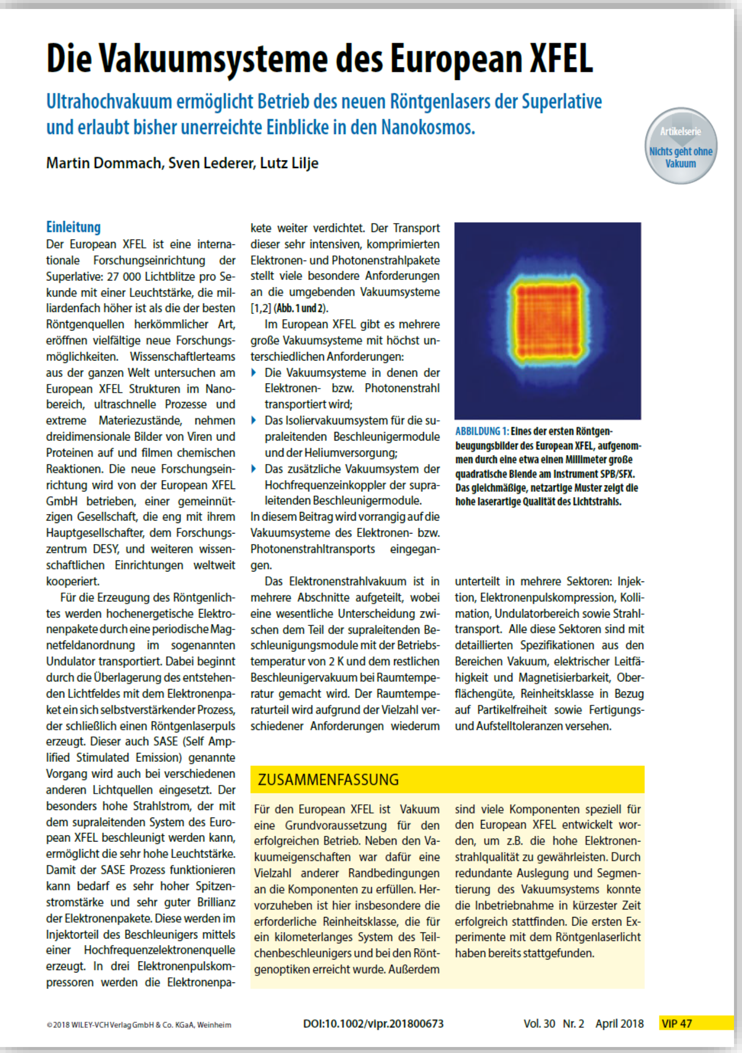
The European XFEL is a hard X-ray free-electron laser (X-ray FEL) with MHz repetition rate that started operation in April 2017 (Altarelli *et al.*, 2006; Decking *et al.*, 2020). The X-ray beam is delivered to the scientific instruments, which are located in the experiment hall at the end of the underground tunnels (Tschentscher *et al.*, 2017). Up to three instruments are located on each of the three photon beamlines.

The photon vacuum beamlines are designed for ultrahigh-vacuum (UHV) conditions with an average pressure lower than 1×10^{-7} mbar and a helium leak tightness of 1×10^{-10} mbar L s^{-1}. A horizontal separation of 1.4 m is required for the vacuum pipes close to the end of the tunnel to have enough space for the scientific instruments in the adjacent experiment hall. At the hard X-ray beamlines, this leads to long vacuum pipe sections to bridge the distance of about 550 m between distribution mirror and instruments, as the deflecting angles are very small. The above-mentioned X-ray mirrors as well as other state-of-the-art X-ray optics (Sinn *et al.*, 2019) are very sensitive to hydrocarbon contamination and dust particles on the optical surfaces. As a bake-out of the entire vacuum system was considered too laborious, all components built into the vacuum beamline were specially cleaned before installation, to remove hydrocarbon-containing residuals from the manufacturing process. Components used in close proximity to (30 m before and after) mirrors and gratings are prepared and installed in cleanrooms to avoid particle contamination on the inner surfaces.

Access to the tunnels is usually limited to two long maintenance periods per year for more extensive interventions; therefore, we have placed special emphasis on the high availability, reliability and serviceability of the system. Wher-

J. Synchrotron Rad. (2021). **28**, 1229–1236 https://doi.org/10.1107/S1600577521005154 1229

https://onlinelibrary.wiley.com/iucr/doi/10.1107/S1600577521005154



Die Vakuumsysteme des European XFEL

Ultrahochvakuum ermöglicht Betrieb des neuen Röntgenlasers der Superlative und erlaubt bisher unerreichte Einblicke in den Nanokosmos.

Artikelserie Nichts geht ohne Vakuum

Martin Dommach, Sven Lederer, Lutz Lilje

Einleitung

Der European XFEL ist eine internationale Forschungseinrichtung der Superlative: 27 000 Lichtblitze pro Sekunde mit einer Leuchtstärke, die milliardenfach höher ist als die der besten Röntgenquellen herkömmlicher Art, eröffnen vielfältige neue Forschungsmöglichkeiten. Wissenschaftlerteams aus der ganzen Welt untersuchen am European XFEL Strukturen im Nanobereich, ultraschnelle Prozesse und extreme Materiezustände, nehmen dreidimensionale Bilder von Viren und Proteinen auf und filmen chemischen Reaktionen. Die neue Forschungseinrichtung wird von der European XFEL GmbH betrieben, einer gemeinnützigen Gesellschaft, die eng mit ihrem Hauptgesellschafter, dem Forschungszentrum DESY, und weiteren wissenschaftlichen Einrichtungen weltweit kooperiert.

Für die Erzeugung des Röntgenlichtes werden hochenergetische Elektronenpakete durch eine periodische Magnetfeldanordnung im sogenannten Undulator transportiert. Dabei beginnt durch die Überlagerung des entstehenden Lichtfeldes mit dem Elektronenpaket ein sich selbstverstärkender Prozess, der schließlich einen Röntgenlaserpuls erzeugt. Dieser auch SASE (Self Amplified Stimulated Emission) genannte Vorgang wird auch bei verschiedenen anderen Lichtquellen eingesetzt. Der besonders hohe Strahlstrom, der mit dem supraleitenden System des European XFEL beschleunigt werden kann, ermöglicht die sehr hohe Leuchtstärke. Damit der SASE Prozess funktionieren kann bedarf es sehr hoher Spitzenstromstärke und sehr guter Brillianz der Elektronenpakete. Diese werden im Injektorteil des Beschleunigers mittels einer Hochfrequenzelektronenquelle erzeugt. In drei Elektronenpulskompressoren werden die Elektronenpakete weiter verdichtet. Der Transport dieser sehr intensiven, komprimierten Elektronen- und Photonenstrahlpakete stellt viele besondere Anforderungen an die umgebenden Vakuumsysteme [1,2] (**Abb. 1 und 2**).

Im European XFEL gibt es mehrere große Vakuumsysteme mit höchst unterschiedlichen Anforderungen:

- Die Vakuumsysteme in denen der Elektronen- bzw. Photonenstrahl transportiert wird;
- Das Isoliervakuumsystem für die supraleitenden Beschleunigermodule und der Heliumversorgung;
- Das zusätzliche Vakuumsystem der Hochfrequenzeinkoppler der supraleitenden Beschleunigermodule.

In diesem Beitrag wird vorrangig auf die Vakuumsysteme des Elektronen- bzw. Photonenstrahltransports eingegangen.

Das Elektronenstrahlvakuum ist in mehrere Abschnitte aufgeteilt, wobei eine wesentliche Unterscheidung zwischen dem Teil der supraleitenden Beschleunigungsmodule mit der Betriebstemperatur von 2 K und dem restlichen Beschleunigervakuum bei Raumtemperatur gemacht wird. Der Raumtemperaturteil wird aufgrund der Vielzahl verschiedener Anforderungen wiederum unterteilt in mehrere Sektoren: Injektion, Elektronenpulskompression, Kollimation, Undulatorbereich sowie Strahltransport. Alle diese Sektoren sind mit detaillierten Spezifikationen aus den Bereichen Vakuum, elektrischer Leitfähigkeit und Magnetisierbarkeit, Oberflächengüte, Reinheitsklasse in Bezug auf Partikelfreiheit sowie Fertigungs- und Aufstelltoleranzen versehen.

ABBILDUNG 1: Eines der ersten Röntgenbeugungsbilder des European XFEL, aufgenommen durch eine etwa einen Millimeter große quadratische Blende am Instrument SPB/SFX. Das gleichmäßige, netzartige Muster zeigt die hohe laserartige Qualität des Lichtstrahls.

ZUSAMMENFASSUNG

Für den European XFEL ist Vakuum eine Grundvoraussetzung für den erfolgreichen Betrieb. Neben den Vakuumeigenschaften war dafür eine Vielzahl anderer Randbedingungen an die Komponenten zu erfüllen. Hervorzuheben ist hier insbesondere die erforderliche Reinheitsklasse, die für ein kilometerlanges System des Teilchenbeschleunigers und bei den Röntgenoptiken erreicht wurde. Außerdem sind viele Komponenten speziell für den European XFEL entwickelt worden, um z.B. die hohe Elektronenstrahlqualität zu gewährleisten. Durch redundante Auslegung und Segmentierung des Vakuumsystems konnte die Inbetriebnahme in kürzester Zeit erfolgreich stattfinden. Die ersten Experimente mit dem Röntgenlaserlicht haben bereits stattgefunden.

DOI:10.1002/vipr.201800673 Vol. 30 Nr. 2 April 2018 VIP 47

https://onlinelibrary.wiley.com/doi/full/10.1002/vipr.201800673

Transitioning from construction to operation…

2017 to 2019

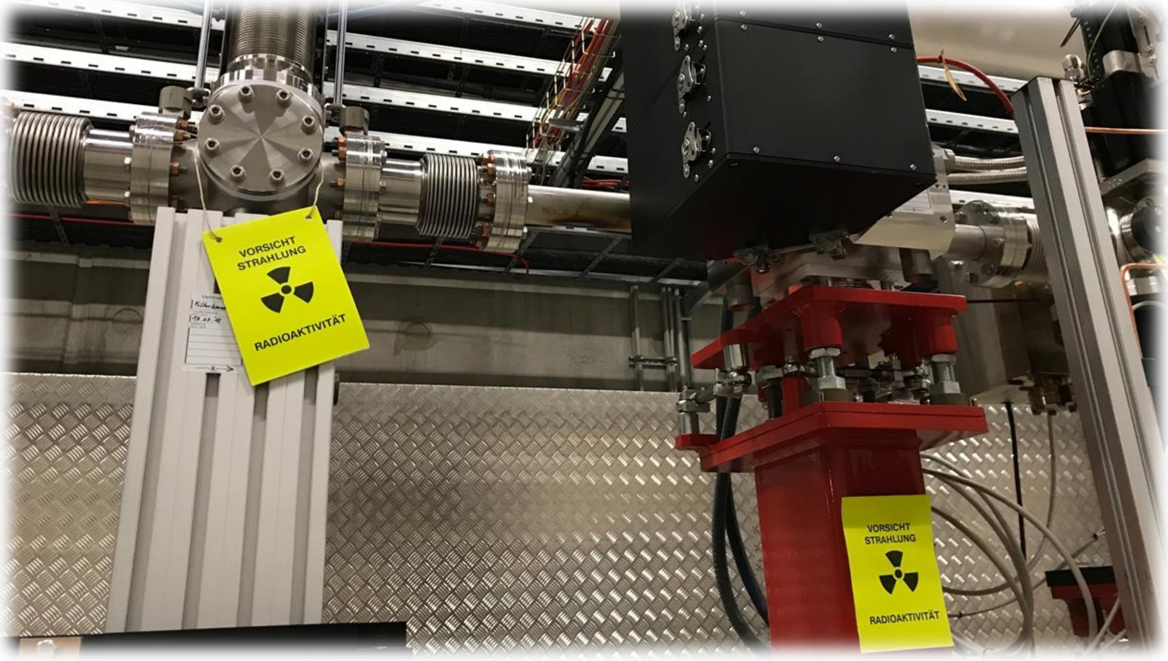
First light in 2017. First simultaneous lasing in 2018.

Some start-up issues & adjustments

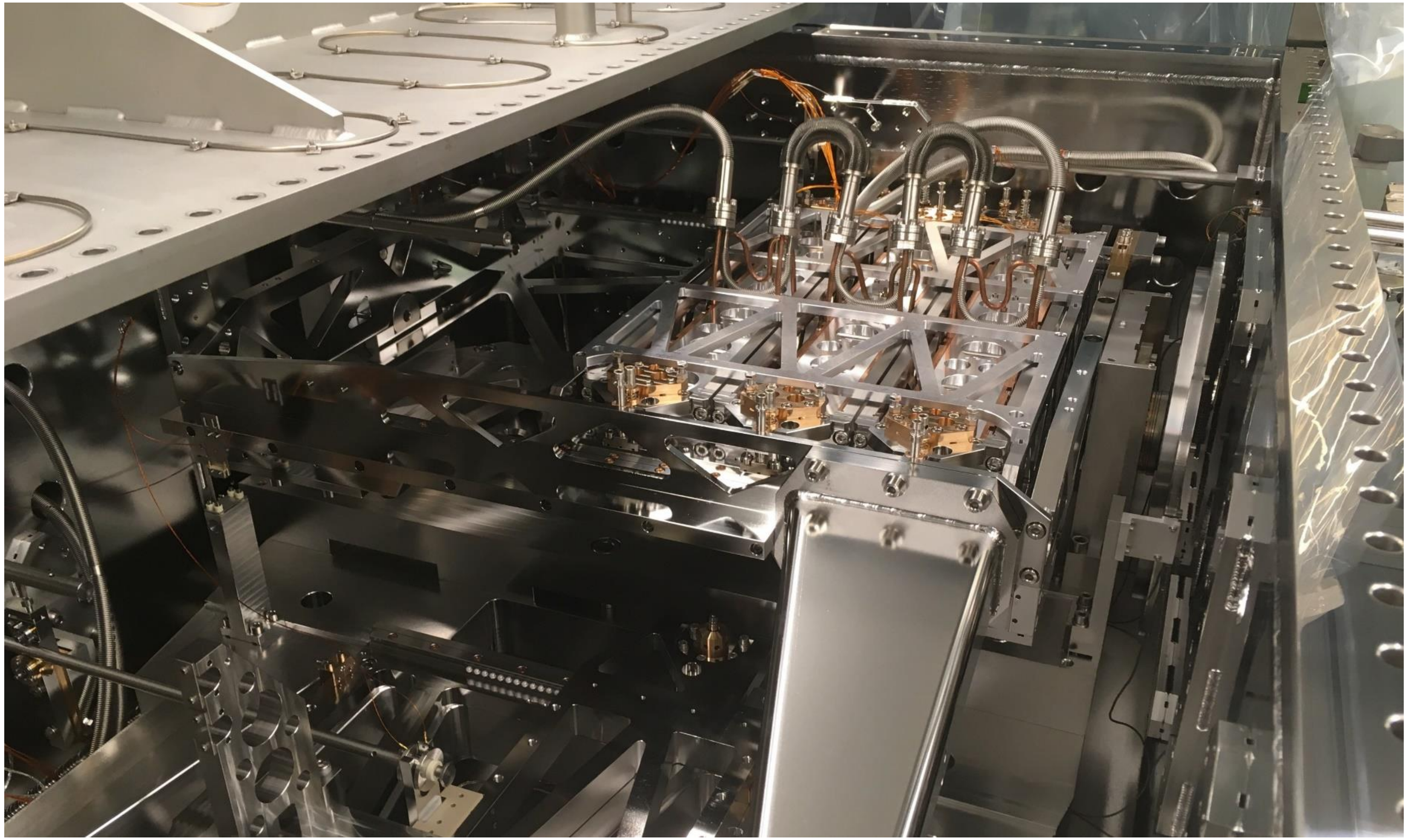
- Adjustments on interlock definitions.
- Unveiling some system complexities (i.e. impact of power glitches on vacuum systems).
- High tasks loads: operation of SA1 & SA3 beamlines and simultaneous commissioning of SASE2.
- “Last minute” hardware modifications on some electronic components.
- Consolidation of sector gauges installation programme.
- Increased support for experimental stations/instruments.

Testing an e-beam welder….

- September 2017: E-beam “welding“ @T4D
  - Malfunction of dipole magnet, beam was steered downwards by safety magnets
  - Leak just right before SASE3 V0
  - Two sections of the photon vacuum were vented



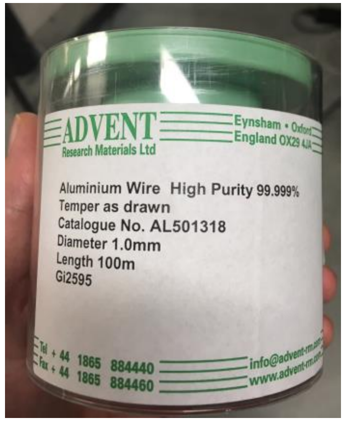
Upgrades on large and complex beamline components

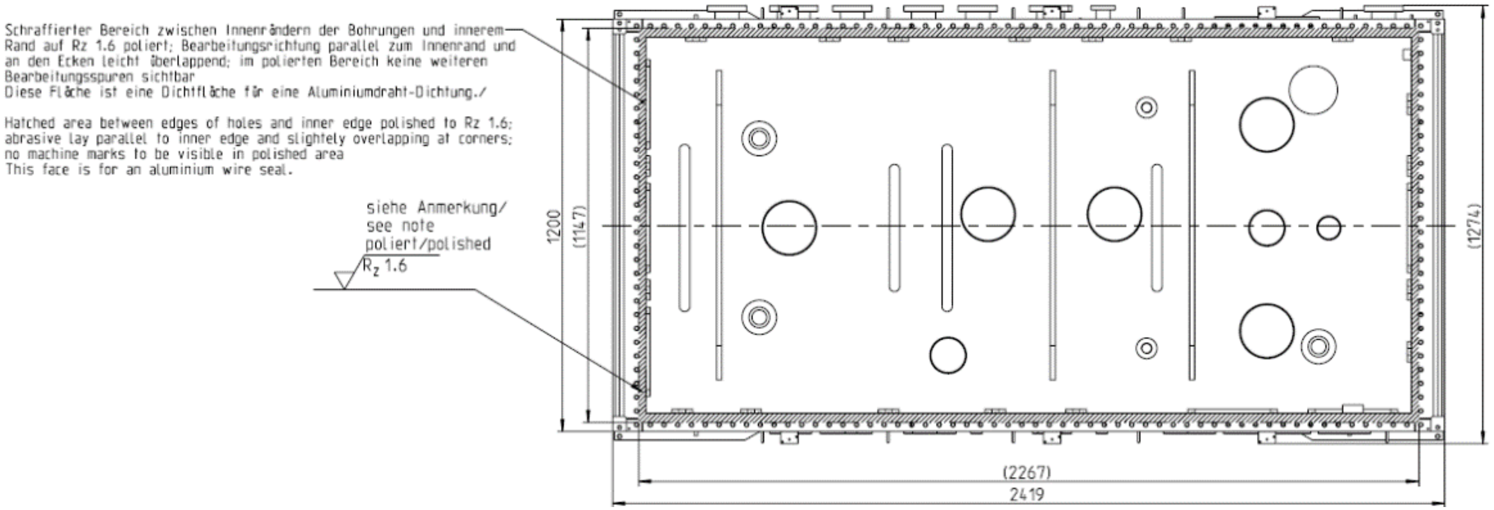


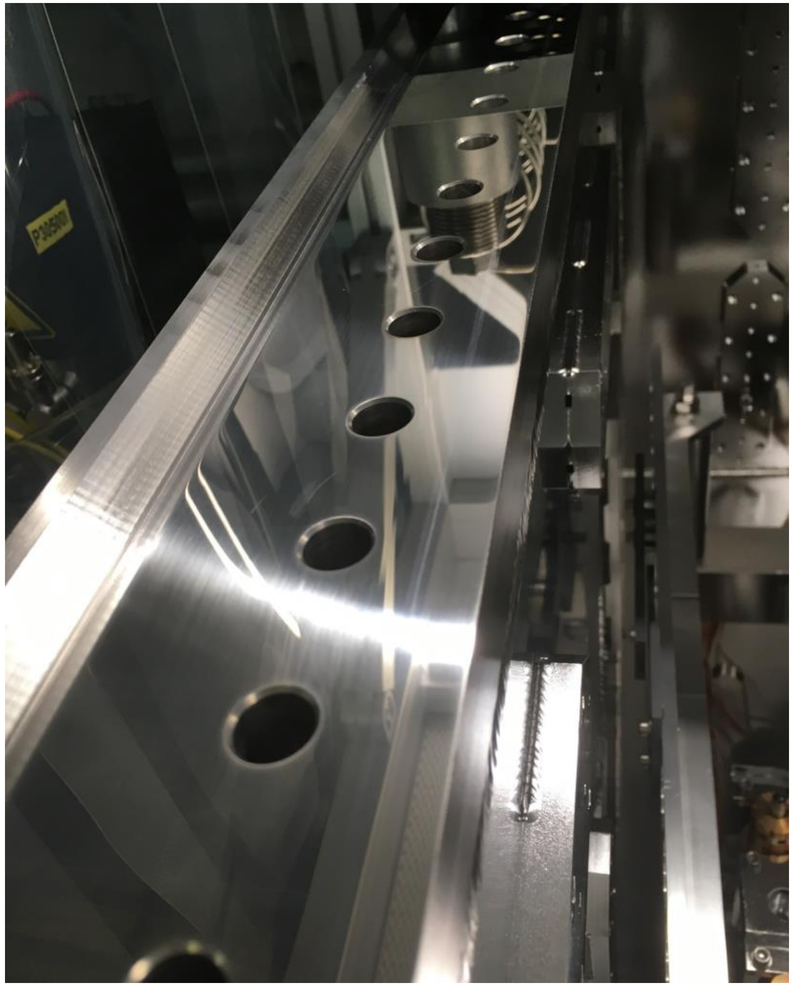
Referenced materials: courtesy of Daniele La Civita [Mech. Engineering]

Upgrades on large and complex beamline components

- Non-conventional Al-wire seal.
- Very large chamber.
- Mastering the sealing procedure resulted almost as an art.
- Now translated in documented protocol.







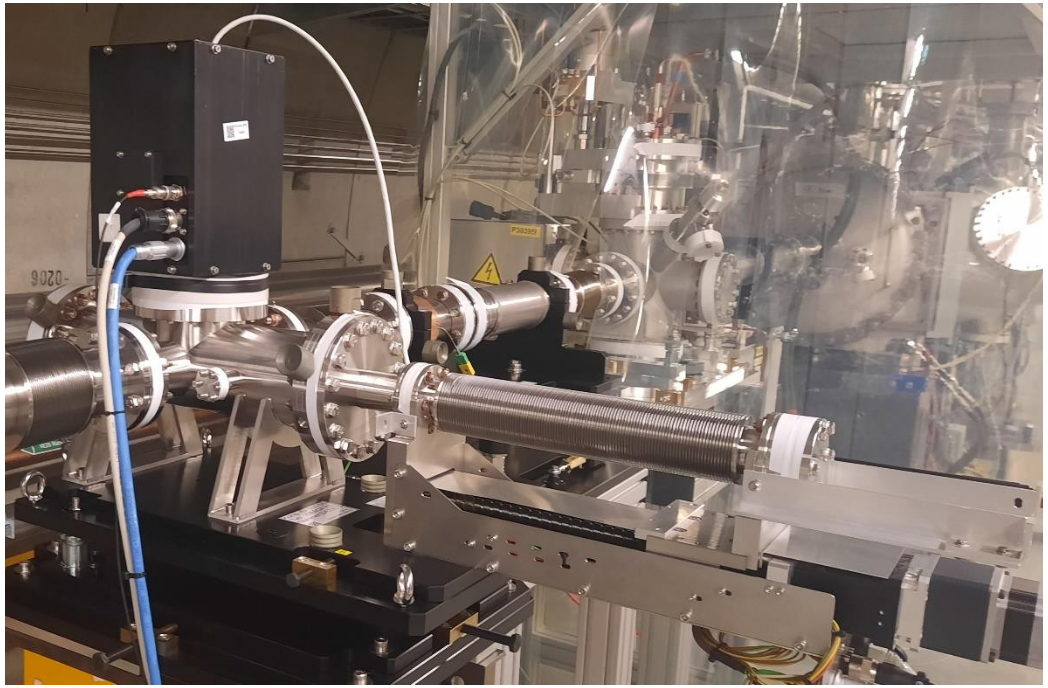
Referenced materials: courtesy of Daniele La Civita [Mech. Engineering]

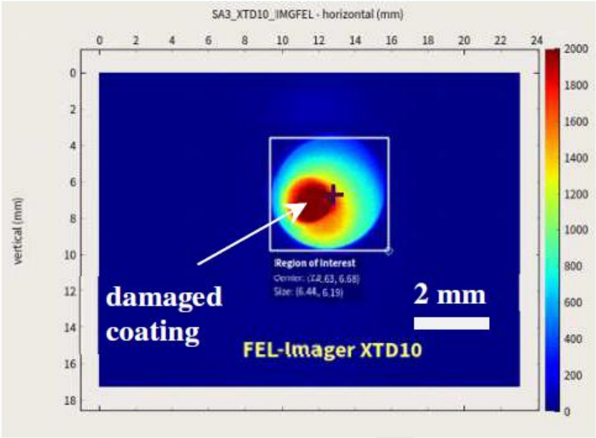
The „peaceful“ years…

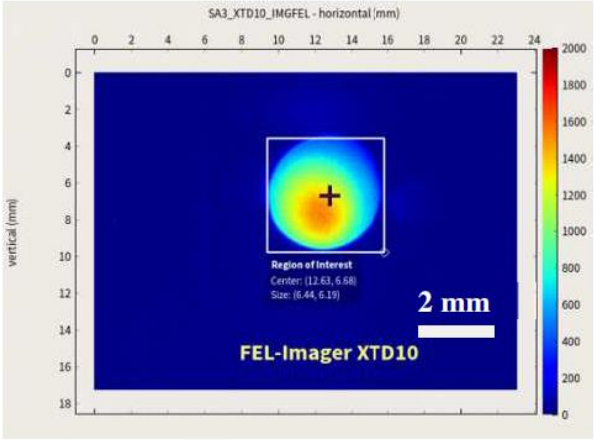
…despite COVID crisis.

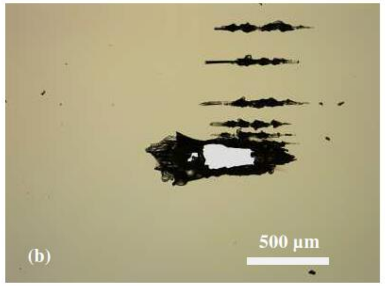
From 2019 to 2022

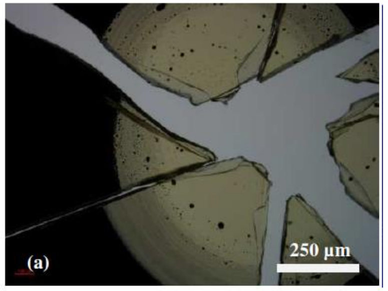
First (and recurrent) replacement of damaged imager screens

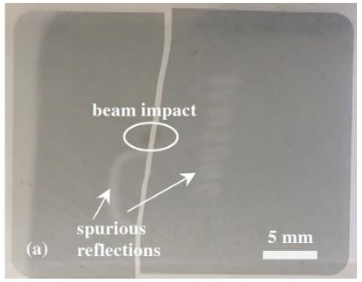










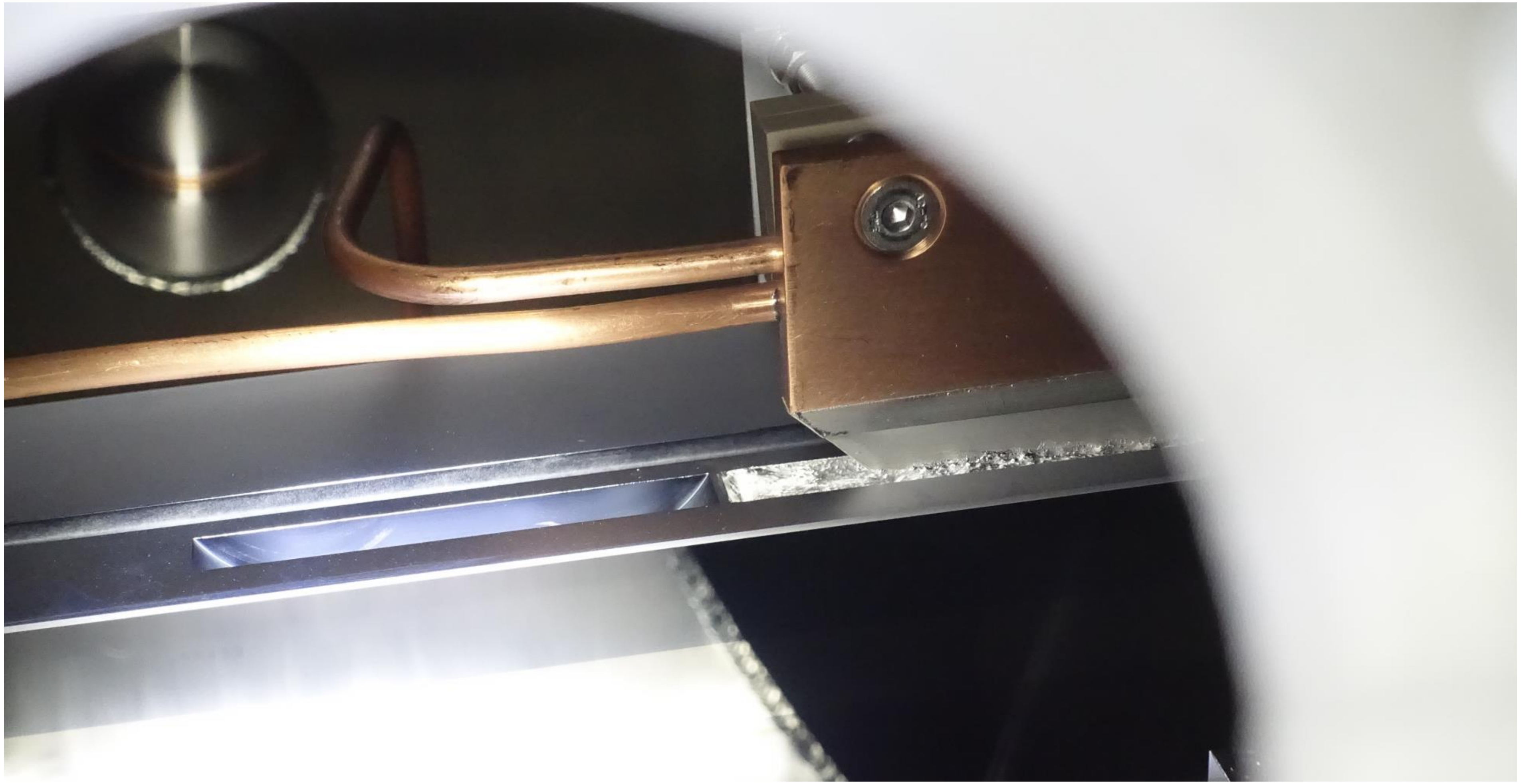


Andreas Koch, Jan Grünert, "Radiation hardness of luminescent screens under FEL radiation," Proc. SPIE 12578, Optics Damage and Materials Processing by EUV/X-ray Radiation (XDam8), 1257803 (6 June 2023); doi: 10.1117/12.2665629

Event: SPIE Optics + Optoelectronics, 2023, Prague, Czech Republic

Referenced materials: courtesy of Andreas Koch [X-Ray Diagnostics]

Eutectic cooling of Mirrors – GaInSn as heat transfer interface.



Referenced materials: courtesy of Antje Trapp and Idoia Freijo-Martín [X-Ray Optics]

Eutectic cooling of Mirrors – Required preconditioning.

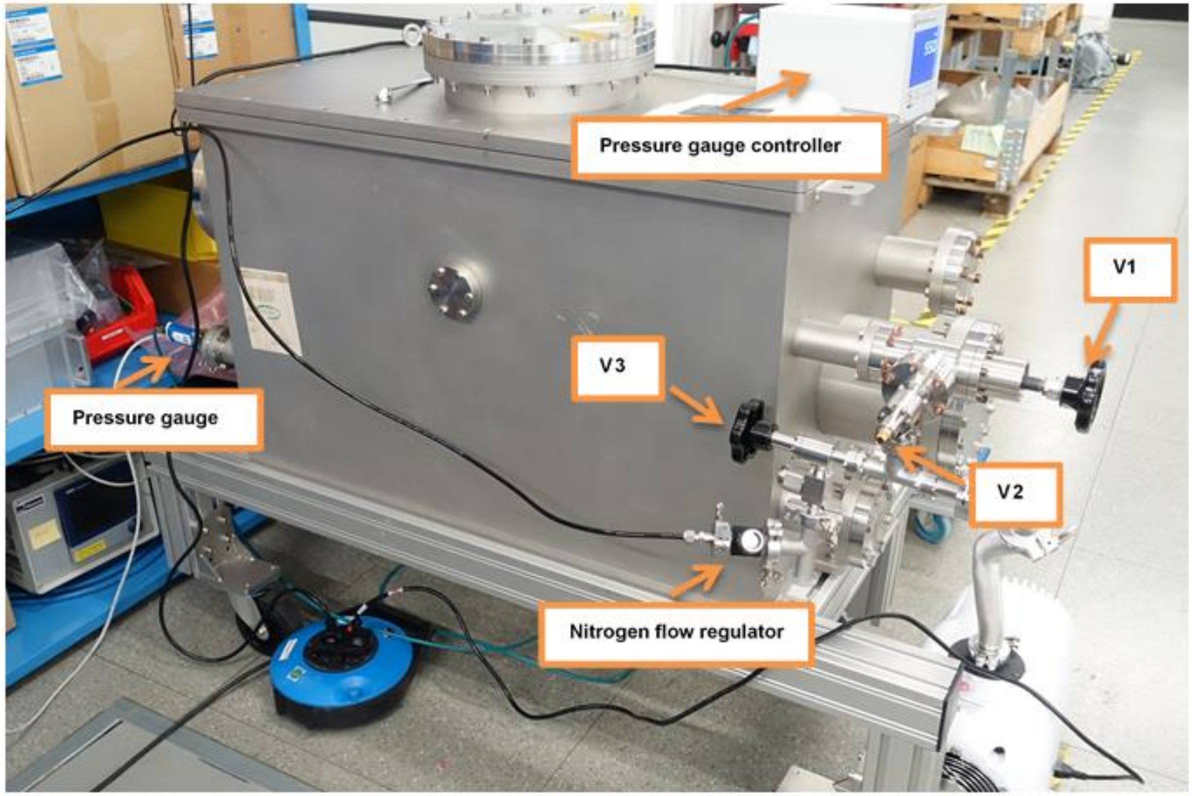
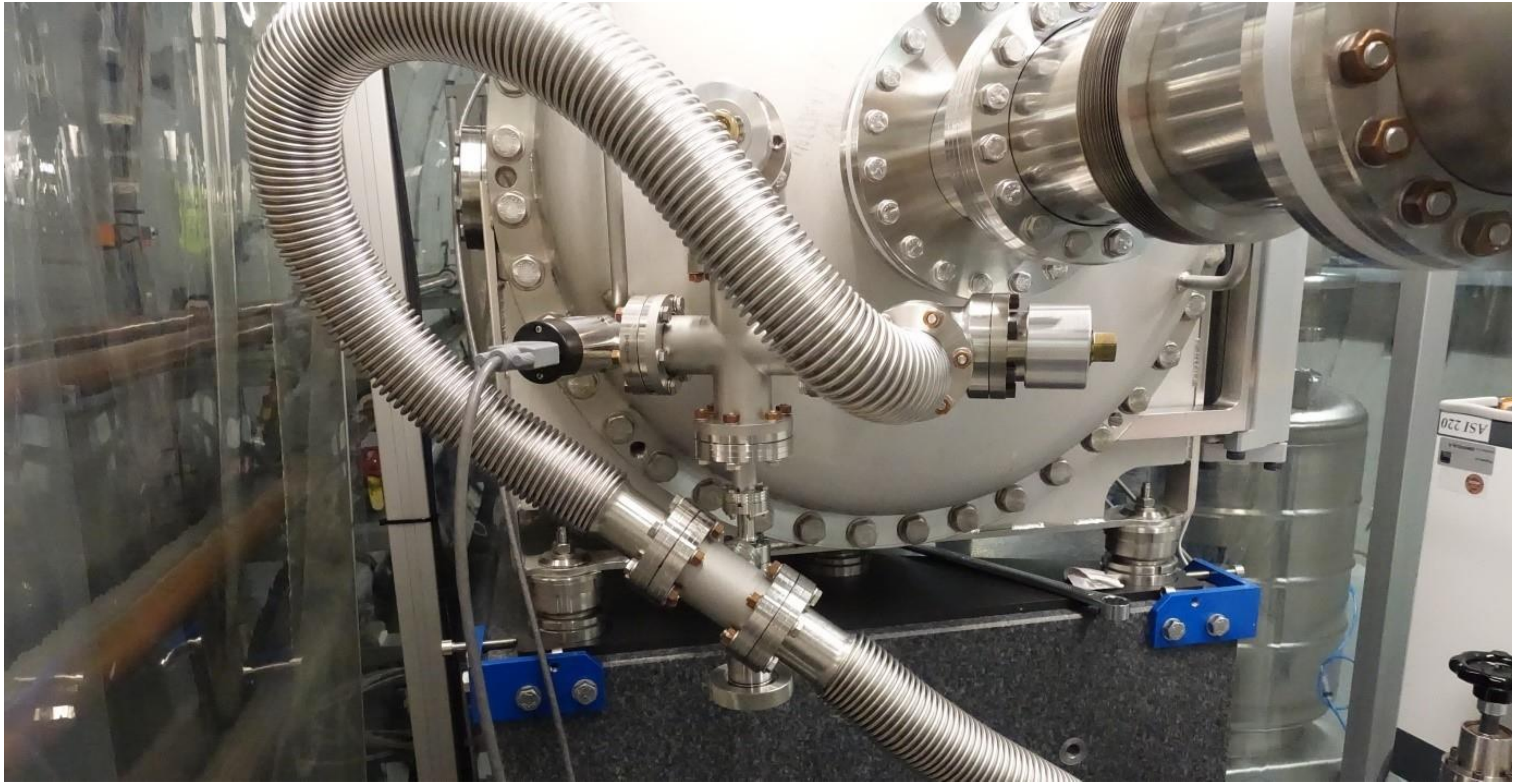


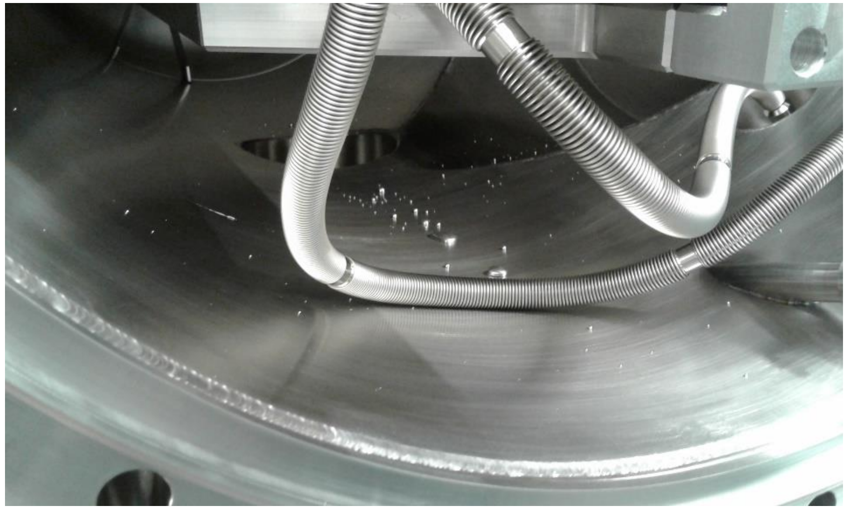
Figure 1: Pre-conditioning chamber set-up.V1 is the chamber valve, V2 is the scroll-pump valve. V3 is the venting valve.

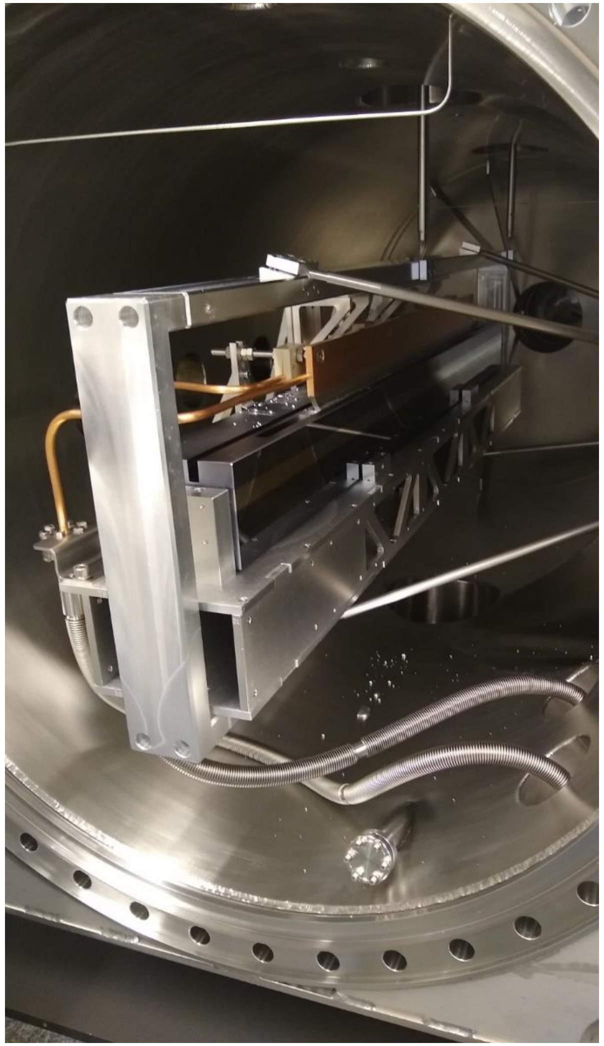
Eutectic cooling of Mirrors – Very slow pump-down

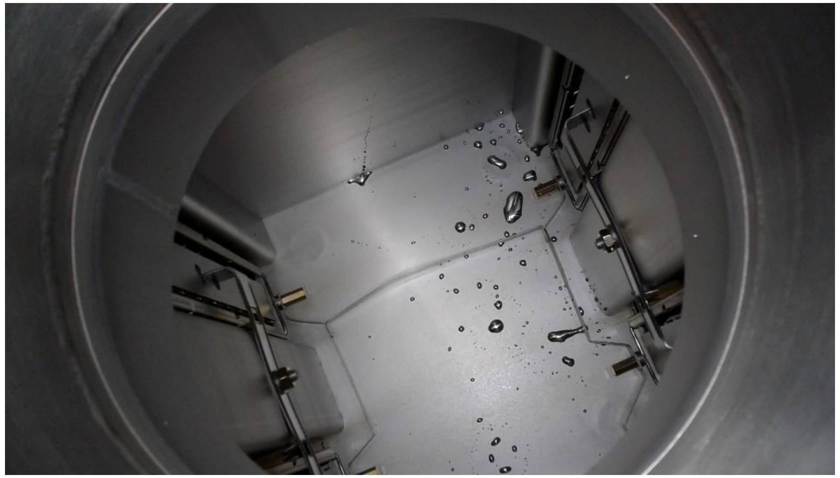


Referenced materials: courtesy of Antje Trapp and Idoia Freijo-Martín [X-Ray Optics]

Eutectic cooling of Mirrors – Accidental spillage





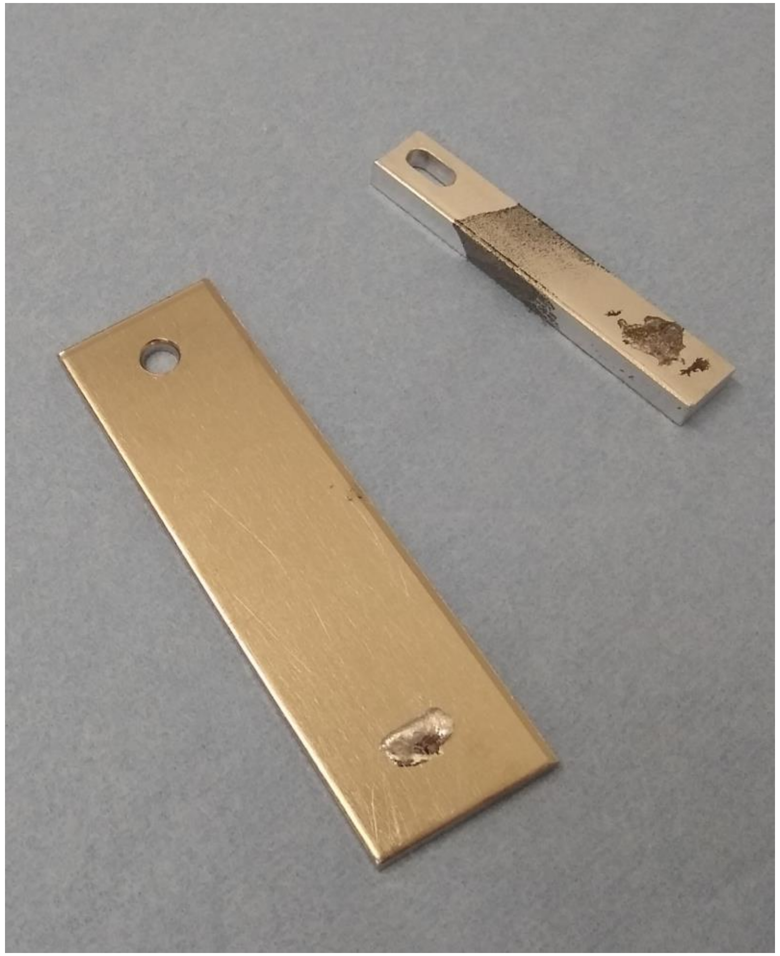


Referenced materials: courtesy of Antje Trapp and Idoia Freijo-Martín [X-Ray Optics]

Eutectic cooling of Mirrors – Overview

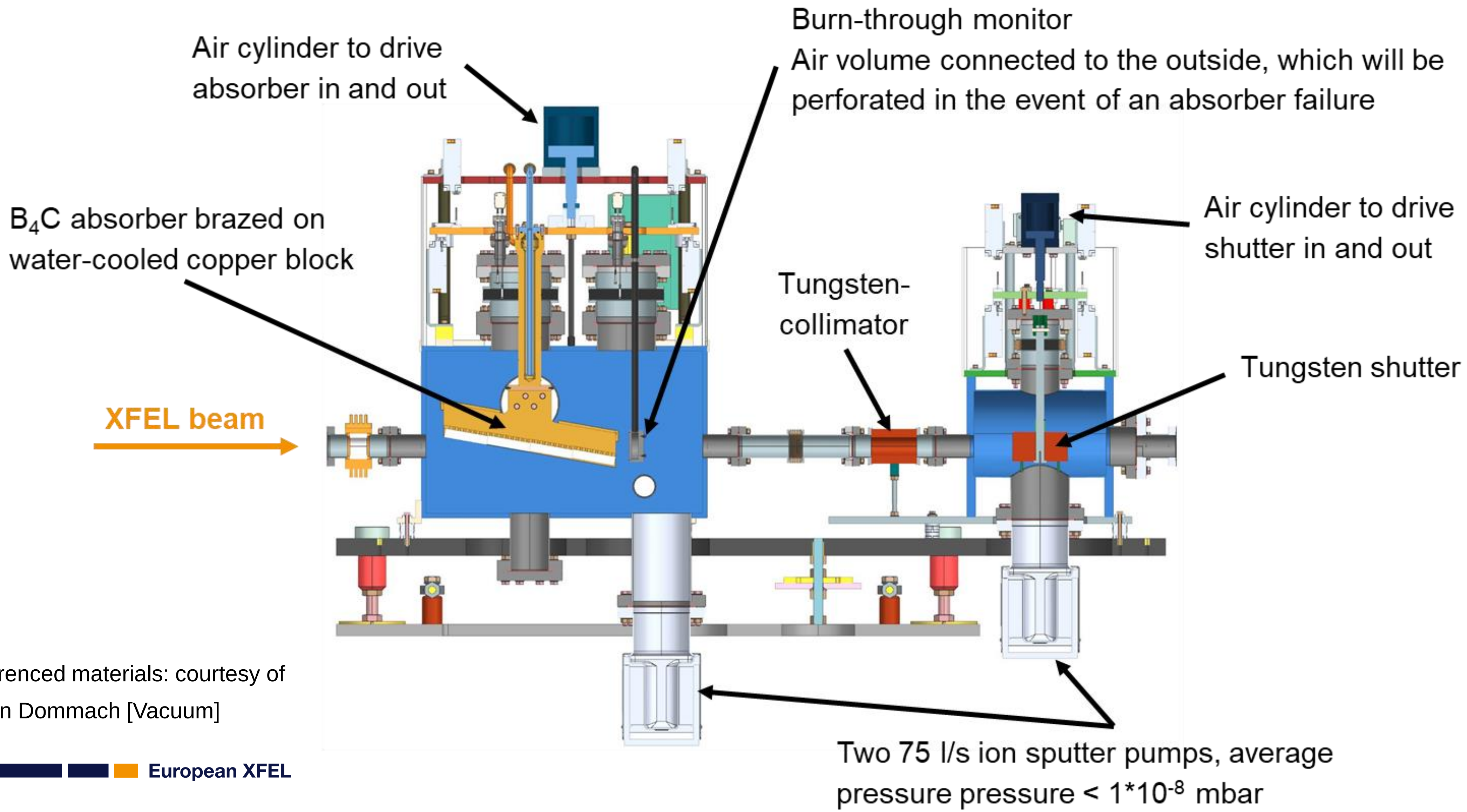
Some lessons learned

- Hazardous substance → lots of safety measures + special rules for disposal
  - Get in touch with experts
- High surface tension → does not stick to surfaces easily
  - Surface structure is important
  - Wetting of surfaces
- Gas bubbles → may release and pop in vacuum
  - Pre-condition liquid in vacuum
  - Avoid to stir
  - Very slow pump down
- Aggressive on aluminium → danger to your components
  - Nickel coating
- How do you clean it up???
  - Very tedious procedure



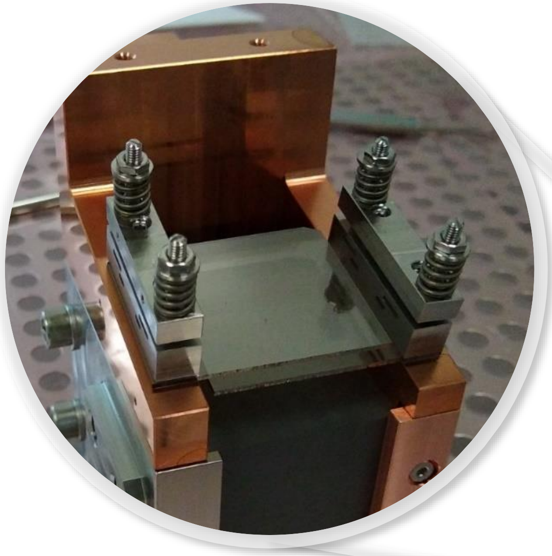
Referenced materials: courtesy of Antje Trapp and Idoia Freijo-Martín [X-Ray Optics]

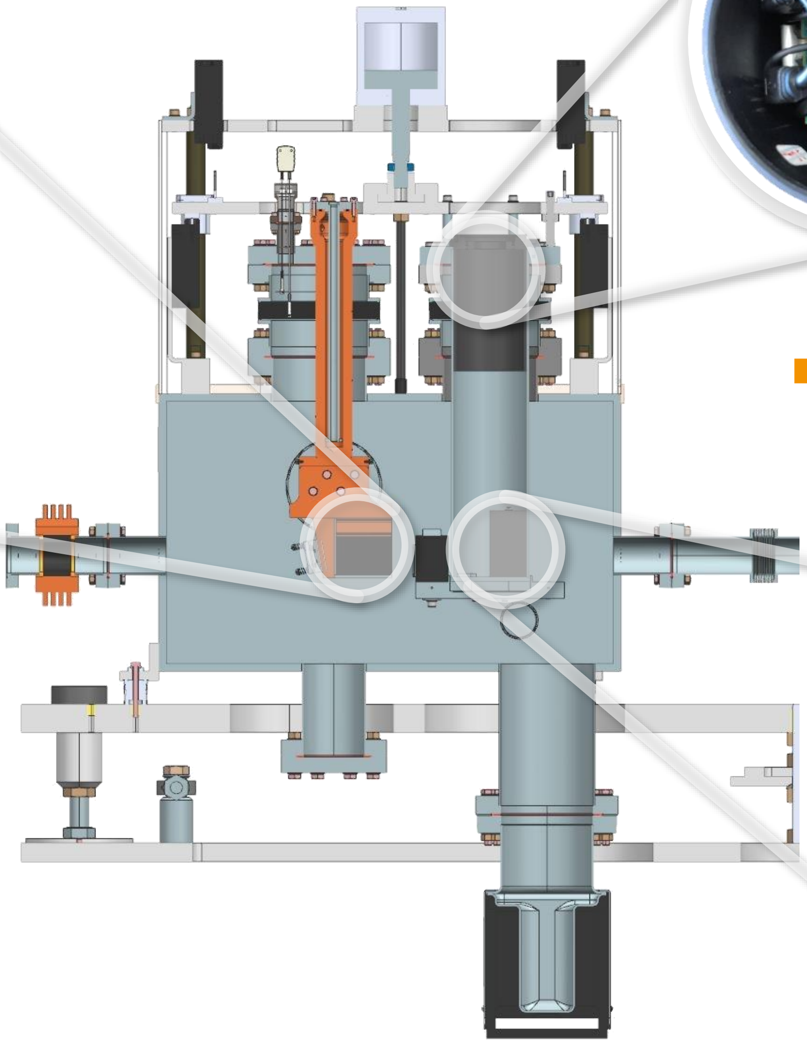
Front-end upgrade program

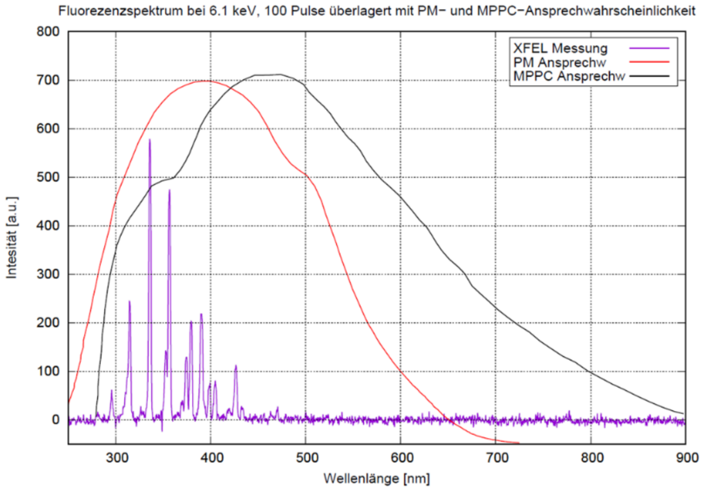


Referenced materials: courtesy of Martin Dommach [Vacuum]

Front-end upgrade program





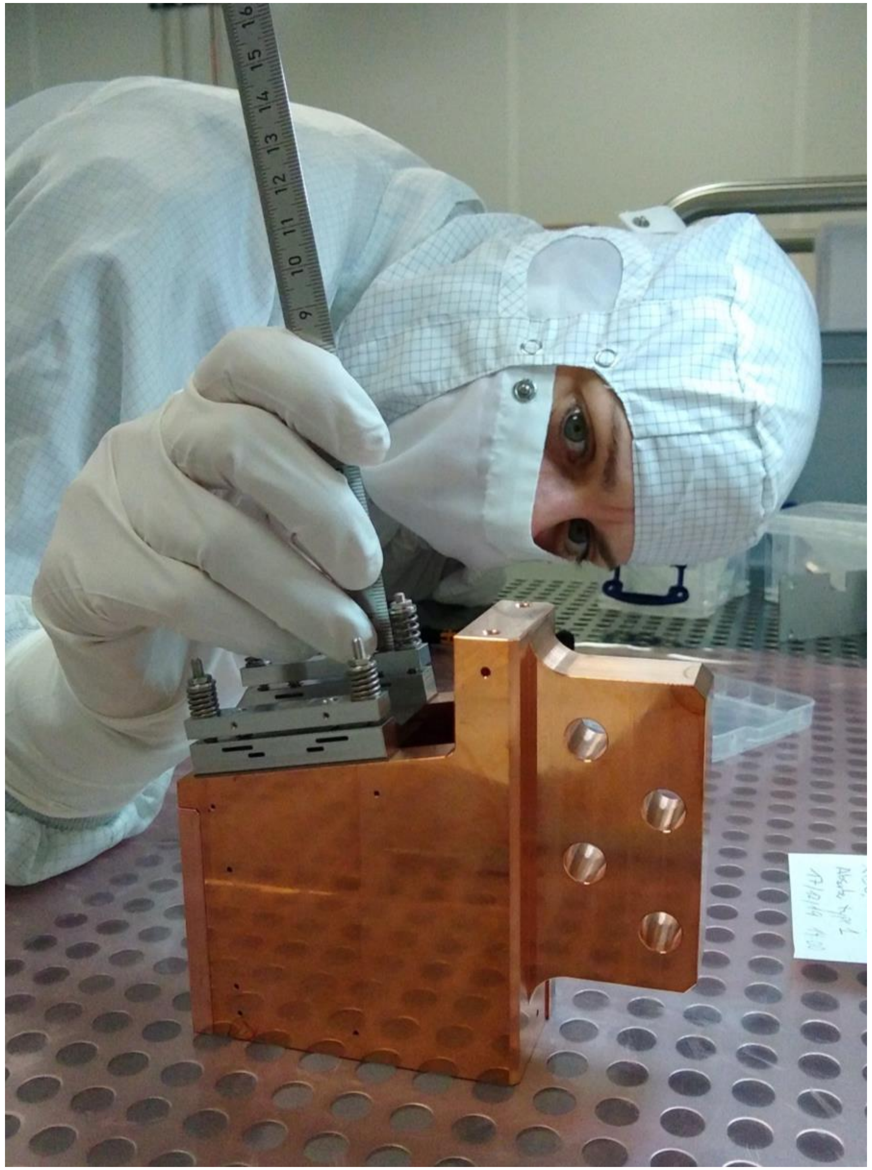


- **New burn-through detectors (DESY-D3):**
  - Redundancy concept (MPPC & PM)
  - Built-in LEDs for auto-diagnostic.

- **New absorber:**
  - 2 CVD diamond plates
    - ▶ 2 mm thick
    - ▶ Single side clamped
  - 60 mm B_4C block
  - Water cooled

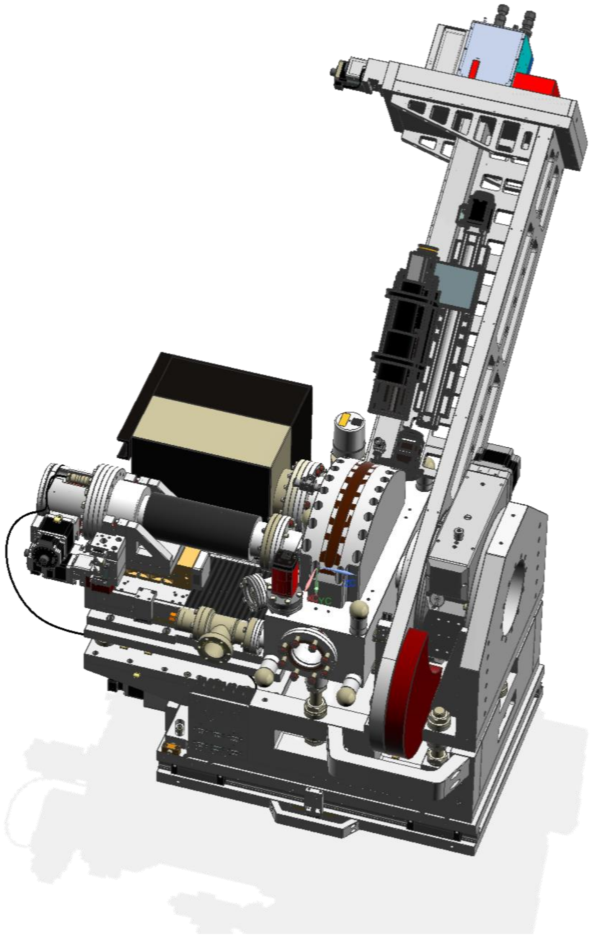
- **New burn-through system**
  - Pipe insert
  - B_4C block 35 mm (vacuum)
  - Graphite block 40 mm (air)

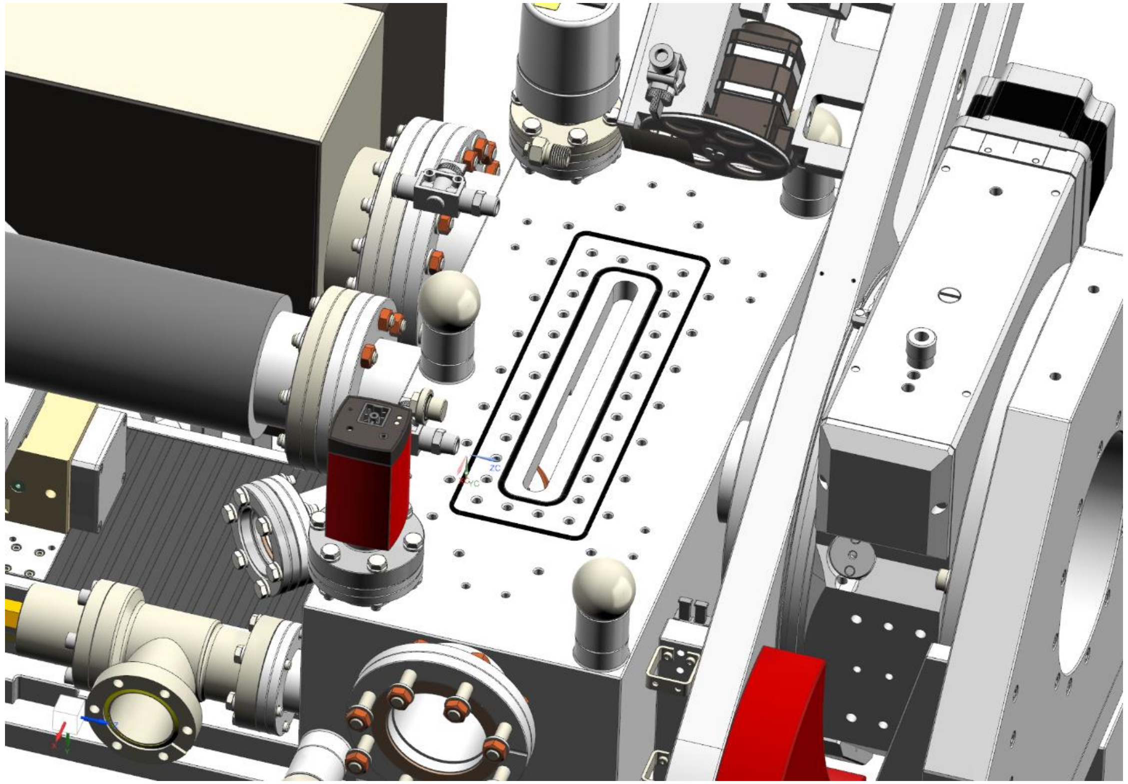
Front-end upgrade program

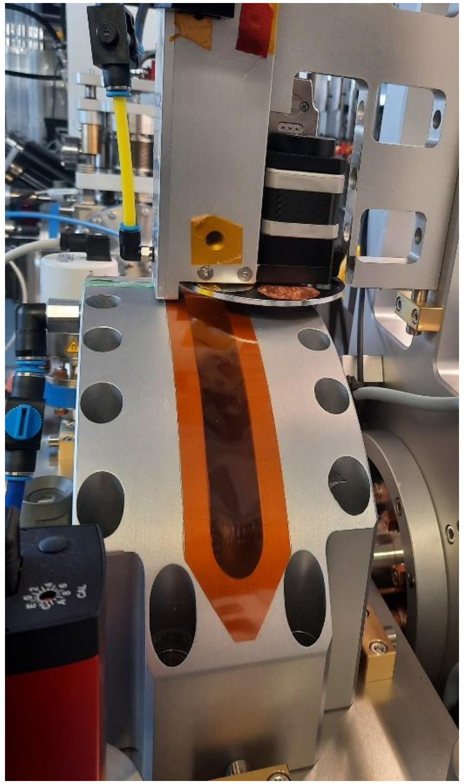


- From 3rd generation light source concept to XFEL-enabled version.
- 12 front-end absorbers modified during one winter maintenance period (5 weeks aprox.)
- 4 additional pre-absorbers installed nearby CRL systems to ensure safe operation of the shutters.
- Operation constrains on CRLs were lifted, all focussing options available (Only integrated beam power is restricted now to 40W).

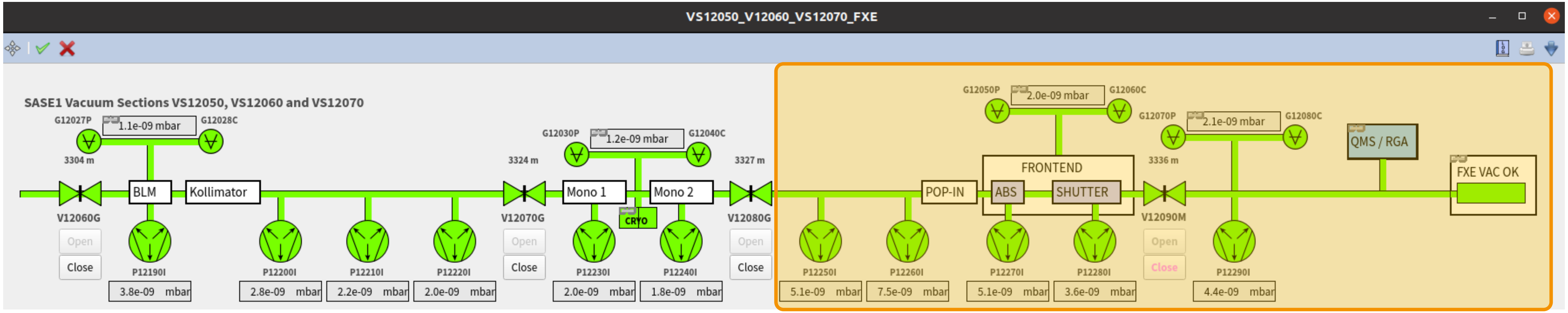
A somehow unexpected visitor: Helium from an experimental station.





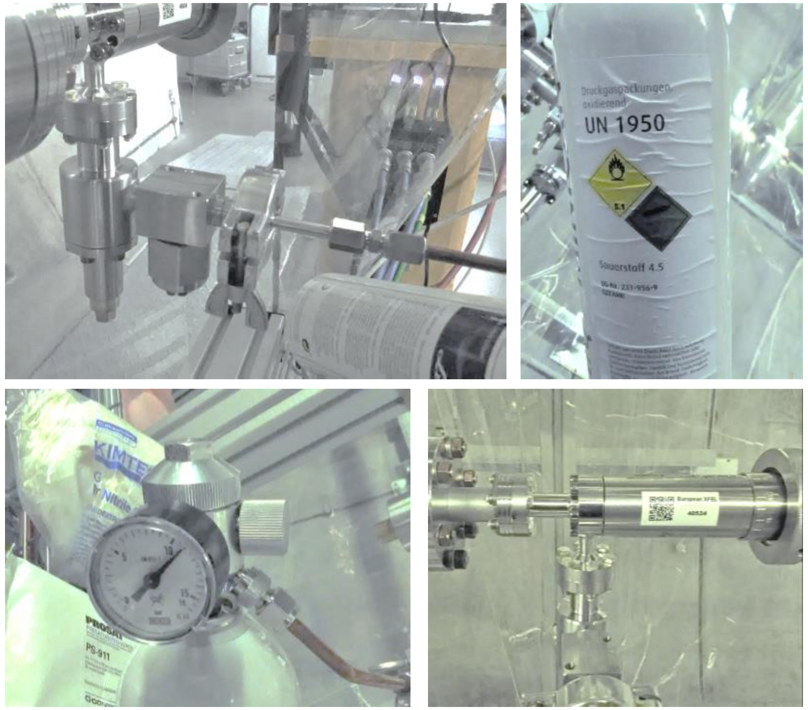


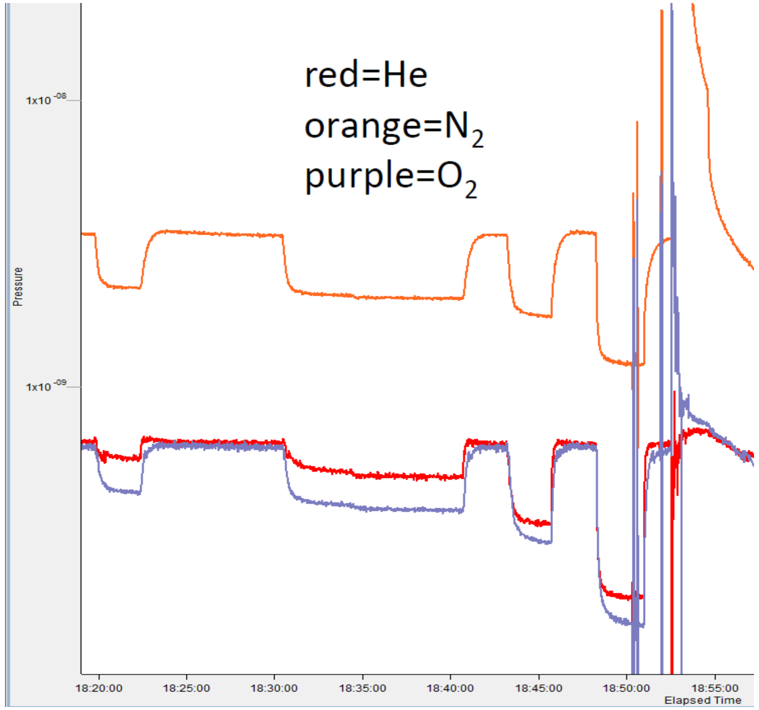
A somehow unexpected visitor: Helium from an experimental station.



- O-ring sealed Be-window.
- Dome volume backfilled with He-gas.
- First instablities observed at the instrument Ion pumps. Later affecting to tunnel beamline sector.

A somehow unexpected visitor: Helium from an experimental station.



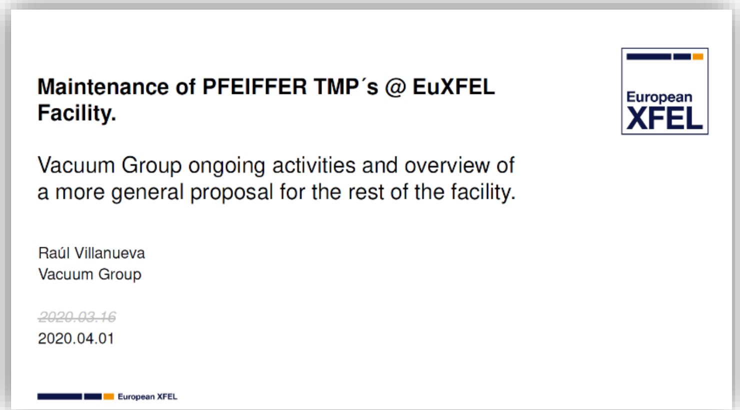


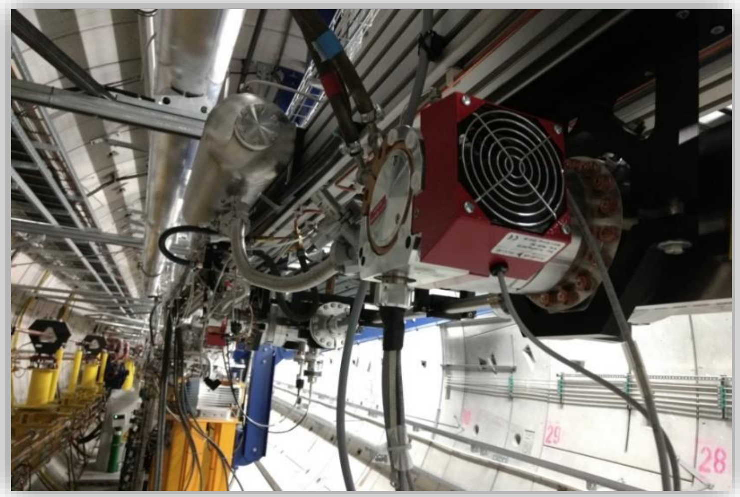
Procedure

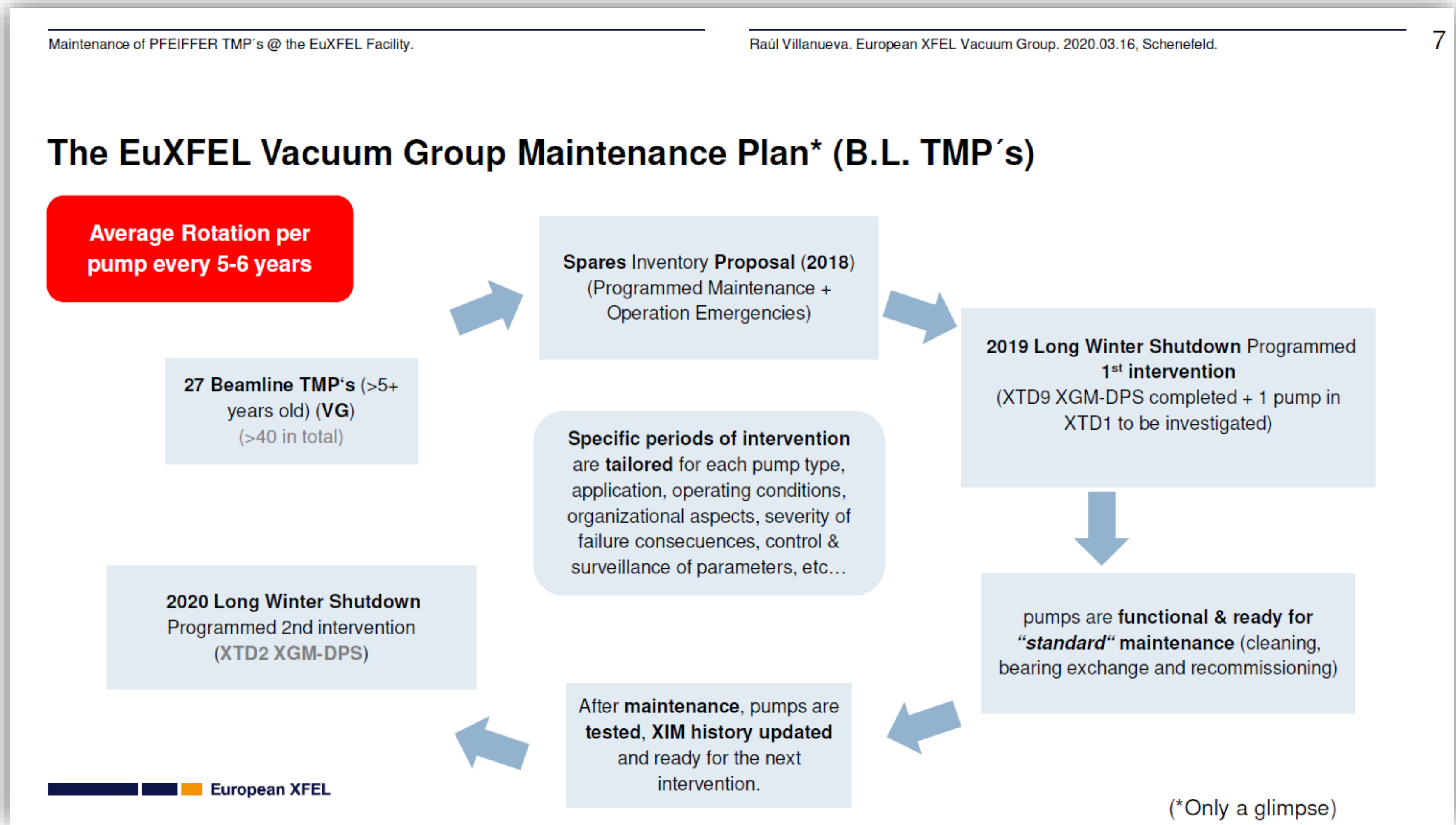
- Install ionpump, pumpcart and O_2-supply on chamber
- Purge with Oxygen up to 1e-2mbar, evacuate until 5e-6mbar
- Switch on ionpump with pumpcart running and ensure that pressure on ionpump stays beyond 1e-6mbar
- When pressure has stabilized keep pump runing for 5mins
- If more than one pump, do one after another
- Afterwards switch off pump(s) and bake pumps for 24hrs with pumpcart connected
- Do 5-6 cycles

Referenced materials: courtesy of Michaela Petrich [Vacuum]

Release of facility wide preventive maintenance programme for TMP`s and mechanical pumps







The first signs of maturity

From 2022 onwards

Power supplies on fast valves controllers

≈ 4,5 h.
Beamdown

Vacuum related problem in SASE3 / beam down in SA1+SA3
Effects: beam down in SA1 and SA3 since shortly after 20h.
Initial Analysis: The Fast Valve in SASE3 / XSDU2 closed and interlocked. SQS notified the PRC. VAC-OCD informed, DOC informed.
DOC, VAC-OCD and EEE working together to solve the issue. Conclusion towards 22h: the fast valve could not be opened from remote, probably a controller / hardware issue.

Physical repair: At 22h it was clear that an access was necessary. BKR was instructed to prepare a ZZ access.
PRC and VAC-OCD came onsite and accessed the tunnel together from XHE3 to XTD4 to XSDU2.
One of the two controllers of the Fast Valve was found dead. A fuse was blown as well.
One new crate was installed and some modules exchanged from the old to the new crate (see attachments # 1 and #2)

Repair completed by 0h15, out of tunnel by 0h25 and beam back to SASE1 and SASE3 at 0h32.
Root cause of this first-time failure of this controller will be investigated in the lab.
Radiation damage could be an issue since this controller is located in the most upstream photon system rack of SASE3, directly above the dump DU2.

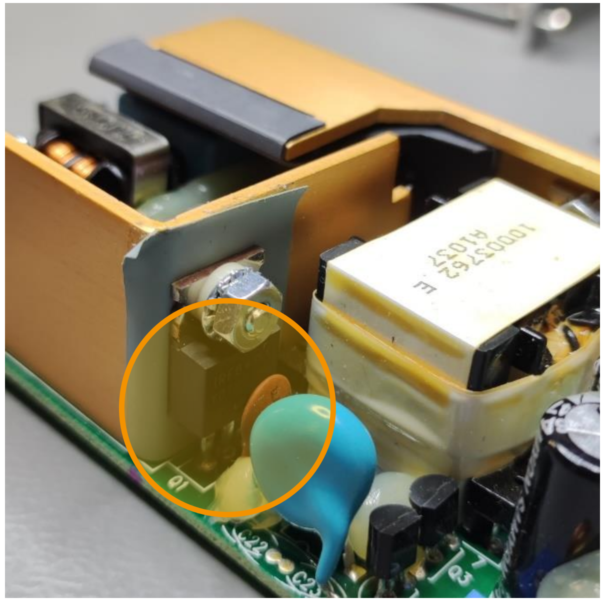
Total SA1+SA3 downtime due to this event: 20h05 to 00h32 = 4 hours 23 min
SASE2 was unaffected and continued to measure happily throughout this.

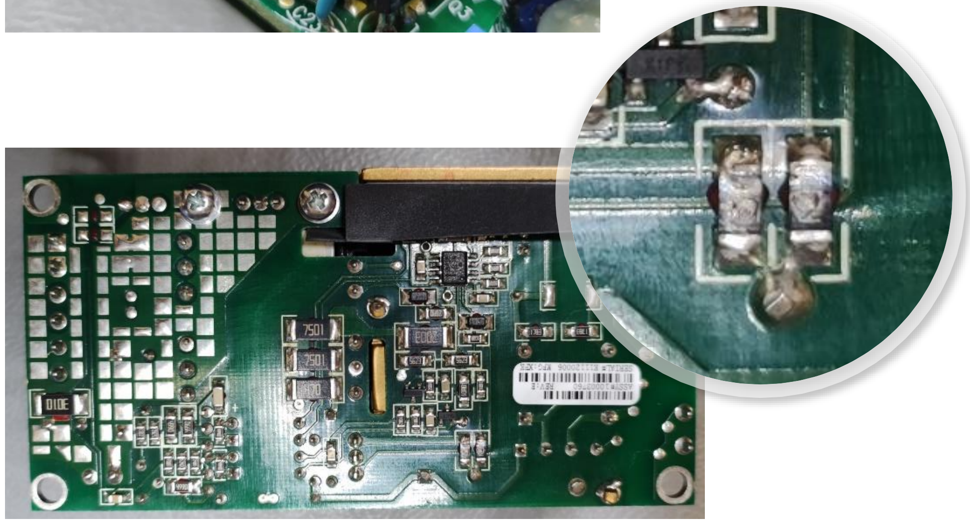
Total SA1+SA3 downtime due to this event: 20h05 to 00h32 = 4 hours 23 min
SASE2 was unaffected and continued to measure happily throughout this.

Referenced materials: courtesy of Benoit Rio [Vacuum]

Power supplies on fast valves controllers

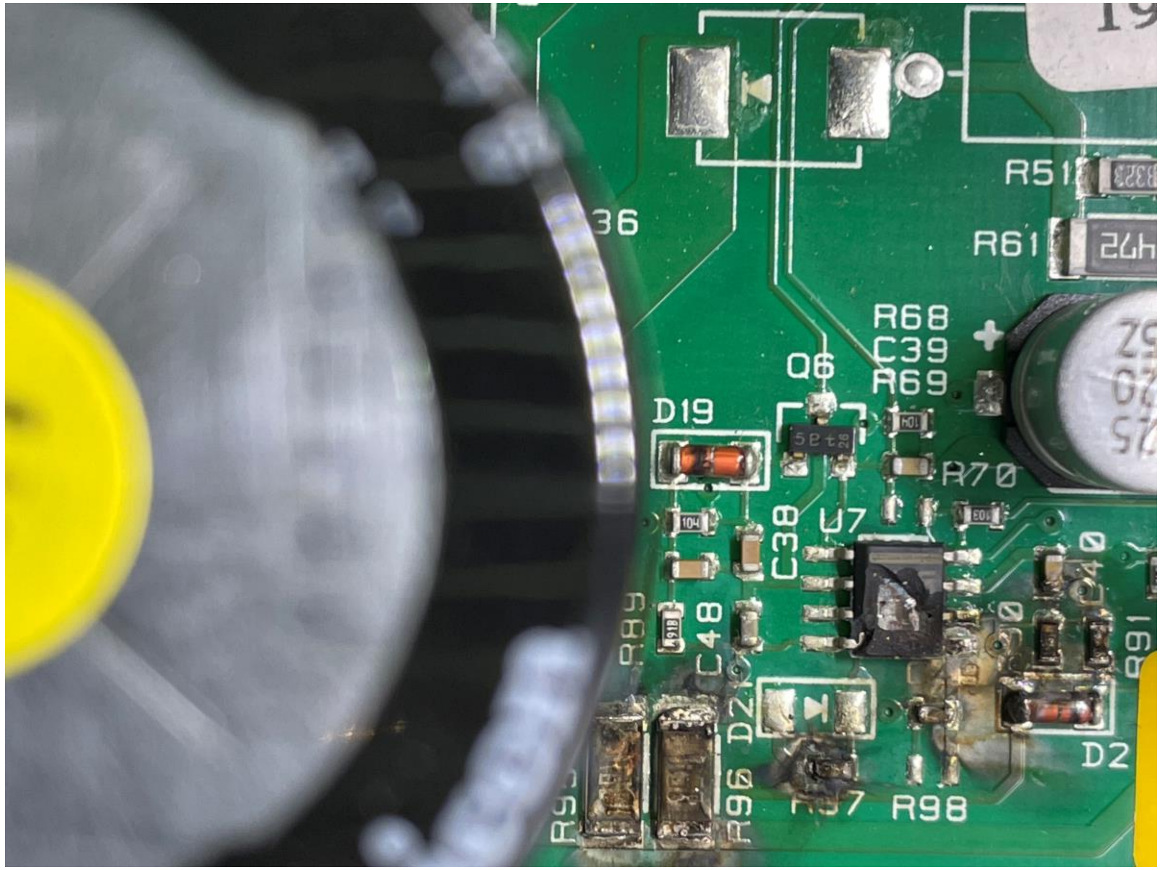
- Root cause is not completely clear.
- All affected controllers failing in a short term period.
- Preventive exchange of all power supplies
- Unexpensive action but with high impact on operation.





Referenced materials: courtesy of Benoit Rio [Vacuum]

Ion pump controllers



- Agilent 4UHV ion pump controller
  - Old models tend to break when being switched on
  - Spare units
  - Ongoing exchange programme

Increased number of field interventions on solid attenuators (damage and repositioning)

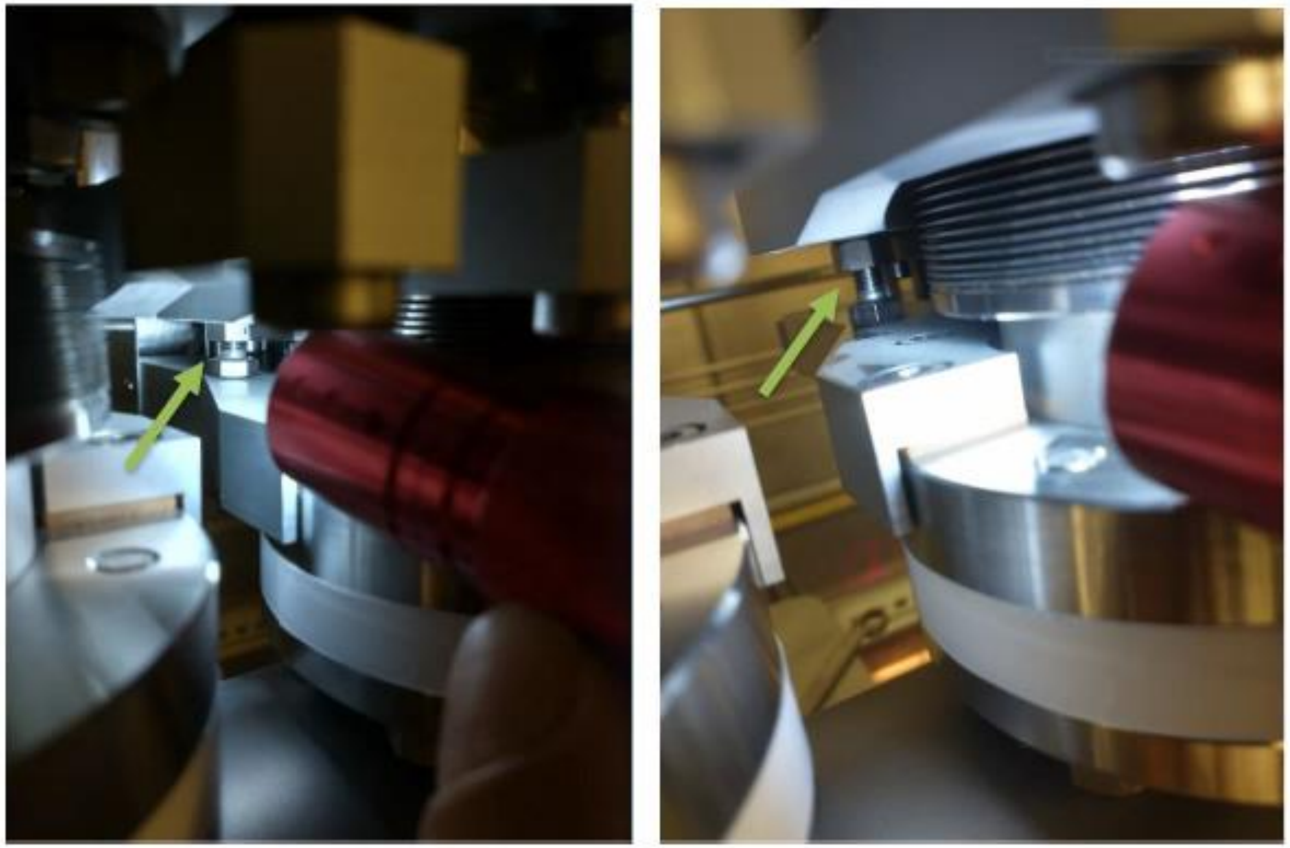
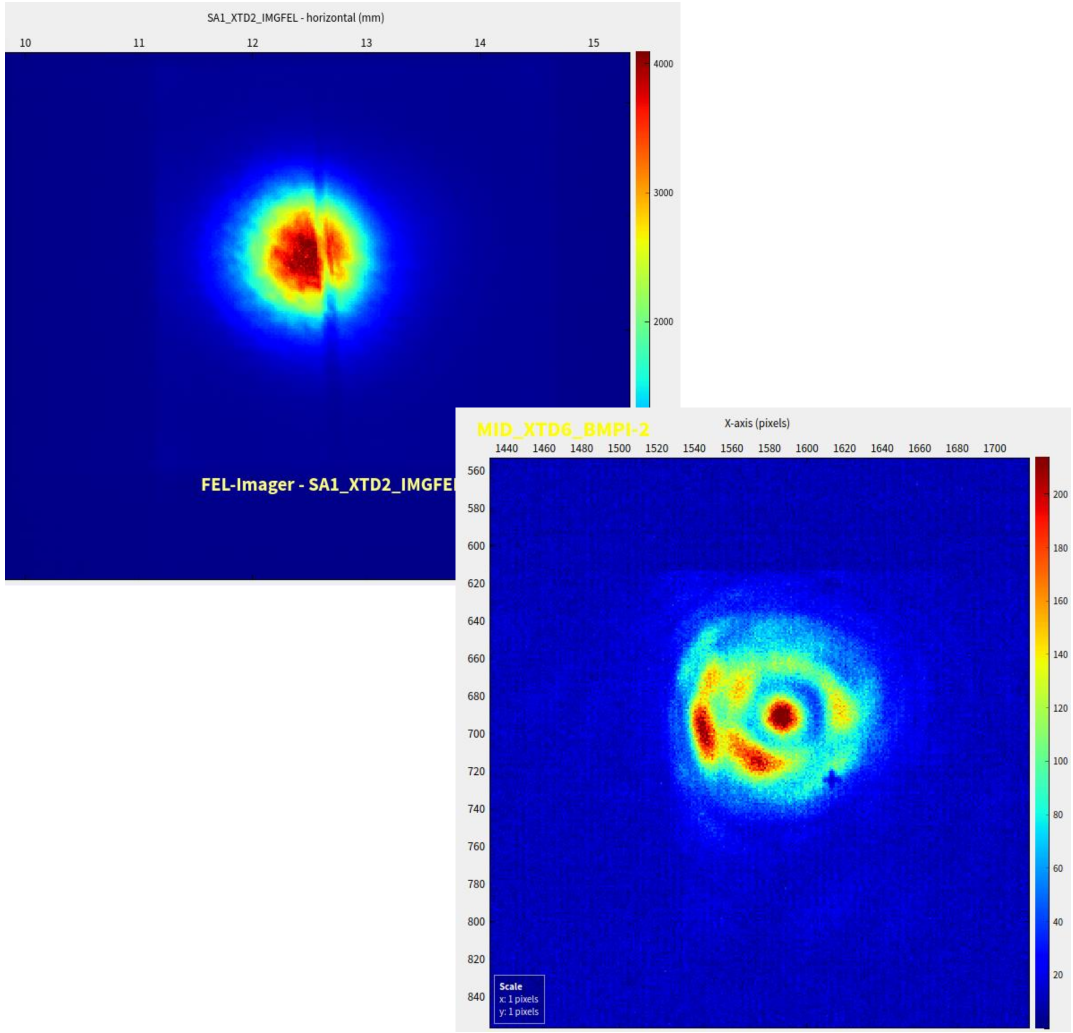
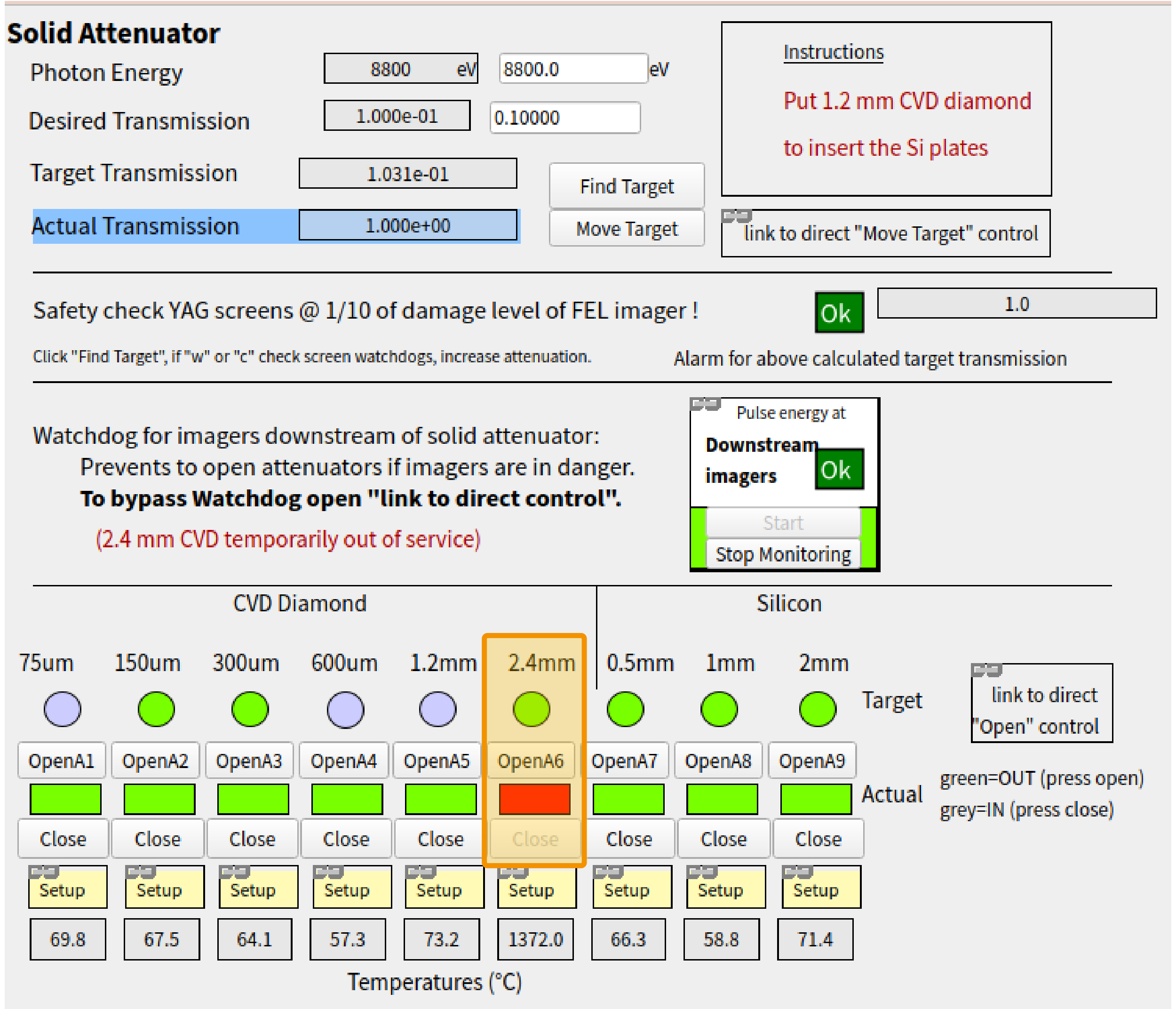


***Figure 1:** Limiting screw before (left) and after (right) intervention*



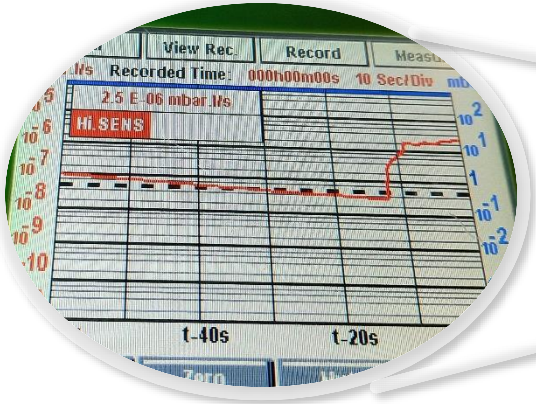
Reaching the limit of material fatigue in bellows.

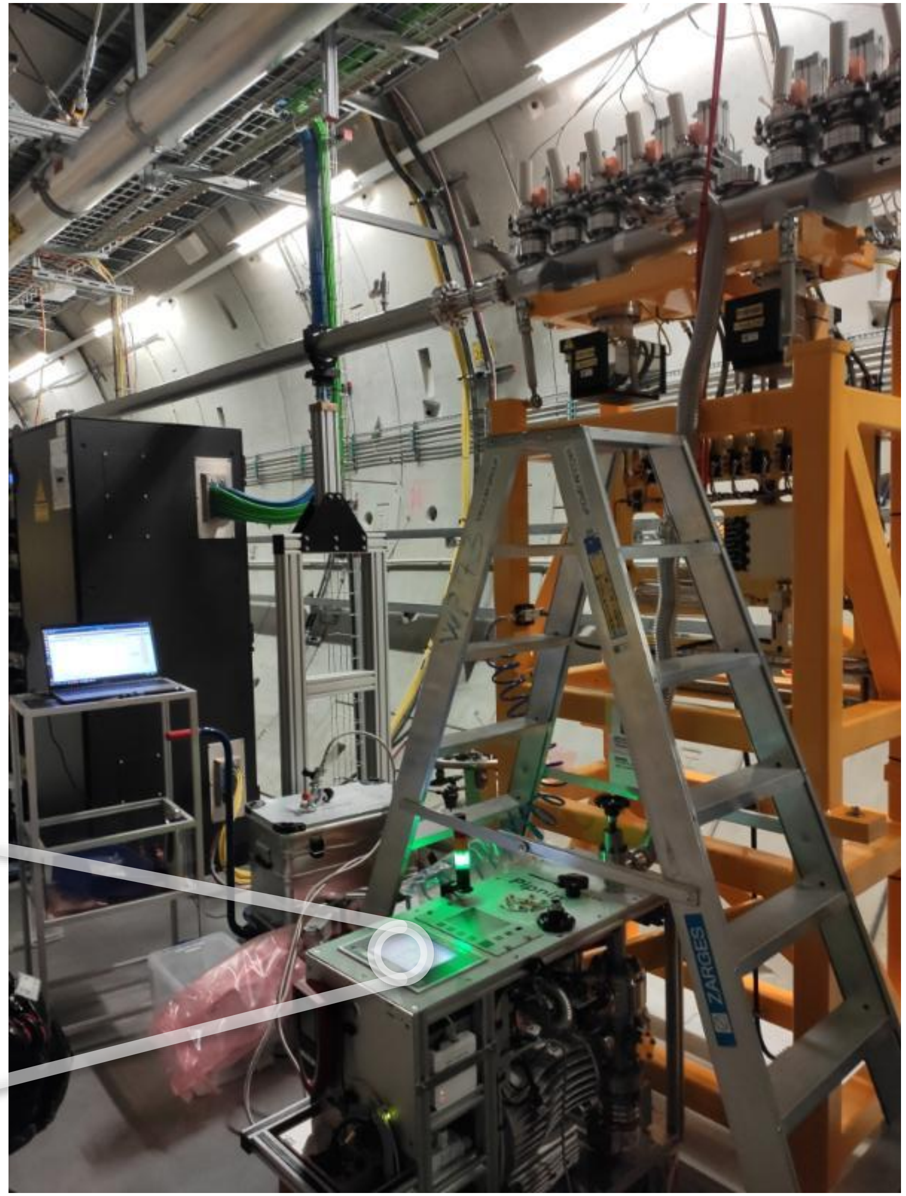
- First evidences: OCD Call.
  - Beam permission removed during user´s run.
  - Pressure burst in Solid Attenuator sector.
  - Remote evaluation possible…



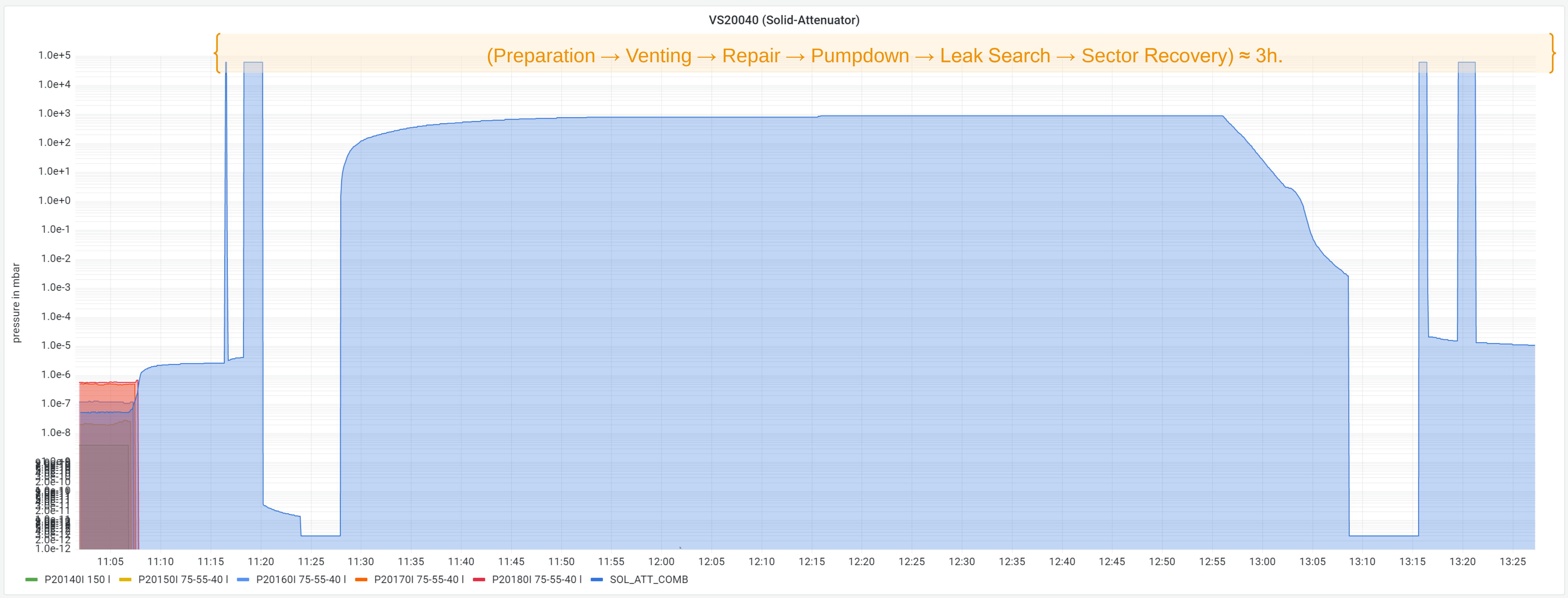
Reaching the limit of material fatigue in bellows.

- In situ intervention confirmed the working hypothesis.
- After first mitigation measures to resume operation, the expected questions arised.
- Further evaluation on system management and maintenance programme now in place.

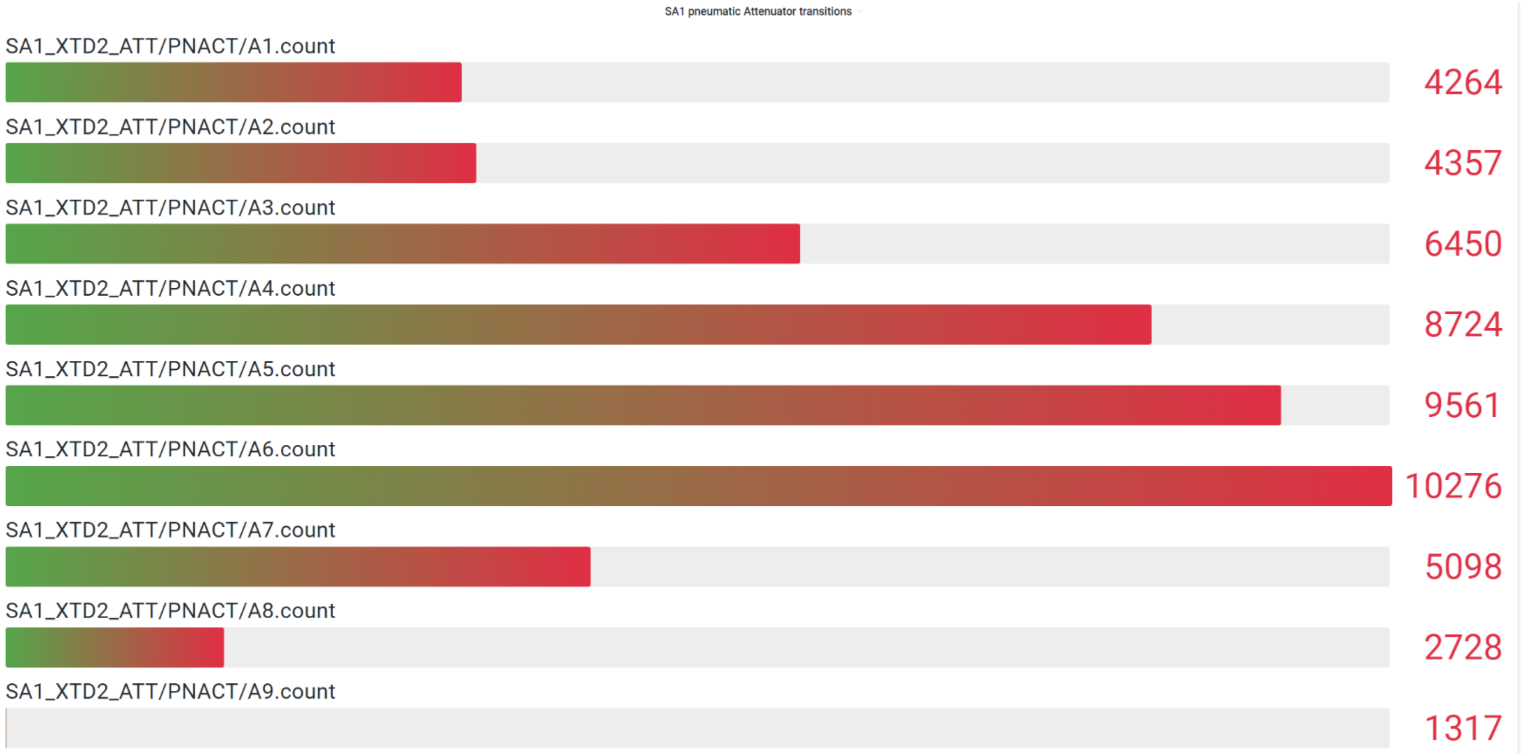




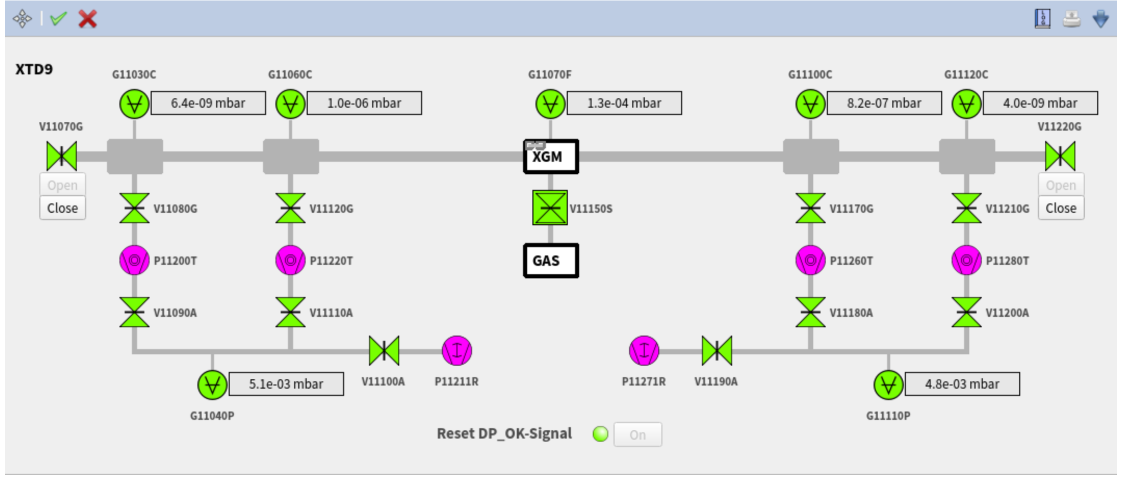
Positive outcome #1: testing high-speed interventions!

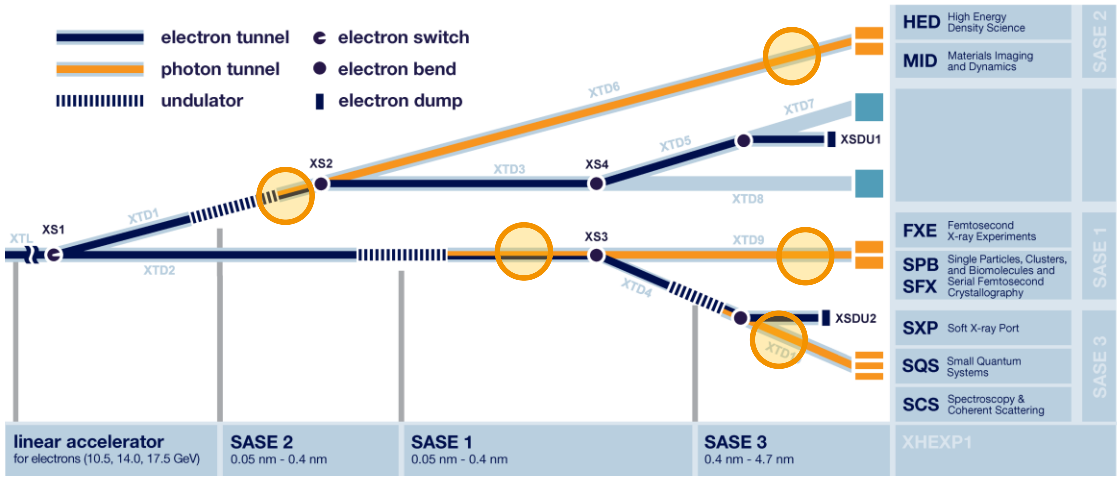


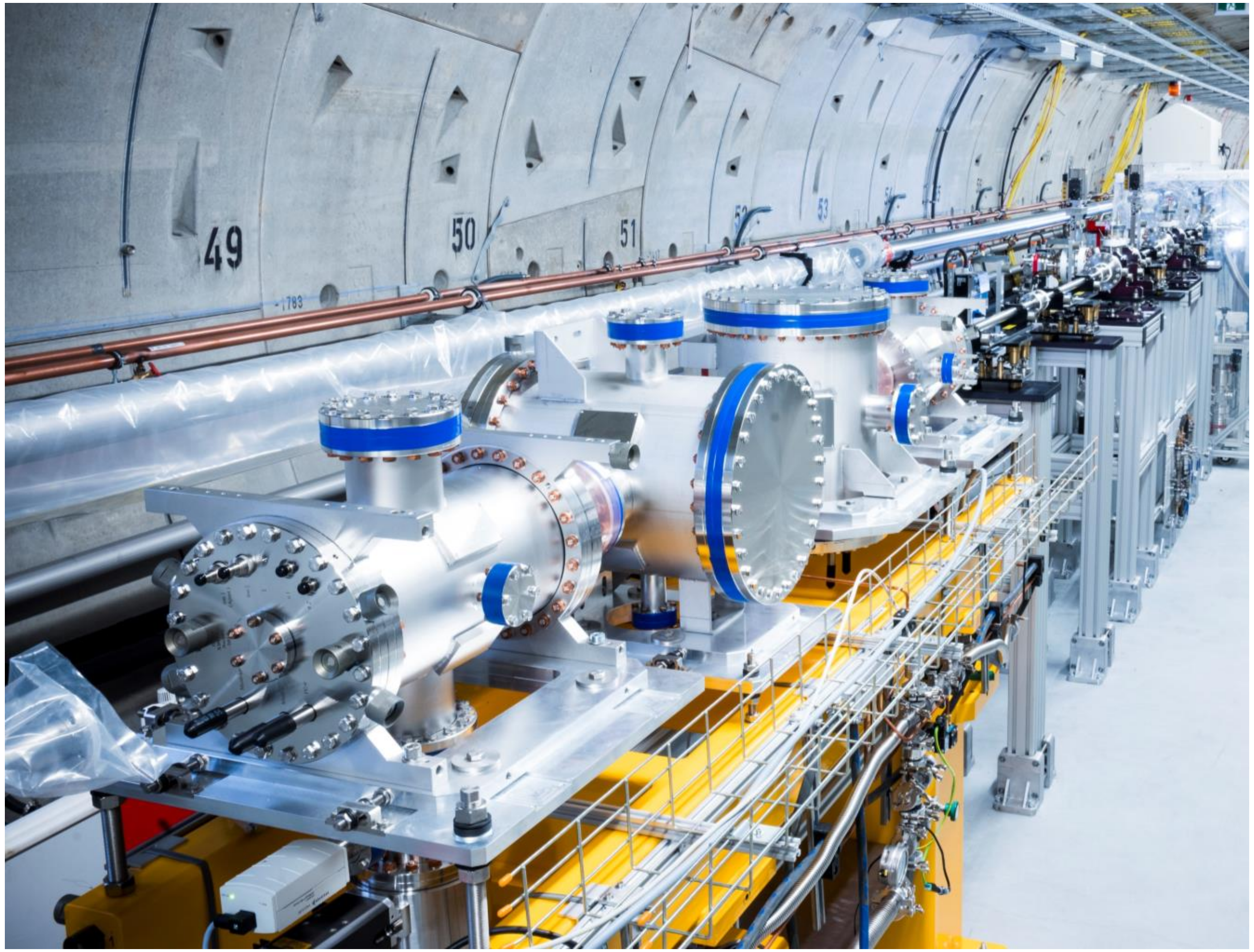
Positive outcome #2: increasing use of survey tools for scheduling maintenance duties.



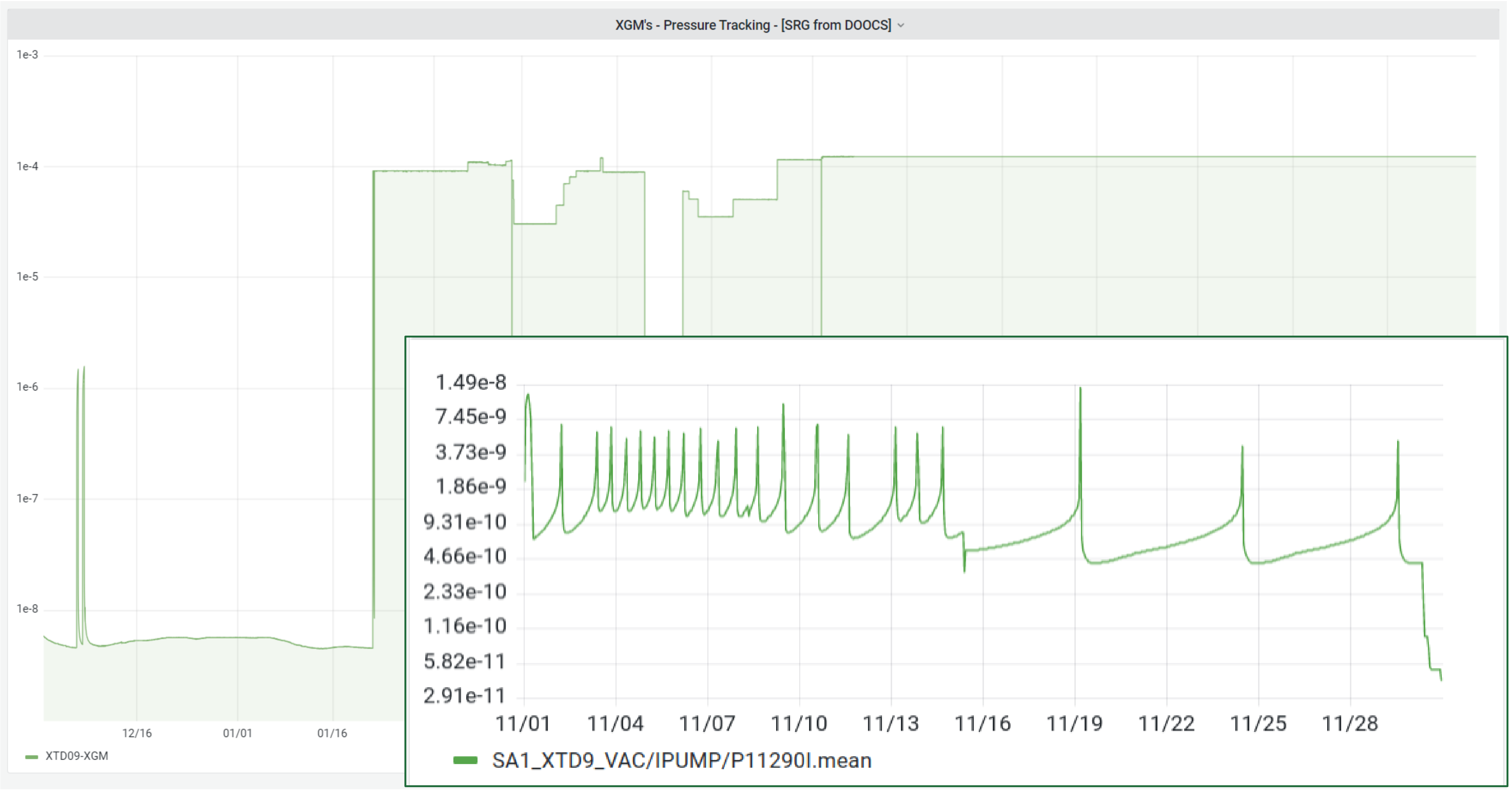
Noble gas instabilities







Noble gas instabilities



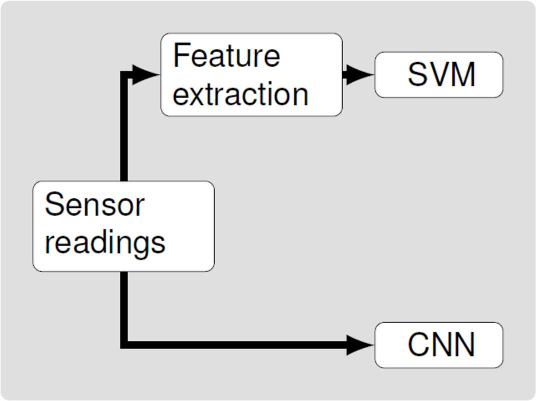
Noble gas instabilities

- It was clear that this would occur, the question was: After how many years of operation?.
- Most frequent operation setpoint is now in the 10^{-4} mbar regime (one order of magnitude higher than initially specified).
- First evidences in early 2023. Logs indicate that first events started happening in mid 2022.
- Estimated flow (roughly) < $5\cdot10^{-10}$ mbar·l/s (measured partial pressure < $8\cdot10^{-11}$ mbar)
- In the short term, adapted interlock conditions around is minimizing impact on operation.
- Currently deployed: scheduled pump replacement and recovery strategy.
- Under preparation: laboratory test bench for specific characterization campaigns.

…but also some time for developments & collaborations.

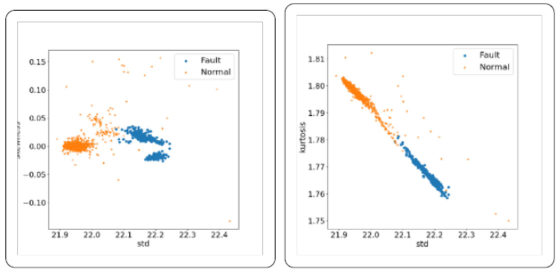
Machine learning to anticipate noble gas bursts

How can we detect it?



Method	Accuracy [%]	Precision	Recall
SVM	99.98	1.00	0.96
CNN	99.95	0.99	0.99

(Amna Majid)



- Two methods researched with similar performance.
- SVM makes a linear cut in the feature space of peak characteristics → easy **interpretation** and based on **context**.
- CNN uses all information.
- Prefer interpretable method!
- Web interface for monitoring ⇒ **quality control**.

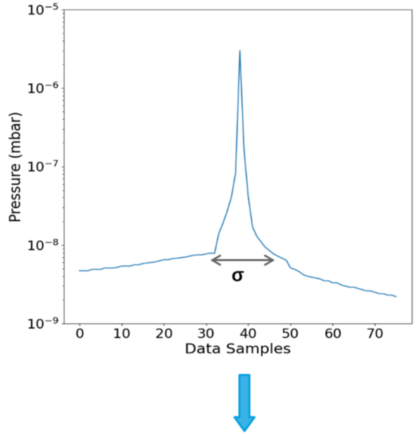
SVM: Support Vector Machines

CNN: Convolutional Neural Networks

Feature Extraction

Statistical moments

- X_1 Standard deviation (spread)
- X_2 Skewness (symmetry)
- X_3 Kurtosis (flatness)
- X_4 Hyper skewness (tail behavior)

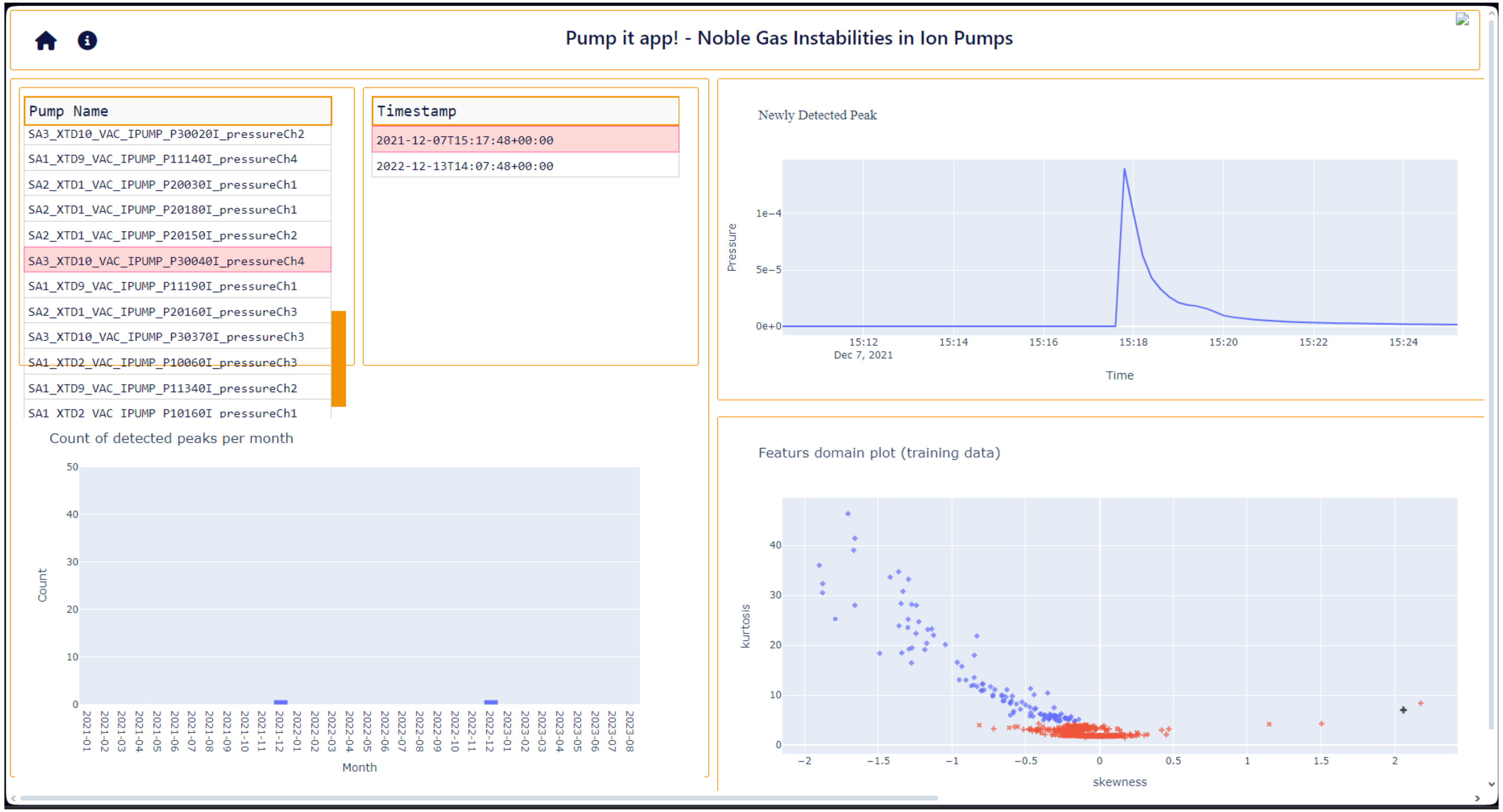


$[X_1, X_2, X_3, X_4]$

Referenced materials: courtesy of Danilo Ferreira and Amna Majid [Data Analysis]

Machine learning to anticipate noble gas bursts

- SVM as most convenient approach.
- In preparation: web interface for expert supervision & feedback to the model training.



Referenced materials: courtesy of Danilo Ferreira and Amna Majid [Data Analysis]

Device developments for experimental stations

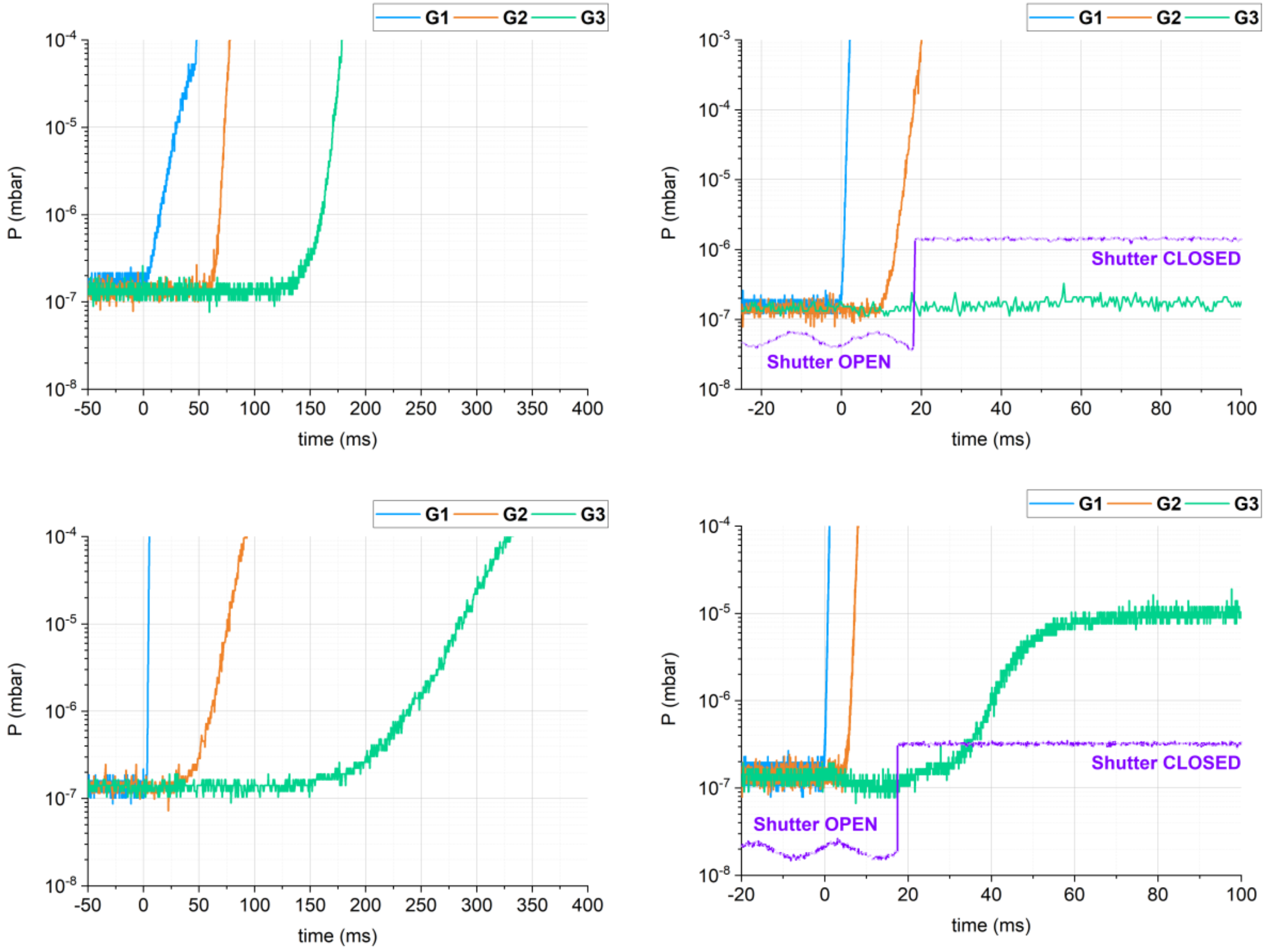

XFEL.EU XX-201X-XXX

Conceptual Design Report

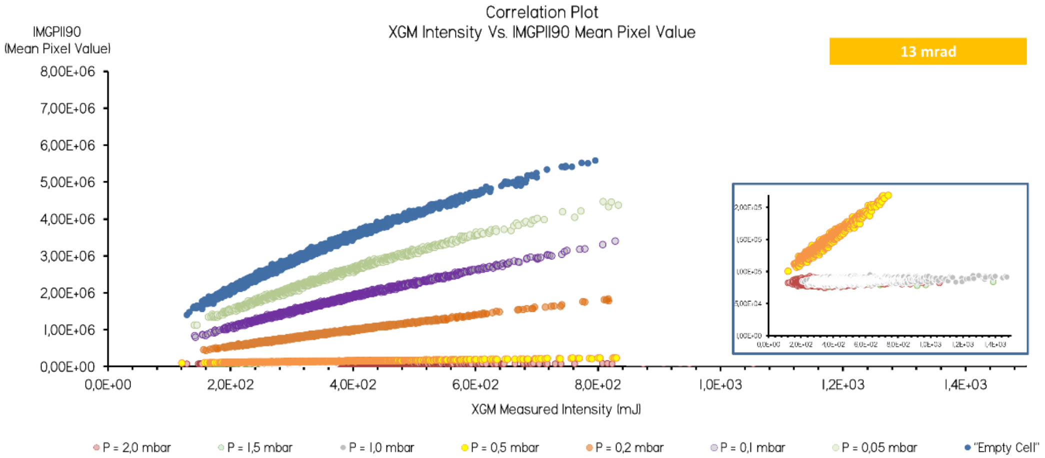
Sonic Delay Line design proposal for SPB/FXE Instrument

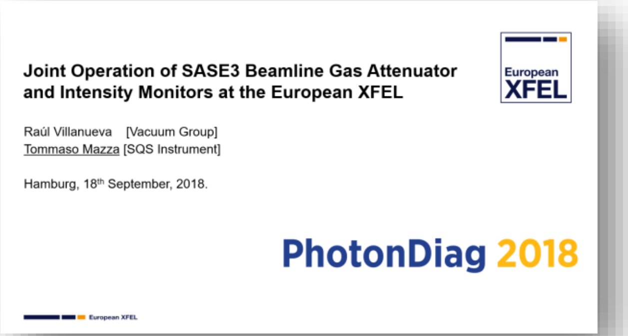
May 2017

Raúl Villanueva
on behalf of the Vacuum Group (VG)
at the European XFEL



Studies on FEL beam interaction with gas targets:





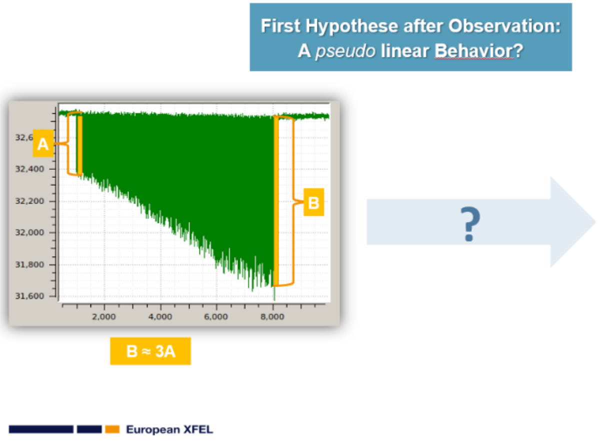
Joint Operation of SASE3 Beamline Gas Attenuator and Intensity Monitors at the European XFEL

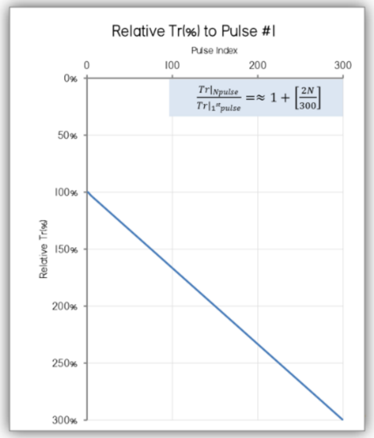
Raúl Villanueva [Vacuum Group]
Tommaso Mazza [SQS Instrument]

Hamburg, 18th September, 2018.

PhotonDiag 2018

European XFEL





Present and future perspectives

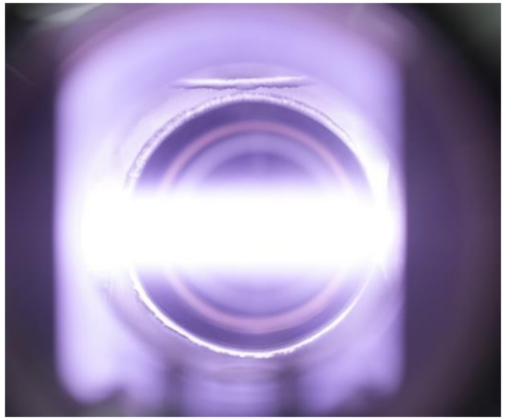
General considerations

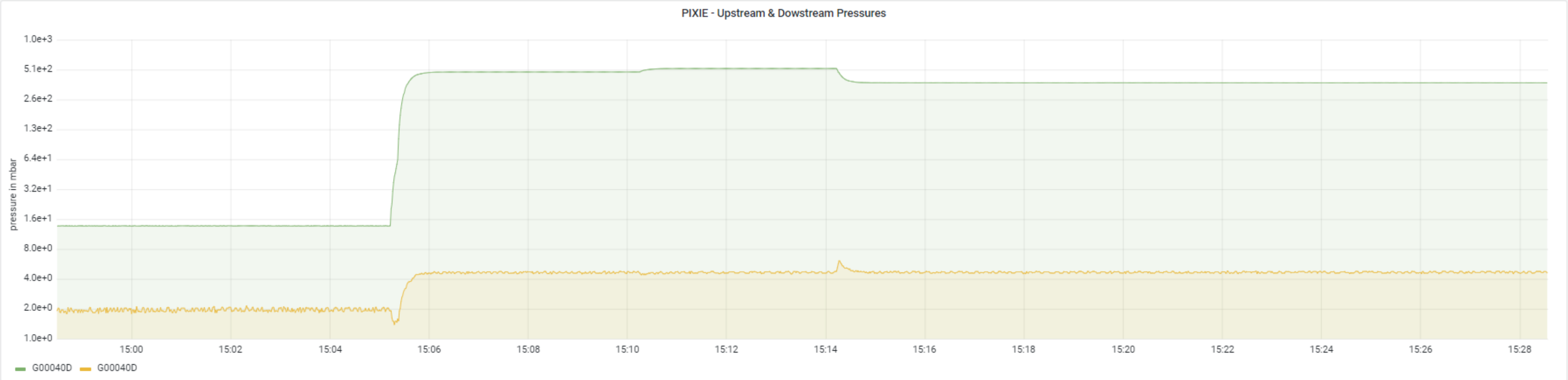
- Next big tasks: long shut-down 2025 & HXS beamline installation.
- Special attention to electronics lifetime.
- Progressive substitution of scroll pumps against small footprint multistage Roots.
- Extension of RGA constellation for active & constant monitoring of experimental station interfaces.
- Studies on characterizing noble gas critical dose, and ion pump recovery strategies.
- Earlier stage access to future design of components for the tunnels: reinforcing compliance for vacuum performance, reliability and maintainability.
- Increase of automation for survey and control (i.e. collaboration with EEE, CTRL & DA groups).
- Effort in harmonization of experimental station vacuum systems (enhance serviceability)

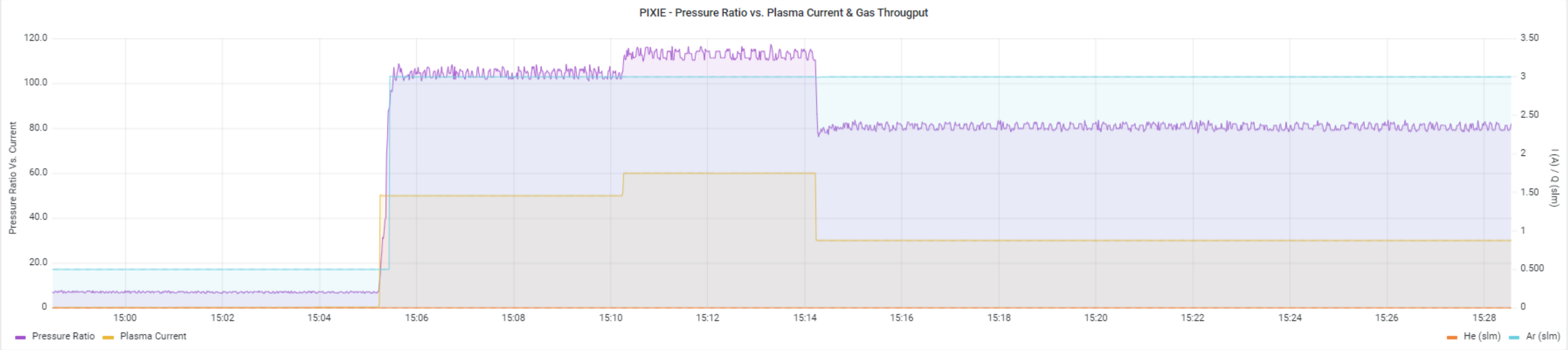
….one last thing

PIXIE: A Plasma Interface for XFEL atmospherIc-pressure Experiments

First plasma ignited last week!







Thank you for your attention!