18th International Symposium on Magnetic Bearings

18 – 21 July 2023 Lyon France

# Experience in Magnetic Bearings Lessons Learnt and Expectations

by Antoine LUCAS and Alain GELIN

# Content

1. Introduction, TotalEnergies in brief
2. Experience in Magnetic Bearings
3. Integrated Compressors: Where we came from… and where we want to go
4. AMBs - Lesson Learn and Expectations
5. Conclusion, *“We have a dream…”*

# 01.

# Introduction, TotalEnergies in brief

# About TotalEnergies: our ambition and our mission

TotalEnergies is a **global multi-energy company** that produces and markets energies: oil and biofuels, natural gas and green gases, renewables and electricity.

Active in more than 130 countries, TotalEnergies puts **sustainable development** in all its dimensions at the heart of its projects and operations to contribute to the well-being of people.

As a major player in the energy transition, TotalEnergies' ambition is to **reinvent the way energy is produced and consumed to get to net zero by 2050**, together with society, and to resolve the climate challenge.

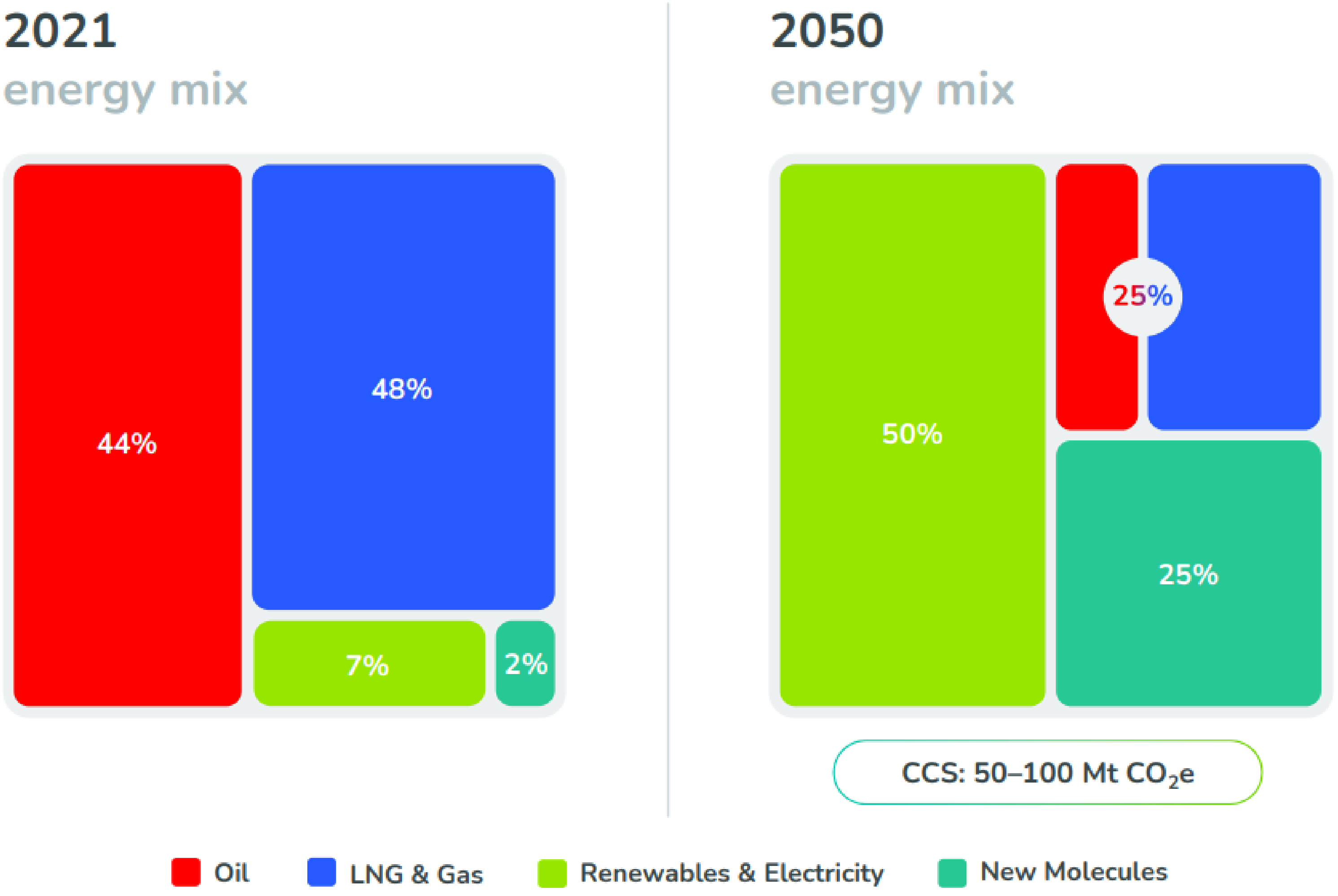
**OUR MISSION**
**Our 101,000 employees are committed to energy that is more affordable, cleaner, more reliable and accessible to as many people as possible.**

**More energy**

**Less emissions**

**Always more sustainable**

# A multi-energy company, our vision in 2050



# A multi-energy company, our key figures

TotalEnergies

**$18.1bn**
in adjusted net income **in 2021**

**World no.2***
in liquefied natural gas

**8.8 million**
gas and power **customers**
in Europe

**150,000**
**charge points**
for electric vehicles
by 2025

**> $3bn**
**invested**
in renewables and electricity
**in 2021**

**> 100 GW**
of production capacity for **renewable electricity** by 2030

**30%**
**circular polymers**
by 2030

More than
**8 million**
customers served in nearly **16,000 service stations** each day

**150**
**hydrogen filling stations**
operated in Europe by 2030

**2.8 Mboe/day**
produced in 2021, of which
**54% natural gas**

**740**
business-related competencies

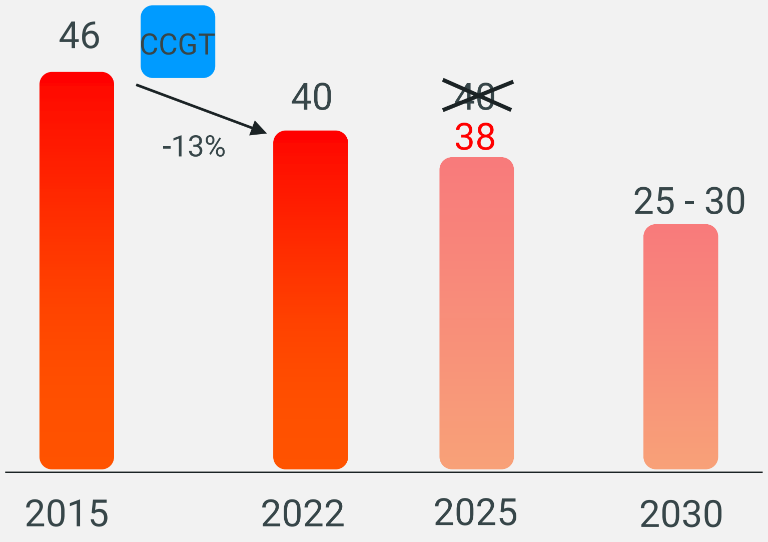
More than
**4,000**
**researchers**
in our
**18 R&D centers**

**± $1bn**
invested in R&D in 2021, of which
**50% devoted to decarbonation solutions**

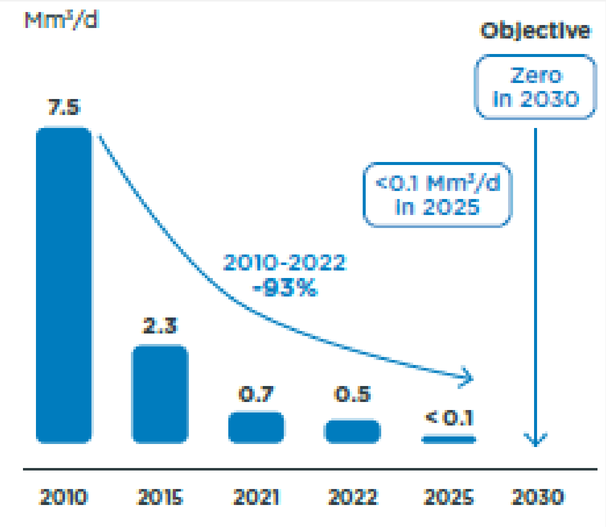
# Emissions reduction roadmap

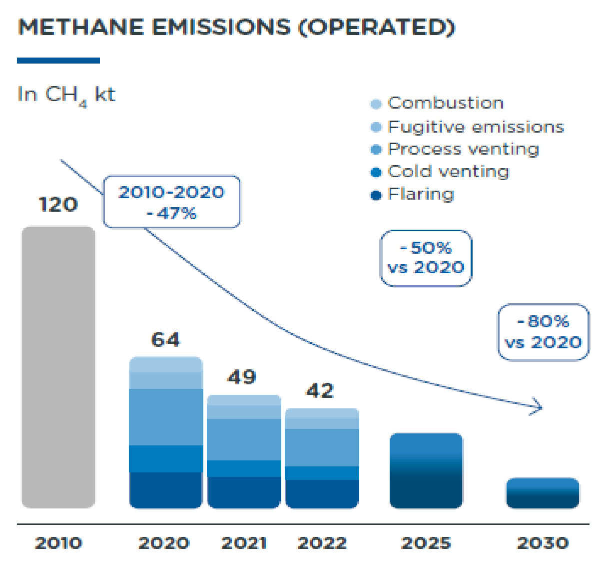
## Reducing Emissions…

**$CO_2eq$ emissions**
(MT) Scope 1+2 operated



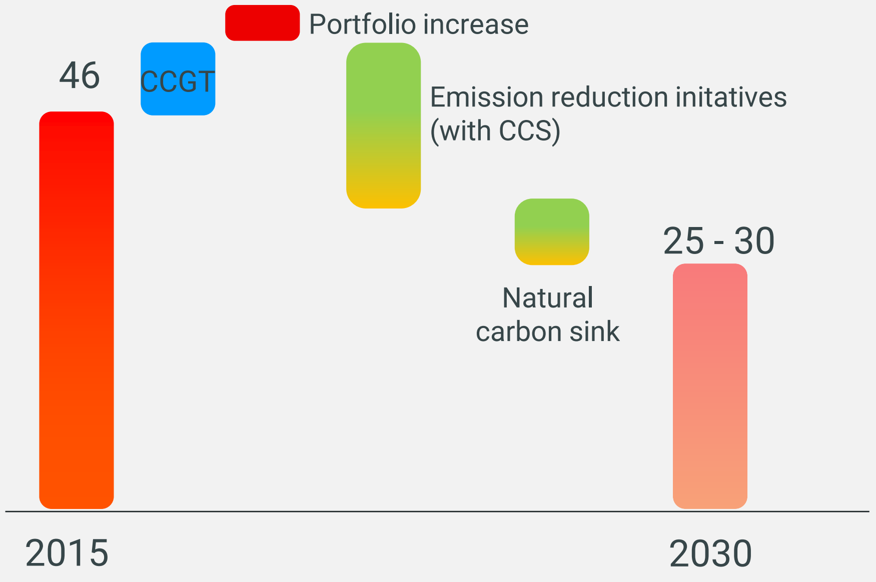

## Stopping routine flaring




## Being more efficient and capturing…

**$CO_2eq$ emissions**
(MT) Scope 1+2 operated



# Sustainable energy and climate

To **get to net zero by 2050**, together with society, the Company is taking action to:

## Reduce emissions from its operated industrial facilities

by over 40% by 2030 and disclose the progress made at its operated and non-operated facilities.

TotalEnergies is particularly working on reducing **methane** emissions: -50% by 2025 and -80% by 2030, compared to 2020 levels.

## Reduce the indirect emissions related to its products

together with society – i.e., its customers, its suppliers, its partners and public authorities – by helping to transform its customers' energy demand.

Active Magnetic Bearings (AMBs) will be part of the solution

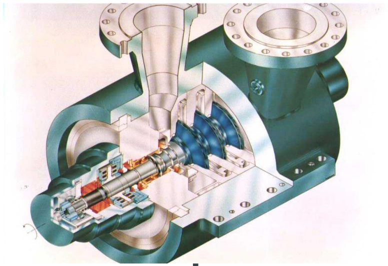
# 02.

# Experience in Magnetic Bearings

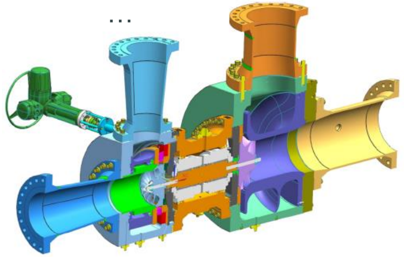
# Experience in Magnetic Bearings

## A long experience including compressors, turbo-expanders and electrical motors

Lacq - France
- KB-403 World First
- K31-816
- 2 Boosters



Turbo-Expanders (TEXs)
- UK, Belgium, Congo, Algeria, Russia, Kazakhstan, Denmark …



Incahuasi Bolivia - 2 ICL$^{TM}$ units
- From 73 to 106 bar
- 4.5 MW @ 12000 rpm

Tyra Offshore – Denmark
- 7 HSEM Stand Alone + 2 TEXs
- Up to 15.9 MW @ 8500 rpm

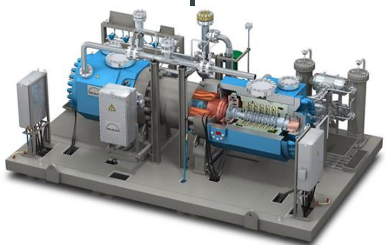
Brunei – Export Gas ICL$^{TM}$
- From 13 to 59 bar
- 10.8 MW @ 8500 rpm

1987… | 1994 | From 1996… | 2007… | 2015 | 2016 | 2021 | 2022 | 2023

Donges Refinery - France
- HSEM Stand Alone (Oil Bearing)
- 0.9 MW @ 12500 rpm

Qualification of ICL$^{TM}$ from BH
- Dry Commercial Gas
- Water Saturated Gas few years after

Saint-Auban - France ICL$^{TM}$
- From 13 to 90 bar
- Ethylene compressor – 9 impellers
- 2.8 MW @ 11000 rpm



* Picture from Website

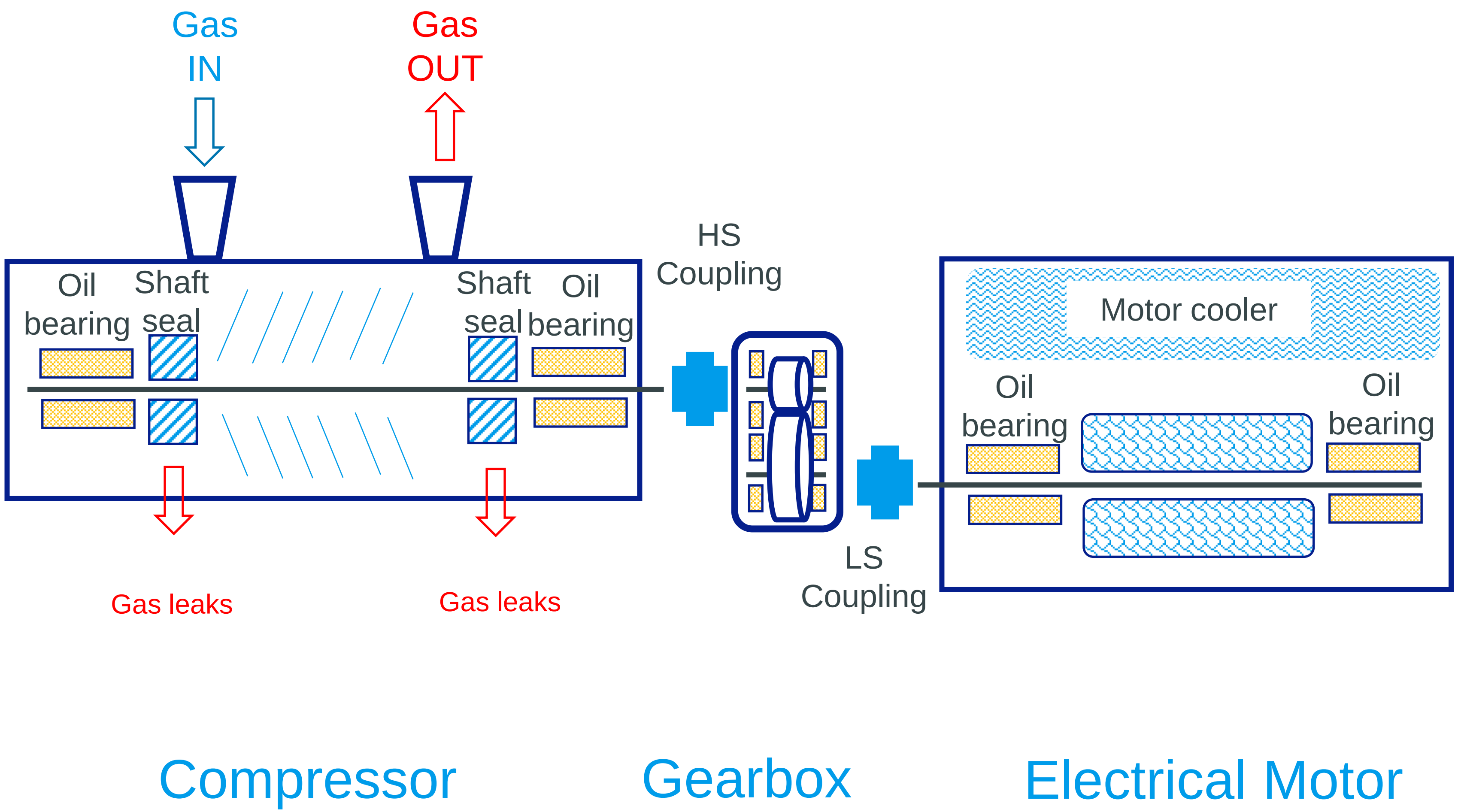
Qualification of MAN-ES
- Sealed HOFIM$^{TM}$ (with MECOS AMBs)
- Dry / Water Saturated Gas

# 03.

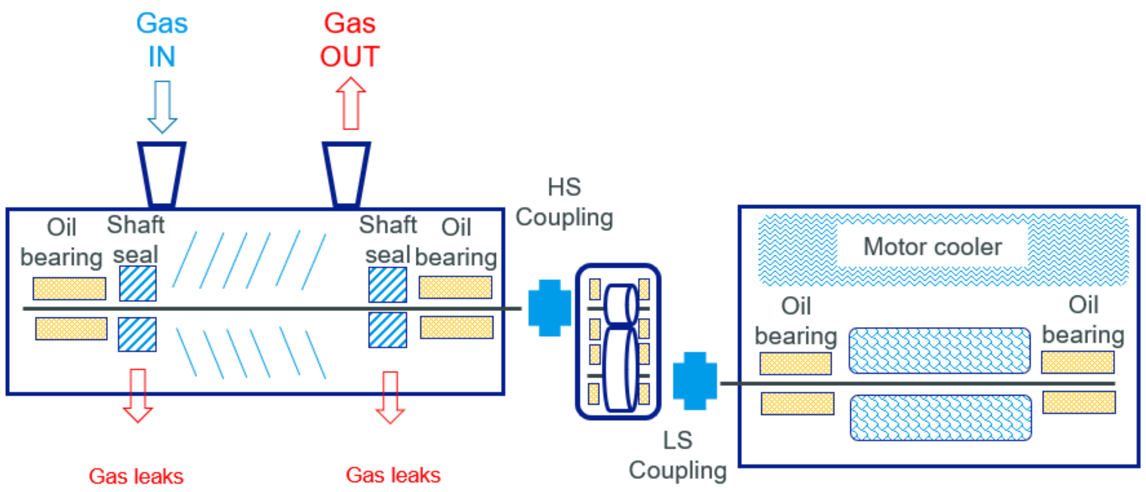
# Integrated Compressors

Where we came from… and where we want to go

# Electrical motor driven centrifugal compressor at a glance



# Electrical motor driven centrifugal compressor at a glance




Conventional Package

## Complex system

### Auxiliaries

- Lube oil system
- Seal gas system
- Tenth of instruments

### Sensitive systems

- Dry gas seals with need for seal gas conditioning
- Lack of Reliability

## Emissions

- Direct emissions (HC leaks to flare through shaft end seals) – **Routine flaring**
- Induced $CO_2$ emissions (seals failure ⇨ compressor unavailability) – **Non-Routine flaring**
- Noise

# Conventional solution, in short…

- Pros
  - Compression architecture covered by many standards (API, ISO, etc.…).
  - Technology well known worldwide including field operation teams.
  - Technology well known by EPCs.
  - Competition between Suppliers/OEMs (Baker Hughes, MAN-ES, MHI, Siemens/DR).
  - Can accommodate high pressures and all type of gases.

- Cons
  - Complex architecture including multiple instruments.
  - Multiple auxiliaries (lube oil, sealing gas, cooling system).
  - Need for utility fluids (air, oil, nitrogen, water).
  - Dry Gas Seals (OPEX, lack of reliability).
  - Emissions (hydrocarbons to flare, $CO_2$ from FG combustion).
  - Weight/Footprint (Offshore)

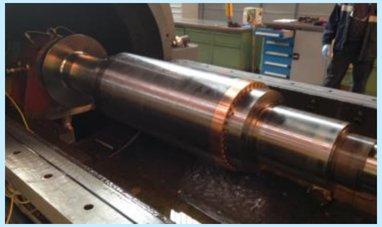
How to move forward…

# Two proven technologies from 90's

TotalEnergies

## High Speed Electric Motors HSEMs

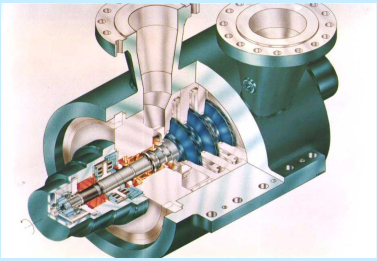
- VSD driven, Spinning at high speed
- Rotor supported by active magnetic bearings
- Cooled by atmospheric air or by pressurized process gas



**No more gear box requirement**

## Active Magnetic Bearings AMBs

- Rotor supported by magnetic field
- Well proven technology since the 90's (experience KB303 Lacq SNEA(p) – 1987)
- Experience from other Projets

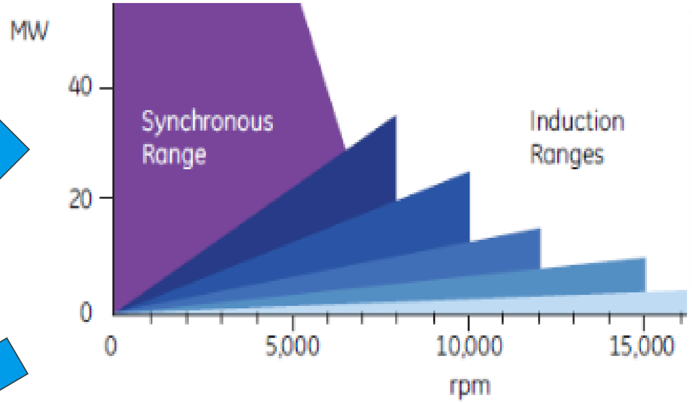


**No more lube oil requirement**

# From Conventional to Integrated

## Conventional Package

## Thanks to HSEMs and AMBs



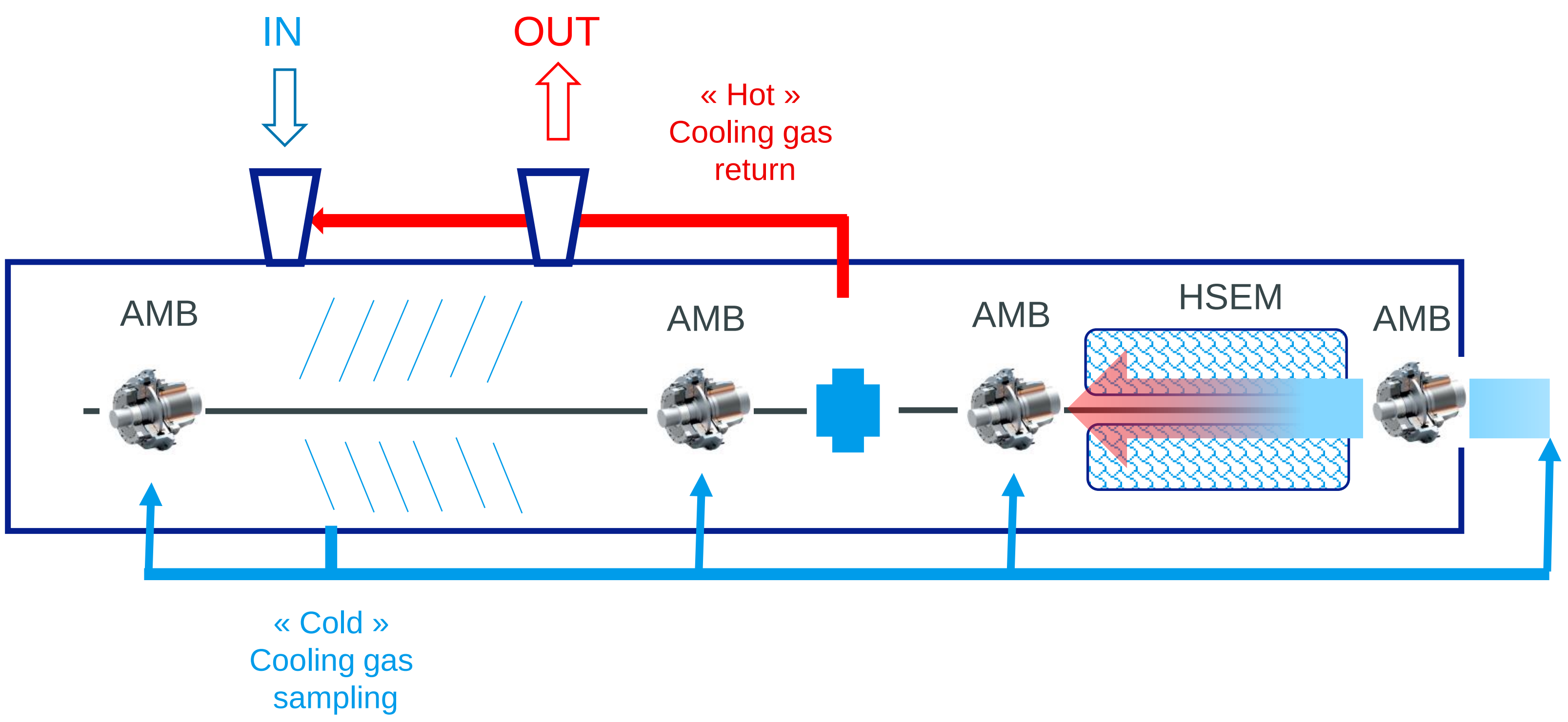

## Stand Alone Packages

- **HSEMs & AMBs cooled with atmospheric air**
- **Compressor still with Dry Gas Seals (reliability concern)**

## Integrated (Hermetic) Packages

- **HSEMs & AMBs : Pressurized and cooled with Process Gas**
- **No more Dry Gas Seal for Compressor (better reliability)**

# From Conventional to Integrated



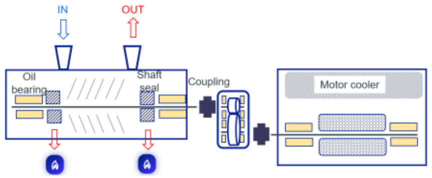

Integrated (hermetic) compressor

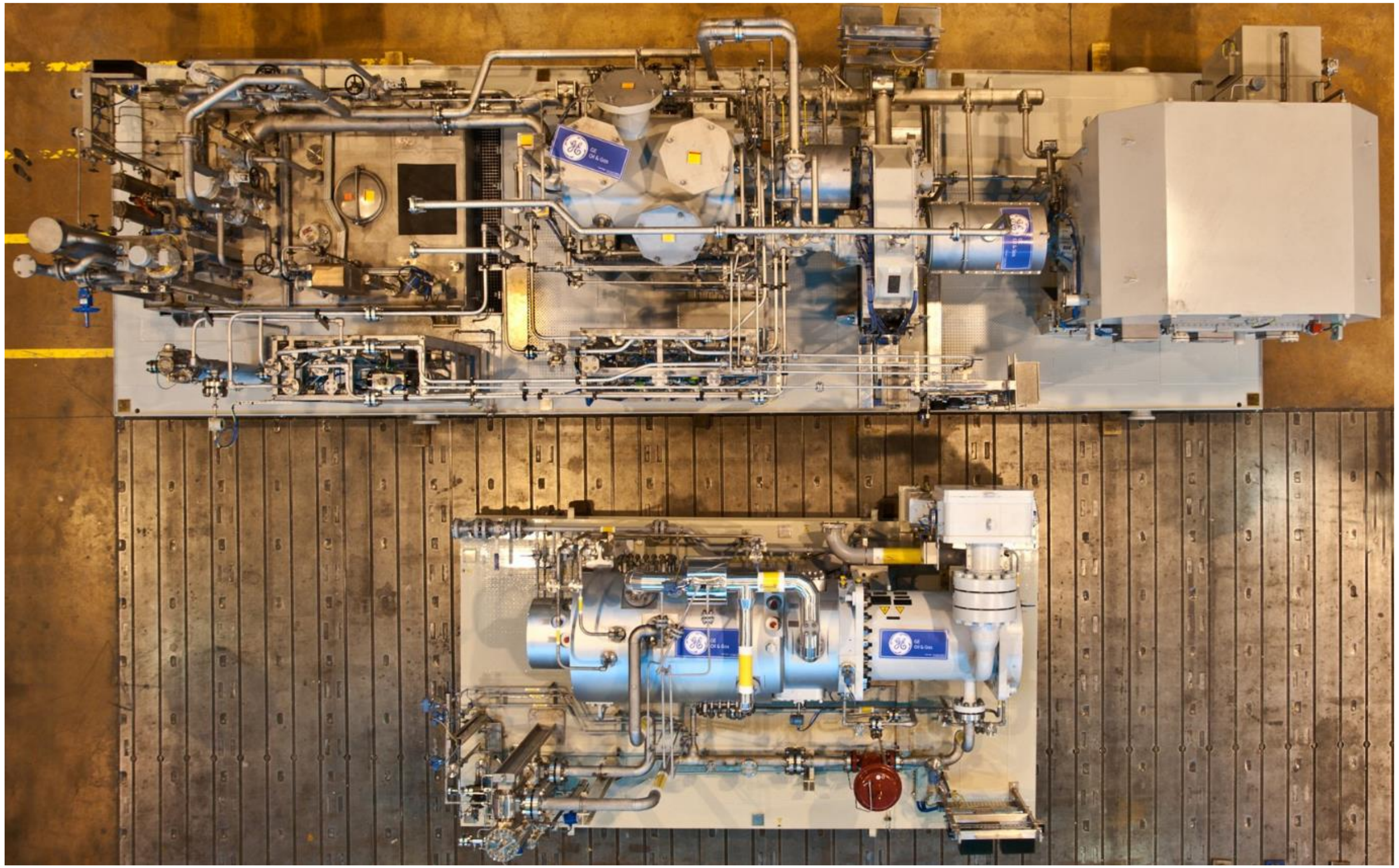
**Highlights**

- No dry gas seals
- No lube oil system
- No cooling water
- No utilities
- No emission (gas, oil, noise)
- Only few instruments

**Simple, lean package**

# Conventional vs Integrated in brief



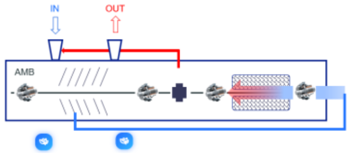



## Highlights

- **Fully Hermetic (no flaring)**
- Footprint reduction (~50%)
- Weight reduction (~25%)

**Simple, lean package**

* Courtesy of BH



# Integrated Compressors, in short…

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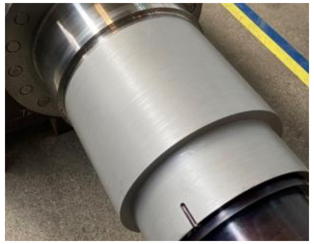
## Pros

- All electrical
- No auxiliary system (only VSD)
- No air, no nitrogen, no cooling water
- No direct emission from seals
- No dry gas seals (increased availability for upstream applications ⇨ Reduced flaring)
- Reduced footprint and weight (lower CAPEX installation cost)
- Simplified maintenance (lower OPEX)

## Cons & Limitation

- Cannot be used with some gases (limitations in $CO_2$ and $H_2S$ contents)
- Limited in discharge pressure (~300 bara)
- Less competition on the market
- CAPEX



… Still some limitations from Active Magnetic Bearings

# Integrated Compressors, Today  To come


To comply with TotalEnergies Ambition

# 04.

# AMBs - Lessons Learnt and Expectations

# Availability/Reliability

Feedback from TTE Operators over the years (few Verbatim):

- *"No major issue from hardware"*
- *"Nothing to report, No negative feedback"*
- *"Generally reliable but if we have issues, we are wholly reliable on equipment OEM and AMB suppliers, Black Box"*

**5.1 Availability terminology and calculation**

- RUN — Running Period
- ABNR — Available But Not Required
- SCH — Scheduled downtime for maintenance
- UNSCH — Unscheduled downtime for maintenance
- MTBF — Mean Time Between Failure
- MTTR — Mean Time To Repair (or Restore)
- TOTAL TIME (TT) — TT = RUN + ABNR + SCH + UNSCH
- USE FACTOR (U) — $U = \frac{RUN}{TT}$
- AVAILABILITY (A) — $A = \frac{RUN+ABNR}{TT}$
  Ability of an item to be in a state so that it performs a required function, at a given instant or within a given lapse of time, assuming the availability of all necessary means.
- RELIABILITY (R) — $R = \frac{RUN+ABNR+SCH}{TT}$
  Ability of an item to perform a required function within a given lapse of time with given conditions.

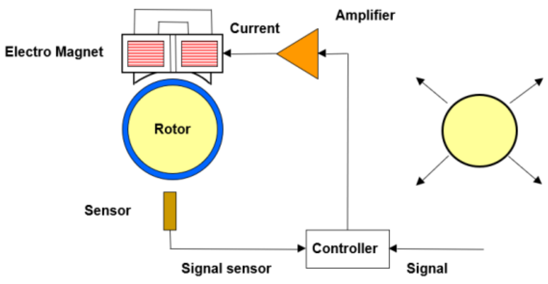
TotalEnergies Target : Availability 95% / Reliability 97%

Confirmation from Bolivia – Incahuasi ICL$^{TM}$ units

<u>Reliability since 2018 (yearly average)</u>
10-KA-3101A: **99.7%**
10-KA-3101B: **99.9%**

**AMBs are Reliable –** Very low preventive maintenance

# Transfer Function and "Valley of the Death"




- Typical transfer function of AMBs
- Induction limitation ~1.5 Tesla (FeSi laminations)
- AMB Controller/Amplifier (PID)
- Stiffness/Damping ~10 time lower than oil bearings
- Lack of Stiffness/Damping at Low Frequency

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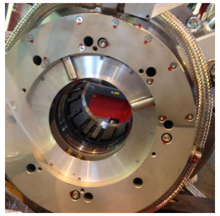
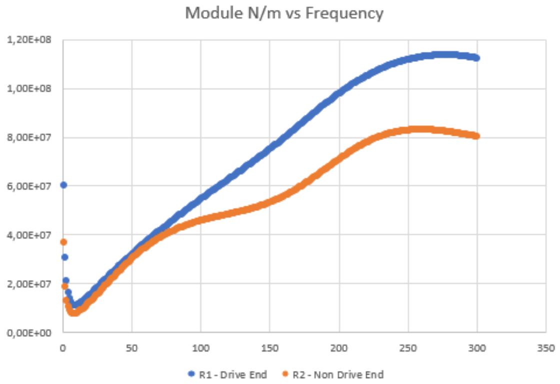
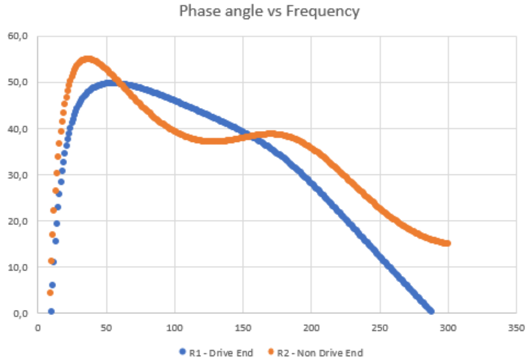
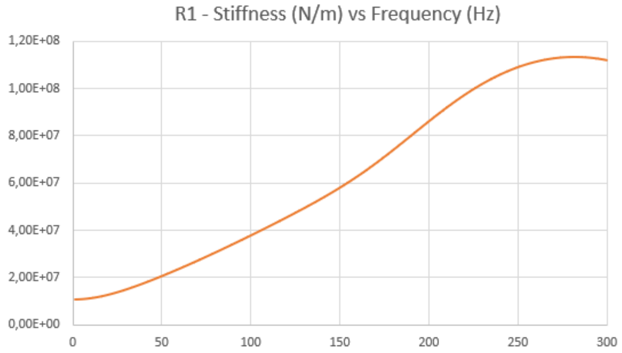


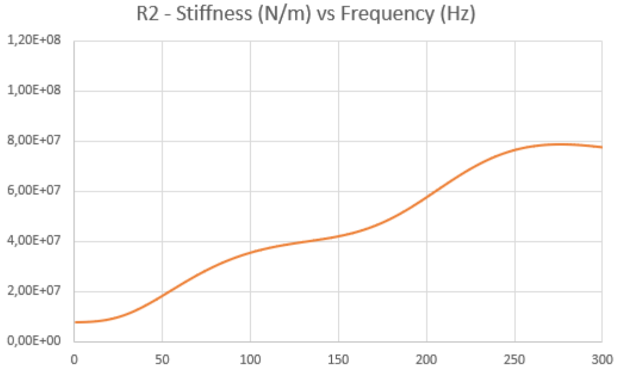



$$Stiffness\left(\frac{N}{m}\right): K = magnitude * \cos\alpha$$

$$Damping\left(\frac{Ns}{m}\right): C = \frac{magnitude * \sin\alpha}{2\pi f}$$

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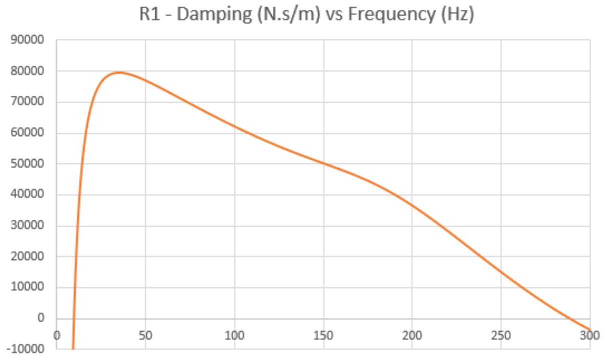
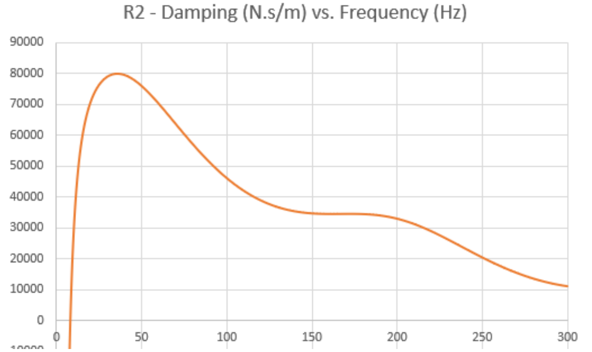
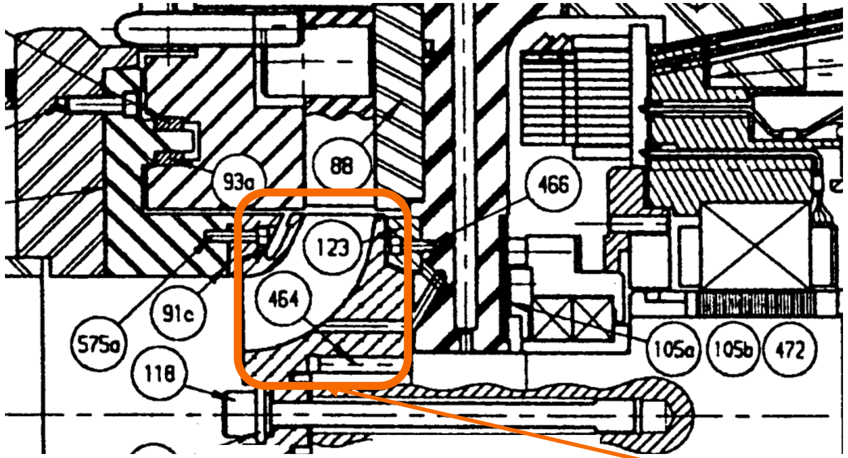


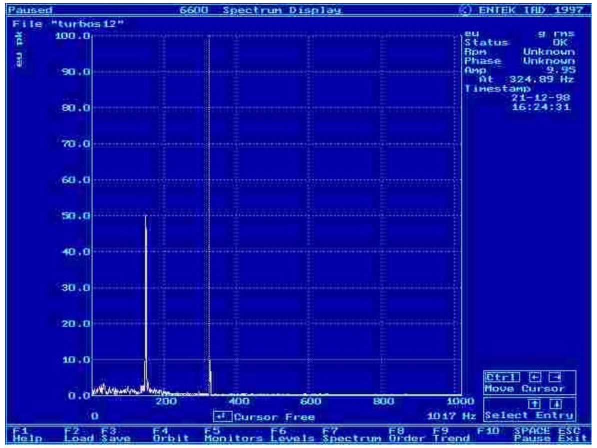



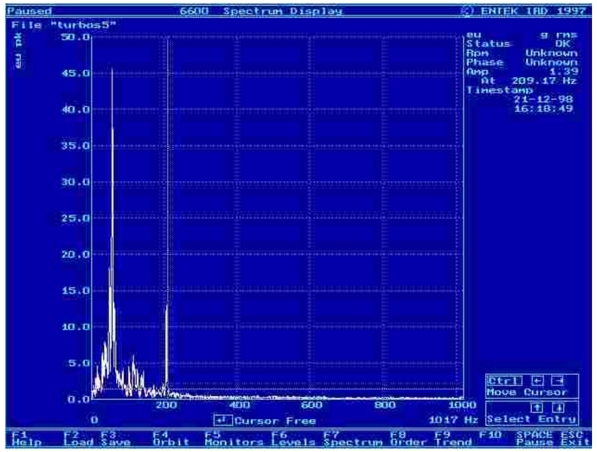

## How to increase the Stiffness at Low Frequency ?

# Turbo-Expanders – Lack of Stiffness at Low Frequency




Upset, transient process conditions…may induce liquid formation on turbine side and low frequency excitation leading to labyrinth wear, contact, rubbing, internal damages and failures.



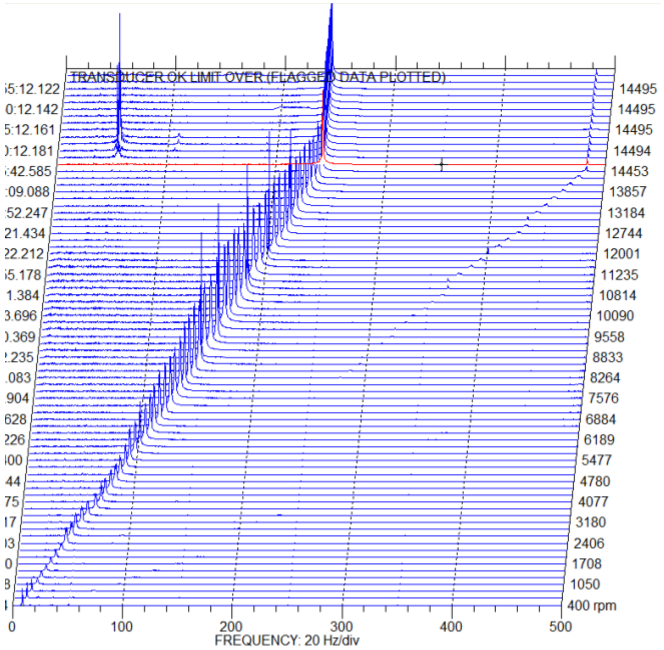




How to increase the Stiffness at Low Frequency ?

# Centrifugal Compressor & Sub-synchronous instability

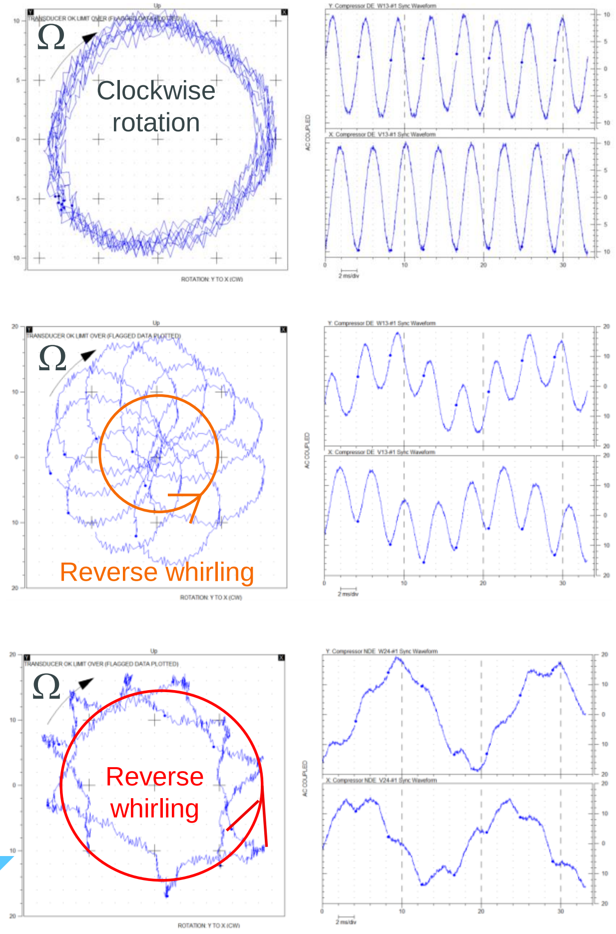
TotalEnergies

- API Stability Analysis – Main focus on Forward
- But what about Reverse/Backward direction ?

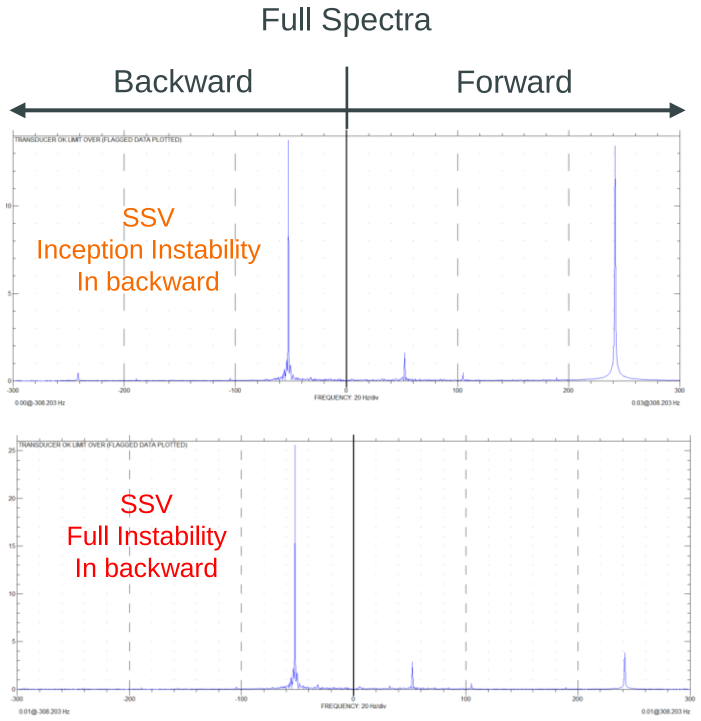



Sub Synchronous Instability
First natural frequency in backward motion
during compressor loading !

Compressor Loading




No Sub Synchronous Instability at Low Pressure




See also: Stability considerations of centrifugal compressor equipped with active magnetic bearings, Proc. 48th, Turbomachinery Symposium, Houston, 2019 Bidaut Y, Somaini R and De Lima Rugue

Compressors with AMBs very Sensitive : Forward but **also Backward**

# Transfer Function, Stability and High Frequency

TotalEnergies

**Many types of algorithms and considerations**
(see also API-617 Annex-E and ISO-14839 Part 3)

- SISO vs MIMO control system
- Residual negative electrical stiffness of AMBs
- Non-collocation between sensors and bearings
- …

**E.4.8.6.2 Acceptance Criteria**

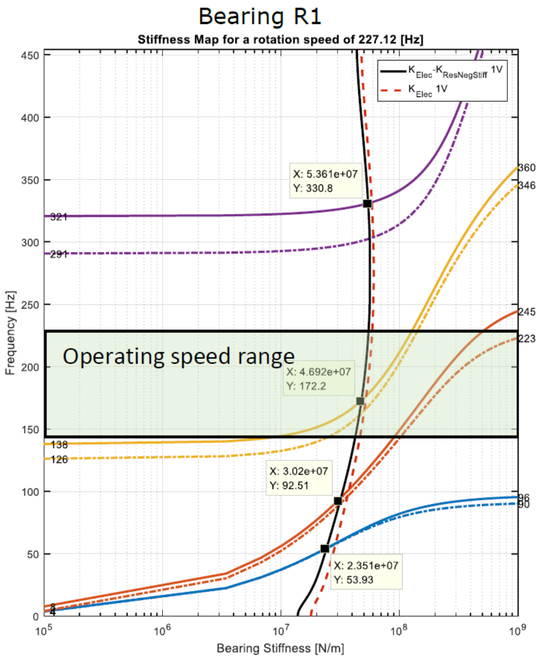
The Level II stability analysis shall indicate that the machine, as calculated in E.4.8.6.2:

a) has a final log decrement greater than 0.1 for all modes between 0 and $N_{mc}$,

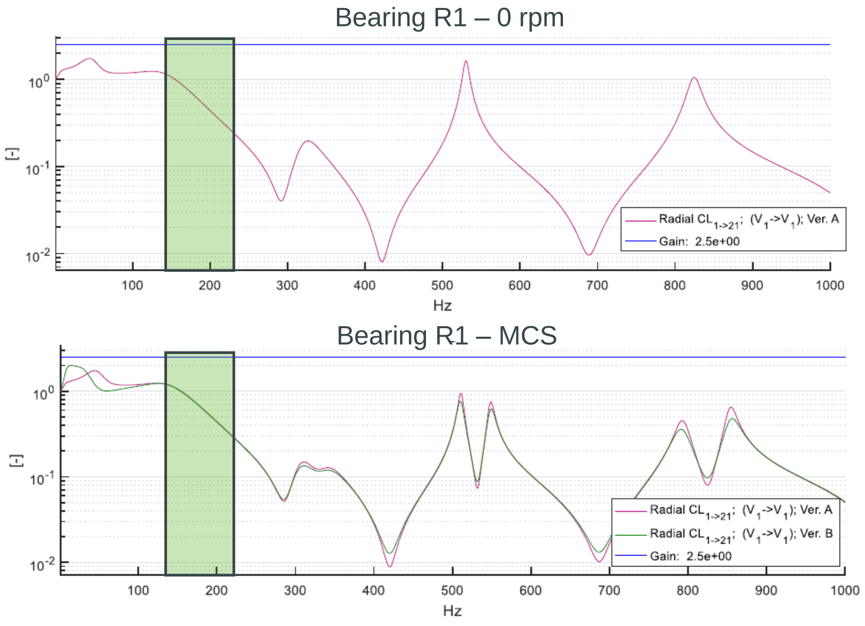
b) has a final log decrement greater than 0.0 for all modes greater than 125 % of $N_{mc}$,

c) has a final log decrement greater than $\delta_{min\ allowable}$ given by Equation (E.3) for any mode between $N_{mc}$ and 125 % of $N_{mc}$.

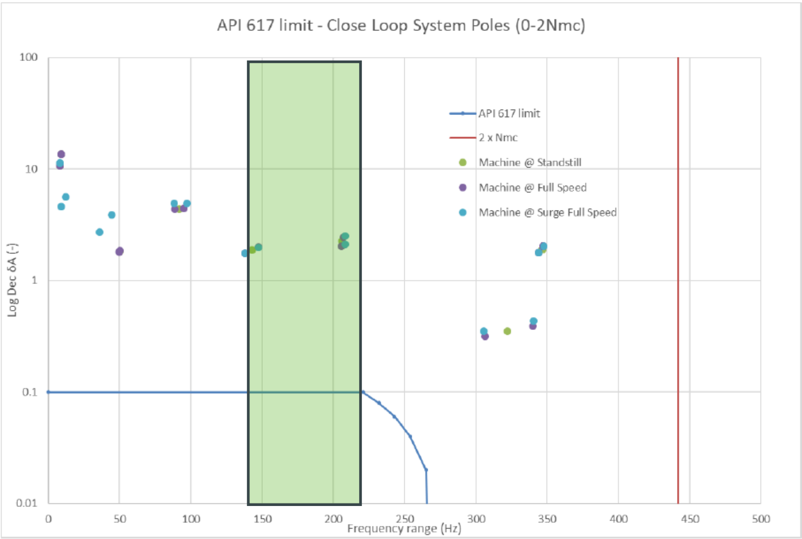
$$\delta_{min\,allowable} = 0.5 - 0.4\frac{N_{mode}}{N_{mc}} \quad \text{(E.3)}$$




Undamped Critical Speed Map



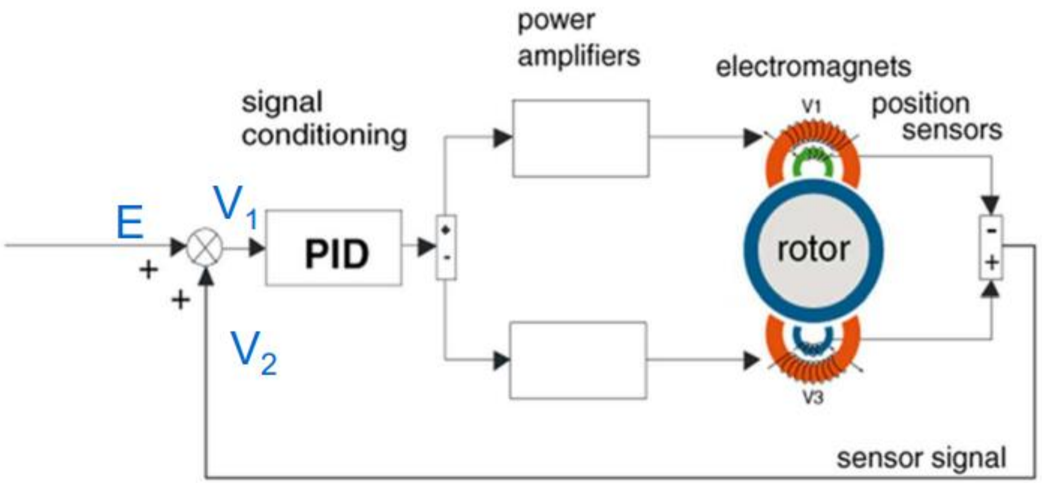

Closed loop transfer functions




API-617 Stability Plot (log dec vs frequency)

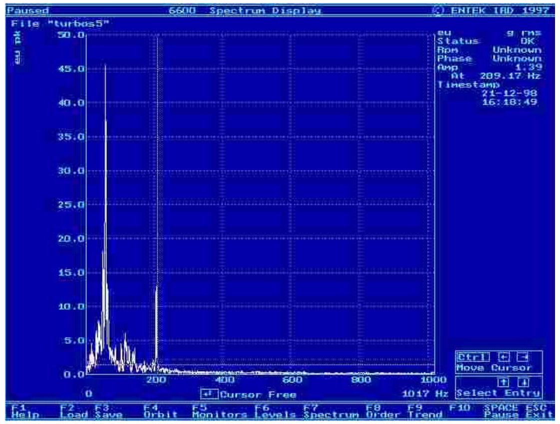
**High Frequency is less a concern – *"Speed, Aerodynamic, Friction… Damping"***

# Transfer Function and Filters (Synchronous, but…)




**Different types of synchronous filters**

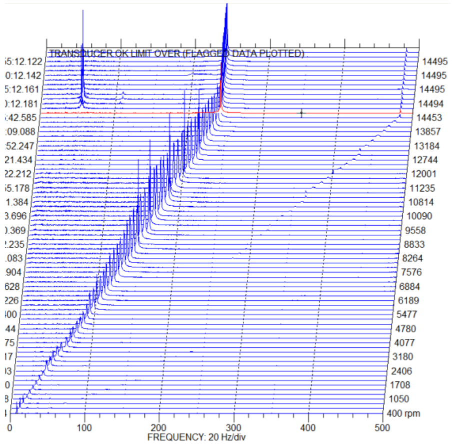
- Acting on Lower Stiffness and/or Higher damping
- To facilitate critical speed crossing (C ↗)
- To let the rotor to run around its own axis of inertia (K ↘). Unbalance automatic cancelation, but large “run-out” at probe location
- To limit transmission of force to bearing housing




**BUT**

Main instability issues are not synchronous
Balancing, thermo/mechanical rotor stabilizations are well known practices

**Sub-synchronous filters could help**




What about Sub-Synchronous Narrow Filters (tracking sub-frequency of concern) ?

# API-617 - Part 1 / Annex E "Magnetic Bearings"
# ISO-14839 - Part 3 "Evaluation of Stability Margin"

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**Very good supports for Design:**

- Campbell in Free-Free condition
- AMB Transfer Functions vs Frequency
- AMB Stiffness & Damping vs Frequency
- Closed Loop transfer functions (Gain)
- Stability checks (log dec extraction)
- Unbalance responses with and w/o filters

**BUT…**

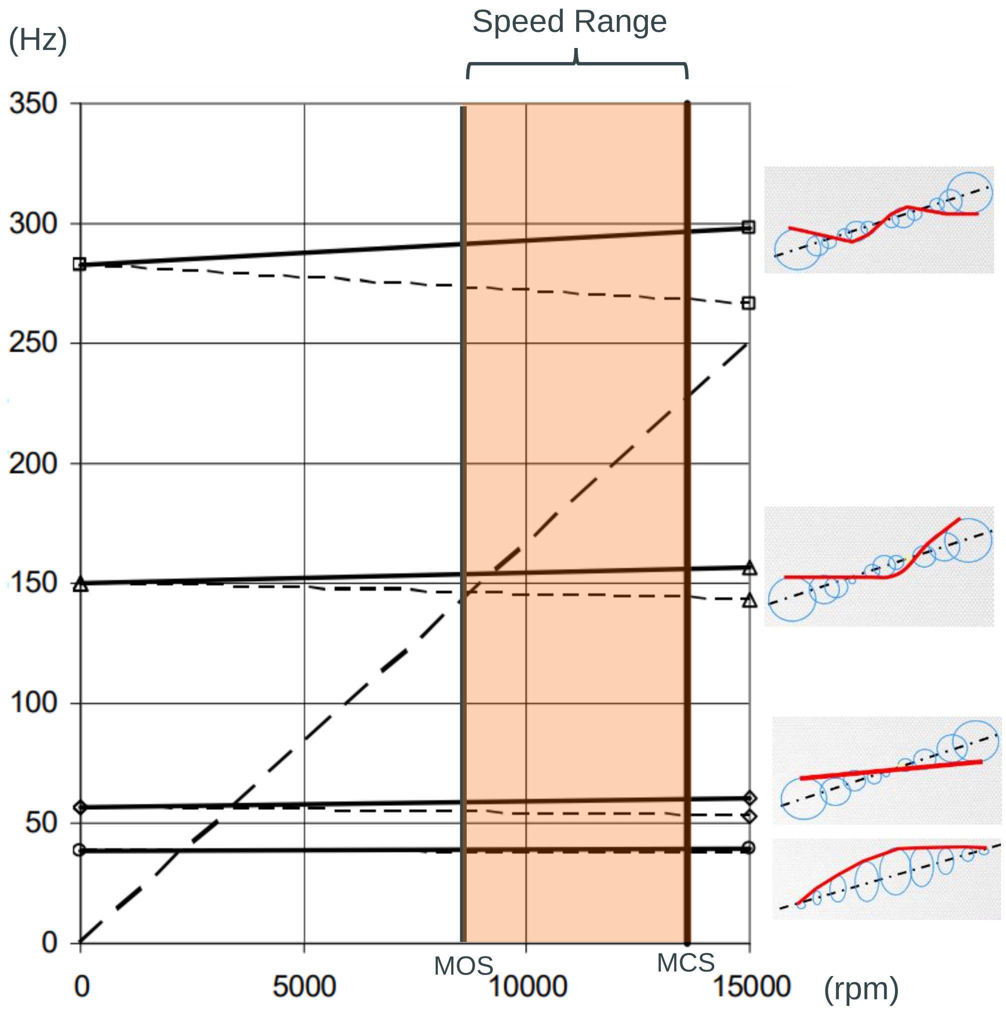
- **Campbell Diagram on AMB is missing**
- Indication of Oper. Speed (from MOS to MCS)
- Up to 2 x Rev in Frequency domain
- Mode shapes (F/B) and Damping (log dec)
- **More practical / mechanical approaches**

From ISO-14839 Part 3
Evaluation of stability

**Table 1 — Peak sensitivity at zone limits**

| Zone | Peak sensitivity | |
|---|---|---|
| | Level | Factor |
| A/B | 9,5 dB | 3 |
| B/C | 12 dB | 4 |
| C/D | 14 dB | 5 |

| Damping | | |
|---|---|---|
| AF | ~ log dec | Gain (dB) |
| 1 | 3,14 | 0,0 |
| 2,5 | 1,26 | 8,0 |
| 5 | 0,63 | 14,0 |
| 7,5 | 0,42 | 17,5 |
| 10 | 0,31 | 20,0 |
| 20 | 0,16 | 26,0 |
| 30 | 0,10 | 29,5 |




Campbell diagram part of lateral analysis, even if not required by API/ISO

# API-617 / Annex E “Magnetic Bearings” Vibration Criteria

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**E.4.8.8.1** During the mechanical running test of the machine, assembled with the balanced rotor, operating at any speed within the specified operating speed range, the peak-to-peak amplitude of unfiltered vibration in any plane, measured on the shaft adjacent and relative to each radial bearing, shall not exceed the smaller of Equation (E.4) or 0.3 times the minimum diametral close clearance (typically the auxiliary bearing), over the range of $N_{ma}$ to $N_{mc}$ as shown in Figure 3.

$$A_{vl} = 3\left(25.4\sqrt{\frac{12{,}000}{N_{mc}}}\right) \quad \text{(E.4)}$$

**API only refers to unfiltered peak/peak vibration during Mechanical Running Test…**

**BUT**

- Consideration to be made between No Load MRT vs Full Load String Testing (FLST)
- Vibratory Criteria to consider also 1X filtered vibration and non-synchronous indications
- No unsteady vibration to be accepted (inception/indication of Natural Frequency instability)
- Criteria on 1X (Unbalance) Vector Change between “HOT” vs “COLD” conditions. See Also API 541/546 for Induction and Synchronous Electrical Machines
- Criteria on AMB Current limitations – Margin prior saturation
- Criteria on AMB Temperatures – Efficient cooling
- In any case, Criteria during FAT/SAT < Alarm & Trip protection Levels

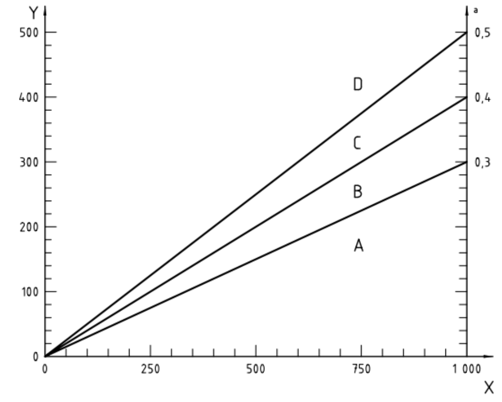
**Criteria should be part of Standards**

From ISO-14839 Part 2 (Evaluation of vibration)

**Table 1 — Recommended criteria of zone limits**

| Zone limit | Displacement $D_{max}$ |
|---|---|
| A/B | $< 0{,}3\ C_{min}$ |
| B/C | $< 0{,}4\ C_{min}$ |
| C/D | $< 0{,}5\ C_{min}$ |

NOTE $C_{min}$ is the minimum value of radial or axial clearance between rotor and stator.




Clear suggestion to OEMs (Original Equipment Manufacturers)

# Axial compensation and Thrust bearing

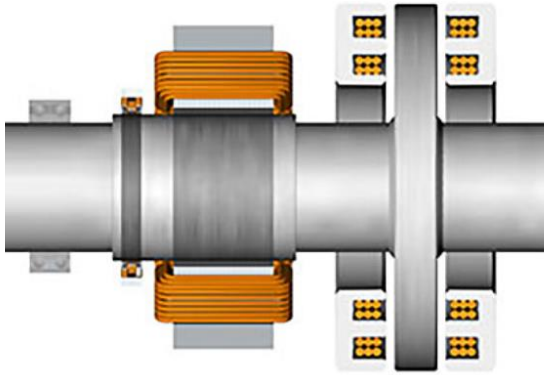


Axial thrust bearing
larger than compressor impellers !
Induction limitation to ~1.5 Tesla

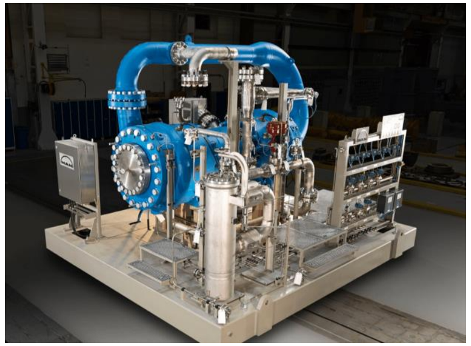
- Compliance to API requirements:
  Thrust Capacity at least 2 times expected load
- To cope with upset & transient conditions
- Weight, Overhang, Unbalance concerns
- Back-To-Back compressor is recommended to limit axial load and variation
- HSEM bilateral cooling is also preferred

How to increase the Thrust Magnetic Bearing Capacity ?

# Compatibility with Upstream and Water Saturated Gas

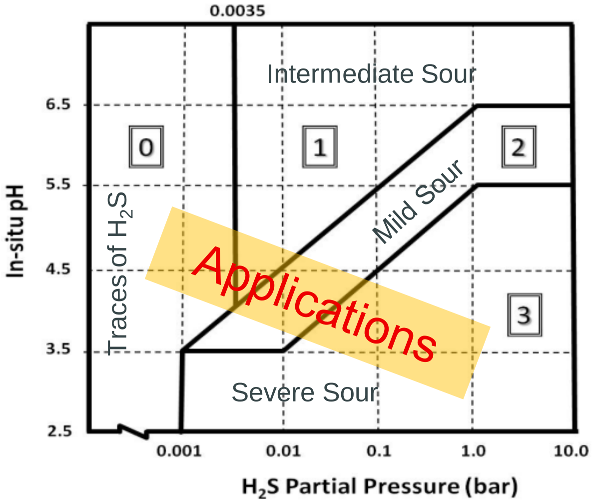


Originally AMBs were designed for:
- *Operation with atmospheric air (Stand Alone HSEM)*
- *High Speed drives and HVAC air compressors*
- *Clean & Dry Commercial Gas application (MoPiCo™)*




**Components to be considered**

- Sensor and laminations
- Bearing and laminations
- Speed Sensor
- Temperature probes
- Wirings and insulation
- Connectors
- Auxiliary bearings




**Key Challenges for Upstream and Associated Gases**

- Compatibility with $CO_2$, $H_2S$, MEG/TEG, Methanol, Hg
- Suitability with Water Saturated Gas conditions
- Free Water during Settle Out Pressure (SOP)
- NACE Diagram Zones 0, 1 and 2 ?
- (1 bar ppH2S @ 100 bar = 1% H2S in gas composition)
- Rapid Gas Decompression (RGD) tenth bars / min
- Connectors/Penetrators qualification vs pressure
- Floating installation is not considered critical

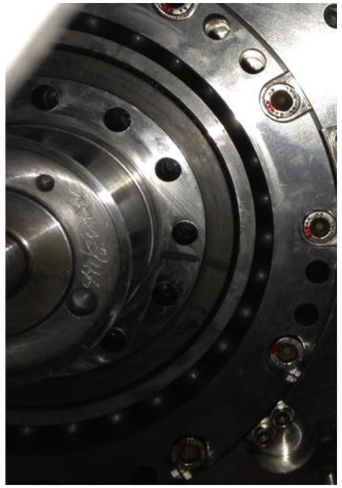
Some developments are still required to meet future challenges

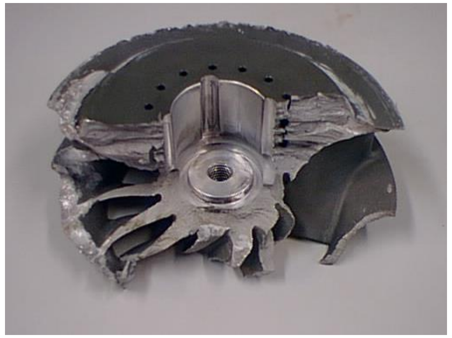
# Auxiliary bearings and recommendations

- Required to support rotor at rest
- To avoid any contact between rotor/stator laminations (active parts or sensor elements)
- To avoid equipment/AMBs complete damage
- Lot of rotordynamics about landing…

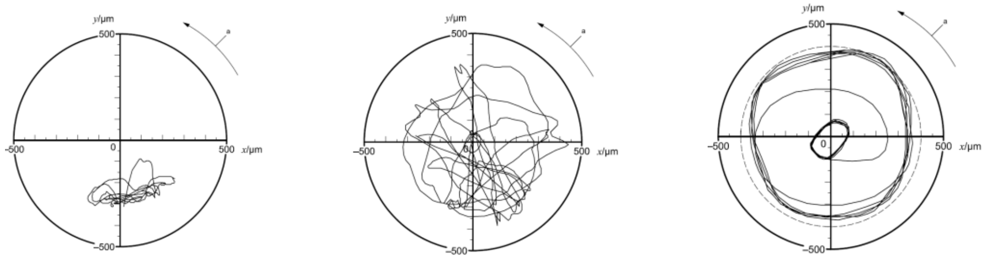
**BUT**

- Sacrificial elements, to be considered as such
- Different type of sophisticated technologies
- No clear definition of "Soft" vs "Hard" landings
- Monitoring prior to restart (after landing events)
- Not "off the shelf" components (time delivery)
- Very expensive components
- Spare part management (Capital Spares)





Reference made also to ISO-14839 Part 4



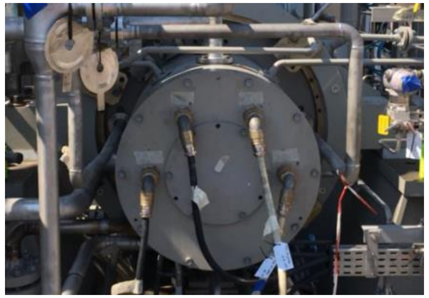

Recommendation:
**No delevitation/landing during Factory Test**

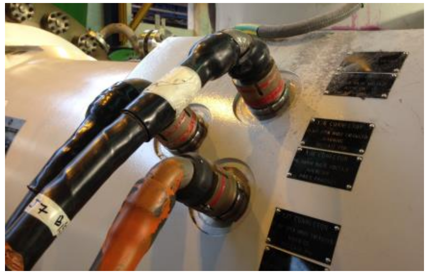
Sacrificial components, Capital Spares, Simple and Cost Optimization

# Cables, Connectors, Auxiliaries…

Few Quality issues about Sensors, Cables, Connectors, Insulation, Cabinet…

Connector/Cables
routing and insulation





Liquid migration within connectors (sensor/power)

Junction Box
Arrangement Cabling

High Tech: Strong QA/QC – Factory and Site Installation/Cabling…

# AMB Tuning and Commissioning

## Always time-consuming and not fully justified activities

- Doesn't deem necessary thanks to Upfront Lateral and Stability analysis
- Implemented Transfer Functions as per anticipated ones (from lateral analysis)
- Identical Transfer Functions for identical equipment
- Factory Testing with Project/Contractual cables (length, impedance…) OR how to considered proper influence without Project cables (electrical compensation) ?
- Any modification of Transfer Functions shall be fully justified and documented
- If modifications applied during FAT, Lateral analysis to be rerun with last revision
- **No AMB re-tuning is anticipated during commissioning activities at SITE**

**To make them fully democratized,**

**AMBs shall be as simple as lubricated bearings**

AMBs, No more considered as a "Black Box"

# Control Cabinet: Obsolescence / Retrofit / UPS

## Obsolescence / Retrofit

- Needs to be fully understood and anticipated on Project basis
- Power Supply, Magnetic Bearing Control, Cards, Amplifiers…
- System Interface/Communication with Package UCP / Plant DCS
- **Cabinet retrofit might be required after 10, 15 years**

## Redundant Internal Batteries vs Plant UPS

- TotalEnergies preference is Plant UPS (Uninterrupted Power Supply) for Maintenance purpose (no battery within AMB Cabinet)
- Auxiliary batteries for Factory Testing (Workshop backup)

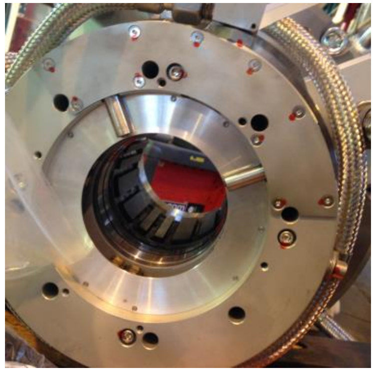
# Summary on AMBs from an Operator

TotalEnergies

- **Well proven technology for many years (Compressors, TEXs, HSEMs…)**
- **Reliable from Hardware to Control, with limited maintenance**

**BUT still some Challenges …**

- Limitations in term of capacity (Journal / Thrust)
- Sub-synchronous (Low Frequency) is always a concern (stiffness, stability…)
- API/ISO Standards to be improved (Mechanical stability analysis, Campbell)
- Acceptance criteria need to be revisited (Vibrations, but also Current / Temperature limitations)
- Some limitations in terms of “contaminants” for Upstream and Water Saturated applications
- Touch Down / Auxiliary bearings … Consumable components, Spare parts (and Cost), Monitoring
- OEM Factory Tuning & Site Commissioning to be simplified (and documented)
- Obsolescence (Electronics) / Spare part management to be anticipated
- Integrated Compressor = Integrated “Organization” with Compressor Vendor fully Responsible
- and COST



To make AMBs fully attractive and democratized, and No more a **“Black Box”**

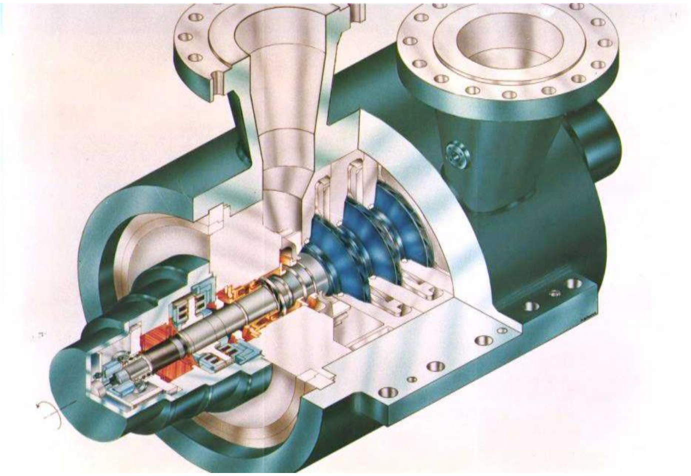
# 05.

## Conclusion - *“We have a dream…”*

# To meet future climate challenges …

TotalEnergies

| 1987 in Lacq | Today | Near future, our Dream |
|---|---|---|
| Active Magnetic Bearings (AMBs)<br>Dry Gas Seals (DGSs) | Only few AMBs !<br>All Compressors with DGSs | All Compressors with AMBs<br>No more DGSs |



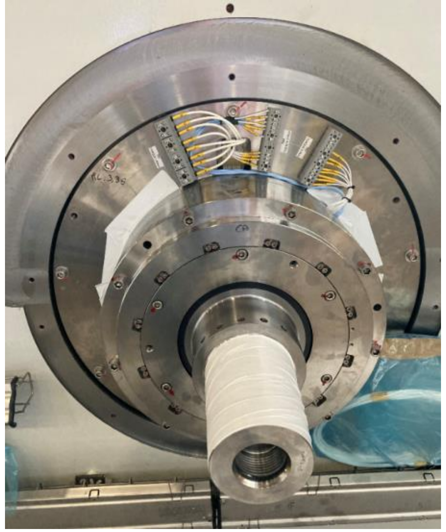
Conventional

## … We count on you to make this dream a reality

TotalEnergies

# Thank You

# Q & A



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