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PS/PO/Technical Note

A NEW B-TRAIN SYSTEM FOR THE PS ACCELERATOR

Peter Dreesen, Ivan Garcia-Alfonso

Abstract

This paper describes the new B-Train system for the CERN Proton Synchrotron accelerator, based on a discrete digital voltage-to-frequency converter. The new system is currently running in the PS Booster and AD accelerators. This new B-Train has been tested in PS with satisfactory results improving the performance of the old measuring system as well as its maintenance features.

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1. INTRODUCTION: WHY A NEW B-TRAIN SYSTEM IN PS?

The B-Train system is a high precision measuring device used to provide a real-time reliable measurement of the magnetic field in the bending magnets of the PS circular accelerator. This information is essential for longitudinal and transversal beam control, for power supply regulation and for interpretation of acquired data and calculation of the relativistic beta and gamma of the beam during acceleration [1].

The present B-Train system installed in the PS accelerator contains three independent measurement chains. Each chain comprises 2 pick-up coils (focusing and defocusing), 2 peaking-strip field markers and a voltage-to-frequency converter (VFC) fed with the mix of the two signals coming from both pick-up coils. The peaking-strip field markers trigger the distribution of the B-Train pulses. Only one of these chains (the number 2) is used for operation, the remaining ones have a crosschecking function.

This B-Train system has a 0.1 Gauss resolution with a long-term stability and reproducibility on the 10^{-4} level. The key specifications satisfy the current request of all users, however its maintenance is becoming complicated since several components are obsolete and some parameters remain unknown. Moreover, non-desired effects as the drift of the converter or the distribution of negative B-field values at the end of several cycles justified, at the end of year 2000, the decision of replacing the 25 years old present B-Train system for a new one.

The new B-Train system which we will describe has a 0.1 Gauss resolution and is based on a high-speed 16-bit Analog-to-Digital Converter (ADC) and on a digitally controlled pulse generator, built with a Field Programmable Gate Array (FPGA). The ADC has an internal offset/gain auto-calibration feature to compensate its drifts in function of temperature and time and to improve its reproducibility to the 10^{-5} level.

The new electronics are already installed in the PS Booster for driving its digital RF beam control and are being used as a magnetic field monitor in the Antiproton Decelerator (AD).

2. B-TRAIN SYSTEM DESCRIPTION

The new B-Train system, located in the PS reference magnet room (unit 101, building 355-R-012), is shown in **Figure 1**.

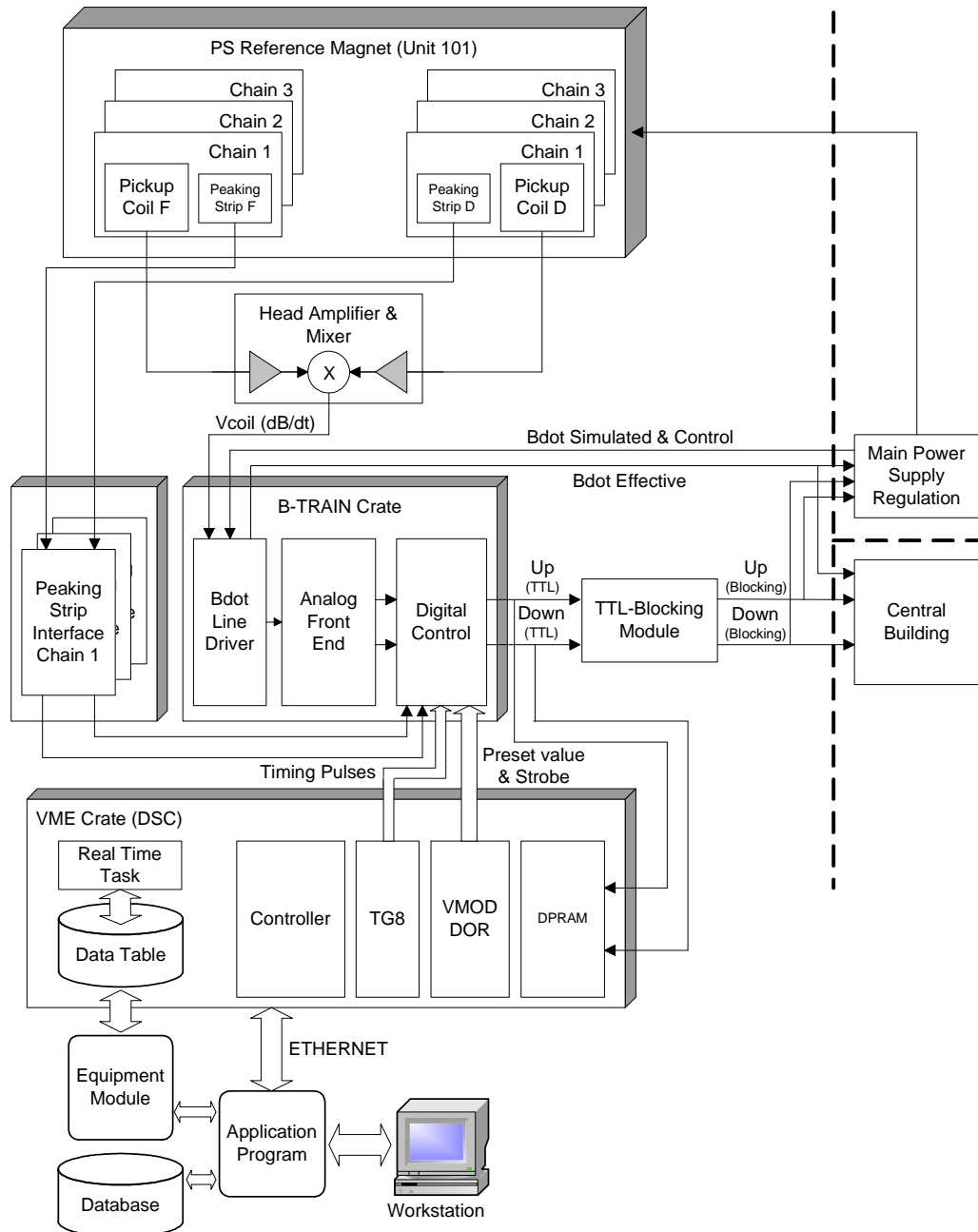


Figure 1. System Overview.

2.1. PICK-UP COILS

The 6 pick-up coils located inside the PS reference magnet are connected to the 3 measuring chains. Two pick-up coils compose each chain : one coil for the focusing part of the reference magnet and the other one for the defocusing part. Each measuring chain generates a voltage signal directly proportional to the time derivative of the magnetic flux crossing it - V_{coil} (dB/dt), and is the result of an amplification and a mixing process on the voltage signals coming out of the pick-up coils.

This V_{coil} will differ slightly from one chain to the other since the coils are physically installed in different places of the reference magnet. Note also that the reference magnet is connected in series with the 100 main bending magnets and is located outside the accelerator tunnel, in building 355 : this makes the B-Train system installation and maintenance tasks much easier since the access to its location is always possible.

2.2. HEAD AMPLIFIER & MIXER

The Head Amplifier & Mixer module, bolted on the reference magnet support, processes the signals coming from both the focusing and defocusing pick-up coils corresponding to chain number 1. Signals are amplified, scaled and mixed. Chains number 2 and 3 are still being used by the old B-Train system.

This processed signal V_{coil} (dB/dt) feeds the B-Train Crate located in Rack RR26.

2.3. B-TRAIN CRATE

The B-Train Crate is principally based on three cards: The Bdot Line Driver, the Analog Front-End Card and the Digital Control Card.

2.3.1. BDOT LINE DRIVER

This board is essential for the Main Power Supply (MPS) regulation. Figure 2 shows how the Bdot Line Driver switches between the V_{coil} signal provided by the Head Amplifier & Mixer module and the Bdot Simulated signal coming from the MPS, so that the system can distribute a measured or a simulated B-Train. This switch is remotely controlled from the MPS.

The other Bdot Line Driver main function is to provide the MPS and the Central Building (353-R-002) with an ultra low-noise analog signal coming from the PS Reference Magnet or with a processed version of the Bdot Simulated. This high-quality analog signal is called Bdot Effective and closes the regulation loop in the MPS. It is also used for phase programming in the Central Building.

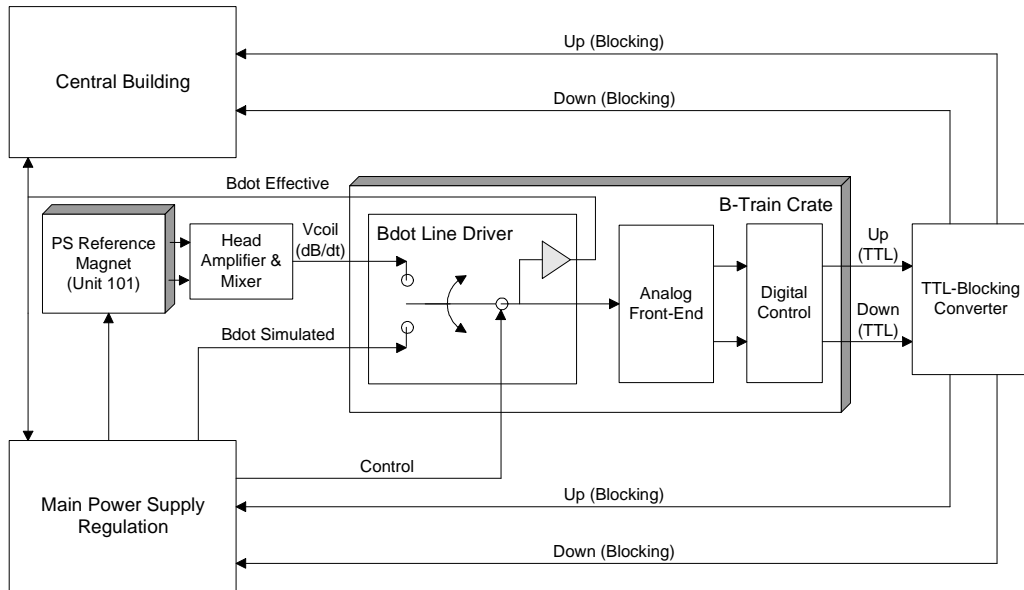


Figure 2. Bdot Line Driver block diagram.

2.3.2. ANALOG FRONT-END CARD

This module integrates the V_{coil} signal by its high-speed 16-bit ADC and its digital logic programmed in the FPGA. This card acts as the Main B-Train Pulse Generator (BTG). Each UP/DOWN pulse it generates represents a 0.1 Gauss increment or decrement of the magnetic field inside the reference magnet. The pulse generation frequency is proportional to the absolute voltage level of the pick-up coil signal, thus proportional to the magnetic flux to time derivative.

2.3.3. DIGITAL CONTROL CARD

The Digital Control Card distributes the generated pulses synchronizing them with the PS standard timing system. This module also handles the alarms (peaking-strip missing, overflow and out-of-range calibration), it triggers the auto-calibration feature (this subject will be covered later) and it controls the Liquid Crystal Display (LCD), which gives on-line information about the integrated B field, the preset value, and the flat-top B field.

The B-Train Crate has two auxiliary cards (the Noise Monitor Card and the ADC Test Card) to perform system-level diagnostics and debugging.

2.4. DEVICE STUB CONTROLLER (DSC)

A VME Crate containing the DSC [2], labeled as DCPSBGEN and located in Rack RR25, controls the B-Train Crate. Two digital Input/Output (I/O) modules (VMOD-DOR) manage the communication between the DSC and the Digital Control Card located in the B-Train Crate, sending information about alarm status and the threshold field level for the peaking-strip field marker (preset value).

The absolute magnetic field can be calculated on-line by counting the number of pulses distributed since the start of a magnetic cycle. A DPRAM module (Dual Port Random Access Memory) also installed in Rack RR25, does this function.

2.5. DISTRIBUTION SYSTEM

The pulse distribution system converts the TTL compatible UP/DOWN pulses sent by the Digital Control Card to the PS standard 24V pulses before being distributed towards the MPS and the Central Building.

Fast pulse repeaters are required since the maximum pulse frequency of the B-Train system reaches 500 kHz when sending the initial burst.

3. PEAKING-STRIP FIELD MARKERS

An external magnetic marker is needed to initialize the integrator every magnetic cycle and so to calibrate the magnetic field inside the reference magnet.

Two peaking-strip field markers designed for working in a low-field region (less than 100 Gauss) are used to perform this initialization. One peaking-strip goes with the focusing and the other with the defocusing pick-up coil.

Also these peaking-strip probes are located inside the reference magnet, and generate a magnetic marker pulse when the magnetic field in the probe crosses a predefined and remotely settable level. This level is approximately 50 Gauss (during the PS Machine Development in October 2001 a 49.8 Gauss value was used). When the peaking-strip sends a signal, the magnetic field is known with enough precision and the B-Train integrator can be calibrated to this absolute value.

In the old B-Train system, both field markers were used to trigger the distribution of the UP/DOWN pulses - distributing roughly 50% of the generated pulses after receiving the first magnetic marker pulse and 100 % of the generated pulses after the second magnetic marker pulse was received. This way of operation was conceived to avoid errors in case of the extra “loop-of-8” currents in the reference magnet.

The new B-Train system logic only uses one magnetic marker pulse to initialize the integrator (a second one is foreseen for further calibration tasks). In order to minimize the modifications and to keep the compatibility with our other new B-Train systems already running in PS Booster and AD, the preliminary tests were performed using only one of the peaking-strip signals and distributing all the UP/DOWN pulses generated as soon as the magnetic marker pulse was detected. No errors concerning “loop-of-8” currents were detected.

The new B-Train systems installed in the PS Booster and AD were designed to use a Nuclear Magnetic Resonance (NMR) probe for magnetic marking. A NMR Interface Card has been developed to provide the B-Train system with a negative TTL level signal from the analog magnetic marker pulse (generated by the NMR probe) using different filters and discriminators. This NMR Interface Card is not used in PS : the peaking-strip probes have their own signal conditioners, inside the racks containing the old B-Train electronics (RR21, RR22 and RR23 for the measurement chains 1, 2 and 3 respectively).

For the moment, the new B-Train system uses the 8 μ sec TTL negative level pulse provided by the existing peaking-strip signal conditioner in Rack RR21. The two LEMO connectors in the B-Train chassis rear panel foreseen for the analog NMR magnetic marker pulses can be connected directly to the Digital Control Card, bypassing the NMR Interface cards.

4. PS B-TRAIN TIMING

In order to synchronize the whole PS complex, several messages are broadcasted by the Master Timing Generator (MTG) [3]. These messages are received by a TG8 module in the DSC (see diagram depicted in Figure 1), providing the B-Train system with timing pulses for its correct operation.

Three timing pulses are needed for operation - a fourth timing pulse is used for monitoring and debugging tasks. The timing sequence is shown in **Figure 3**. All the pulses are referenced to SCY (Start of CYcle) load event in $c = 0$ ms.

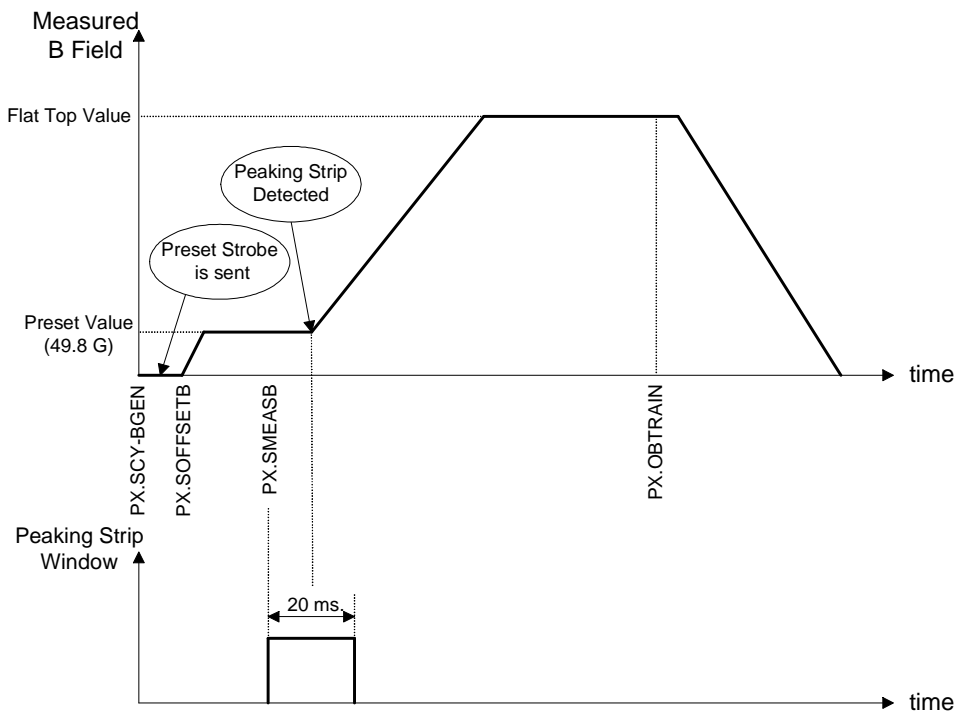


Figure 3. Timing Sequence in the PS accelerator.

PX.SCY-BGEN (Start CYcle): this timing pulse is generated at the beginning of every B cycle in $c = 0$ ms. The B-Train integrator is reset to prevent its drift being accumulated from one cycle to the next one. After a few milliseconds, the DSC informs the B-Train Crate about the threshold field level (preset value) at which the integrator will start counting the UP/DOWN pulses coming from the Analog Front-End Card. The DSC sends this information via an 18-bit word over a parallel link (VMOD-DOR) and generates a strobe, BT_PRESET, to validate it.

PX.SOFFSETB (Send OFFSET B): this timing pulse has been set to arrive at $c = 25$ ms and asks the B-Train system to send the B Offset. At the same time it triggers the auto-calibration of the BTG. The integrator is initialized to the previously defined

peaking-strip threshold value. The B-Train Crate distributes to the users an initial burst of UP pulses (0.1 Gauss each one) corresponding to this preset value at maximum speed. In the PS, the preset value is 49.9 Gauss and the maximum transmission rate is 500 kHz, so the transmission takes close to 1 ms.

The software task that controls the DSC in the PS takes 12 ms from the beginning of each magnetic cycle to send the preset value and its strobe. This delay results of software priorities. If the PX.SOFFSETB signal arrives before $c = 12$ ms, the state machine programmed in the DCC's FPGA will be blocked until the next magnetic cycle - since it is still waiting for the preset value and its strobe - and no UP/DOWN pulses will be sent. To avoid this undesirable scenario the PX.SOFFSETB was set to $c = 25$ ms.

PX.SMEASB (Start MEASuring B) : this signal is used as a reference for the beginning of the 20 ms peaking-strip window. This window, whose length is set by two hardware mono-stables, is used to avoid undesirable peaking-strip signals : only the one magnetic marker pulse detected during this time interval will be considered as a valid one. So when the peaking-strip magnetic marker signal is detected inside the window interval, the system starts measuring and distributing the UP/DOWN pulses. If the peaking-strip magnetic marker is not detected before the peaking-strip window's timeout, the window closes, the measurement and distribution starts and an alarm is set on the DCC's front panel, remaining until the next magnetic cycle. The peaking-strip magnetic marker pulse is expected in the PS, around $c = 105$ ms. Considering a peaking-strip window of 20 ms and trying to center this window around the magnetic marker expected detection, PX.SMEASB was set by hand at $c = 95$ ms.

PX.OBTRAIN (Observation B-TRAIN): the B-Train Crate uses this signal locally to display the calculated value of the field at different points of the cycle. When the B-Train system detects it, the B field calculated value is shown on the B-Train Liquid Crystal Display and remains displayed until the next PX.OBTRAIN's arrival. The user can move this timing pulse along the magnetic cycle by software and this feature has been used as a calibration and debugging tool.

5. SOFTWARE CONTROL

The Digital Stub Controller (DSC) controls the complete system. This front-end VME computer runs a Lynx-OS real-time task on its PowerPC processor. This task performs Read and Write operations from and to a Data Table contained in the VME controller memory. All these transactions happen at very precise moments signaled by the arrival of VME interrupts generated by a TG8 timing receiver module.

The user can interact remotely with the B-Train system accessing this Data Table using the *Nodal* interpreted language from any application program on workstations through a software interface called Equipment Module. The program that controls the access can be developed in Visual Basic or Excel using the *passerelle* [4][5].

The Equipment Module associated with this system is called **bbtrn**. It allows any programmer to access the different values of the variables associated with the system.

A DPRAM memory module calculates on-line the B field by counting the UP/DOWN pulses generated by the B-Train system. In order to use the current settings in the Xsamp application, the UP/DOWN pulses were directly connected to the DPRAM used by the old B-Train chain number 1.

The user can interact with the B-Train system by changing the preset value, displaying the B-Train alarms and/or moving the observation timing pulse (PX.OBTRAIN). The workstation *psxt13* installed in the PS reference magnet room is ready to perform all the operations and was used for the new B-Train system calibration and debugging during the preliminary tests.

5.1. HOW TO CHANGE THE PRESET VALUE AND READ THE ALARMS

To access the preset value and alarms of the B-Train, next steps are required :

1. Open an *Xterm* (from a *pslinux1* or *pslinux2* connection)
2. Type *rlogin dcpsbgen* to access the DSC that controls the B-Train in PS. This is an optional step.
3. Type *nodal* (low level control software for the DSC)
4. Type *set c = 0* (sets the completion code - typing 's' instead of 'set' is also valid)
5. Type *type c* (displays the completion code - typing 't' instead of 'type' is also valid)
6. Type *set en = 3002* (sets the equipment number in PS)
7. To change the B-Train preset value type:

for i = 0, 24; set bbtrn (en, ccv, i, c) = 500; type c!

This command sets the B-Train integrator initialization value for every magnetic cycle. Note that the preset value is represented in tenths of Gauss, so 500 corresponds to 50.0 Gauss (to keep the 0.1 Gauss resolution) - this is also the number of UP pulses that will be distributed during the B-Train initial burst.

The peaking-strip couldn't and still can't be configured by software, only the value that loads the B-Train can be changed.

8. To read the alarms value in different points of the magnetic cycle type :

for i = 0, 24; type bbtrn (en, staq, i, c) c! (displays the alarms at the beginning of the magnetic cycle for our different users. The value shown should be 0 because the system is reset before the PX.SCY-BGEN timing pulses' reception, when no alarms are expected)

for i = 0, 24; type bbtrn (en, staq1, i, c) c! (displays the alarms before a flattop for the different users)

for i = 0, 24; type bbtrn (en, staq2, i, c) c! (displays the alarms after a flattop for the different users)

5.2. HOW TO MOVE THE OBSERVATION TIMING PULSE PX.OBTRAIN

The PX.OBTRAIN timing pulse is useful for the system calibration since it displays the B field measured in the B-Train LCD (i.e. moving this timing pulse to $c = 180$ ms, the B-Train system displays the B field at injection for every magnetic cycle). To move it, the user should follow the next steps:

1. Open an Xterm (from a pslinux1 or pslinux2 connection)
2. Type *rlogin dcpsbgen* to access the DSC that controls the B-Train in PS. This is an optional step.
3. Type *nodal* (low level control software for the DSC)
4. Type *set c = 0* (sets the completion code, 's' instead of 'set' is also valid)
5. Type *type c* (displays the completion code, 't' instead of 'type' is also valid)
6. Type *set en = 7003* (Observation pulse for PS)
7. Type *for i = 0, 24; type ptim (en, ccv, i, c); type c!* to display the pulse position
8. Type *for i = 0, 24; set ptim (en, ccv, i, c)=180; type c!* to move the pulse position 180 ms. in terms of its load event, SCY in $c = 0$ ms. This command will place the PX.OBTRAIN at the injection time.

6. B-TRAIN SYSTEM FEATURES

The system performance is strongly related to the characteristics of the ADC. The linearity of the BTG, which is one of its key specifications, is ultimately limited by the linearity of the ADC itself. This effect determines the irreducible error of the system (most of the other errors can be reduced using autocalibration techniques).

The key parameters of the systems are shown in **Table 1**.

<i>B-TRAIN GENERATOR</i>	
Resolution	0.1 Gauss
Drift	0.1 Gauss each 2.5 seconds
<i>ANALOG INPUT</i>	
Configuration	Differential
Voltage Signal Range	± 10 Volt
50Hz Feedthrough ($V_{in} - V_{out}$)	150 nV _{rms}
DC Impedance, Vin terminal	2.2 M Ω
<i>ACCURACY</i>	
Warm Up Time	20 min to 15ppm of Full Scale
Positive Range Nonlinearity (max.)	15 ppm of Full Scale
Negative Range Nonlinearity (max.)	-30 ppm of Full Scale
<i>GAIN REFERENCE STABILITY</i>	
Temperature (max.)	1ppm/ $^{\circ}$ C
Supply Voltage (max.)	7ppm/V
Time (max.)	30ppm/1000h
<i>OFFSET/GAIN CALIBRATION</i>	
Offset Error (max.)	± 2 ppm
Gain Error (max.)	± 2 ppm
<i>FREQUENCY OUTPUT</i>	
Compatibility	TTL Compatible Pulses (active low)
Fan-Out	15 TTL LS loads
Pulse Width	1 μ sec
<i>TEMPERATURE RANGE</i>	
Operating	+10 $^{\circ}$ C to +50 $^{\circ}$ C

Table 1. System Specifications.

The B-Train drift has been calculated assuming a Head Amplifier offset of 10 μ Volts, a 10 Volts full scale, a sampling rate of 1 MHz and an overflow value (this concept will be covered in the next point) of 80000.

7. B-TRAIN SYSTEM CALIBRATION

Once the B-Train chassis is installed, the control hardware and software ready, the timing properly set and the PS reference magnet running, it is time to calibrate the B-Train system in three stages.

The first calibration concerns the offset and gain adjustment of the 16-bit ADC - by two analog potentiometers - whilst monitoring the ADC output on the Noise Monitor Card. This adjustment is only done during the B-Train system installation and it may be performed once a year, preferably before every PS machine startup.

The second stage, named auto-calibration, is performed on the offset and the gain of the ADC by the AFEC card itself - after a certain number of magnetic cycles - using three digital 8-bit potentiometers. These adjustments guarantee a long-term reproducibility and stability of the BTG. The Digital Control Card triggers this auto-calibration after having received a number (between 1 and 16) of the PX.SOFTWARE timing pulses, determined by a 4-bit DIP switch.

Finally and most important, the 'gain' of the BTG has to be set. This gain is the ratio between the pulse output frequency and the input voltage and will be determined by the overflow value imposed on the accumulator. This overflow value is set by a 24-bit DIP switch. This value is chosen to allow the accumulator to generate an UP/DOWN pulse every time the field has increased/decreased by 0.1 Gauss.

2 known B field values are required to set the gain. The first value, at the beginning of the ramping-up B field, is the preset value that sets the integrator to 49.8 Gauss when the peaking-strip magnetic marker arrives. The second value (ideally close to the end of the ramping-up B field) was taken from the old B-Train system installed in the PS measurement chain number 2 (this is the one used in operation) at $c = 900$ ms during an AD cycle. The Operation Group (PS/OP) knows this B field value precisely and by applying the equation (1), the accumulator overflow value can be calculated.

$$NextOverflowValue = \frac{CurrentOverflowValue \cdot NumberPulses(Generated)}{NumberPulses(Expected)} \quad (1)$$

The new overflow value is found to be 79845 - so the 24-bit DIP switch was set to

(MSB) 0000 0001 0011 0111 1110 0101 (LSB)

This number must be calculated again when there are outside modifications, such as a PS measurement chain change.

Different ways are used to determine the second B field value, by considering theoretical values or by connecting the PS measurement chain number 1 to the old B-Train system and comparing the old and new measured B fields in a given point.

The most important factor is to avoid drifts and to assure an excellent reproducibility and a long term stability.

The Bdot Line Driver card must also be calibrated once in order to provide a proper analog Bdot Effective signal for the MPS regulation loop stability, with precisely known offsets.

8. FIRST TEST RESULTS

During the PS Machine Development (MD) in October 2001, several tests were performed on all operational beams (SFTPRO, AD, TOF, LHC and EASTB) to determine the viability of the new B-Train system for the PS accelerator [6].

No significant short-term differences were observed between the new and the old B-Train systems except for a few Gauss in the measurement at ejection.

When the RF control switched to the new B-Train, all beams could be accelerated and be extracted except the LHC beam - due to a RF cavity problem.

The temperature stability of the new B-Train system was tested. The crate's temperature was increased from 22°C to 30°C over one hour. No changes on the measured B field were observed.

Finally, a drift analysis on a LHC flat bottom determined an excellent long-term stability of the new B-Train system as well as a remarkable drift improvement compared to the old measurement system.

9. CONCLUSIONS

The new B-Train system greatly improves the old measurement system in terms of linearity, stability and reproducibility, and is suitable to be used in all the accelerators of the PS complex.

Preliminary tests in the PS accelerator have shown that the new system is able to measure the magnetic field with the precision required by the power supply tracking characteristics, and to successfully drive the digital RF beam control. All the tests performed during the MD in October 2001 were pleasing.

The maintenance of the new system has been improved since all its components are standard and easy to purchase. Moreover, there exist fully operative spare chassis - of which one is used as a "hot spare" - and a whole set of spare components.

As the system performance is strongly related to the characteristics of the ADC itself, the system could be improved if needed by simply redesigning the hardware around another ADC with even better resolution and linearity.

10. ACKNOWLEDGEMENTS

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Finally, we would especially like to thank Michael Benedikt (PS/OP) for the B-Train coordination tasks in the PS complex and for performing field tests with beam and validating the results included in this paper.

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12. BACKGROUND

Additional literature about the new B-Train system can be found in the following technical notes.

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