Status and outlook of B-train systems for magnetic field control

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1. Introduction

What are B-train systems ?

• **"B-train":** real-time measurement of local or integral field in a reference dipole, used to infer $\int B d\ell$ over the whole machine

• **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 …

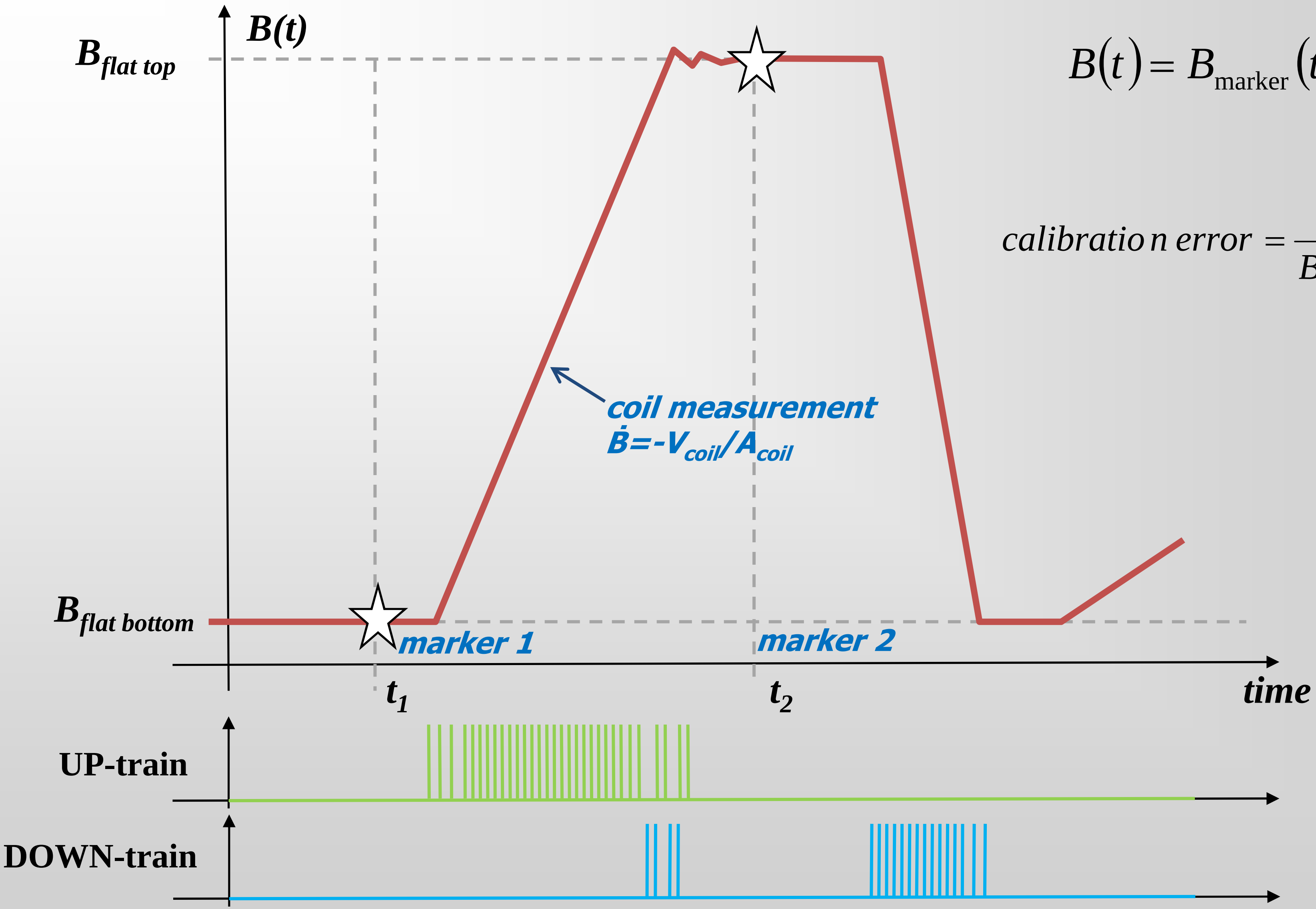
• **Users:** knowledge of the field is necessary for:

- RF frequency control (mandatory !)
- beam diagnostics and control
- power supply control
- qualitative feedback to operation

• **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, also 0.02G for the SPS)

• **General strategy**: a pick-up coil provides the rate of change of the field from $V_{coil}=-A_{coil}\dot{B}$;
a field marker may be needed to provide the initial offset (and possibly intermediate or final values, for calibration and cross-check purposes).

Principle of B(t) measurement

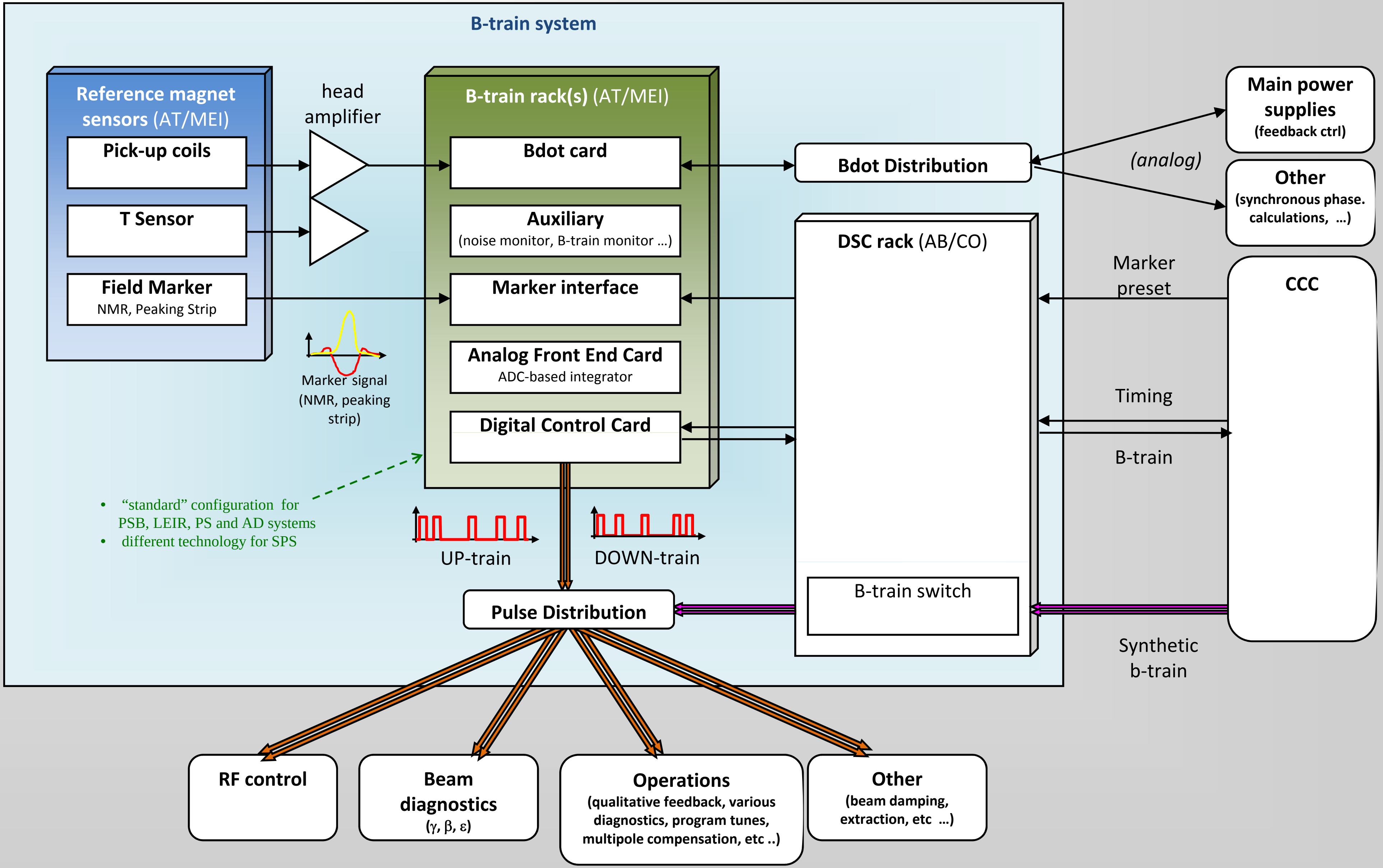


$$B(t) = B_{\text{marker}}(t_1) + \int_{t_1}^{t} \dot{B}dt$$

$$\textit{calibration error} = \frac{\int_{t_1}^{t_2} \dot{B}dt}{B_{\text{marker}}(t_2) - B_{\text{marker}}(t_1)} - 1$$

PS pulses (24 V, 1 μs)

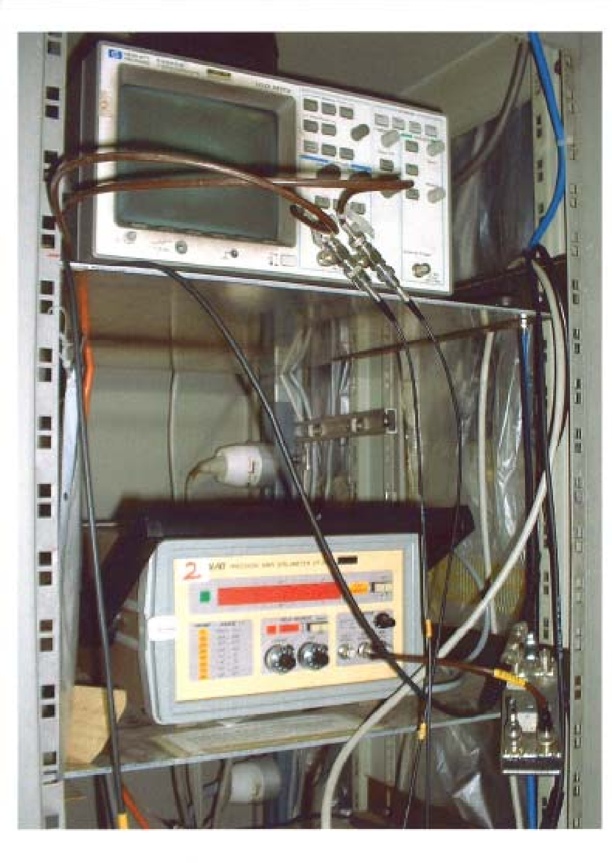
B-train systems: simplified generic block diagram



Field markers

- **NMR**

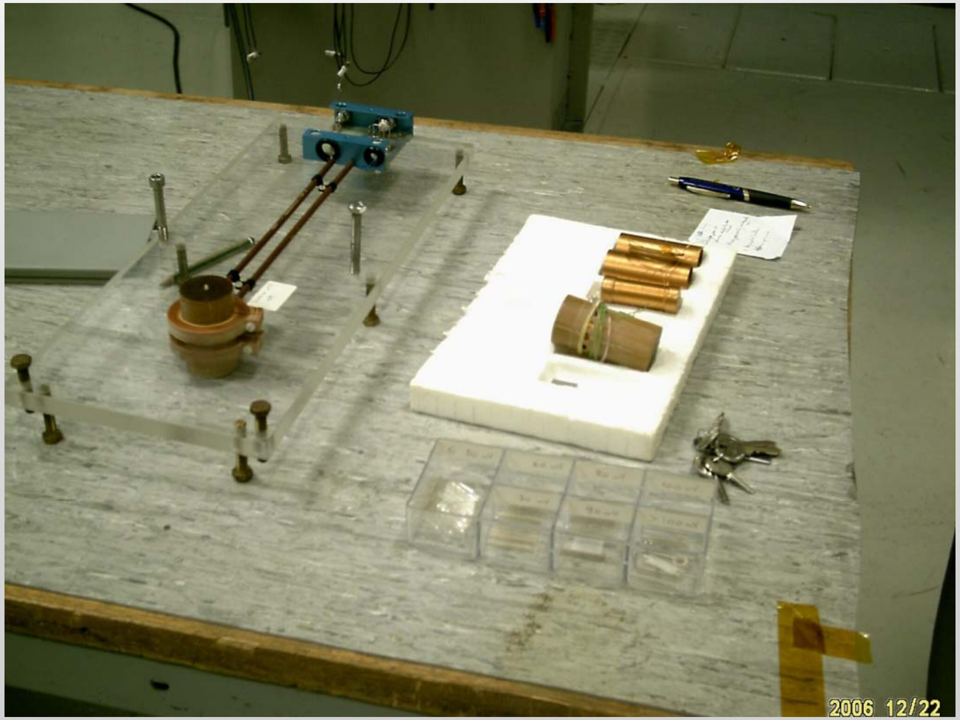
- Best resolution (~0.1 ppm) and absolute accuracy (~5 ppm) sensor.
- Commercial solution for all applications at CERN: Metrolab 2025
- Main limitations: does not work if the field is low (typically > 100 G), not uniform (gradient compensation coils required) or rapidly changing



Field markers

• **Peaking Strip**

- Optimal solution for combined-function PS magnets, developed at CERN ~50y ago.
- Based on a pre-stressed magnetic needle: magnetization flips over at a preset level and generates a pulse detected by a pick-up coil
- Two powered coils for bias and screening field, pulsed to avoid overheating
- Main constraints: difficult at high field (> 400 G), signal gets stronger at high ramp rates
- Experience shows that this sensor is exceptionally stable and reproducible (all existing units drifted <0.5G drift in 20 years !), however know-how necessary to build has been lost



Field markers

• **Other sensors:**

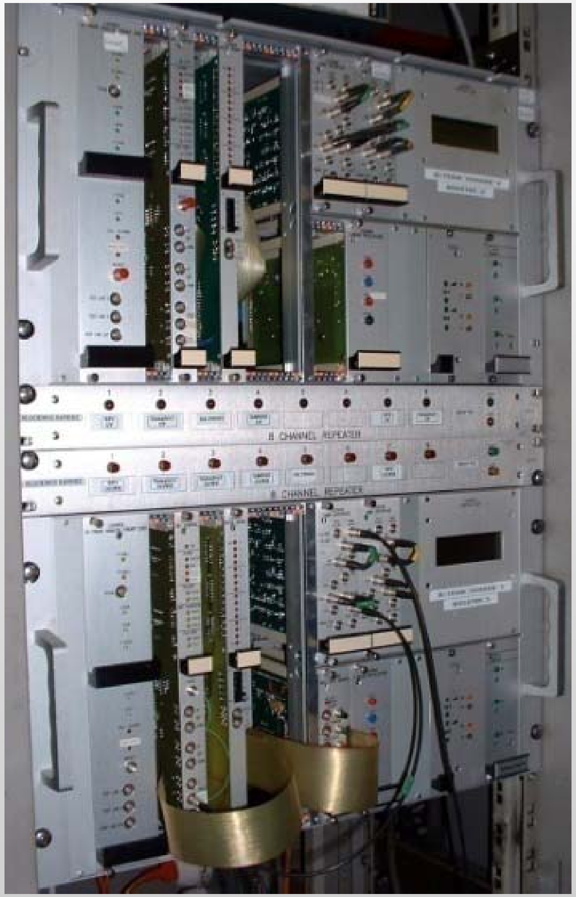
FMR (FerriMagnetic Resonance): this sensor provides an absolute measurement at high field, insensitive to ramp rate and field uniformity; however, the prototype installed in the PS reference magnets must be operated manually and has never been exploited for operation

Hall probes: fundamental difficulty to provide stable reference: accurate temperature and current control, long-term stability issues

General criterion for choice:
reproducibility and long-term stability
(absolute accuracy not strictly required for operation)

2.1 Booster B-train: hardware

- **Configuration:** 2 parallel chains (can be switched by swapping cables, procedure detailed in EDMS 825281), separate reference magnet powered in series to the machine
- **Marker**: two NMR probes for low and high field. High field probe proved unnecessary and is not used regularly today.



Booster B-train: reliability

- **Synthetic B-train:** adequate for regular operation (~1 G accuracy), with automatic commutation in case of NMR signal missing.
- **Recent malfunctions**:
  - ❑ missing NMR signal, fixed by lowering detection threshold from 150 to 100 mV (2006)
  - ❑ faulty repeater card exchanged (2006)
  - ❑ integrator ADC overflow caused by coil voltages spikes due to the post-regulator switching converter (not used anymore)

  Diagnostics and repairs may take few hours to few days, but generally carried out during commissioning
  ⇒ not much disruption to operations

- **Spare parts:**

  - B-train rack: 1 × hot spare rack + 1 × AFEC, DCC, aux cards
  - NMR probe/teslameter: commercial system, many spares available
  - Pick-up coil: 1 × hot spare
    (few days needed to build, calibrated and install short coils)

PSB B-train system not critical for LHC operation

2.2 LEIR B-train: hardware

2 × B-train crates

- **History:** System originally used in LEAR (1982)
- **Configuration:** 2 parallel chains, machine dipoles BHN20, 30 used as references
- **Marker**: no marker needed, preset offset sufficient

One of the 5m long, 90° bending magnets used as a reference

LEIR B-train: reliability

• **Faulty pick-up coil**: one of the two coils has been out of order for several years. Repairs have been deemed not worth the effort ⇒ <u>both chains use the same coil signal as input</u>

• **Synthetic B-train:** adequate for regular operation (~10 G error at the end of ramp-up can be tolerated)

• **Recent malfunctions:**

❑ Erroneous high field readout of only 6800G was due to an open 50 Ω terminator on the connection of the DOWN channel on the VME rack (2006)
❑ Timing error traced back to software (2005)

In both cases, switching on the second chain allowed uninterrupted operations.

• **Spare parts:**

- B-train rack: 1×hot spare full system + 1× AFEC, DCC, aux cards
- Pick up coils: no spares (several weeks estimated to repair broken coil)

LEIR B-train system not critical for LHC operation

2.3 PS B-train: hardware

- **Configuration:** 2× parallel chains (can be switched by swapping connectors, procedure detailed in EDMS 764266), separate reference magnet (U101) powered in series to the machine. The reserve chain has been made operational in 2006 with new head amplifiers, the two chaines give same results within ~1G.

•**Marker**: 3 × parallel chains with 2 × Peaking Strip each (F and D blocks), electronics on 3 separate racks. Only one marker is used at any given time.
An experimental FMR marker is also installed, but is not operational.

•**Bdot output**: analog signal used for MPS control (also for analog RF synchronous phase calculations). *[note: the future MPS control system shall be based on B, not Bdot]*.

3 × peaking strip racks (powering & acquisition)

B-train crate

PS B-train: U101 reference magnet

3 × peaking strip (F block)
3 × peaking strip (D block)

3 × coils (F block)
3 × coils (D block)

Head amplifiers

FMR marker

PS B-train: reliability

- **Synthetic B-train:** NOT adequate for regular operation (used only for diagnostics, restarts). As an emergency safeguard, automatic commutation system in case of peaking strip signal missing.

- **Recent malfunctions**:
  - ❑ noisy analog Bdot signal, problem still open (investigations pending, not critical)
  - ❑ MPS trips due to Bdot spikes caused by interference with upgraded PFW powering, problem emerged during commissioning and was solved by reducing the PFW ramp rate (2007)
  - ❑ timing pulse distribution errors due to repeater being not powered, leading to MPS trips problem solved in ~2 hours, operation not affected (2006)

- **Spare parts:**

- B-train rack:	1× hot-spare rack, 1×AFEC, DCC, aux cards.
- Peaking Strips:	5× hot-spares, 1×additional unit, many individual components (strips, coils etc …) fabrication technique not fully documented (⇒ impossible to make a new one today)
- Peaking Strip rack:	2× hot-spare racks, no additional components
- Peaking Strip P.S.:	2× hot-spares, construction and programming details undocumented (⇒ impossible to make a new one today)
- Pick-up coils:	5× hot-spares

PS B-train system is critical for LHC operation
availability during regular use is acceptable
low risk, but few spares for essential components

2.4 AD B-train: hardware

- **Configuration:** 1 acquisition chain only, 1×reference magnet in the machine (MB45).
- **Marker**: 3×NMR probes with gradient compensation coils originally installed to provide 5 reference measurements during long (~1 min) pulses. Complex system, requires accurate adjustement of compensation coils, never used in practice.
- **Non-standard control system on a local PC**.

AD B-train: reliability

- **Synthetic B-train:** not only adequate for regular operation, but even preferable (no fluctuations during long pulses). Only the synthetic train is used for operation, the measured train being reserved for diagnostics and calibration.
- **Recent malfunctions**: none
- **Spare parts:**

  - B-train rack: no hot-spare rack, 1×AFEC, DCC, aux cards.
  - Pick-up coils: no spare

AD B-train system not critical

2.5 SPS B-train: hardware

- **Configuration:** 2 parallel chains (can be swapped via a single switch, procedure in EDMS 825330),
2 separate reference magnets (MBA and MBB) powered in series to the machine
- **Marker**: two NMR probes installed in the magnets, without the relative acquisition electronics ⇒ never used. A preset value is used instead to initialize the train.
- **Electronics**: the acquisition system, initially developed and maintained by the RF group, is different from the other B-train racks (no timing cards, incompatible analog front-end and digital controller)

2× B-train racks

Reference dipoles

SPS B-train: reliability

- **Synthetic B-train:** not implemented
- **Recent malfunctions**: none
- **Spare parts:**

- B-train rack:	1× hot-spare rack, several spare cards
- Pick-up coils:	1× hot-spare, (time needed to build and calibrate 7-m coils: 1-2 months)

SPS B-train system is critical for LHC operation

availability during regular use is acceptable

3. B-train maintenance policy

- **Responsabilities:** as of 2006, **AT/MEI** (former AT/MTM) is fully responsible for the maintenance and upgrades of the measured B-trains.

- **Standard maintenance:** carried out routinely during shutdowns
  - systematic calibration campaigns
  - minor upgrades , e.g. new peaking strip signal outputs for OASIS, LCD field display, refurbishment of cabling …

- **In case of problems:**

  - Call AT/MEI expert's "first line": R. Chritin, D. Giloteaux or P. Galbraith
    NB: the service is based on "best effort" and is NOT a piquet
  - if the problem is not solved rapidly, operation is switched on the reserve B-train
    (typical time required: of the order of minutes for measured B-train)
  - diagnostic and repair interventions proceed usually in parallel with operation
    (typical time required: a few hours to a few days)

  Transfer of "switching duties" to AB/OP and AB/RF piquet teams: discussed in the past, documentation produced, little or no opportunity to put it in execution during 2007

> experience shows that most problems appear during commissioning and restart
> complex, strongly coupled system (feedback loops) ⇒ diagnose in actual working conditions

Main goal:

- ensure that existing systems keep working, in their current conditions, until the end of the lifetime of each machine *(10 years for PSB ? 30 years for SPS ??)*

  To be kept in mind: systems will get older and more fault-prone; staff will get older and retire …

Additional objectives:

- reduce downtime: improve reliability of components, facilitate maintenance, calibration and repairs
- improve existing systems, if required:
  · add new functionality (e.g. more diagnostics, easier switching between trains, put in operation existing but disused components, etc …)
  · enhance accuracy and resolution
- design and implement new systems (AD/ELENA)

B-train rack electronics

- **Issues and external constraints**
  - The question: do we want to keep existing electronics as it is for the next decades ?
  - Existing spare stock not homogeneous (lots of different versions, full list in preparation)
    $\Rightarrow$ the availability of spares in good working order might have been estimated too optimistically
  - Fabrication of additional AFEC/DCC spare cards with their current design is not practical:
    essential components such as ADC, relays, microcontroller are discontinued,
    FPGA code not documented
  - Radical update of component and technologies apparently incompatible with CERN infrastructure

- **Proposal: modernization of electronic cards**
  - objective: replace existing VME cards with more modern components, produced in suitable quantities,
    to be integrated in the existing infrastructure
  - working hypothesis: two new AFEC/DCC cards integrating most of the functions of a whole B-train rack.
    Identical cards for all machines, functions switched on or off according to specific needs
  - Preliminary study started in 2007, a detailed proposal is being prepared for discussion

Field sensors

- **Pick-up coils**
  the risk for coils installed inside reference magnets is low (at least, external to the machine …) but the potential consequence of accidents are serious (e.g. for SPS)
  - a detailed survey of spare coils available and of requirements (geometry, materials etc.) is necessary
  - the opportunity to fabricate additional spares might then be discussed

- **NMR**
  No problem for all Metrolab 2025 models (plenty of spares at CERN, excellent manufacturer's support).

- **Peaking Strips**
  40 years of experience prove that risk is low, but should an accident arrive today it is not possible to repair/rebuild the marker ⇒ most critical component in all the B-trains.
  We propose to investigate along two lines:
  a. Extract all information from existing documentation and spare components to evaluate the feasibility of **building replicas of existing strips** (possibly working at higher field)
  b. Study the feasibility of alternative marker types, e.g. **NMR probe with passive gradient compensation** (i.e. a suitably shaped ferrite block)

in any case:
maybe we should think about storing safely our precious spares AWAY from the components in use …

5. Conclusions

- All **existing B-train systems** are in acceptable working order, with low expected downtime, and no immediate concerns.
- The **strategy to mitigate** the effects of faults, i.e. switching onto redundant acquisition chains while carrying out repairs is well tested ⇒ very little lost machine time

however

- The **general availability of spares** is uncomfortably low considering the long-term
- The measured B-trains of PS and SPS have a critical importance (no operation with simulated train) yet are potentially vulnerable:

  PS: peaking strips (+ their powering) are irreplaceable today
  SPS: very few spares (nonstandard cards, long coils), difficult to replace

- **Proposed actions**:
  - ❑ Consolidation of documentation, to prevent the dissipation of crucial know-how
  - ❑ Standardization and modernization of electronics for existing and future systems, to ensure long-term survival of the systems and improve the availability of the machines
  - ❑ Assess the feasibility of Peaking Strip and pick-up coil replacements
  - ❑ According to needs and demands from AB, evaluate possible implementation of functional improvements