Real-Time Distribution of Magnetic Field Measurements Over White-Rabbit

9th White Rabbit Workshop, Amsterdam, March, 2016

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March 2016
1 Introduction
- CERN Accelerators
- Magnets in Accelerators
- Real-Time Magnetic Field Measurements
- B-Train

2 The New PS B-Train
- B-Train upgrade
- B-Train Firmware Architecture
  - Hardware
  - Software

3 PS B-Train over White-Rabbit
- White-Rabbit
- General Architecture/Wiring
- VHDL Streamers
- B & I Frames
- Tests
Outline

1 Introduction
   - CERN Accelerators
     - Magnets in Accelerators
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   - B-Train upgrade
   - B-Train Firmware Architecture
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   - Tests
CERN Accelerators Chain

European Laboratory for Particle Physics

- LHC (Large Hadron Collider) - 27 km
- SPS (Super Proton Synchrotron)
- ATLAS
- CMS
- LHCb
- PS (Proton Synchrotron)
- PSB
- Linac 2 (Protons)
- Linac 3 (up to 75%)
CERN Accelerators Chain

- European Laboratory for Particle Physics
- Established in 1954 @ Geneva, Switzerland
CERN Accelerators Chain

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- 24 Member states
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- 2 beams circulating in opposite directions in LHC
- 4 main experiments
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Magnets in Accelerators

Why??

The roll of the magnets in the accelerators is to guide the beam throughout the whole ring.
Magnets in Accelerators

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- Dipoles to bend the beam;
Magnets in Accelerators

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- Quadrupoles to focus it;
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- Sextupoles to correct chromaticity.
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Precise knowledge in real time of the magnetic field in the reference magnet is important for longitudinal and transversal beam control.
Real-Time Magnetic Field Measurements

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- Measurements are carried out in a reference magnet placed in series with the accelerator magnets chain.
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- Power supplies, RF cavities, and beam control use this input as feedback in the control loop.
- Measurements are carried out in a reference magnet placed in series with the accelerator magnets chain.
- Typically, this measurement is obtained by means of, either high-performance magnetic measurements systems or mathematical models.
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What are B-Train systems

B-train:
Real-time measurement of local or integral field in a reference dipole, used to infer $\int Bdl$ over the whole machine.
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**Motivation:**
The field produced by a given current is not always predictable to the required accuracy ($10^{-4}$) with a mathematical model (synthetic or simulated B-train), due to: iron hysteresis, eddy currents, temperature effects, ageing, DCCT accuracy, etc.
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**Markets:**
- **Particle accelerators:** 6 B-Trains at CERN.
- **Medical applications:** Cancer treatment using proton accelerators.
Why a train??

The field value is distributed on a dual digital serial channel, where one pulse represents a given increment/decrement (step = 0.1G in general).
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\[ B(t) = B_{\text{marker}}(t_1) + \int_{t_1}^{t} \dot{B} \, dt \]

\[ \text{calibration error} = \frac{\int_{t_1}^{t_2} \dot{B} \, dt}{B_{\text{marker}}(t_2) - B_{\text{marker}}(t_1)} \]

**Coil measurement**

\[ \dot{B} = -\frac{V_{\text{coil}}}{A_{\text{coil}}} \]
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B-Train system upgrade

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New hardware components, firmware algorithms and White-Rabbit field distribution.
PS B-Train upgrade

From Mark III to Mark IV
New **FMR** marker sensors are being used in the new PS-BTrain prototype.
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- 2 AnaPico 20 GHz signal generators for FMR F,D halves working @1.7GHz;
- Direct acquisition of the resonance peak;
- Commercially available sensor;
- Works up to several T/s;
- Larger dynamic range for a given sensor (current unit: 60-300 mT).
B-Train system upgrade

FMR Probe

Signal at FMR frequency 1.70 GHz

601.2 Gauss (0.06012 Tesla) @ 1.7 GHz
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B-Train Firmware Architecture

Prototype installed in PS-Reference magnet (building 355/R-012)

The New PS B-Train

White-Rabbit Switch

Cross Point Switch

2x FMC mezzanine cards: Front-End components for B field acquisition, FMR field markers peak detection and LCD interface.

2x SPEC Carrier Cards: B-field integral calculation and Peak detector using Xilinx Spartan 6 FPGA.

WHite-Rabbit B-field distribution to the users.
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Hardware - CERN standard platform

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**Wishbone** serializer bridge FPGA core - used for setting/reading firmware parameters and DMA access.
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**SPEC** (Simple PCIe FMC carrier) + **FMC** (FPGA mezzanine cards) for modular custom electronics.

**Wishbone** serializer bridge FPGA core - used for setting/reading firmware parameters and DMA access.

**White Rabbit** serial link - used to distribute the real time magnetic field to the various users along CERN.
Software - CERN standard platform

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VHDL

*Hdlmake* – Tool to construct the VHDL project with OH Repo IP cores

*wbgen2* – Tool to generate automatically wishbone interface for VHDL and C header.

*White-Rabbit* – VHDL core to distribute B field and synchronize phase / offset between different oscillators

Driver

*C, gcc* – Programming Linux driver with interrupts and DMA to control the hardware (spec-bmeas)

FESA

*C++, VM, Eclipse* – Middleware home made to control devices @CERN

The New PS B-Train

B-Train Firmware Architecture
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PS B-Train over White-Rabbit

Fully deterministic Ethernet-based network + Sub-nanosecond Synchronization

White Rabbit

White Rabbit PS-BTrain WR Switch and all cabling + spares in place @PS reference magnet; Operational & Spare systems are being sent at the same time using VLANs; PS-BTrain WR Network: 1 master and 6 nodes (WR slaves).
PS B-Train over White-Rabbit
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White Rabbit

Cheap, robust, scalable, fast over standard multimodal fibers;
**White Rabbit**

- **Cheap, robust, scalable**, fast over standard multimodal fibers;
- **Ethernet** standard: maintainability and interoperability with future control systems;
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### White-Rabbit PS-BTrain

- **WR Switch** and all cabling + spares in place @PS reference magnet;
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- **PS-BTrain WR Network**: 1 master and 6 nodes (WR slaves).
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PS-BTrain White-Rabbit Distribution Architecture

**B-Train**

- **PS B-Train**
  - WR Slave Node

**POPs**

- WR Slave Node (Main Power supply)

**PFW**

- WR Slave Node (Pole-face windings)

**CPS RF**

- WR Slave Node (Complex PS)

**MM Lab**

- WR Slave Node (Magnetics Measurements)

**Beam**

- WR Slave Node

**Users**

- Power-Supply

**Diagnostic Tools**

- Beam Diagnostics

**Magnetic Measurement**

- $\oint B \, dl$

- $B(t) I(t)$

**PS Dipole Reference Magnet**

**WR Master Switch**

**WR Slave Node**

- Beam Diagnostics

**Beam Diagnostics**

- F rev

**Diagnostic Tools**

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System CLK : 62.5MHz

Note:
The frame must be read before the next come.

Note:
"type" is used to differentiate B frame as Imain frame (see frame sheet).
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WR Ethernet Frame Payload

B & I Frames

- Bit 7 – 0: Frame type
  - 0x42, ASCII code of 'B', used for the B field measurement frame
  - 0x49, ASCII code of 'I', used for the Imain frame

- Bit 8: Simulation/Effective bit, '0' if the B field sent is measured, '1' if the B field sent is simulated.

- Bit 9: Error flag bit, '1' if one of error detection systems see something wrong.

- Bit 10: C0 pulse

- Bit 11: Zero cycle pulse

- Bit 12: Focusing low marker flag (optional)

- Bit 13: Defocusing low marker flag (optional)

- Bit 14–15: Don't care, not defined control bits.

Ethernet Padding to have 64 bytes

Frame ctrl 16 bits

- B (dipole) 32-bits (signed) 10 nT (LSB) (> ±20 T range)

- Bdot 32-bits (signed) 1 \( \mu \) T/s (LSB) (> ±2 KT/s range)

- G (quadrupole) 32-bits (signed) 1 \( \mu \) T/m (LSB) (> ±2 KT/m range)

- OLD Bup-Bdown 32-bits (signed) 10 nT/ (LSB) (> ±20 T range)

CRC 16 bits

B frame: (for the PS, ELENA, BOOSTER)

I frame: (for the PS)
## WR Ethernet Frame Payload

### B & I Frames

#### B frame:
(for the PS, ELENA, BOOSTER)

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame ctrl 16 bits</td>
<td></td>
</tr>
<tr>
<td>B (dipole) 32-bits (signed)</td>
<td>10 nT (LSB) (= ±20 T range)</td>
</tr>
<tr>
<td>Bdot 32-bits (signed)</td>
<td>1 μT/s (LSB) (= ±2 K T/s range)</td>
</tr>
<tr>
<td>G (quadrupole) 32-bits (signed)</td>
<td>1 μT/m (LSB) (= ±2 K T/m range)</td>
</tr>
<tr>
<td>OLD Bup-Bdown 32-bits (signed)</td>
<td>10 nT/ (LSB) (= ±20 T range)</td>
</tr>
<tr>
<td>CRC 16 bits</td>
<td></td>
</tr>
</tbody>
</table>

### Ethernet Padding to have 64 bytes

### Frame ctrl 16 bits:

<table>
<thead>
<tr>
<th>Bit 15–0: Frame type</th>
</tr>
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<tbody>
<tr>
<td>0x42: ASCII code of 'B', used for the B field measurement frame</td>
</tr>
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<td>0x49: ASCII code of 'I' used for the Imain frame</td>
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</table>

### Bit definitions:

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### B & I Frames

**B frame:**  
(for the PS, ELENA, BOOSTER)

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<tr>
<th>Frame ctrl</th>
<th>B (dipole)</th>
<th>Bdot</th>
<th>G (quadrupole)</th>
<th>OLD Bup-Bdown</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 bits</td>
<td>32-bits (signed)</td>
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<td>32-bits (signed)</td>
<td>16 bits</td>
</tr>
<tr>
<td></td>
<td>10 nT (LSB)</td>
<td>1 μT/s (LSB)</td>
<td>1 μT/m (LSB)</td>
<td>10 nT/ (LSB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(&gt; ±20 T range)</td>
<td>(&gt; ±2KT/s range)</td>
<td>(&gt; ±2KT/m range)</td>
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<td>14</td>
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<tr>
<td>13</td>
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<tr>
<td>12</td>
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<td>8</td>
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<tr>
<td>7</td>
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<tr>
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**I frame:**  
(for the PS)

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<th>Imain</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 bits</td>
<td>32-bits (signed)</td>
<td>16 bits</td>
</tr>
<tr>
<td></td>
<td>1mA (LSB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(&gt; ±20 kA range)</td>
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**Ethernet Frame Payload**

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White-Rabbit Synchronization

PS B-Train over White-Rabbit

Tests
RF & POPs tests
wrpc v2.0 core

Considering 2.9 T/s the PS B-field ramp rate:
RF 10 µs latency seen by CPS RF receiver @250KHz.
With 10 µT latency, gives us 29 µT error;
POPs 5.6 µs latency seen by POPs receiver @1KHz.
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These error values are fine for PS machine but might be a problem for smaller machines, i.e. ELENA.
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Summary

White-Rabbit fully tested and working in the new PS-BTrain prototype; bigger speed rates to be tested in the next few weeks; 10 µT latency might be a problem for the upcoming upgrades on the B-Train systems.

Outlook
WRPC v3.0 core to be deployed on the system; improve diagnostics on the systems; huge VHDL project with some timing failures - needs to be cleaned up; White-Rabbit B-field distribution to be implemented in all B-Train systems @CERN, ELENA is the next one.
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For Further Reading I

N. Sammut, L. Bottura, J. Micallef.
Mathematical formulation to predict the harmonics of the superconducting Large Hadron Collider magnet.

P. Arpaia.
Metrological Characterization of a Ferrimagnetic Resonance Transducer for Real-Time Magnetic Field Markers in Particle Accelerators.

A. Beaumont, M. Buzio.
A NMR marker for CERN PS Combined Function Magnet.
*International Magnetic Measurement Workshop (IMMW16), Bad Zurzach, Switzerland, 2009*

P. Arpaia, M. Buzio, F. Caspers, G. Gollucio, C. Petrone.
Static Metrological Characterization of a Ferromagnetic Resonance Transducer for Real-Time Magnetic Field Markers in Particle Accelerators.
*IEEE International Instrumentation and Measurement Technology Conference, May 3-6, 2011, China.*
White rabbit: a PTP application for robust sub-nanosecond synchronization.
*Precision Clock Synchronization for Measurement Control and Communication (ISPCS), 12-16 September, Munich, Germany.*

Simple PCIe FMC Carrier (SPEC)
http://www.ohwr.org/projects/spec/wiki
Thank you!

Feel free to make any questions.