RF & longitudinal diagnostics system for ELENA

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Outline

1. **Overview**
2. HLRF
3. LLRF
4. Longitudinal diagnostics system
5. Conclusions
6. References
7. Additional slides

1. Overview

RF workpackage includes:

- High-Level RF (HLRF)
- Low-level RF (LLRF)
- Intensity and Schotty longitudinal diagnostics [1]
  - High sensitivity magnetic Longitudinal Pick-ups (LPUs) + electronics
  - Digital DAQ and signal processing

Topics of this talk

Collaboration with BI on longitudinal diagnostics from distributed electrostatic system [2] (see G. Tranquille's talk).

- BI in charge of the system
- Same DAQ & processing h/w as LLRF
- Same digital signal processing as for magnetic LPU case (after signals rotation & sum)

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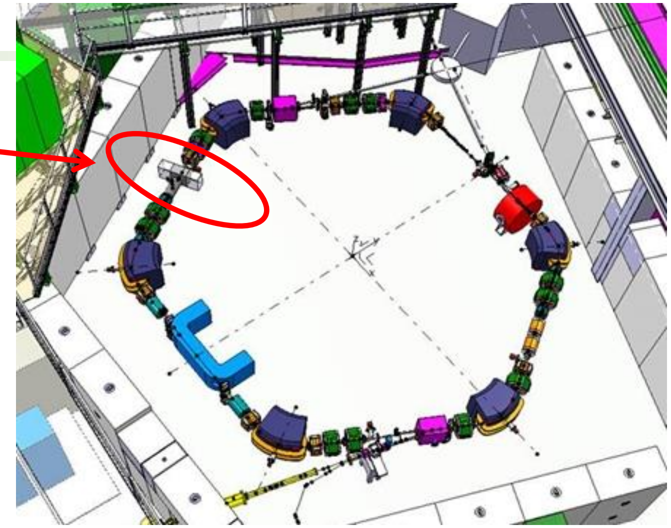
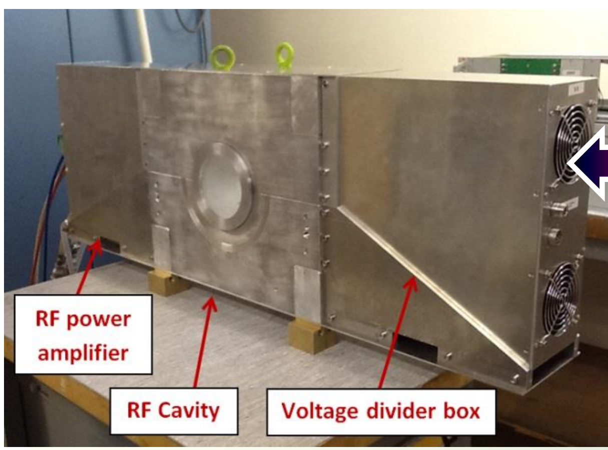
2. High-Level RF

- Located in ELENA's section 5.
- Finemet-based, broadband, untuned cavity.
- Operating freq. range: 144 kHz → > 2 MHz
- Voltage:
  - 100 V , f< 500 kHz
  - 500 V , f≥ 500 kHz

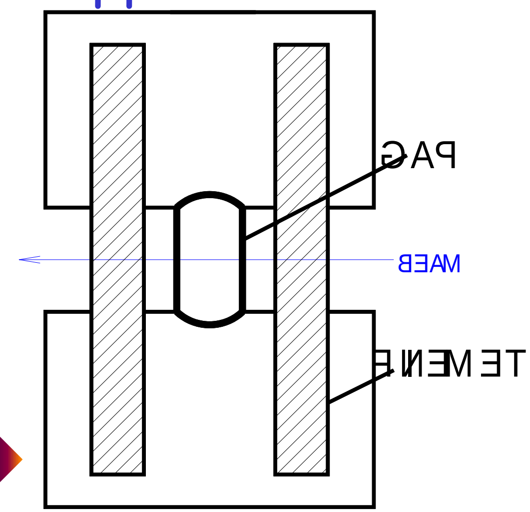


- Voltage amplitude/phase loop by LLRF.
- Gap-relay shortcircuits cavity when no voltage is applied.



Cavity, amplifier & box assembly (JPARC system)

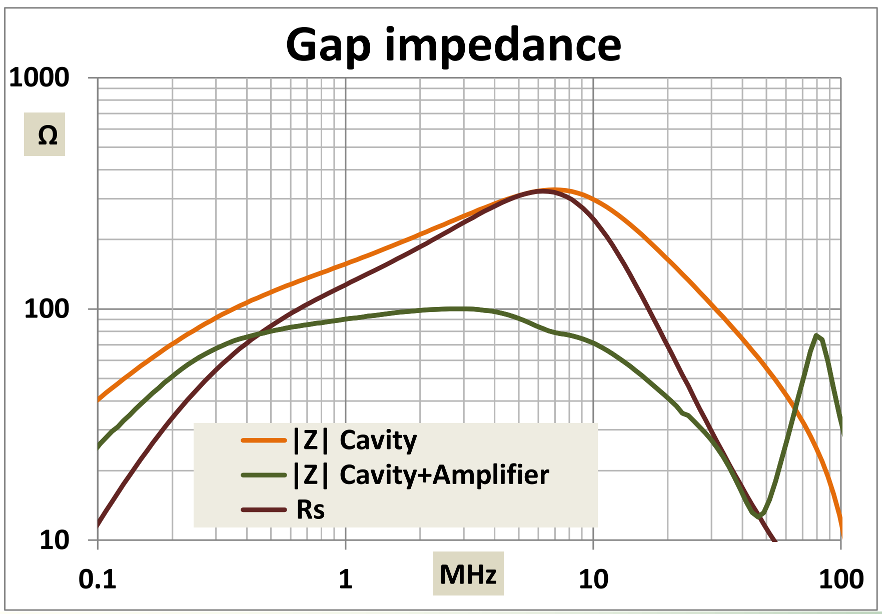
Cavity structure

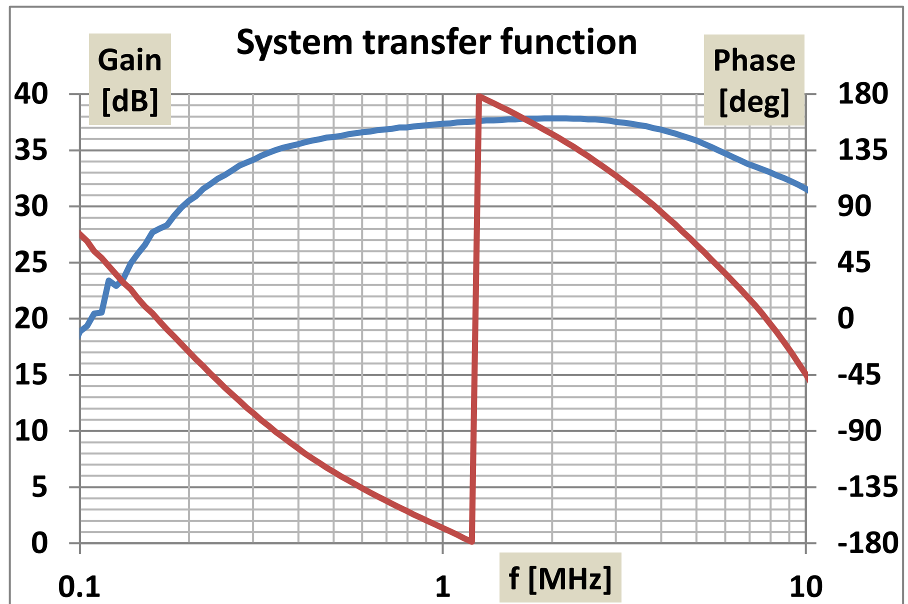


2. High-Level RF (cont'd)

- Sample Finemet ring tested [3] by TE/MSC to **evaluate magnetic perturbations on beam** (residual field + interactions with external fields). ***OK!***
- **Noise** (cavity, driving chain) might heat beam. Under evaluation: beam diffusion rate as a function of Δp/p & cavity noise.

  NB: feedback @additional harmonics will allow to lower gap impedance seen by the beam, if needed.





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3. LLRF: required capabilities

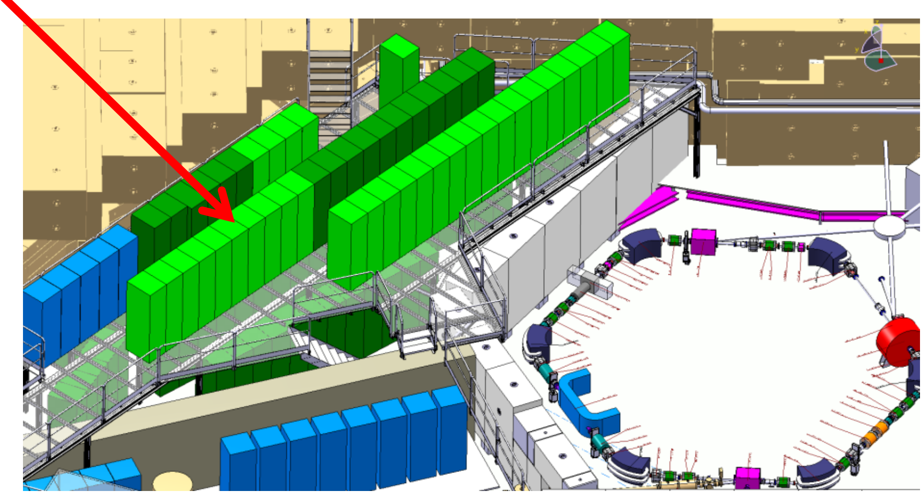
- **Frequency program**
  - Compatible with new Btrain distribution
- **Beam phase loop**
  - Input from high sensitivity magnetic longitudinal PU
- **Radial loop**
  - Input from one electrostatic TPU
- **Injection/extraction synchronisation loops.**
- **Cavity amplitude/phase loop + real-time control of gap-relay**
  - [I,Q] coordinates.
  - > 72 dB dynamic range available
  - Includes double-harmonic control. More harmonics easily controllable (modular system).

3. LLRF: hardware

- ***State-of-the-art*** digital h/w + signal processing
- LLRF h/w + s/w family for Meyrin machines (consolidation) **[4]**, ***not*** ELENA-specific development.

  To be deployed: in MedAustron + PSB LLRF (**2014**), LEIR LLRF (**2015**), ELENA LLRF+diag. (**2016**), AD LLRF+diag. (**>=2017**) …

- Location: RF01+RF02 in ELENA hall to minimize cable length from ring equipments (LPU).

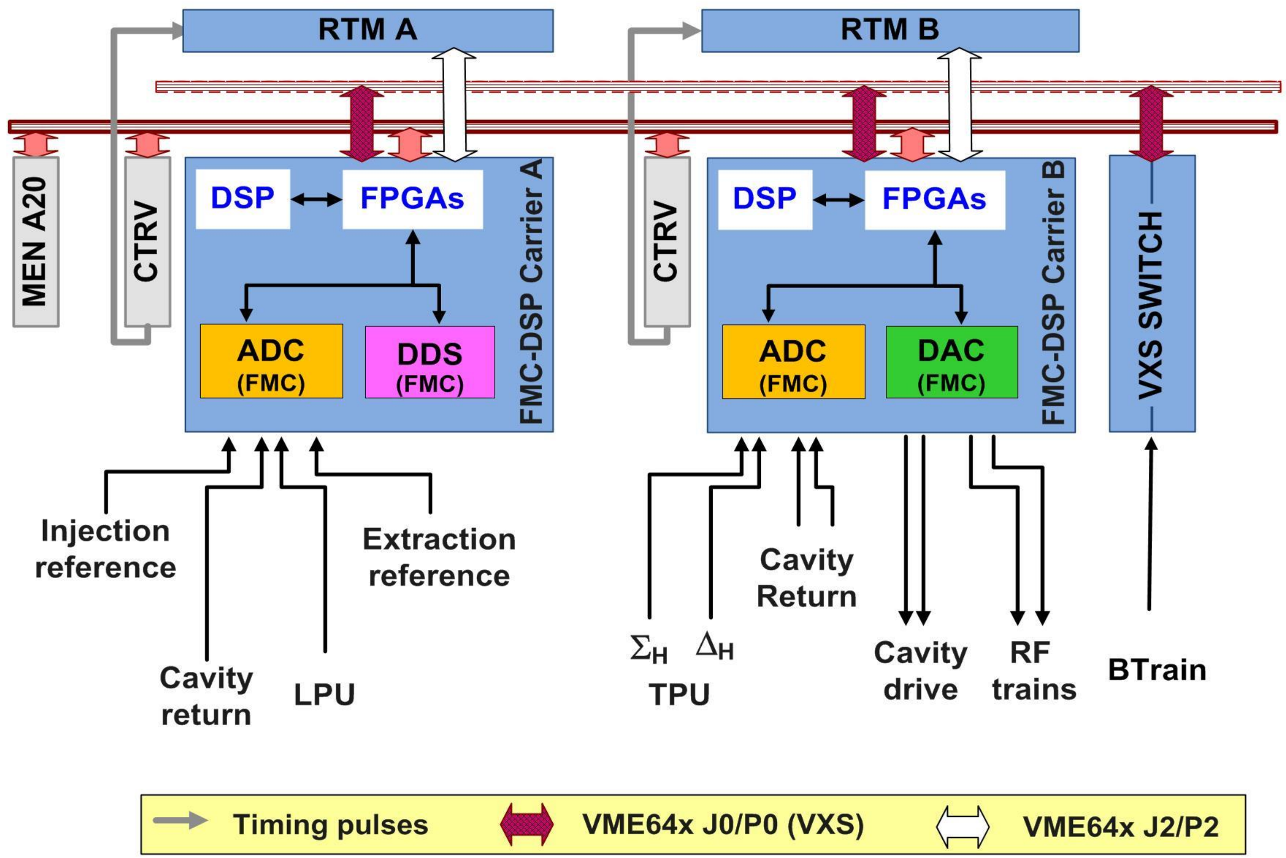


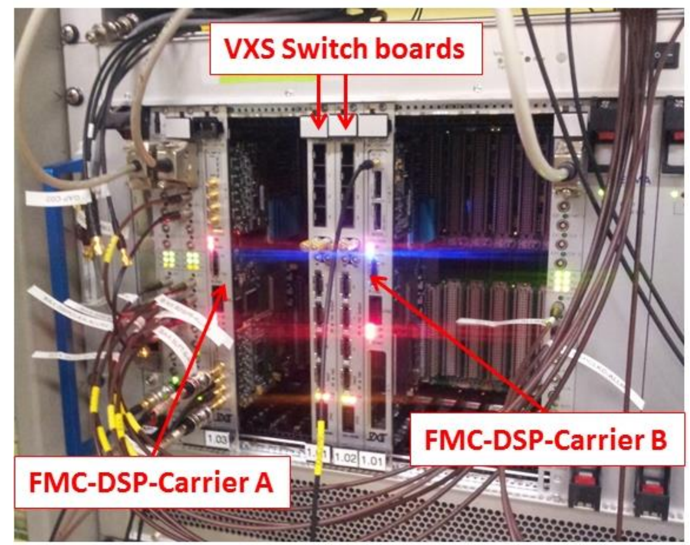
- RF clock + turn (TAG) marker, cavity voltage + f_{REV} available also over optical fiber (to beam orbit/distributed electrostatic PU system).

3. LLRF: layout

Frequency program
Phase loop
Injection synchro
Extraction synchro

Cavity servoloop & gap control
Radial loop
RF trains generation





2-boards test system installed in PSB (2013 run).

Outline

1. Overview
2. HLRF
3. LLRF
4. **Longitudinal diagnostics system**
   - High-sensitivity longitudinal PU & electronics
   - Digital signal processing system
   - Calibration
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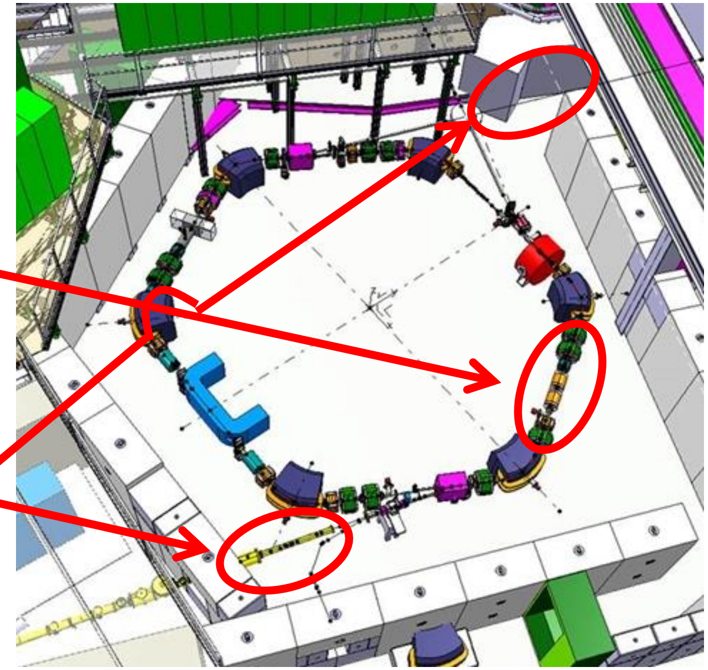
4. Longitudinal diagnostics: LPU overview

High sensitivity PUs + electronics

- **Output**: analogue signal.
- **Ring**: high-frequency (HF) + low-frequency (LF) in section 2.

  Combined BW = [0.003 – 30 MHz].
- **Extraction lines**: 2 LF as single-pass beam transformers (only intensity meas needed).



- **Users**:
  - **LLRF**: beam phase + synchronisation loops.
  - **Longitudinal diagnostics processing** (see next slides)
  - **Tomoscope [5]**: bunch length, emittance
  - **Oasis**: analogue signal acquisition
  - **TRIC system [6]** (BI): single-pass intensity meas in extraction lines

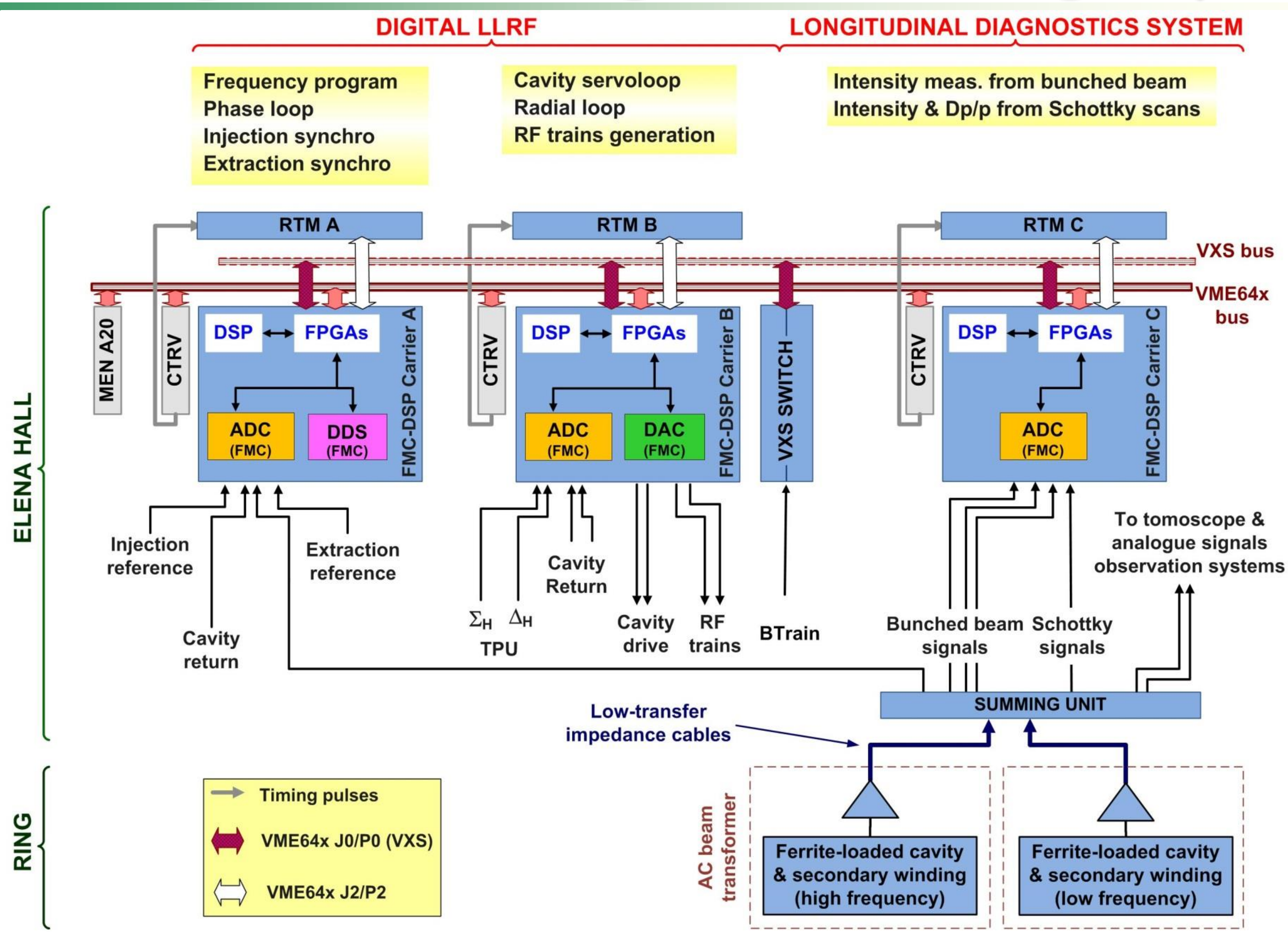
(LLRF, Longitudinal diagnostics processing, Tomoscope: **ring**)

4. Longitudinal diagnostics: processing overview

Longitudinal diagnostics processing system

- **Output**: longitudinal beam parameters for ring signals
- **Bunched beam**: intensity
- **Debunched beam:**
  - intensity (from Schottky scans)
  - $\Delta p/p$ (main ecooling diagnostics)
  - $\langle p \rangle$
  - Averaged beam spectra
- Hosted in **same crate as LLRF**.
  - Same h/w & most s/w as LLRF system
  - Interfaced to it as piggy-back (no influence on LLRF operation)
  - receives RF clock, turn marker (TAG), actual V_{cavity} & f_{REV} from LLRF .

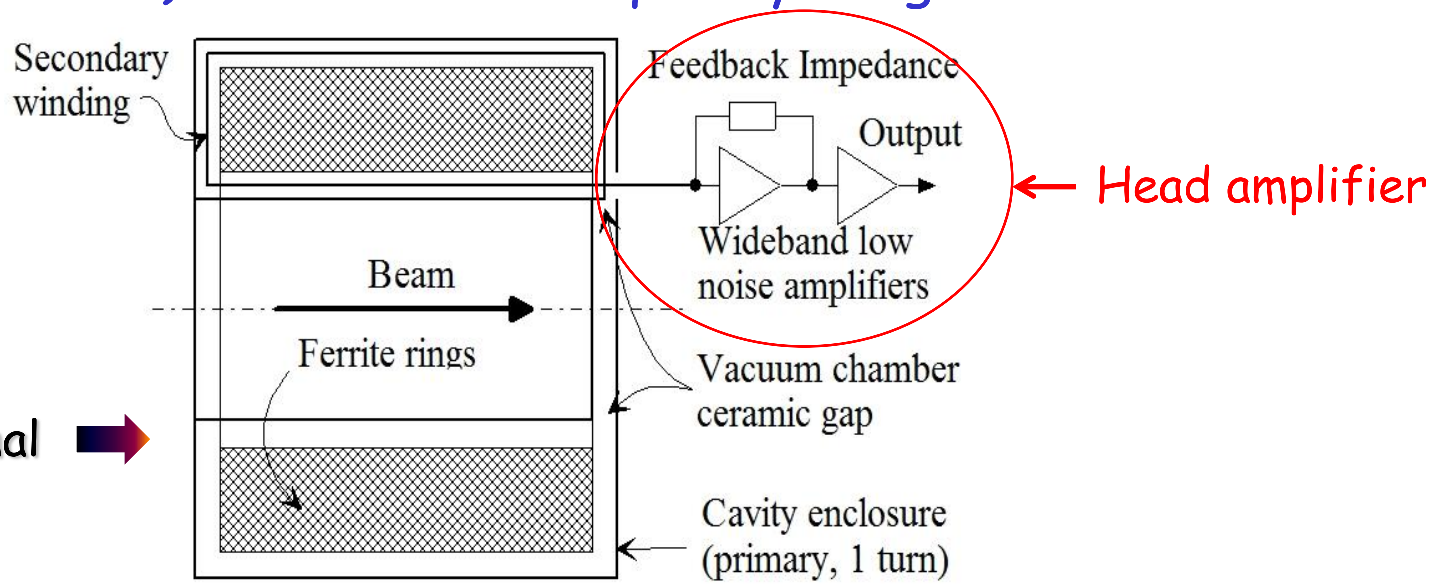
4. Longitudinal diagnostics: ring layout



4. High sensitivity PU: low noise feedback principle [7]

- Make pick-up resonant with high Q to reduce the thermal noise current of the transducer itself.
- Use low noise high impedance amplifier (Si JFET's) and regain broad band properties by strong active feedback without deteriorating the signal to noise ratio .
- The transimpedance amplifier obtained has a very low 'noise temperature' (< 0.5 K) in a certain frequency range.

Schematic view of the high-sensitivity longitudinal beam transformer .



4. High sensitivity PU: design

- **Modification of AD design [7]** due to:
  - Shorter length allocated (1 m in ring, 50 cm in extraction lines)
  - Smaller vacuum pipe diameter
  - Bakeability (200°).
- Ferrite rings: :

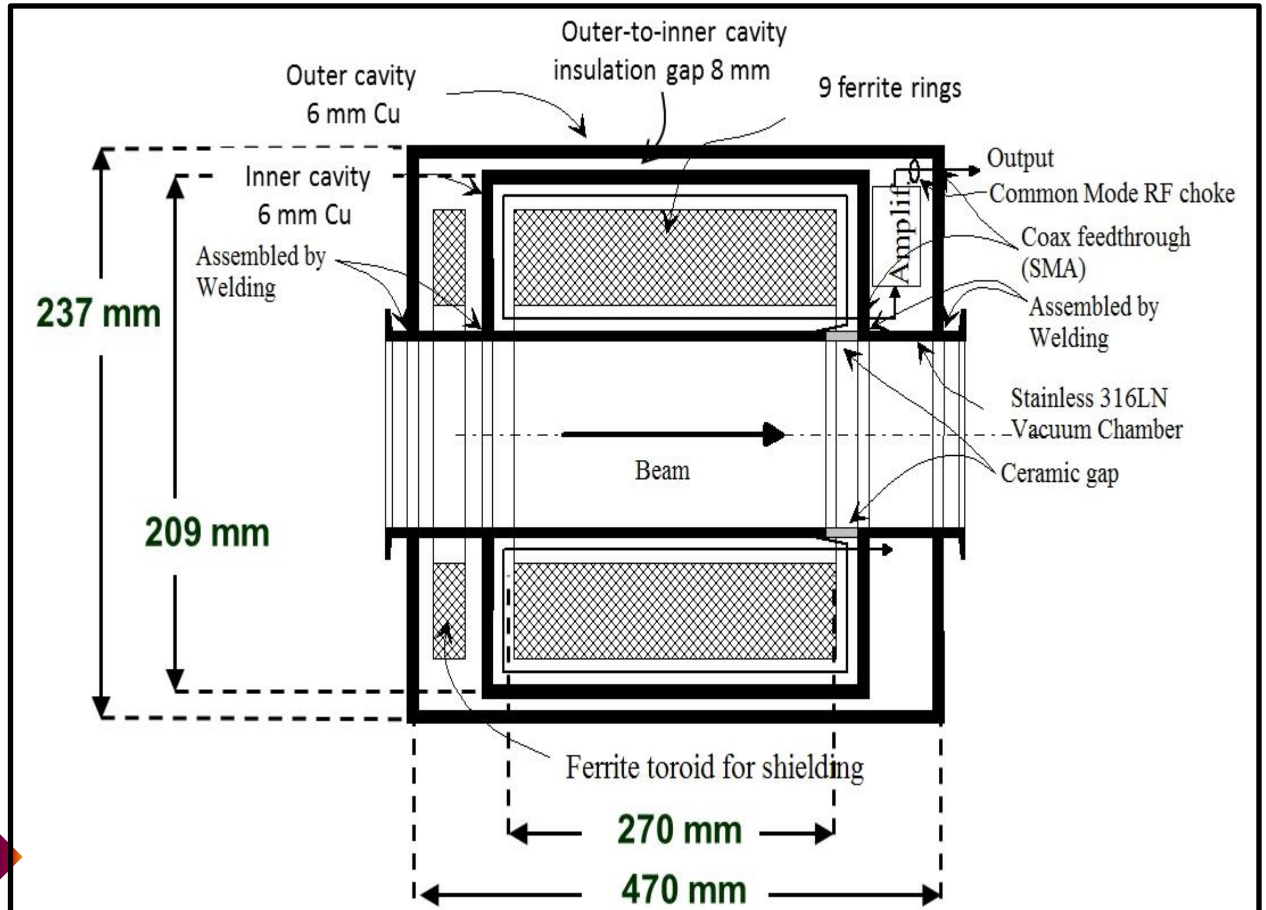
  OD = 185 mm

  ID = 110 mm

  LENGTH: 30 mm

	μ	step-up ratio
LF	1200	4:1
HF	250	1:1

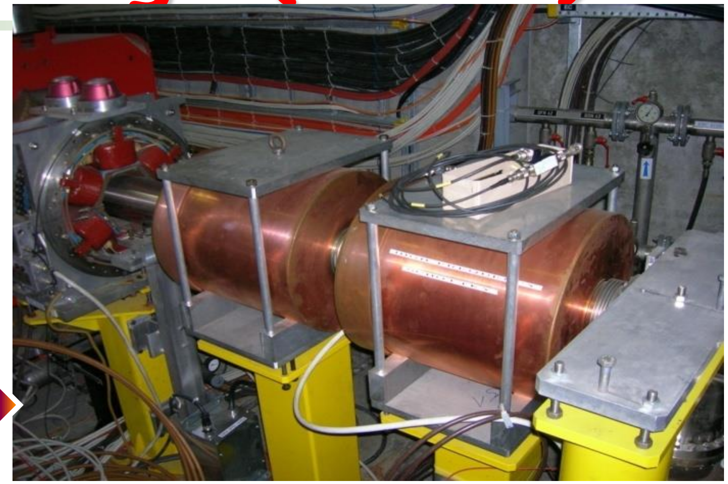
Double-shielded copper cavity with dimensions



4. High sensitivity PU: design (cont'd)

- LF & HF back-to-back in ring to reduce gap distance.

HF + LF LPUs in AD ring



- Thermocouples + holes for He injection (vacuum leaks detection)
- NEG coating applied where possible
- Prior to welding, bakeability tests with be done in collaboration with TE/VSC.
- "Pot" for measurements to be constructed.

AD "pot" for testing

- NB: **Fringe fields from nearby magnetic elements might affect ferrite permeability**. Study ongoing to evaluate effects.

4. High sensitivity PU: head amplifier

Modified version of the AD LF & HF designs.

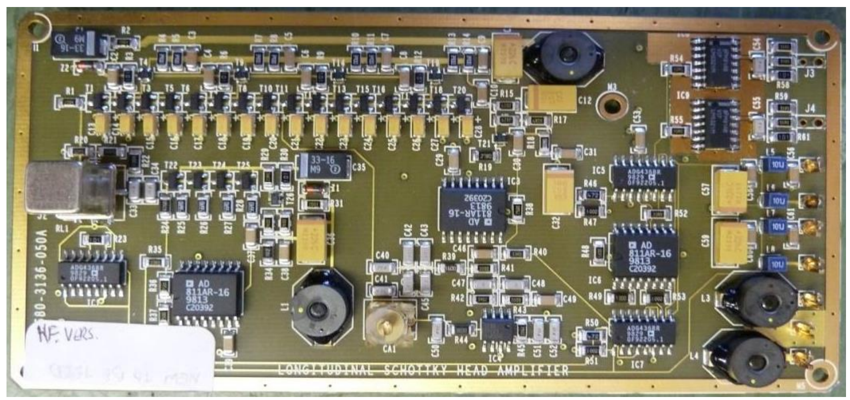
- Transistor BF862 replaces BF861C (lower voltage noise).
- HF: transfer function to adapt to different step-up ratio
- LF: low frequency cutoff lowered to 3 kHz to shift baseline droop outside ~6 μs observation window for extracted bunches.

NB: current assumption is all bunches extracted in one turn!!

- Two gain settings (instead of 4 as in AD), fast & remotely controllable. Might take the place of AD second stage ampli.

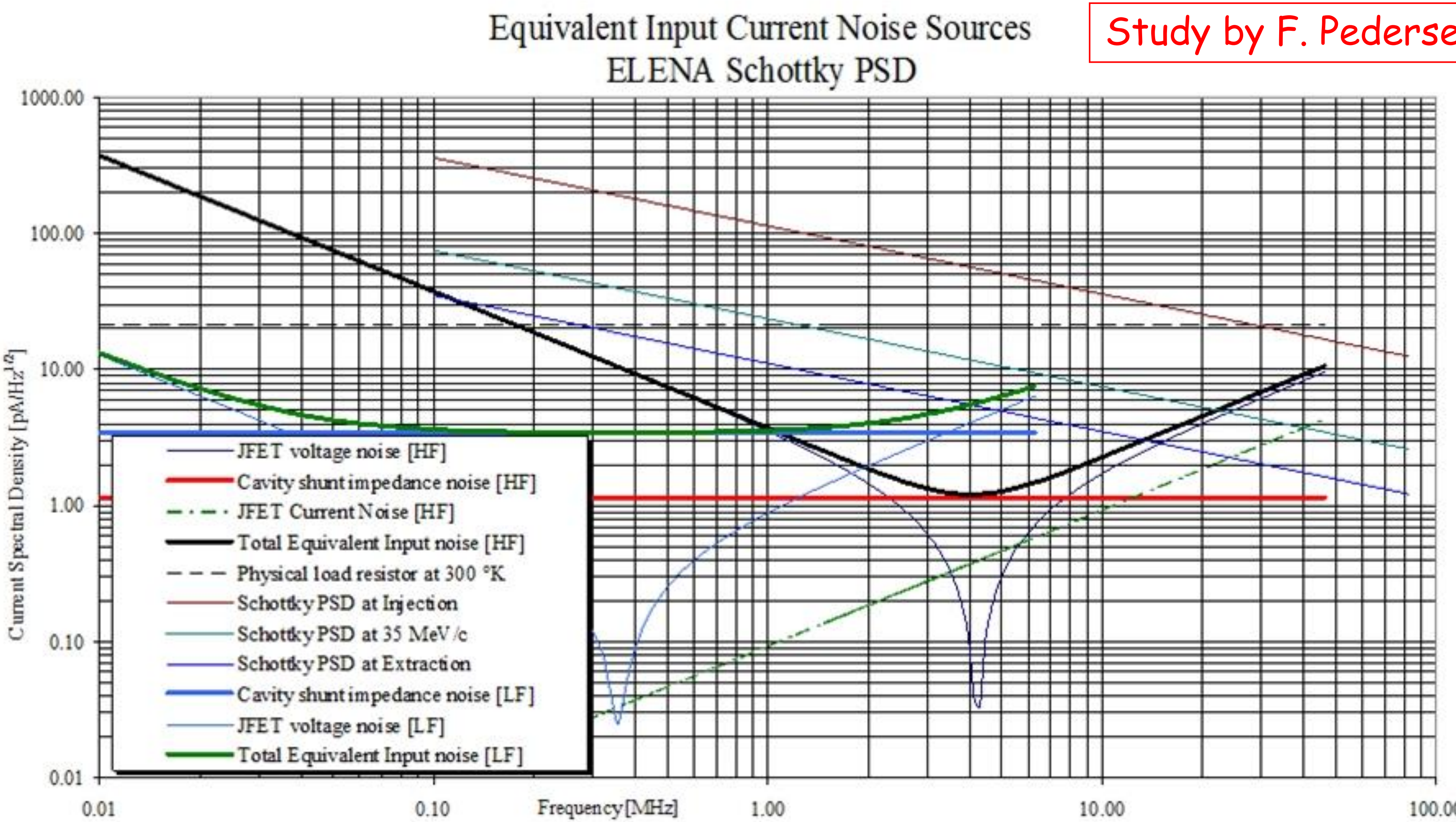
- Head amplifier will be removed during bake-out (no dedicated cooling).

LF head amplifier used in the AD.



4. High sensitivity PU: expected noise

Study by F. Pedersem



Expected noise performance of ELENA low noise beam transformers. Comparison with typical Schottky power spectral densities vs. frequency for $N = 10^7$ antiprotons.

4. High sensitivity PU: transmission & other units

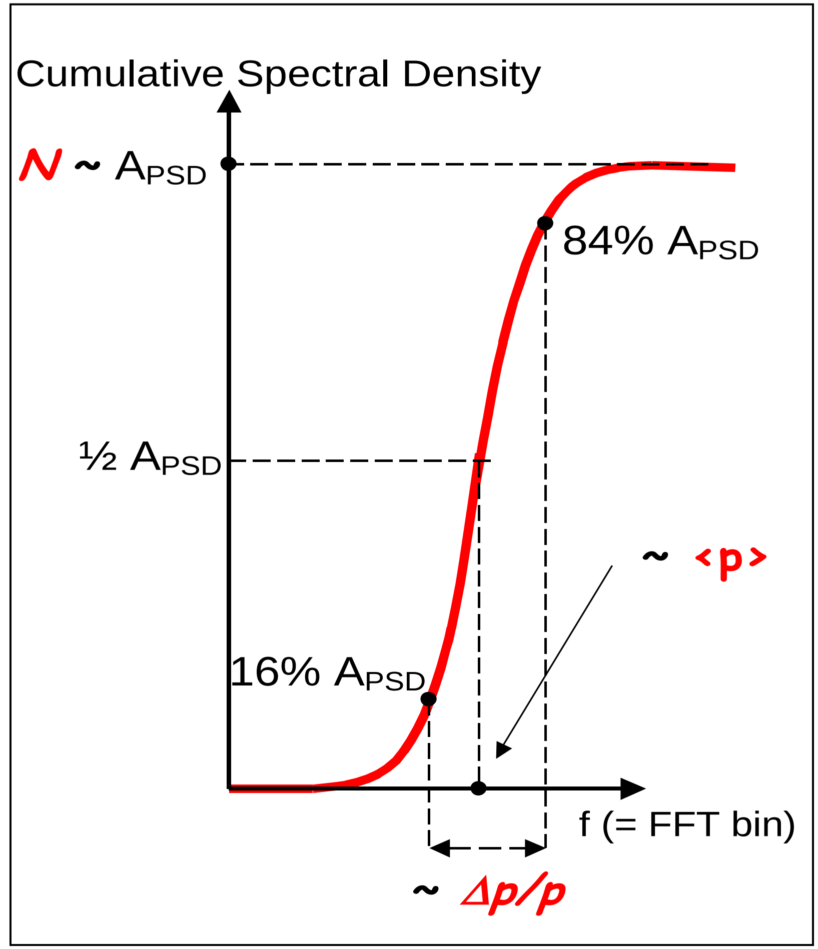
- **Analogue signal transmission** with low-transfer-impedance cables
  - Successfully used in the AD since ~2001
  - Solution adopted for beam orbit/distributed electrostatic PU system
  - Other solutions technically possible, but no manpower to evaluate them
  - Processing h/w as near as possible to ELENA ring

- **Summing unit**
  - Implements cable-loss compensation (as in the AD)
  - Flight-time compensation needed because of lower β in ELENA
  - LF and HF outputs available as well
  - LLRF might be connected to LF LPU only if need be (to avoid phase discontinuity @ signal overlap).

- **Second stage amplifier**: need for it is under evaluation.

4. Processing system: debunched beam [8,9]

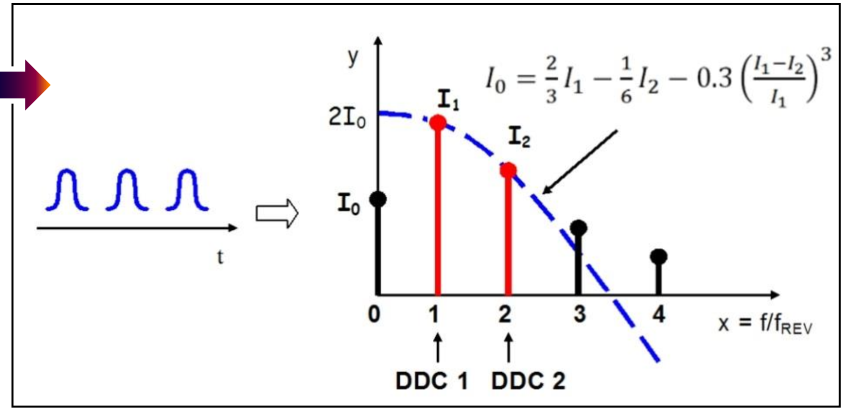
- Spectral analysis of Schottky signals to obtain longitudinal beam parameters.
- Intrinsically noisy: noise statistical properties (incoherent signal) observed.
- In AD: sensitive to instabilities, filamentation/ external noise…→Schottky power "explodes".
- Noise offset calibration needed
- S/N improved by FFT averaging.
- AD typical meas. rep. period: ~ 1 s.
- Observation BW changed during cooling.



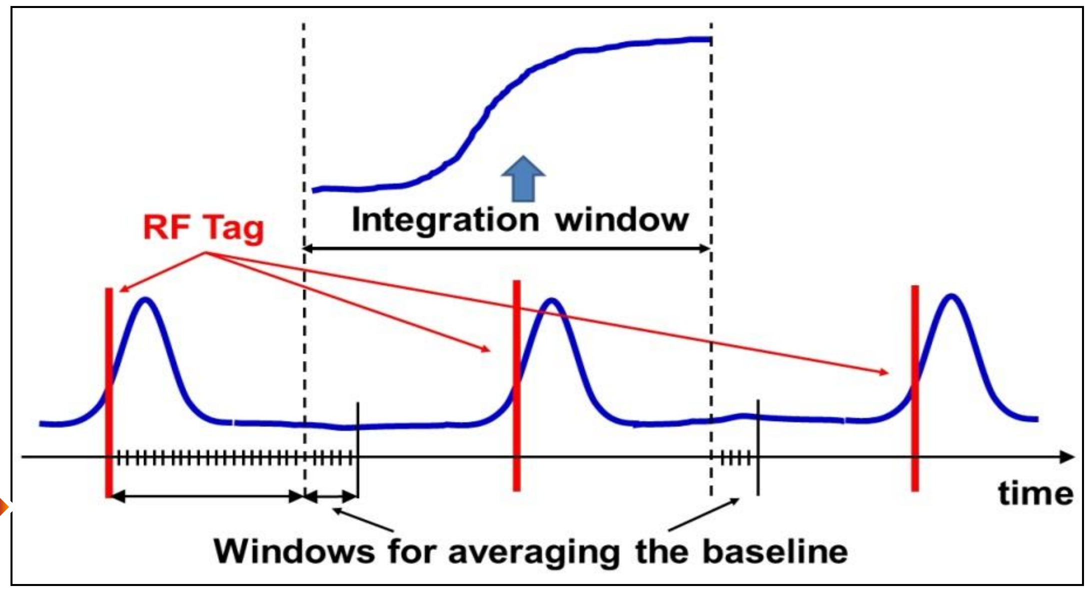
Longitudinal Schottky integrated power.

4. Processing system: bunched beam [8,9]

- DAQ clocked at $h \cdot f_{REV}$.
- AD method: Fourier analysis of RF harmonics assuming a certain bunch shape.
- Drawback: dependency on bunch shape.
- New h/w + firmware allows integrating over bunch shape and subtracting the baseline.



Longitudinal bunched processing: RF harmonics Fourier analysis.



New bunched-beam digital signal processing.

4. Longitudinal diagnostics calibration

Bunched beam intensity vs. debunched Schottky meas.

- Same magnetic LPU and control chain
- Debunched intensity = f(GAIN^2), bunched = f(GAIN).

Bunched beam intensity @extraction vs. LF LPU in transfer line

- Extraction LPUs can be calibrated in absolute way via C discharge.
- Bunched measurement before extraction compared to measurement in extraction line (single-pass beam transformer)
- Assumptions: 100% extraction efficiency.

4. Conclusions

- **RF workpackage well advanced for ELENA project.**
  - ***MANY*** discussions since September 2011 (machine parameters, extraction schemes, how to obtain longitudinal debunched signals…)
  - Now **main decisions taken**.
  - LPU drawings and material order soon to start.
  - Remaining studies to be completed within next few months.

- **ELENA project will profit from:**
  - **RF injectors consolidation** (HLRF + LLRF h/w & s/w).
  - **AD experience** (high sensitivity longitudinal PU & processing).

- RF group committed **to deliver in time**, even with the many other engagements/projects under way.

5. References

[1] M.E. Angoletta et al., "An Ultra-Low-Noise AC Beam Transformer and Digital Signal Processing System for CERN's ELENA Ring", IBIC 2013, Oxford, September 2013, TUPF27.

[2] M.E. Angoletta et al., "Longitudinal Beam Diagnostics from a Distributed Electrostatic Pick-Up in CERN's ELENA Ring", IBIC 2013, Oxford, September 2013, WEPF28.

[3] M. Buzio, V. Della Selva, "DC field perturbations due to a Finemet ring", note to be published.

[4] M. E. Angoletta et al., "A Leading-Edge Hardware Family for Diagnostics Applications and Low-Level RF in CERN's ELENA Ring", IBIC 2013, Oxford, September 2013, TUPF28.

[5] http://tomograp.web.cern.ch/tomograp

[6] A. Monera et al., "Upgrade of the CERN PSB/CPS Fast Intensity Measurements", DIPAC'11, Hamburg, May 2011, MOPD66, p. 185 (2011).

[7] C. Gonzalez, F. Pedersen, "An Ultra Low Noise AC Beam Transformer for Deceleration and Diagnostics of Low Intensity Beams", PAC'99, New York, March 1999, THAR6, p 474 (2004).

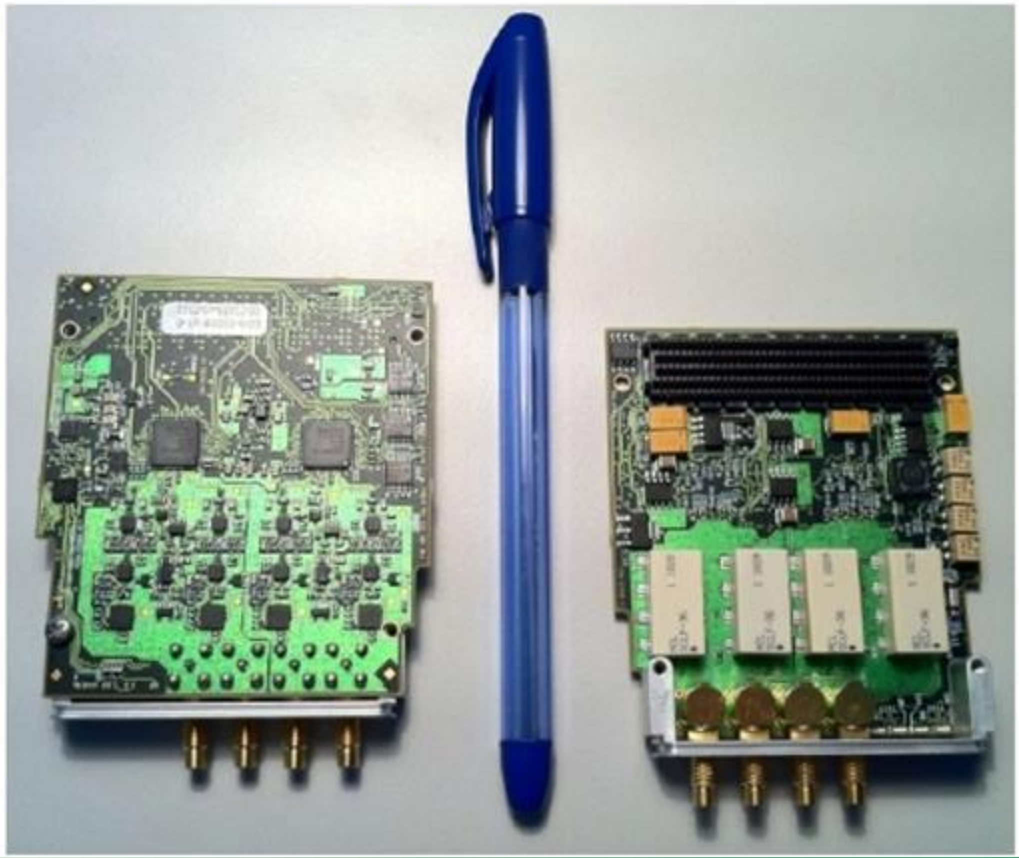
[8] M.E. Angoletta et al., "The New Digital-Receiver-Based System for Antiproton Beam Diagnostics," PAC'02, Chicago, June 2001, WPAH122, p. 2371 (2001).

[9] M.E. Angoletta et al., "Upgrades to the Digital Receiver-Based Low-Intensity Beam Diagnostics for CERN AD", PAC'03, Knoxville, May 2003, WPPB023, p. 2461 (2003).

Additional slides

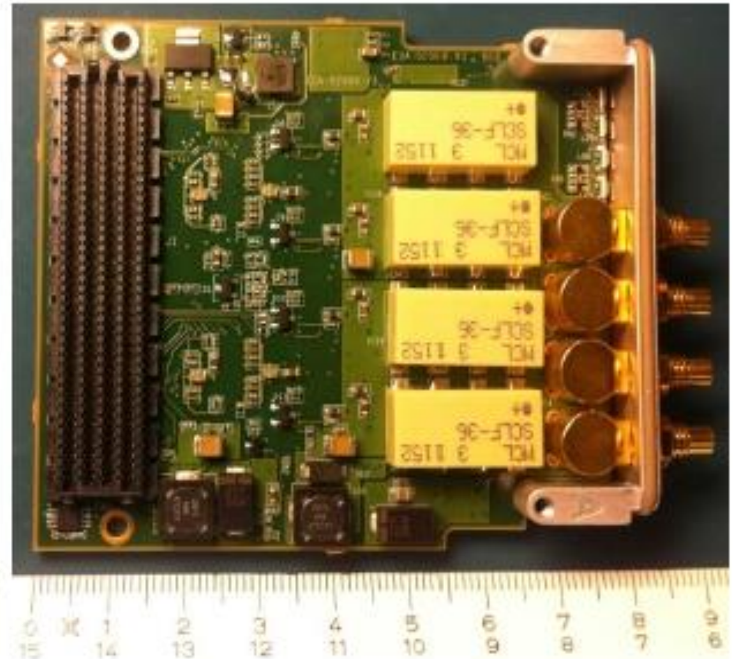
LLRF Hardware: FMC modules

- High Pin Count FMCs Developed
  - ADC 16 bit 125 MS/s (DDC)
  - DAC 16 bit 250 MS/s (SDDS)
  - DDS (can be used as Master Direct Digital Synthesis)



Notes:
DDC = Digital Down Converter
SDDS = Slave Digital Direct Synthesizer

LLRF Hardware: ADC FMC module



Characteristics:

- General purpose 4 channel, 125MS/s acquisition module with 16bits architecture.
- Provides signal conditioning with an analogue front-end featuring DC coupling, low noise, low distortion and gain switching (equivalent to 3 LSBs).
- DC to 40MHz (oversampled) bandwidth. Can be extended by a factor of 10.
- SNR > 77dB (12.5 ENOB), SFDR > 70dB

LLRF Hardware: DAC FMC module

Characteristics

- 2 x 16bit Dual DACs (AD9747), Fs <= 250MS/s -> 4 identical CHs
- DC coupled output, 40MHz analog bandwidth, peak output voltage 3.6 Vp-p
- 400-pin FMC connector for parallel data interfacing
- Low noise and low distortion amplifiers
- Compact front-panel for heat dissipation and 3-color status indication LEDs
- Unique PCB identification by silicon ID chip and a system monitor chip
- IPMI EEPROM with HW specific information (FMC type, Version number, operating voltage etc.)
- Programmable 18 dB analog gain switch < 30 ns for dynamic range shift
- Measured wideband SFDR > 60 dB

LLRF Hardware: DDS FMC module

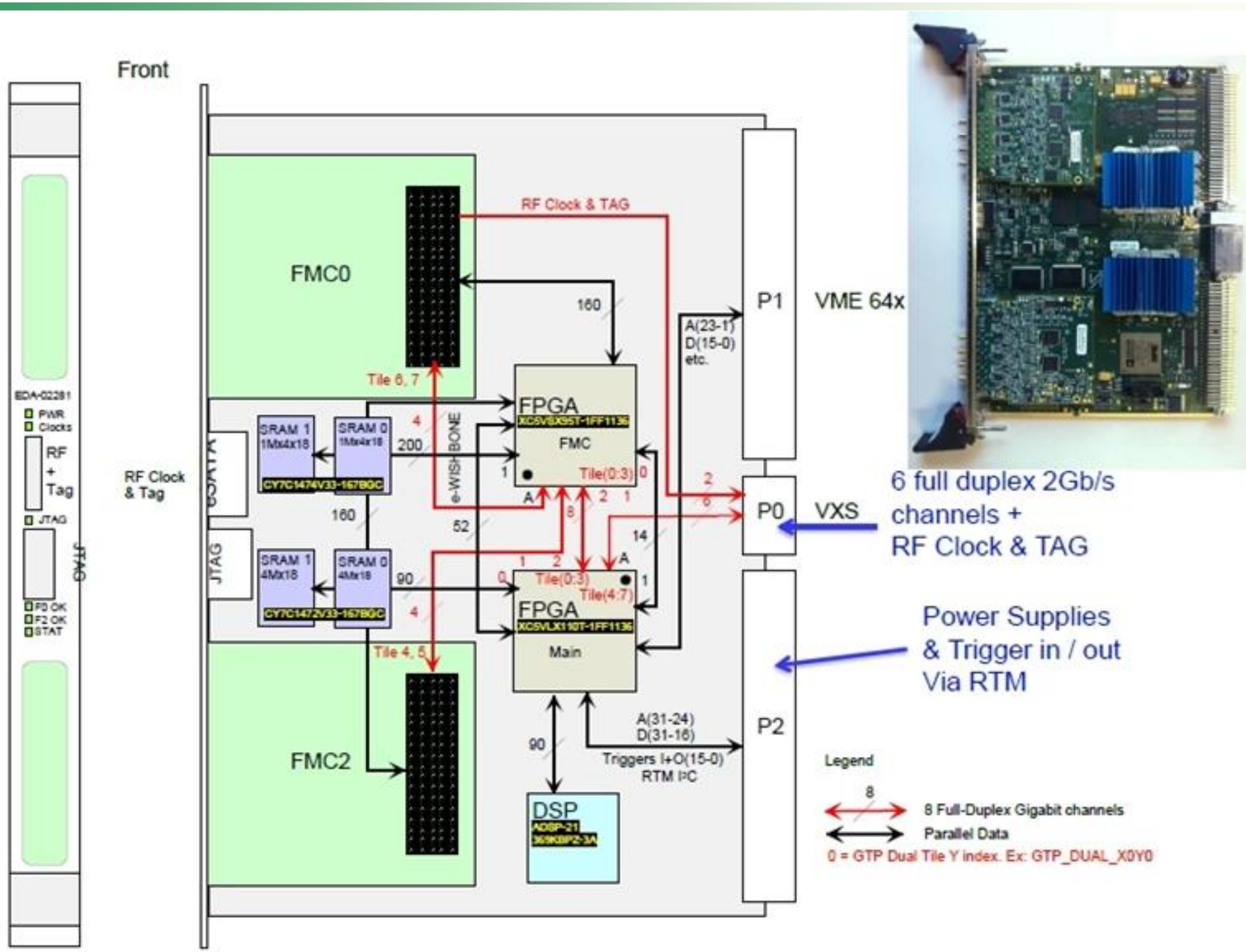
Characteristics:

- High quality compact clock and synchronism generator.
- Integrated random time jitter: 674 fs RMS
- Can generate a clock signal from 62.5 MHz to 125 MHz, and the associated revolution synchronism signal at any FRev sub-harmonic from 1 to 16535.
- It features **two** independent channels, synchronized to the same reference, with synchronization pulse (tag) generators.
- 32bit DDS core: 232 mHz frequency step resolution.
- Compatible with LPC and HPC FMC standard.

LLRF Hardware: Carrier board

- A VME64x board with VXS
  - VXS bank A banks fully equipped with 4 full-duplex channels, bank B with 2
  - Raw link-speed either 2 Gb/s.
- Two High-pin count FMC sites
  - Sites have independently programmable Vadj
  - 4 FPGA IO banks (~20 diff pairs/bank) per FMC site.
    3 FPGA IO banks for FMC Bank A, 1 FPGA IO bank for FMC Bank B.
  - 4 full-duplex Serial Giga-bit links to FMC_FPGA per FMC site.
- Two Virtex5 FPGAs: XCVSX95T-1FF1136 & XC5VLX110T-1FF1136
  - FMC_FPGA hosts the FMC DSP intensive code, interfaces with both FMCs, communicates to the Main_FPGA via 8 Serial Giga-bit links and a parallel bus.
  - Main_FPGA manages the communication with: VXS, FMC_FPGA, VME64x, DSP.
- A Sharc DSP 400MHz: ADSP-21369
  - A16 / D32 interface with Main_FPGA.
  - Alternate Serial ports connected to Main_FPGA.
- Memory Banks
  - Two 4 M x 18 @ 100 MSPS (CY7C1472V33)
  - Two 1 M x 4 x 18 @ F-RF MSPS (CY7C1474V33)
- RF Clock and Tag distribution.

LLRF Hardware: Carrier board (cont'd)



Expected performance from one electrostatic PU

Study by F. Pedersem