Elettra Sincrotrone Trieste

# Pilot-Tone Compensation concept and its application to BPM technology

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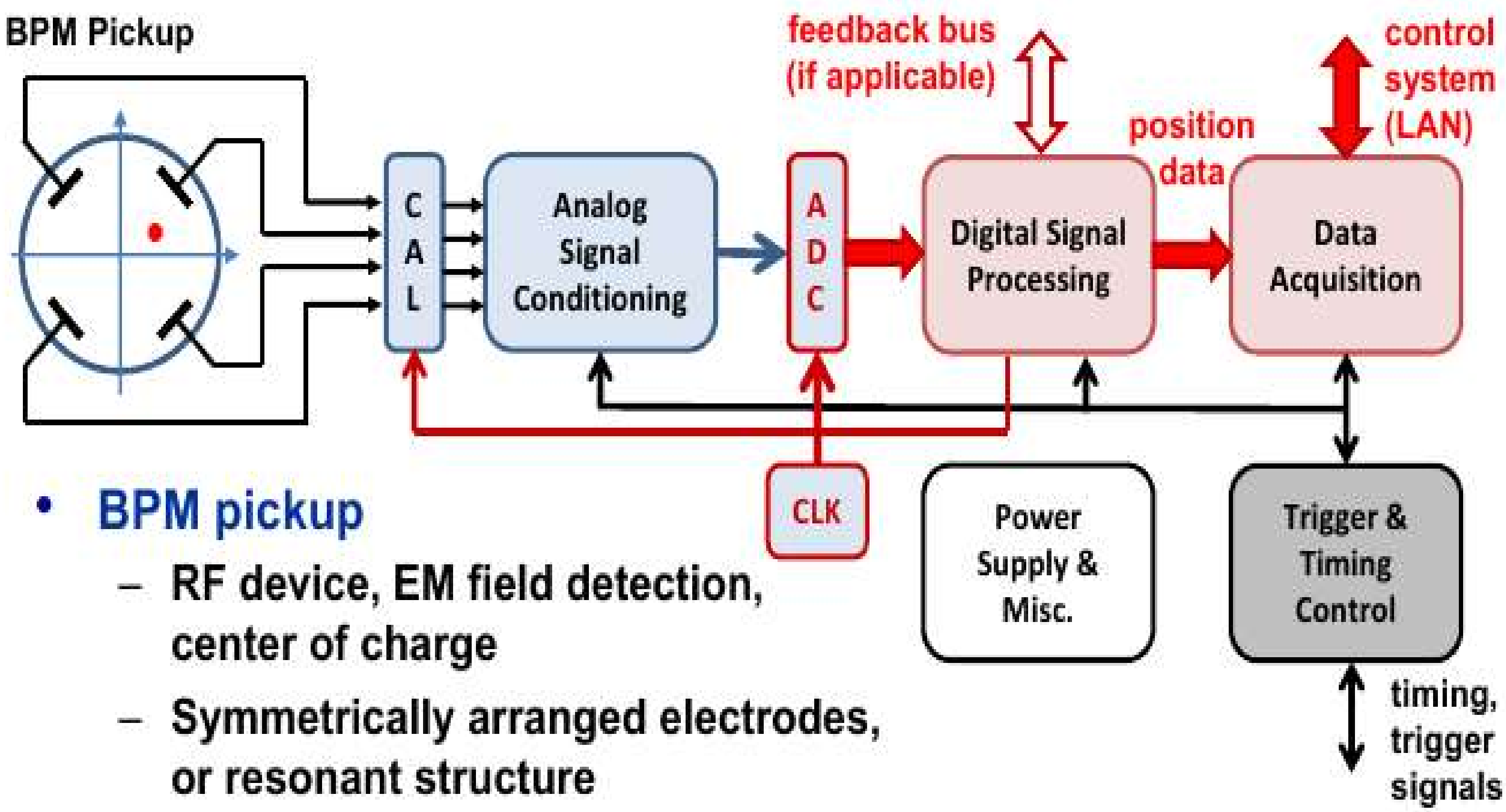
# Modern BPM architecture

*A modern BPM is, basically, a multi-channel Software Defined Radio (SDR)*




*ref: Hermann Schmickler, "BPM System Design", Invited tutorial at IBIC 2015*

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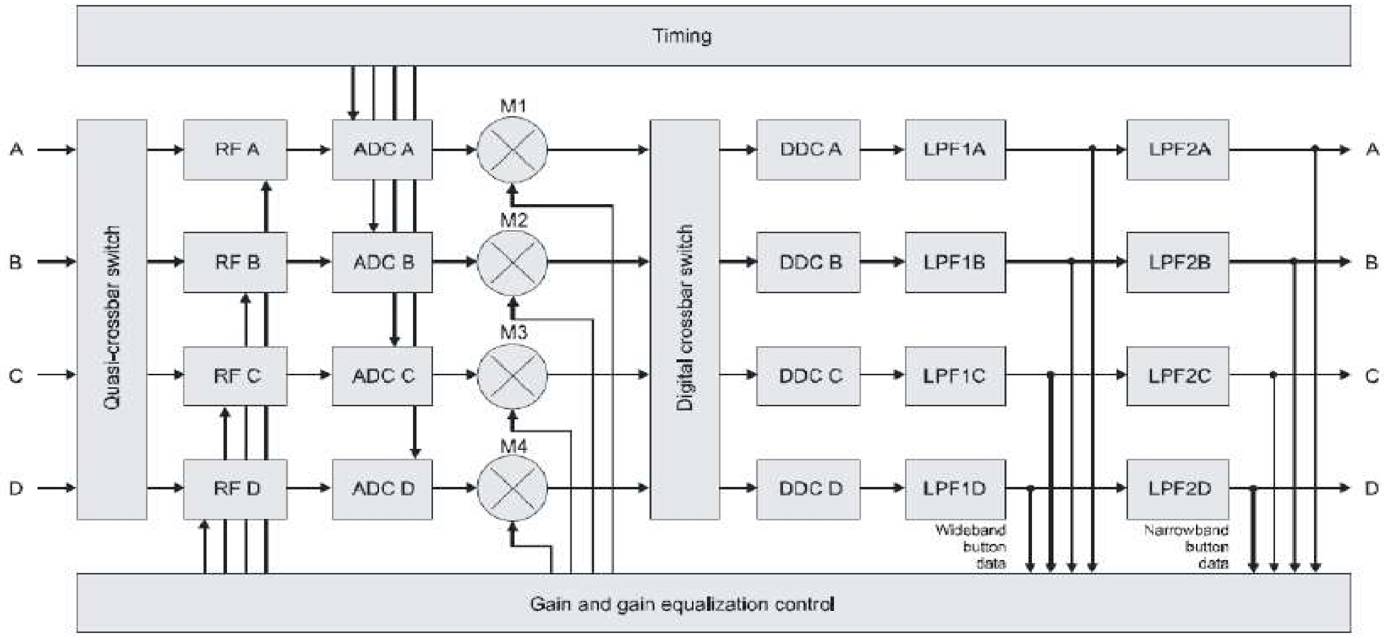
# RF Front End

*The "quality" of BPM's Front End strongly affect the "quality" of the BPM:*

- *How the real RF "FE + cables" characteristics affect the RF signals (load, noise, drift, distortions, cross-talk, ...)?*
- *How can these effects be taken in account and/or compensated?*
- *Can extra functions be integrated (AGC, ...) to improve the behavior of the next stages (ADC, …) or of the whole BPM?*




*Compensation method applied in Libera Brilliance and Electron devices - DSC*

*ref: F. Schmidt-Föhre, G. Kube, J. Maass, K. Wittenburg, "FRONTEND MEASUREMENTS AND OPTIMIZATIONS AT LIBERA BRILLIANCE BPM ELECTRONICS DURING COMMISSIONING OF THE PETRA III SYNCHROTRON LIGHT-SOURCE", DIPAC 2011*

# Pilot tone extra brief history

- Well-known from the ‘50s:
  - *M. J. Kelly, et al., "A transatlantic telephone cable," in Transactions of the American Institute of Electrical Engineers, Part I: Communication and Electronics, vol. 74, no. 1, pp. 124-139, March 1955*

    *“A pilot tone at a frequency slightly displaced from 84 kc per second will be injected into each group of 12 channels at a point where the channels appear in the 60- to 108-kc-per-second range. Measurements of the received level of the tone will give an indication of the overall net loss; later the received tone may be used to control automatically the gain of terminal amplifiers on each group. In addition, 92-kc-per-second pilot tones, similarly injected, will be transmitted over each cable section to give an indication of the net loss of the section. These tones will be blocked from passing from one section to another.”*
  - *Y. Niiro, System equalization for repeatered submarine cable system, 1975 Patent*

- Widely used in today’s telecommunications standards:

  *L. Tong, et al., "Pilot-assisted wireless transmissions: general model, design criteria, and signal processing," in IEEE Signal Processing Magazine, vol. 21, no. 6, pp. 12-25, Nov. 2004.*

# Pilot tone “definition” and goal

- pilot tone: a well known extra signal (digital/analog) injected in a (telecommunication) system;
- it is aimed to improve the system's overall performance;
- its effectiveness can be measured by one ore more system's figures of merit;
- it can be a fixed tone, a sequence of symbols, …
- it is useful in both wired and wireless environments

# Pilot tone applications

- application examples:
  - estimation of channel response/channel quality
  - RF chain control (AGC, ...)
  - fault detection
  - synchronization of receiver
  - adaptive equalization
  - error recovery/correction
  - <u>RF Front End optimization</u>

# Pilot tone approach in BPMs

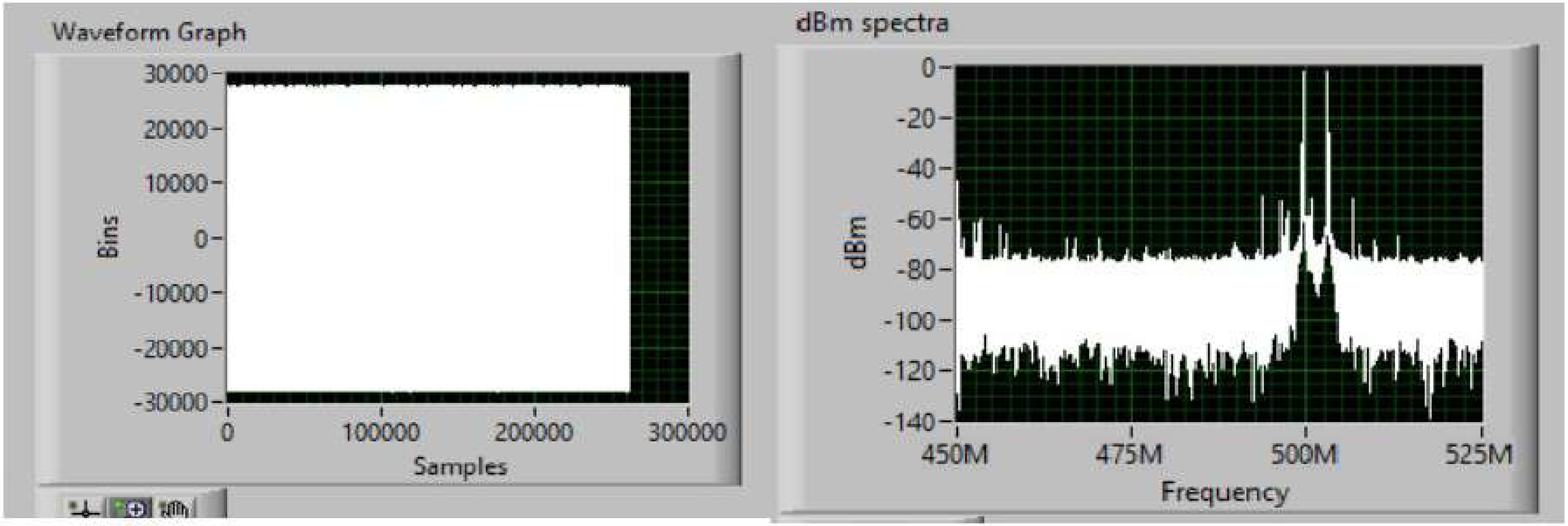
- Similar idea proposed in SLS digital BPMs (1999):
  - *M. Dehler, et al., "New digital BPM System for the Swiss Light Source", Proceedings of DIPAC 1999, pp. 168-170.*
  - Not implemented at that time

- Also found in NSLS-II and Sirius:
  - *J. Mead, et al., "NSLS-II RF Beam Position Monitor Commissioning Update", Proceedings of IBIC 2014, pp. 500-504.*
  - *R. Baron, et al., "Development of the RF Front-End Electronics for the Sirius BPM System", Proceedings of IBIC 2013, p. 670.*

- *Elettra – Sincrotrone Trieste: eBPM project - Goal of the project is the development of a prototype of an innovative device (e²BPM) for the measurement of the beam position, both for rings (Elettra and Elettra2) and single-pass machines (Fermi).*

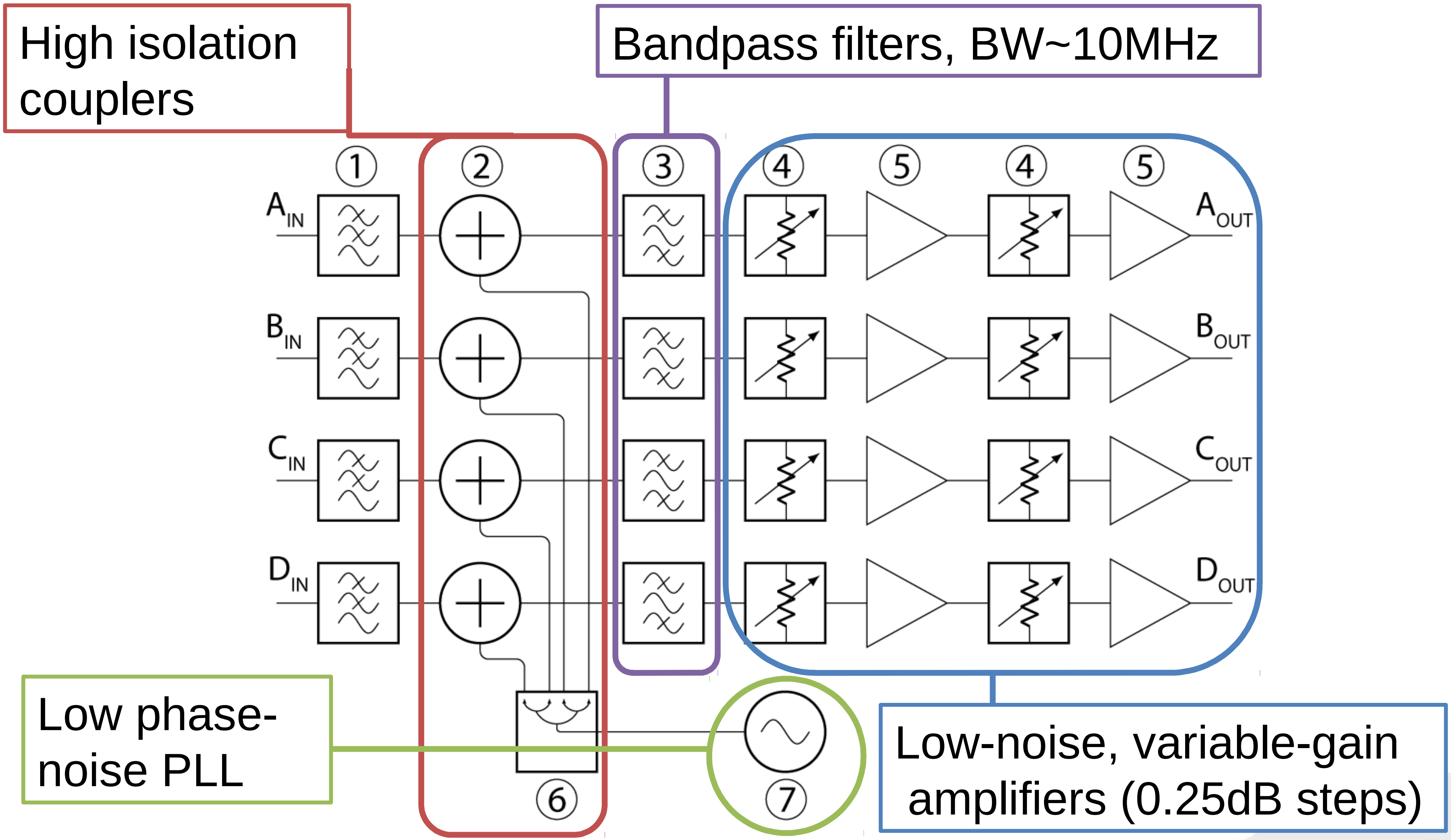
# Proposed implementation by Elettra

- A fixed frequency sinusoidal tone is added to the original signal generated by the beam;
- The 4 channels use the same tone as reference;
- The pilot tone frequency is put next to the "carrier" frequency;
- The pilot tone signal must not interfere with the carrier;



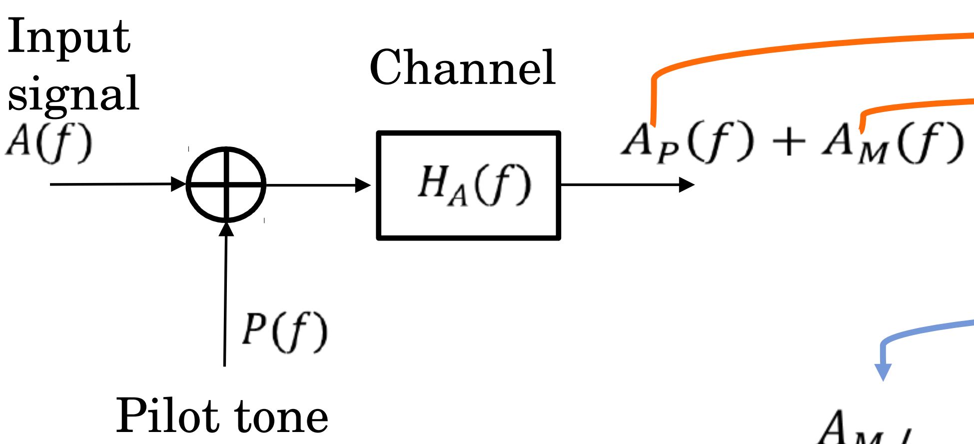

*Storage Ring Rev. Freq.(carrier): 499.654 MHz, Pilot Tone Freq.: 503.123 MHz*
*ref: R. De Monte, G.Brajnik, "ADC behaviours in Electron Beam Position Detectors (eBPM)", DEELS 2017*

# Front end block diagram



# Compensation technique theory

Hypothesis: every channel variation affects in the same way both the carrier and the pilot




$$A_P(f) = H_A(f) \cdot P(f)$$

$$A_M(f) = H_A(f) \cdot A(f)$$

$$A(f) = \frac{A_M(f)}{A_P(f)} \cdot P(f)$$

$$x = K_x \cdot \frac{A_M/A_P - B_M/B_P - C_M/C_P + D_M/D_P}{A_M/A_P + B_M/B_P + C_M/C_P + D_M/D_P}$$

Compensated position in classical Difference-over-Sum (DoS) equation

# Advantages in beam diagnostics

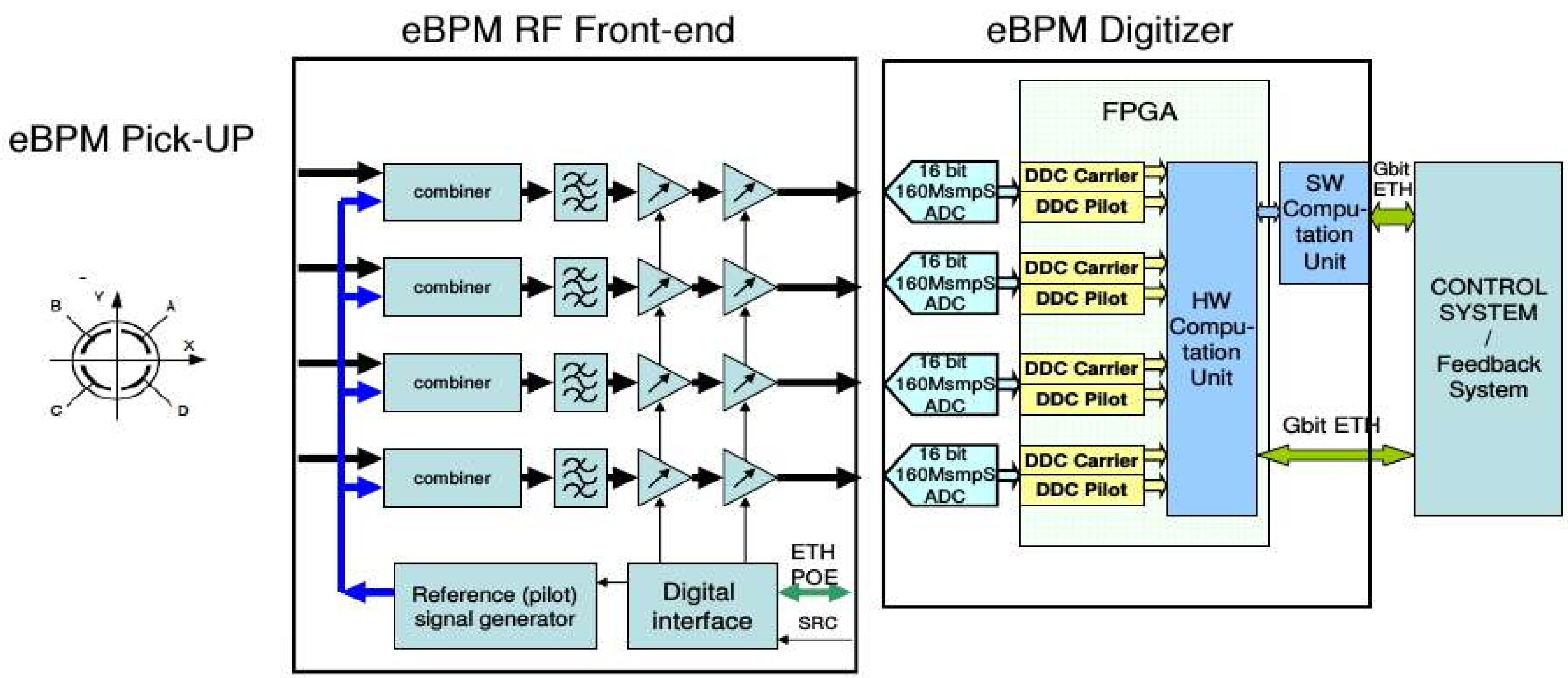
- Compensation of cables
  - Possible when the tone is injected near to the pick-ups
- No need for thermoregulation
  - Thermal drifts are the same for carrier and pilot
- Reduced current dependence
  - The pilot can be used as a “dithering” with low beam currents
- The pilot position returns a diagnostic of the system status
  - Hardware faults can be identified
- Theoretically simple

References:

- *G. Brajnik, et al., “A novel electron-BPM front end with sub-micron resolution based on pilot-tone compensation: test results with beam.”, IBIC'16.*
- *G. Brajnik et al., “Reducing current dependence in position measurements of BPM-systems by using pilot tone: quasi-constant power approach.”, IBIC’17.*
- *R. De Monte et al., “Integration of a novel BPM system within the global orbit feedback environment of Elettra.”, DEELS’18.*

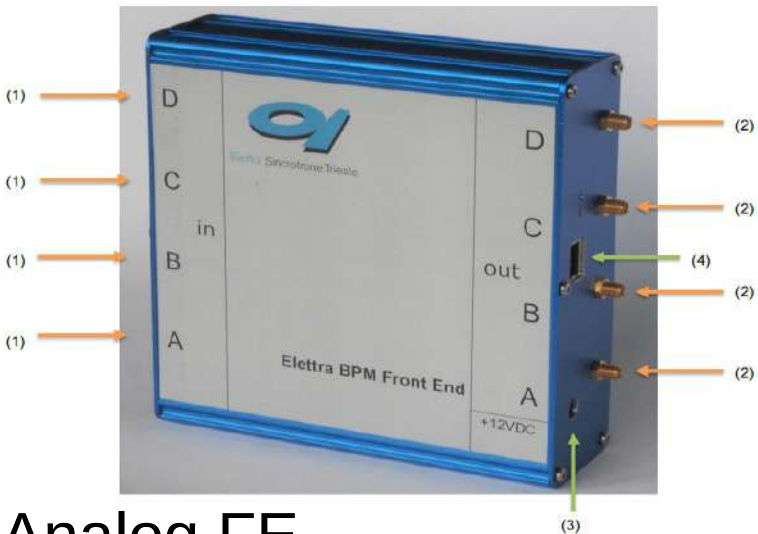
# Disadvantages

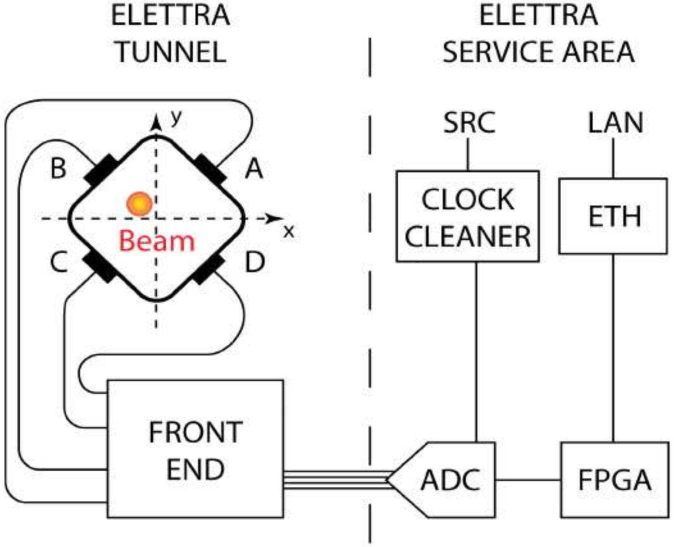
- Freq. Resp. Ha(f) has to be “flat” enough in the band of interest;
- The pilot tone amplitude must be known over the time (sync with ...);
- Pilot Tone generation requires extra RF HW (RF gen, combiners, …);
- It works only in frequency domain;
- Pilot Tone demodulation consumes FPGA resources (“2” x SDR);



# e²BPM: modular architecture - 1

- Modular approach: the building blocks can be separated and ...
  - The Analog FE is located in the machine tunnel (cables compensation)
  - The Digitizer is put in the service area




- Analog FE
  - Low noise figure
  - Ethernet controlled / PoE capable
  - Generation and injection of pilot tone
  - Variable gain

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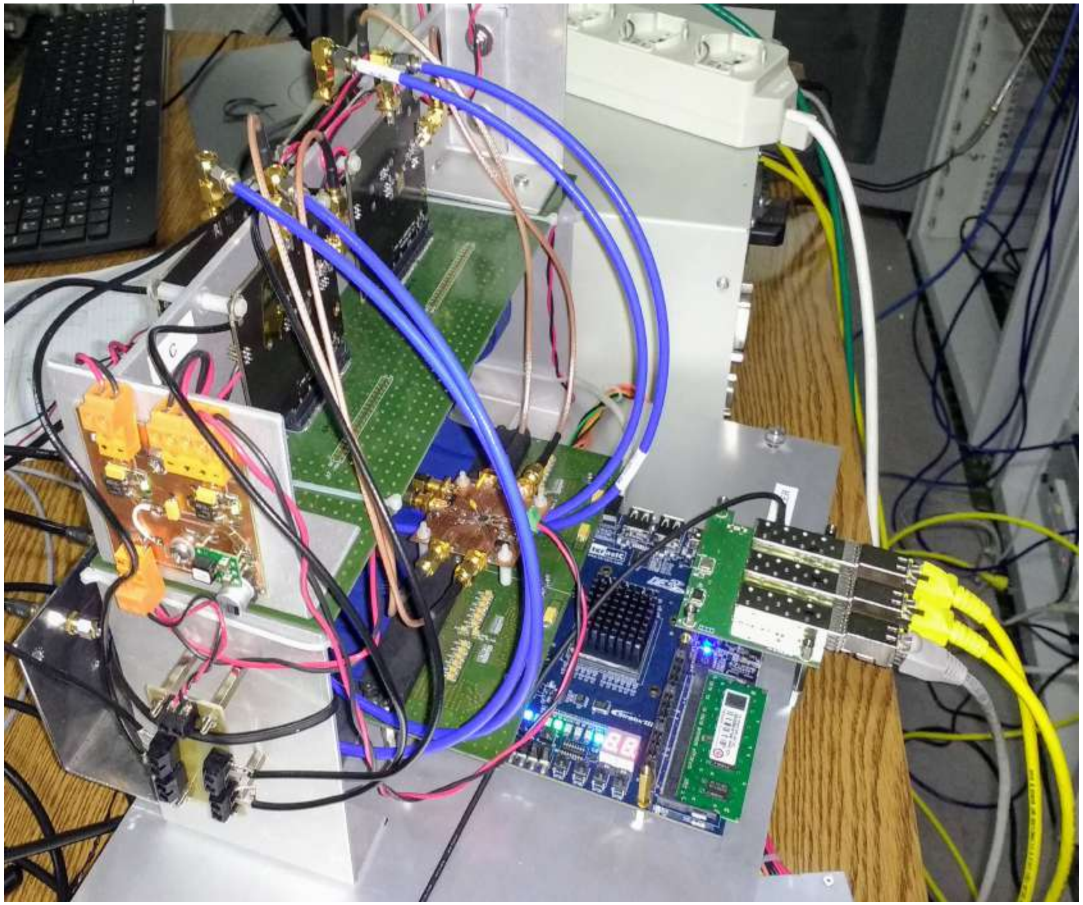
# e²BPM: modular architecture - 2



- Digitizer
  - High speed ADCs (160 MS/s, 16bit) working in undersampling
  - Double digital receiver in FPGA (Altera Stratix III)
  - Continuous and parallel demodulation of both carrier and pilot

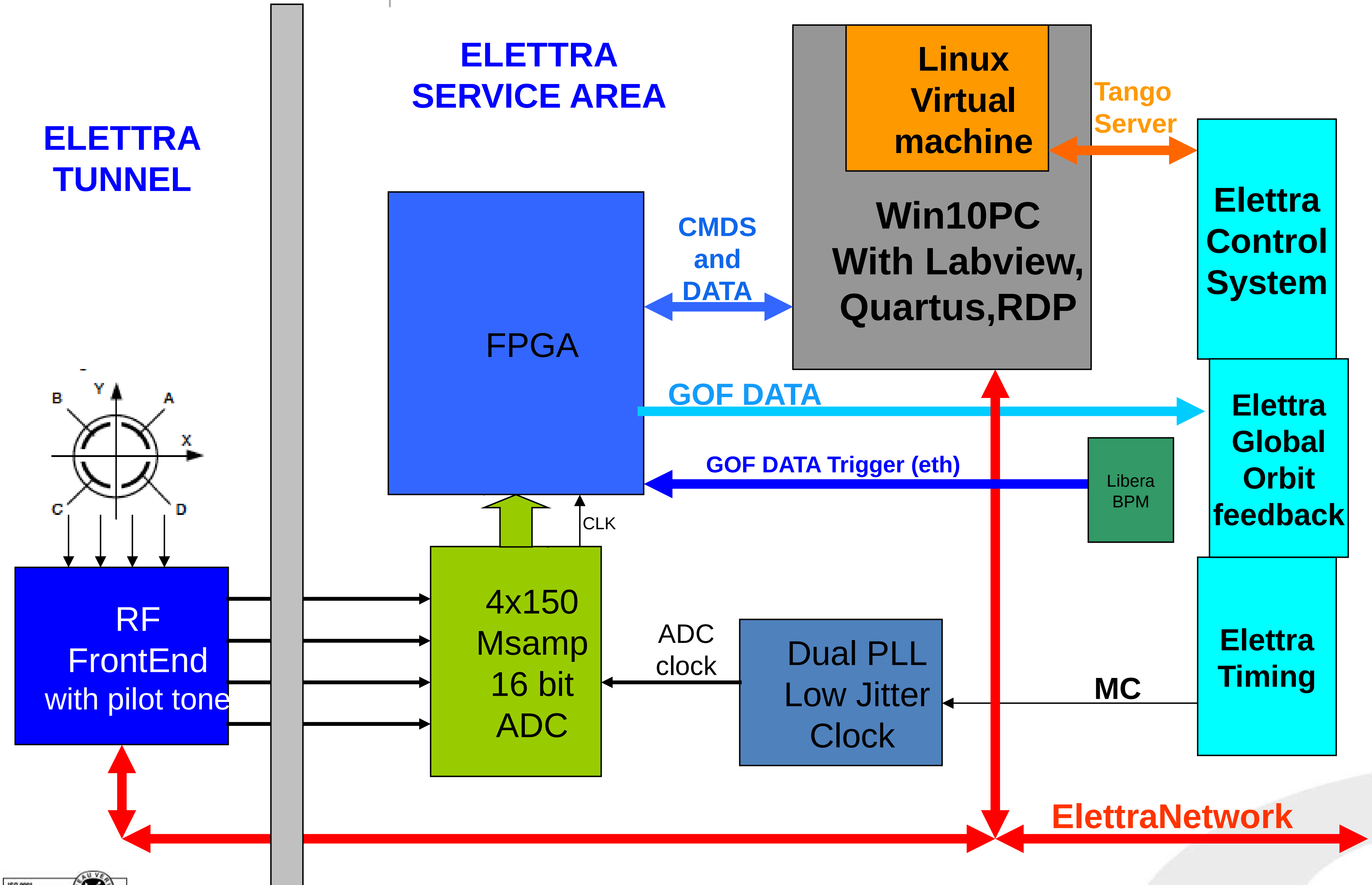
# **e²BPM**: integration in the Elettra CS - 1

- To fully validate its performance, an e²BPM prototype has been integrated in the Elettra Control System;
- A number of additional signals/interfaces are required;
- e²BPM IN signals:
  - Machine Clock, ≈1.154 MHz (MC = rev. freq. / 432);
  - Gb ethernet syncronization (trigger);
- e²BPM OUT (fast) data:
  - 1 Gb ethernet UDP packet, ≈10 kHz, GOF (global orbit feedback) dedicated;
- e²BPM IN/OUT (slow) data:
  - 100 Mb ethernet TCP/IP interface, used both for house-keeping tasks and Tango Device Server communication;

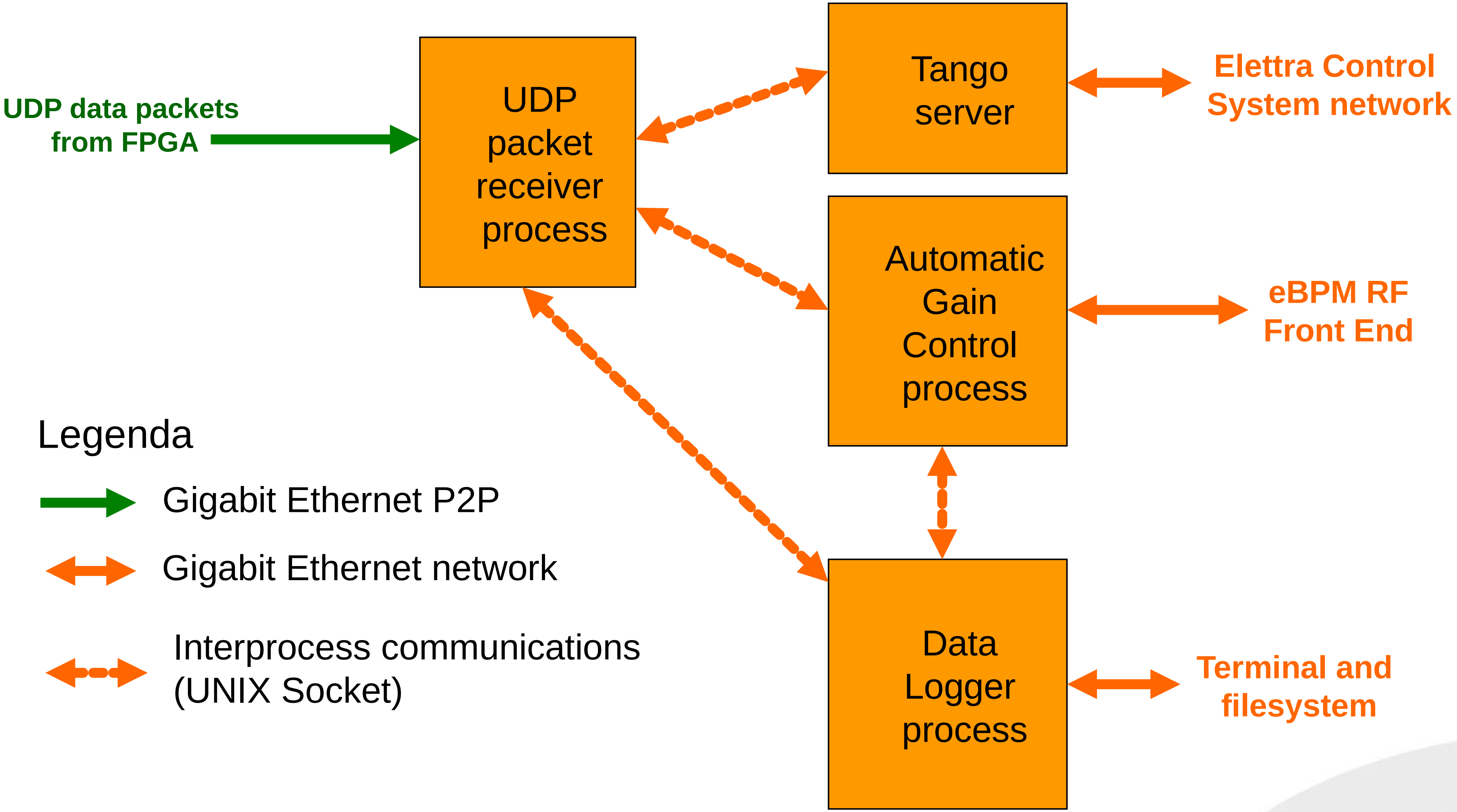
# e²BPM: integration in the Elettra CS - 2

- Timing constraints:
  - GOF acquires the whole set of UDP packets accordingly to the repetition rate of the Libera devices;
  - e²BPM adopts a slightly different rep. rate so a Libera is used to synchronize the e²BPM packet

# e²BPM: integration in the Elettra CS - 3

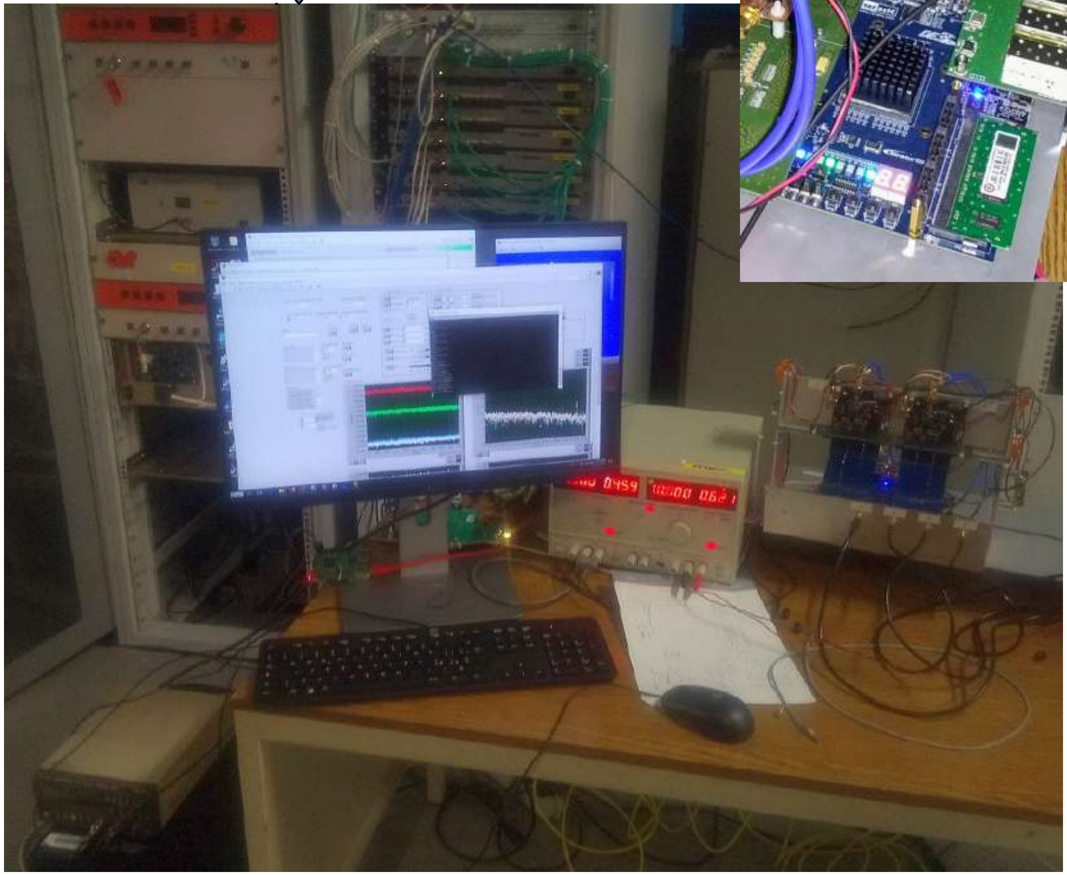


# e²BPM: integration in the Elettra CS - 4



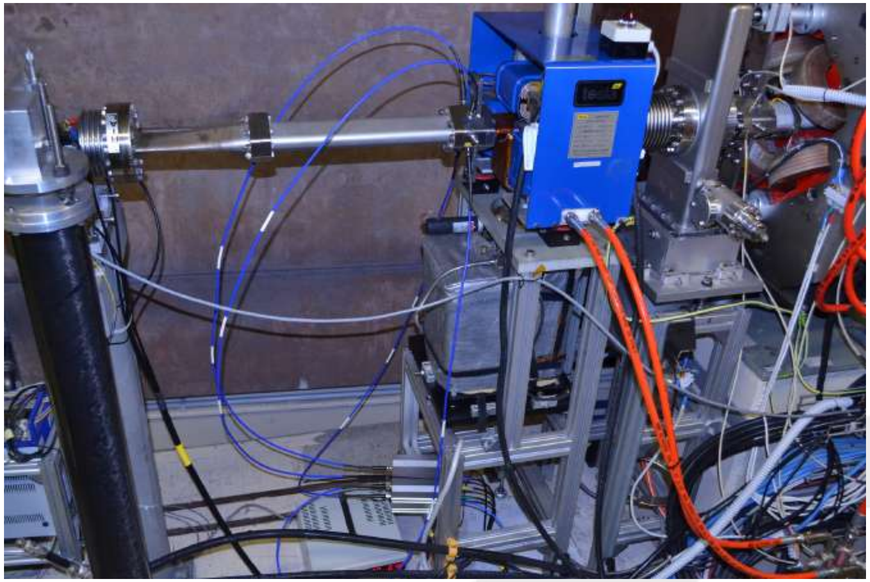
# e²BPM: integration in the Elettra CS - 5

Elettra Service Area



FPGA and Gigabit Ethernet detail

Elettra Tunnel



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# $e^2$BPM first results

- The $e^2$BPM worked fine in the real environment, both during Machine Physics and user dedicated shifts;
- FA (≈10 kHz) and SA (≈10 Hz) data were used;
- It operated in “frequency domain” only;

# next steps

- Analog front end:
  - Investigate frequency hopping technique to better estimate the channel response;
  - Synchronize the tone level to the gain of the amplifiers (improved AGC);

- e²BPM:
  - Add TbT data to the UDP packet;
  - Increase FA repetition rate;
  - Investigate the use of the pilot tone in First Turn operating mode;
  - Investigate self diagnostic capabilities;
  - Evaluate different compensation algorithms (incl. tone filtering);
  - Evaluate different compensation rates (fast/slow data paths);
  - More general, investigate if and how the pilot tone can be adopted in time domain and extended to BbB operating mode;

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# conclusion

- A prototype of BPM, based on pilot tone compensation, has been successfully developed and tested;
- Measured on field performance (20 mm chamber) were:
  - Resolution: < 200 nm @ 10 kHz;
  - 8 hrs stability: < 500 nm RMS

- To validate the quality of the analog FE, third parties have been involved (still ongoing ...):
  - Diamond Light Source, thanks to G. Rehm and his staff;
  - Instrumentation Technologies, thanks to P. Leban;

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# Thank you!


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