Longitudinal Dampers for Main Injector

Bill Foster, Dennis Nicklaus, Warren Schappert, Dave Wildman
Mar ‘03
MI/RR Damper

• Documentation
• Hardware (longitudinal)
• ACNET Interface
Mother Lode of Damper Papers:
\beamssrv1\minjectr.bd\Damper\Papers

- Missing (hardcopy only):
  - Lambertson AIP proceeding on EM theory of pickup & kickers
  - Papers on FNAL super-dampers for MR & TeV

- Intention (~1/4 complete) is to have online directory & summary.
Wide Variety of Beam Dampers Required in MI & Recycler

1) Transverse (X,Y) and Longitudinal

2) 53 MHz, 2.5 MHz, 7.5 MHz, and DC Beam

3) Single Bunches, Full Batches, Short Batches

4) Injection, Ramping, and Stored Beam

5) Pbar and Proton Directions (different timing)
Beam Bunch Structures in Fermilab Main Injector

53 MHz
BATCHES
(84 Bunches)

SHORT
BATCHES
5-15 Bunches

COALESCED
2.5 MHz
BUNCHES

2.5 MHz
BUNCHES

2.5 MHz
Antiprotons

7.5 MHz
COALESCED

7.5 MHz
Antiprotons

... plus unbunched DC Beam in Recycler...

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## Damper Operating Modes

<table>
<thead>
<tr>
<th></th>
<th>Booster</th>
<th>Main Inj.</th>
<th>Recycler</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>53 MHz Full Batches</td>
<td>X</td>
<td>X</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>53 MHz Short Batches</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>53 MHz Coalesced Bunch</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X X</td>
</tr>
<tr>
<td>2.5 MHz Batch (4)</td>
<td>X</td>
<td>C</td>
<td>X C</td>
<td></td>
</tr>
<tr>
<td>7.5 MHz Batch (12)</td>
<td>X</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC Beam</td>
<td></td>
<td></td>
<td>X</td>
<td>C</td>
</tr>
</tbody>
</table>

**X** = Operation  **C** = Commissioning & Tuneup

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Longitudinal Beam Instability in MI

- Occurs with as few as 7 bunches (out of 588)
- Prevents low emittance bunch coalescing and efficient Pbar bunch rotation

Driven by cavity wake fields within bunch train
Seeded by Booster & amplified near MI flat top.

First Bunch ~ OK
7th Bunch Trashed

see Dave Wildman's Talk
Damper Priorities in Main Injector & Recycler

1. Main Injector Longitudinal Dampers
2. Main Injector Transverse Dampers
3. Recycler Transverse Injection Dampers
4. Recycler Longitudinal Dampers
5. Recycler Broadband (DC Beam) Dampers
Advantages of Digital Filters

• Digital filter can also operate at multiple lower frequencies ...simultaneously if desired.
  ? MI will not be blind for 2.5 and 7.5 MHz Beam
• Digital filters more reproducible (=>spares!)
• Re-use Standard hardware with new FPGA code
  – or same code with different filter coefficients
• Inputs and Outputs clearly defined (& stored!)
  – filters can be developed & debugged offline
Generic Damper
tolerating frequency sweep

FIFO needed due to phase shifts between DAC and ADC clocks as beam accelerates
Echotek Card Used for Initial Dampers

EIGHT CHANNEL
ANALOG TO DIGITAL CONVERTER
WITH DIGITAL RECEIVER
ECDR-814/X-AD

FEATURES

- 8 IF INPUTS
- SIMULTANEOUS SAMPLING
- EIGHT ANALOG TO DIGITAL CONVERTERS (ANALOG DEVICES AD6645, 14 BIT, 65 MSPS)
- SFDR > 90 dB FS
- HEADER INSERTION
- VME 64X, SINGLE SLOT
- RACE++ OUTPUT
- AVAILABLE AS A/D CONVERTER AS AN 8, 4, OR 2 CHANNEL MODULE
- VARIABLE GAIN (-10 TO +20 dB) OR LOW PASS FILTER

PRIETO, MEYER ET. AL. EVALUATING 65MHZ DDC FOR RR BPM UPGRADE
ASMANSKAS, FOSTER, SCHAPPERT TESTING 105 MHZ VERSION FOR RR DAMPERS

212 MHz DAC Daughter Card (S. Hansen/PPD) due this week

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Digital Signal Processing with FPGA’s

• Commercial card from Echotek
  – 8 channels of 14-bit, 106 MHz Digitization

• One card does all dampers for one machine

• Customized FPGA firmware
  – Bill Ashmanskas
  – GW Foster
  – Warren Schappert…

• Handles Wide Variety of Bunch Structure
All-Coordinate Digital Damper

- Stripline Pickup
- Power Amp
- > 27 MHz

- Transverse Dampers
- Identical X & Y
- Resistive Wall Monitor
- Broadband Cavity
- Longitudinal (Z) Damper

- Fast ADC
- Minimal Analog Filter
- FAST DACs

- Monster FPGA(s)
- 53 MHz, TCLK, MDAT,....
- 106 / 212 MHz
- 14
- 2-10

- VME

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New Damper Board (A. Seminov)

• **SINGLE** high-end FPGA  (vs. 5 on Echotek)
• Four 212 MHz ADCs       (vs. 106 MHz on Etk.)
• Four 424 MHz DACs       (vs. 212 MHz on Etk.)
• Digital Inputs:
  – TCLK, MDAT, BSYNCH, 53 MHz, AA
• Digital Outputs:
  – Pbar/P TTL, scope trigger, 1 GHz serial Links..
• NIM module with Ethernet interface to ACNET

☞ Other possible uses include replacing entire Booster LLRF system, and Universal BPM.
Recycler Broadband RF Cavity
(3 similar new for broadband damper)

Non-Resonant Cavity looks like 50-Ohm Load in parallel with a large Inductor
Wideband Power Amplifiers

- Recycler has four of these amps, capable of generating +/-2000V or arbitrary waveform.
- MI (D. Wildman) ordered 3 more for longitudinal Dampers, due ~May.

~1800V of broadband voltage in MI
Pbars vs. Proton Timing: Longitudinal

- 3 Cavities spanning 5-10 meters
- Bunch-by-bunch kick needs separate fanout for Protons and Pbars
- Either:
  - One DAC per Cavity
  - Relay switch box with different cable delays
    - this option chosen
    - single TTL bit Pbar-P
“Universal-Damper” Application: Signal Processing Steps (transverse)

1) Bandwidth-Limit input signal to ~53 MHz
2) 14 Bit Digitization at 106 MHz or 212 MHz
3) FIR filter to get single-bunch signal
4) Sum & Difference of plate signals
5) Multi turn difference filter (FIR) w/delay
6) Pickup Mixing for correct Betatron Phase
7) Bunch-by-bunch gain, dead band etc.
8) Timing Corrections for Frequency Sweep
9) Pre-Distortion for Kicker Power Amp
10) Power Amp for Kicker

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1. Longitudinal Damper in Main Injector

1. Benefits to Bunch Coalescing for Collider
   - “Dancing Bunches” degrade Proton coalescing and \( ?_L \)
   - Affects Lum directly (hourglass) and indirectly (lifetime)
   - We are deliberately blowing \( ?_L \) in Booster

2. Benefits for Pbar Stacking Cycles
   - Bunch Rotation is generally turned off! (x1.5 stack rate?)
   - Slip-Stacking etc. (Run IIb) will require stable bunches

3. Needed for eventual NUMI operation
Longitudinal Damper Works by Modulating Phase of RF Zero Crossing

\[ \frac{V_{KICK}}{V_{RF}} = ?? \]
Damping of Bunch Motion by Modulation of Center of Rotation (RF zero-crossing) on Alternate Half-cycles of Synchrotron Motion

Rotation about “A” when Damper senses \( d\theta /dt > 0 \)

Damping Rate is \( 4\theta \) per cycle

Rotation about “B” when Damper senses \( d\theta /dt < 0 \)

Unperturbed Motion in \((?E, ?)\) Phase Space

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Numerical Examples for Longitudinal Dampers

<table>
<thead>
<tr>
<th></th>
<th>MI at Injection</th>
<th>Recycler</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Voltage</td>
<td>1000 kV</td>
<td>2 kV</td>
</tr>
<tr>
<td>Damper Voltage</td>
<td>0.6 kV</td>
<td>0.1 kV</td>
</tr>
<tr>
<td>RF frequency</td>
<td>53 MHz</td>
<td>2.5 MHz</td>
</tr>
<tr>
<td>Sychrotron Freq.</td>
<td>870 Hz</td>
<td>8.5 Hz</td>
</tr>
<tr>
<td>Damping Time for</td>
<td>145 periods</td>
<td>1.7 periods</td>
</tr>
<tr>
<td>20 degree phase osc.</td>
<td>0.17 sec.</td>
<td>0.21 sec.</td>
</tr>
</tbody>
</table>

Damping can be made faster by raising $V_{\text{DAMPER}}$ and/or lowering $V_{\text{RF}}$.
Longitudinal Damper FPGA Logic

Individual Bunches are kicked + or - depending on whether they are moving right or left in phase
FPGA Code for Longitudinal Damper

-- Longitudinal Damper (53 MHz Bunch-by-Bunch)

-- Damper senses direction that bunch phase is changing, with RC lowpass filter to suppress noise.
-- RC filter takes a fraction of the difference between incoming sample and current value of filter,
-- and adds this fraction to the filter value for next time. (The fraction determines filter time constant).
-- This procedure makes equilibrium value of filter equal to the incoming value, independent of time constant chosen.
-- This property is useful so that schmidt-trigger hysteresis value on filter output independent of time constant.
-- VME register selects time constants of 1, 2, 4 or 8 turns (corresponding to fraction = 1/0.5, 0.25 or 0.125)

-- bunch-by-bunch storage for filter output values (slightly less than 1 turn to allow for pipelined filter calcs)
() = delay_longfilt : alshift_taps()
  with (NUMBER_OF_TAPS=1, TAB_DISTANCE=RING_HARMONIC_NUMBER=1, WIDTH=16) returns (.taps[0]);

-- RC filter subtractor to take difference between incoming sample and current value of filter
() = sub_longfilt : lpm_add_sub() with (LPM_WIDTH=16, LPM_DIRECTION="sub") returns (.result[0]);
  sub_longfilt.data[] = Chl.q[]; -- incoming sample: quadrature signal from Chl measure phase
  sub_longfilt.datab[] = delay_longfilt.shiftout[]; -- minus current filter value

-- arithmetic shifter to choose 1-turn, 2 turn, 4-turn, or 8-turn time constant
() = shifter_longfilt : lpm_clshift()
  with (LPM_WIDTH=16, LPM_WIDTHDIST=2, LPM_SHIFTTYPE="ARITHMETIC") returns (.result[0]);
  shifter_longfilt.data[] = sub_longfilt.result[]; -- input from subtractor (new value-filter value)
  shifter_longfilt.distance[1..0] = reg_DDLG12.q[1..0]; -- shift count controlled by register bits
  shifter_longfilt.direction = VCC; -- shift direction always to right (makes fraction 1/1/2/1/8)

-- Pipelined Adder to apply shifted difference to previous filter value to get longitudinal kick value
() = long_kick : lpm_add_sub() with (LPM_WIDTH=16, LPM_DIRECTION="add", LPM_PIPELINE=1) returns (.result[0]);
  long_kick.data[] = shifter_longfilt.result[]; -- add fraction from shifter
  long_kick.datab[] = delay_longfilt.shiftout[]; -- filter value from last time
  long_kick.clock = adclkby2;

-- Return filter value to shift register for next time around
  delay_longfilt.shiftin[] = long_kick.result[];
  delay_longfilt.clock = adclkby2;
  Longitudinal_Kick[] = long_kick.result[];

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MI Longitudinal Damper

(Ashmanskas, Foster)

? 80 Bunch-by-Bunch synchrotron oscillations (on Pbar Stacking Cycle) measured with Echotek board & custom firmware

Single Bunch Digital Kick ? using Digital Velocity Filter implemented in FPGA firmware
MI Longitudinal Damper Kick Calculated in FPGA Firmware

(Ashmanskas, Foster)
ACNET Issues

• Damper must behave differently for different bunches ✈ bunch-by-bunch RAM
  – Specifies Damper Gain, anti damp, noise injection, pinging, etc. on bunch-by-bunch basis.

• Damper must behave differently on different MI cycles
  – Each control register becomes an ACNET Array Device indexed by RF State
  – Register contents switch automatically when MI State changes (D. Nicklaus)
## ACNET Control Devices (>250 total)

- **MasterControl**
  Registers typically single devices

- Most control registers are array devices indexed by MI State

<table>
<thead>
<tr>
<th>Command</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/D</td>
<td></td>
<td></td>
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<td>Conv-U</td>
<td></td>
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<tr>
<td>Copies</td>
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</tr>
</tbody>
</table>

**Example Code:**

```
T4 D/ 5 V 473.15 473.9 303.2 303.47
fbc... sbd... sgev... ibem's tune... ipm... toroid DAMPER
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
I:DDCM38 Damper MI State Selac 0 0
```
I34

COMMAND ---- Volts I= 0 I= 475.16 , 473.9 , 303.2 , 303.47
-< 2>+ One+ AUTO F= 600 F= 475.19 , 473.93 , 303.23 , 303.5

fbi.... sbd.... 8gev... ibeam's tune... ipm.... toroid DAMPERS
-I:DDCMSS Damper MI State Select 0 0

!THRESHOLD THRESHOLDS AND DIAGNOSTICS
!-------------------------------------------
-I:DD2THF Z Dampr Thresh Beam P 0 0

! THRESHOLD FOR BEAM KICKED [0:30]
-I:DDXTHK X Dampr Thresh to Kic 0 0
-I:DDYTHK Y Dampr Thresh to Kic 0 0
-I:DDZTHK Z Dampr Thresh to Kic 0 0

!NUMBER OF BUNCHES PRESENT ABOVE THRESHOLD
I:DDXNPR X Dampr Nbr Bunches P 0 Bnch
I:DDYNPR Y Dampr Nbr Bunches P 0 Bnch
I:DDZNPR Z Dampr Nbr Bunches P 0 Bnch

! NUMBER OF BUNCHES KICKED (INCL. PINGER)
I:DDXNKI X Dampr Nbr Bunches K 0 Bnch
I:DDYNKI Y Dampr Nbr Bunches K 0 Bnch
I:DDZNKI Z Dampr Nbr Bunches K 0 Bnch
COMMAND ---- Volts I= 0 I= 475.16 , 473.9 , 303.2 , 303.47
-< 5>+ One+ AUTO F= 600 F= 475.19 , 473.93 , 303.23 , 303.5

fbi.... sbd.... 8gev.... ibeam's tune.... ipm.... toroid DAMPERS
-I:DDCMSX Dampr MI State Selec 0 0

! DAMPER TIMER DEVICES
! ----------------------

! TIME BASE (NONEXISTS)
-I:DDXTBA X Dampr Time Base 0 0
-I:DDYTBA Y Dampr Time Base 0 0
-I:DDZTBA Z Dampr Time Base 0 0

!DAMPER FIRST TURN [0:30] 21 BITS
-I:DDXD1T X Dampr 1st Turn Acti 0 0 Turn
-I:DDYD1T Y Dampr 1st Turn Acti 0 0 Turn
-I:DDZD1T Z Dampr 1st Turn Acti 0 0 Turn

!DAMPER LENGTH IN TURNS [0:30] 21 BITS
-I:DDXDLT X Dampr Length in Tur 0 0 Turn
-I:DDYDLT Y Dampr Length in Tur 0 0 Turn
-I:DDZDLT Z Dampr Length in Tur 0 0 Turn

! DAMPER TURN COUNTER SINCE MI RESET (NEEDS DDXBKO)
I:DDXTCR X Dampr Turns since R 2 Turn
I:DDYTCR Y Dampr Turns since R 223076 Turn
I:DDZTCR Z Dampr Turns since R 223076 Turn

! DAMPER TURNS ACTIVE COUNTER
-I:DDXDTA X Dampr Active Turns 0 Turn
-I:DDYDTA Y Dampr Active Turns 0 Turn
-I:DDZDTA Z Dampr Active Turns 0 Turn

!NUMBER OF MI RESETS
-I:DDXNR X Dampr MI 19143 19156 19156
-I:DDYNR Y Dampr MI 19144 19157 19157
-I:DDZNR Z Dampr MI 19133 19146 19146
I34

COMMAND ---- Volts I= 0 I= 475.16, 473.9, 303.2, 303.47
<- 7>+ One+ AUTO F= 600 F= 475.19, 473.93, 303.23, 303.5

fbi.... sbd.... 8gev.... ibeam's tune.... ipm.... toroid DAMPERS

BEAM PINGER CONTROL REGISTERS

PINGER ENABLE/MUTE[0:30] 0=OFF, 1=MUTE, 2=ON
-I:DDXPMEN X Dampr Finger Ena/Mu 0 0
-I:DDYPMEN Y Dampr Finger Ena/Mu 0 0
-I:DDZPMEN Z Dampr Finger Ena/Mu 0 0

PINGER TUNE REGISTER [0:30] PARTS PER 1E6
-I:DDXPTU X Dampr Finger Tune 0 0
-I:DDYPTU Y Dampr Finger Tune 0 0
-I:DDZPTU Z Dampr Finger Tune 0 0

PINGER TUNE COUNTER
-I:DDXPTC X Dampr Finger Tune C 0 0
-I:DDYPTC Y Dampr Finger Tune C 0 0
-I:DDZPTC Z Dampr Finger Tune C 0 0

PINGER TUNE BIT
-I:DDXPBBI X Dampr Finger Tune B 0 0
-I:DDYPBBI Y Dampr Finger Tune B 0 0
-I:DDZPBBI Z Dampr Finger Tune B 0 0

PINGER GAIN REGISTER (NONEXISTS)
-I:DDXPGA X Dampr Finger Gain 0 0
-I:DDYPGA Y Dampr Finger Gain 0 0
-I:DDZPGA Z Dampr Finger Gain 0 0

PINGER MODE AND PINGER XOR REGS (NONEXIST)
-I:DDXPMO X Dampr Finger Mode 0 0
-I:DDYPMO Y Dampr Finger Mode 0 0
-I:DDZPMO Z Dampr Finger Mode 0 0
-I:DDXPMO X Dampr Finger XOR 0 0
-I:DDYPMO Y Dampr Finger XOR 0 0
-I:DDZPMO Z Dampr Finger XOR 0 0
fbi.... sbd.... 8gev... ibeam's tune... ipm.... toroid DAMPERS
-I:DDCMSS Damper MI State Select 0 0

! PINGER ACTIVE SIGNAL
I:DDXPAC X Dampr Pinger Active 0
I:DDYPAC Y Dampr Pinger Active 0
I:DDZPAC Z Dampr Pinger Active 0

! PINGER 1ST TURN TO ACTIVATE
-I:DDXP1T X Dampr Pinger 1st Tu 0 0
-I:DDYP1T Y Dampr Pinger 1st Tu 0 0
-I:DDZP1T Z Dampr Pinger 1st Tu 0 0

! PINGER LENGTH IN TURNS TO STAY ACTIVE
-I:DDXP1T X Dampr Pinger Len.Tu 0 0
-I:DDYP1T Y Dampr Pinger Len.Tu 0 0
-I:DDZP1T Z Dampr Pinger Len.Tu 0 0

! PINGER 1ST BUCKET TO HIT
-I:DDXP1B X Dampr Pinger 1st Bk 0 0
-I:DDYP1B Y Dampr Pinger 1st Bk 0 0
-I:DDZP1B Z Dampr Pinger 1st Bk 0 0

! PINGER LENGTH IN BUCKETS TO HIT
-I:DDXP1B X Dampr Pinger Leng. 0 0
-I:DDYP1B Y Dampr Pinger Leng. 0 0
-I:DDZP1B Z Dampr Pinger Leng. 0 0

! PINGER ACTIVE TURN COUNTER
I:DDXPAT X Dampr Pinger Turnco 0
I:DDYPAT Y Dampr Pinger Turnco 0
I:DDZPAT Z Dampr Pinger Turnco 0
What ADC Clock Speed is needed?

• ~53 MHz Bandwidth limited signal, sampled by 106 MHz ADC, measures either in-phase (cosine) or quadrature (sine) component – but not both ==> ADC clock phasing matters!

• 212 MHz sampling measures both in-phase and quadrature components. Phasing is not critical to determine vector magnitude.

• 212 MHz ⚪ built in phase measurement
Bandwidth Limit Signal

• Raw signal has high-frequency components which can cause signal to be missed by ADC
  – “Aliasing”

• Bandwidth limited signal (to ~50 MHz) cannot be missed by 106 MHz ADC

• Eliminate low-frequency ripple, baseline shifts, etc. with Transformer or AC coupling
  – Digital Filtering can provide additional rejection
Gaussian Filter - Impulse Response

- Spreads signal +/-5ns in time so it will not be missed by ADC
- Reduces ADC Dynamic Range requirement, since spike does not have to be digitized

- Many implementations, e.g. traversal filter
In-Phase and Quadrature Sampling

"A - B" gives bunch-by-bunch "in-phase" signal

"D - (C+E)/2" gives bunch-by-bunch "out-of-phase" or "quadrature" signal

Vector Sum $\sqrt{I^2 + Q^2}$ is insensitive to clock jitter

• This is the argument for sampling at 2x Nyquist