CERN

7th International Workshop on Cryogenics Operations,
October 25-27, 2016
Fermi National Accelerator Laboratory, USA

Vibration monitoring of the rotating machines of the CERN cryogenic systems

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- Cold/hot spares strategy
- Vibration monitoring and analysis
- Set up of vibration monitoring at CERN
- Examples of vibration monitoring and analysis
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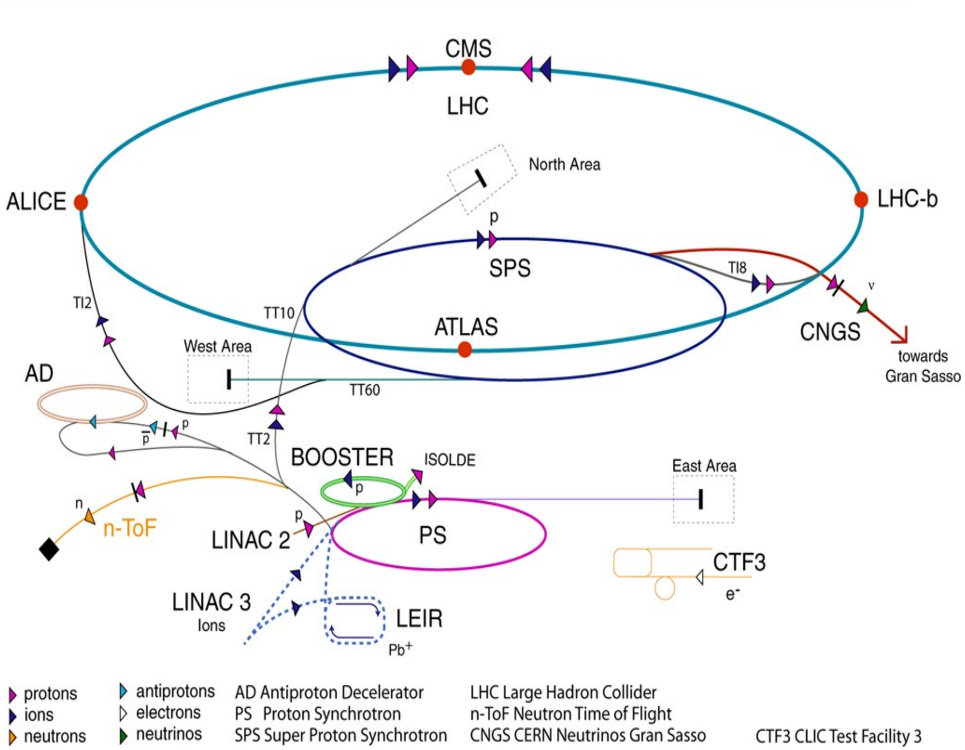
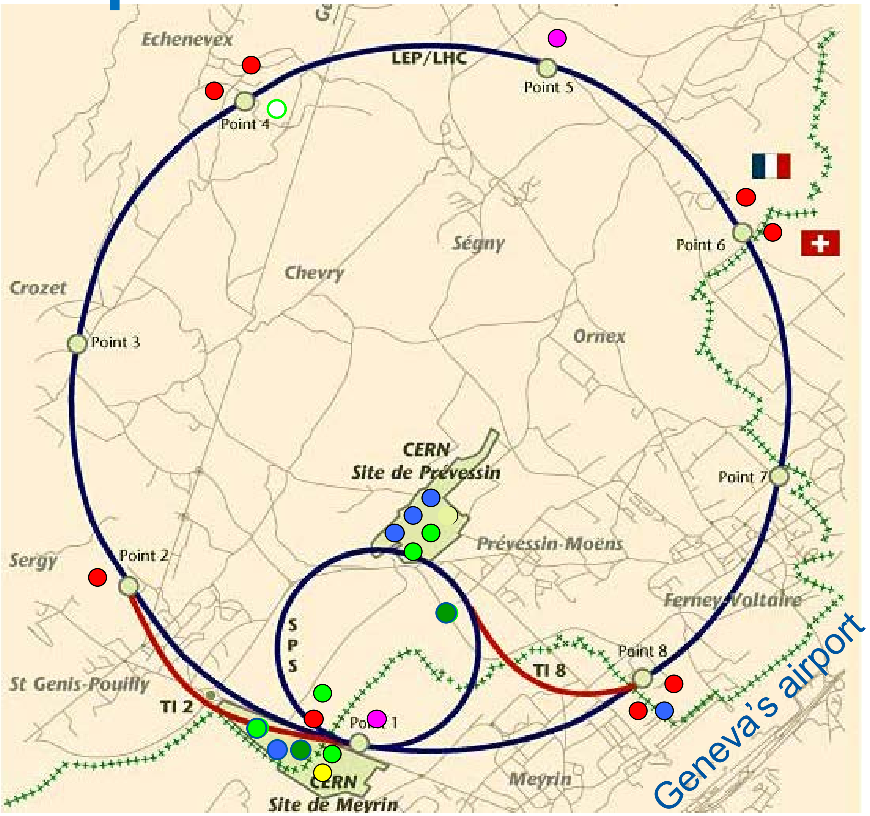
CERN accelerator complex

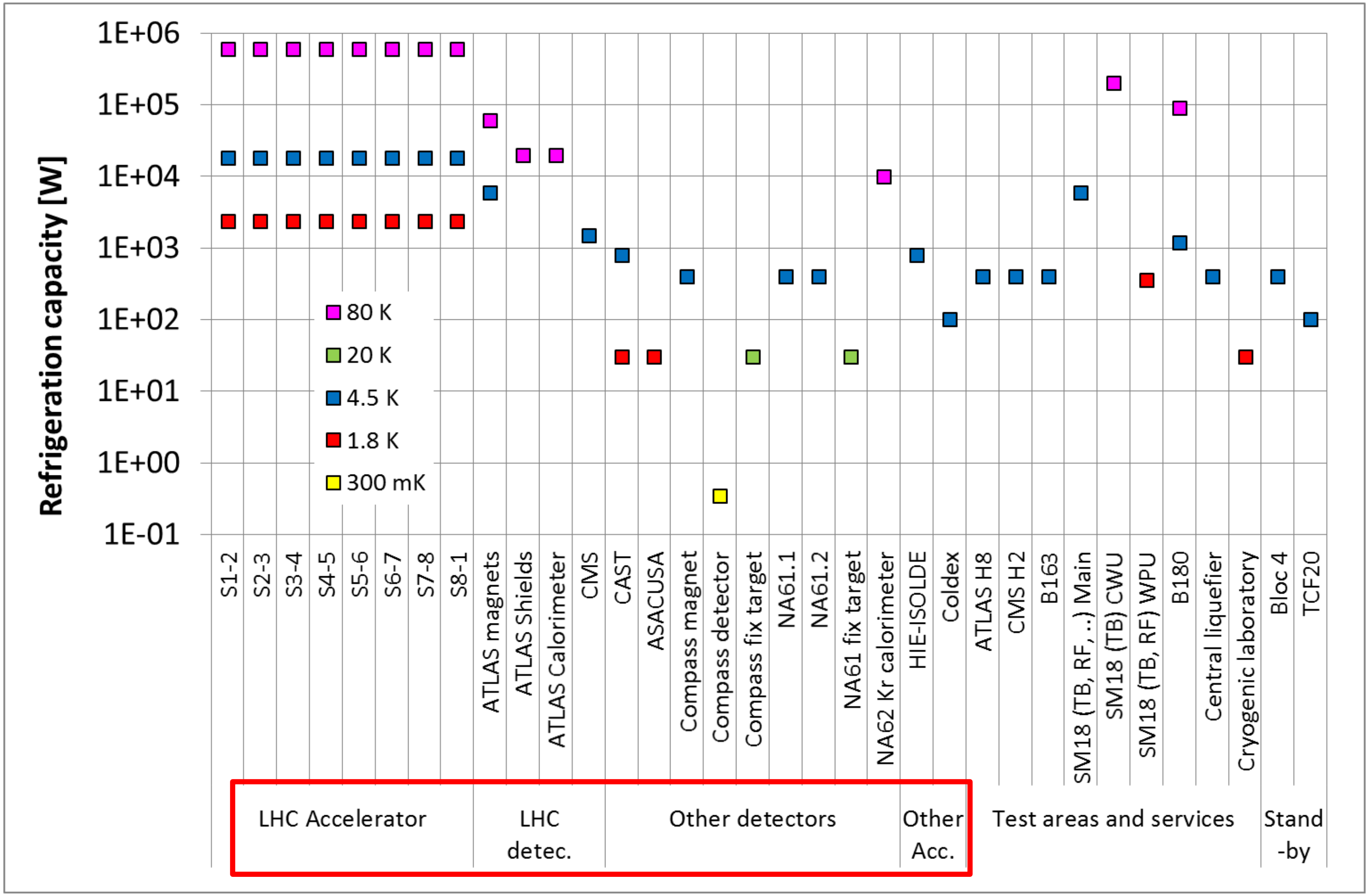




T level	Installed capacity	# of plants
80 K	5.2 MW	14
4.5 K	164 kW	24
20 K	60 W	2
1.8 K	19.7 kW	12
300 mK	350 mW	1

- LHC accelerator
- LHC detectors
- Other detectors
- Other acceler.
- Test areas
- Central services
- Standby

Inventory of cryogenic installations at CERN (34)



23 cryogenic installations are part of the core infrastructure running 24/7/365 for the CERN physics reasearch program where availability & reliability are essential

INTRODUCTION

- In case of breakdown of rotating machinery severe downtime can be induced : couple of days for the exchange of a motor / compressor / turbine / …

-> Strategy is needed to ensure availability and reliability of rotating machinery :

  - Redundant equipment, cold and hot spares
  - Preventive maintenance : exchange or revision of components based on integrated running hours
  - *Predictive maintenance : anticipate issues and possible interventions to correct problems*

INTRODUCTION

Inventory of rotating machinery and main critical components in cryogenic plants :

At cryogenic temperature :

- Turbines in refrigerators
- Cold compressors / Pumps

CERN, Cryo-Ops 2014

-> 0 % downtime

-> Process control, cabling & electronic issues (active magnetic bearing)

At room temperature :

most critical

- Motor-compressor systems (screw and piston type)
- Motor-pump systems (oil or vacuum)

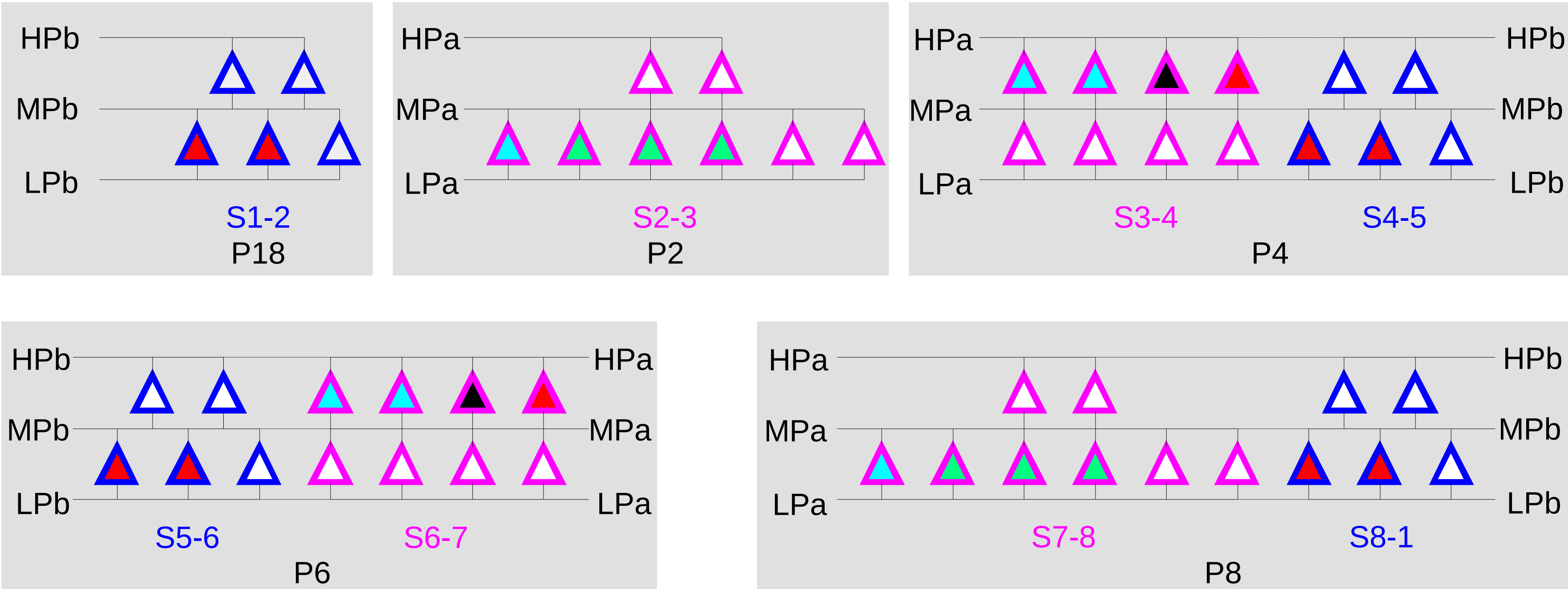
At CERN

-> 88 compressors

-> 60 oil pumps + 6 Roots

- Powerful systems, generating large vibrations
  -> increased wear
  -> increased risks and collateral damages : leaks, pollution (He , environment)
- High costs in case of breakdown
- Long downtime
- Experience of severe breakdowns during LHC run 1 (see Cryo-ops 2014)

LHC cryogenic warm compressors layout

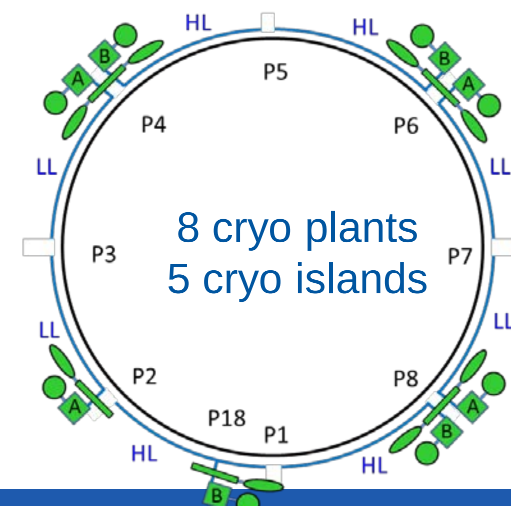


9 types of compressors:

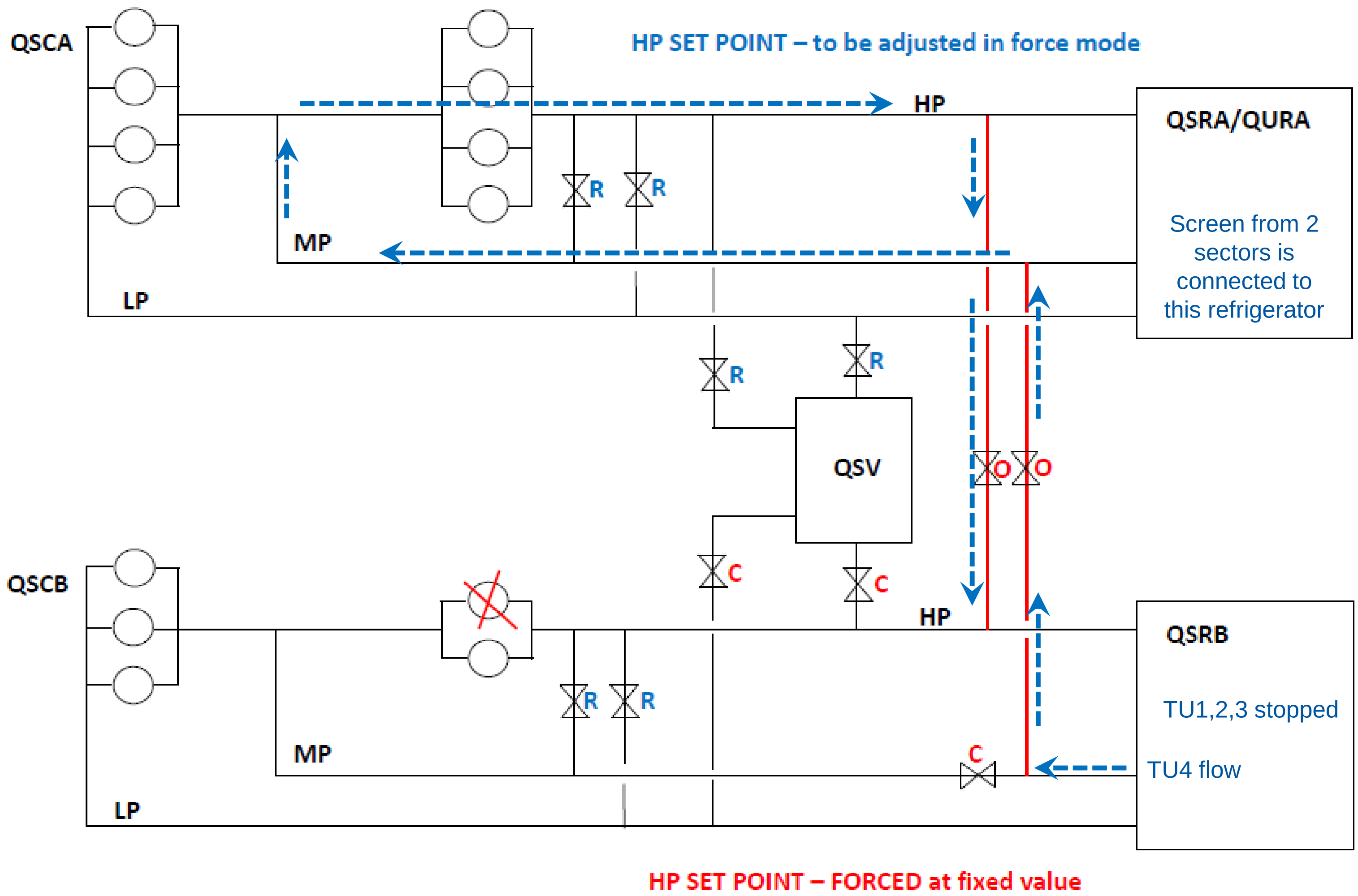
- 2 Aerzen types (536aM & 536aH)
- 7 Stal types (S73_LP, S73_HP, S75, S87, S89, S93_LP & S93_HP)

Aerzen
Stal

Available spares (2016) (HP/ LP) (HP/ LP)



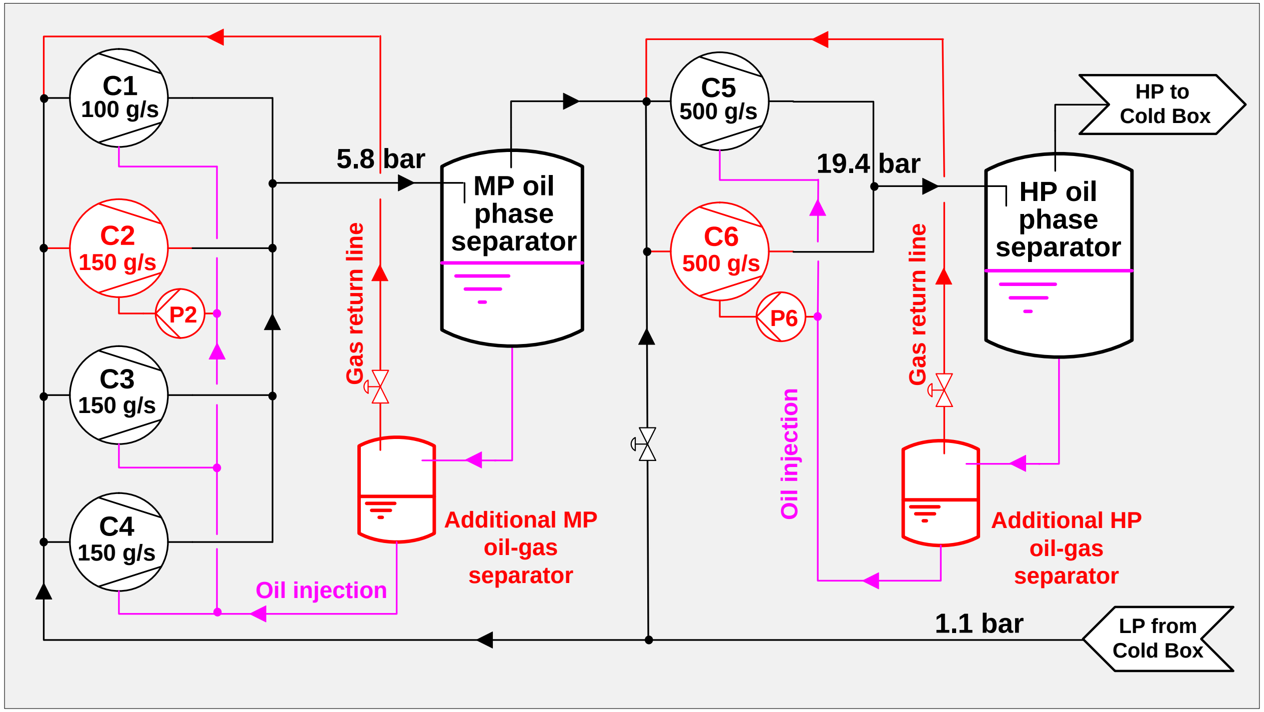
LHC "Hot spare" solution

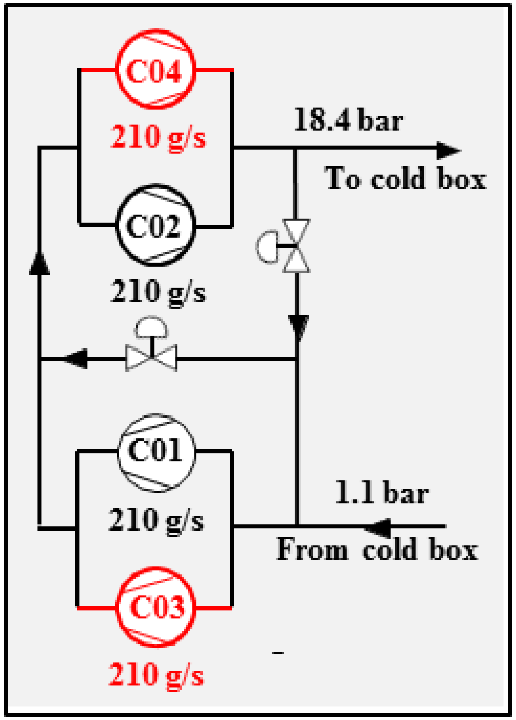


Configuration without one HP compressor. Similar configuration can be applied for LP stage compressors and in such case LP and MP bypasses between the cryo plants will be open.

ATLAS & CMS "Hot spare" solution

Upgrade of ATLAS and CMS compressor stations during first long shutdown (LS1) period of LHC (2013-2014)



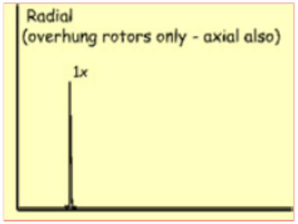


ATLAS : exchange of C2 compressor to ensure a mininimum of 400 g/s with three boosters, and new C6 compressor

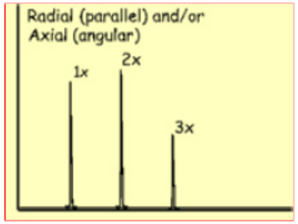
CMS: new hot spare compressors

Vibration monitoring and analyis

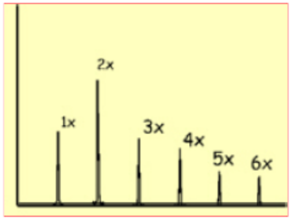
- Vibration measurement techniques have been developed for rotating machinery since 1950's
- In the 1980's, Portable Data Collectors (PDC) were introduced, combined with condition monitoring software
- Since then, there is a continuous enhancement of these products and their capabilities in parallel with development in electronics for hardware and software
- It is now possible to anticipate issues and to diagnose many problems for rotating machinery :
  - Unbalance ,
  - Misalignment, soft foot,
  - Bearing faults,
  - Structural looseness or resonance,
  - Belt drive faults,
  - Gear faults,
  - Electrical motor faults (rotor bars, eccentricity rotor/stator)
  - Hunting Tooth Frequency (FHT), …
- A set of specialized standards is available : ISO, VDI, API



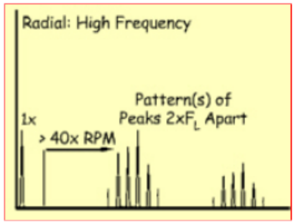
Unbalance



Misalignment



Sleeve Bearings
(Looseness/Rubs)



AC Motor Problems:
Loose Rotor Bars / Windings

Predictive maintenance and compressor station at CERN

Before 2007

Occasional use of vibration meters to check components (compressor, pipework, valve, …)

2008 - 2011

Measurements of only global acceleration/behavior of the motor-compressor systems (1 measurement point, 0-1000 Hz)

2011 - 2012

Investigations with a vibration expert

2012 - 2014

Set up of a predictive maintenance plan based on vibration monitoring

2013 - 2016

Condition based maintenance for screw compressors, roots and oil pumps and the associated electrical motors

2007	2008	2009	2010	2011	2012	2013	2014	2015	2016

2007 : purchase of a first PDC (Emerson™ CSI 2130) in view of LHC run (numerous CPs, higher vibrations)

Dec-2009
QSCB-8-CP3
Roller bearing (failure)
VMY536aH

Dec-2010
QSCB-4-CP6
Roller bearing (breakdown)
VMY536aH

Feb-2011
QSCA-2-M08
Journal bearing (failure)

Jun-2011
QSCB-8-CP7
Roller bearing (breakdown)
VMY536aH

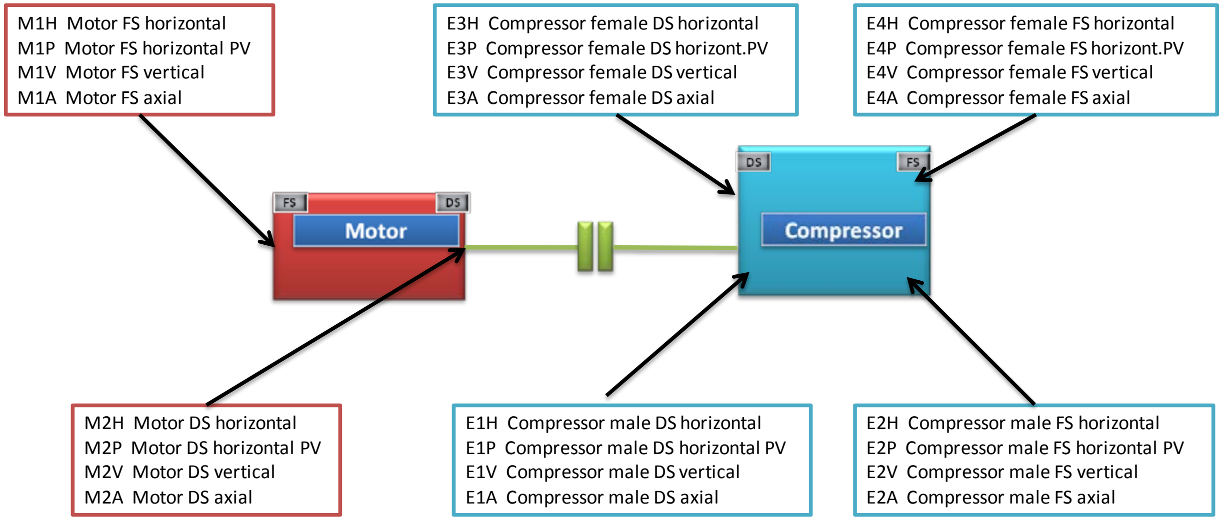
Dec-2011
QSCB-8-CP6
Plain bearing (wear)
VMY536aH

Feb-2012
QSCB-4-CP7
Damaged rotor
VMY536aH

Nov-2012
QSCA-8-M08
Journal bearing (wear)

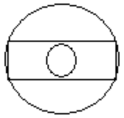
Jun-2014
ANRS
Roller bearing (breakdown)
Kaeser

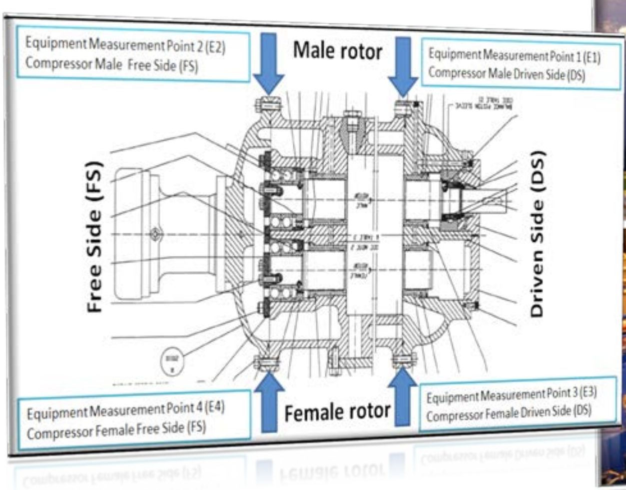
Measurement points for a compressor system

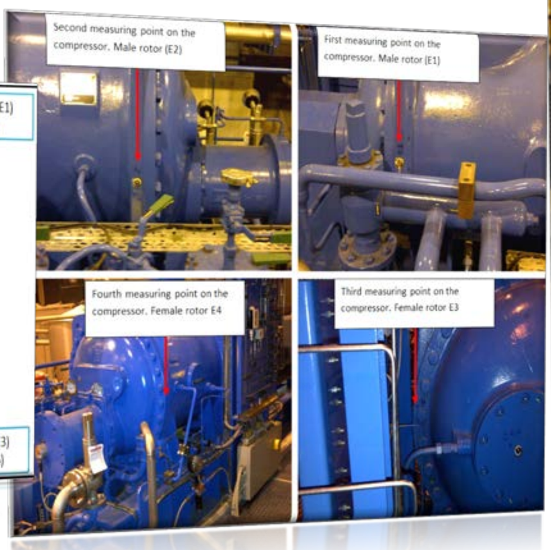


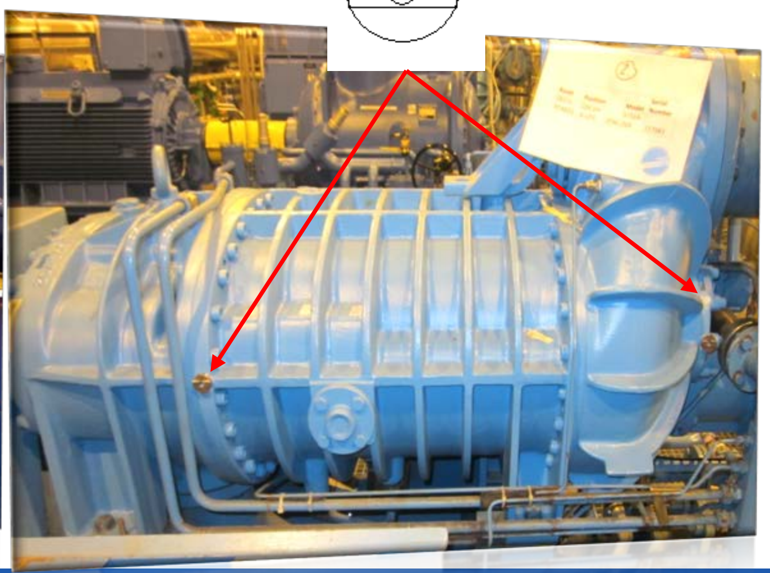
Tri-Axis Sensor

Fixed coded pin









Vibration analysis

- **Vibration analysis**
  - **Wear**
    - Roller / plain / journal bearing
    - Rotor bars (motor)
    - …
  - **Weakness**
    - Unbalance (1 x n)
    - Alignment (2 x n)
    - Asymetric magnetic field (2 x f.net)
    - Skid (resonance, Looseness)
    - …

Problems which may evolve more or less rapidly

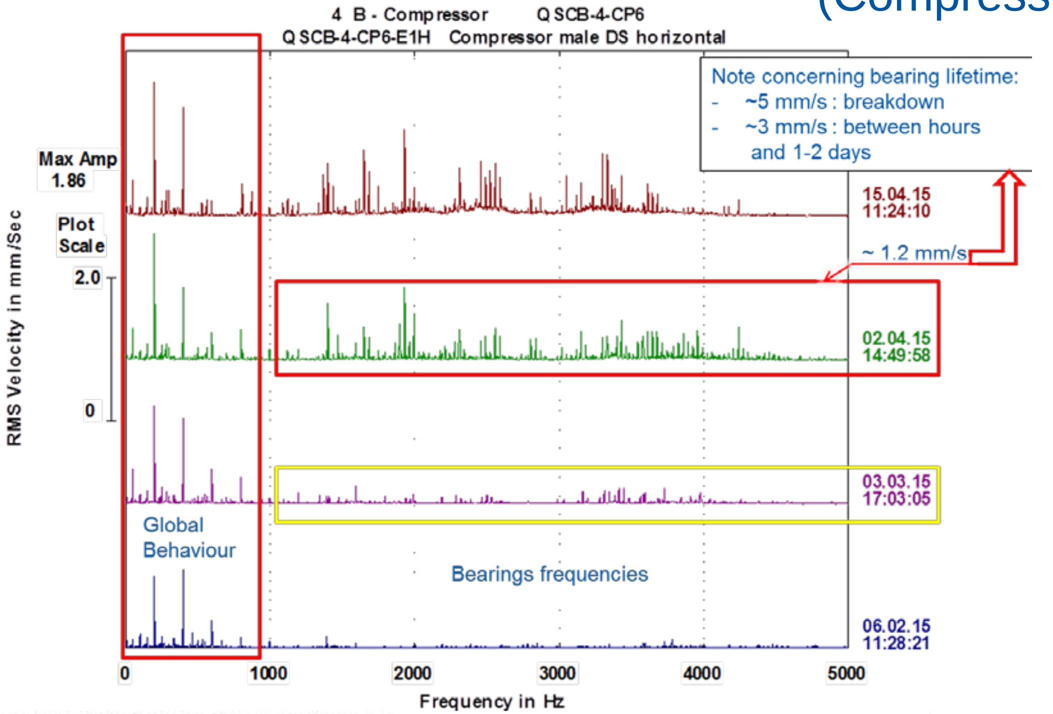
Avoid breakdown

Problems which, if corrected, will improve the system

Higher reliability and availability, lower wear and maintenance costs

Example 1 : roller bearing QSCB-4-CP6 (VMY536aH, April 2015)

(Compressor major overhauled 2 years ago!)



Result of examination / findings:

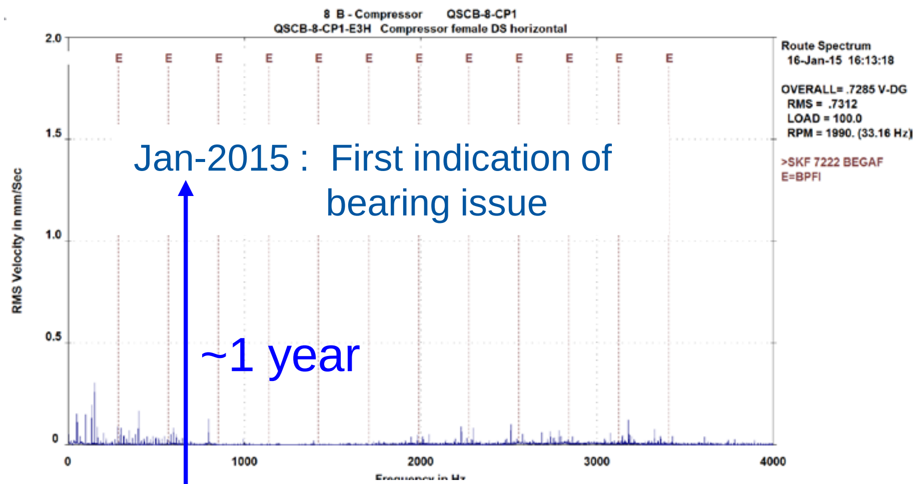
The compressor was supplied at the 20.07.2015. Dismounting and taking down findings has been taken place the 24.07.2015.
The above mentioned parts have to be replaced.
It were measured abnormalities of the thrust bearing by the customer. This had to investigate now and to replace the bearings.

The rolling elements of the positive thrust bearing of the female rotor were partially destroyed. It was found, that the retaining ring of the bearing was no longer glued. As a result, the ring has rotated with the bearing and the pins of the coil springs were grinding against the outer ring of the bearing and have produced a lot of abrasion that destroyed the bearing.

(Aerzen's expertise 29 July 2015)

⇨ Assembly error during major overhauling

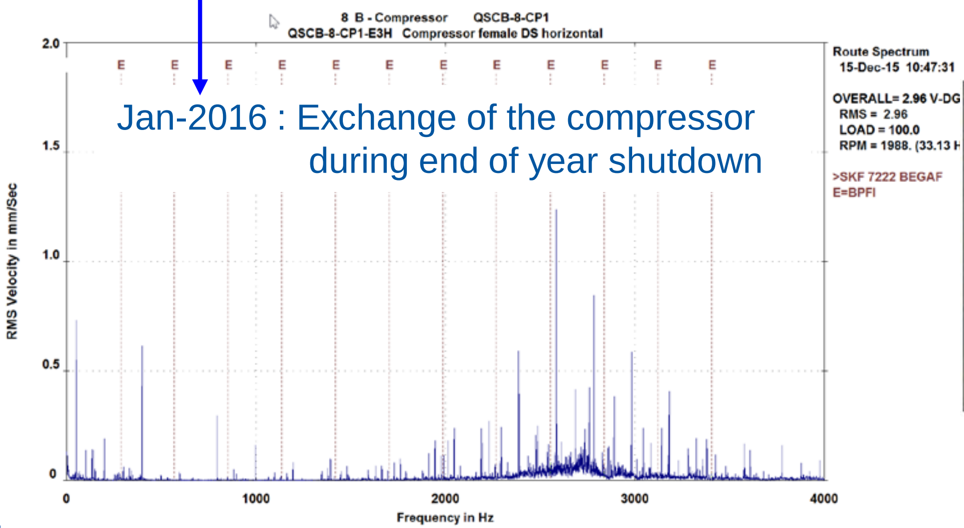
Example 2 : roller bearing QSCB-8-CP1 (VMY536aM, 2015)



Jan-2015 : First indication of bearing issue

~1 year

Only one spare and concern with other CP of the same type



Jan-2016 : Exchange of the compressor during end of year shutdown

SKF report (bearing after 1 year)

The inner ring shows two small flaking areas, a large number of overrolled indentations caused by soft and large, but also hard micro-particles, as well as abrasive removal of the machining pattern in the ball path. A large number of wear marks are visible which are either round or have the shape of circle segments, with surface distress on the bottom and which were overrolled in operation (Figs. 2 to 13). In addition to one flaked are, the machining pattern was worn off due to vibration with the bearing stationary.

Fig. 2: The inner ring with 2 flaked areas. One flaked area is identified by the arrow.

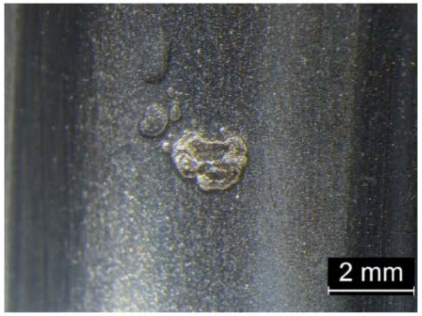


Fig. 3: Detail photo of the flaked area from Fig. 2.

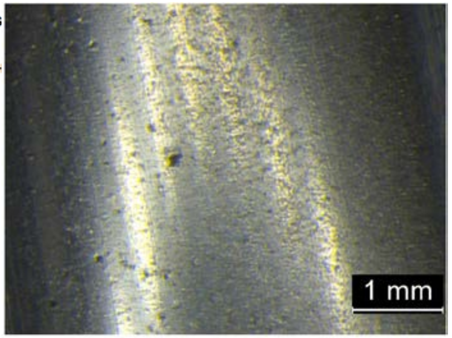


Fig. 18: Detail photo of the ball path. The machining patterns are worked off.

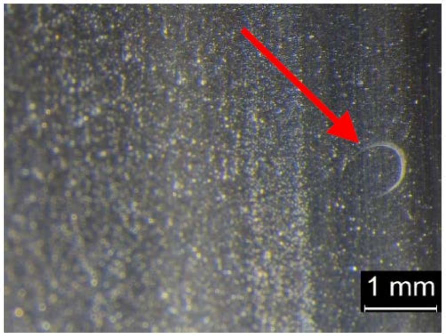
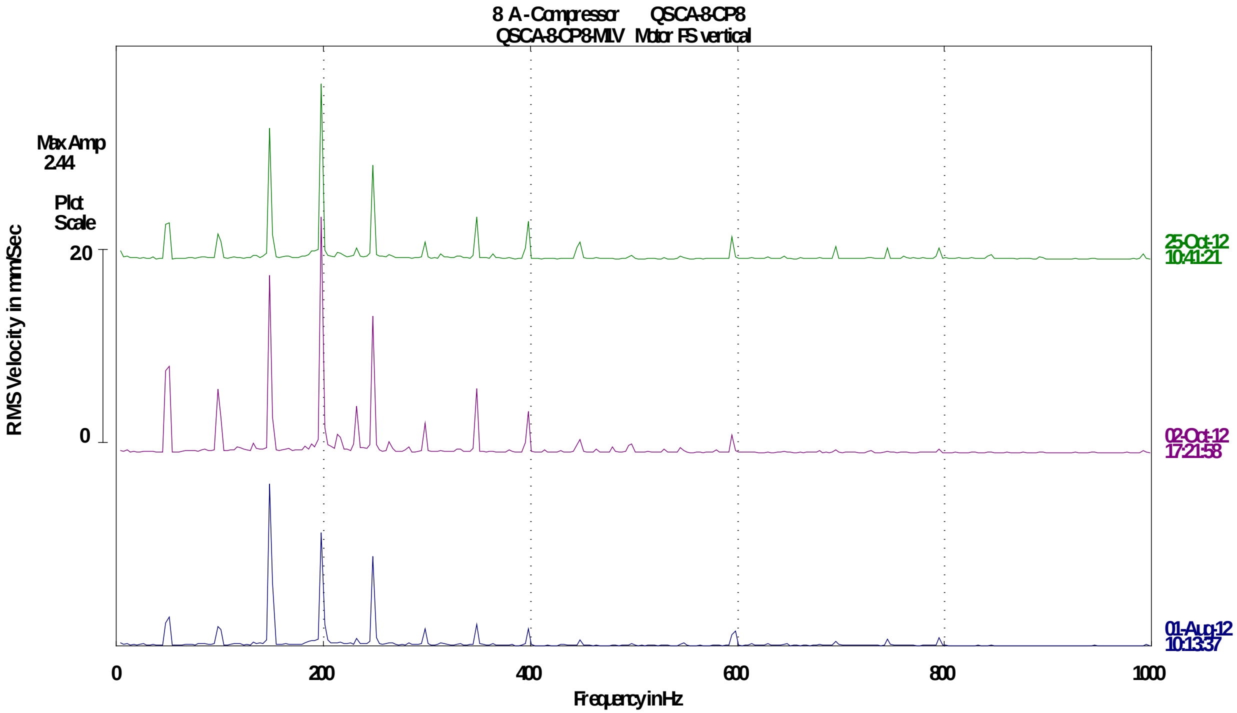
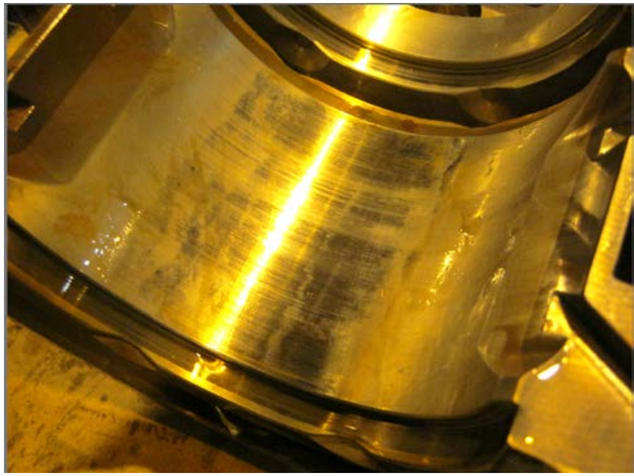


Fig. 5: The machining pattern on this raceway is removed by abrasive wear, and there are ring-shaped wear patterns (arrow).

Example 3 : journal bearing QSCA-8-M08 (2012)





Detection of a faulty journal bearing in a motor (August 2012) :

« Internal play in the journal bearing is increasing slowly but continuously over last few months »

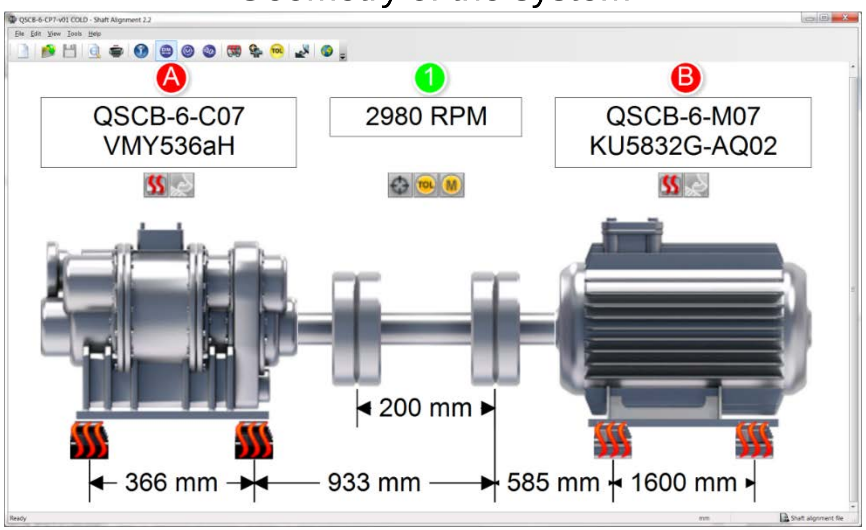
-> Replacement of the bearing during a technical stop in November 2012

Example 4 : vibration analysis & alignment practice

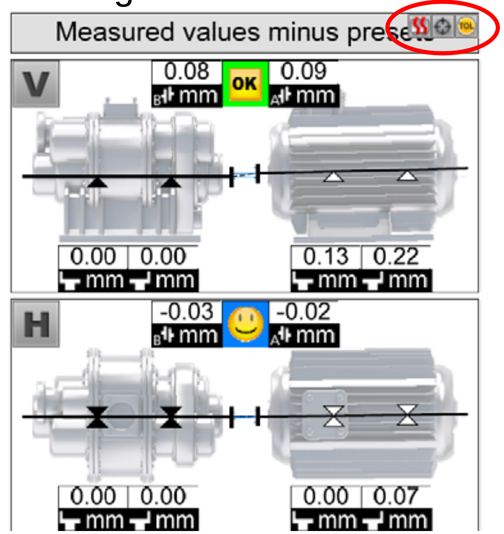
- During the set up of the vibration monitoring, many problems of misalignment were reported
- Investigation wrt alignment practice. Findings :
  - *Configuration errors in the database (geometry, length,…)*
  - *Faulty soft foot check*
  - *Thermal growth not taken into account*
  - *Dynamic tolerances not well taken into account*

Laser shaft alignment system : OPTALIGN®

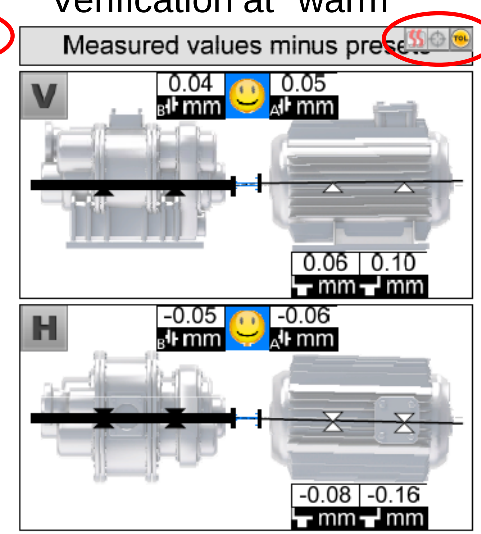
Geometry of the system



Alignment at "cold"



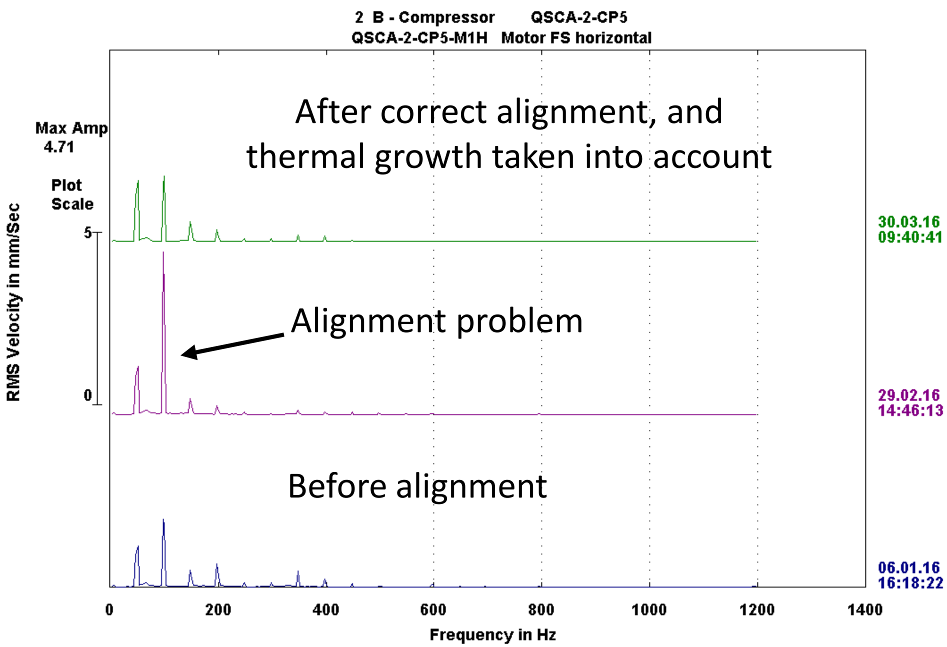
Verification at "warm"



-> <u>Complete review of the alignment procedure and QAP</u>

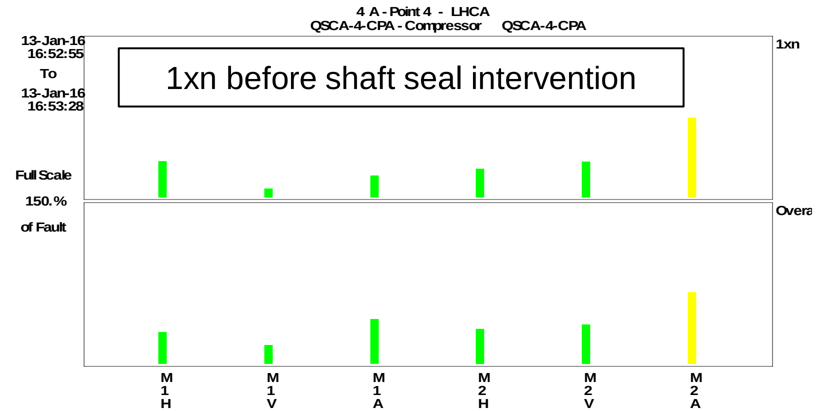
Example 5 : maintenance practice & Quality Control

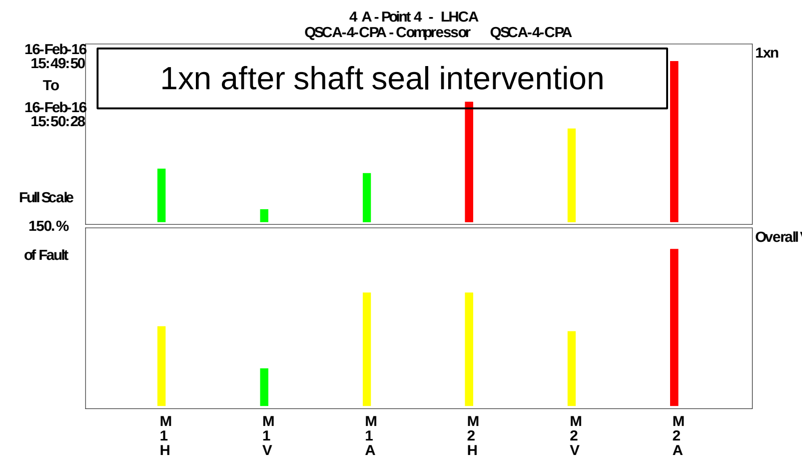
- Alignment issue found on compressor QSCA-2-CP5 (Feb-2016)
- Investigations -> alignment during Jan-2016
- Thermal growth not taken into account during alignment process



- **Vibration analysis contributes valuably and efficiently to QC**
- **Correct alignment improves bearing and seal life, and reliability of rotary machinery**

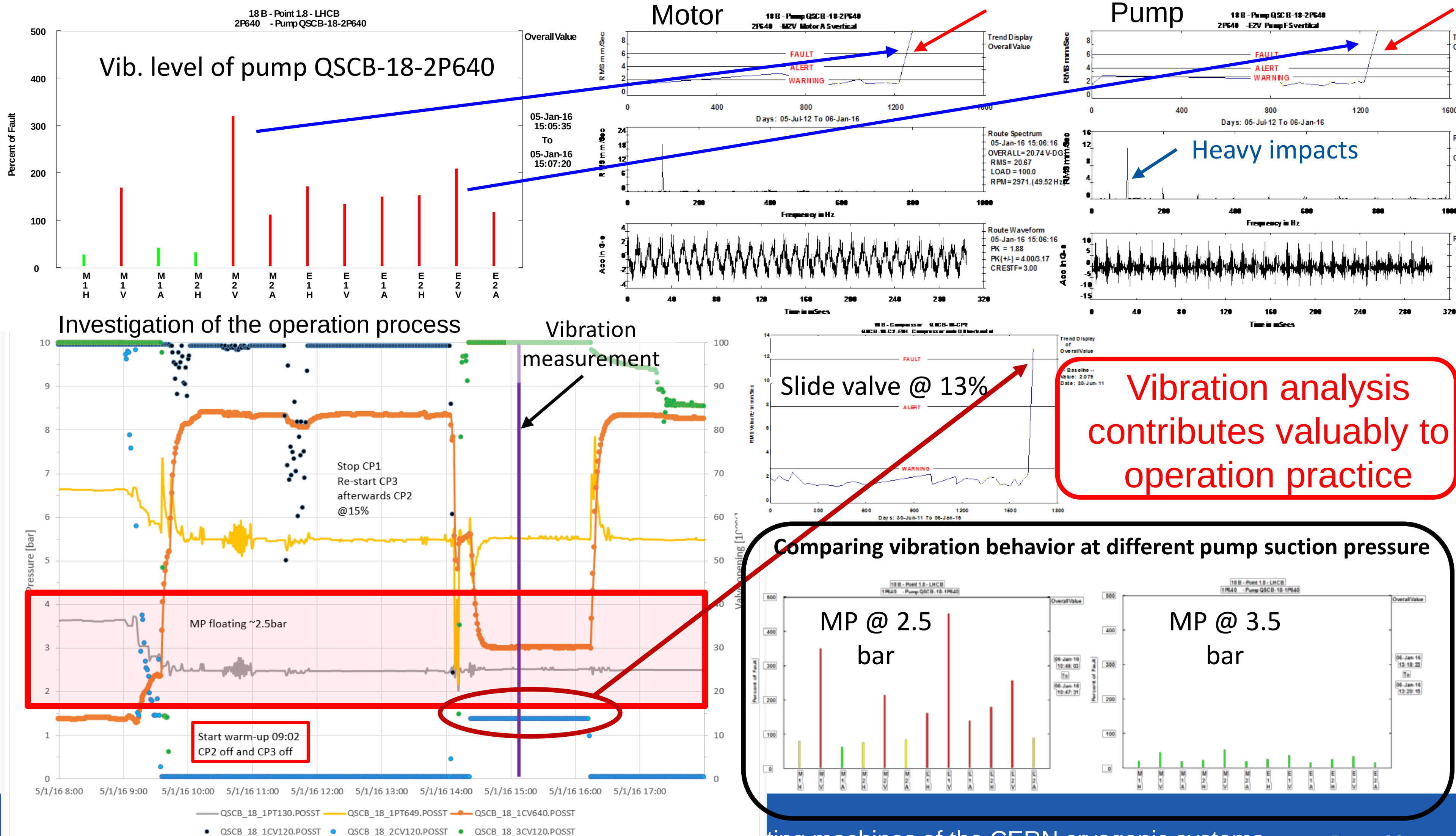
- Balancing issue found on motor QSCA-4-M0A (Feb-2016)
- Investigations -> there was an exchange of shaft seal during Jan-2016
- Bad remounting of coupling (unsymmetrical mounting of the conical clamping ring)





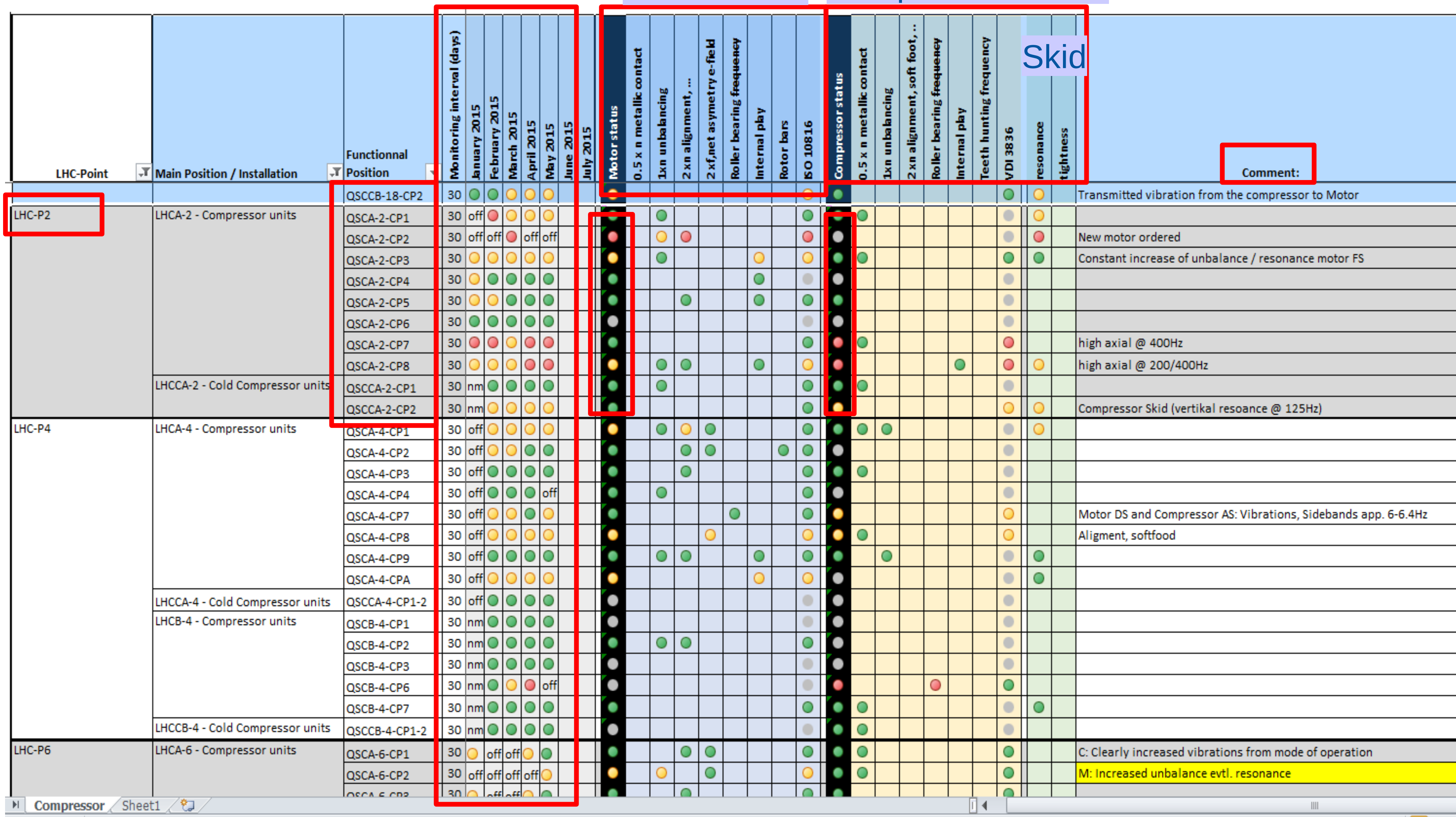
Example 6 : Operation practice (Jan-2016)

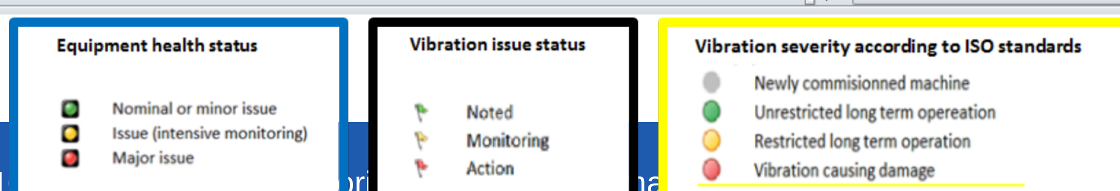
During a vibration measurement, very high vibrations are recorded for the oil pump QSCB-18-2P640 (motor & pump) : cavitation



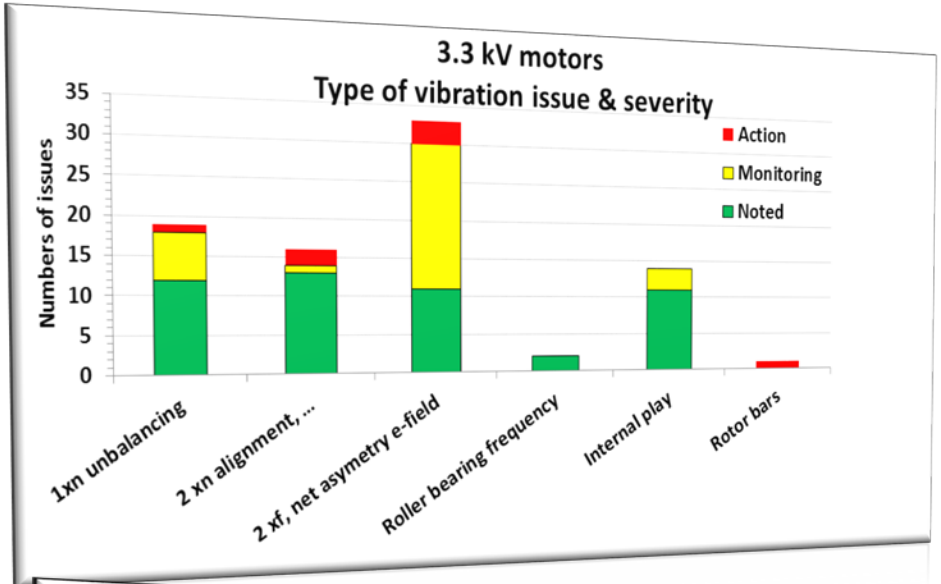
Vibration analysis contributes valuably to operation practice

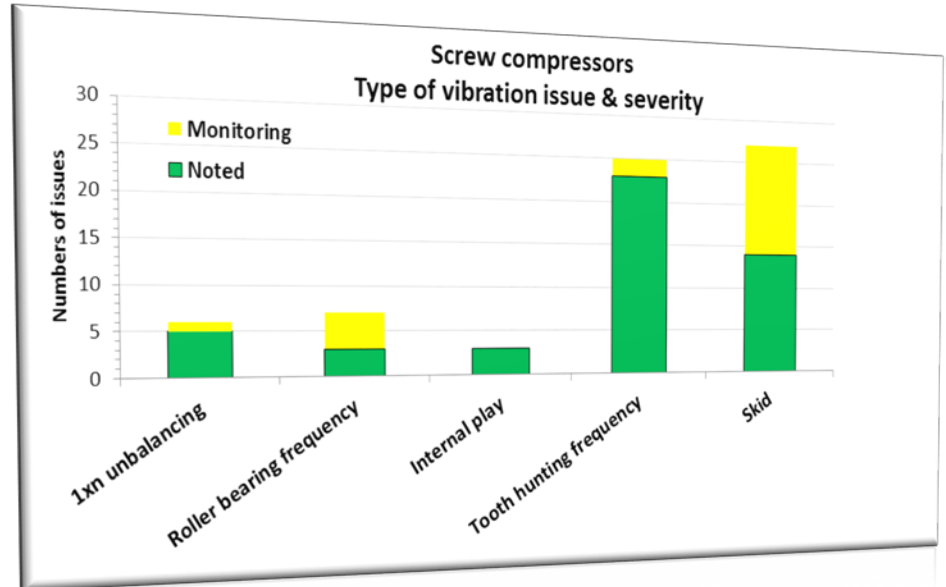
Vibration monitoring : detailed dashboards

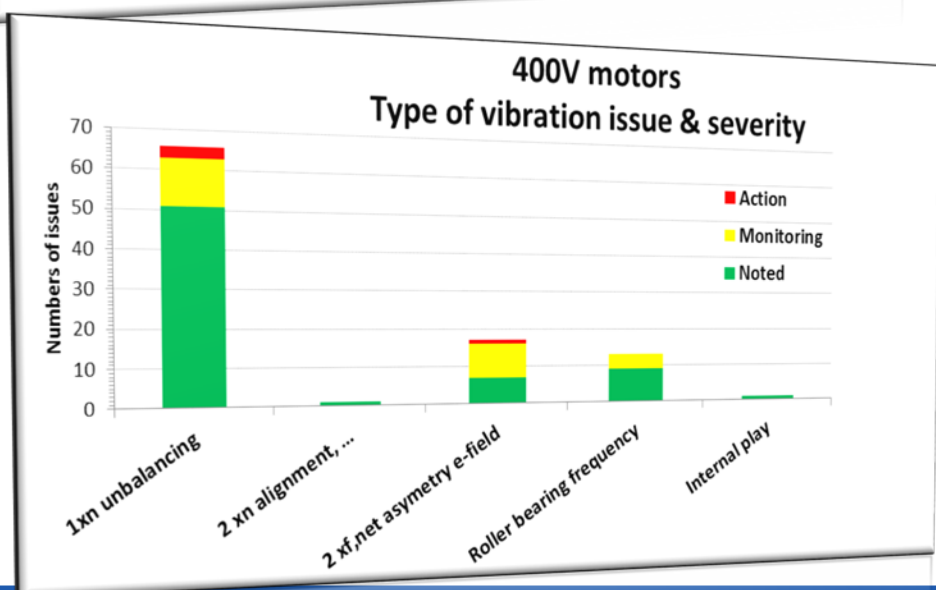


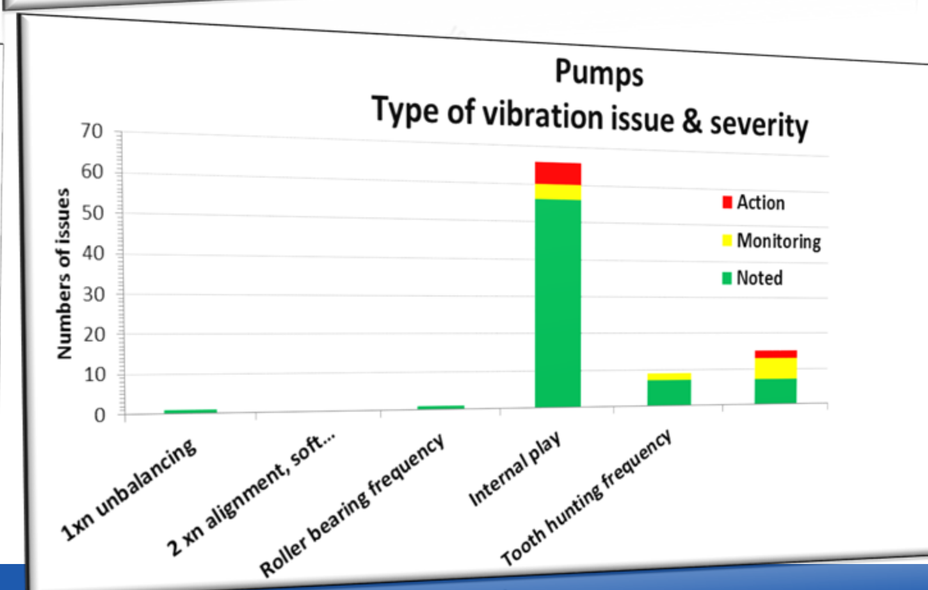


Vibration monitoring : dashboards & statistics

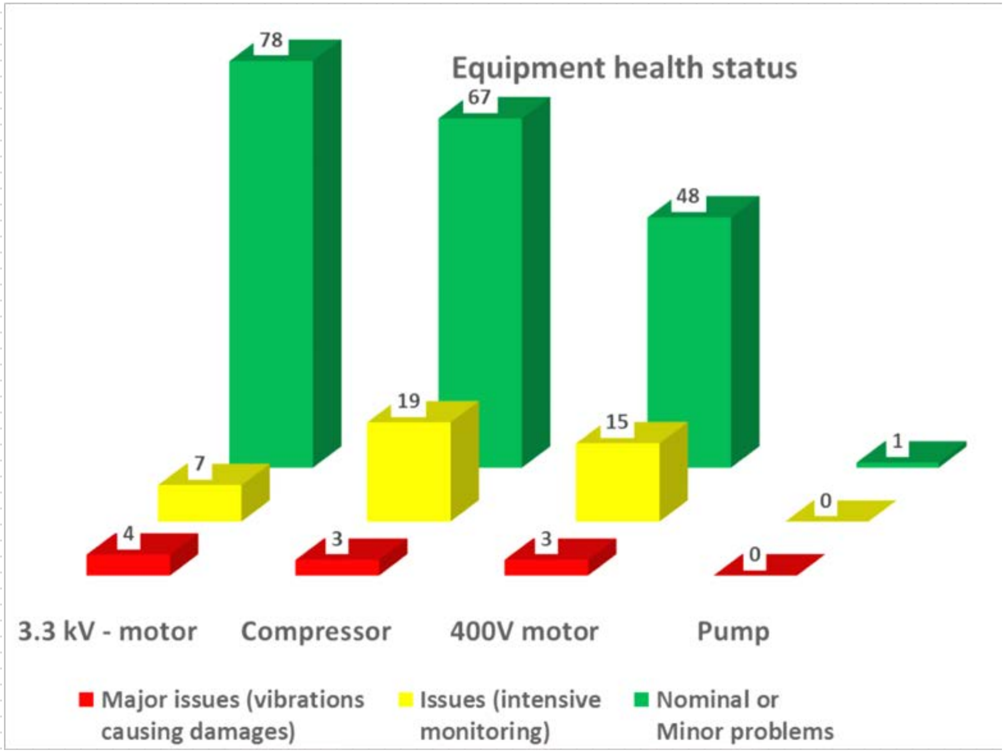


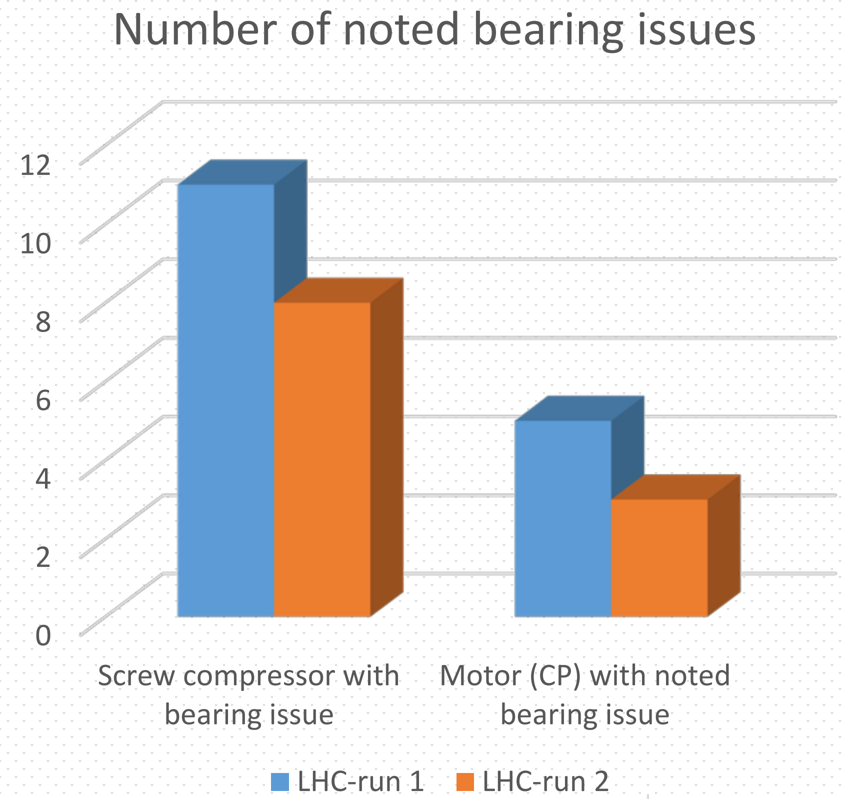


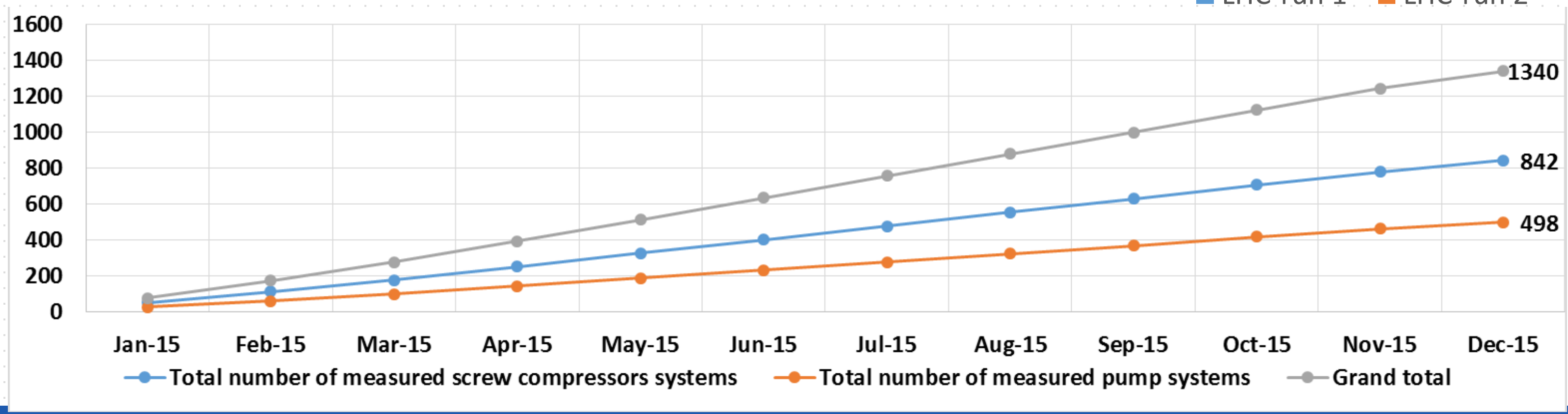




Vibration monitoring : dashboards & statistics







SUMMARY

- Vibration monitoring of rotary machinery is the first brick of the predictive maintenance plan for CERN cryogenic plants
- It is a complementary and an essential tool to cold/hot spares strategy and preventive maintenance : it allows to anticipate issues and program interventions during technical stops, to prioritize the issues, and in case of urgency to switch to a hot spare configuration or to stop before the destruction of the machine
- Vibration monitoring has allowed to revise major overhauling intervals and reduce preventive maintenance costs. Nevertheless major overhauling can not be skipped (slide valves, plain bearing,…)
- Vibration analysis is a powerful tool for the QC. It was shown that it contributes to improve efficiently the maintenance and operation practices
- Vibration monitoring increases the confidence in the equipment health status and increases the availability and reliability of the cryogenic plants

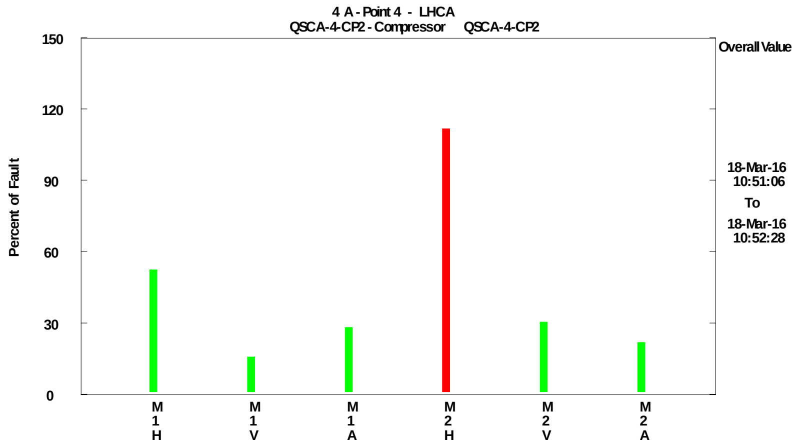
Next steps :

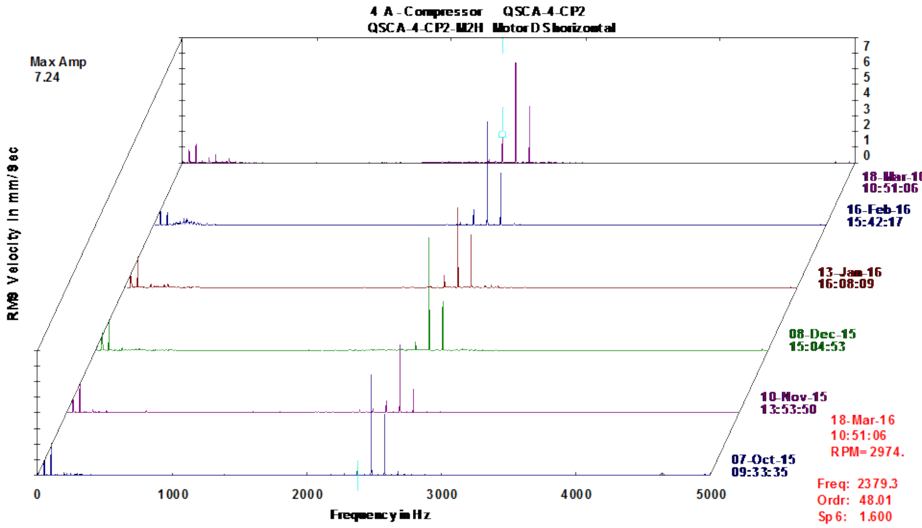
- Incorporate oil analysis
- Monitoring of plain bearings
- Investigate online monitoring

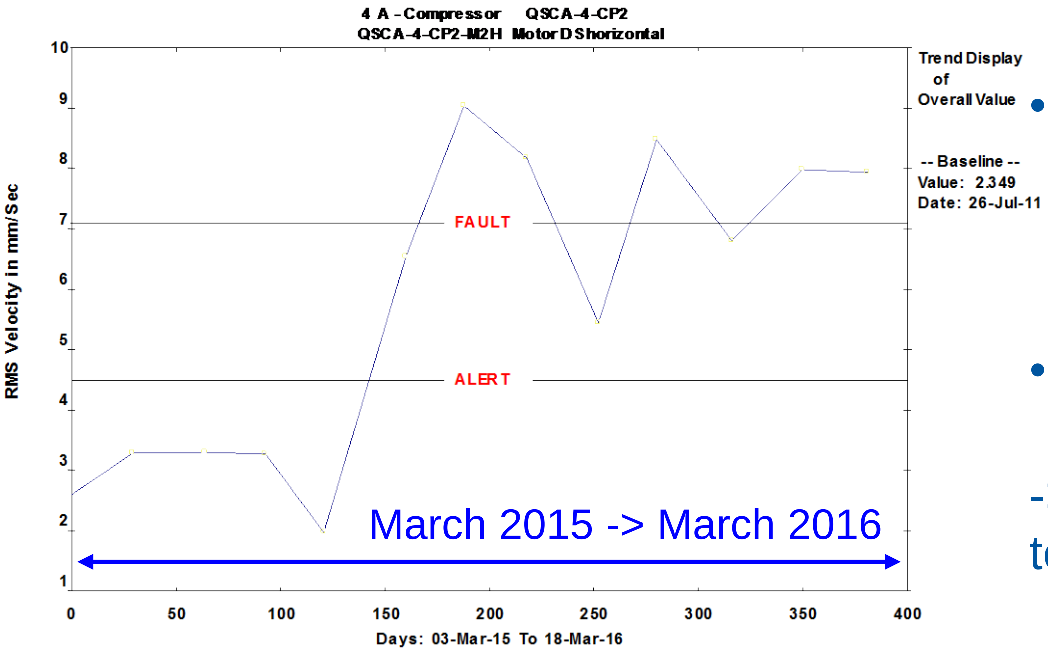
Thank you for your attention

Additional slides

Example : Rotor bars in motor (QSCA-4-M02, 2015-2016)





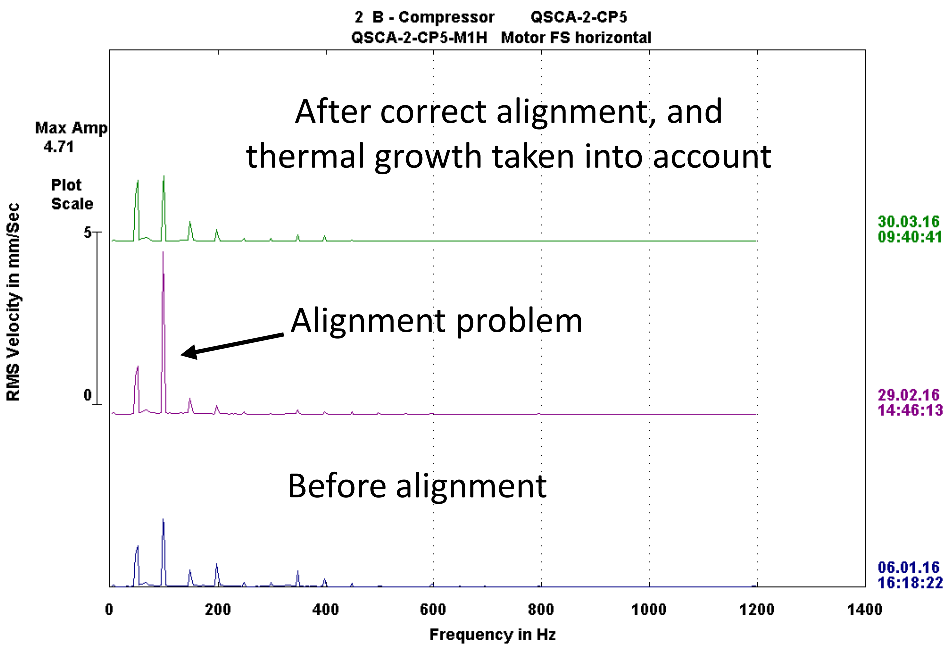


- Sep/2015: Detection of a problem with rotor bars in motor QSCA-4-M02 (Alert: high vibration due to an asymmetry in the magnetic field)
- Mar/2016 : Constant fault threshold

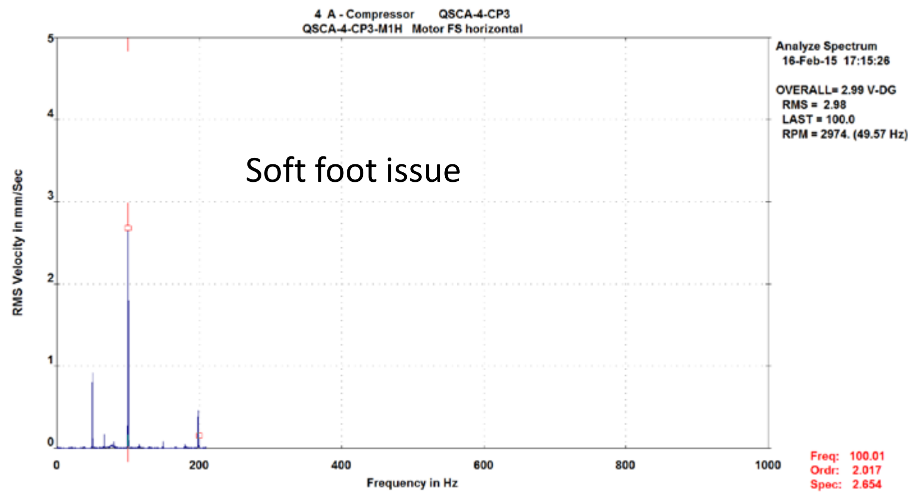
-> Replacement of the motor during the technical stop of May 2016

Example : maintenance practice & Quality Control

- Alignment issue found on compressor QSCA-2-CP5 (Feb-2016)
- Investigations -> alignment during Jan-2016
- Thermal growth not taken into account during alignment process



- Soft foot issue detected for QSCA-4-CP3 (Feb-2015)
- Investigations -> alignment during Jan-2015
- In alignment report, one foot was found out of tolerance



Extract from alignment report in the DB

Softfoot	
Machine A:	
No softfoot available!	
Machine B:	
Right front	0.06 [mm]
Right back	0.08 [mm]
Left front	0.05 [mm]
Left back	0.04 [mm]

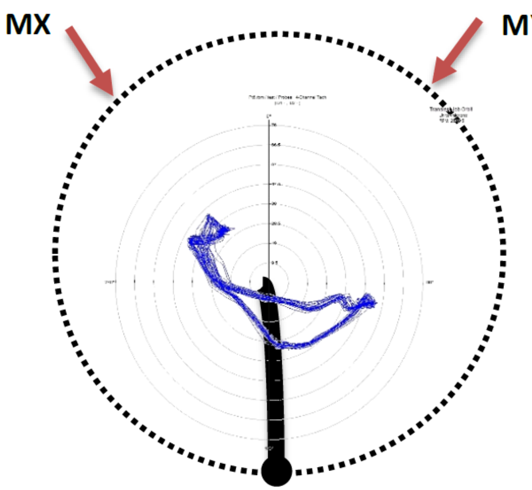
> max 0.06

- **Vibration analysis contributes valuably and efficiently to QC**
- **Correct alignment improves bearing and seal life, and reliability of the CS**

Vibration measurement : displacement probes

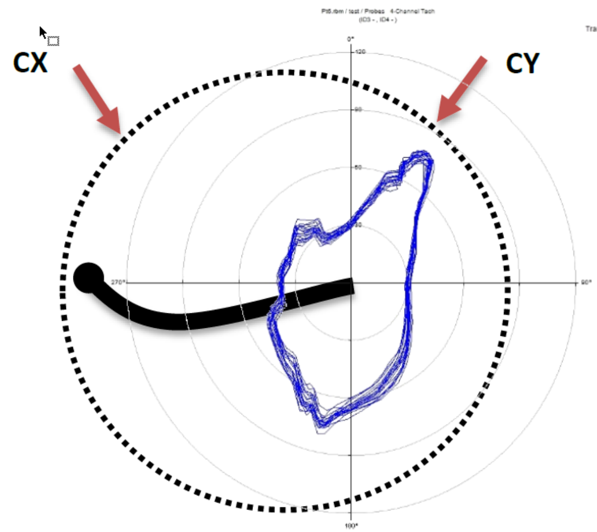
- Despite big progress with the alignment practice, vibration analysis was continuously reporting an alignment problem for one type of compressor system (Stal S87/S89)
- Noncontact displacement sensors were used to measure the displacement and shaft vibration

Results for shaft centerline and for dynamic measurements



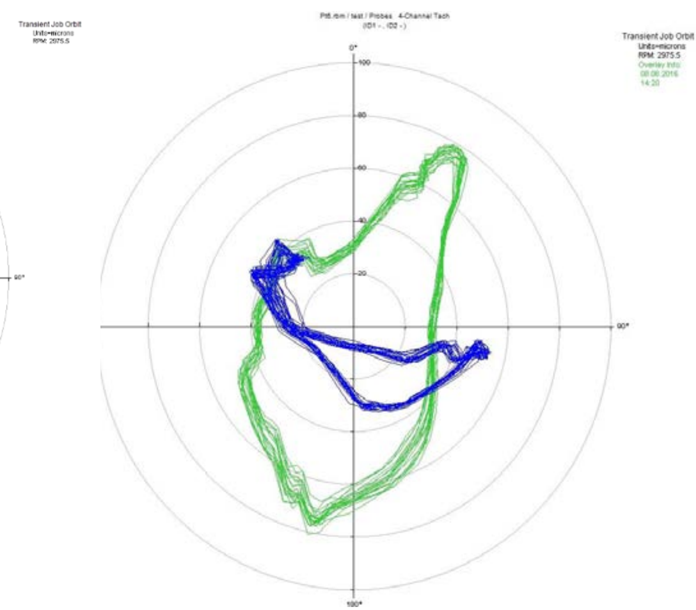
Motor shaft moves ~57 µm up and 4 µm to the left

No influence of the thermal growth



Compressor shaft moves horizontally 110 µm to the right

Big influence of thermal growth : 90 µm



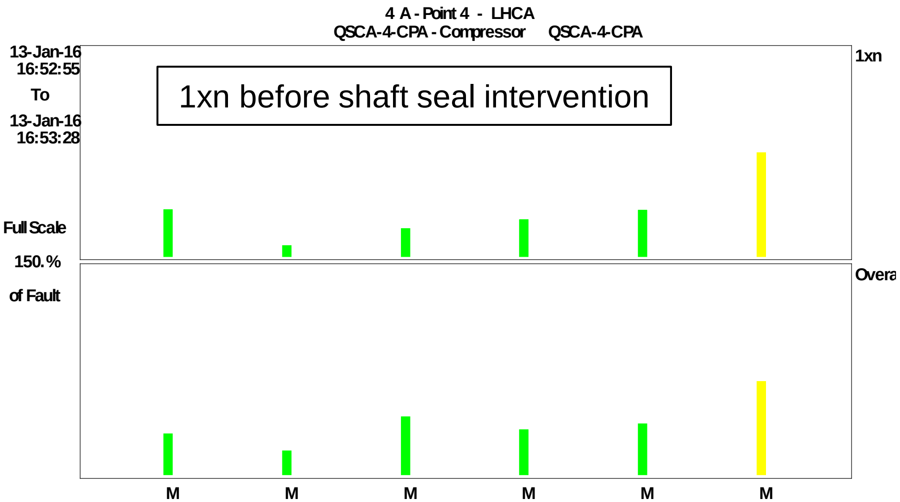
Unfiltered orbit of compressor (green) and motor (blue)

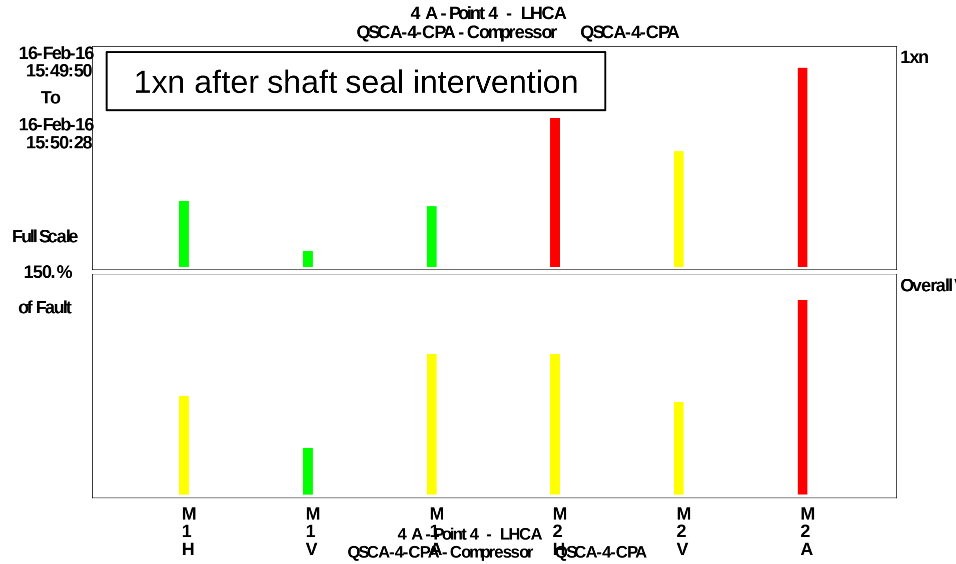
Motor bearing heavily preloaded in MY

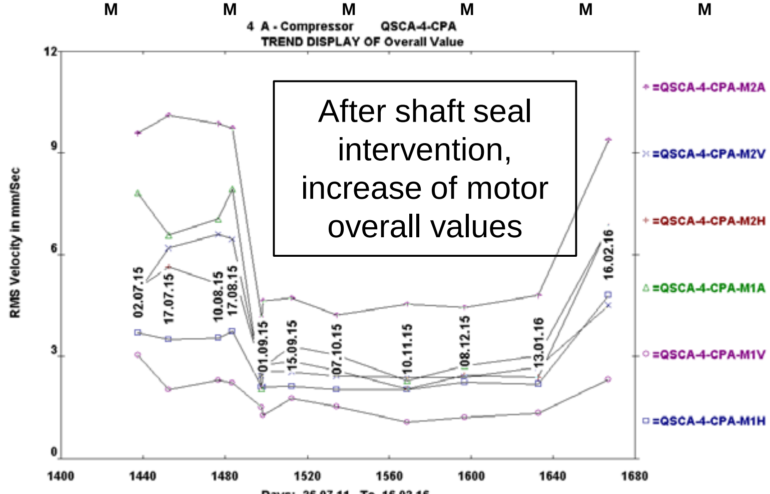
Condition and time	MX	MY	CX	CY
Initial position	**-11.44**	**-12.61**	**-11.30**	**-12.95**
16:02, Just after starting	-11.12	-12.25	-11.68	-12.81
16:30	-11.09	-12.17	-11.60	-12.71
17:05	-11.10	-12.26	-11.73	-12.50
The day after	-11.08	-12.24	-11.71	-12.24

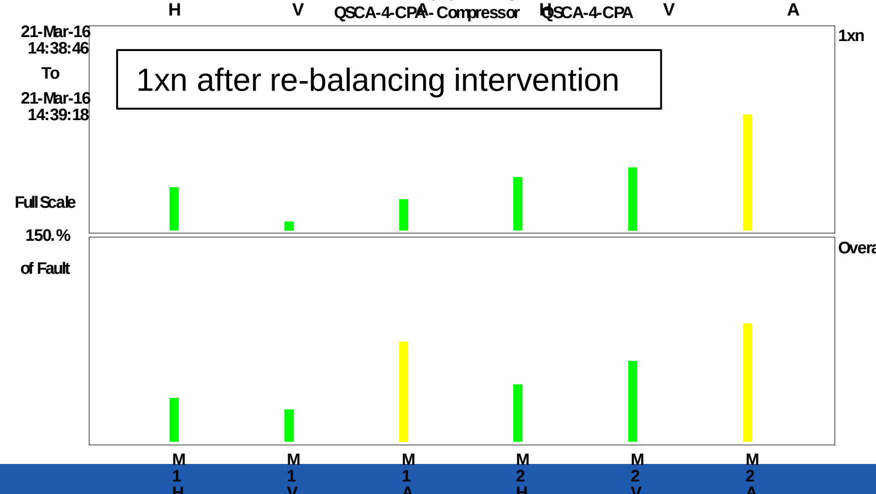
Example : Unbalancing after shaft seal intervention

- Balancing issue found on motor QSCA-4-M0A (Feb-2016)
- Investigations -> there was an exchange of shaft seal during Jan-2016
- Bad remounting of coupling (unsymmetrical mounting of the conical clamping ring)



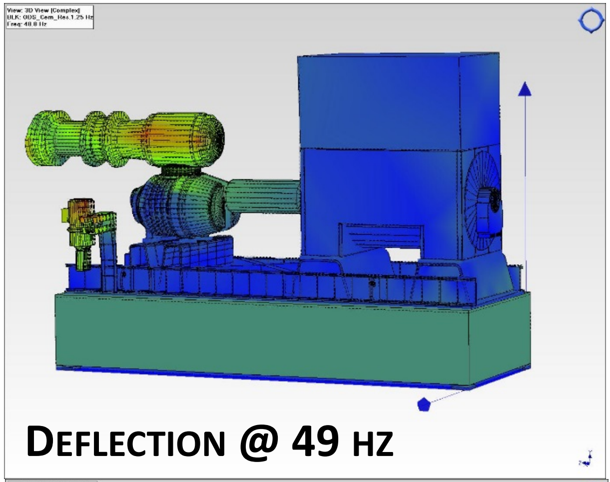


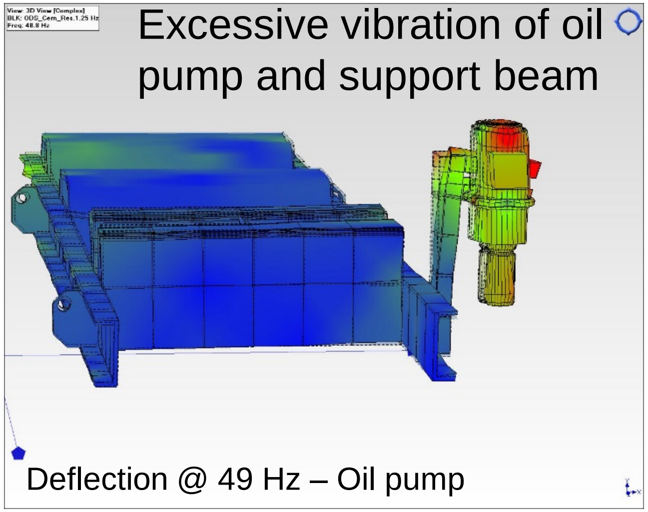




Example of Operation Deflection Shape measurement

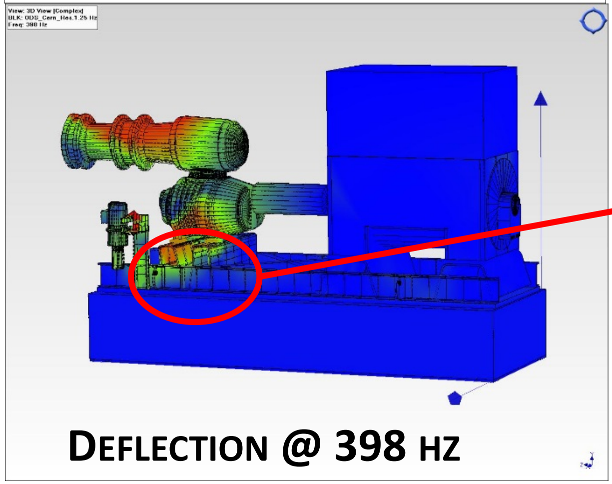
- A set of high stage compressors (Stal S93) was presenting very high vibration level (global). High sensitivity wrt operation conditions (MP/HP ratio)
- Can we improve the system and its dynamic behavior ? -> ODS measurement





Outcome:

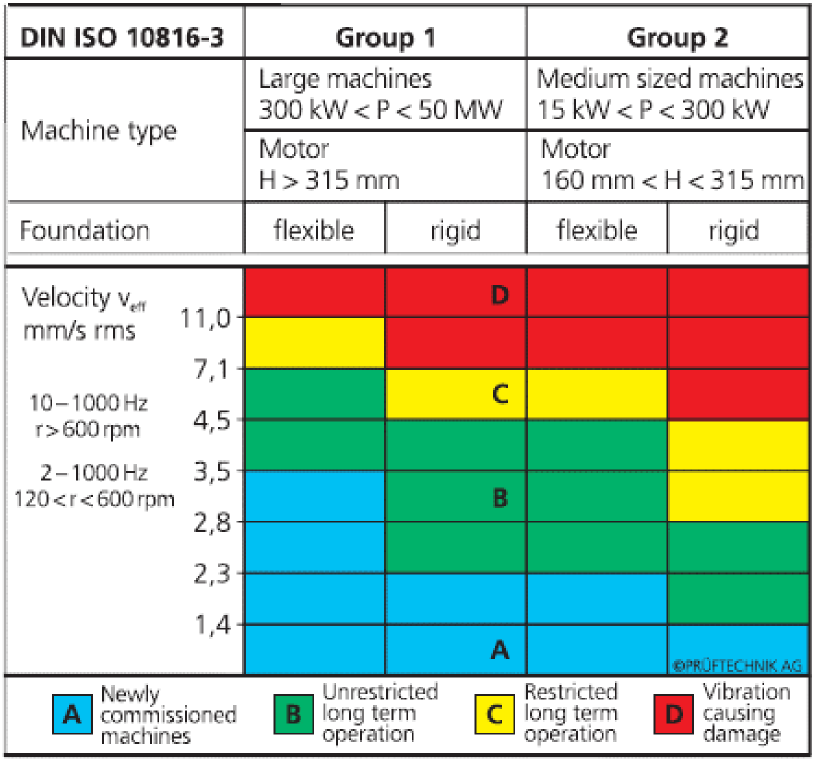
- Oil pump has been installed on a separate frame
- Frame and pipework support need to be re-inforced (stiffness & fixations)



eformation
rt frame

Condition Based Maintenance for CS

- A set of specialized standards is available : ISO, VDI, API



ISO 18816-3 for electrical motor

ISO 18816-7 for pump

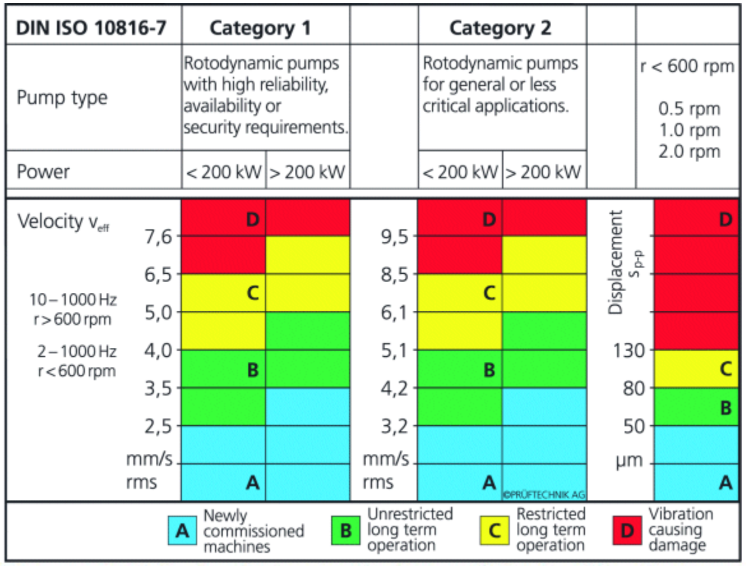


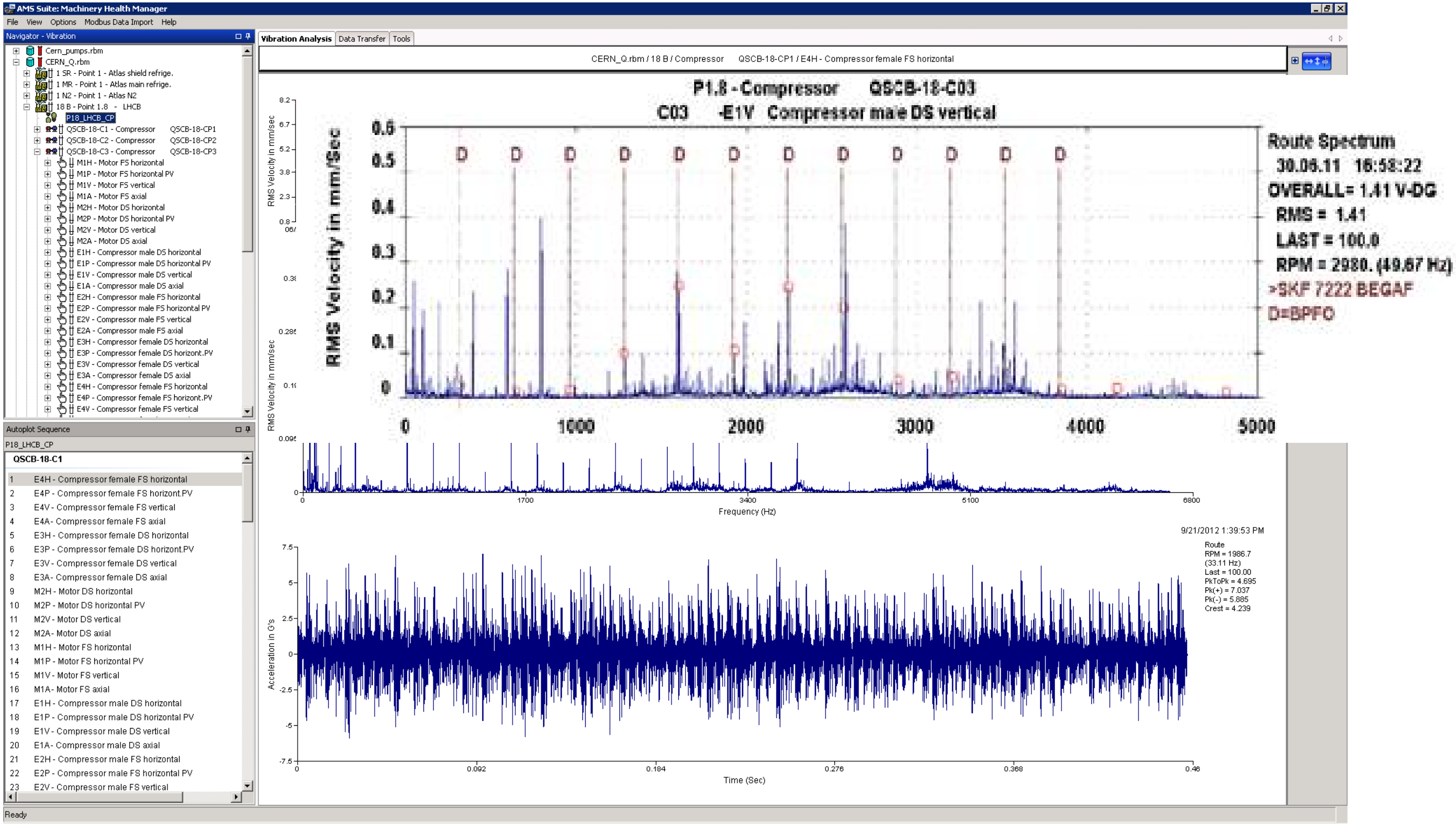
Table 1. Recommended limit values for housing vibrations as RMS value of the vibration velocity in mm/s

Machine group	Type of installation	Zone limit	Frequency range A	Frequency range B
Group 1 Screw compressors with sleeve bearings and timing gears $P \geq 55$ kW	rigid	I/II	8,0	3,0
		II/III	12,0	4,5
	resilient	I/II	10,0	4,5
		II/III	15,0	7,0
Group 2 Screw compressor with roller bearings or roller and sleeve bearings and timing gears $P \geq 37$ kW	rigid	I/II	10,0	3,0
		II/III	15,0	4,5
	resilient	I/II	12,0	4,5
		II/III	18,0	7,0
Group 3 Screw compressors without timing gears $P \geq 55$ kW	rigid	I/II	8,0	3,0
		II/III	12,0	4,5
	resilient	I/II	10,0	4,5
		II/III	15,0	7,0
Group 4 Roots blowers with roller bearings $P \geq 22$ kW	rigid	I/II	10,0	4,5
		II/III	15,0	7,0
	resilient	I/II	12,0	7,0
		II/III	18,0	11,0

VDI 3836 for screw compressor

Vibration analysis

AMS suite – Machinery Health Manager

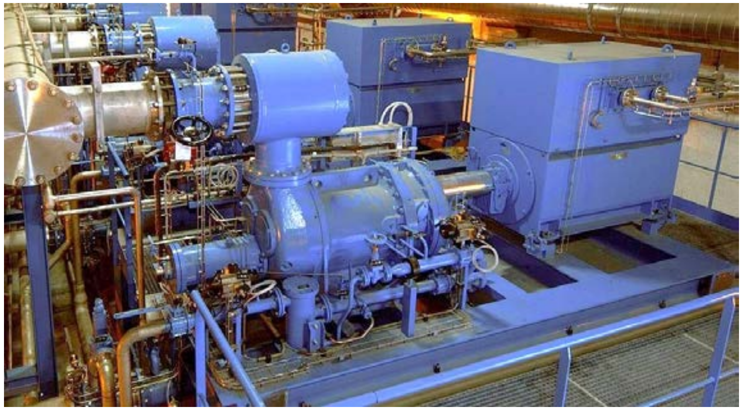


Preventive maintenance (Cryo-Ops 2014)

Major overhauling periods have been revised according to criticality criteria wrt process, redundancy, cost, available spare, and predictive maintenance plan

Screw compressors major overhauling		
Manufacturer	Recommendation	CERN preventive plan
Aerzen	20'000 h	40'000 h
Stal	40'000 h	
Kaeser	40'000 h	
Mycom	20'000 h	
Howden	4 years of operation	

Motors major overhauling			
Type	Voltage	Power	CERN preventive plan
Ball bearings Journal bearings	3.3 kV	-	30'000 h 40'000 h
Ball bearings (oil pumps)	400 V	> 10 kW ≤ 10 kW	30'000 h Replacement (new)



Pumps major overhauling		
Manufacturer	Recommendation	CERN preventive plan
IMO	16'000 h	24'000 h
Stal	5'000 h	24'000 h
Desmi	8'000 h	8'000 h
Kral	40'000 h	40'000 h
Mayekawa	40'000 h	40'000 h
Allweiller	16'000 h	40'000 h
Leybold	20'000 h	40'000 h

Vibrations

What Is Vibration Caused By ?

Imperfections in the Machine:

Design	Assembly
Manufacture	Operation
Installation	Maintenance

What Are Some Common Machine Problems That Generate Mechanical Vibration:

Misalignment	Unbalance
Worn belts & pulleys	Bearing Defects
Hydraulic Forces	Aerodynamic Forces
Reaction Forces	Reciprocating Forces
Bent Shafts	Rubbing
Gear Problems	Housing Distortion
Certain Electrical Problems	Frictional Forces

What Are Some Common Machine Problems That *Amplify* Mechanical Vibration (But Don't *Cause* It):

Resonance	Looseness

Set up of vibration measurements

Database setup, for every system :

- Inventory of all characteristics to configure the condition monitoring software and its database (kinematic chain, geometry, bearing data, …)
- Monitoring program : selection of all the measurement points and their characteristics (freq. ranges, resolution, …)
- Define and configure routes in the PDC
- Equip each systems with fixed coded pins to avoid measurement errors
- Define the alarm thresholds for the various faults
- Define the measurement intervals