Dust issues at DESY and how to avoid them at PETRA III, XFEL and FLASH

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CERN , 13.6.2023

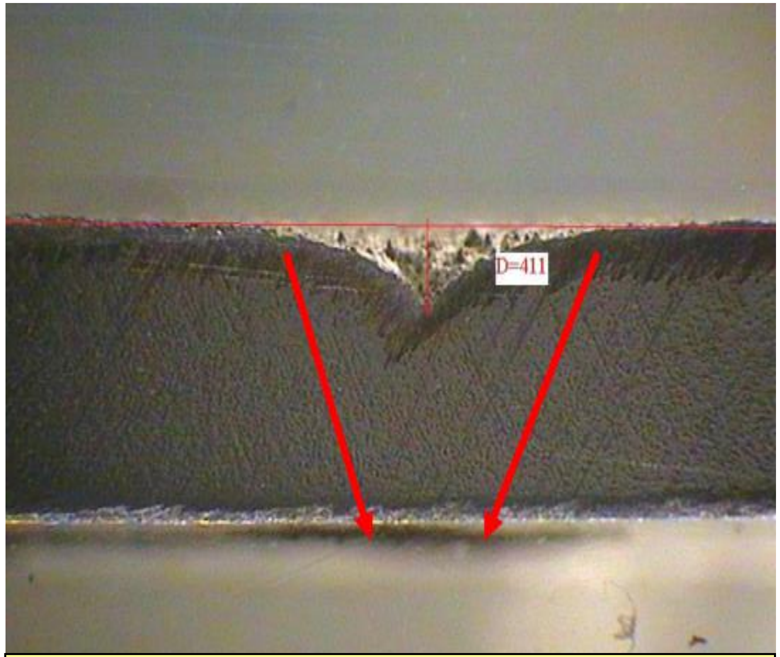
Initial Definitions for this Talk

- "Dust" is somewhat misleading
  - Problems can occur from air-born particulates which everybody knows (as well as intergalactically transported ones as well….)
  - But sometimes accelerator components or even the accelerator itself produces "dust" as well - which are metallic particulates mostly.

- Dust is composed of particulates.
  - A particle accelerator accelerates particles: electrons, protons, ions

- When people aim for „particle-free“ vacuum systems, they mean a vacuum system with the lowest possible count of particulates
  - A truly particulate-free accelerator is difficult – if not impossible – to achieve.

By: A,Ocram – Own Work, CC0, https://commons.wikimedia.org/w/index.php?curid=47821242



By: C. Maccarrone, Agilent Technologies, CAS2017

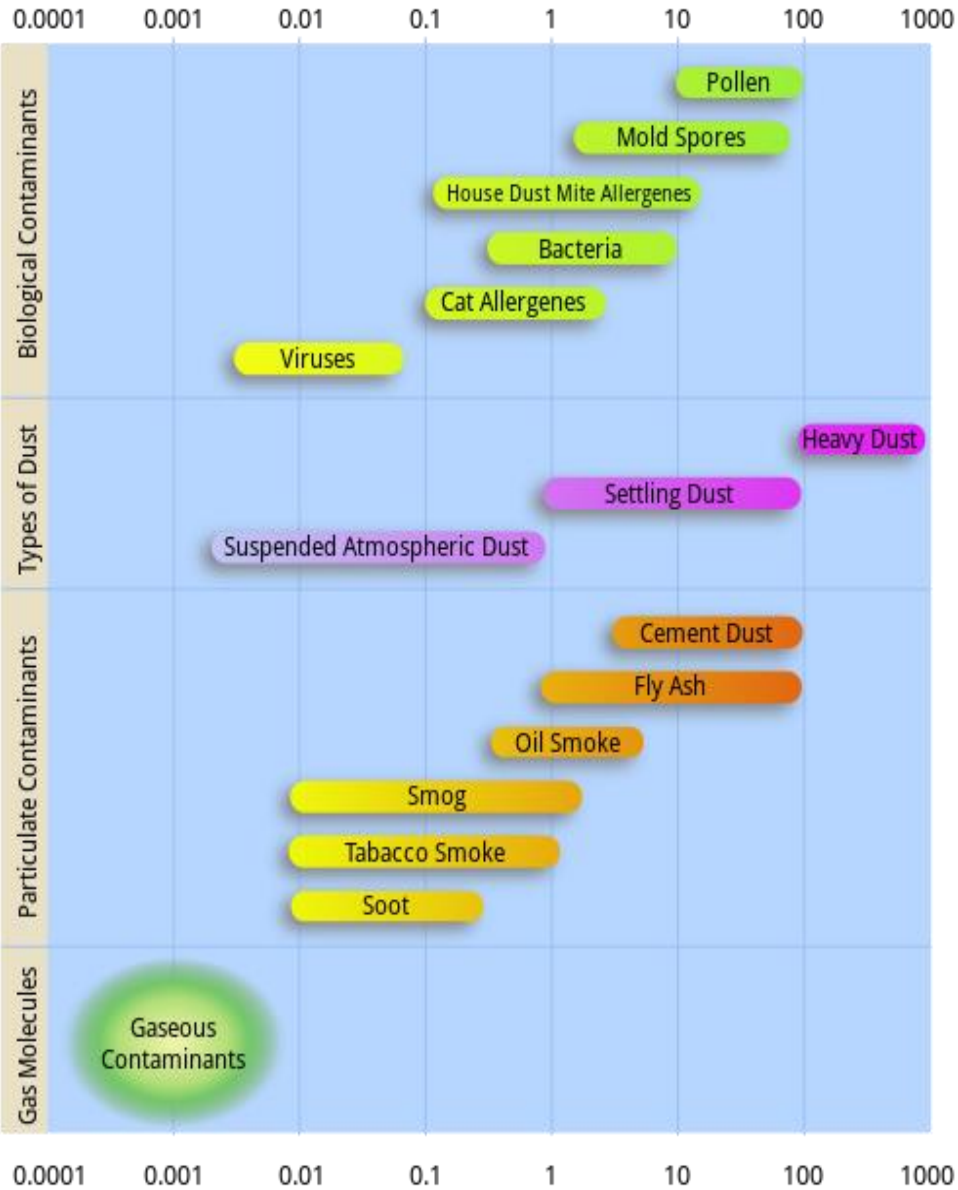
Outline

- What are Particulates?
- What are Particulate Sources in Accelerators?
- Problems caused in Particle Accelerators by Dust Particulates
  - HERA and DORIS
  - (CEBAF)
- Examples for accelerators without dust issues
  - PETRA III
  - XFEL and FLASH

What are Particulates?

- Particulates can both be airborne e.g.classical dust or being generated during the assembly processes e.g. while bolting down screw connections.
- Humans as a dust source missing in the diagram

H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51



From Wikipedia "Particulates"
Sizes in micrometers

What are Particulate Sources in Accelerators?

- External sources causing particulate contamination
  - Exposure of components to “normal” air or similar gasses
    - Drying, filtering, control of flowrates
    - Cleaning
  - Assembly of components in uncontrolled environments
    - Control environment (clean rooms or similar)
  - … and many more

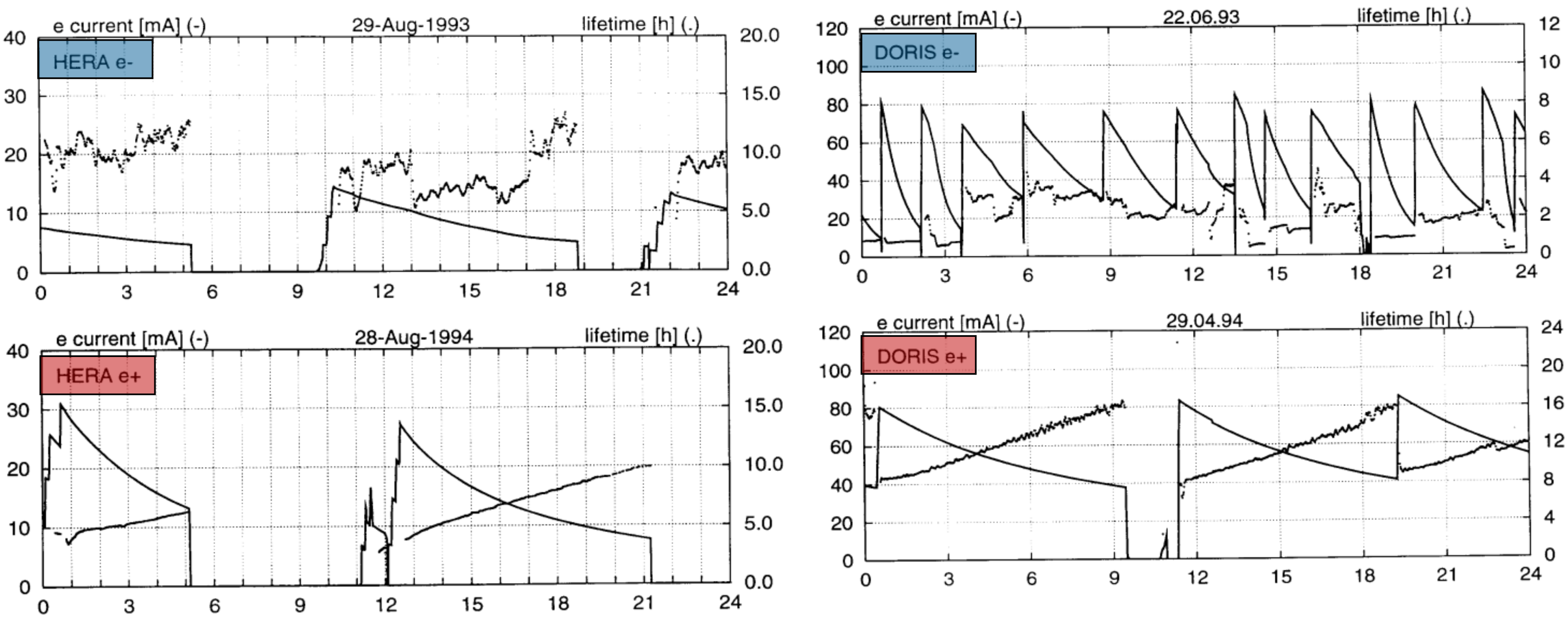
- Internal sources generating particulates
  - Moving mechanical parts e.g. gate valves, diagnostic components or RF fingers
    - Reduce the number of movements
    - Do not transport particulates be e.g. turbulent gas flows
  - Physical processes like conditioning can generate new particles
    - Conditioning can be difficult to control
    - Operation of sputter ion pumps can set particles free
  - … and probably more

Dust and Particulates in Particle Accelerators

- Dust and Particulates are not just a nuisance
- Several components in accelerators are sensitive to contaminations with particulates
- Severe, permanent performance deterioration might occur in components
- Examples in this talk:
  - HERA and DORIS electron-life time problem and its mitigation
    - DESY had to learn a lesson
    - Particulates are produced in the accelerator
  - FLASH and XFEL
    - Lesson learned from CEBAF
    - External contaminations have to avoided

Particulate-related Degradations: Beam Lifetime in HERA and DORIS

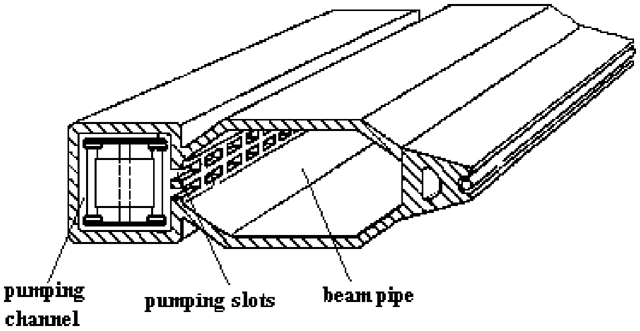
Daren Kelly, Many-Event Lifetime Disruption in HERA and DORIS , DESY HERA 95-02



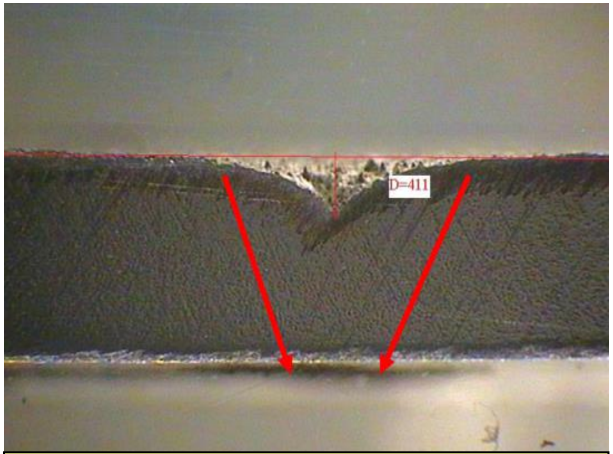
- When the accelerators where operated with **electrons** (TOP) beam lifetime showed unexpected degradations.
- Operation with **positrons** does not show this phenomenon (BOTTOM).

Particulate-related Degradations: Beam Lifetime in HERA and DORIS

- Changes in the operation conditions of the integrated sputter ion pumps could be used to provoke lifetime degradations
  - Transients like switching on or off and bad pressure pressure can provoke particulate ejection



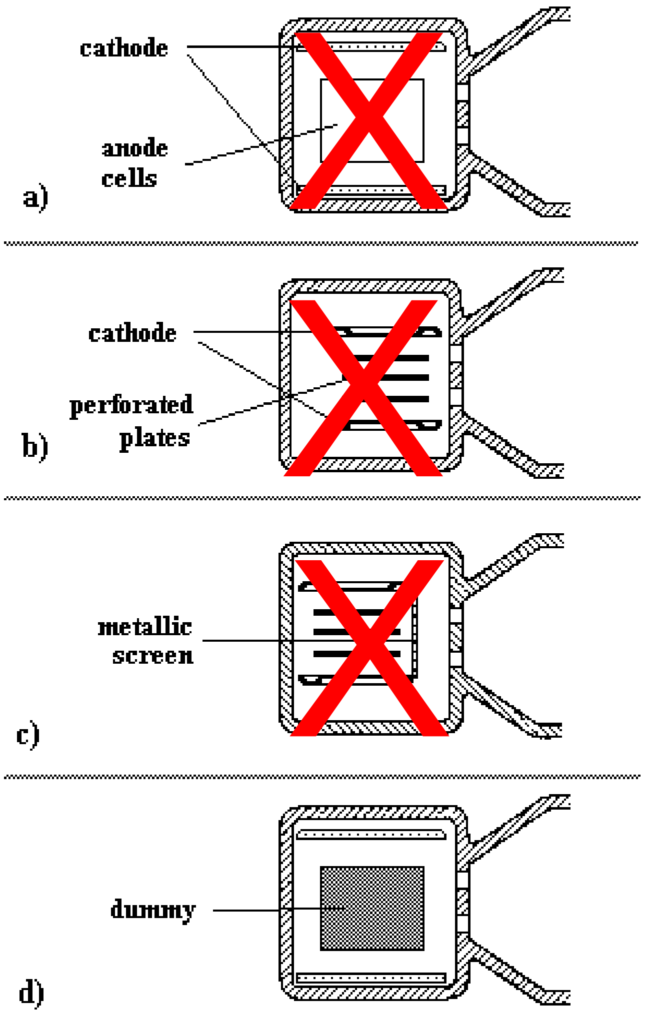
- Events have been traced to positively charged particulates which have been emitted by the sputter-ion pumps integrated in the vacuum chamber.
  - Material of the particles has not been identified initially
  - Suspicion was that SiO particulates would be required due to their thermal properties (high melting ppoint)
  - I'm not able to judge the simulations for the reports done at that time, but what I've seen yesterday seemed way more sophisticated.
  - The melting point alone is not the only relevant parameter, presumably.



By: C. Maccarrone, Agilent Technologies, CAS2017

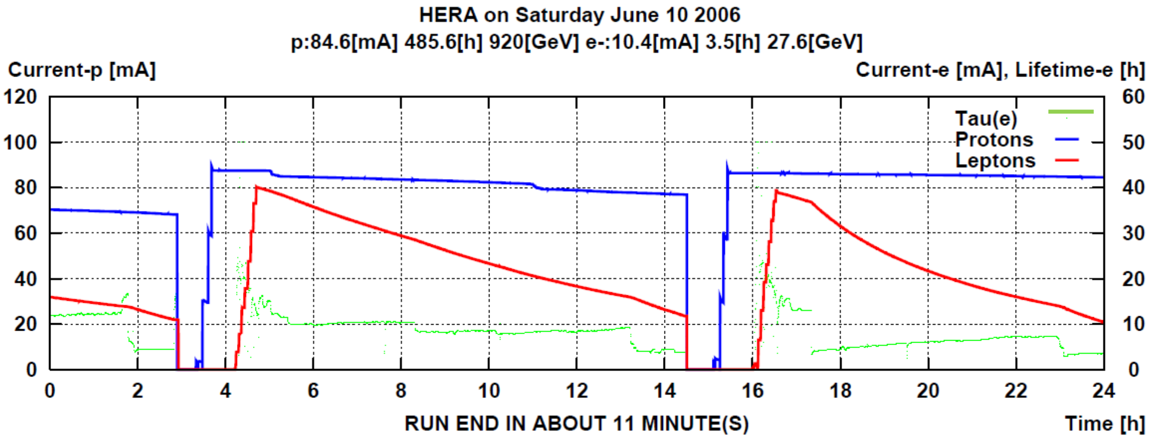
- …. but apparently, titanium particles are the root cause. See below.

Particulate-related Degradations: Beam Lifetime in HERA and DORIS



K. Balewski et al.,
INFLUENCE OF VARIOUS INTEGRATED ION GETTER PUMPS ON ELECTRON LIFETIME

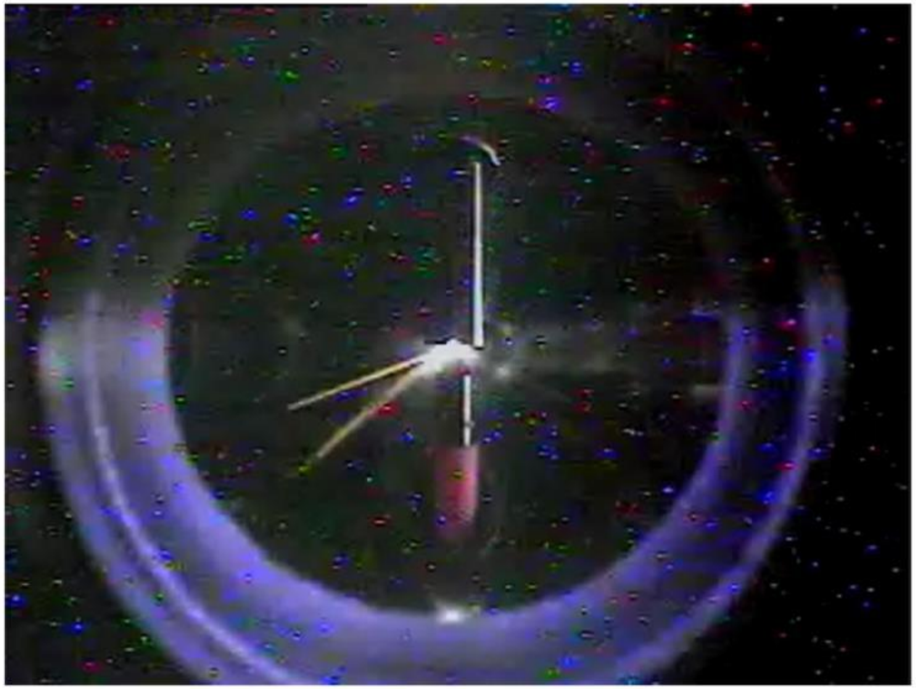
- Geometry changes of the sputter ion pumps did NOT improve the situation
- Removal of integrated sputter ion pumps improved the situation significantly
- Even after exchange of most chambers to a system with integrated NEG strips the effect could be observed albeit less pronounced
- HERA and DORIS have been operated with positrons most of the time after this discovery.
- PETRA III has never had these issues with life-time
- Colleagues at KEK's photon factory observed that titanium particulates could be caught by the beam

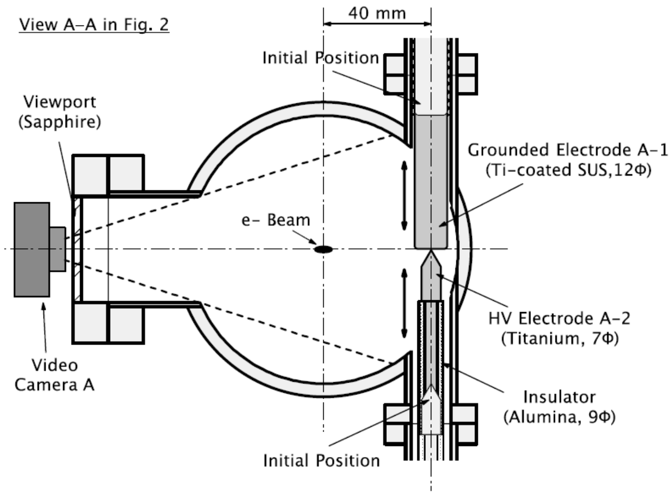


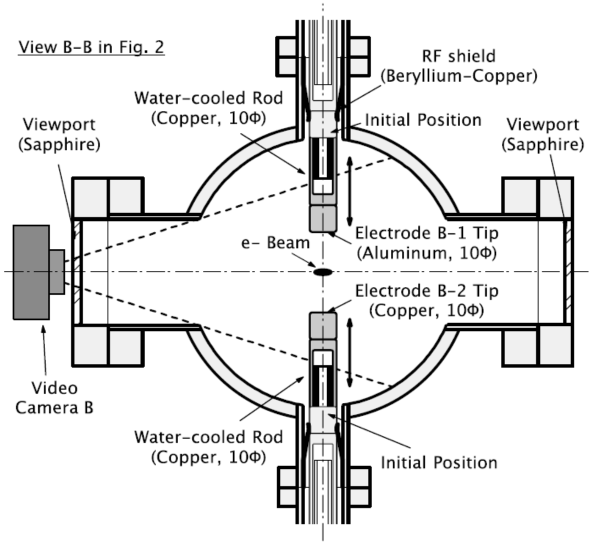
Alexander Kling, Dust particles in HERA und DORIS, EPAC 2006

Particulate-related Degradations: KEK Photon Factory

- Dedicated experiment to demonstrate the effect of “dust” particles
  - Includes titanium particulates!
- Movable electrodes on and off the beam axis
- Picture of a captured particle which evaporates



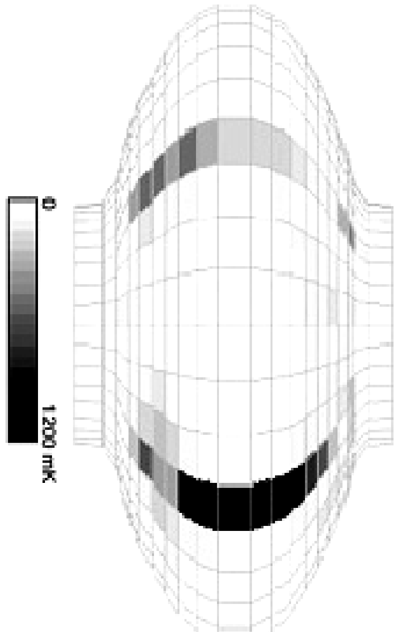




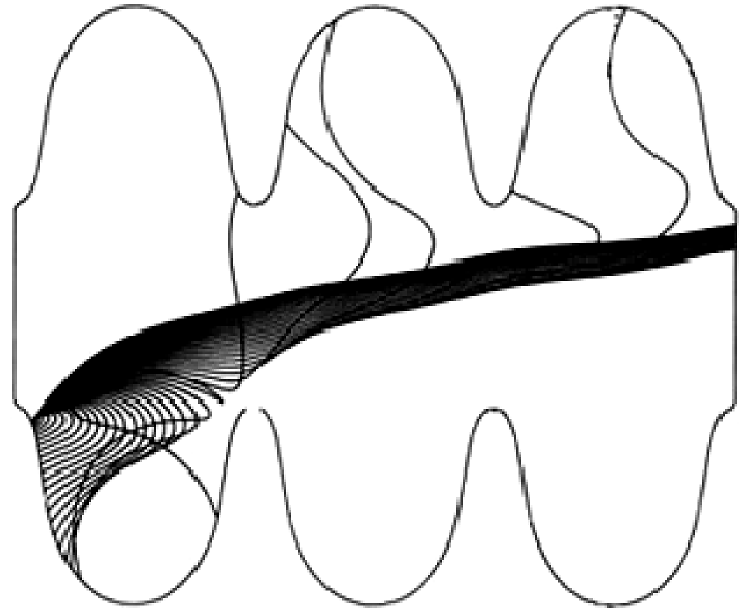
Experimental demonstration and visual observation of dust trapping in an electron storage ring, Yasunori Tanimoto, PRST-AB 12, 110707 (2009)

Particulate-related Degradations: Field Emission in Superconducting Accelerating Cavities

Particle causing field emission



Temperature map of a field emitter



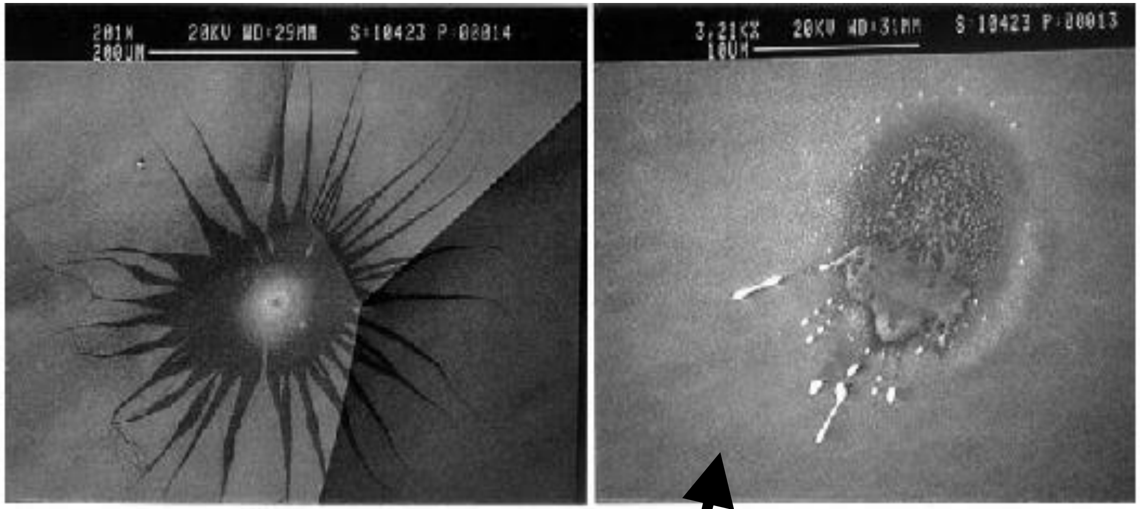
Simulation of electron trajectories in a cavity

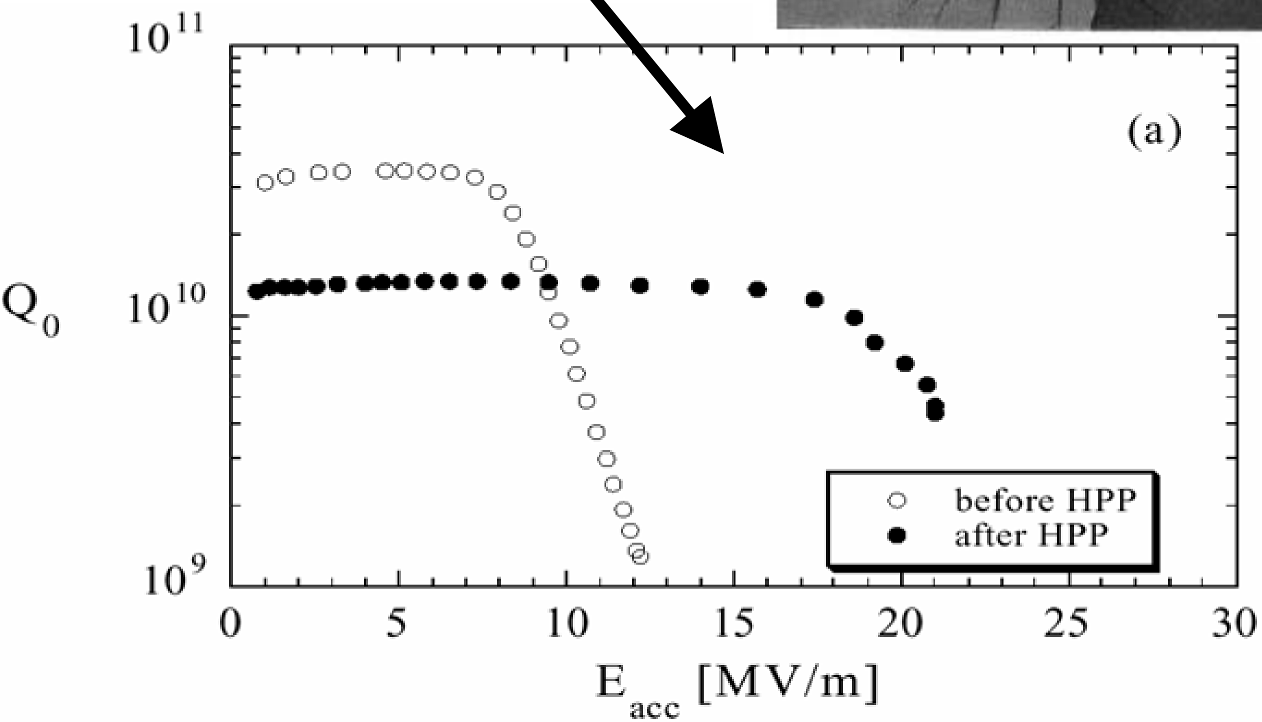
Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51

Possible Cures for Field Emission: High Power RF Conditioning

SEM Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51

In some cases applying high RF power to the cavity can cause the destruction of field emitters and improve the cavity gradient

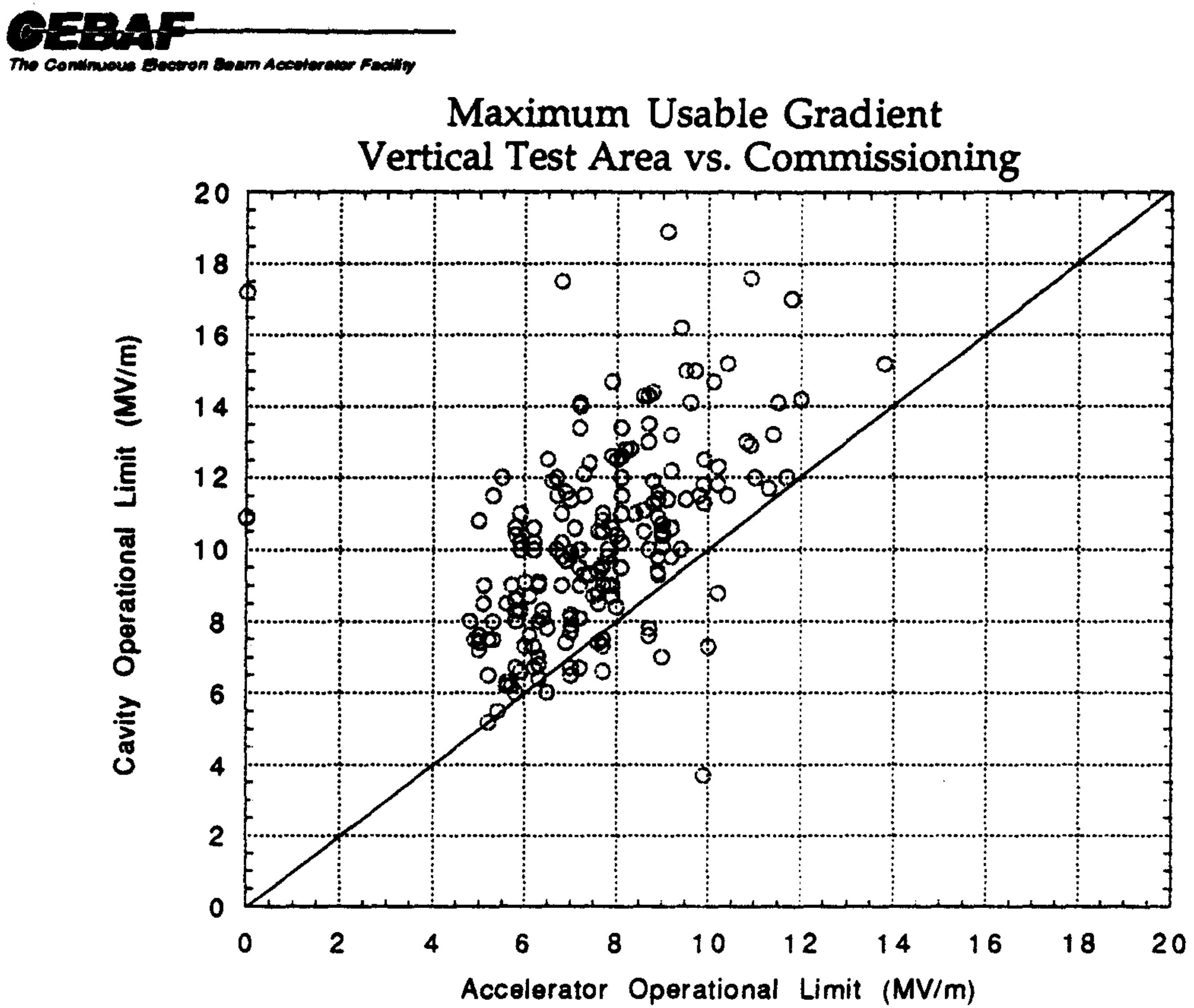




SEM pictures of a molten particle after application of high RF power

In-situ processing can sometimes cause new problems e.g. lower Q_0

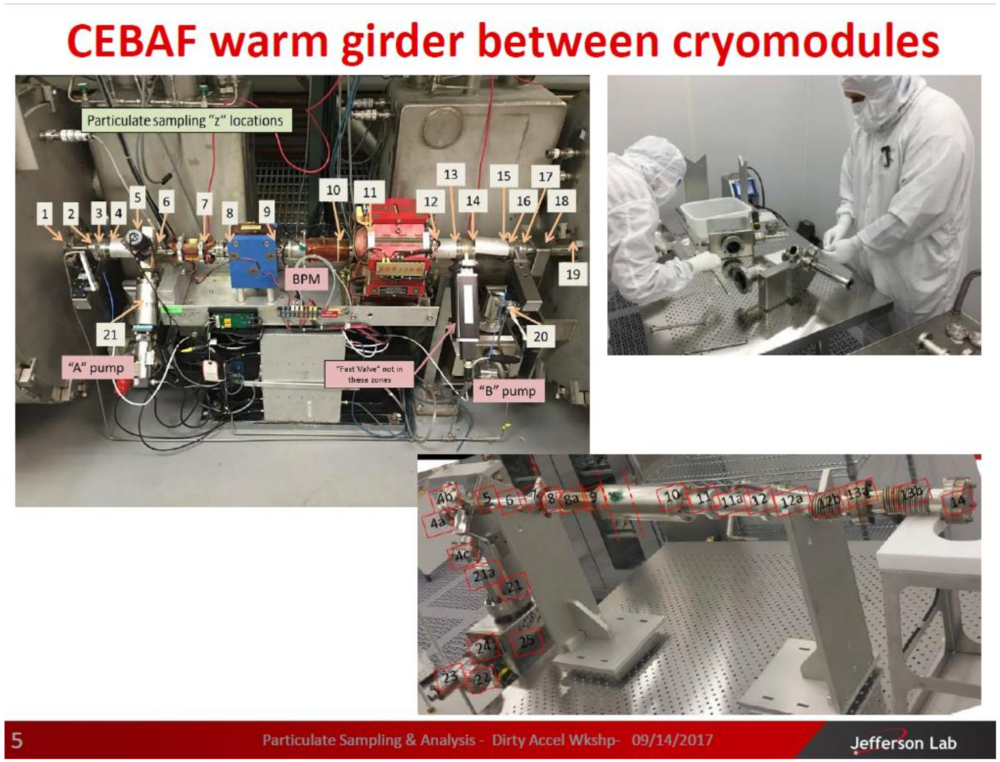
Particulate-related Degradations:
Cavity Accelerating at CEBAF

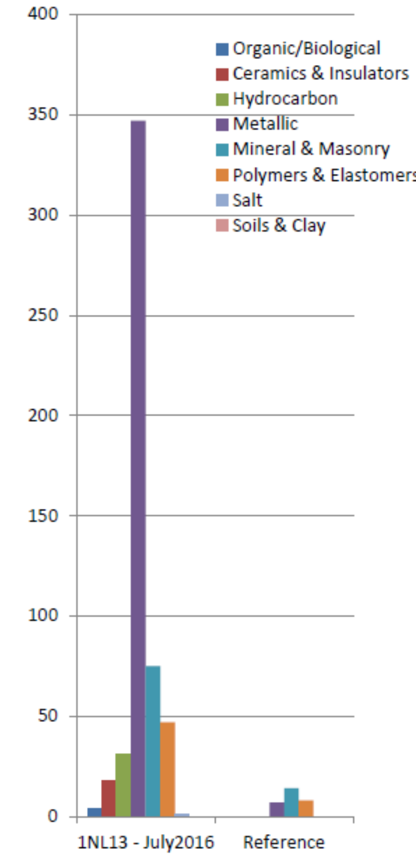


Particulate-related Degradations: Cavity Accelerating at CEBAF

- Suspicion was always that particulate contamination was critical, but where from?
- Years later a systematic study found:

“Particulate Sampling of cavity and warm beampipe surfaces removed from CEBAF” , C.E. Reece et al. , 2017





- “Particulate load in the sampled girders from CEBAF is far above any current standard for SRF accelerator beamlines.
  - 100s of copper and stainless steel particulates larger than 40 µm
  - Distinct particles of aluminium, silver, titanium, zinc, nickel, and minerals also common.
  - Particulates of soil and clay found rather frequently.
  - Non-distinct polymers observed, some of which may have been associated with the collection media.”
- Similar particulates found in an module vented accidentally

Origin of Particulates: Know your enemy….

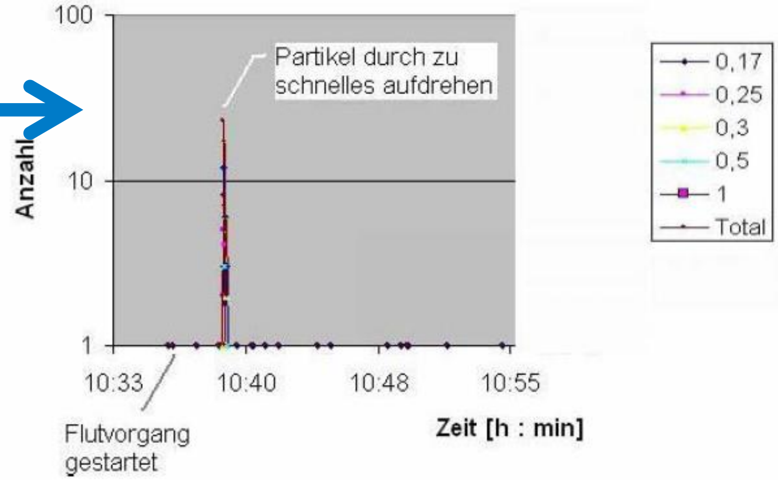
- Particulates are from several origins
  - Air pollution
    - Sahara, Diesel engines etc.
  - Fabrication
    - Machining, Drilling etc.
  - Assembly
    - Humans, friction
  - Operations
    - Friction, Charging, Aging

- Particle Properties
  - Size, Mass and Forces are very diverse
  - Nonetheless these help to develop countermeasures

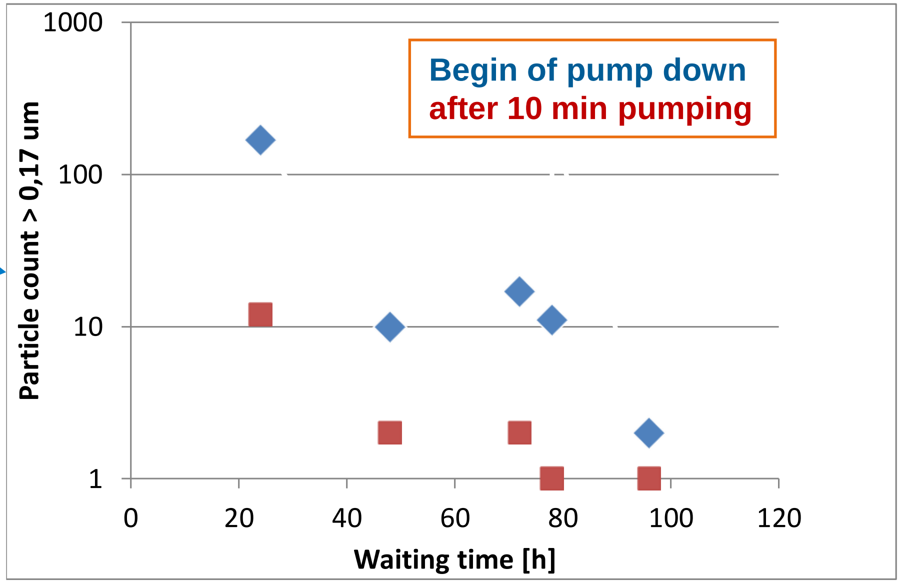
From Wikipedia "Particulates"
Sizes in micrometers

Transport of Particulates

- Particulates can be dislodged from the surface if subjected to …
  - Mechanical vibrations
    - E.g. valve opened too quickly
  - Turbulent gas flow e.g. during pump down
  - Charging up



- Particles can be transported for significant distances in gaseous media even when the gas does not move itself
  - E.g. observation of Brownian motion using dust particles
  - It takes several hours in vented vacuum systems for all particles to settle on the surface



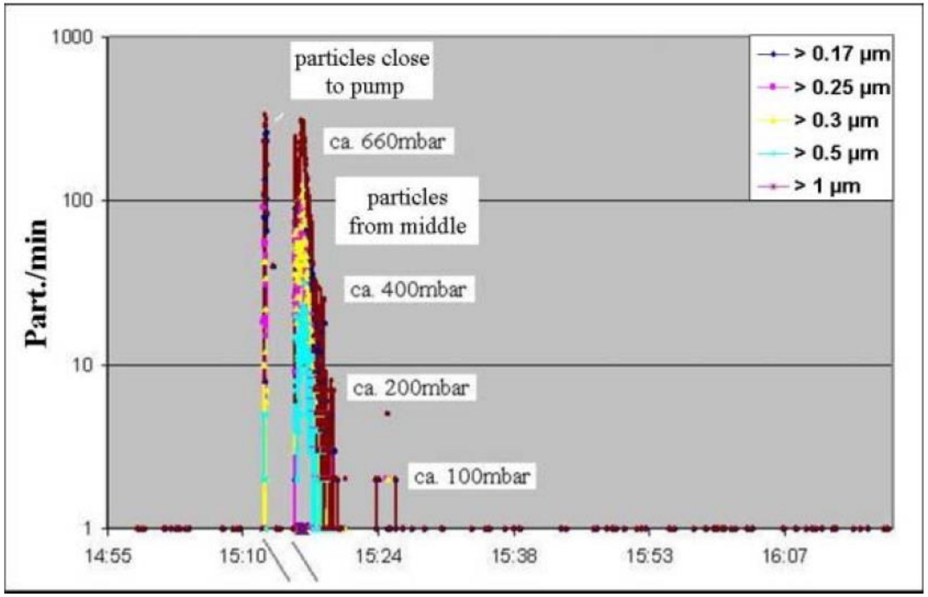
- In vacuum things are very different
  - Particles will fall down and do not move further unless severe vibrations or charge up occur
  - Van der Waals force helps

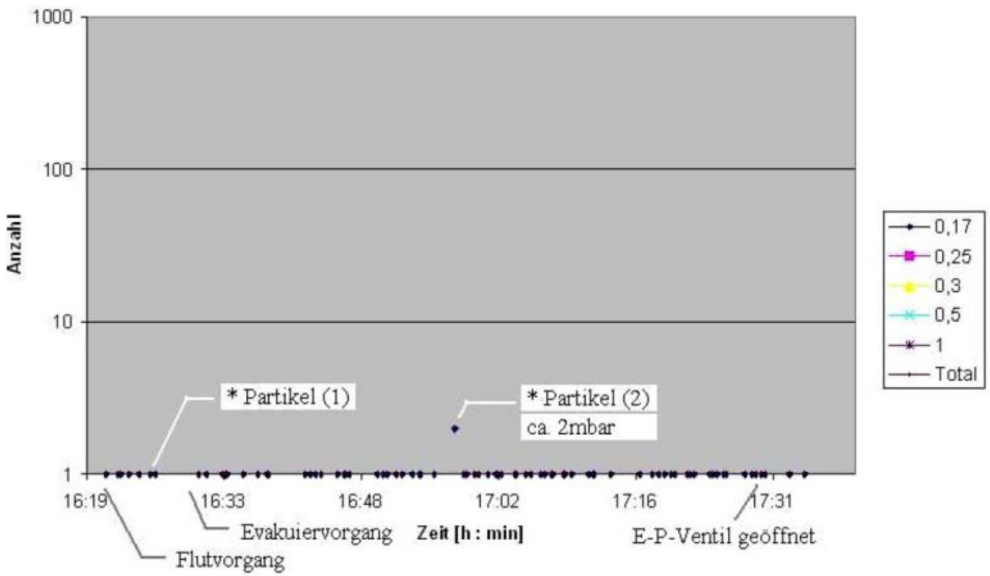
Avoiding Particulate Transport during Pumpdown and Vent

- Particle transport will be avoided by careful operation of the vacuum system

- Avoiding vibrations is mandatory in general
  - When there is no vacuum, this is even more important

- Use laminar gas flow while venting and pumping vacuum systems
  - Avoid turbulences
  - Even with laminar gas flow mechanical vibrations can lead to long distance particle transport

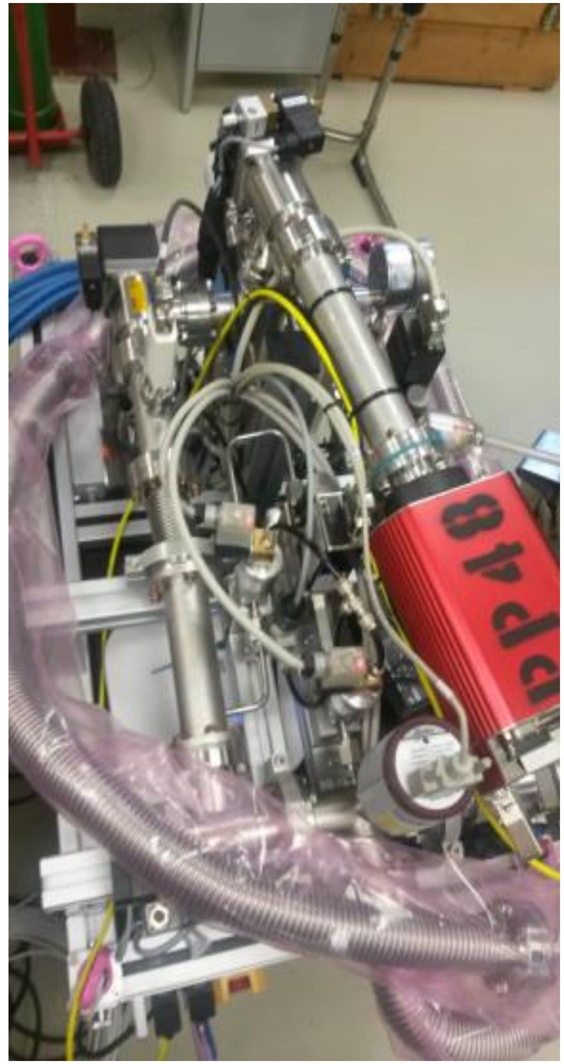


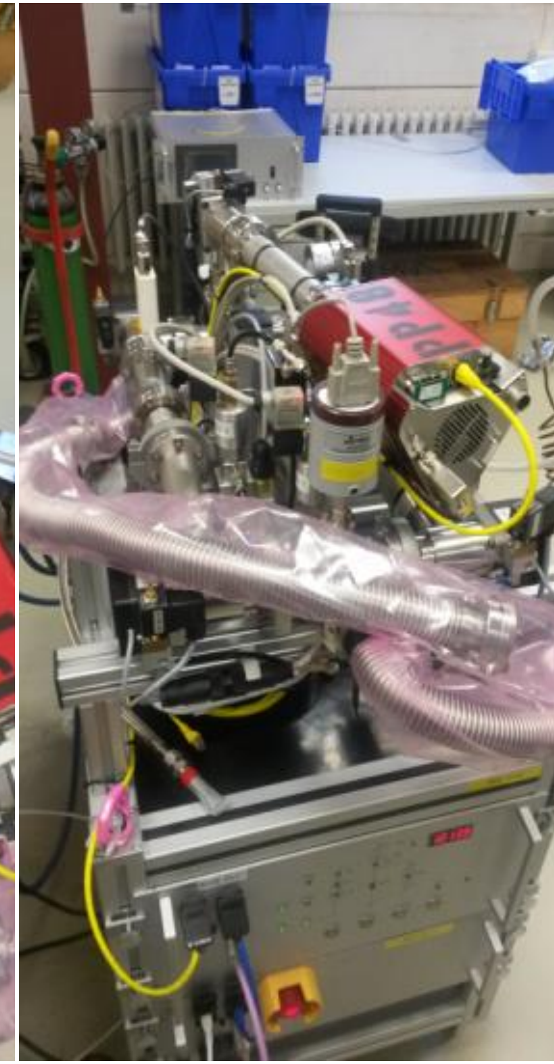


K. Zapfe, J. Wojtkiewicz
SRF2007, WEP74

Venting and Pump Down of “Particle Free” Sections

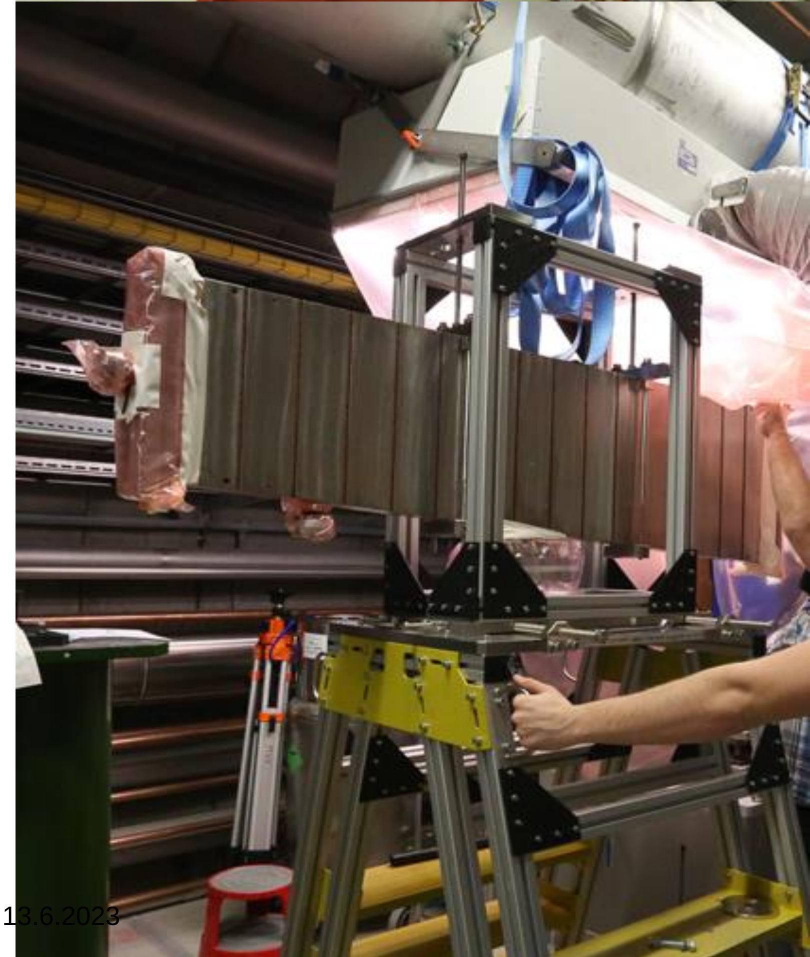
- There are and always will be particles in the vacuum system!
- Developments of pumping / venting procedures by means on in-vacuum particle counter. No particles are transported if either:
- **Flow ≤ 3 l_n/min, or**
- **Pressure < 1 mbar**
- Automatic pumping / venting units developed
- Constant flow of 3 l_n/min of nitrogen or argon, by means of mass flow controllers.
- Units have been widely used for XFEL





Storage and Transport of Cleaned Vacuum Components

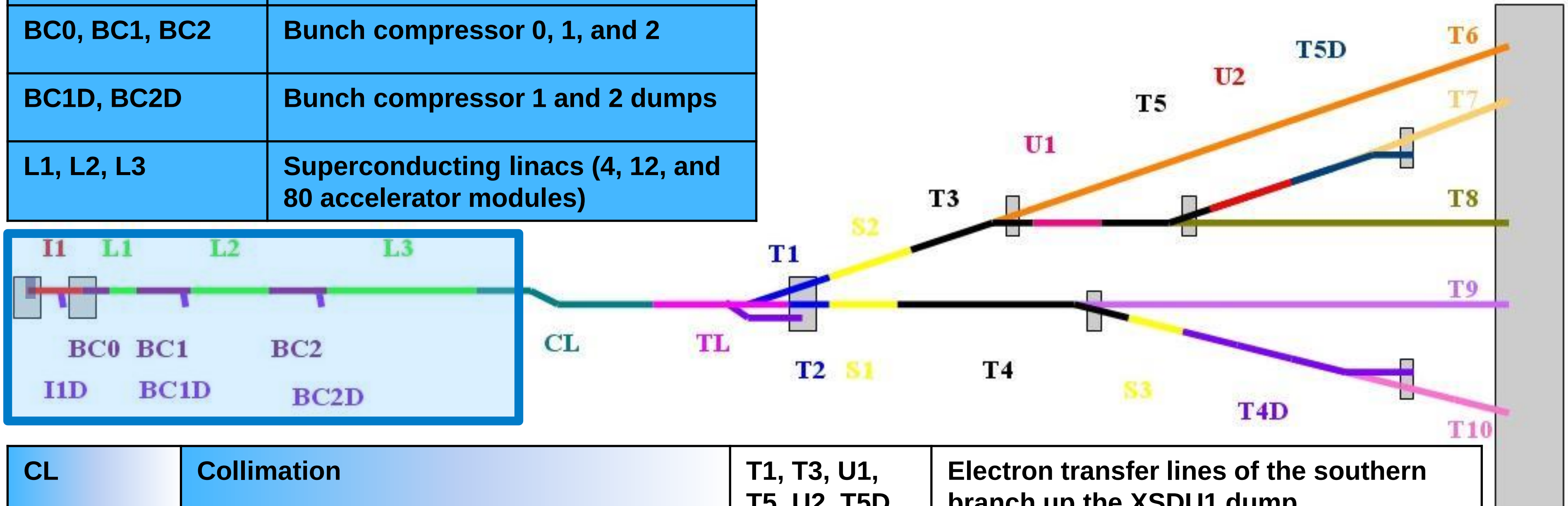
- **Inside**
  - **Vacuum**
    - Pro: Particulates will not move
    - Con: More effort e.g. additional valves, gauges, pumpdown and venting
    - Justified for the most critical components (cavities and modules)
  - **Filtered Nitrogen backfill**
    - Pro: Less effort
    - Con: Components more sensitive to particulate transport which have been dislodged by vibration
    - Use for simpler components like bellows
    - Or even not so simple ones….
- **Outside**
  - Double bagged in antistatic foil




XM 47
European XFEL
ABB

Example XFEL: Overview of “Particle-Free” Sections

I1, I1D	**Injector, Injector dump**
BC0, BC1, BC2	**Bunch compressor 0, 1, and 2**
BC1D, BC2D	**Bunch compressor 1 and 2 dumps**
L1, L2, L3	**Superconducting linacs (4, 12, and 80 accelerator modules)**



CL	**Collimation**	**T1, T3, U1, T5, U2, T5D**	**Electron transfer lines of the southern branch up the XSDU1 dump**
TL, TLD	**Switch-Yard, electron transfer line to XS1 dump**	**S2**	**SASE section of the southern branch**
T2,T4, T4D	**Electron transfer lines of the northern branch up the XSDU2 dump**	**T6, T7, T8**	**Photon transfer lines of the southern branch ***
S1, S3	**SASE sections of the northern branch**		
T9, T10	**Photon transfer lines of the northern branch ***		

And the X-ray optics areas, too.

(not covered here)

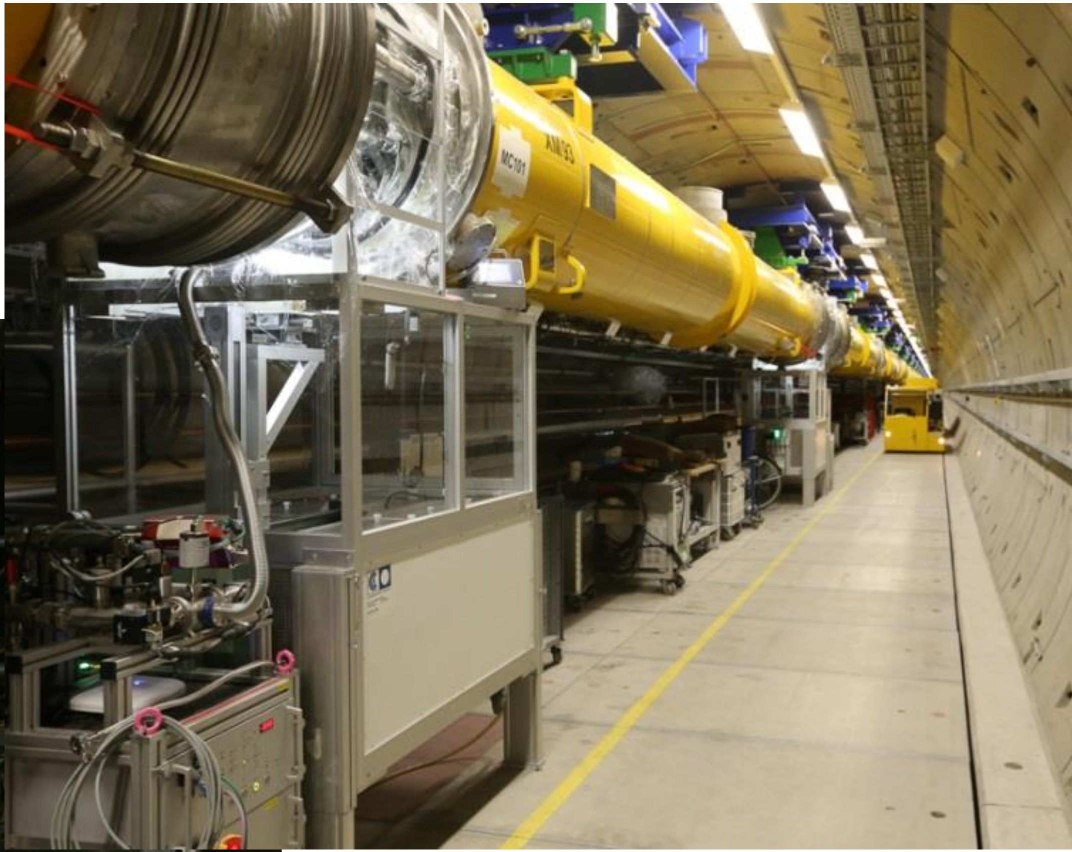
European XFEL

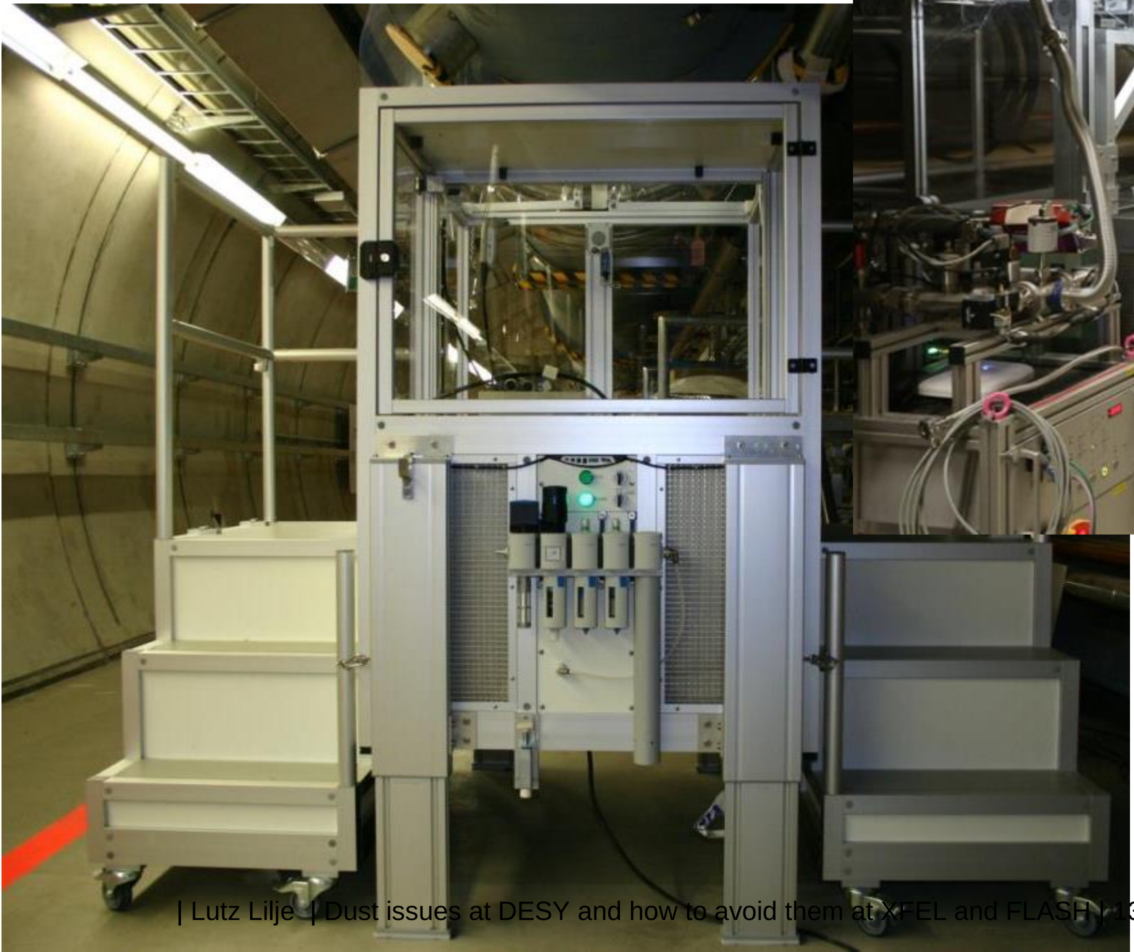
Particle Cleanliness: Segmentation

- Segmentation is important
  - Pumpdown time needs to be acceptable
  - Efficient leak searches
  - Cleaning of subsections in an optimised environment i.e. normal clean room
  - Steel flanges , plastic caps
- Reduction of types and number of flange connections to be made in the tunnel
  - Better reproducibility
  - Time saving

Mobile Clean Rooms: Example XFEL HOM-Absorber

- Air flow from below
- Access from both sides
- Handling system for the component





- Stairs can be removed for transports

Mobile Clean Rooms: Injector Version

- Filter system attached to blower unit and can be tilted
- Access with two people possible

Mobile Clean Rooms: Injector Version

XFEL „Particle-free“ Highlights in Numbers

- 1 RF Gun including cathode handling system
  - Very delicate components, very little space, very demanding requirements
- 38 girders with 5 m each
  - More than 500 different pieces
  - Tubes, pumps, compensators, diagnostics incl. transverse deflecting structure,
- Laser heater chicane
- 3 Bunch Compressor Chicanes
  - Long chambers
  - Large flanges
- 6 pressure stages at warm cold transition
- 3 dump lines
- 60 m warm beam line at the end of the cold linac as a buffer zone
- For the 100 accelerator modules
  - 200 all metal gate valves
  - 800 cavity and 800 coupler bellows
  - 200 coupler pump lines with TSP, sputter ion pump
  - 100 HOM Absorbers
  - Plus testing, installation etc.
- **More than 1,5 km of vacuum chambers have been cleaned (without the cavities)**

XFEL „Particle-free“ Highlights…

- No obvious degradations due to particulates have been observed
  - Previous facilities have shown systematic degradations over the years
- Continuous operation 24/7
  - Scheduled maintenance times
    - About a day every other week
  - Longer shutdowns for upgrades and new features
    - Typically 2-3 weeks
- Availability
  - 95 % over 2020
  - Best weeks in 2022 and 2023 99%!
  - …

Basic Guidelines for a „Particle-free“ Accelerator

- Avoid particulates at every stage and include this requirement into the mechanical design phase already
- Remove particulates at every stage possible (cleaning, cleaning, cleaning)
- Do not produce particulates especially during installation and operation
- Never transport particulates

- … be prepared for reasonable compromises!

Summary

- At DESY particulate-related degradations
  - … have been observed
    - HERA and DORIS suffered from titanium particulates of integrated sputter ion pumps
  - … have been avoided
    - by using NEG pumps generating significantly less particles (PETRA III)
    - by avoiding contaminations using
      - Design, cleaning, controlled environments and gas flows etc.
      - Successful operation large-scale infrastructure like XFEL and FLASH
- Transport of particulates must be avoided to avoid spread of contamination
  - Methods to avoid turbulent flows during pump-down and venting are available

Thank you…

… for your attention…

… please forgive, but before you ask me - I´ll ask you some things.

Questions to the Workshop

This is a little provocative - no offence ...

- Do we really know our prime suspect?
  - I have heard tungsten particulates kickstarted by fireballs, SiO, titanium, AlO and nitrogen snowflakes which can potentially inhibit the operation of high power machines.
  - There are some strong indications for titanium (change of complete vacuum systems and an experiment at KEK) and a little less strong indications (a mass spectrum of an accelerator section with an unknown amount of gas transported into it) for snow flakes.
    - Certainly one has to look into more detail into the simulations, because the pure temperature resistance (melting point) alone does not seem to be the right answer. This is very interesting.
    - Titanium and aluminum oxide won't be the only answer, obviously.
  - From field emission conditioning it is known that gas layers can influence the probability for an emitter to condition i.e. explode (see also starburst patterns). Could gas layers play a role in the detachment of particulates and the interaction with the beam?

- Have we looked at all means of particulate transport?
  - The workshop is biased to accelerator simulations somewhat. It is evident that a high power particle beam causing particulate movements is considered first.
  - Transport, detachment and levitation of particulates due to gas dynamics or vibrations have to be considered. Experiments with "hammers" have been presented here already. One might consider the mechanical pumps as hammers to some degree.

- And as a practical consequence of that question:
  - Do we properly account for all transitions during operation and maintenance:
    - Warm-ups, Cool-downs, Ventings, Pump-downs, Assemblies, Repairs….
  - The need of conditioning after interventions could be a hint to do so.

Contact

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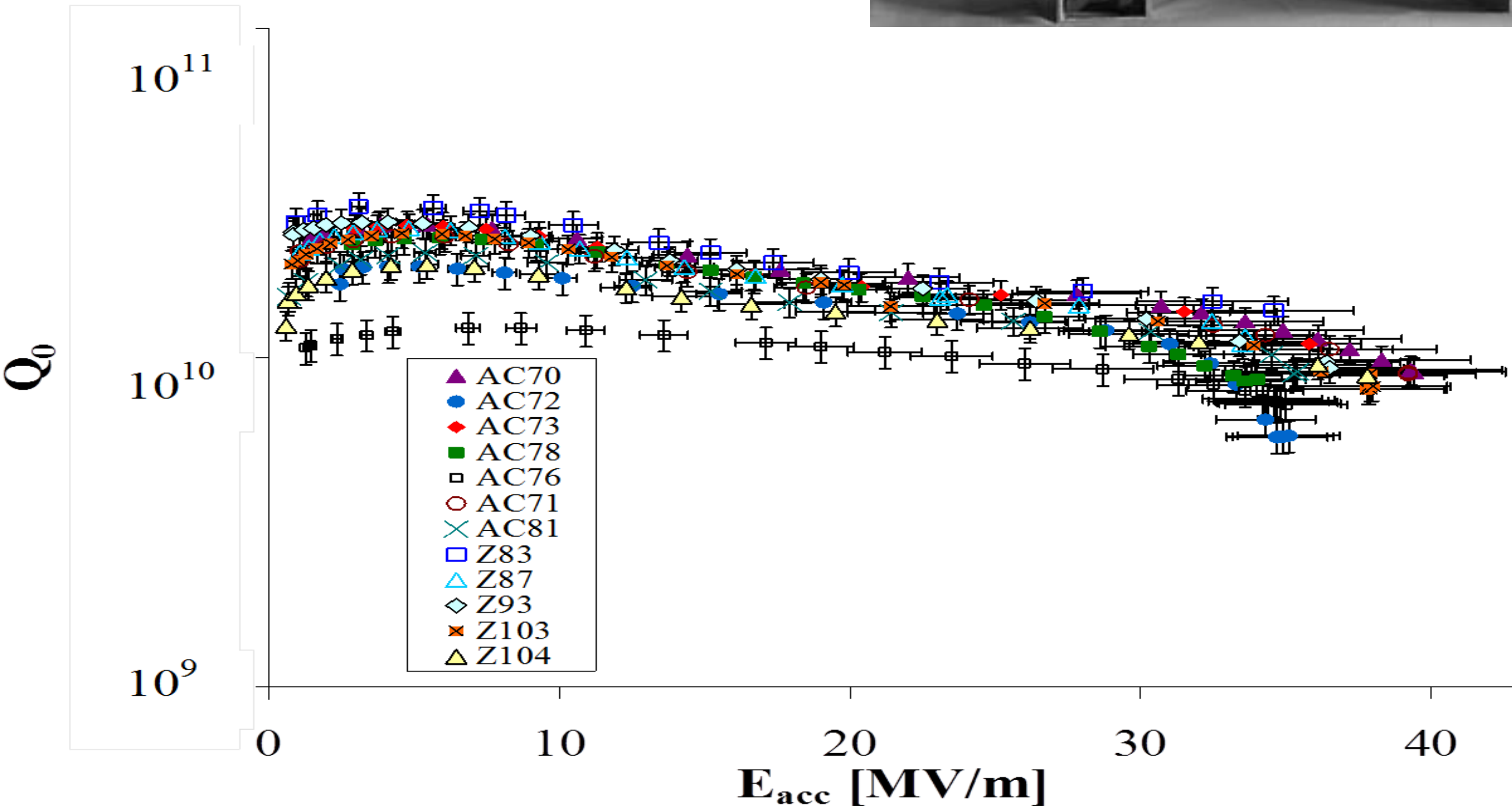
Superconducting Accelerating Cavity Performance



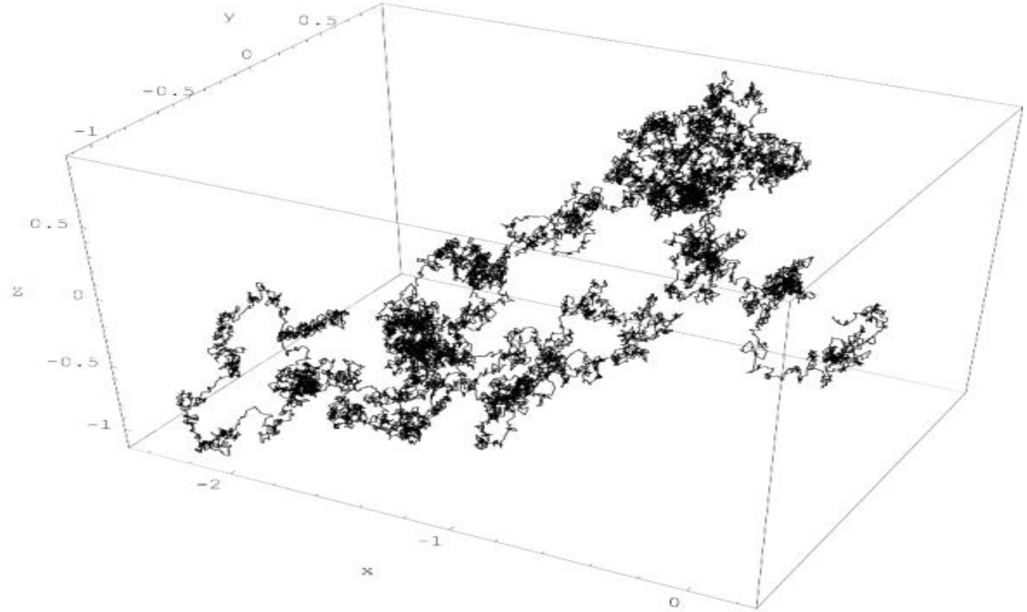
- High quality factor and high accelerating gradient at T=2K
- Very efficient tool to accelerate particle beams even when cryogenic efficiencies are included
- European XFEL uses ~800 of these

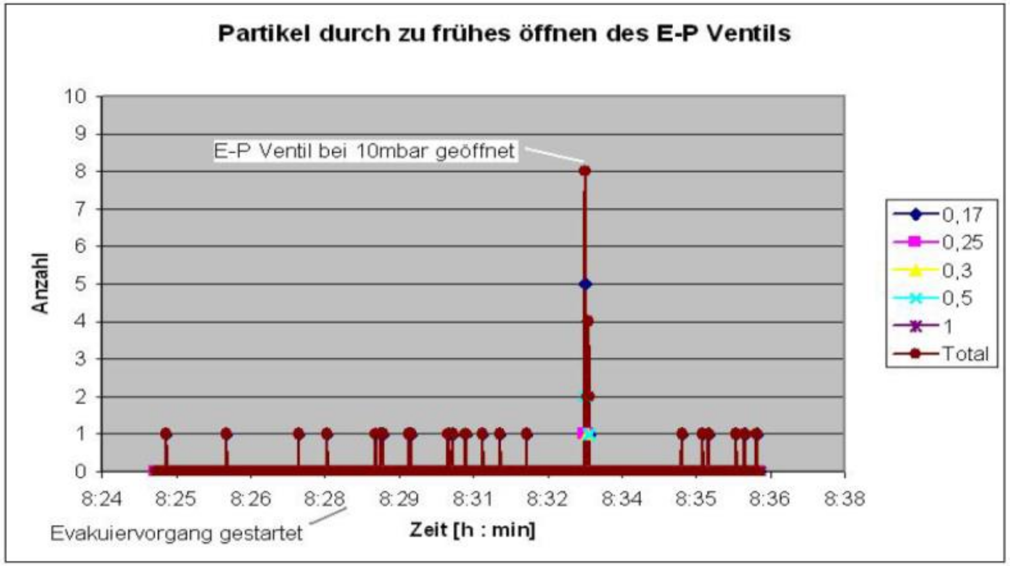
ISO 14644-1 Cleanroom Standards

Class	maximum particles/m^3						FED STD 209E equivalent
	≥0.1 µm	≥0.2 µm	≥0.3 µm	≥0.5 µm	≥1 µm	≥5 µm	
ISO 1	10	2.37	1.02	0.35	0.083	0.0029	
ISO 2	100	23.7	10.2	3.5	0.83	0.029	
ISO 3	1,000	237	102	35	8.3	0.29	Class 1
ISO 4	10,000	2,370	Cavities	352	83	2.9	Class 10
ISO 5	100,000	Electron and photon beam line	[illegible]	[illegible]	[illegible]	29	Class 100
ISO 6	1.0×10^6	237,000	102,000	35,200	8,320	293	Class 1,000
ISO 7	1.0×10^7	2.37×10^6	1,020,000	352,000	83,200	2,930	Class 10,000
ISO 8	1.0×10^8	2.37×10^7	1.02×10^7	3,520,000	832,000	29,300	Class 100,000
ISO 9	1.0×10^9	2.37×10^8	1.02×10^8	35,200,000	8,320,000	293,000	Room air

Mass of Particulates

- They have mass
  - 6,2 mg per m^2 per day …
- In vacuum they fall down
  - A particle needs a few ten milliseconds to traverse a typical beam pipe (if only accelerated by gravity)
- BUT: They have only a small mass
- They will be transported in gaseous media at pressures above 1 mbar.
  - Opening an angle valve at 10 mbar while pumping a system

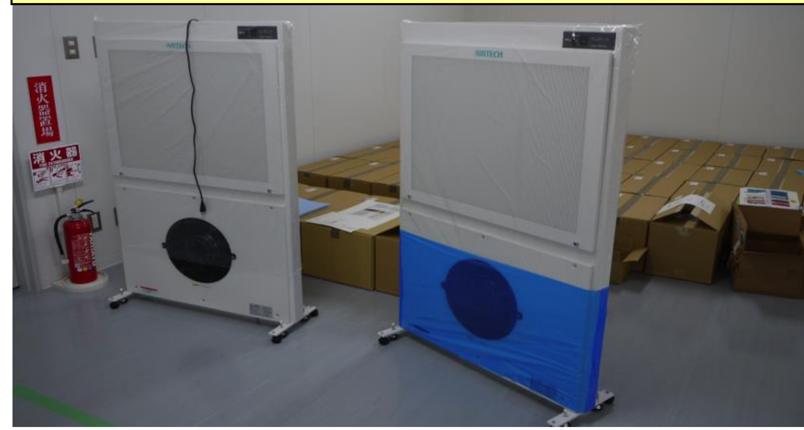




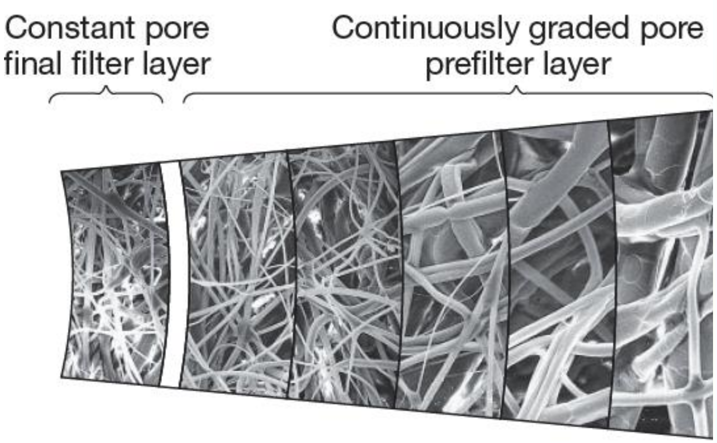
Size of Particulates

- Typical particulates are of micrometer size
- Countermeasures:
- Filter media like air and process fluids appropriately
- Depth and membrane filters
  - 0,3 µm filters are readily available and standard nowadays
  - Air filters i.e. cleanroom environment
  - Filter liquid media
    - Water for rinsing e.g. HPR for superconducting cavities

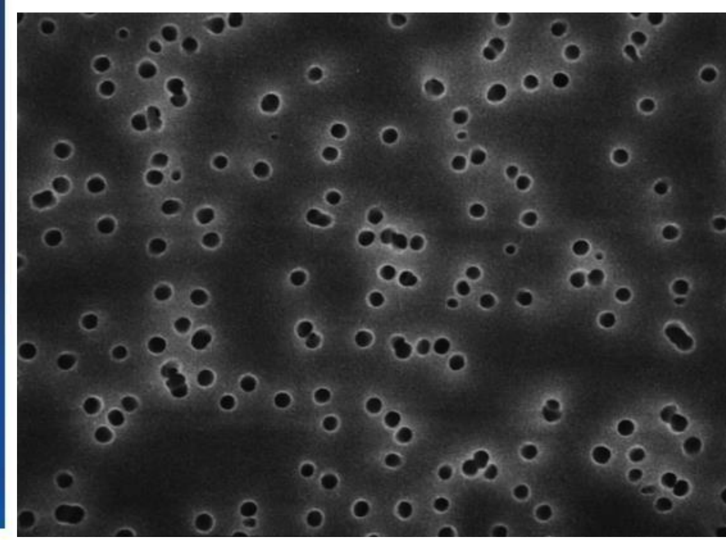
High efficiency particulate air (HEPA) filters , Spring8



Examples of depth filter Material, PALL brochure



Membrane filter 0,4 µm , Merck/Millipore



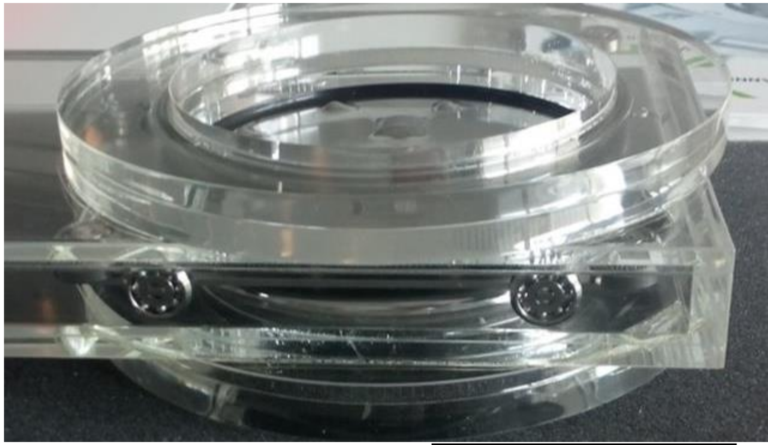
Forces on Particulates

- They stick to the surface: Van der Vaals
- BUT: They can be detached easily by mechanical vibration already
- A vented vacuum system needs more care
  - Particles can be dislodged and moved too places where they might really hurt

- Countermeasures using forces for cleaning:
  - Ionized nitrogen blowing
  - Ultrasonic cleaning
  - High pressure water rinsing
  - Dry-ice cleaning

Particulate Sources in Accelerator Operation

- Accelerator operation inevitably leads to the production of particulates
- Moving components generate dozens to hundreds of particles
  - Diagnostic components e.g. screens
  - Valves
- Movements of valves should be minimised in critical areas
  - Only in emergency
  - Persons entering the area
- RF fingers and sliding contacts
  - Electrical contact required
  - Movements generate particulates
  - Experiences?
- (Beam hitting material)
- Pumps



Gate Valve Model
CAS2017

LHC Beam Tube Interconnection
CAS2017

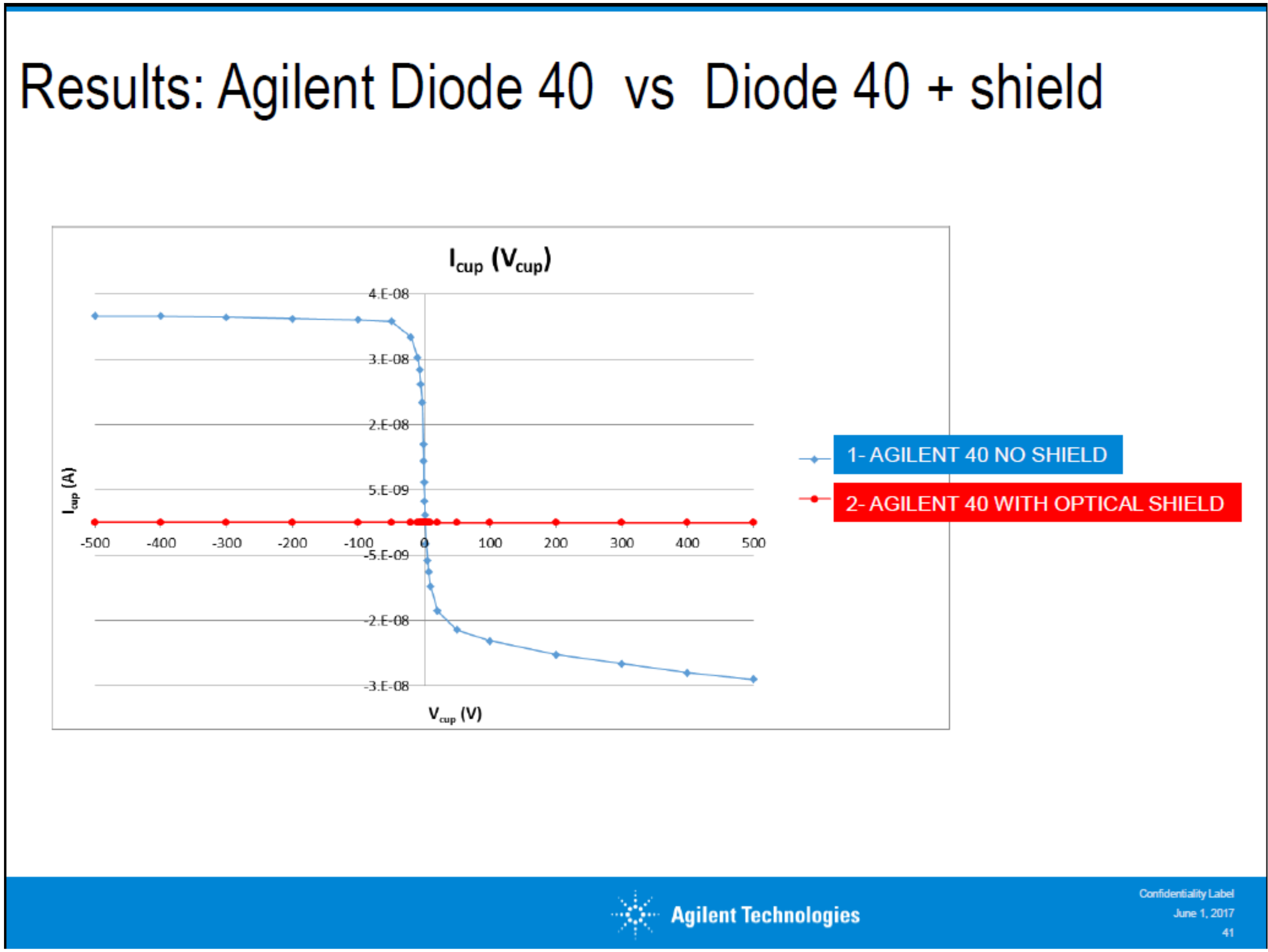
Pumps and Particulates: Mechanical Pumps

- Particle Production is certainly possible
- E.g. Scroll Pumps
- Photo is probably an exaggeration
- With regular maintenance and quality control, scroll pumps have not shown to be an issue (yet)
- Design of the pumping stations is crucial
  - Additional valve for protection mandatory
- DESY has experience during XFEL assembly and installation

Mechanical Vacuum Pumps, H. Barfuss (Pfeiffer Vacuum), CAS2017

Pumps and Particulates: Sputter Ion Pumps

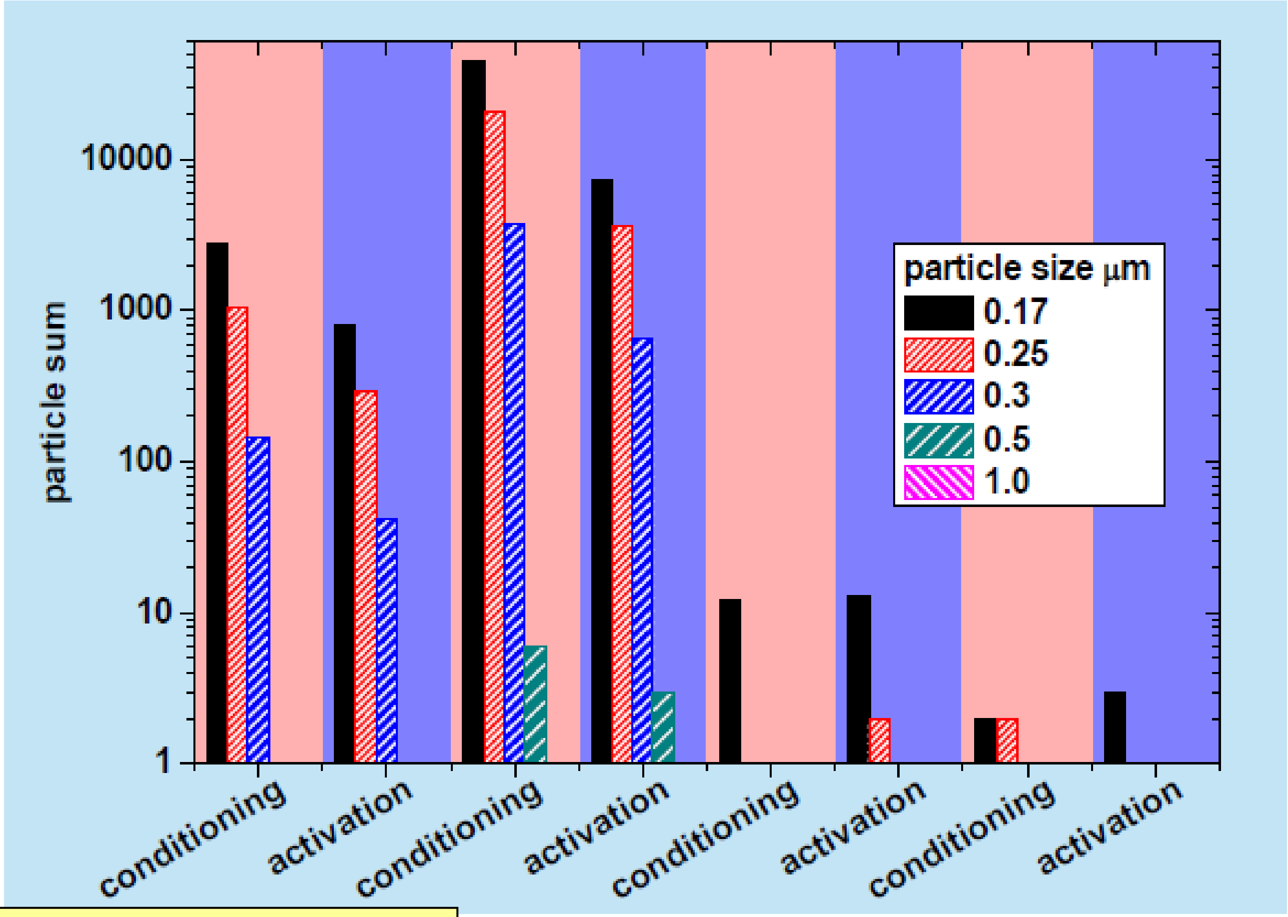
- Have shown problems when integrated into vacuum chambers e.g. HERA
- Standard ion pumps have shown particle production
  - Initial start-up
  - At high pressures
- Measures exist to reduce particle transport e.g. optical shields



Ion Getter Pumps
C. Maccarrone (Agilent), CAS2017

Pumps and Particulates: NEG cartridges

- Tests on CapaciTorr pumps for several conditioning and activation cycles
- Number of particulates generated is at acceptable levels after 4 repetitions



S. Lederer et al., IPAC 2017

Vacuum Systems Specifications of the European XFEL Accelerator: Warm Beam Line

Requirements from beam dynamics
Except μ_r and RF-shielding absolutely new requirements
on an accelerator vacuum system

	Material properties			alignment		RF shielding	Vacuum (**)	
	conductivity	rel. magnetic permeability μ_r	R + 50*O	max. step at flanges	max. longitudinal gap	Flanges, bellows, pumps, valves	Particle free	Average pressure
	µΩcm		nm	mm	mm			mbar
RF-gun (up to L0)	75	<1.01	---	---	---	---	ISO 5	$< 10^{-10}$
I1, BC0, BC1-, BC2-chicane	3	1.01	1250	0.2	0.5	YES	ISO 5	$< 2\ 10^{-8}$ *
I1, BC1, BC2 dump	3	1.05	2000	0.2	0.5	NO	ISO 5	$< 2\ 10^{-8}$
BC1,2	3	1.05	1250	0.2	0.5	YES	ISO 5	$< 2\ 10^{-8}$ *
CL, TL, T1, T2, T3. T4, T4D, T5, T5D, U1, U2	3	1.05	1250	0.2	0.5	YES	NO	$< 2\ 10^{-8}$ *
S1, S2, S3	3	1.01	550	0.1	0.5	YES	NO	$< 2\ 10^{-7}$
Right in front of main dumps	3	1.05	2000	0.2	0.5	NO	NO	$< 2\ 10^{-8}$

(*) close to SRF modules 10^{-10} mbar
(**) In addition all components have to be in accordance to the DESY vacuum specification

European XFEL