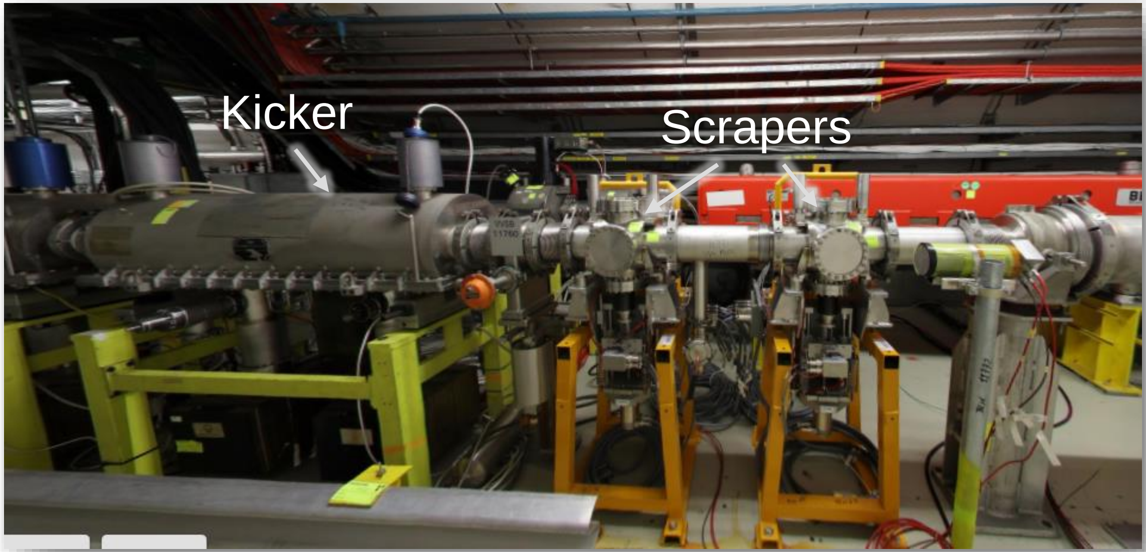
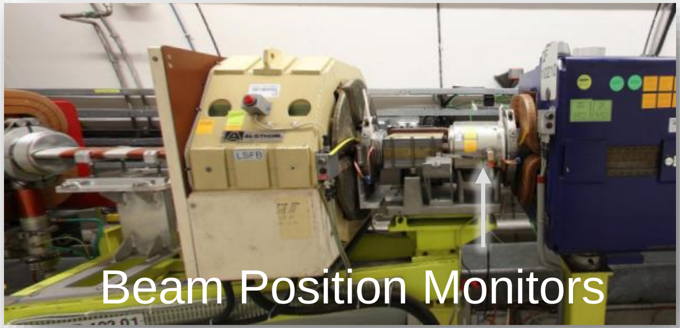
VACUUM ACCEPTANCE TESTS FOR PARTICLE ACCELERATOR COMPONENTS AT CERN

OUTLINE

- What is a vacuum acceptance test?
- Why is it needed?
- How is it performed? which physical quantities and information are we interested in?
- How to use the results?
- Few examples;
- What happens in case of non conformity?
- Some statistics.

What is a vacuum acceptance test of a component of a particle accelerator?





In order to check if the component outgassing and eventual contamination can alter the vacuum conditions of the accelerator, specific tests are performed to evaluate its gas load and its residual gases footprint.

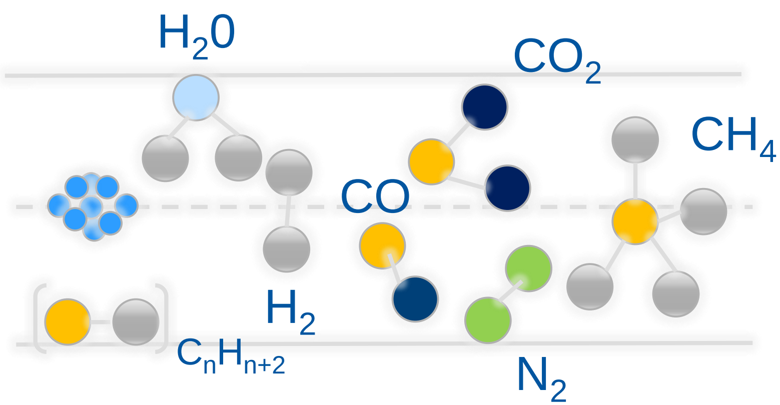
Why is it needed?

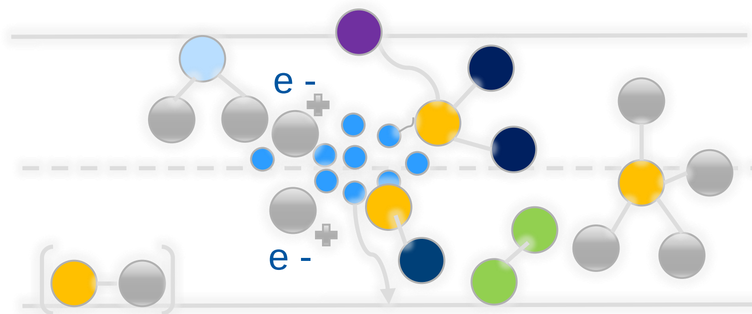
- In order to guarantee a certain beam lifetime, or certain machine operation conditions, a maximum acceptable pressure is defined for each machine. Therefore, vacuum components' outgassing and residual gas analysis have to be compliant with these acceptance levels.
- One of the main mandates of TE-VSC is to provide beam operation with the required vacuum in our accelerators.

Questions box:
- Is the existing pumping layout going to cope with the additional gas load?
- Is the component going to degrade the beam vacuum?(leaks, hydrocarbons..)
- For new layouts: do I have to modify the vacuum layout accordingly? Or foresee a specific procedure for critical components?
- Is the component going to limit the machine operation?

REMINDER!! Outgassing rates spans over orders of magnitude, while the effective pumping speed is conductance limited.

Beam and residual gas interactions





Types of interactions:

- Nuclear interactions → high energy particles ( ) → particle loss, radiation to equipment and background to detectors;
- Electromagnetic interactions → elastic scattering → emittance growth;
  → inelastic scattering → energy spread;
- Ionisation of residual gases → Ion induced desorption;
  → e- cloud;
- Synchrotron radiation → photon induced desorption;
  → e- cloud;

Beam instabilites and particles loss

Beam and residual gas interactions

Particles loss leads to a decrease of bunch population:

$$N(t) = N_0 * e^{-t/\tau}$$

where

$$1/\tau = \sigma * f * \theta$$

$N_0 =' nominal' bunch\ population$
$\tau = beam\ lifetime$
$\sigma = interaction\ cross\ section$
$f = frequency\ of\ interaction$
$\theta = gas\ density$

The probability of a certain interaction depends on the **mass** of the molecule (Z) and **energy** of the particles.

Ex. LHC

GAS	Nuclear scattering cross section(cm^2)	Gas density (m^{-3}) for a 100 hour lifetime
H_2	$9.5\ 10^{-26}$	9.810^{14}
He	$1.26\ 10^{-25}$	7.410^{14}
CH_4	$5.66\ 10^{-25}$	1.610^{14}
H_2O	$5.65\ 10^{-25}$	1.610^{14}
CO	$8.54\ 10^{-25}$	1.110^{14}
CO_2	$1.32\ 10^{-24}$	$7\ \ 10^{13}$

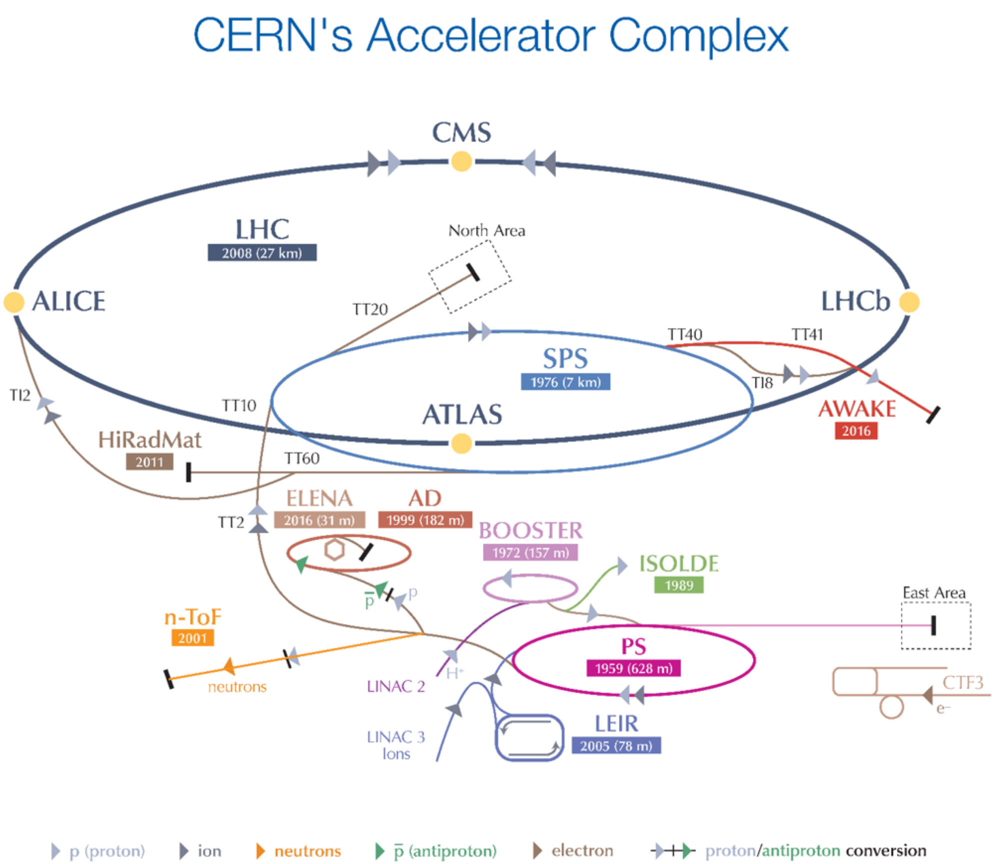
LHC vacuum system, O.Grobner

Particle accelerator vacuum requirements

Beam lifetime is crucial, but is only a part of the full picture:

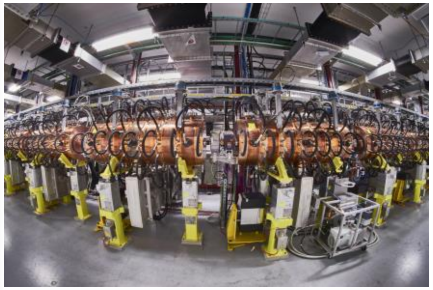
- EQUIPMENT REQUIREMENTS:
  - UHV insulating conditions for high voltage component (septa, kickers);
  - MACHINE OPERATION:
  - Beam downtime: operation should be resumed ASAP!

Operating pressure levels for CERN accelerator complex



Pressure spans over orders of magnitudes!

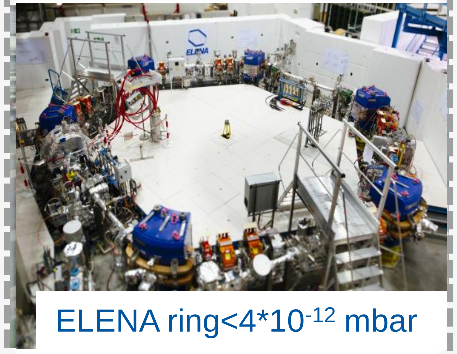
Operating pressure levels for CERN accelerator complex



Linac 4 <2*10^{-6} mbar*

PSB <5*10^{-8} mbar*

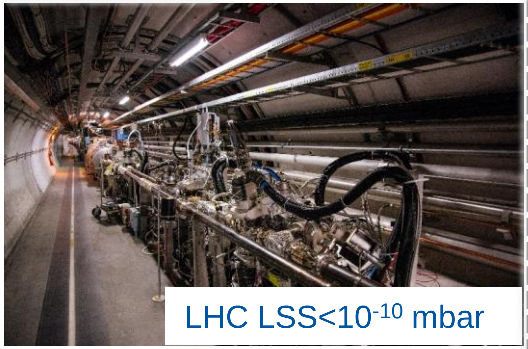
PS<2*10^{-8} mbar*



ELENA ring<4*10^{-12} mbar

SPS LSS <10^{-7} mbar*

LHC arcs <10^{-8} mbar



LHC LSS<10^{-10} mbar

UNBAKED SYSTEMS (SEPTA..):
- TMP, ION PUMPS;
- SUBLIMATORS;

CRYO SYSTEMS:
- CRYOPUMPING;

BAKED SYSTEMS:
- ION PUMPS;
- Non Evaporable Getter (TiZrV) coating

* 24h pumpdown

Pressure requirements for LHC and ELENA

LHC

Area	Pressure requirements	Effective pumping speed (indicative)
Arcs	≤10^{-8} mbar	≥100 $l.s^{-1}$
Experiments	≤10^{-10} mbar	

GAS	Nuclear scattering cross section(cm^2)	Gas density (m^{-3}) for a 100 hour lifetime
H_2	$9.5\ 10^{-26}$	$9.8\ 10^{14}$
He	$1.26\ 10^{-25}$	$7.4\ 10^{14}$
CH_4	$5.66\ 10^{-25}$	$1.6\ 10^{14}$
H_2O	$5.65\ 10^{-25}$	$1.6\ 10^{14}$
CO	$8.54\ 10^{-25}$	$1.1\ 10^{14}$
CO_2	$1.32\ 10^{-24}$	$7\ \ 10^{13}$

LHC ACCEPTANCE THRESHOLDS
Ensures 100 h of circulating beam lifetime and minimize the background to the experiments.

ELENA

Area	Pressure requirements	Effective pumping speed (indicative)
Ring	≤4 x10^{-12} mbar	Depend upon position (NEG sticking probability)
Transfer lines	≤10^{-10} mbar	

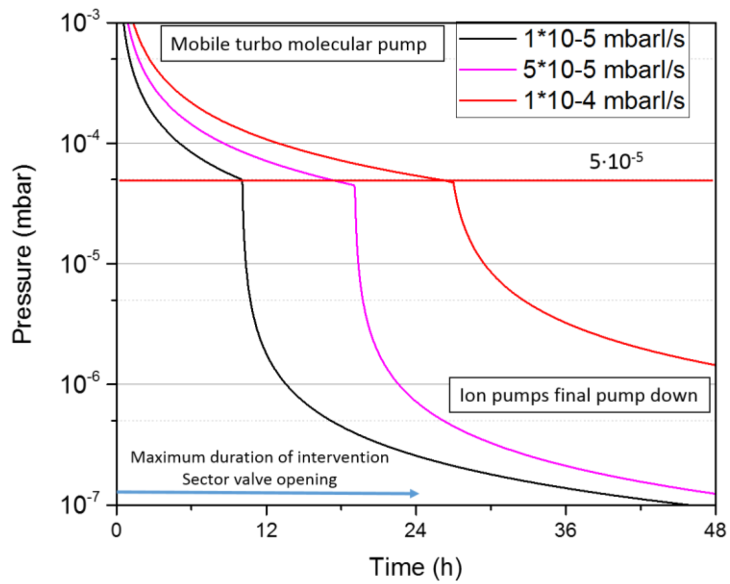
ELENA ACCEPTANCE THRESHOLDS
Ensures the limitation of momentum and emittance blow up induced by the interaction of a low energy (100 keV) antiproton beam with residual gases.

In both examples, the pressure requirements are driven by **beam lifetime** requirements.

Pressure requirements for the LHC Injectors

Accelerator	Area	Operational pressure requirement (24h pumping) [mbar]	Average effective pumping speed (indicative) [l s⁻¹]	Outgassing rate limit at 24 h [mbar.l.s⁻¹]
PS complex	LINACS, ISOLDE AND TRANSFER LINES CLOSE TO PSB AND PS	$\leq 2.10^{-6}$	100	$5 \cdot 10^{-5}$ (*)
	PSB, HIE-ISOLDE, REX AND TRANSFER LINES CLOSE TO THE PS RING	$\leq 5.10^{-8}$	100	5.10^{-6} (*)
	PS ring	$\leq 2.10^{-8}$	70	$1.5.10^{-6}$ (*)
SPS	Arcs	$\leq 10^{-6}$	10	10^{-5}
	LSS (kickers, septa, RF cavities)	$\leq 10^{-7}$	100	10^{-5} (*)
	TI2&TI8: From SPS to TED	$\leq 10^{-5}$	1-2	2.10^{-5}
	TI2&TI8: From TED to LHC	$\leq 5.10^{-7}$	5	$2.5.10^{-6}$

SPS ARCs PUMPDOWN



- Ensure beam operation after 24h pumpdown;
- Ensure proper functioning of High Voltage and RF devices;
- Ensure ion operation at low energy (e.g. LEIR, PS);

→ We must comply with beam requirements minimising the beam downtime

What about contaminations?

3. DETECTION OF CONTAMINATION

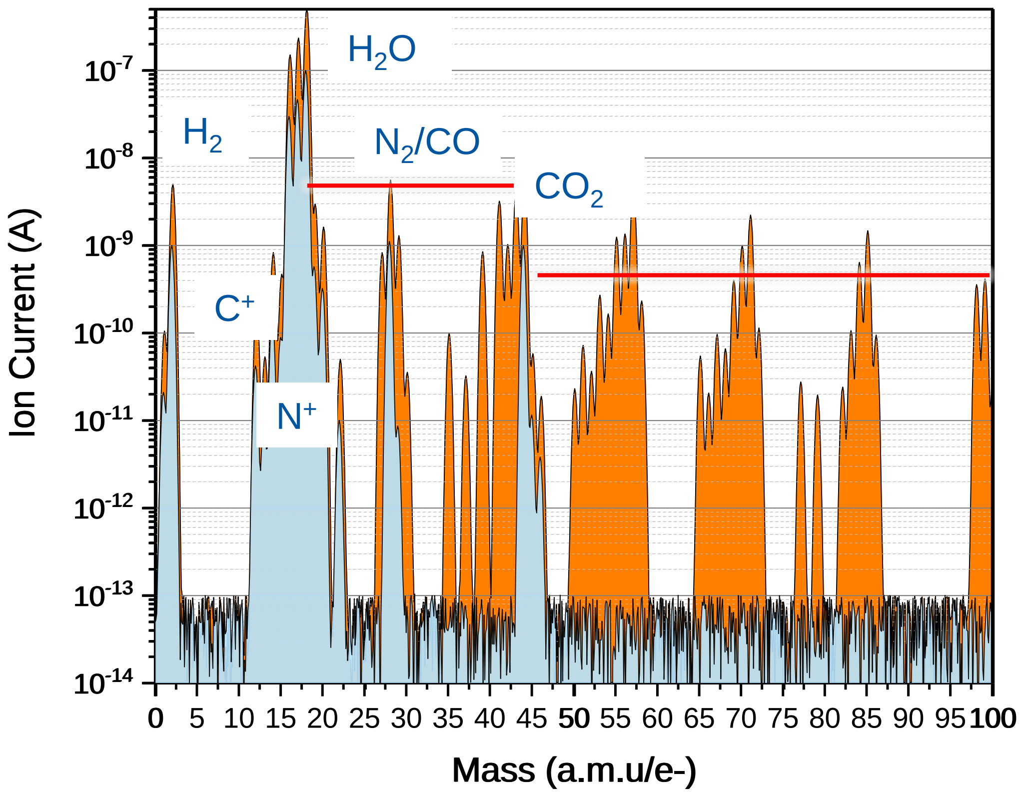
We consider as a sign of contamination:

- an anomalous presence of **hydrocarbons**, most probably due to error in design and/or lack of appropriate cleaning (error in cleaning procedure or post-cleaning pollution); inappropriate choice of materials (polymers, glues, lubricants …);
- higher than expected **CO and CO_2 outgassing** indicating the presence of carbonized elements;
- any chemical element or compound usually not present in the residual gas phase, for example, F and Cl (issue with etching and cleaning), K and Na (manipulation), P and S (issue with electrolytic treatments).

The acceptance criteria are based on characteristic RGA mass peaks normalized to the usual dominant gas peak (18 and 2 amu in unbaked and baked systems, respectively). The threshold limits originate from extensive experience (EDMS 1347196), beam-gas interaction concerns (Z^2), and effects on the pumping speed of NEG pumps.

Criteria for vacuum acceptance tests, P. Chiggiato, J.A.F. Somoza, G. Bregliozzi, EDMS 1752123

Contamination acceptance levels for unbaked components

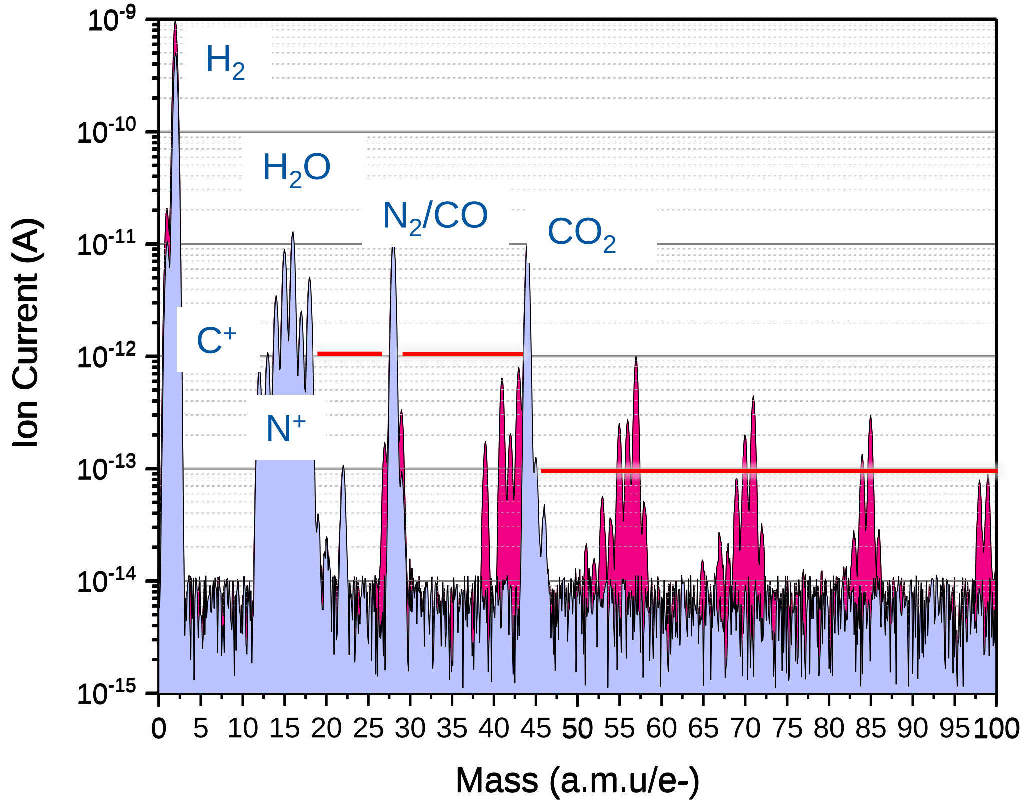


cPS, SPS, transfer lines

The unbaked component is considered accepted if the ratio between the water peak and the peaks up to mass 44 is higher then 100 and if the same ratio is higher then 1000 for peaks above mass 44.

*simulated spectra

Contamination acceptance levels for baked components



e.g. LHC, AD, ELENA

For baked components the H_2 peak becomes the reference with a more stringent acceptance criteria (i.e. 10^4 ratio for masses > 44).

*simulated spectra

What about leak tightness?

- Helium leak rate acceptance threshold is $1*10^{-10}$ mbar *l/s;
- A leak is an indication of possible material defects (precipitates, cracks..), flaws in the fabrication process or in the mechanical assembly.
- No deviation from this value are accepted.

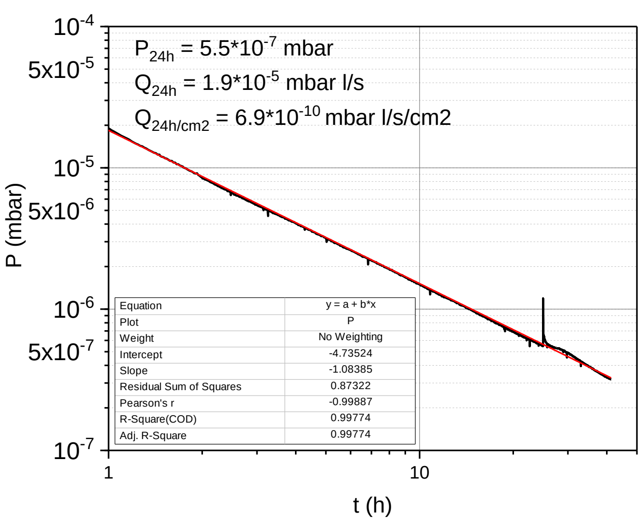
External Leak

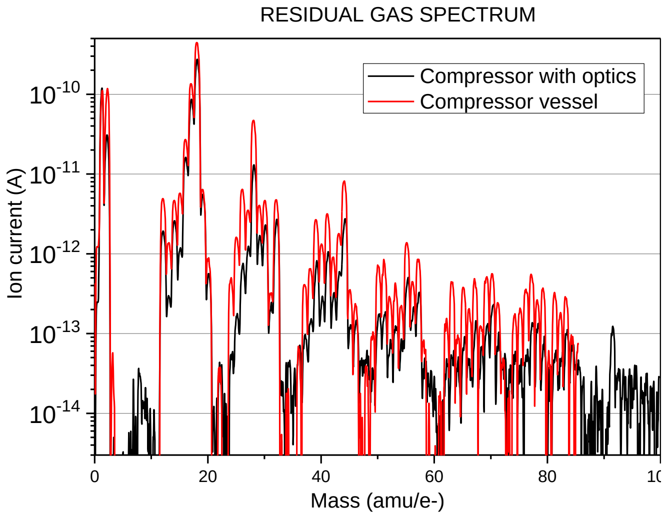
- Internal leak rate acceptance threshold is < $5*10^{-9}$ mbar*l/s both for LHC (NEG saturation), Injectors (<20% of the total pressure).
- It is an indication of flaws in the conceptual design (trapped volumes).
- Leak can be evaluated by accumulation;

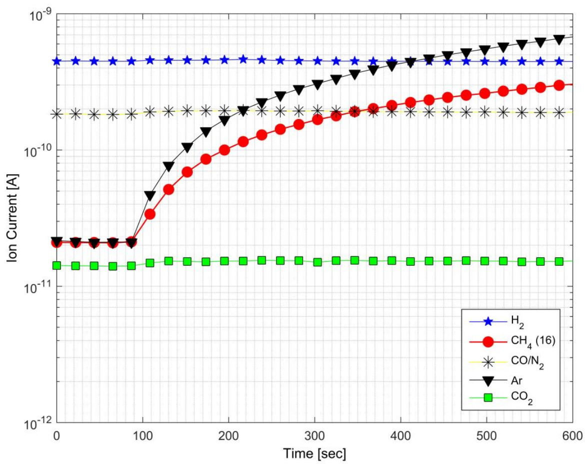
Internal leak

Finally, a vacuum component is accepted for installation if…

- ✓ It is leak tight;
- ✓ Its outgassing is compliant;
- ✓ Its residual gases spectrum is compliant;
- ✓ If no virtual leaks or acceptable virtual leaks are detected.

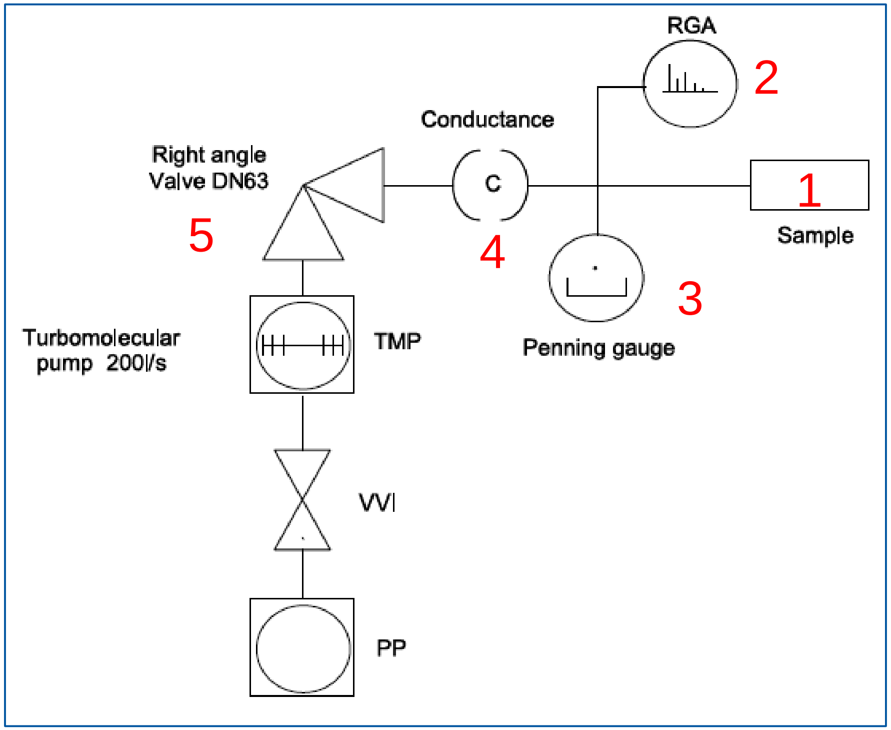






How is a vacuum acceptance test performed?

THROUGHPUT METHOD:



The pressure rise method (accumulation) and the coupled method (througput + accumulation) are often used as well.

How is an acceptance test performed?

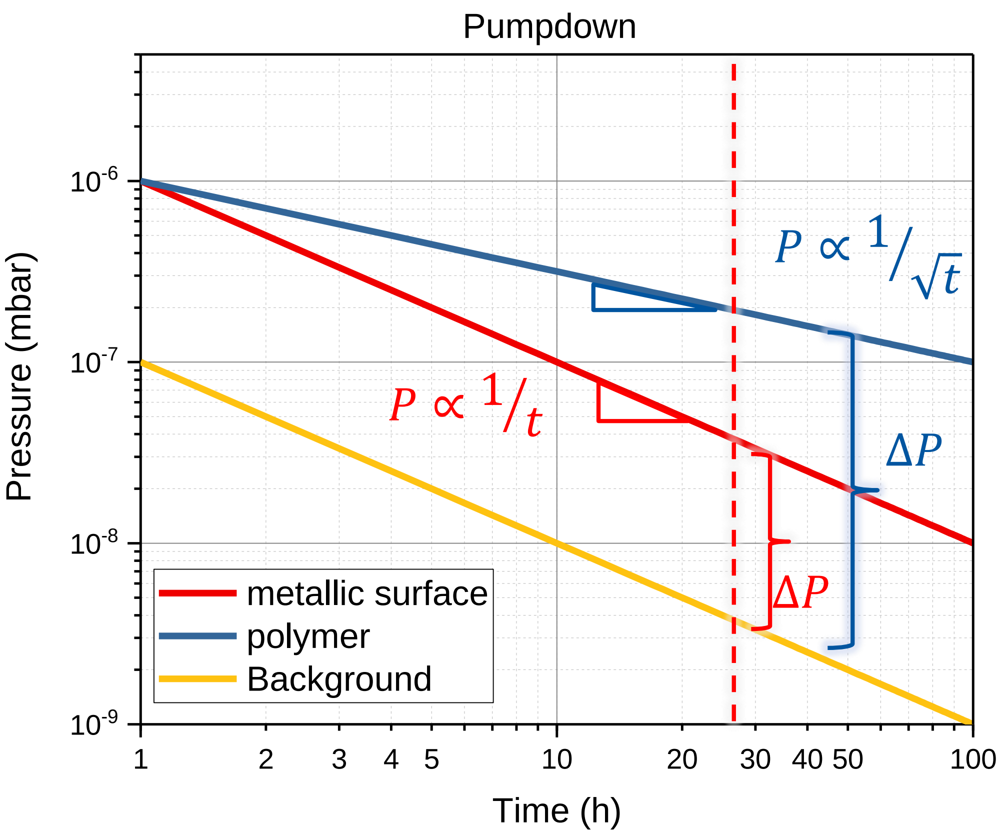
UNBAKED COMPONENTS

- Pumpdown;
- Leak detection;
- Outgassing estimation at 24h;
- RGA scan after 4h of filament conditioning.

BAKED COMPONENTS

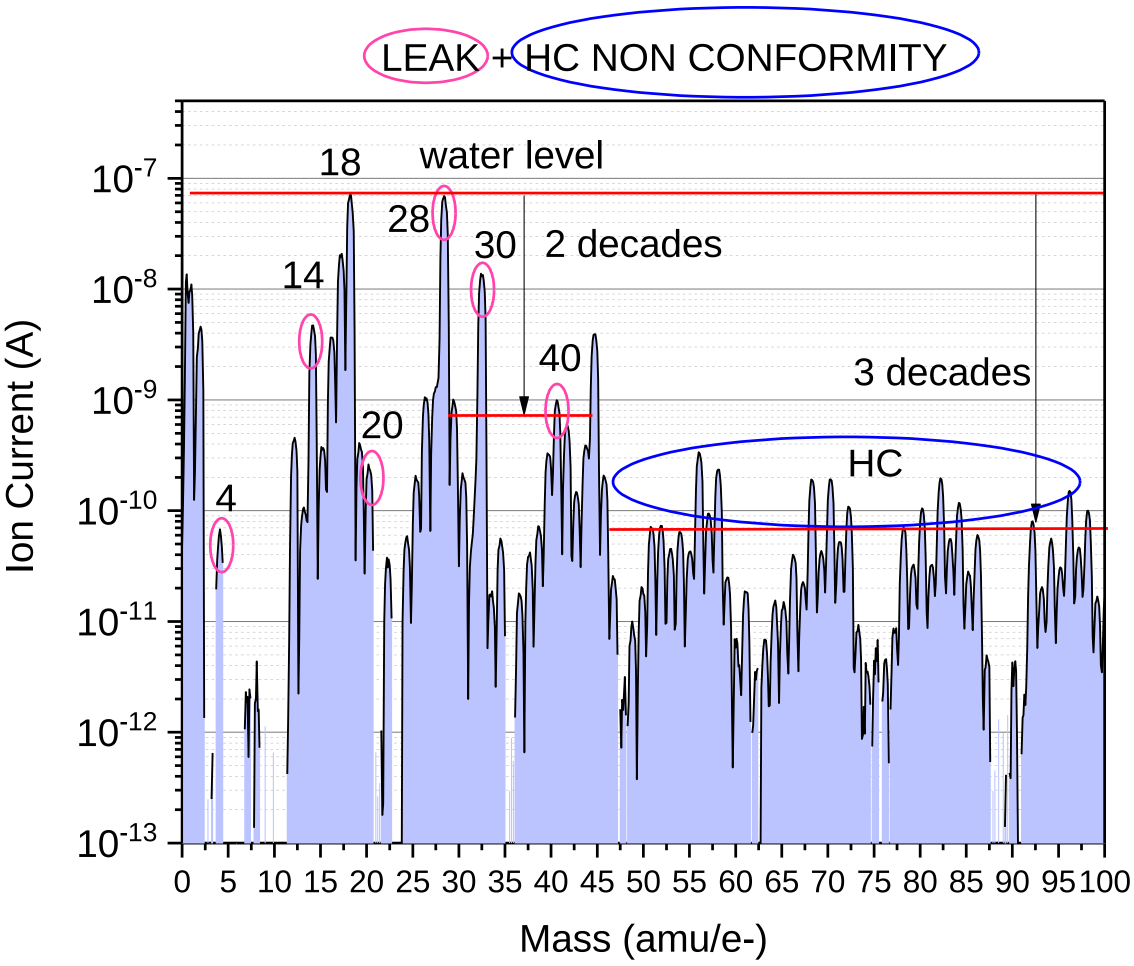
- Pumpdown;
- Leak detection;
- Bake – out (dedicated recipes for specific components);
- Outgassing evaluation at RT after 48h from the end of the bake-out;
- RGA scan;
- Evaluation of possible internal leaks by accumulation.

Which physical quantities and information are we interested in? Pumpdown curve



- Outgassing rate:
  - Unbaked components:
    - $Q_{N2} = (P_{component@24h} -$

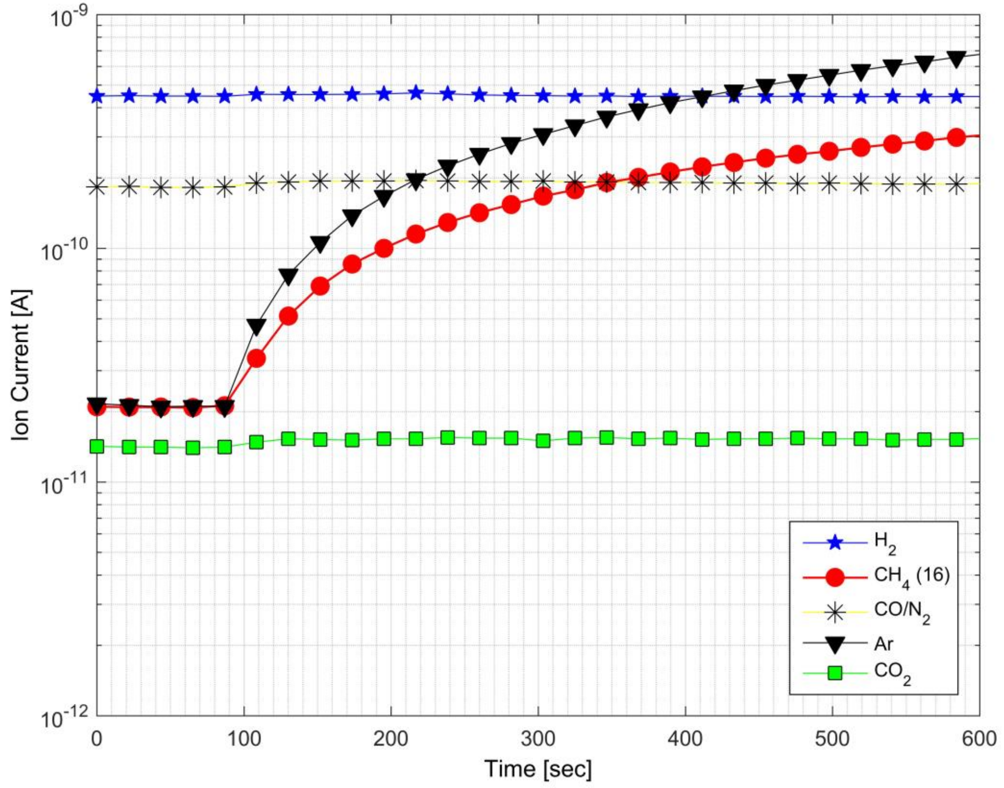
Which physical quantities and information are we interested in? Residual Gas Analisys



The residual gas scan up to 100 a.m.u./e- gives an insight of the residual gases composition: once compared with the system scan, it is possible to attribute to the component its outgassing footprint.

- In this example:
  - Leak?
  - Hydrocarbon contamination?

Which physical quantities and information are we interested in? Internal leak



Leak / internal leak evaluation by accumulation:

$$\Delta P = {Q_{tot}}/{V} * t$$

With a calibrated RGA, an estimation of the leak rate can be obtained by analysing mass 40, 20 pressure rises.

Which physical quantities and information are we interested in? NEG coated components

Getter surfaces are characterized by the sticking probability:

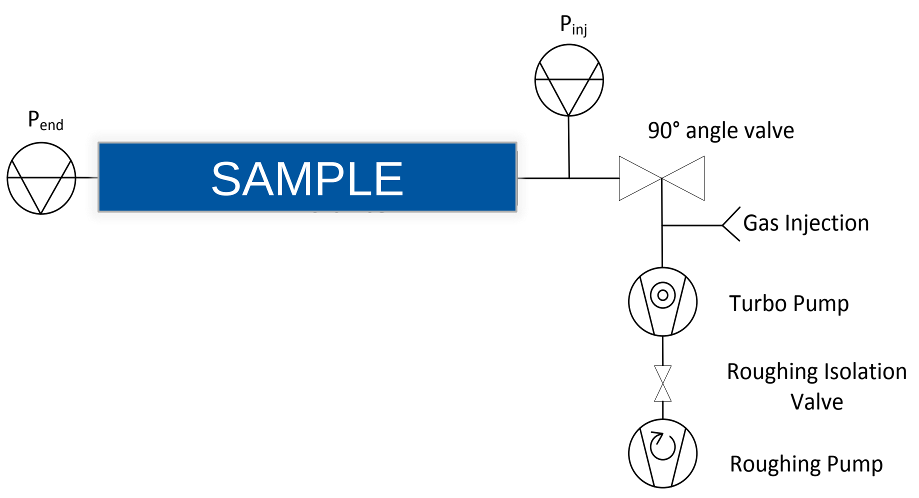
$$\alpha = \frac{number\ of\ molecules\ captured}{number\ of\ molecules\ impinging} \qquad 0 \leq \alpha \leq 1$$

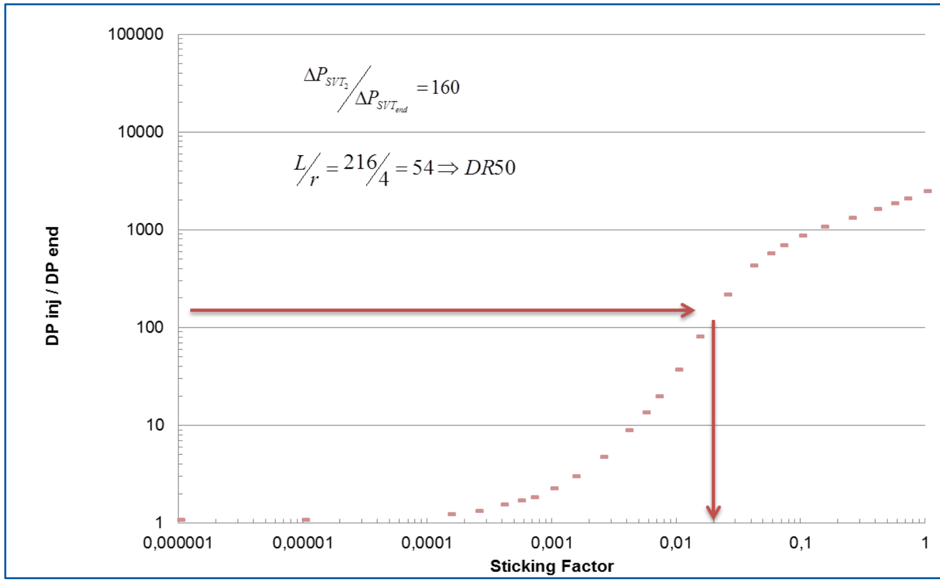
The sticking probability cannot be directly measured, it is obtained by combining experimental pressure measurements and MolFlow simulations.
Two methods are used:

- Fisher-Momsen dome, where the probability that a molecule entering the deposited component is pumped at the surface (capture probability) is evaluated.
- Measurement in transmission, where the probability that a molecule is not pumped and it is transmitted through a component is evaluated.

Which physical quantities and information are we interested in? NEG coated components

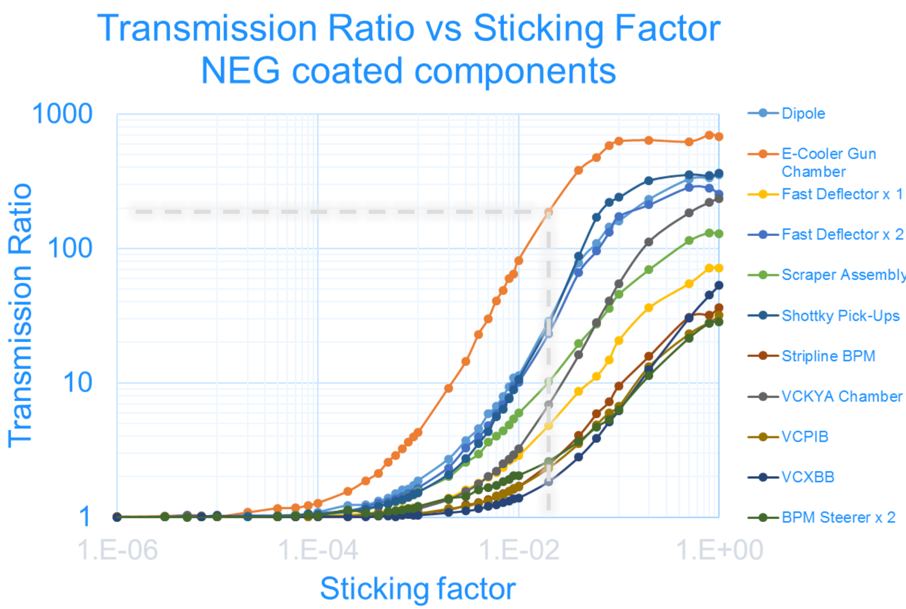
Transmission Probability of NEG coated components

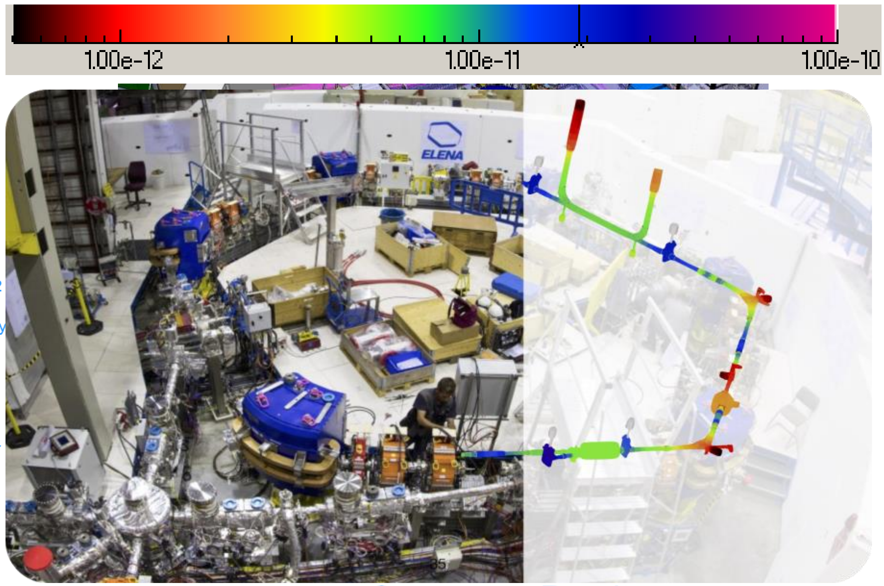


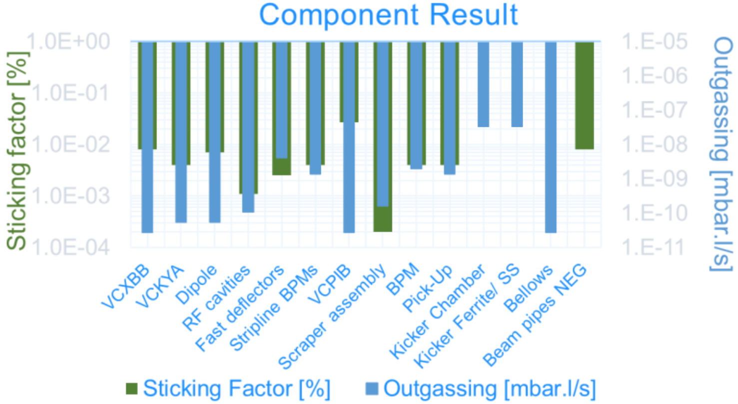


The measured pressure difference must be correlated through a Molflow simulation to the actual sticking probability of the coated surface.

Which physical quantities and information are we interested in? NEG coated components







Courtesy of J. Hellstrom

How do we use these results?

- Compare them with the acceptance levels:
  - Depending on the machine;
  - Depending on the final location of the component (local effective pumping speed);
  - The installation of the component is finally accepted, tolerated or rejected.
- For new machine or new layouts:
  - The measured outgassing data can be used as input for vacuum simulations;
  - The vacuum design can be adapted accordingly;

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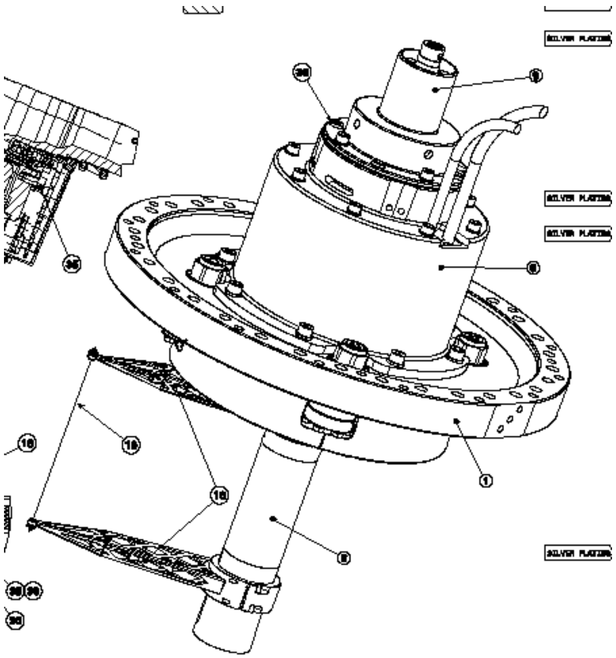
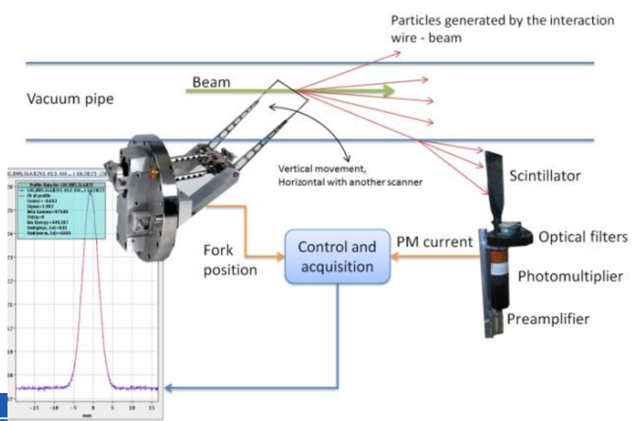
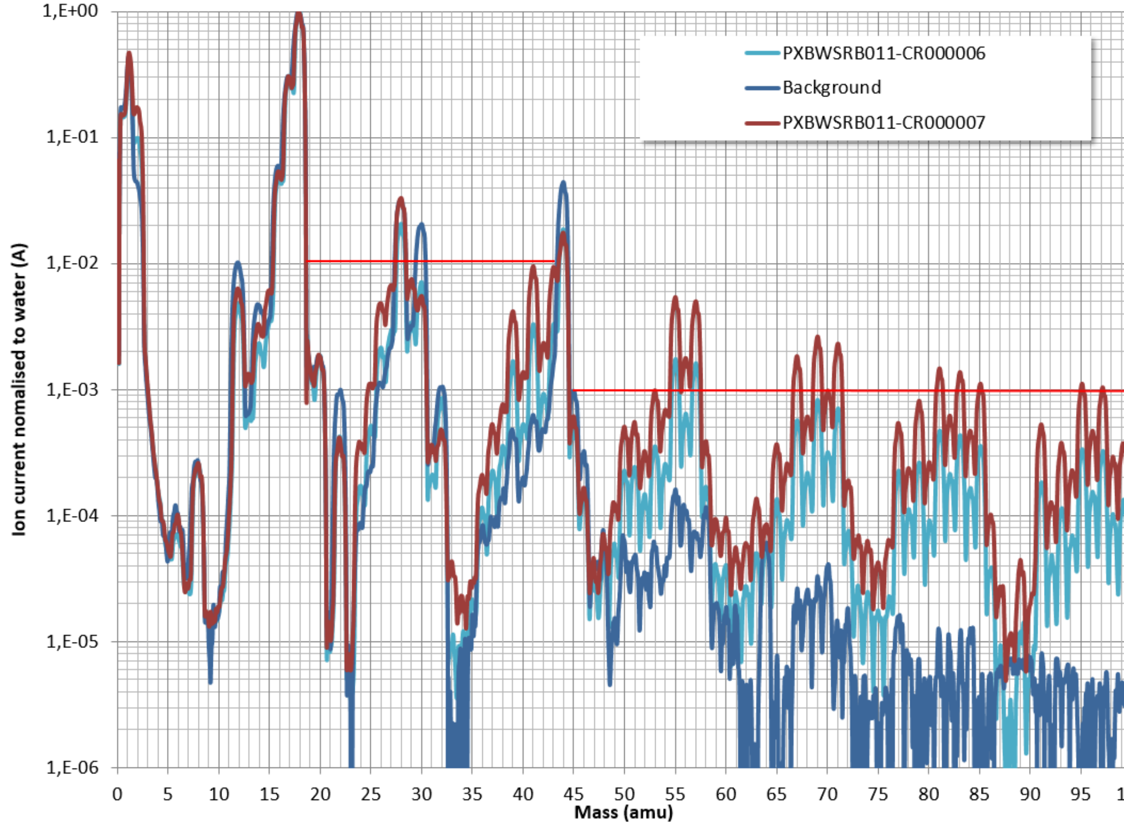
Few examples: PS & SPS FWS



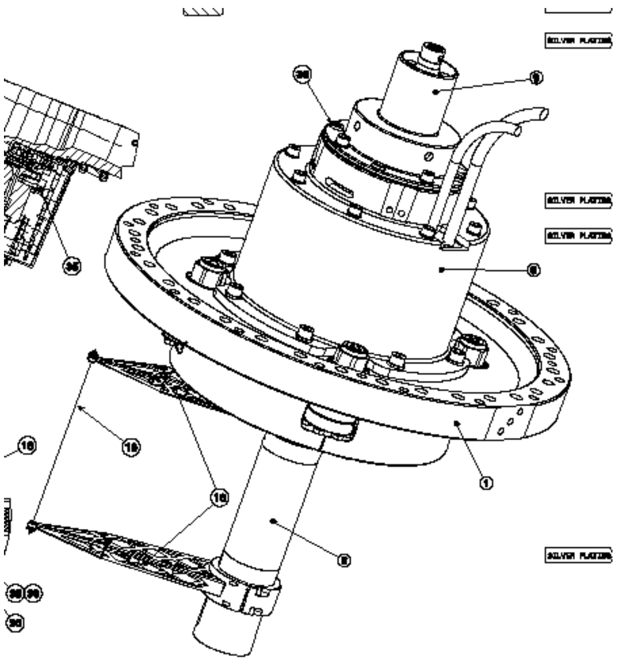


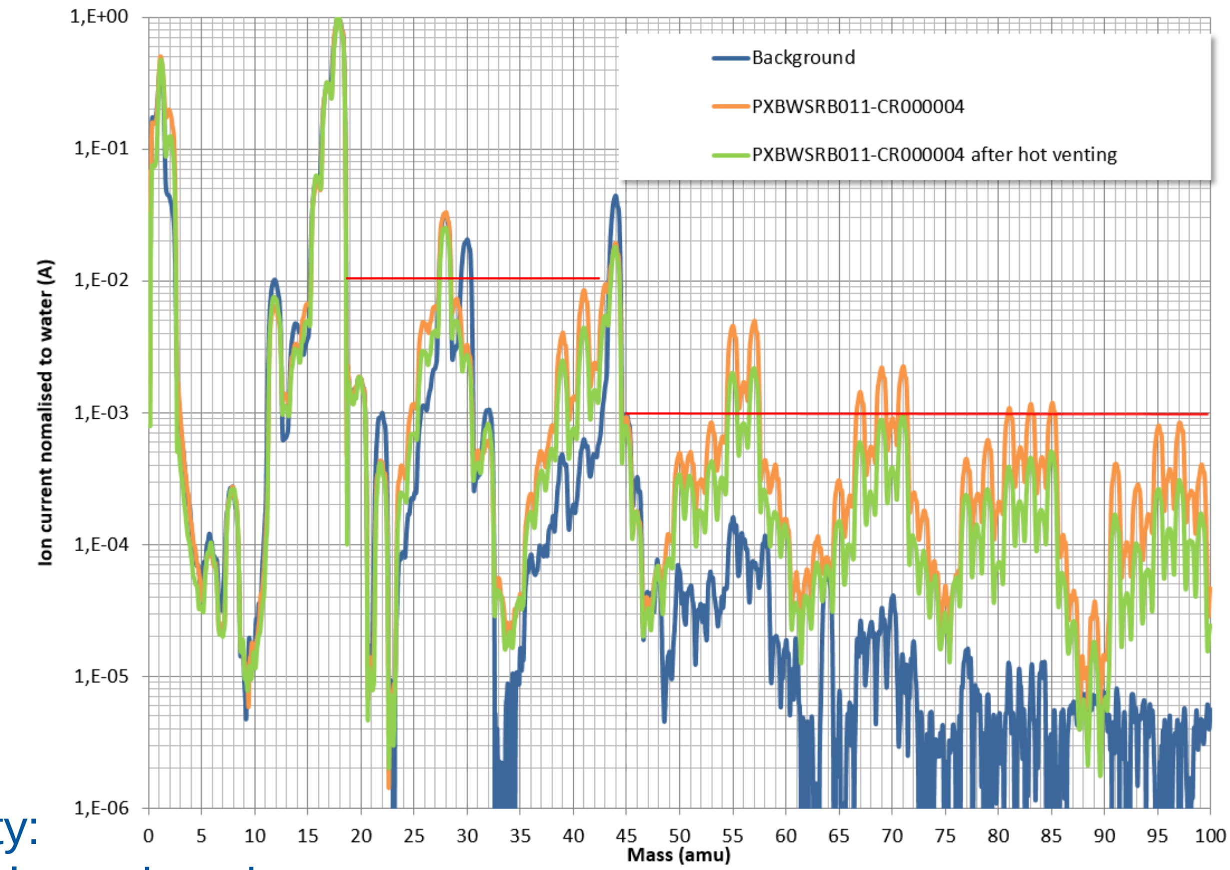


Non conformities detected coming from the fork.

Courtesy of A.Michet and N. Thaus

Few examples: PS & SPS FWS

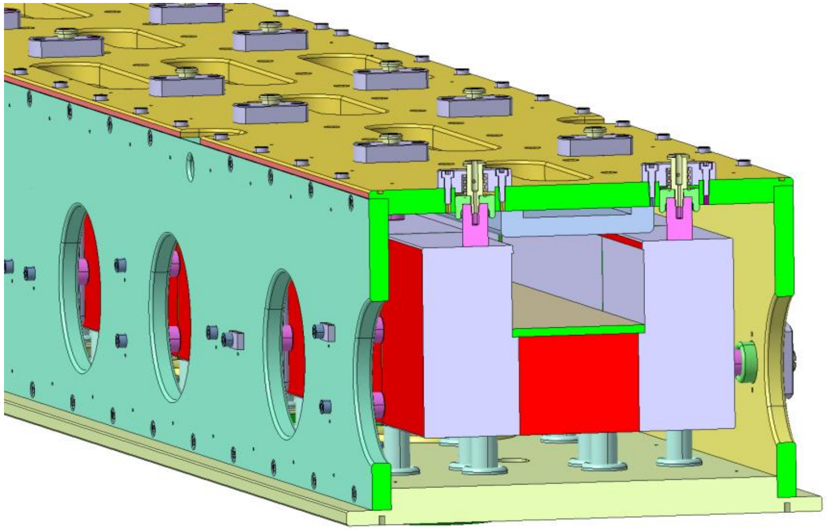


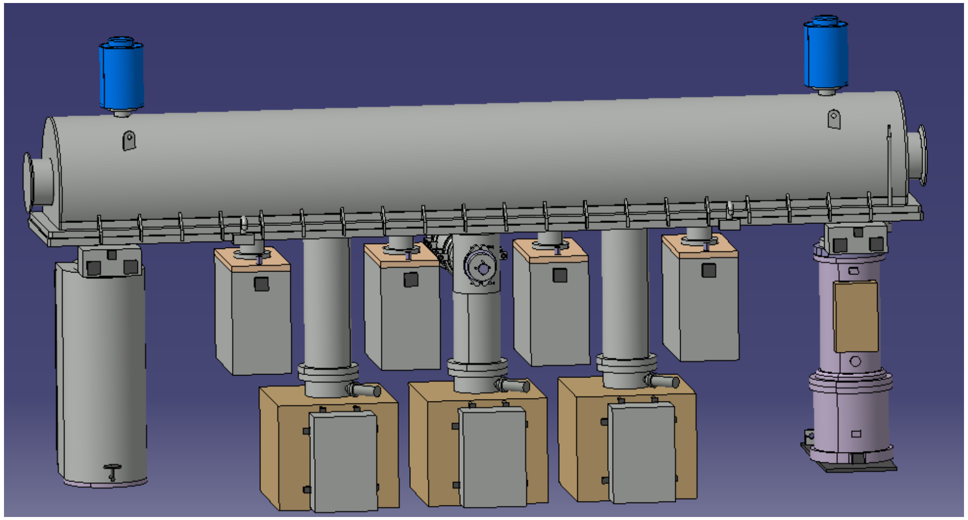


Working toward the conformity:

- ✓ Tanks stripped down and cleaned again;
- ✓ Mild bake-outs;
- ✓ N_2 hot injections;

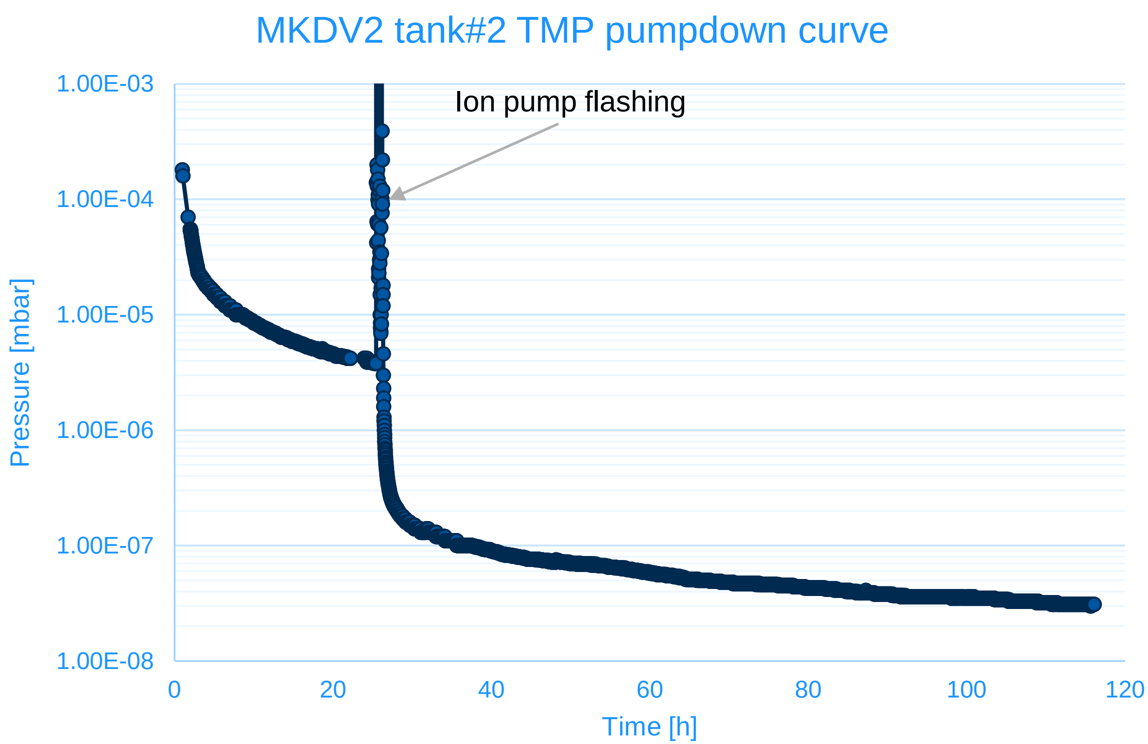
Few examples: SPS MKDV





The MKDVs are kickers magnet meant to vertically deflect the beam toward the dump. They are composed of a stacked lamination of ferrites (8C11, NiZn alloy) and metallic ground plates (AlMg3F26) over 3m length.
300 l/s Ion pumps are directly connected to the tank to cope with the high outgassing rate.

Few examples: SPS MKDV



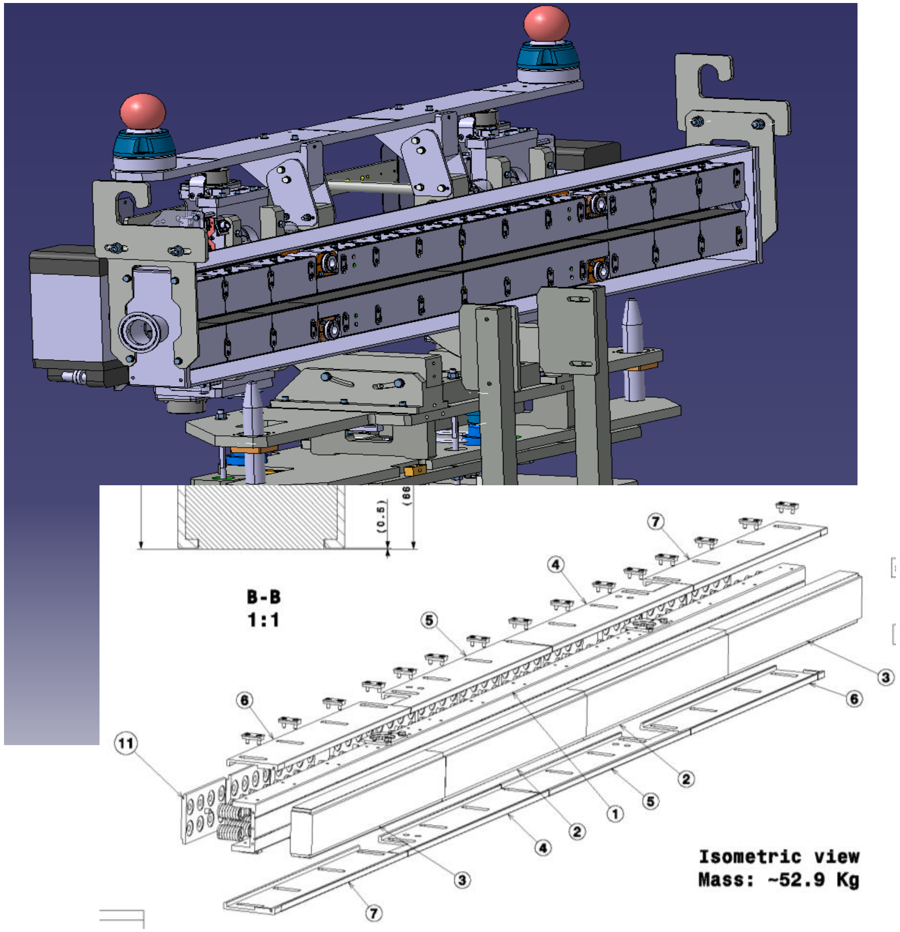
MKDV are and example of **tolerated** components.

Acceptance test is performed with ion pumps as well:

- Outgassing rate at 24h with turbomolecular pumping exceeds the SPS acceptance levels (≈ $9*10^{-5}$ mbar l/s);
- The additional ion pumps, reduce the **pressure** to an acceptable level for operation (≈ 7*10-8 mbar at 48h of ion pumping).

Courtesy of A.Harrison and K. Owens

Few examples: TCDI, TI2-TI8 collimators



12 collimators will be installed in TI2 and TI8 to protect LHC beam injection from eventual mis-stirring of the beam during extraction from the SPS.

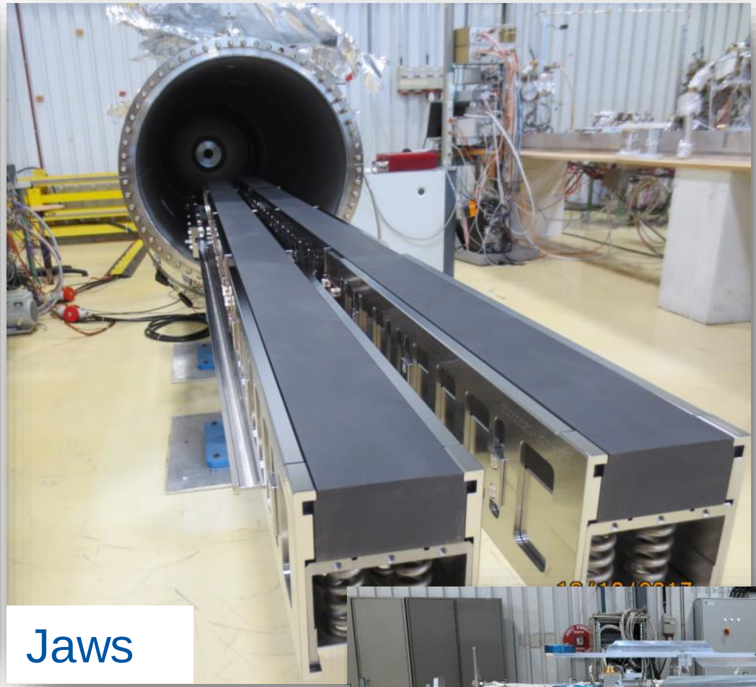
Each collimator is based on 2 graphite (3D-CC + isostatic) jaws, positioned at 4.5 - 5σ from the beam.

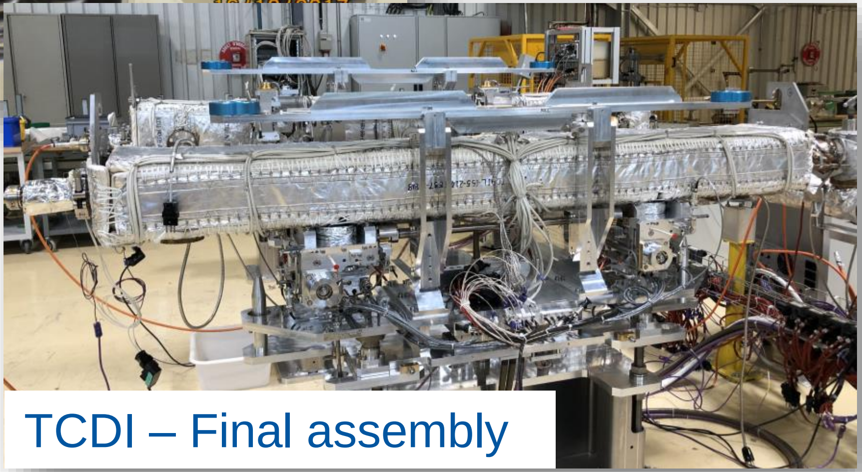
All collimators will be baked in the machine to reduce their impact to the vacuum lines:

- TI2 and TI8 transfert lines are caracterized by a low conductance and lumped, spaced ion pumping;
- Sectors 1204 and 1805 are interfacing LHC NEG coated sectors.

Few examples: TCDI, TI2-TI8 collimators


3D CC blocks


Jaws


TCDI – Final assembly

For complex components, subassemblies are tested in order to anticipate possible non conformities before the final assembly.

Courtesy of G. Cattenoz

Few examples: TCDI, TI2-TI8 collimators

Total Outgassing rate measured after a bake out at 250 C for 48h. RGA scans measured after 48h at room temperature:

- Outgassing rates ≈ $6*10^{-8}$ mbar l/s; → conform!
- RGA scans all within acceptance limit.

Graphite conformity reached thanks to a vacuum firing at 950 ◦C for 6 h.

Courtesy of G. Cattenoz

Non conformities: why?

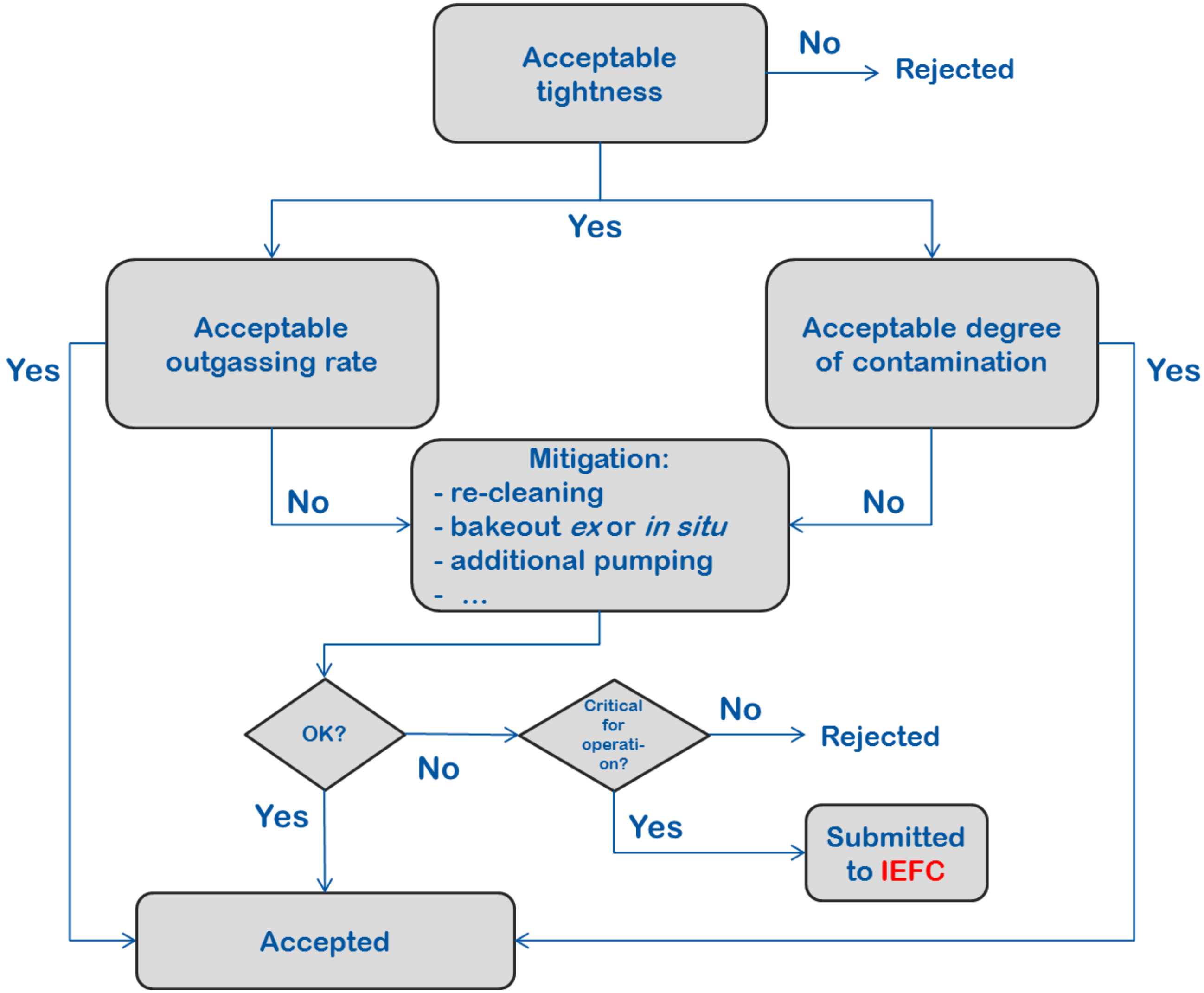
OUTGASSING RATE

- Material choice (polymers, synthered materials, high vapour pressure materials);
- Missing Thermal treatments (vacuum firing, air baking, prebaking for polymers);
- Poor mechanical vacuum design (trapped volumes, wrong welding procedure, brazing alloys);

CONTAMINATIONS

- Non conformity in the design (lubricants under vacuum, glues..)
- Non conformity in the handling procedures;
- Non conformity in the cleaning procedures;

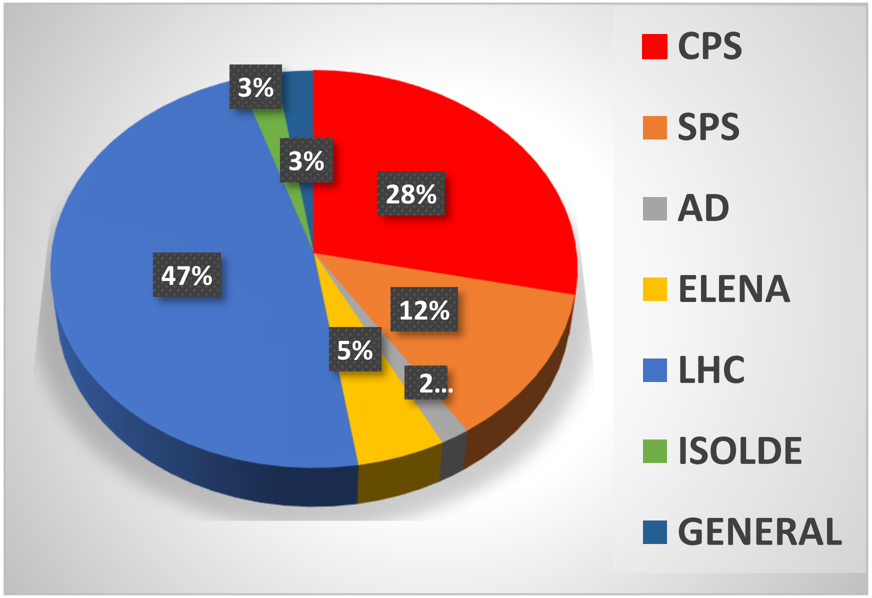
What happens in case of non conformity?

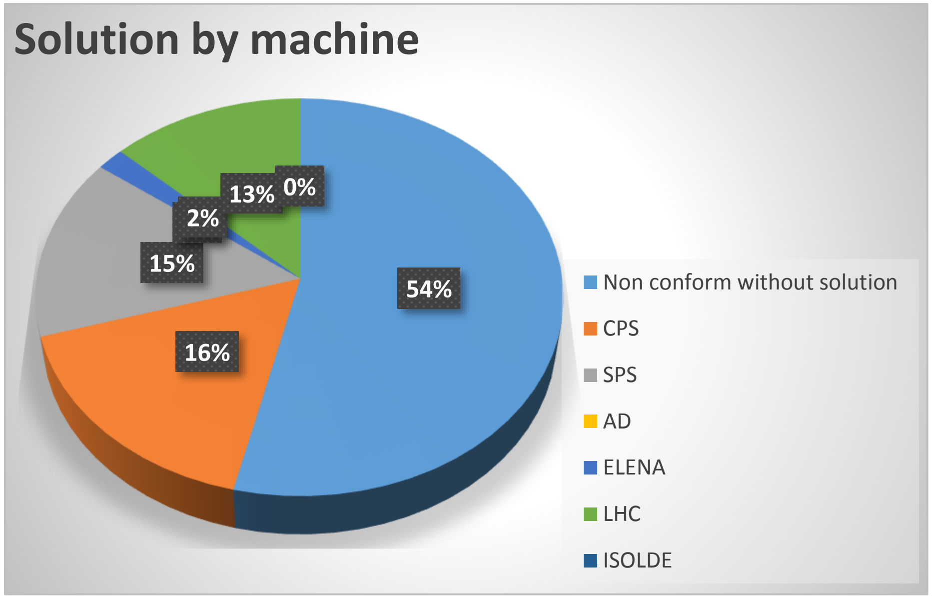


What happens in case of non conformity?

- Best way to deal with a non conformity is to avoid it!
- Early involvement of vacuum experts in the design phase of the components is crucial to avoid common design mistakes that can lead to non conformities at the final stage of the production cycle of the component.

A bit of statistics..

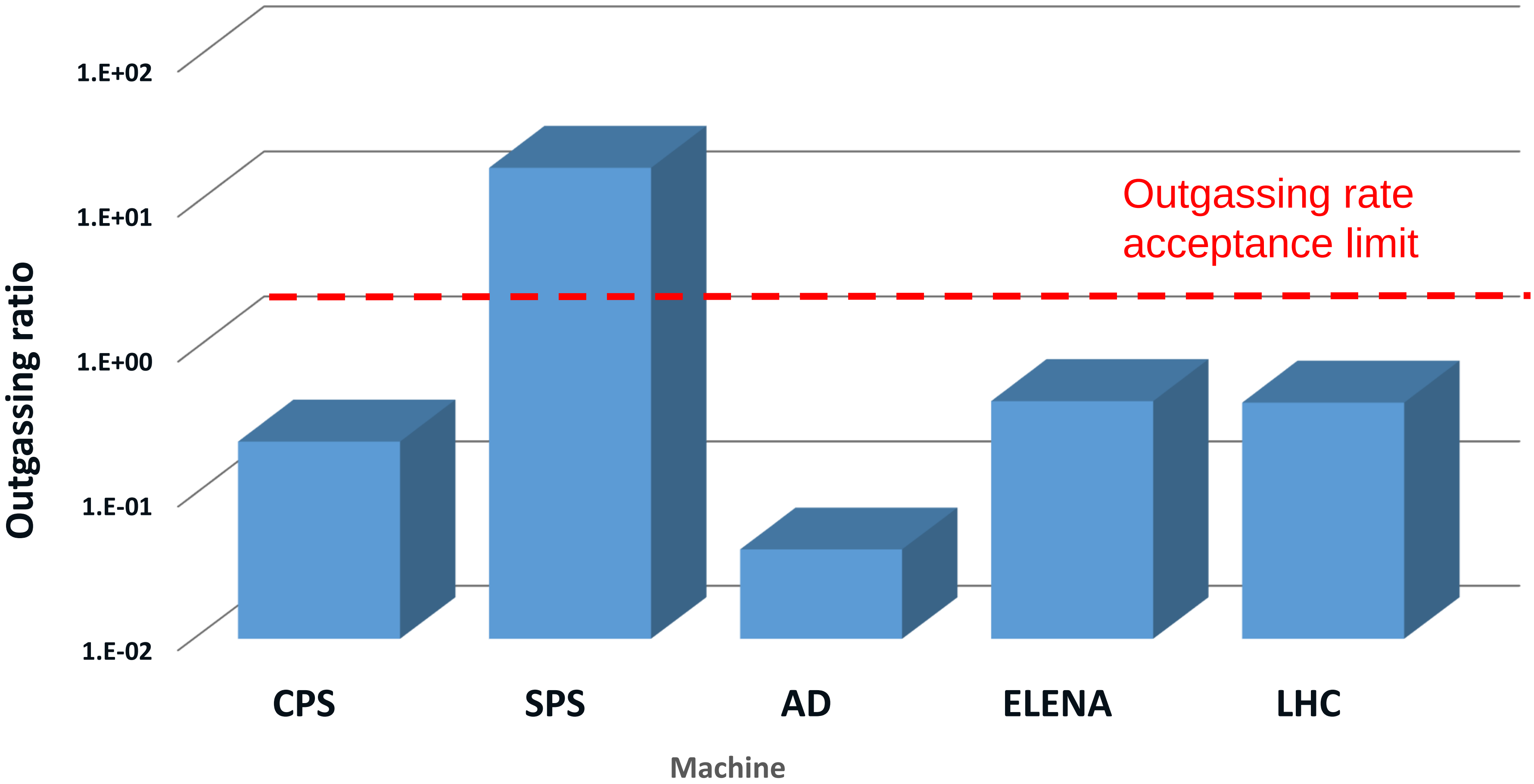




More than 120 components tested last year!

Courtesy of I. Wevers

A bit of statistics..



Courtesy of I. Wevers

Conclusions

- A brief (non –exhaustive!) overview of vacuum acceptance tests;
- Crucial role of BVO in testing and assessing the compliance of vacuum components to be installed in the accelerator chain;
- Thanks to all BVO colleagues involved into these activities!