Monitoring I
Environmental

Georg Viehhauser

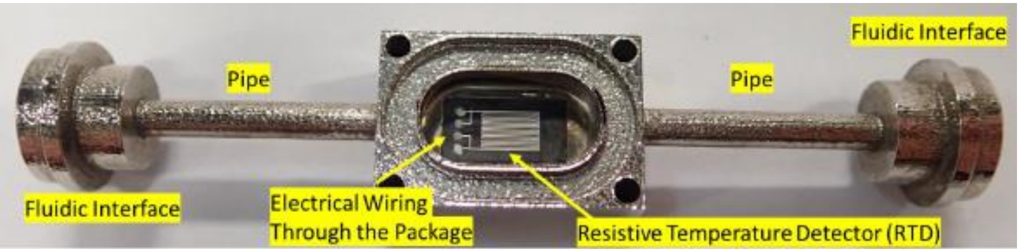
Disclaimer

- I am not an expert on this
- My experiences are biased towards ATLAS & trackers
- I am definitely not qualified to talk about cryogenics, don’t consider this `environment’ (although there will be contact points)
- But will include aspects of thermal management (cooling)
- Thanks for input: Martin Aleksa, Corrado Gargiulo, Greg Hallewell, Eric Hennes, Paolo Petagna, Armin Reichold and others

Introduction

- Purpose of environment monitoring
  - Make sure that environment is suitable so that nothing gets damaged
    - Normally this means turning something off
  - (Ideally) not physics-relevant
  - Detector safety relevant → should be primitive, simple, direct
  - Nothing for a meeting like this
- But that's not all – other use cases
  1. Debugging
     - For complex systems to understand the functioning of individual elements, catch failures early, optimize performance
     - This only is useful if you have some means of control, where you can respond (correct) based on the information
  2. Use in R&D (lab or testbeam) and production and integration QA&QC
     - Usually not radiation hard, smaller overhead (readout etc.)
  - In both cases: more data, higher precision, higher segmentation, possibly higher sampling rate, often with complementary measurements
- Start with discussion of applications, then technologies, then summarize

The simple ones I



C. Manoli et al., Smart Wall Pipes and ducts (SWaP), Attract

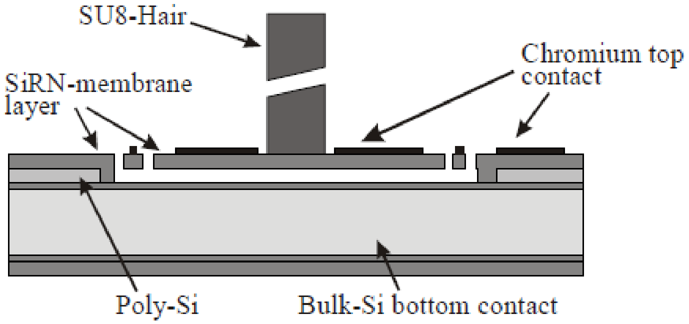
- Temperature
  - Basic technology is trivial (RTDs)
  - Opportunities for integration
    - Sensors embedded in 3D printed metal (tubes, tanks, feedthroughs, HEXs)
    - Sensors embedded in CF
  - High-end T measurements: 0.1 °C precision (FOS)
    - Crystal calorimetry? Liquid TPCs?
- Pressure
  - Opportunity for integration: integrate piezo-electric sensor into 3D printed tube or other vessel
  - Current pressure sensors typically piezo with associated electronics – limited radiation hardness
  - Technology opportunity: MEMS
- Magnetic field
  - Currently:
    - ATLAS and CMS field mapped using Hall probes + fit to Maxwell equations. General precision of measurements is 0.07%
    - Monitoring by 2 or 4 NMRs
  - Technology opportunity: Electromagnetically Induced Transparency (EIT) in Rb vapour: pT resolution
    - This is an optical measurement, so could be made rad-hard, could be used for monitoring as well
  - Another opportunity in the location guidance of the magnetometers during mapping: triangulate position of sensor using accurate distance measurement system (FSI)

M Aleksa et al 2008 J. Phys.: Conf. Ser.110 092018

V. I. Klyukhin et al. 10.1109/TASC.2008.921242

The simple ones II

- Flow
    - Gas/liquid flow meters are standard, mostly volumetric, for mass: Coriolis flowmeters
        - Technology: sonar
    - 2-phase
        - No technology currently available, commercial Coriolis massflow meters do not work
        - Not needed for total flow measurements, but possibly useful for monitoring of flow in parallel evaporators
    - Closed vs open systems
        - Open air flow cooling systems: issue is control of flow (do I get enough heat capacity where I need it?)
        - Technology opportunity: Local gas flow measurement: MEMS with vanes or sense hairs? (could also have spin-out possibilities)
- Gas composition
    - Identify contamination/leaks
    - Mixture monitoring (cooling mixtures, gaseous detectors?)
    - Technology: Sonar
- Vapour quality
    - For evaporative cooling systems: Useful to understand boiling (flow regimes, retarded boiling) in evaporators?
    - Currently no technology available (only optical in transparent tubes)
    - Possibly by capacitive measurement?



GJM Krijnen et al., MEMS based hair flow-sensors as model systems for acoustic perception studies, [doi: 10.1088/0957-4484/17/4/013](doi: 10.1088/0957-4484/17/4/013)

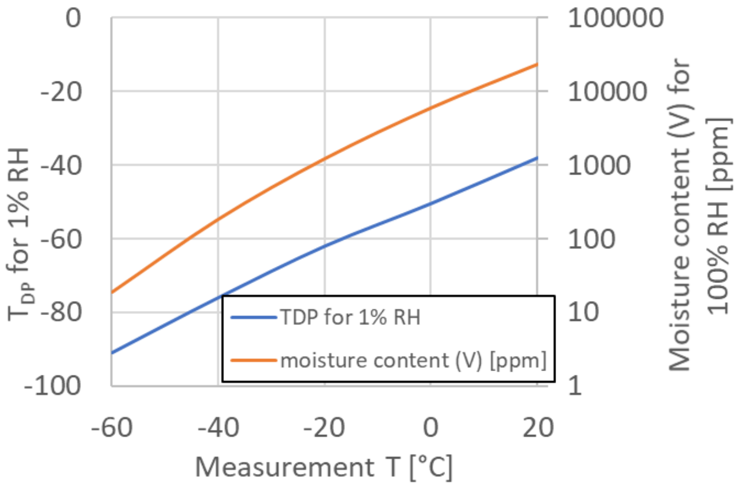
Positions and deformations

- We have the very best radiation-hard position detectors in the world
  - Position of the sense elements found by track based alignment (TBA)
    - Works at smallest required precision (~ μm)
- What else do we need?

1. TBA does rely on stability (over ~ 1d on largest scale, weeks – months on smallest scale)
   - Usually not a problem (loads are low) in closed system (trackers) – more of an issue in open systems (muon spectrometer)
   - What could be useful?
     - Identification of seismic events – shock sensor
     - If there is a higher thermal or mechanical load (for example high-flow gas cooling) - track movements (technologies: FSI – triangular grid, RASNIK – sagitta displacement)
2. TBA gives arbitrary output for some global deformation DOFs (`weak modes' - telescoping, twists, etc.)
   - Standard method is to constrain using low-level physics (reconstruct known mass peaks)
   - Could be easily constrained by a few (tens) of distance measurements
   - Could be useful (technology: FSI), but requires change of mentality of our software colleagues
3. Vibration spectrum information is useful information for design/optimization of support structures
   - Problem: when you get the data it's too late… But it is useful for R&D
   - Technology: MEMS
4. Structural health
   - Measure strain, either directly in or on the object, or from remote optically
   - Technology: Embedded: Strain gauges, FOS, or remote: FSI

Humidity

- Condensation control:
  - Starting point is clear: a dew point below the coldest temperature in the system
  - Direct (reflecting mirror, expensive and not radiation hard) or indirect (RH)
    - Indirect measurement usually not absolute precision, but depending on temperature
    - Technology: FOS, MEMS
- For design and build relevant: derived spec on leak tightness of barriers
  - Here, things become a bit muddled
  - Usually specified as standard helium leak rate and/or overpressure
    - This specification is driven by experimental accessibility plus anecdotal evidence
    - Relation to dew point (or equivalently, moisture content) is not clear (does depend on the shape/aspect ratio of the leak)
  - The actual relevant property is a backdiffusion rate of moisture in relation to dry gas flow into detector volume
    - This is difficult to measure: Put barrier between one high T_{DP} and one low T_{DP} environment and measure moisture content in both volumes over time
    - Problem is that required moisture diffusion rate is usually for low temperature, and tiny at room temperature – not accessible by warm RH measurement
      - $T_{DP} = -60$ °C: 10.6 ppm_V H_2O, with $\Delta R_V/\Delta T_{DP} = 2.5$ ppm_V H_2O/°C, but 1%RH @ 15°C is 170 ppm_V H_2O
    - Need to do cold measurement (which can be difficult), but cheap precise ultra-low humidity measurement would help
    - Or we find an affordable way to directly measure low moisture content/dew point



Fibre-optical sensors (FOS)

- Fibre-Bragg Grating (FBG): G. Berruti et al. https://doi.org/10.1016/j.snb.2012.10.047
  - Modulation of core refractive index, measure strain of core,
  - Humidity measurement from strain introduced by coating (polyimide) absorbing moisture
  - $S_{RH} = 2.1 \pm 0.2$ pm/%RH, $S_T = 10.1 \pm 0.6$ pm/K (resolution of optical interrogator ~1 pm)
    - Strongly temperature dependent (but potential to measure T at 0.1K)
  - B/Ge-doped silica fibres little radiation dependence after pre-irradiation, pure silica FBG tested to 2.5 MGy & 5×10^{15} $1MeV_{neq}/cm^2$
  - Packaging: stress-free
  - 72 FBGs (T+RH) active in CMS since 2014
- Long Period grating (LPG)

  M. Consales et al. https://doi.org/10.1364/OL.39.004128
  G. Berruti et al. https://doi.org/10.1109/jphot.2014.2357433
  - Modulation of core refractive index, coupling of fundamental core mode and cladding modes → spectral variation of attenuation bands,
  - $S_{RH} = 200$ pm/%RH for low (<10%) RH (non-linear), $S_T = 250$ pm/K
  - Irradiated up to 2.5MGy: 10pm/kGy after 30kGy
  - Packaging: pre-stressed
  - Test installation in ATLAS
- More R&D required on radiation hardness (pure silica fibres), packaging & integration
  - Technology opportunity: Integration - Co-cure FBG with carbon fibre: Real-time information of structure deformations/vibration response at sub-μm level
    - Used for AMS2 tracker prototype
    - Commercially used: FBG in wind turbines
    - Possibly combine with a few FSI lines for out-of-plane deformations/absolute distance references

MEMS

- MEMS are widely commercially available (cheap!). Our applications:
    - Accelerometers
        - Commercial: noise density a few 10 μg/√Hz
        - Development for gravitational wave experiments: < 2 ng/√Hz (anti-spring geometry) B. Boom, Thesis
    - Pressure sensors
    - Humidity: ±1.5%RH
- Sense elements are typically piezoelectric, piezoresistive or capacitive + integrated electronics
- Radiation hardness is the issue H.R. Shea, https://doi.org/10.1117/12.876968
    - No commercial market for high radiation (but many devices are marketed as space-hard (30 krad))
    - Radiation-sensitive elements are
        - Mechanics (Si-bulk damage)
        - Sensors
        - Electronics
- Capacitive sensors fail early (few 10 krad) due to charging of dielectrics
- Piezoresistive or piezoelectric more radiation-resistant (>1 Mrad), damage more due to NIEL (depletion of minority carriers)
- There is no inherent reason why these sensors should not survive radiation, there is just no commercial market (yet)
    - But then, we know how to make radiation-hard electronics
    - Development is not trivial, but naively I suspect it can be done (see gravitational wave accelerometers)

Frequency scanning interferometry (FSI)

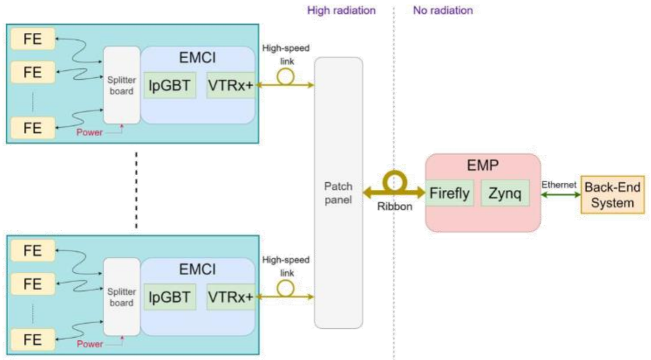
- Frequency scanning interferometry (FSI)
  - Originally developed for ATLAS ID alignment (but never used)
  - Continued development, commercialized ([Multiline™](), by Etalon)
  - Range: 0.1-30m (collimated), 1-30cm (uncoll.)
  - Channels: up to 96 simultaneous
  - Accuracy: 0.5 μm/m abs. distance, also measures vibration response
  - Latency: few s, offline computation
  - Future developments:
    - Improvements to accuracy
    - Pan-Tilt tracking-heads → multilateration co-ordinate measurements
    - Reflectors: Focused beam front-end → diffuse reflecting surface targets, miniaturized reflectors, foil-type reflectors
- Phase Modulation Interferometry (PaMIr)
  - Range, Channels, Sampling same as FSI
  - Continuous real-time measurement
  - Real time output =A-quad-B output
  - Resolution ≈ 10 nm, Accuracy: 0.2 μm/m displacement
  - Higher target speed: < 1m/s, Shorter latency: < 10 μs
  - Future developments:
    - Improve FSI ↔ PaMIr interaction (FSI gives absolute dimension, PaMIr high resolution, FSI used for PaMIr break recovery)

Sonar

- Capacitive transducers
  - Development of Polaroid camera range finder
  - 350V activation/ bias → rapid response
  - 37mm diameter → 50 kHz dominant frequency
  - can operate over wide pressure range (50 mbar to 35 bar)
- Typical systematic uncertainty on speed of sound measurement: $\Delta c = 0.025$ m/s
- Gas mixture measurement of more than two gases possible
- Mixture uncertainty $\Delta mix = \Delta c/\Delta m$ (m is molecular weight difference)
  - e.g. ATLAS cooling: C_3F_8:N_2:CO_2 = 188:28:44 → 0.08 %C_3F_8/ms^{-1}, $\Delta mix = 2\times10^{-5}$
  - Works better for large Δm
- Spinout: Xenon anaesthesia
- Probably not good enough for dew point measurement:
  - Molecular mass of water close to air
  - But, 300 ppm seems doable (dew point of -32°C)
- Possible uses in gas chamber mixture monitoring, gas RICH

Readout

- Standard monitoring readout system at CERN is ELMB
  - Based on ATmega128
  - Designed for large distributed multi-channel readout (CAN bus)
  - My view: not the most accessible
    - Example of better accessibility: Arduino (similarly based on ATmega128)
    - Accessibility is desirable because it allows for use in R&D and carry-over to final systems
  - Can we combine the functionality/scalability of the ELMB with the accessibility of the Arduino?
- Radiation hardness:
  - There is a space-rated (30 krad) ATmegaS128, which is a drop-in replacement
  - This is the core of the ELMB2
  - I am not aware of an Arduino with that chip, but should in principle be possible
  - For higher radiation environment:
    - Development of Embedded Monitoring and Control Interface (EMCI)/ Embedded Monitoring Processor (EMP)
    - This is building on datalinks developed for readout



- Similar standard for readout of fibre-optical systems desirable
  - The cost of FOS system is in the readout
  - Most cost-effective would be one (expensive) readout system and then several branches connected through a 64-way (or similar) switch (relatively cheap)

Standardization

- I personally do not believe in top-down standardization, but think that the free market approach works best
  - As long as there are platforms to share solutions (example: Forum on Tracking Detector Mechanics)
- Highest potential for standardization:
  - Readout:
    - People do not want to spend time developing readout
    - Accessibility & costs will be arguments (in addition to requirements)
  - Possibly software
    - For large monitoring systems (whole experiments)
- Sensors themselves (and their services) are usually simple and require packaging specific to experiment – standardization potential is limited

Technologies summary

- Will give opinion on usefulness (would be nice – useful – essential) and state of development at different radiation levels (speculative – should work, but needs demonstration – advanced)
- My personal opinion – apologies if you disagree/ I'm wrong
- There is also room for other technologies

		Setting			Status of development			Comments/R&D opportunities
		Monitoring	Debugging	R&D and QC	No radiation	Space	Hadron	
Temperature	RTDs	🟩	🟩	🟩	🟩	🟩	🟩	Integration
	FOS	🟧 ?	🟧 ?	🟧 ?	🟨	🟨	🟨	0.1K
Pressure	MEMS	🟩	🟩	🟩	🟩	🟨 ?	🟧 ?	Rad hard MEMS
	Integration	🟩	🟩	🟩	🟩	🟨 ?	🟧 ?	
Magnet	ETI	🟧	🟧	🟧				Together with positioning
Position	FSI	🟨	🟨	🟨	🟨	🟨	🟨	3D triangular grid
	RASNIK	🟨	🟨	🟧	🟩	🟨 ?	🟧 ?	Sagitta measurements
Structural health/deformation	FBG	🟧	🟨	🟩	🟨	🟨	🟨	Integration
Vibration	MEMS	🟧	🟨	🟩	🟩	🟨	🟧	
Humidity	FBG	🟩	🟩	🟨	🟩	🟨	🟨	
	FOS	🟩	🟩	🟨	🟨	🟨	🟨	
Local gas flow	MEMS	🟩	🟩	🟩	🟨	🟨	🟨	
Gas mixture/contamination	Sonar	🟩	🟩	🟩	🟩	🟨	🟧 ?	