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Open Hardware and Application Specific Design for the monitoring system of the Belle II forward/backward electromagnetic calorimeter

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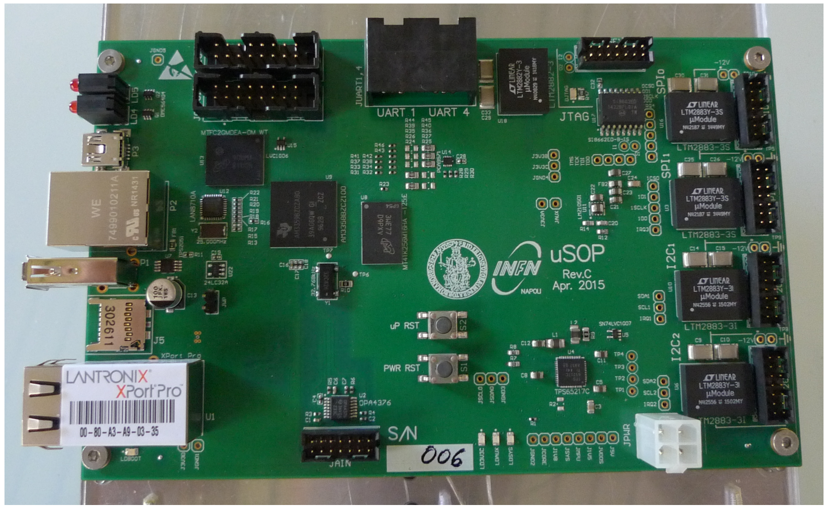
Summary

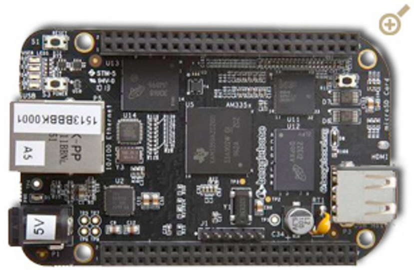
- uSOP: a **S**ervice-**O**riented **P**latform for embedded applications
- Hardware
- uSOP monitoring endcaps of the Belle II experiment at KEK
- Testing the hardware
- Software architecture

Beaglebone Black vs. uSOP

- Running Linux OS (Debian)
  - porting armv7l
- Full support for compilers and applications
- Kernels: major releases available
  - 3.x and 4.x

- **u**P- based, **S**ervice-**O**riented **P**latform for embedded applications
- Strongly oriented to SPI, I2C, JTAG, UART, with isolated power for peripherals and sensors
- Fully managed remotely
- 3U Eurocard native form factor, expandable
- Derived-from and compatible-with BeagleBone Black open-source project





The uSOP board

uSOP – uP and utilities

4 GB Flash eMMC

512 MB DDR3 RAM

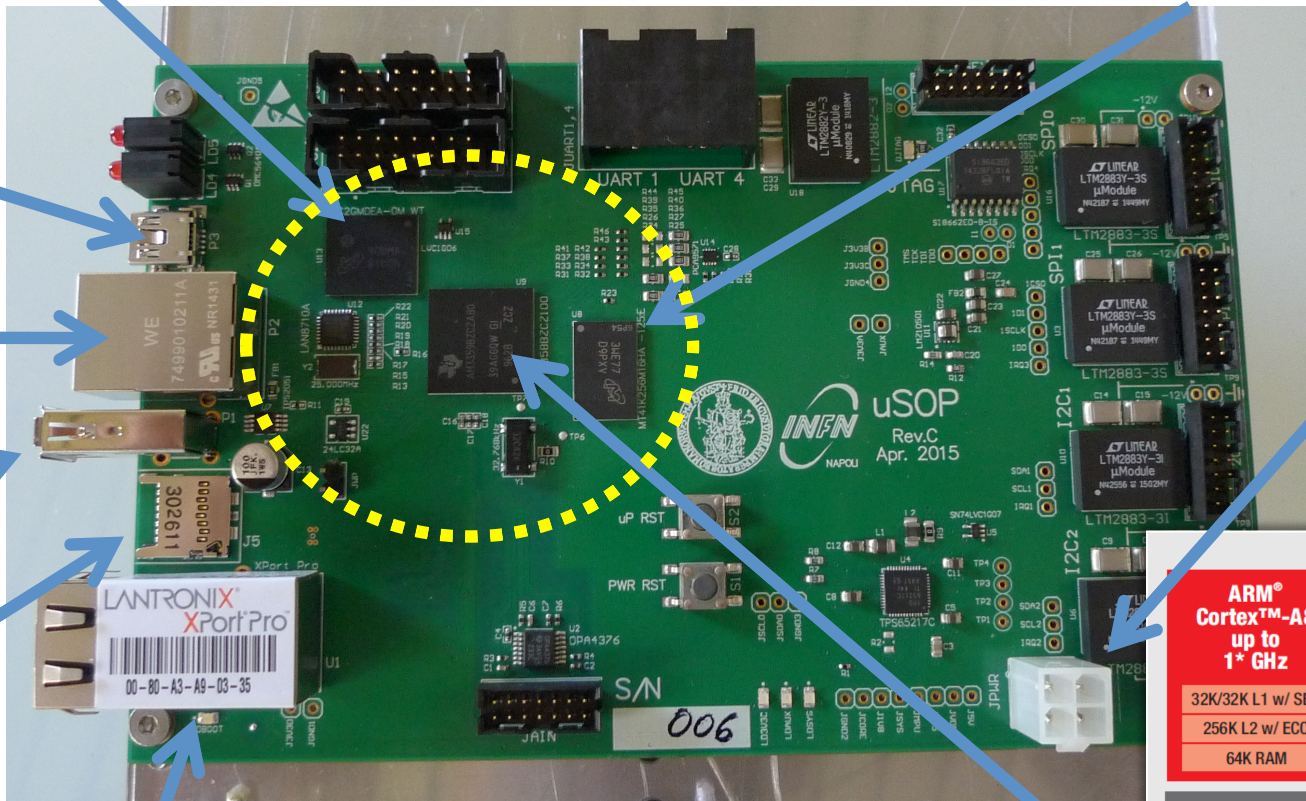
USB device

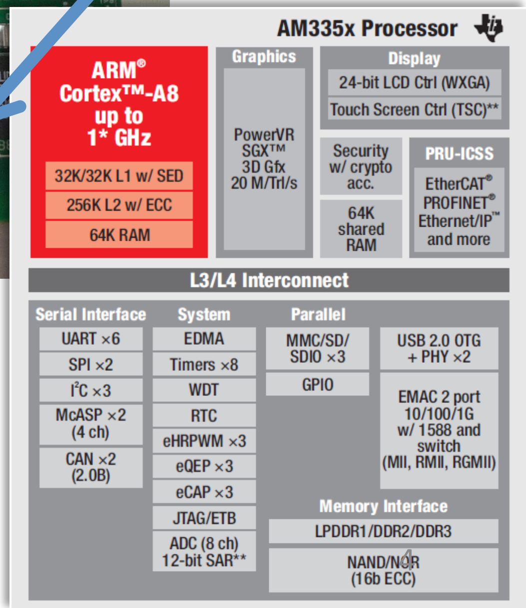
10/100 Ethernet

5V, 500mA (typ)

USB host

uSD





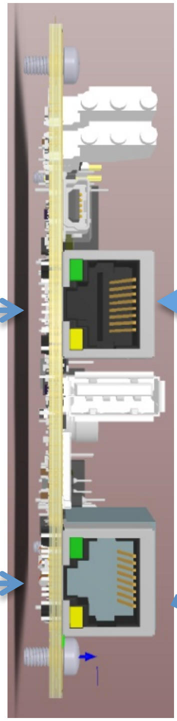
Sitara AM3358

10/100 Ethernet (controls and managament only. **See next slide**)

Remote Management

1) LAN access to Sitara processor

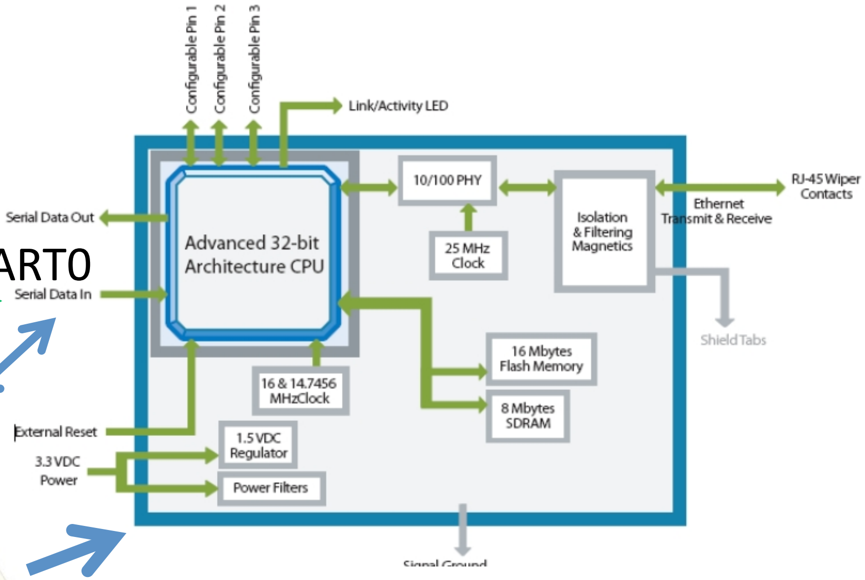
2) LAN for board management



uSOP front view

UART0

Console, bootloader



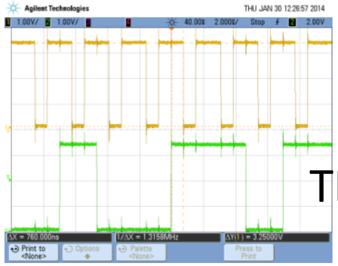
- Remote control over IP for:
  - uP Reset
  - Boot mode
  - Power on/off
- UART over IP:
  - Console
  - Bootloader

```
tortone@nblupo:~$ ssh xport01 -l root
root@xport01's password:
Welcome to

For further information check:
http://www.uclinux.org/

/ #
```

- Based on the latest version of Lantronix Xport-Pro
- µP Freescale MCF5208, MMU-less architecture, 8MB RAM, 16MB Flash
- SoC running uCLinux with a full cross-compiled SDK

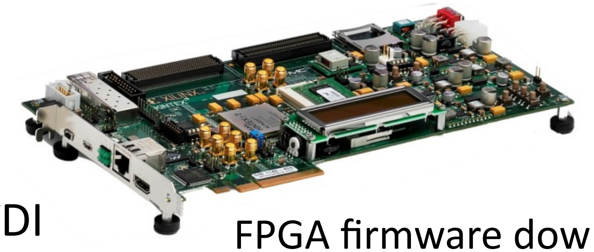
uSOP – Peripherals/Intf

16 x GPIO
- Timers
- PWM
- Event Capture
- PRU



TCK

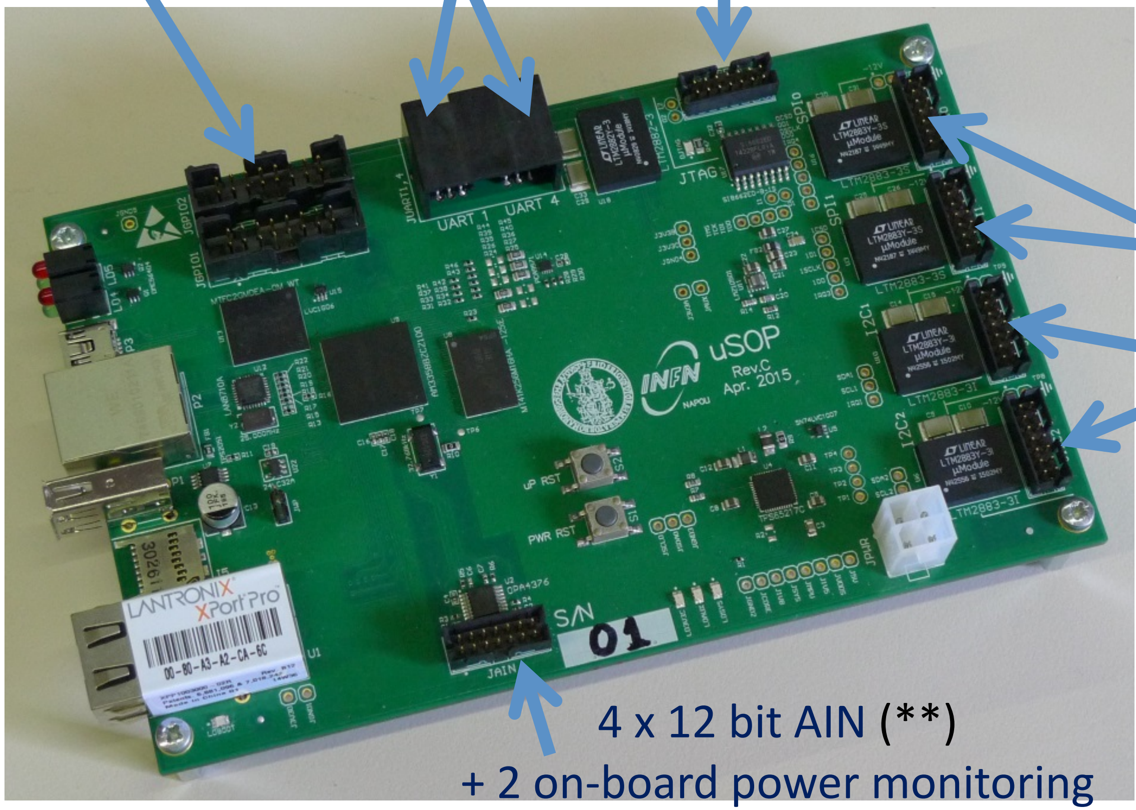
TDI



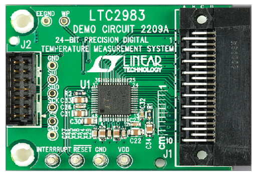
FPGA firmware download

2 x RS232 (*)

JTAG (*)



2 x SPI (*)



2 x I2C (*)

4 x 12 bit AIN (**)

+ 2 on-board power monitoring

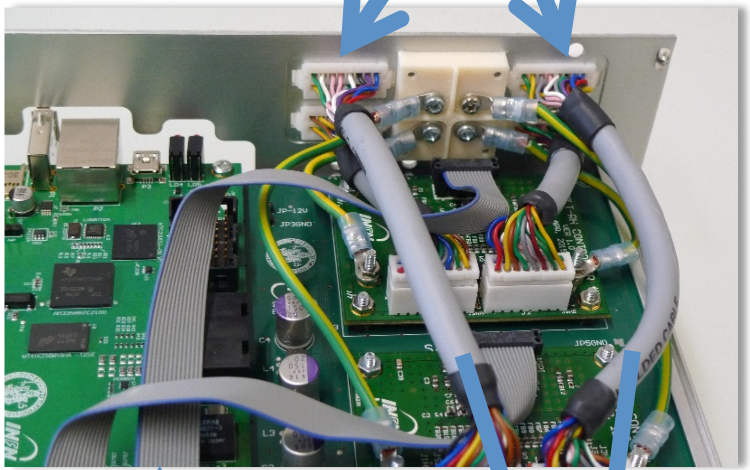
- = fully isolated, 5V-12V supply

** = buffered

Application Specific

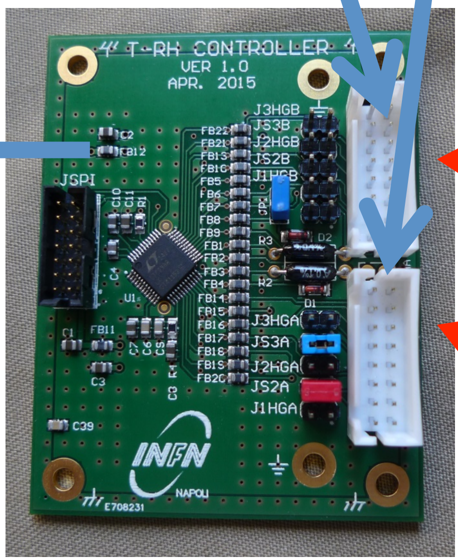
The T-Rh Controller board (LTC2983)

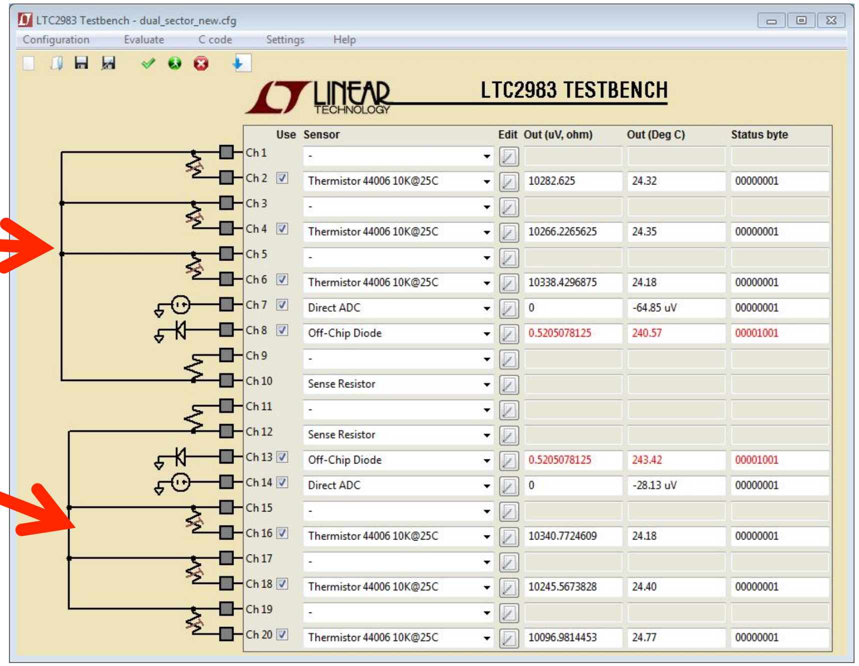
From detector (long cables)



- Designed around the LTC2983 System-on-Chip
- Programmable to handle thermistors, thermocouples, RTD, generic sensors
- Full-feature platform, includes 3 ΣΔ 24-bit ADCs, Analog Front-End, current sources for excitation, uP for sensor linearization and direct output in °C
- Supports 2,3 and 4-wire measurements, with stray thermocouple effects removal

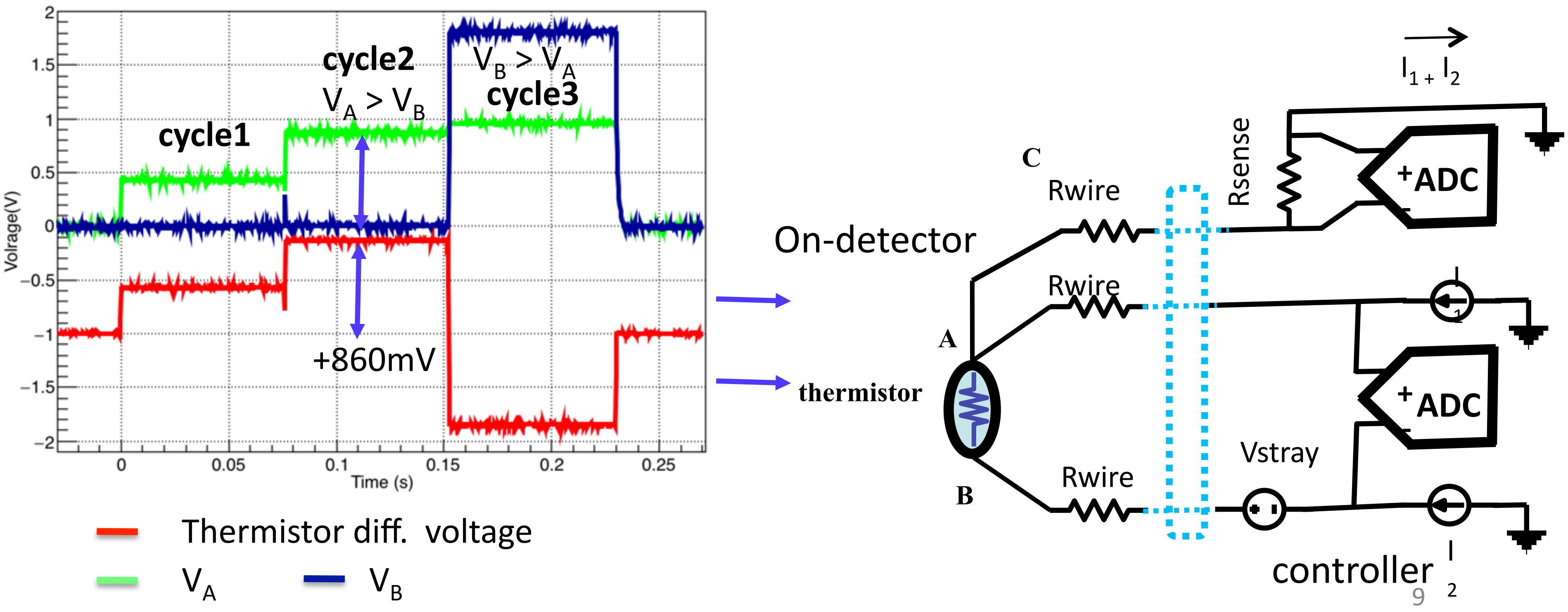
To uSOP (via SPI)





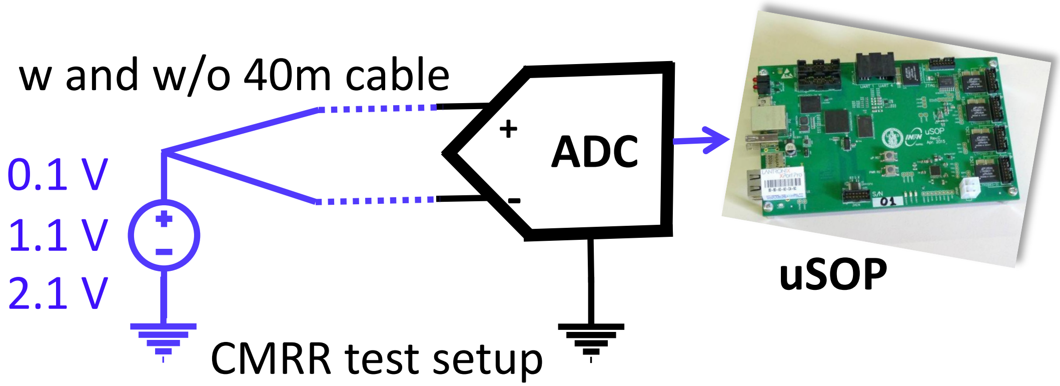
Three steps Cycles:
Excitation, Read-out, Rotation

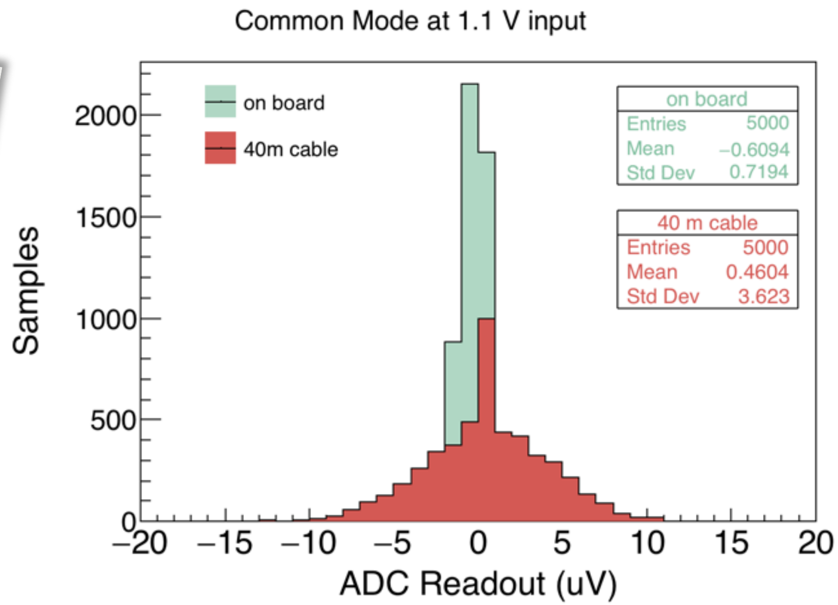
- 3-wire scheme cancels out cable resistance
- Thermistor is first excitated with a trial current injected in Rsense (**cycle1**), actual resistance is calculated in a ratiometric way, then generators establish a voltage of about 1V (best ADC performances) across the thermistor (**cycle2**), and a first sample is taken.
- A new sample is taken after inverting ΔV polarity (**cycle3**). By averaging the two measurements, stray thermocouple effects are removed.



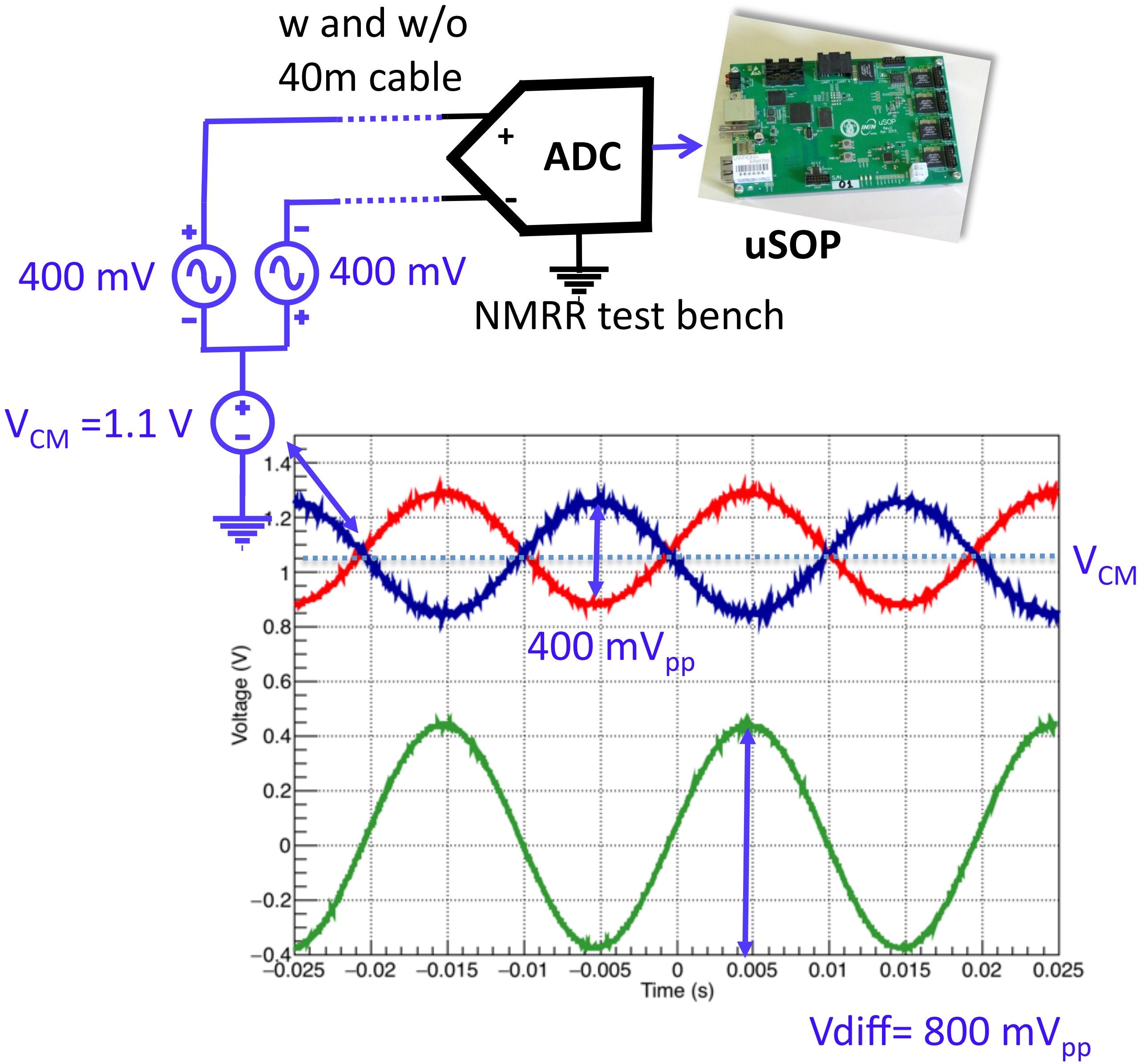
Common Mode Rejection Ratio measurements

- Common-Mode Rejection Ratio (CMRR) is a good figure of merit to determine system performance (important in noisy environment)
- CMRR has been measured at different input DC voltages, both with and without cables
- System level measurements (controller interfaced with uSOP, typical lab environment), give a CMRR of -135db, even better than the datasheet value
- The σ of the noise floor distribution (shorted inputs) increases by a few μV when a 40m cable is connected



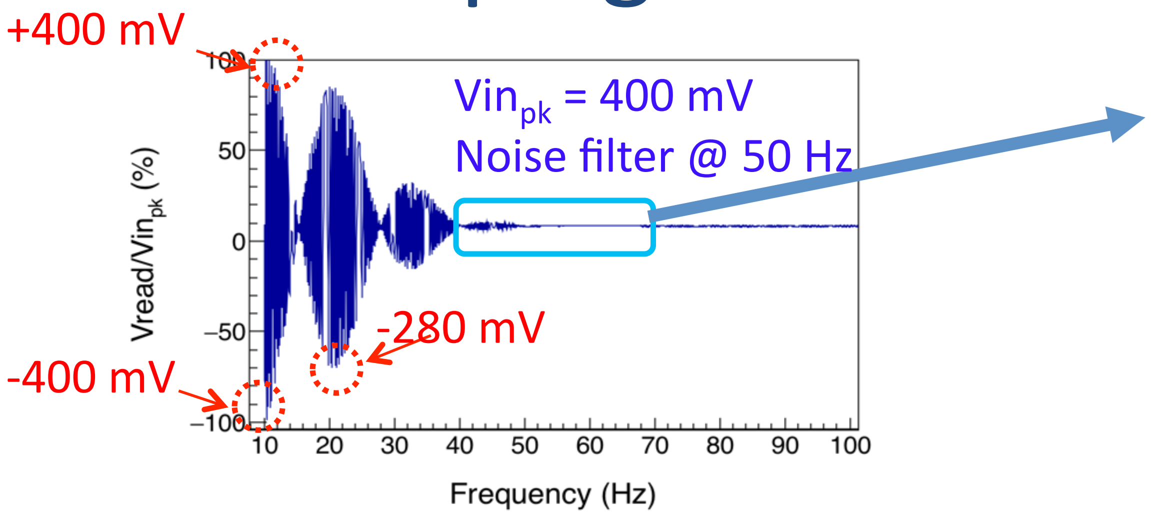


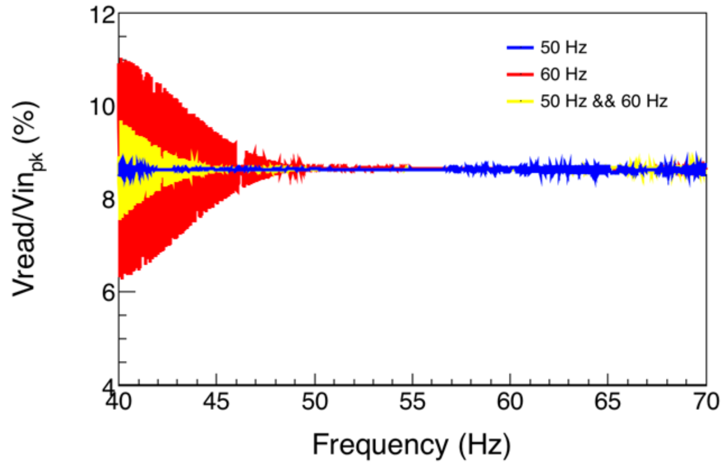
Normal Mode Rejection Ratio measurements



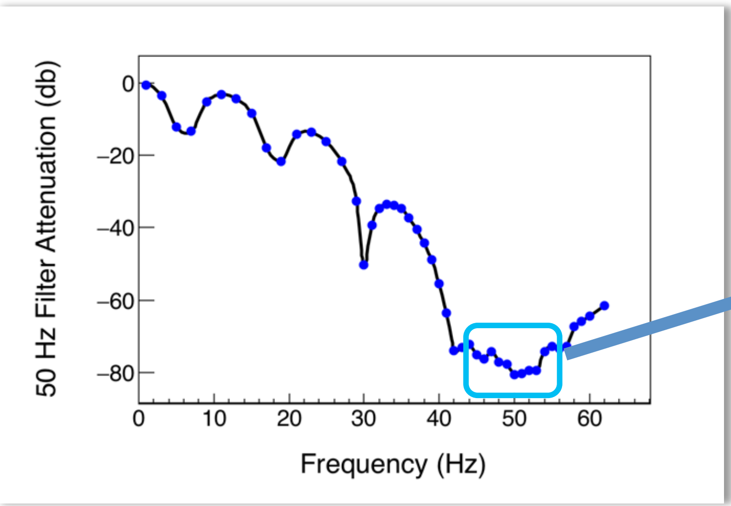
- Typical low frequency noise sneaks in the ADC and it can seriously degradates the sensor read-out
- NMRR has been measured in the range 10 – 100 Hz, comparing the 3 different filtering option offered by the LTC2983
- In this setup, $V_{diff} = V_+ + (-V_-) = 800mV$ and $V_{CM} = 1.1$ V

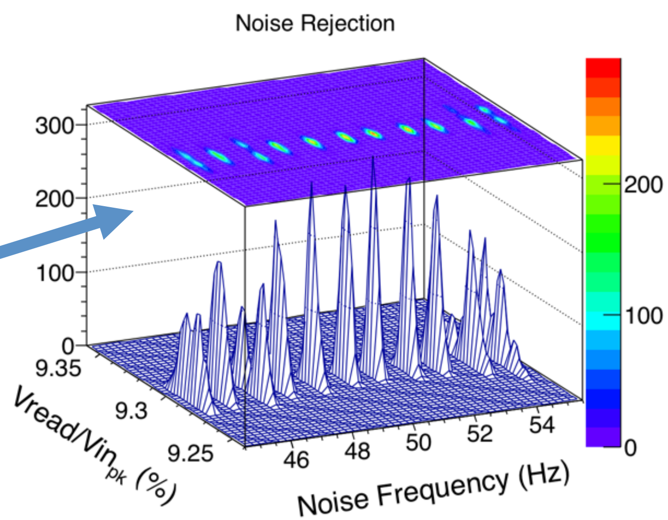
Sweeping the noise – Filtering 50 Hz



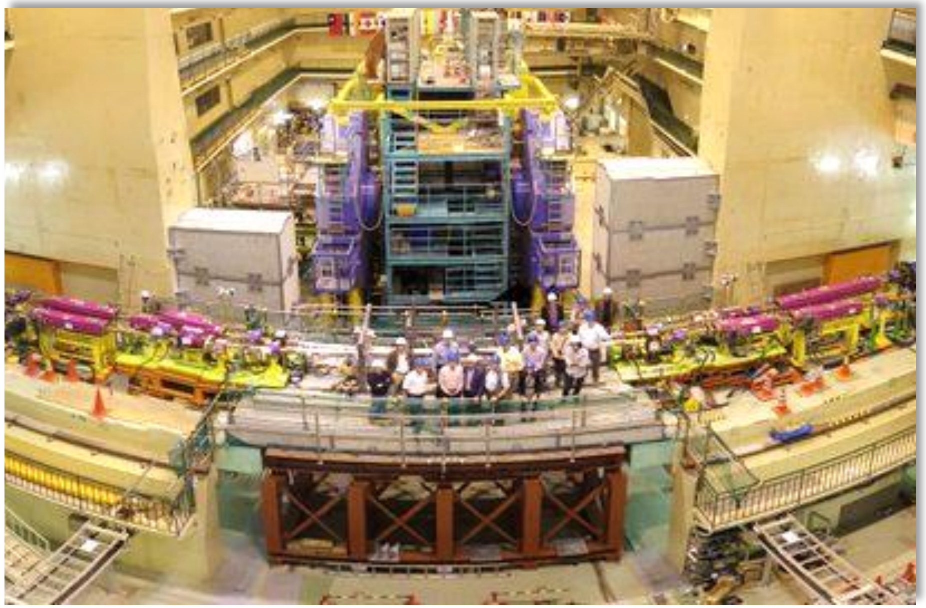


- The on-chip LTC2983 notch filters are programmable on the power grid frequencies of 50 Hz, 60 Hz and 50-60 Hz
- Filters are effectives starting from 40Hz and shows *excellent* rejection of power noise
- In the plots, percentage of the noise amplitude seen by the ADC is plotted vs. noise frequency
- A system test in the lab shows an attenuation of 80db





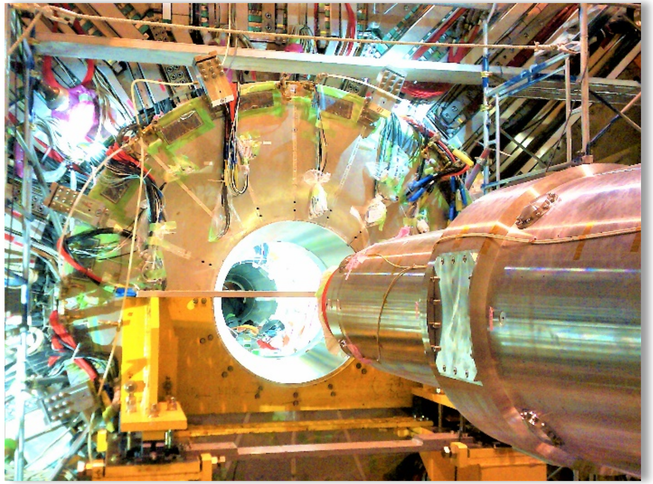
The Belle II Experiment @ KEK



The SupeKEKB interaction point,
KEK (Tsukuba, JP)

- The Belle II experiment is presently in phase 2 operation with colliding beams at the SuperKEKB electron-positron accelerator, KEK (Tsukuba, JP).
- The detector is a major upgrade of the Belle experiment at the former KEKB collider and it is optimized for the study of rare B decays.
- The high-luminosity beam makes it also sensitive to signals of New Physics beyond the Standard Model, including studies of the dark sector.

The ECL Endcap Calorimeter

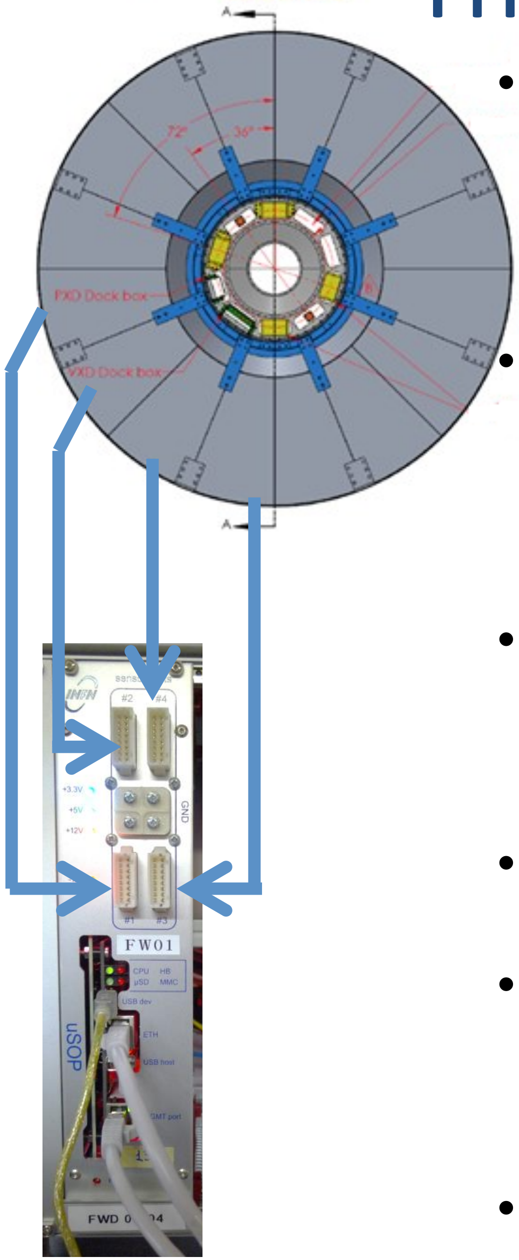


The ECL forward endcap during installation

Detail of an endcap sector cable harness

- The Belle II Electromagnetic Calorimeter (ECL) is based on CsI(Tl) scintillation crystals.
- It splits in a barrel and two annular end cap regions, Forward and Backward, named according to the asymmetric design of the collider.
- 2112 CsI(Tl) crystals are arranged in total in the two end caps, each composed by 16 sectors.
- CsI(Tl) crystals deliver a high light output at an affordable cost, however their yield changes with temperature and can be permanently damaged by humidity, due to the strong chemical affinity for moisture **(Monitoring them is essential)**

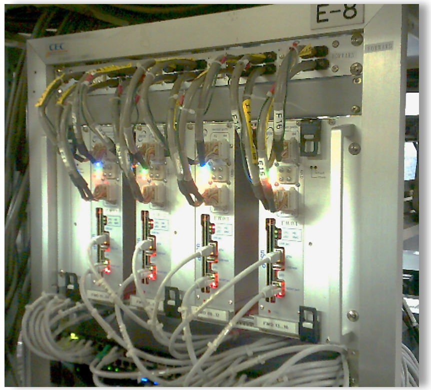
The Endcap Monitoring System

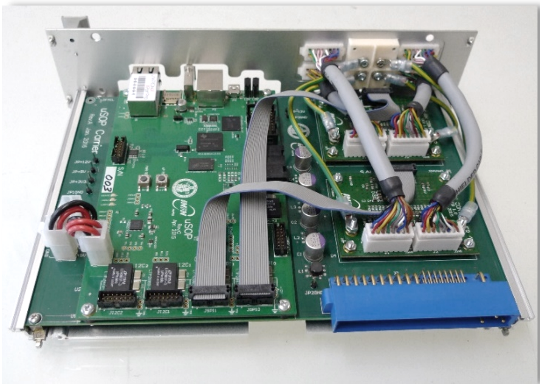


uSOP board wiring scheme

- Each endcap sector is equipped with 3 thermistors and 1 relative humidity active probe (in total 128 analog channels: 96 thermistors +32 humidity ptobes)
- Each uSOP is interfaced with 2 high-performance T/Rh controllers. Each of them takes in input the analog thermistors and humidity signals from 2 detector sectors
- The overall endcap sector is read-out by 4 boards, based on a single-board-computer developed *ad hoc* for embedded applications: uSOP
- 3 Hz readout achievable with good signal integrity up to 40 m cable length
- Acquired and processed data are then sent to an Archiver via Ethernet LAN on a specific backbone assigned to monitoring and controls
- Each board runs the same software and it works independently from the others, such to avoid single-point-of-failures

40m cable

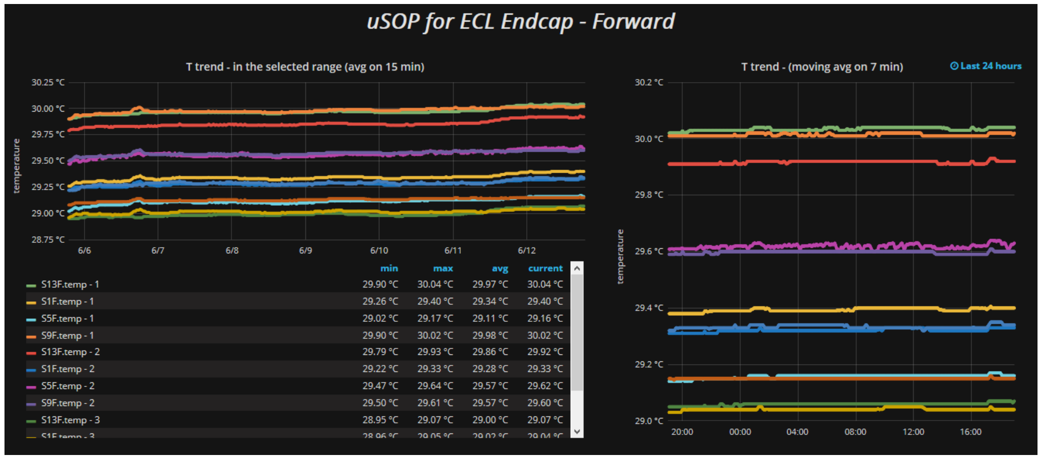




The Software Architecture

- The entire BELLE2 monitoring system speaks EPICS
- EPICS (http://www.aps.anl.gov/epics/) is a set of Open Source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments such as a particle accelerators and large scientific experiments
- uSOP boards sends on a LAN infrastructure PVs with acquired data (T and Rh)
- PVs are consumed by Archivers and GUI based on CSS/Boy
- Experts and developers have access to a web based display showing full-feature information on time series

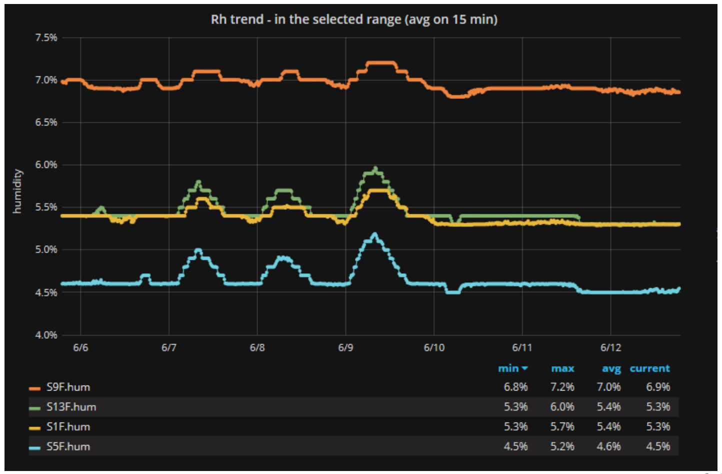
Temperature display



weekly trend

daily trend

Relative Humidity display



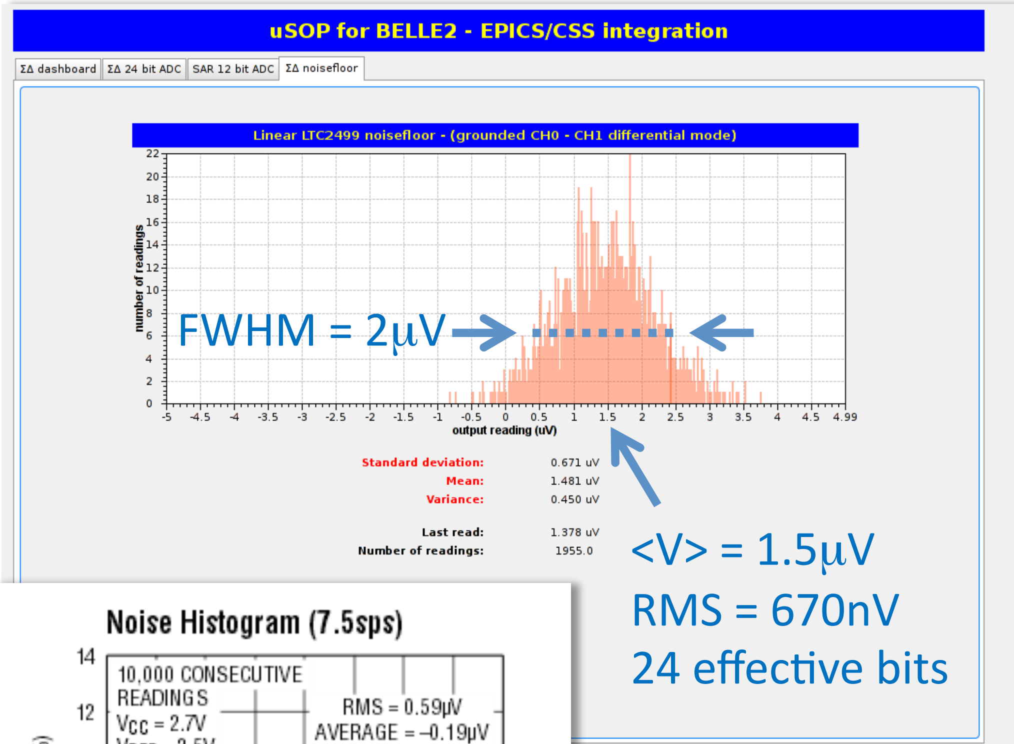
Conclusions

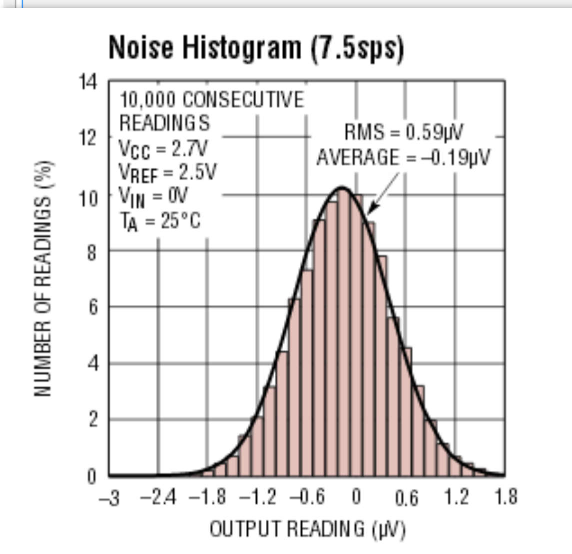
- uSOP Service-Oriented System-On-Chip has been intensively tested at KEK
- It is based an embedded and stable LINUX platform developed *ad hoc*
- uSOP offer hardware controller for all most common serial busses
- Fully (re)configurable and managed remotely
- The monitoring system of the BELLE2 endcap calorimeter matches or exceeds the performance of a lab grade benchtop solution
- Sensor controller is based on LTC2983, a system-on-chip with *excellent* performances and flexibility
- Greatest attention payed to noise issues, galvanic isolation, achievable read-out resolution, reliability
- Lab tests to validate the design
- Architecture fully integrated in the BELLE2 EPICS framework

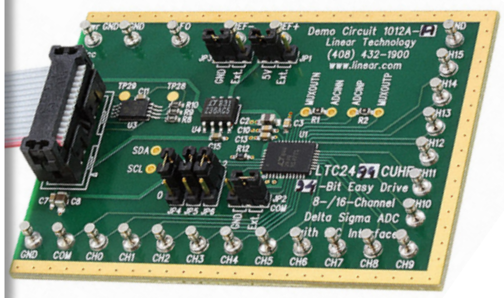

The End

BACKUP

ΔΣ ADC – LTC2499 noise floor



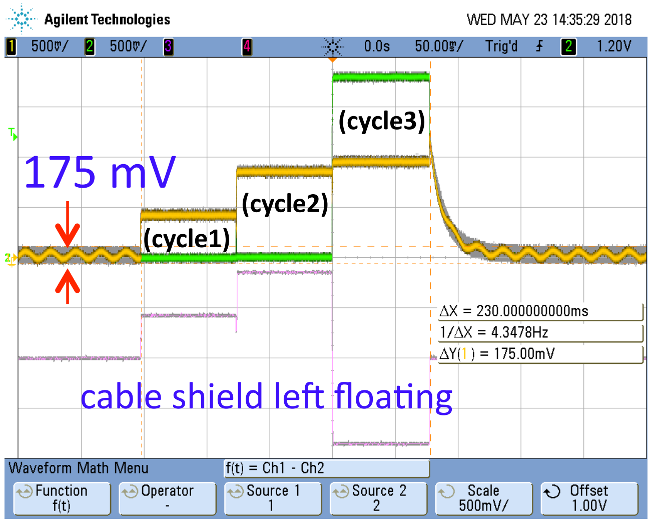


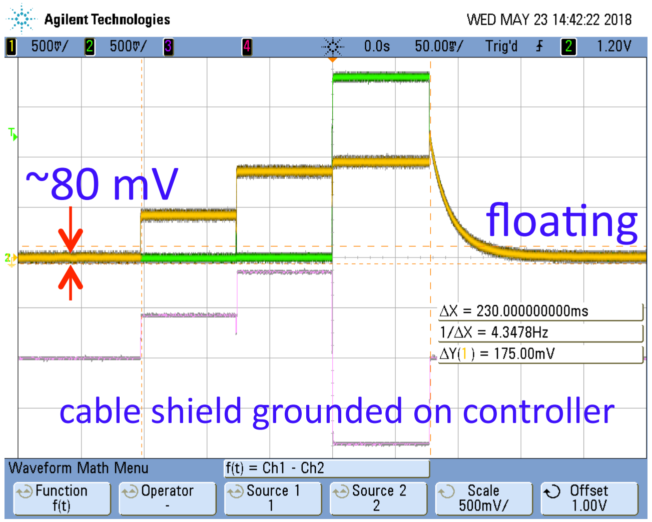


Source: linear.com

- uSOP bench test with LTC2499:
  - ΔΣ ADC, 24 bit
  - I^2C, powered by uSOP isolated supply
  - V_{in} = 0V, Input shorted to local ground
  - ~5 Hz sampling rate
  - 50 Hz filter
  - V_{ref}: 5V
  - Read-out by EPICS IOC
  - GUI by CSS/BOY

Shielding and Grounding



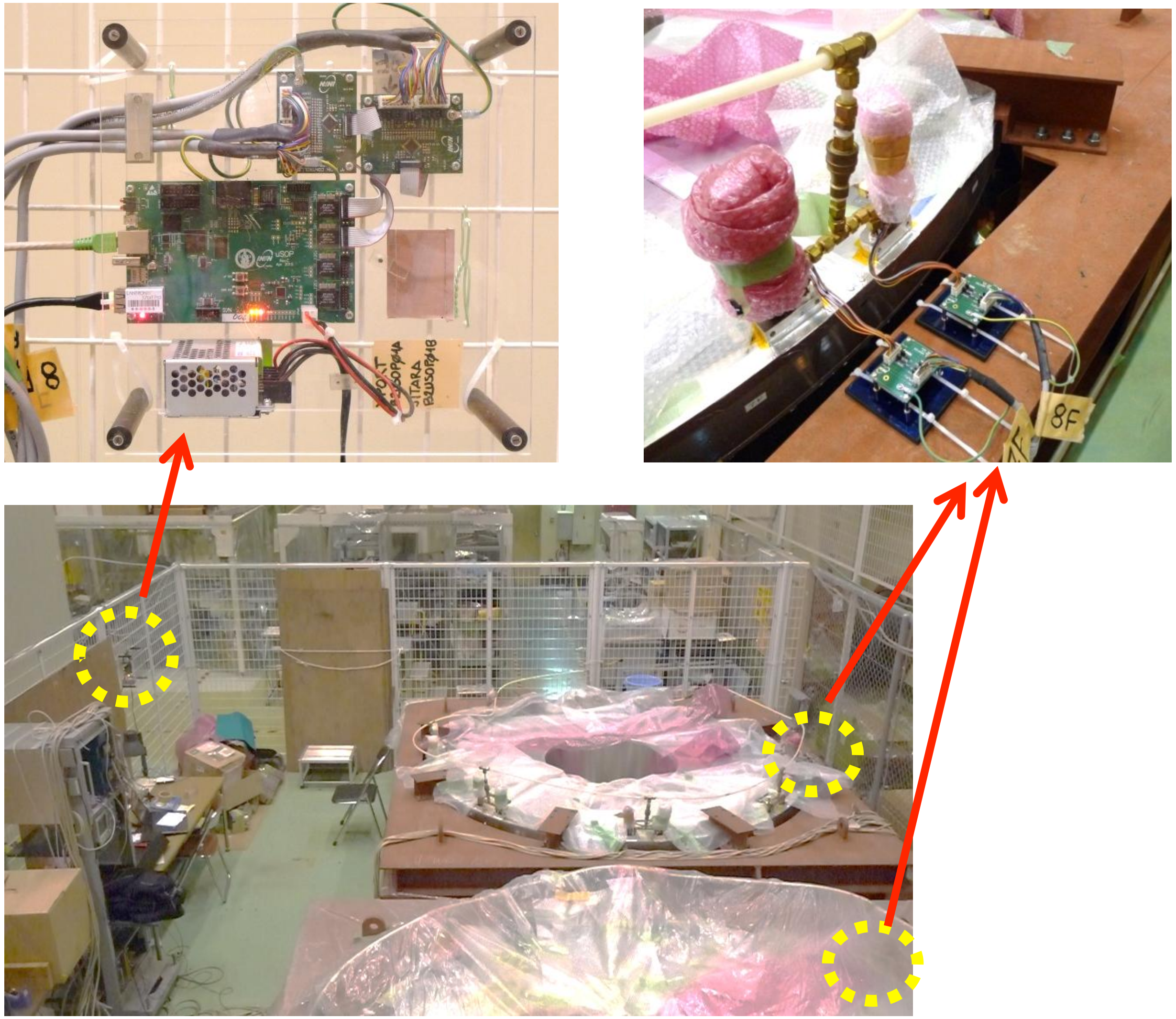


- To avoid self-heating, LTC2983 excitates the thermistors only during read-out
- Cables are left floating in between measurements and they can inject common noise into the detector
- Leaving the cable shield floating on both *near* (controller) and *far* (detector) ends gives the worst case scenario
- Grounding the shield on the controller end gives the lowest noise
- Galvanic isolation of the controller avoids ground loops by design

The Belle2 EndCap at rest: monitoring during upgrade

uSOP box

EndCap Sectors 7F and 8F

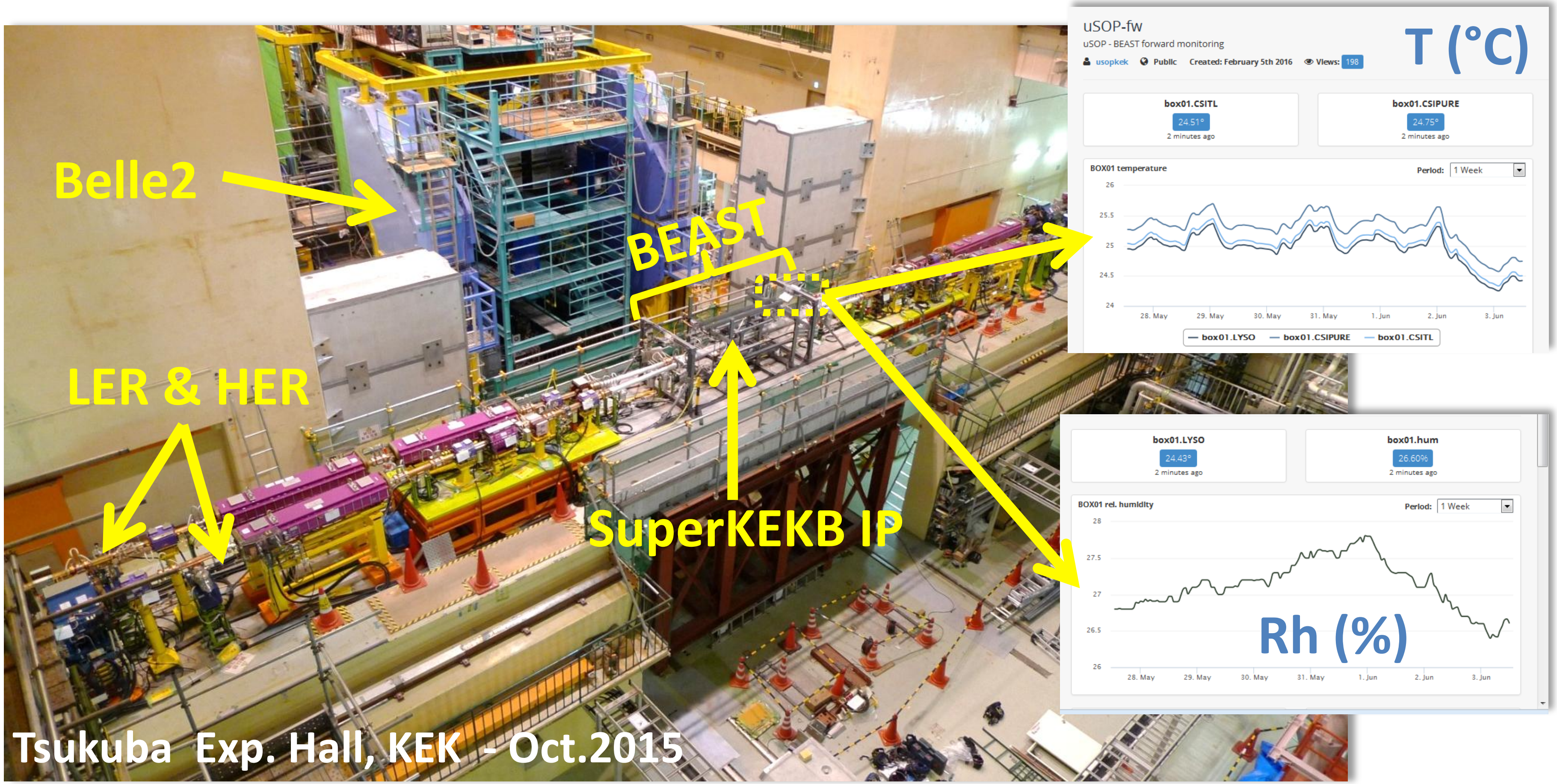


Belle2 EndCap Test Station at Fuji Exp. Hall, KEK

- Minimal, stand-alone monitoring system at the EndCap ECL test station
- 4 sectors over 32 monitored to control the conditioning system (T, Rh)
- Up-time ≈ 2 year
- Data available via both EPICS and cloud

uSOP @ BEAST

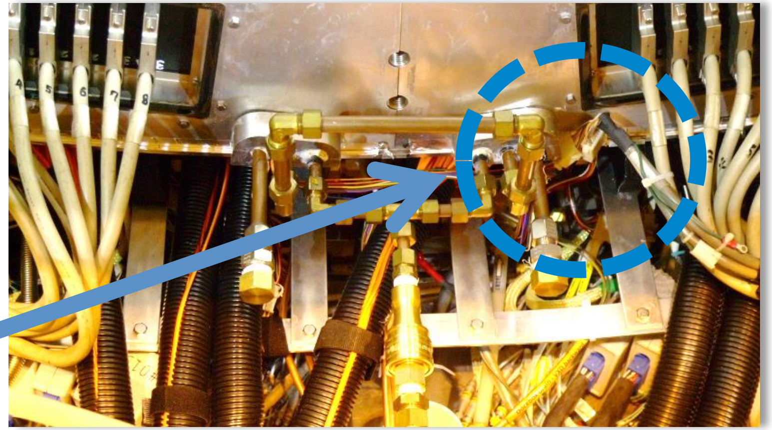
Beebotte Dashboard



- BEAST2 (phase 1) is a detector that has taken data at SuperKEKB Interaction Point, to study beam background (see Miroslav Gabriel talk)
- uSOP has been used to monitor T and Rh of the 18 BEAST2 crystals (LYSO, CsI, CsI(Tl). Data available via EPICS and cloud display (Beebotte)
- uSOP used also to monitor upset in FPGA exposed to beam background (see Raffale Giordano talk)

uSOP minicrate for BEAST

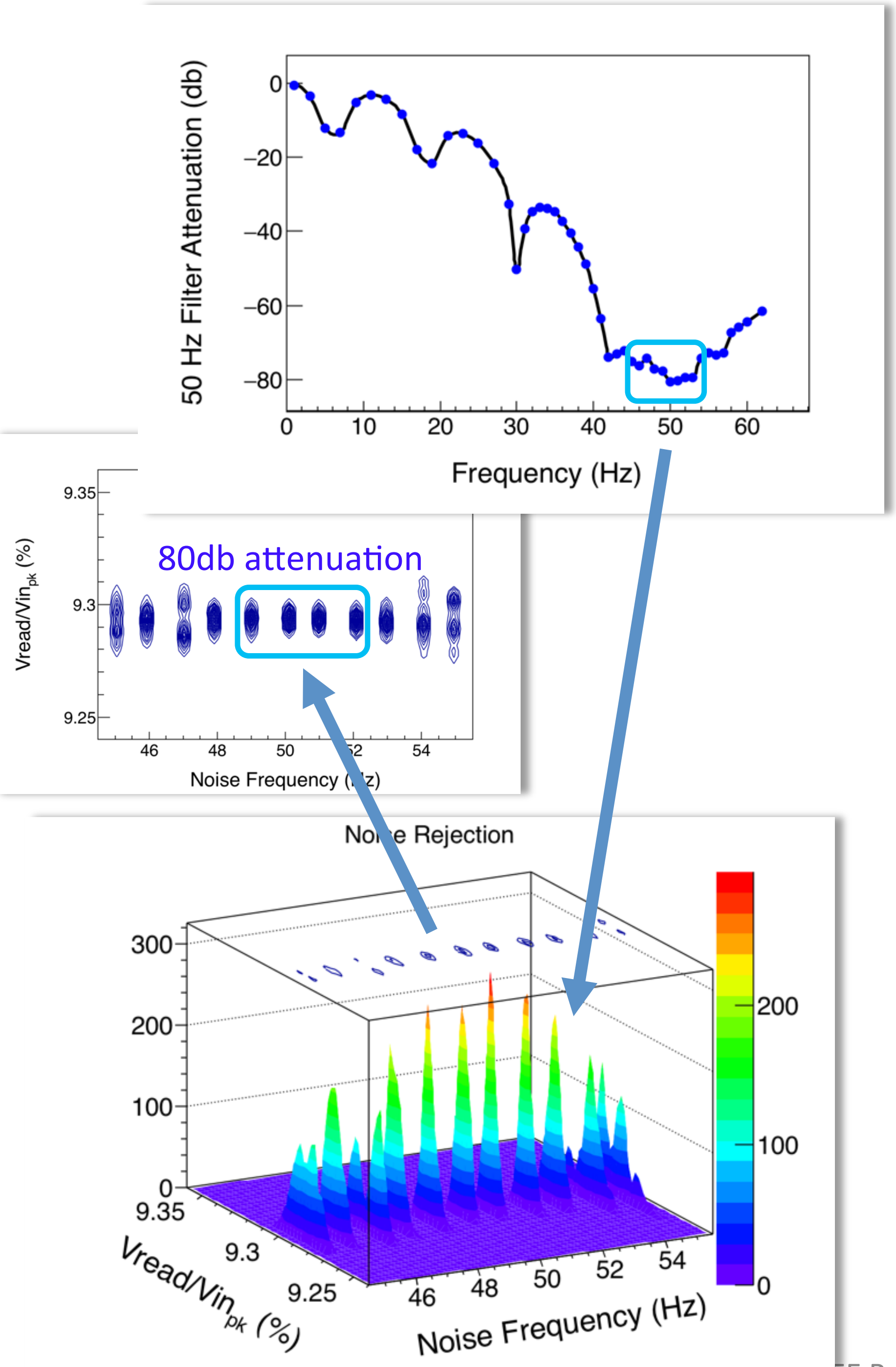
ECL backward installation



Monitor cables

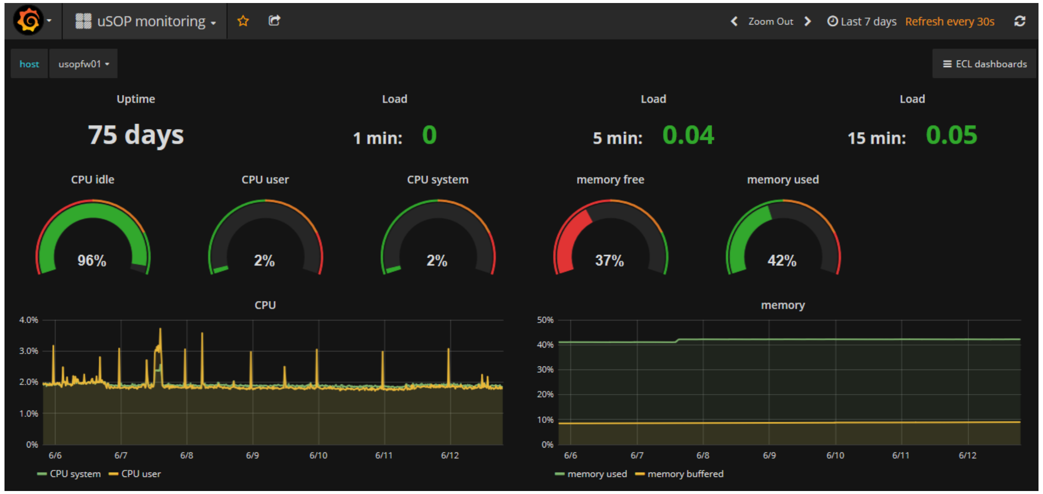
- ECL backward installed in January 2017
- uSOP monitoring connected

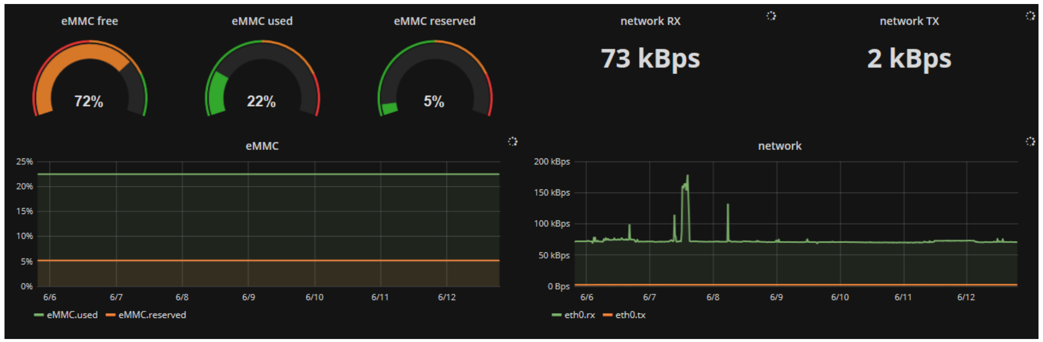
Filtering 50Hz noise



- For the 50Hz filter, the LTC2983 datasheet claims an attenuation of 120db *“… Guaranteed by design, not subject to test…”*
- A system test in the lab shows an attenuation of 80db, nearly flat from 45 to 55 Hz (not that bad !). Mains hum is virtually suppressed.
- 50/60Hz and 60 Hz filters have a similar attenuation, even if datasheet only quotes 75db

uSOP Metrics





- Beside environmental variables, the uSOP most relevant metrics are also monitored, like uptime, CPU load, Memory usage, network activity

Sensors For Belle II ECL

- **Thermistor: SEMITEC 103AT-2**

Resistance -Temperature

Temperature	Type							Temperature	Type						
(℃)	102AT	202AT	502AT	103AT	203AT	503AT	104AT	(℃)	102AT	202AT	502AT	103AT	203AT	503AT	104AT
−50	24.46	55.66	154.6	329.5	1253	3168	11473	35	0.7229	1.424	3.508	6.940	13.06	32.48	60.94
−45	18.68	42.17	116.5	247.7	890.5	2257	7781	40	0.6189	1.211	2.961	5.827	10.65	26.43	48.10
−40	14.43	32.34	88.91	188.5	642.0	1632	5366	45	0.5316	1.033	2.509	4.911	8.716	21.59	38.13
−35	11.23	24.96	68.19	144.1	465.8	1186	3728	50	0.4587	0.8854	2.137	4.160	7.181	17.75	30.44
−30	8.834	19.48	52.87	111.3	342.5	872.8	2629	55	0.3967	0.7620	1.826	3.536	5.941	14.64	24.42
−25	6.998	15.29	41.21	86.43	253.6	646.3	1864	60	0.3446	0.6587	1.567	3.020	4.943	12.15	19.72
−20	5.594	12.11	32.44	67.77	190.0	484.3	1340	65	0.3000	0.5713	1.350	2.588	4.127	10.13	15.99
−15	4.501	9.655	25.66	53.41	143.2	364.6	969.0	70	0.2622	0.4975	1.168	2.228	3.464	8.482	13.05
−10	3.651	7.763	20.48	42.47	109.1	277.5	709.5	75	0.2285	0.4343	1.014	1.924	2.916	7.129	10.68
−5	2.979	6.277	16.43	33.90	83.75	212.3	523.3	80	0.1999	0.3807	0.8835	1.668	2.468	6.022	8.796
0	2.449	5.114	13.29	27.28	64.88	164.0	390.3	85	0.1751	0.3346	0.7722	1.451	2.096	5.105	7.271
5	2.024	4.188	10.80	22.05	50.53	127.5	292.5	90	0.1536	0.2949	0.6771	1.266	1.788	4.345	6.041
10	1.684	3.454	8.840	17.96	39.71	99.99	221.5	95			0.5961	1.108	1.530	3.712	5.037
15	1.408	2.862	7.267	14.69	31.36	78.77	168.6	100			0.5265	0.9731	1.315	3.185	4.220
20	1.184	2.387	6.013	12.09	24.96	62.56	129.5	105			0.4654	0.8572	1.134	2.741	3.546
25	1.000	2.000	5.000	10.00	20.00	50.00	100.0	110			0.4128	0.7576	0.9807	2.369	2.994
30	0.8486	1.684	4.179	8.313	16.12	40.20	77.81								

Unit(kΩ)

- **Relative Humidity Probe:** unfortunately the used probe from Vaisala is no longer produced (Humicap180)
- A new model with similar performance, given as reference, is HMP110 (accuracy 1.5 %)