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Process control system evolution for the LHC Cold Compressors at CERN

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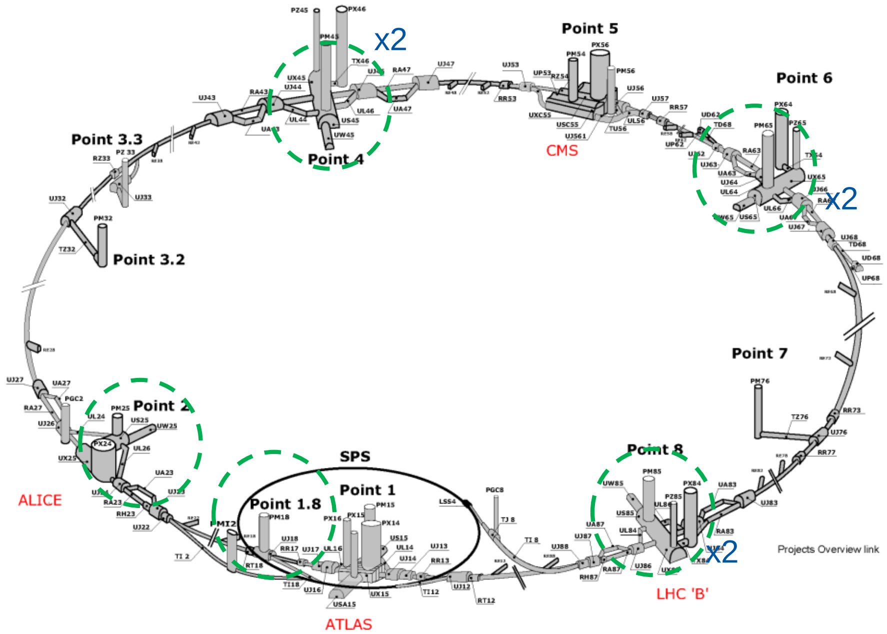
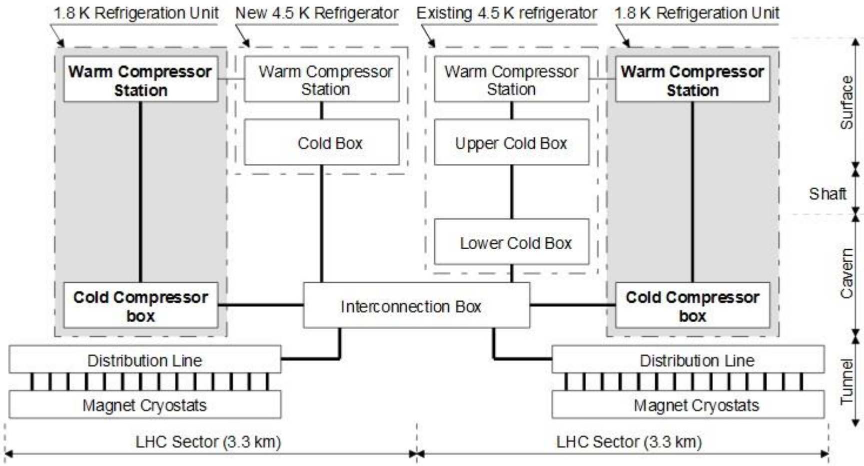
Outline

1. LHC Cold Compressors
2. Process control strategies
3. Upgrade motivations
4. Improvements done
5. Results

Overview





- Eight 2.4 kW @ 1.8 K Refrigeration Units
- Two different designs from two suppliers
- Cold compressors in cavern coupled to warm volumetric screw compressors at surface

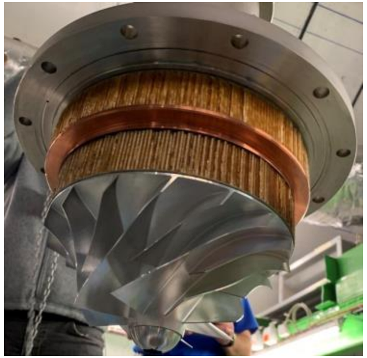
Cold Compressors Basics

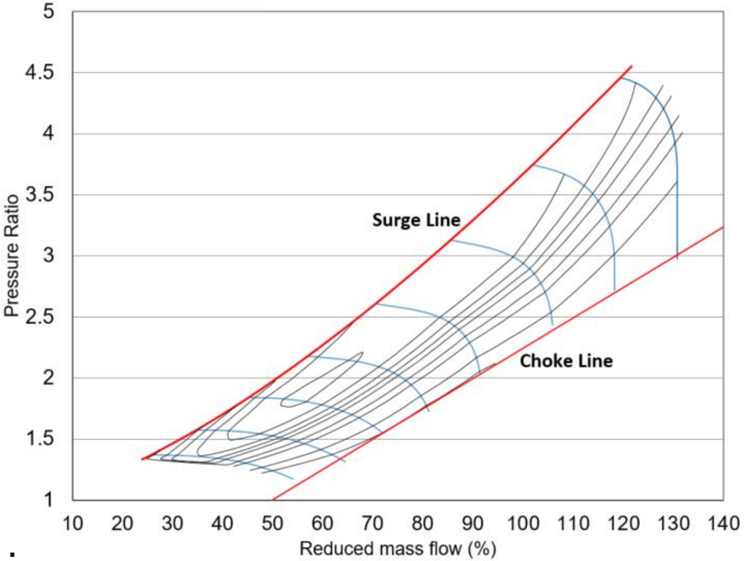
Basics equations :

- $Nr = \left(\frac{N}{\sqrt{T_{in}}}\right) . \left(\frac{\sqrt{Td_{in}}}{Nd}\right)$
- $Mr = \left(\dot{m} . \frac{\sqrt{T_{in}}}{P_{in}}\right) . \left(\frac{1}{\dot{m}d} . \frac{Pd_{in}}{\sqrt{Td_{in}}}\right)$
- $PR = \left(\frac{P_{out}}{P_{in}}\right)$

with :

- N → Speed
- $\dot{m}$ → Mass flow
- r → Reduced values
- T_{in} → Inlet Temperature
- $P_{in}/Pout$ → Inlet/Outlet Pressure
- d → corresponding design values



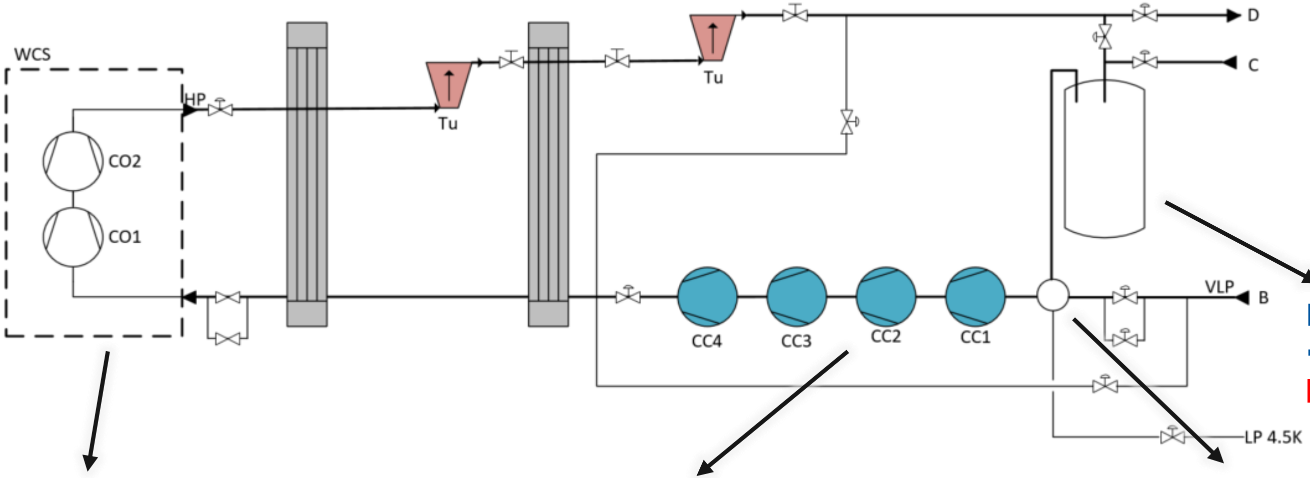


Pressure field :

Nr needs to be between Surge and Choke lines (depending on Mr and PR) to allow for pumping

Process Control Challenges

Type B



Nominal conditions :

- 15 mbar
- ≈ 20 to 30 PR
- 120 g/s
- Inlet at 4.5 K
- 2 x 3.3 km to pump (= 2 x 180 m^3)

Phase separator
➔ reconnection to sectors at low pressure (typically 30 mbar)

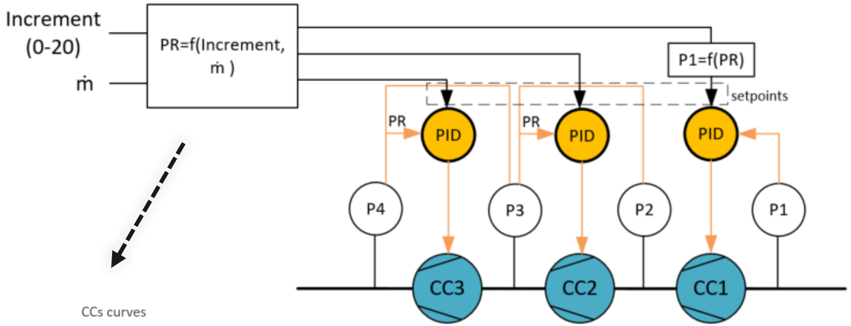
Volumetric screw compressors
➔ mass flow proportional to pressure

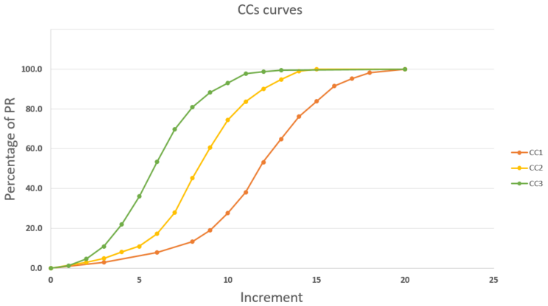
Serial cold compressors
➔ difficult to keep all CCs in good conditions (avoid surge/choke lines)

Mixing chamber for heterogeneous gases
➔ difficult to provide stable conditions for CCs

Process Control Strategies (1/2)

CERN made control (type A unit) :





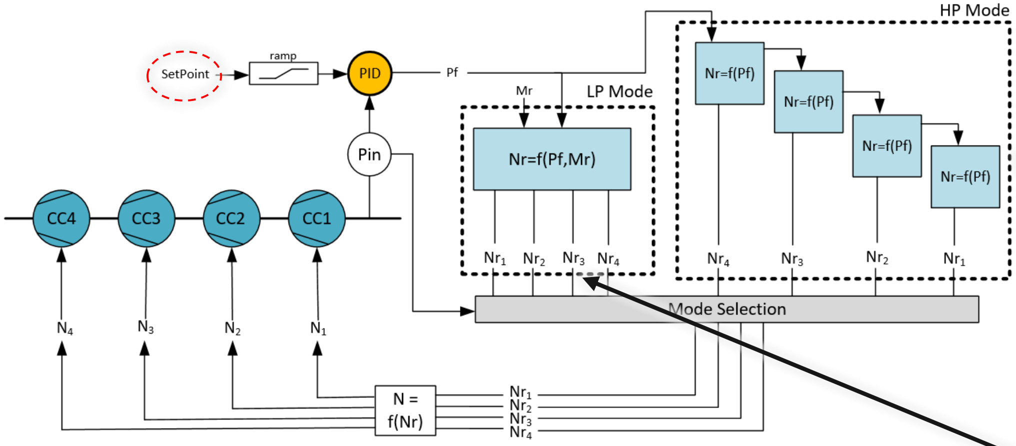
Principle :

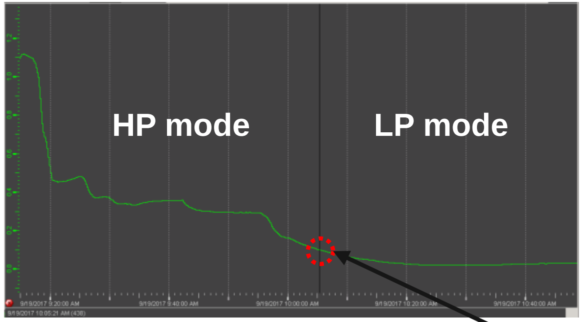
- PID controller over PR for each CC
- CC_1 controls inlet pressure
- CC_3 starts first, then CC_2 then CC_1

→ $CC_{3/2}$ provide large PR
→ CC_1 provides precise pressure
→ Sequential start minimizes flow fluctuations between CCs

Process Control Strategies (2/2)

Two-mode strategy (type B unit):





High pressure mode:

Derivated from CERN made strategy (type A):

- shifted start of CCs
- no direct PR control

Low pressure mode:

Interpolation based:

- inputs: pressure and flow
- outputs: Nr of each of the four CCs

Principle:

- One mode for **high pressure**, one for **low pressure**
- Use of reduced values

Motivations for the upgrade

Context:
- Process control delivered more than 13 years ago
- End of electrical components life cycle (updates initiated in 2015)
- Logic running on dedicated Programmable Logic Controllers
- Old PLCs replacement campaign for Long Shutdown 2 (2019-2020) of LHC

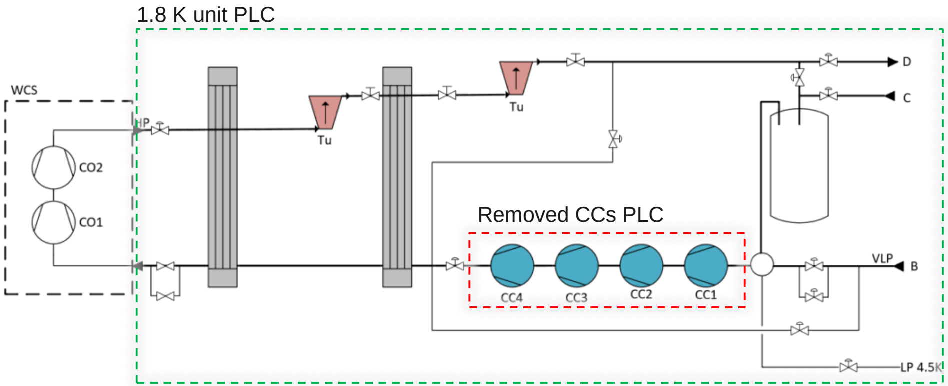
Existing problems:
- Complicated diagnostic
  → Logic is a “black box”, not CERN standards
  → Hardware redundancies
- Numerous manual operations
  → Impact on reconnection time
  → Human factor influence

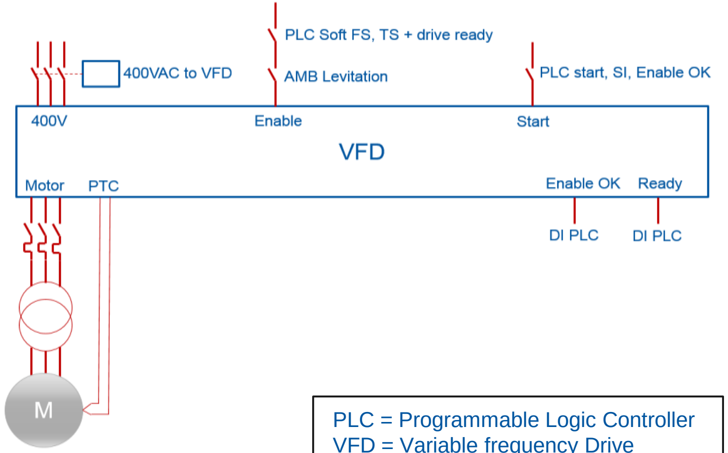
Deployment process:
- Development of a first version for each unit type
- Tests on site and/or on simulation
- Deployment on all units during LHC LS2

Hardware Changes

Objectives:
- Maximal availability
- Minimal diagnostic time
- Minimal maintenance

Hardware simplification:
- Standalone PLC removed (logic inclusion into existing 1.8 K unit PLC)
- Remove of most of the hardware interlocks (redundant with PLC interlocks)
  → Ultimate machine protection (AMB levitation signal) only on hardware
  → PLC interlock goes to VFD that cut input power of the motor



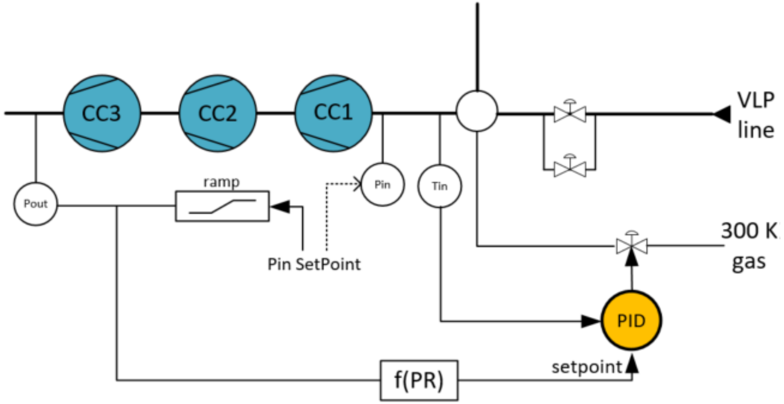


PLC = Programmable Logic Controller
VFD = Variable frequency Drive
AMB = Active Magnetic Bearing

Warm Gas Inlet Control

Context:

- Warm gas (@ 300 K) control valve
- Inlet temperature control
- Need to lower the temperature to pump down
- Temperature set-point calculated depending on total PR

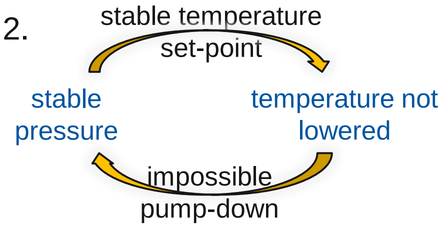


Problems:

1. Vicious circle in case of pressure fluctuations
2. Blocked situations, impossible to pump-down

➔ Valve operated manually most of the time

2.



Solution:

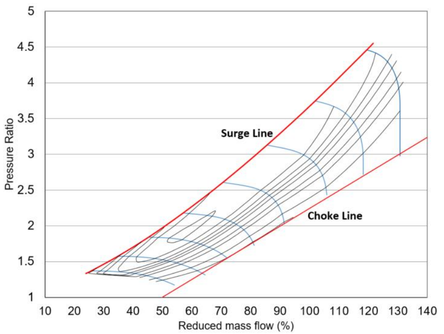
Calculate set-point depending on desired PR (P_{out} / P_{in} set-point)

1. P_{in} set-point not subject to fluctuations
2. P_{in} set-point is ramped down so no frozen situation

Surge Detection

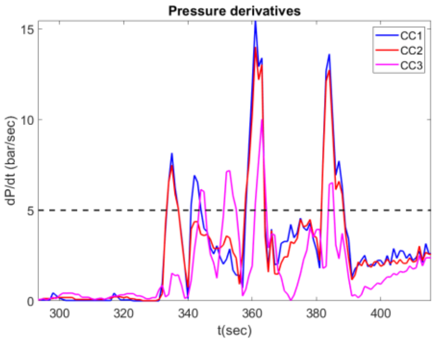
Context:

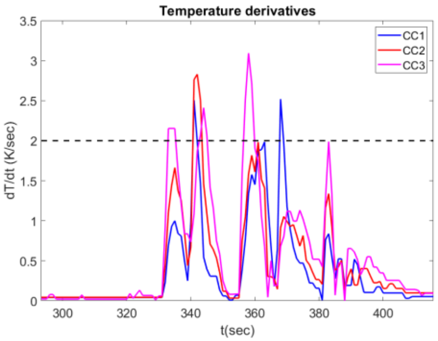
- Surge occurs when Nr is too high in Mr/PR field
- Brutal loss of pumping capacity
- Machine protection issue
  → strong constraints on magnetic bearings
- Previously detected using theoretical Nr values
  → can induce trips even if no effect is detected
  → can continue process when effects are visible



Case study:

- Study of consequences of previous surge line crossing
- Pressure and temperature simultaneously rise/fall brutally

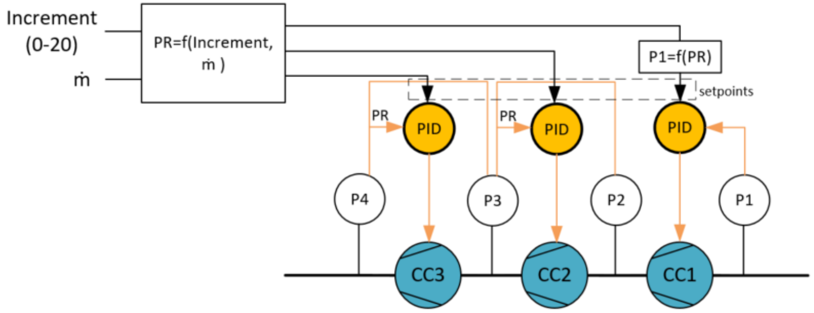




Solution:

- **Use pressure and temperature derivatives** on each CC
- If both values reach their dedicated threshold (5 mbar/s, resp. 2 K/s) within the same timeframe, stop is triggered
  → validated on simulation and on site

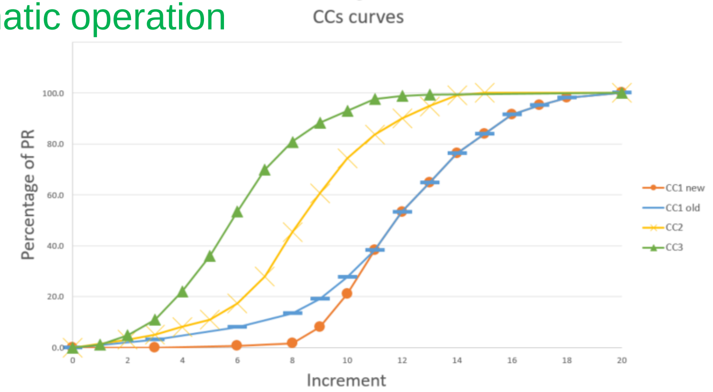
Automatic “Increment” Calculation



Type A unit

Solutions:

- Calculate total PR depending on increment value
- Knowing actual flow and desired input pressure, calculate corresponding increment value
  → Ramped desired input pressure value
  → Automatic pump down to this value
- Correction of CC_1 curve to start later
  → Automatic operation



Problems:

1. Increment value not meaningful to operators
2. CC_1 starts too early causing trips
   → Has to be operated manually

Results

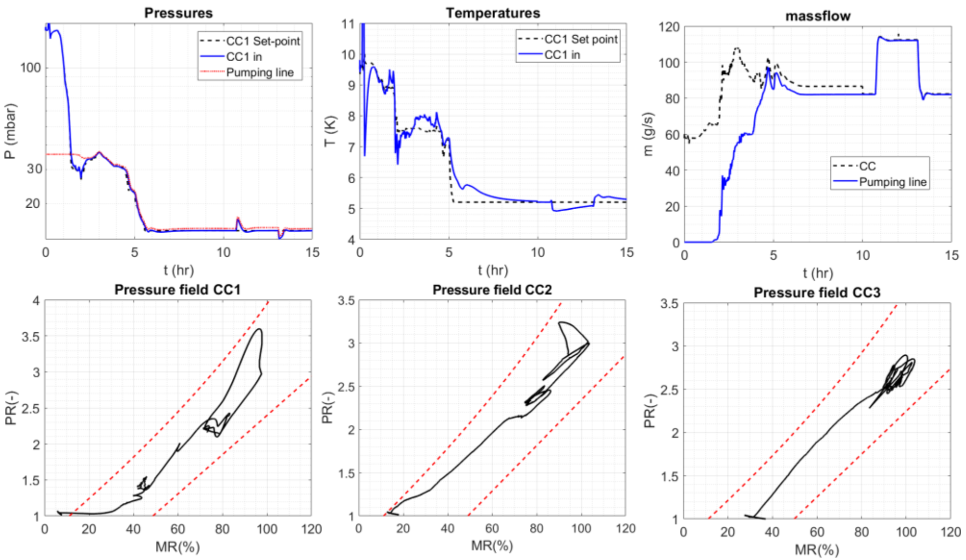
Type B:

- Heavily tested on site,
- Normal operation of LHC for more than a month without interruption

Type A:

- First tests on site
- Final tests on simulation (control system copy + EcosimPro dynamic model)

→ **Satisfying results on both unit types, models validated**



Global achievements:

- **Easier diagnostic** (better knowledge of the process, CERN standards)
- **Reconnection time stability** (process automatization)
- **Reliability improvement** (process automatization, less hardware breakpoints)
- **Operation standardization and simplification**

Perspectives:

- Deployment during Long Shutdown 2
- Use during LHC Run 3
- Great asset for future HL-LHC cold compressors

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