Precise TDI gap measurement for BETS interlock

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Thanks to inputs from M. Di Castro, F. Loprete

Contents

1- Requirements from BETS

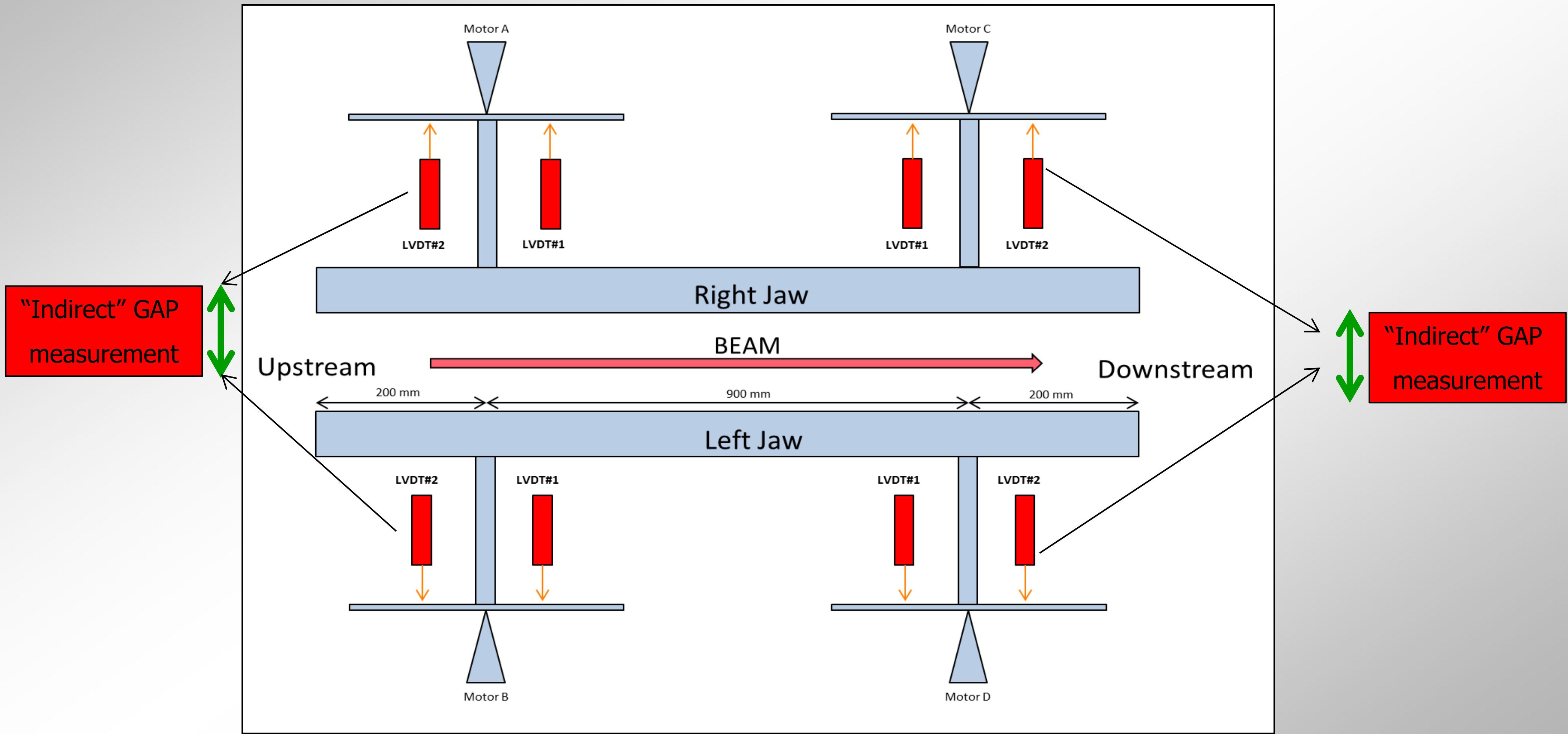
- The BETS interlock on the TDI shall be on the gap between the jaws. Two channels are needed per beam, for the upstream and downstream gaps.
- The function for the threshold shall be such that injection is inhibited for all energies above 450 GeV, i.e. as soon as the LHC starts ramping. This can be done by requiring an unphysical position for beam energies different from 450 GeV.
- The interlock is to be connected to the injection BIS, together with the BETS MSI interlock
- The interlock needs masking with the Set-up Beam Flag
- The proposed tolerance is ± 1.0 σ on the gap at 450 GeV (about 0.6 mm).

↓

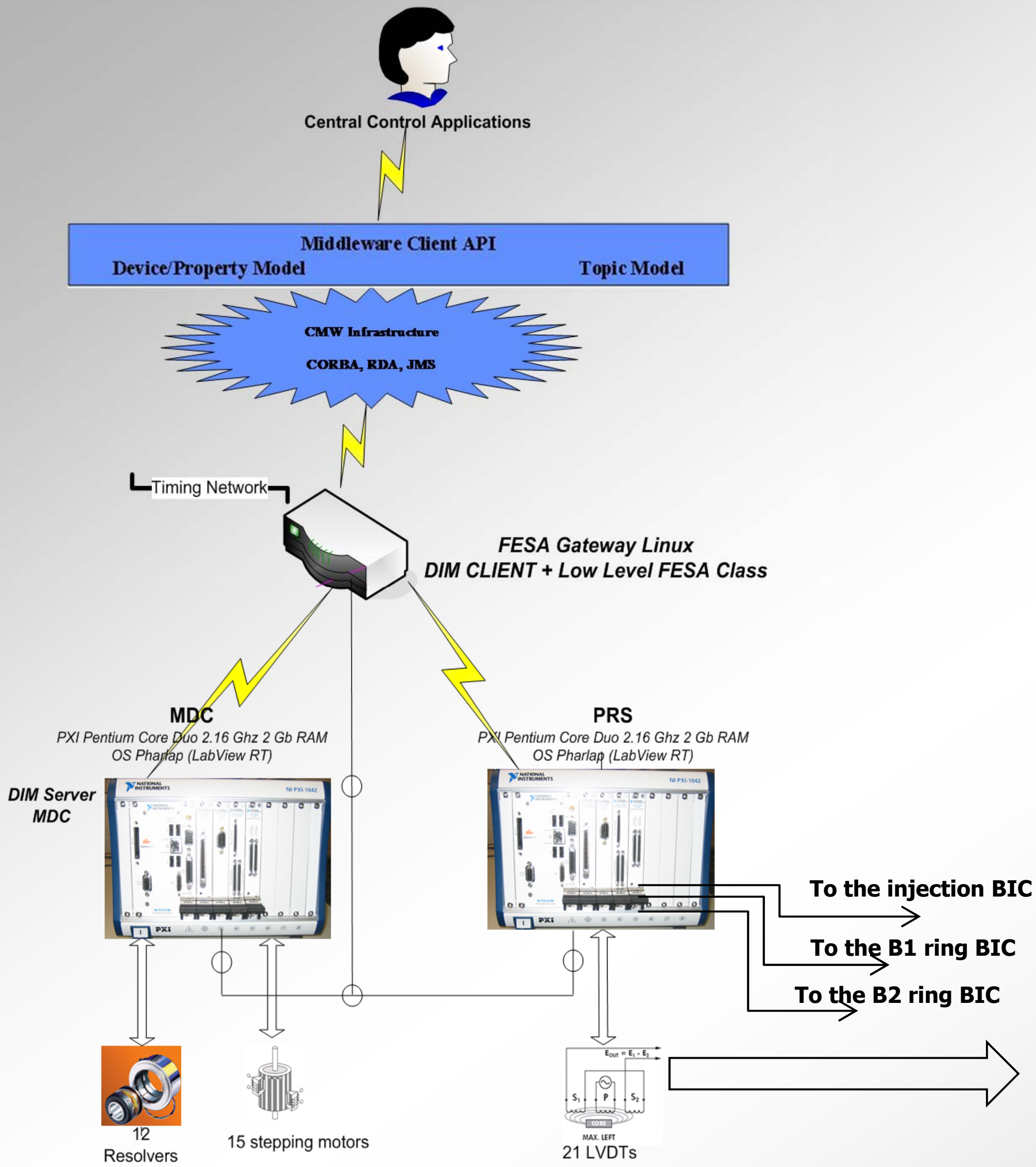
- The BETS interlock on the gap measurement should be redundant and related to an independent gap position measurement
- No additional false interlocks should be introduced in operation

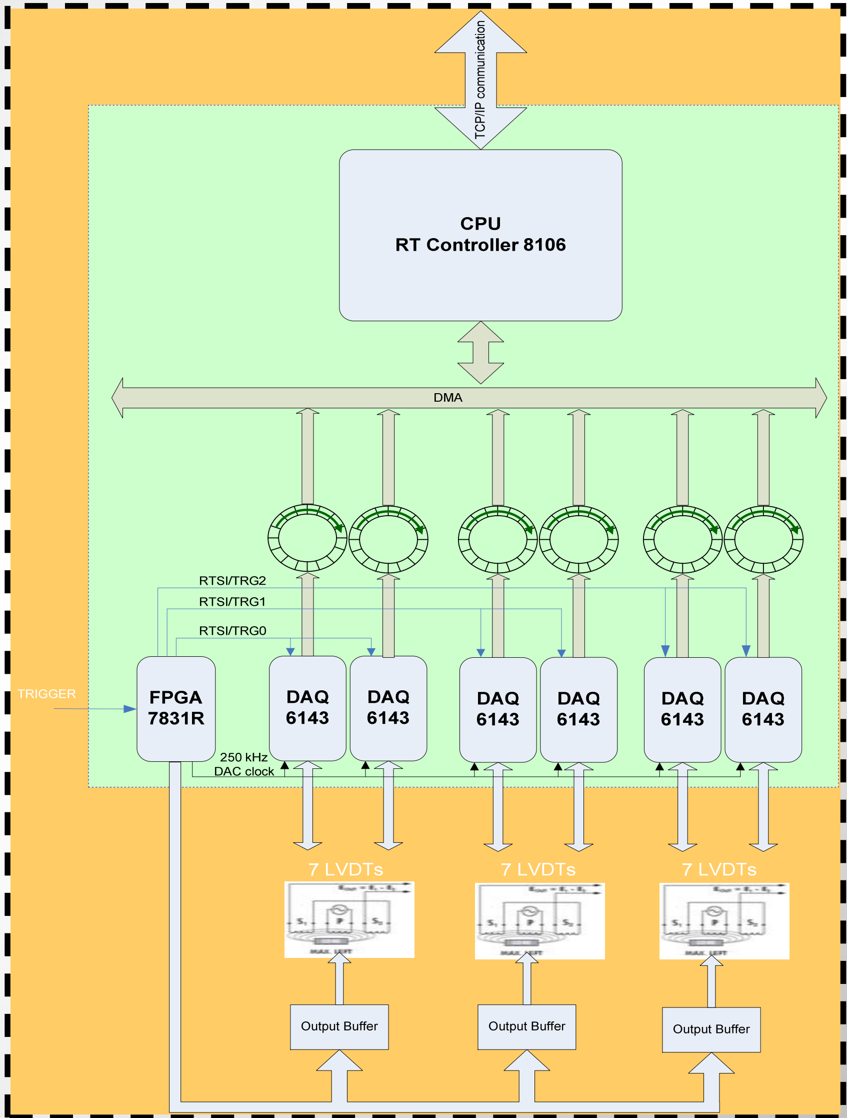
2- TDI gap measurement and interlocking

- **4 + 4 LVDTs installed on the TDI to measure the axis positions**
- **Indirect upstream and downstream gap measurements through difference of the related axis position measurements**



2- TDI gap measurement and interlocking





No failure on the low level control system experienced in the last 3 years of operation has compromised the machine safety

2- TDI gap measurement and interlocking

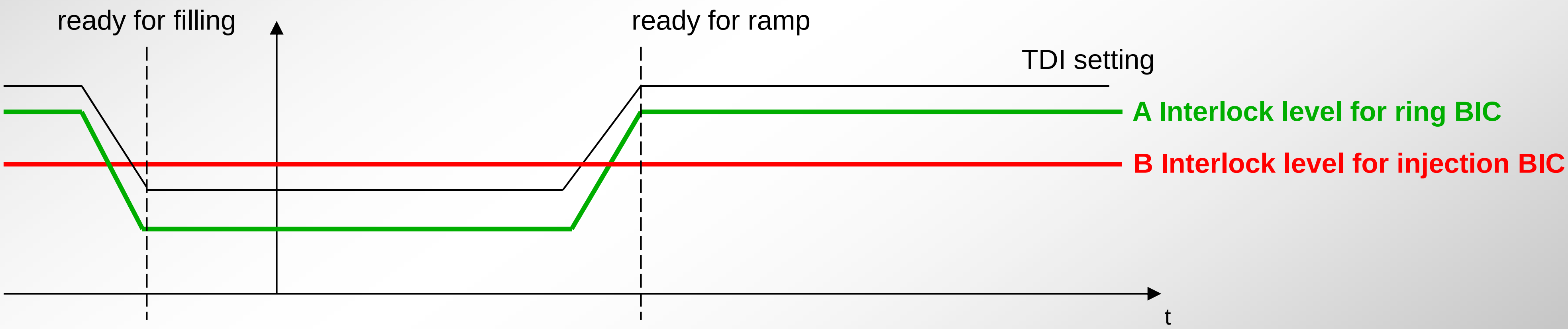
Interlocks Implemented:

Position limits on the axes and gap

- USER INJ PERMIT TRUE If Axes position + gap up and gap dw < Injection Interlock threshold
- USER RING PERMIT B1 and B2 TRUE If Axes position + gap up and gap dw > Ring Interlock threshold (jaws not stopped if limit violated)

Energy limit

USER INJ PERMIT TRUE If gap up and gap dw < Injection Energy Interlock threshold

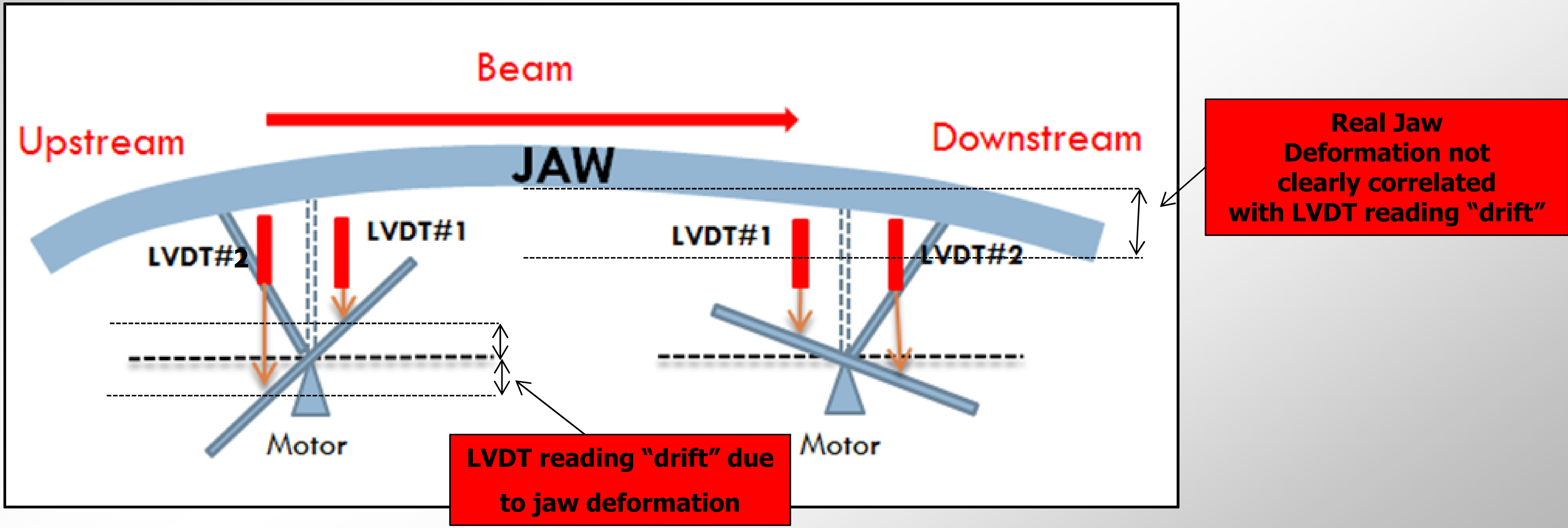


TDI setting < B: .true. for injection BIC
TDI setting > A: .true. for ring BIC

<u>The energy limit verification already represents a valuable low level control software redundancy</u>

3- TDI jaw deformation problem

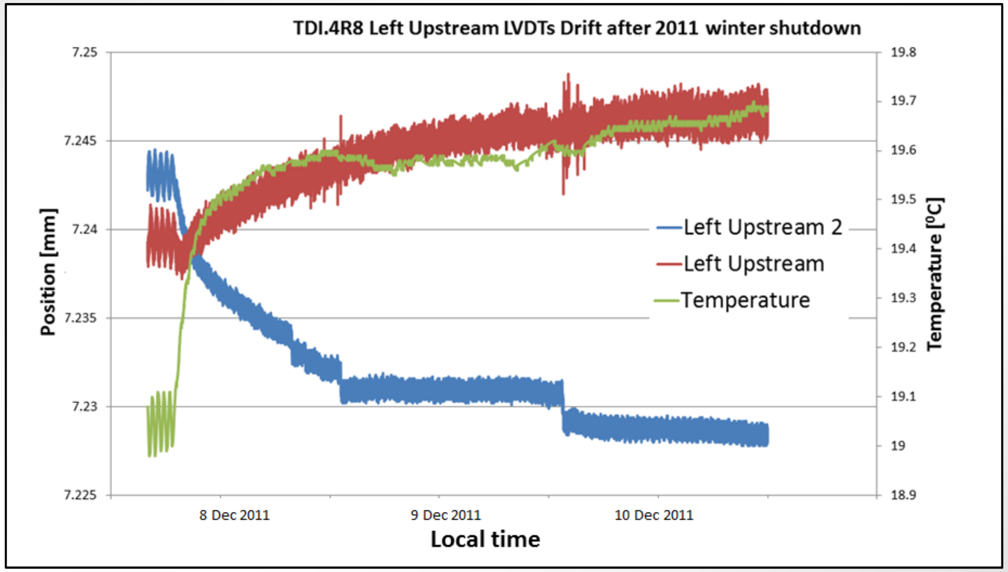
- Jaw heating in beam physics ⟹ Jaw thermal expansion ⟹ Mechanical deformation
- 0.5 °C TDI cooling water temperature variation ⟹ 150 µm LVDT position reading deviation

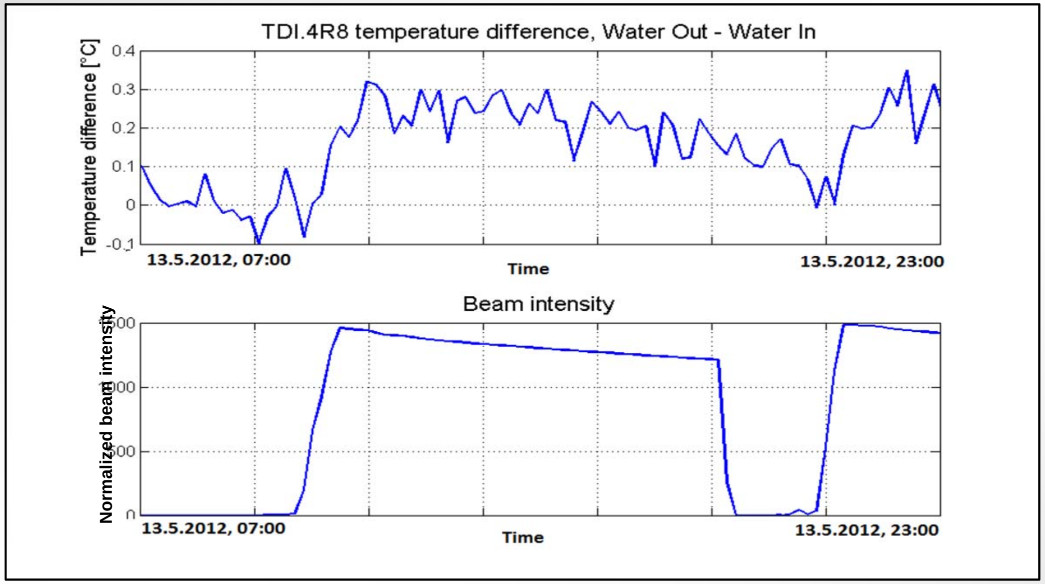


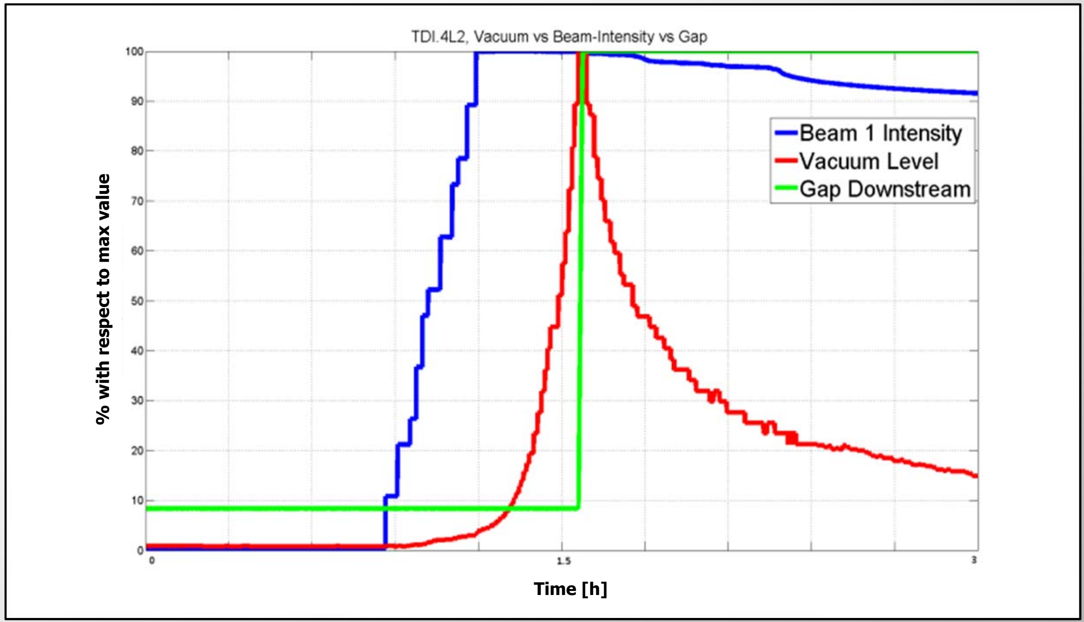
3- TDI jaw deformation problem

- The redundant LVDTs give clear signs of jaws deformations - Cooling water and vacuum level signs of jaws heating- Anyway a direct measurement of the real deformation is not available

- The interlock thresholds have been adjusted several times during the operation to avoid possible “false” interlocks

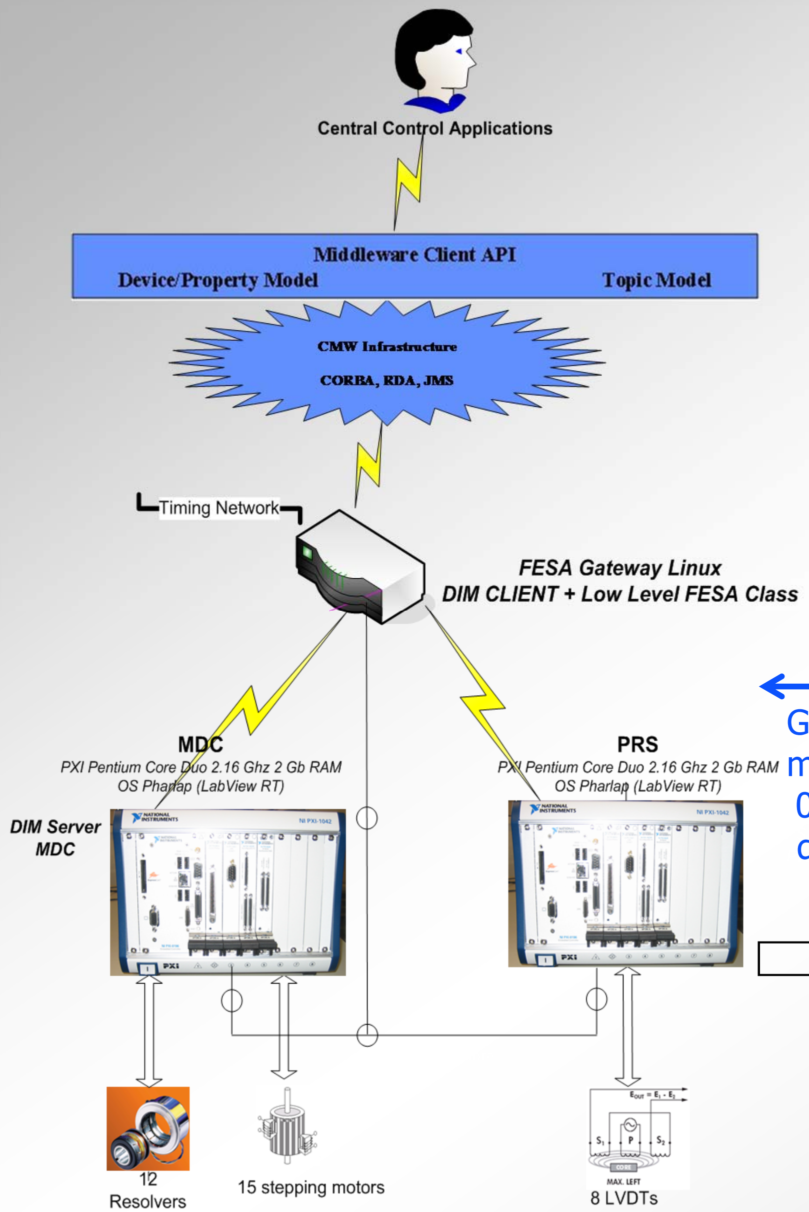






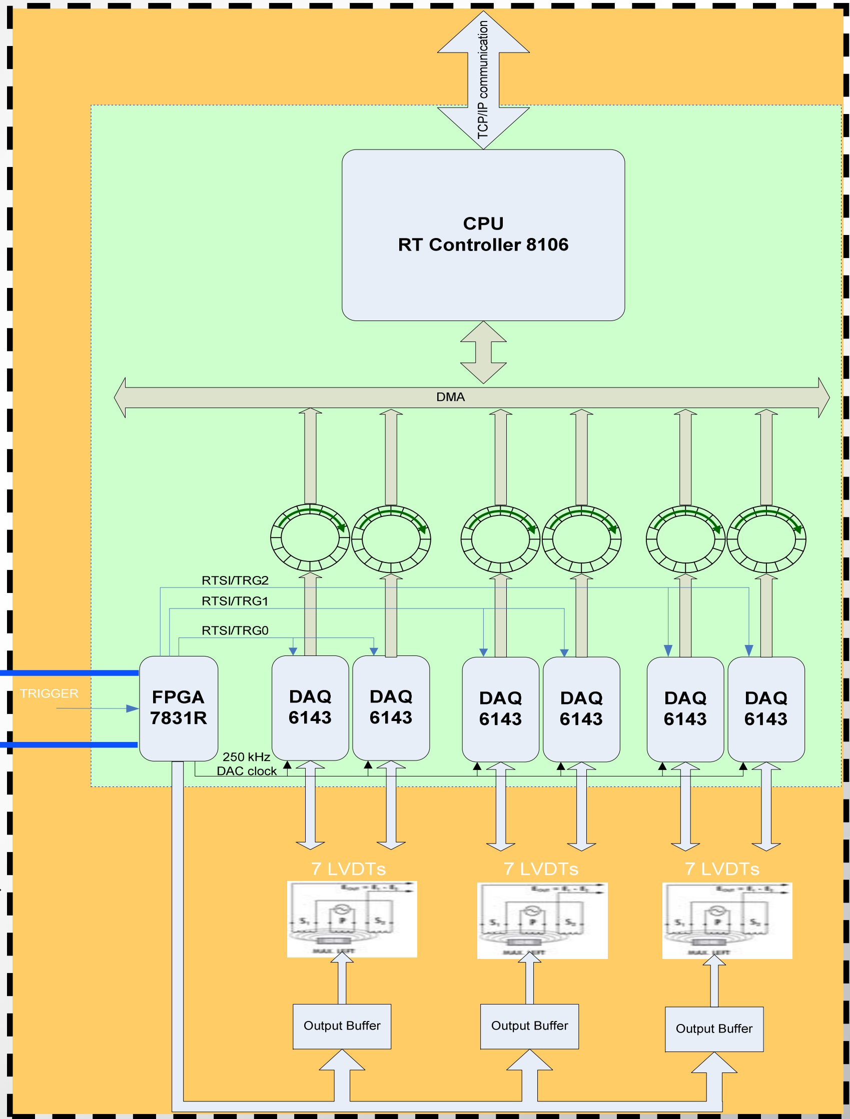
4- The possible solutions for BETS interlock implementation

1- Direct connection of the TDI PRS system to the BETS



Gap upstream measurement on 0-10 V signal or digital on 16 bit

Gap downstream measurement on 0-10 V signal or digital on 16 bit



4- The possible solutions for BETS interlock implementation

Solution: 1- Direct connection of the TDI PRS system to the BETS

Cost: few tens of KCHF

Time: 1 month

Pros:

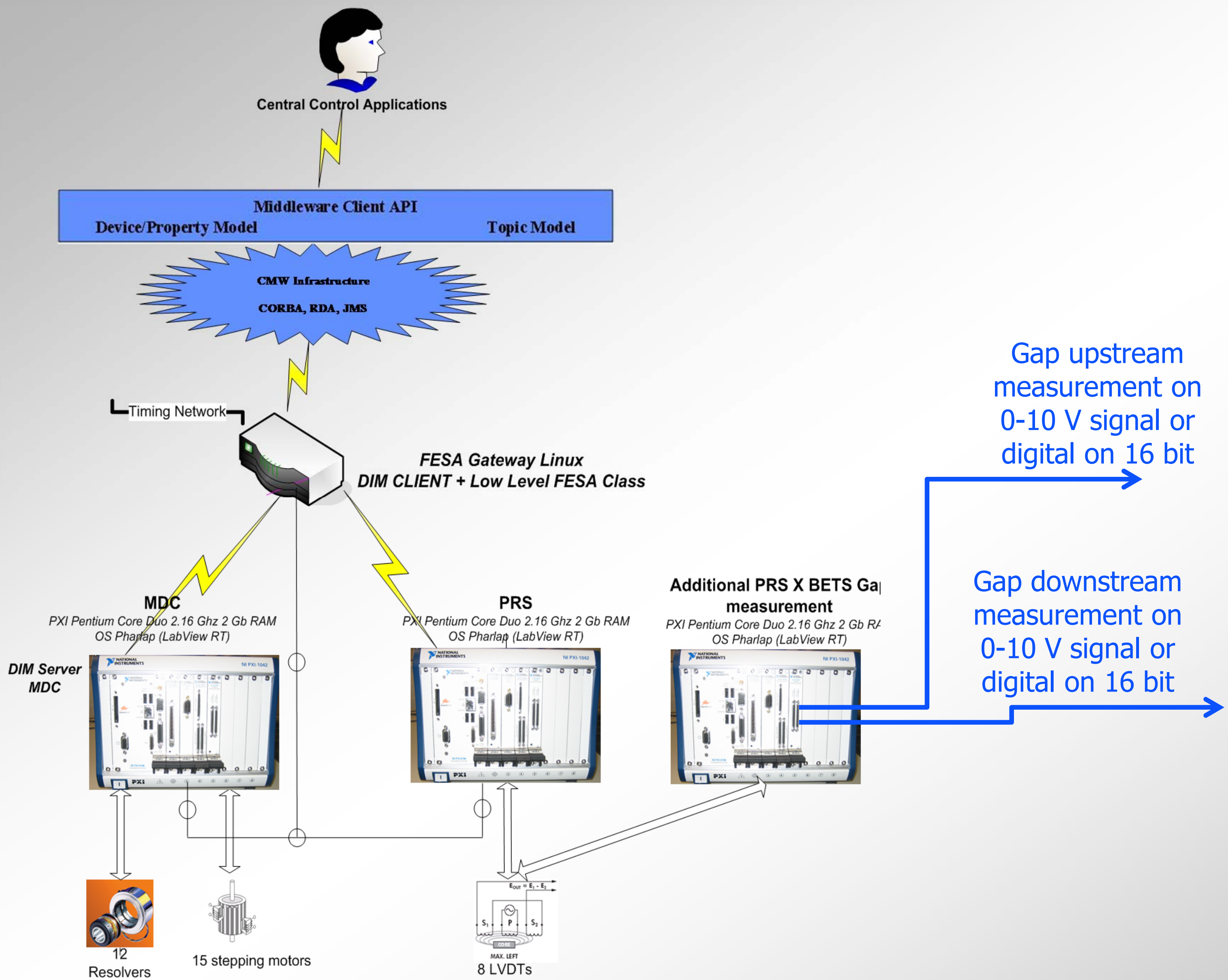
- Cost and implementation time

Cons:

- NO hardware redundancy
- Risk to increase the false interlocks and the LHC downtime (because of the jaw deformation problem)
- Limited added value

4- The possible solutions for BETS interlock implementation

2- Additional PRS system for the BETS gap measurement



4- The possible solutions for BETS interlock implementation

Solution: 2- Additional PRS system for the BETS gap measurement

Cost: roughly 130 KCHF

Time: 1 month

Pros:

- Implementation time

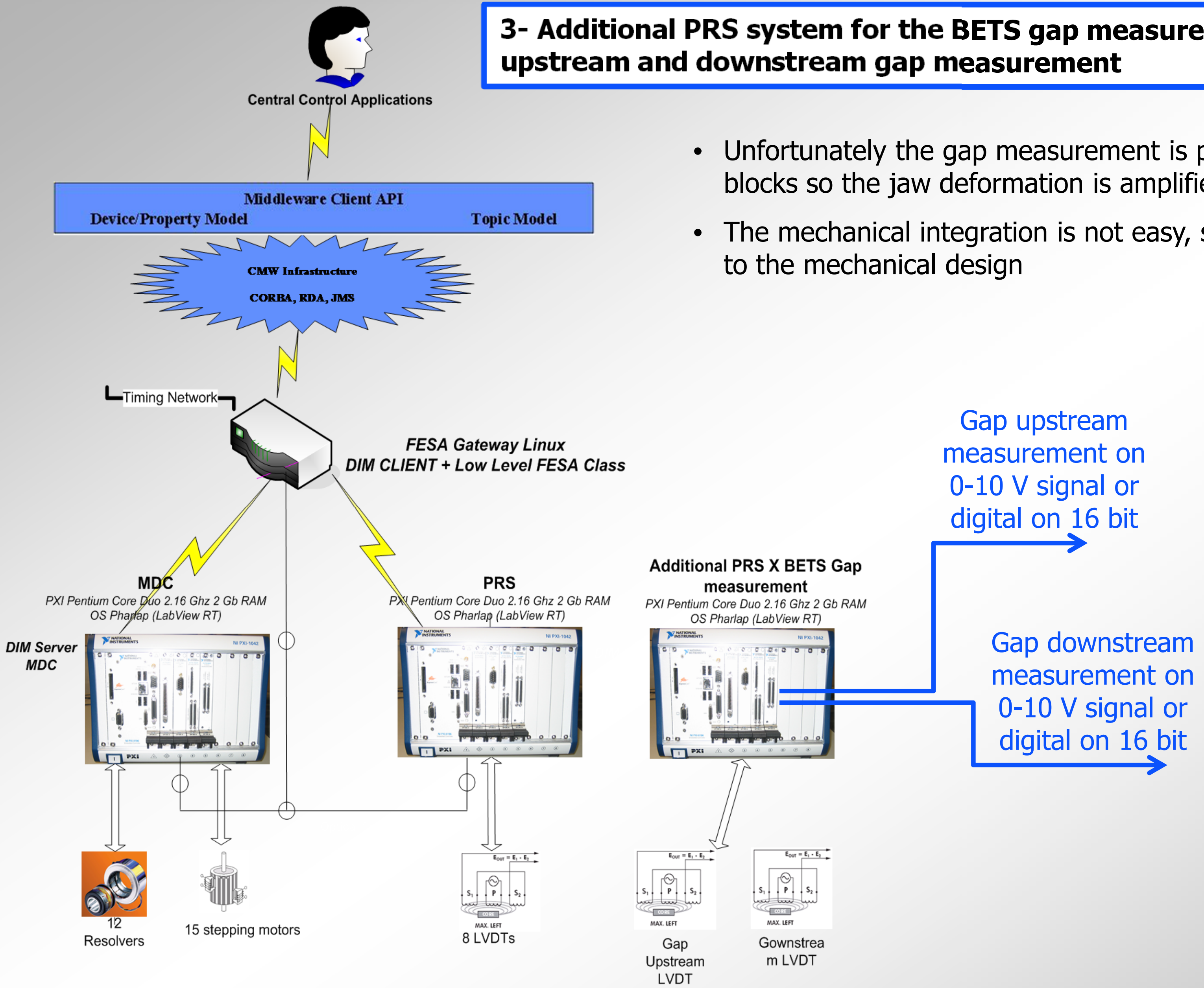
Cons:

- NO hardware redundancy at the sensor level
- Gap measurement not redundant and affected by the same problems experienced in 2010-13 operation
- Risk to increase the false interlocks and the LHC downtime (because of the jaw deformation problem)

4- The possible solutions for BETS interlock implementation

3- Additional PRS system for the BETS gap measurement + 2 additional LVDTs for upstream and downstream gap measurement

- Unfortunately the gap measurement is performed close to the motorization blocks so the jaw deformation is amplified on the measurement
- The mechanical integration is not easy, since it requires significant modifications to the mechanical design



4- The possible solutions for BETS interlock implementation

Solution: 3- Additional PRS system for the BETS gap measurement + 2 additional LVDTs for upstream and downstream gap measurement

Cost: roughly 300 KCHF

Time: Several months- Not sure to be ready by LS1

Pros:

- Well known measurement solution

Cons:

- Cost
- Implementation time
- Gap measurement affected by the same problems experienced in 2010-13 operation
- Risk to increase the false interlocks and the LHC downtime (because of the jaw deformation problem)

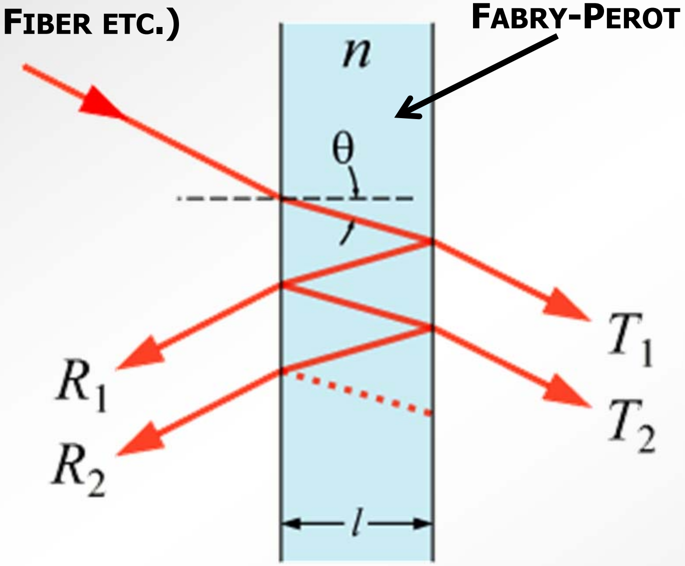
Solution: 4- The interferometric position sensor

The working principle

OPTICAL SIGNAL

(SOURCE: OPTICAL FIBER ETC.)

FABRY-PEROT CAVITY



INTERFERENCE SIGNAL

(SUPERPOSITION OF DIFFERENT PHASE SHIFTED REFLECTIONS)

= f(l)

INTERFERENCE SIGNAL

(SUPERPOSITION OF DIFFERENT PHASE-SHIFTED TRANSMISSIONS)

= f(l)

PHASE SHIFT BETWEEN SOURCE AND SENSING BEAMS (REFLECTION BEAMS) →

$$\delta = \frac{4\pi n}{\lambda} \cdot l$$

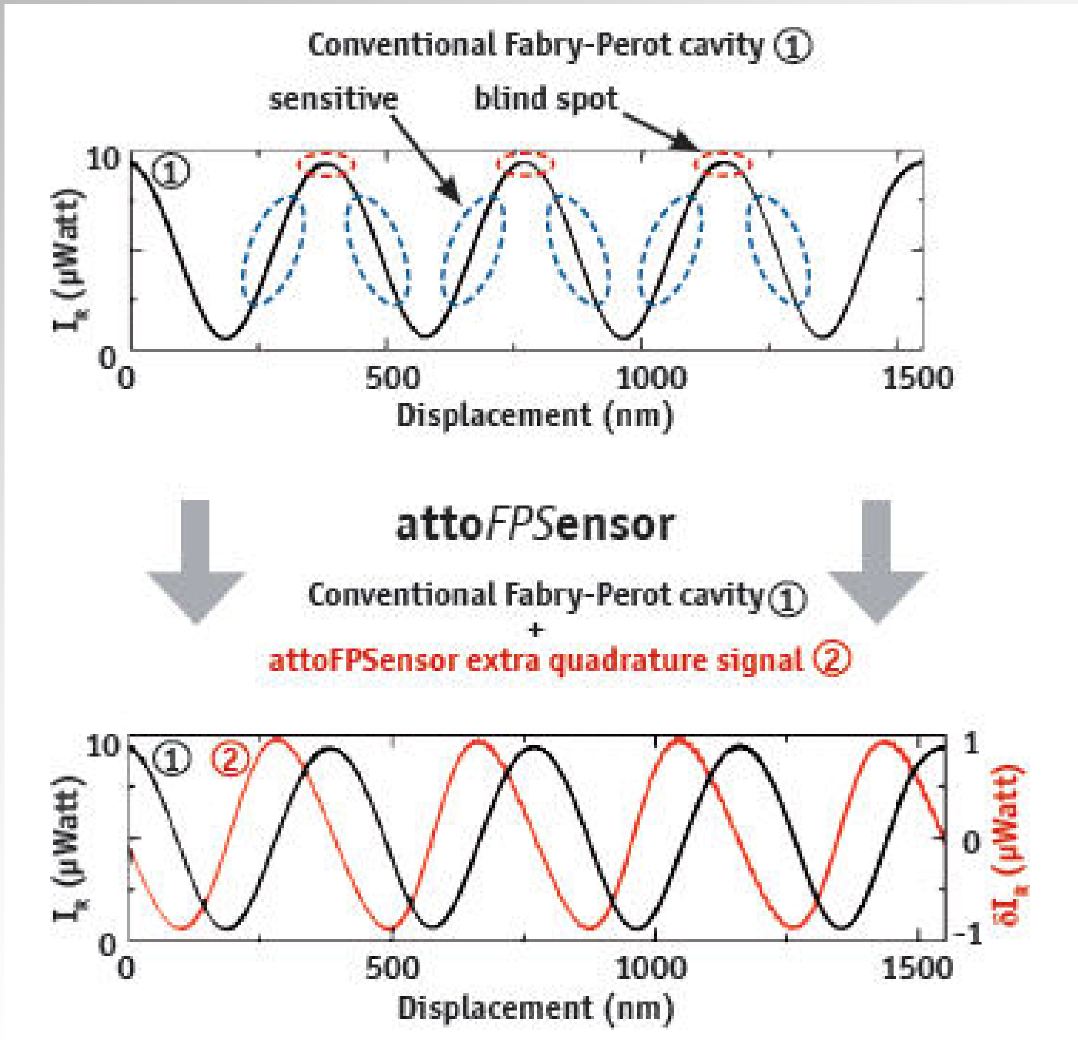
← **REFRACTIVE INDEX OF THE CAVITY**

← **DISPLACEMENT**

← **WAVELENGTH**

4- The possible solutions for BETS interlock implementation

Solution: 4- The interferometric position sensor

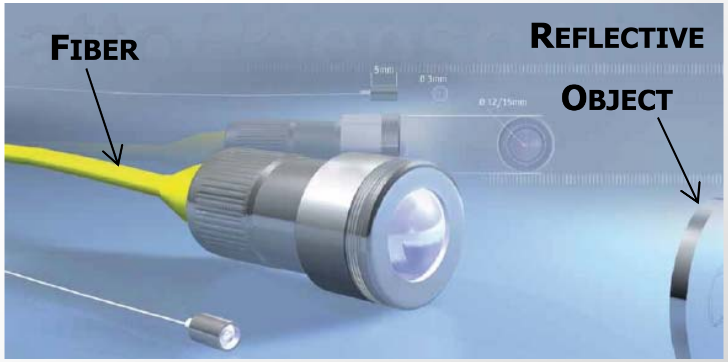


FABRY-PEROT CAVITIES CANNOT DETECT DISPLACEMENT SIGN

DIFFERENT SENSITIVITY REGIONS (BLIND SPOTS)

ADDED EXTRA QUADRATURE SIGNAL

BETTER SENSITIVITY AND DISPLACEMENT SIGN RECOGNITION

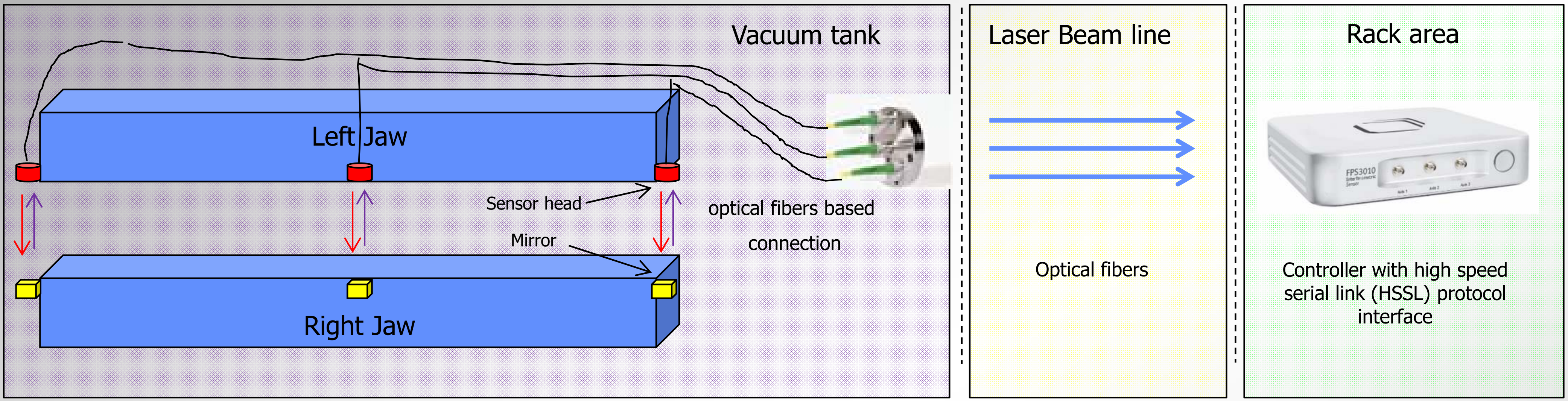


UP TO 30 pm RESOLUTION
±0.5 PPM ACCURACY
0 TO 20 CM POSITION RANGE

SOURCE: WWW.ATTOCUBE.COM

4- The possible solutions for BETS interlock implementation

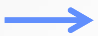
Solution: 4- Possibility of interferometric position sensor heads installation @ TDI



 = - Interferometric position sensor head, metal FC/PC and FC/APC connectors.
- Draka rad-hard fiber, polyimide coated (RIA ≈ 35 db/km @ 10 MGy, max working temperature = 300 °C).

 = - Protected gold mirrors to avoid solarisation of the reflecting surface due to radiation.

 = - Vacuum feedthrough (3 channels).

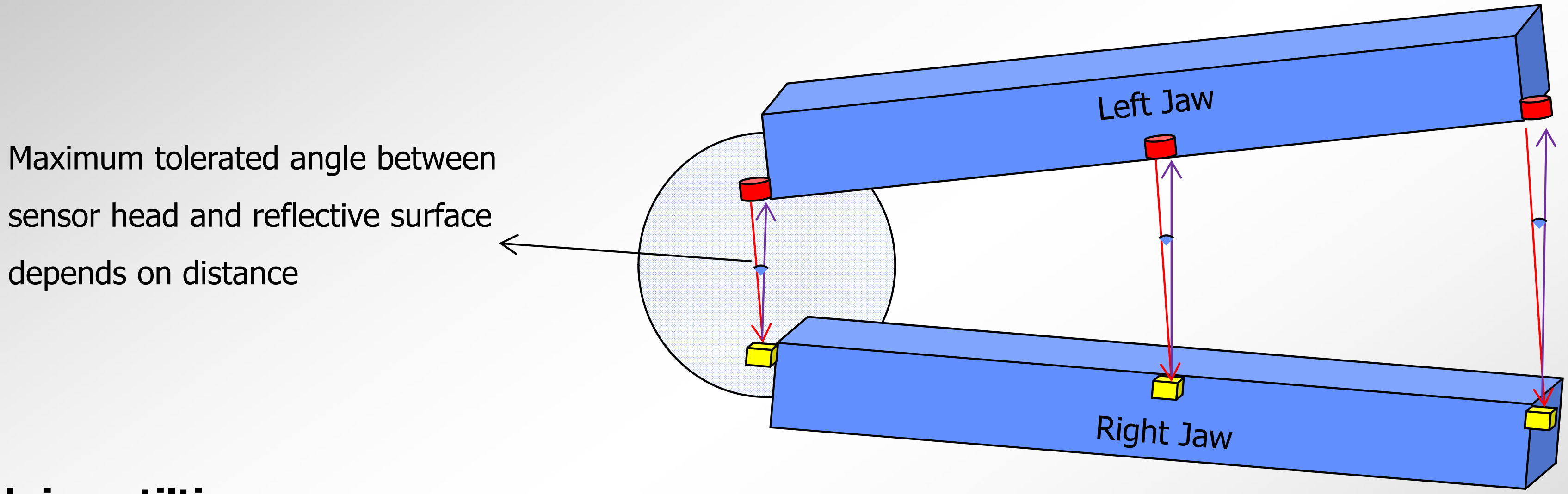
 = - Fujikura rad-hard fiber, "UV-acrilate" coated (RIA ≈ 30 db/km @ 10 MGy, max working temperature = 85 °C).

 =
- Attocube FPS3010, 3 channels controller, 10 MHz sampling rate, 20 ppb stable laser source.
- Real- time digital sensor outputs through 48 bit high-speed serial link (HSSL), output signals frequencies at 400 kHz.

4- The possible solutions for BETS interlock implementation

Solution: 4- TDI tilt angle limitation

- TDI jaw tilt could be limited by the position sensor head alignment tolerances
- The jaw tilt limitation depends on the distance between the sensor head and the reflecting surface (Gap)



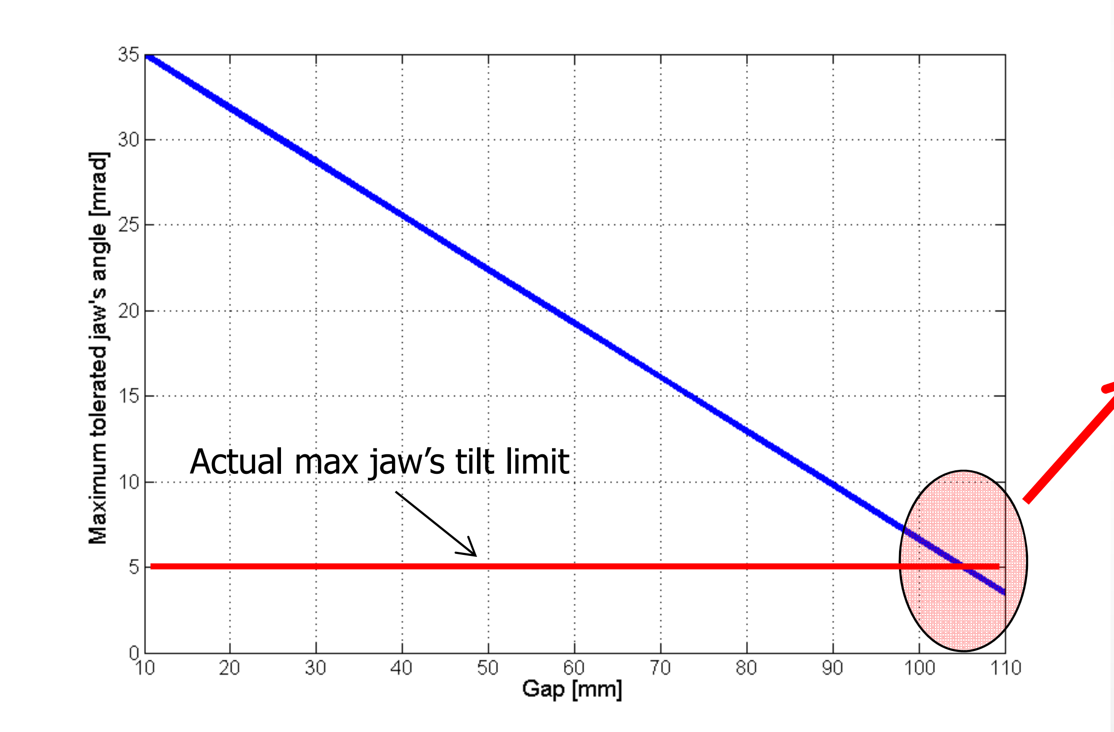
With both jaws tilting

- At injection position, gap ≈ 10 mm, → maximum tolerated single jaw angle ≈ +/- 35 mrad,
  - ✓ maximum difference between upstream and downstream axis ≈ 77 mm
- At parking position, gap ≈ 110 mm → maximum tolerated single jaw angle ≈ +/- 3.5 mrad,
  - ✓ maximum difference between upstream and downstream axis ≈ 7.5 mm
- Actual TDI limit on the maximum tolerated single jaw angle ≈ +/- 5 mrad,
  - ✓ maximum difference between upstream and downstream axis= 11 mm

4- The possible solutions for BETS interlock implementation

Solution: 4- TDI tilt angle limitation

TDI jaw maximum tolerated tilt angle as a function of the gap for the use of the Attocube FPS3010 interferometric position sensors



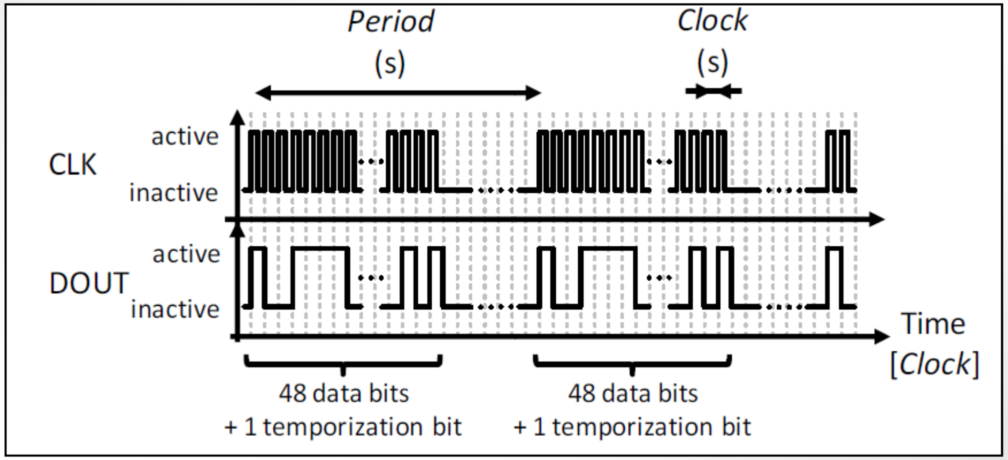
@ Park position (Gap ≈ 110 mm), the actual tilt limit (5 mrad) is greater than the maximum allowed (3.5 mrad) by the alignment tolerances of the sensor head

Approaching parking position, jaws must be tilted less than the actual limit. This is anyway already the case of the parking settings used in the last 3 years operation where both jaws are with 0 tilt angle in parking position.

Solution: 4- FPS3010 controller HSSL output data protocol

- Real- time digital positions outputs
- HSSL (High Speed Serial Link) protocol is defined by its period (position output rate) and clock time (bit output rate).
- Synchronous protocol with two signal lines: CLK (clock) and DOUT (data out).
- The data are synchronized with the rising edge of the CLK signal.
- No usage of header or checksum.
- Clock period and the Period -repetition rate- time can be user adjusted in the FPS3010 software control.
- Currently implemented to use 48 bits position output with 1pm resolution.
  - ✓ Clock duration ≈ 80 ns
  - ✓ The minimum period time is equal to 48 times the clock value
- **Data transmission time for a single position word = 4 µs (→ 250 kHz)**
- **Protocol latency time insignificant (<< 4 µs)**

Protocol's chronogram



- **The data output will be coded on 16 bit Manchester using a stand-alone FPGA card to be read by the BETS**
- **Two gap measurements (upstream and downstream) will be provided to the BETS**

Solution: 4- Radiation effects on optical fibers and sensor working capabilities

- Influence on attenuation of the optical fiber [1] [2]
  - ✓ Measured RIA on Fujikura and Draka rad-hard fiber ≈ 35 db/km @ 10 MGy
  - ✓ 3.0 db expected attenuation on the Fujikura fibers that will link the vacuum feedthrough and the control electronics (≈ 100 m)
  - ✓ 0.15 db expected attenuation on the Draka fibers working under vacuum linking the sensor head to the vacuum feedthrough (≈ 5 m)
  - ✓ Attenuations will not influence the sensor working capabilities because the controller makes the ratio between sent/incident and received/reflected signals.

[1] Miller, E.K.; Macrum, G.S.; McKenna, I.J.; Herrmann, H.W.; Mack, J.M.; Young, C.S.; Sedillo, T.J.; Evans, S.C.; Horsfield, C.J.; , "Accuracy of Analog Fiber-Optic Links for Inertial Confinement Fusion Diagnostics," Nuclear Science, IEEE Transactions on , vol.54, no.6, pp.2457-2462, Dec. 2007

[2] Ott, M.N.; "Radiation effects data on commercially available optical fiber: database summary," Radiation Effects Data Workshop, 2002 IEEE , vol., no., pp. 24-31, 2002

4- The possible solutions for BETS interlock implementation

Solution: 4- The interferometric position sensor

Cost: 200 KCHF

Time: Approximately 6 months - it should be ready by LS1

Pros:

- Direct jaw aperture measurement. A real deformation can be detected without false interlocks
- Additional measurement in the middle
- Fully redundant solution (measurement principle, hardware and software)
- This solution represents a prototype to be used for future TDI collimators

Cons:

- Solution never installed in the LHC but extensively tested in the lab and through radiation characterization campaigns. The same solution will be used on the Crystal Piezo Goniometer to be installed in IP7 by the end of LS1

5- Comparison of the proposed solutions

Solution	Redundancy	Reliability	Effectiveness	Experience	Time	Cost
1- PRS connected to the BEDS	🌧	🌧	🌧	☀	☀	☀
2- Additional PRS	⛅	🌧	⛅	☀	☀	⛅
3- Additional LVDT for gap measurement	☀	🌧	⛅	☀	🌧	🌧
4- Interferometric sensors	☀	☀	☀	⛅	⛅	⛅

- **Redundancy:** 🌧 **No redundancy;** ⛅ **reading electronics;** ☀ **sensor + reading electronics**
- **Reliability** **~ risk of false interlocks due to jaws` deformation, reading instability, electronics failure :** 🌧 **High;** ⛅ **Low;** ☀ **Really low**
- **Effectiveness** **~ Additional safety for the machine:** 🌧 **No added value;** ⛅ **additional gap monitoring;** ☀ **More effective gap measurement system + additional monitoring**
- **Experience:** 🌧 **Solution not tested at all;** ⛅ **successfully tested in the lab and deeply characterized but no experience in real operation;** ☀ **already installed in the machine and successfully experience from operation**
- **Time:** 🌧 **Not in time for LS1;** ⛅ **several months but in time for LS1;** ☀ **few months**
- **Cost:** ☀ **few tens of KCHF;** ⛅ **around 150- 250 KCHF;** 🌧 **more than 250 KCHF the cost estimation refers to only two TDI plus some electronics spare**

6- Conclusions

- **The use of BETS interlock on the TDI gap provides an additional machine safety level without increasing the probability of false interlocks and machine downtime if the provided gap measurement is redundant, effective and reliable**
- **The current gap measurement solution based on LVDTs installed on the motorization axes does not provide a direct gap measurement and it is affected by measurement drift due to possible jaw deformation. The jaw deformation measurement is not available and the correlation between real jaw deformation and axis position measurement drift is not clear. Several "false" interlocks have been experienced in operation and the interlock thresholds have been adjusted many times to allow operation.**
- **After a careful investigation of the possible solutions to provide TDI gap information to the BETS it came out that the installation of innovative interferometric sensors inside the TDI jaws for a direct upstream and downstream gap measurement as well as the real deformation measurement is the most cost effective and reliable solution.**
- **Although the interferometric sensor solution has never been installed in a device in the machine, successful laboratory tests and a full characterization campaign have proven the reliability of this solution. The same solution has been used on the crystal piezo goniometer to be installed in IP7 by the end of the LS1.**
- **The installation timeline is very tight. To be ready by the end of the LS1 the funding and the green light should arrive before September.**