

Measurements of the PSB LLRF multi-harmonic beam loading compensation system

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CONCLUSIONS





CONTEXT - CERN ACCELERATOR COMPLEX



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CONTEXT - PSB FINEMET SYSTEM

Ring4

Ring3

Ring2

Ring1

Proton Synchrotron Booster



- 4 super-posed rings
- Accelerating from 160 MeV to 1.4 - 2 GeV
- Large revolution frequency sweep: 0.994 kHz-1.81 MHz (factor of 2 increase)





Modular RF System: Finemet Magnetic Alloy (MA) wide-band cavities



- 3 sectors per ring (S5, S7, S13)
- 12 cells per sector \Rightarrow 36 cells per ring
- Max $V^{PK} = 8 \text{ kV per sector}$
- Multi-Harmonic operation \Rightarrow operational flexibility





CONTEXT - BEAM STABILITY

Wide-Band response of the Finemet loaded cells require actions on many harmonics



Longitudinal impedance:

- Mainly resistive in the operational range
- $f_{RF} = h \times f_{REV}$ (h = 1,...,16)
- Fast RF feedback applied

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Further impedance reduction on the revolution frequency lines by **long delay feedback**

General: induced voltage by a beam undergoing longitudinal oscillations has power at the discrete frequencies:

$$f = f_{RF} \pm n f_{REV} \pm m f_S$$

At carrier frequency: Stationary beam loading Side-Bands at f_{REV}: transient beam loading Side-Bands at synchrotron frequency : f_{REV} with phase modulation at f_S

PSB: $f_{RF} = f_{REV} \rightarrow Narrow-Band Multi-Harmonic$ feedback wit fREV side-bands treated individually



CONTEXT - BEAM STABILITY

PSB 2 GeV cycle



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Longitudinal stability dependent on LLRF system configuration.

One example: When servo-loops active observation of instabilities in Single RF operation starting at low intensities.

→ Characterization of the LLRF for model implementation in macroparticle simulator BLonD (Beam Longitudinal Dynamics) [2].





One servo-loop per each revolution harmonic:





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One servo-loop per each revolution harmonic:



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One servo-loop per each revolution harmonic:



Finemet cavity

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Measurements on a Test-Stand of the LLRF cavity control system isolated from the cavity.

Measurement setup[3][4]



Configuration:

- Cavity emulated by cable
- Induced voltage to be compensated emulated by excitation given by the **VNA**
- VNA Port 1 gives the excitation
- VNA Port 2 detects the excitation
- Cavity loops suppress the excitation close to the revolution harmonic
- Set-Point to 0









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Harmonic 1 at 1 MHz (Flat-Bottom):
Attenuation: ~ - 60, -65 dB
-3 dB Band-Width: 11.5 kHz

Harmonic 1 at 1.81 MHz (Flat-Top):
Attenuation: ~ - 55, -60 dB
-3 dB Band-Width: 16.4 kHz

Harmonic 8 at 1 MHz (Flat-Bottom):
Attenuation: ~ - 60, - 65 dB

•-3 dB Band-Width: 7.67 kHz

Harmonic 8 at 1.81 MHz (Flat-Top): • Attenuation: ~ -60 dB • -3 dB Band-Width: 12.2 kHz

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Evaluation of filter response in a frequency range around the resonant frequency spanning a fs of 2 kHz (pink span) and 6 multiples of it (blue span).



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HARDWARE CHARACTERIZATION - COMPARISON



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Same setup but LLRF connected to the cavity and



CERN

HARDWARE CHARACTERIZATION - COMPARISON

Total Transfer Function with external VNA and closed loop response measured with the Embedded VNA.[5]



The embedded Network Analyser sweeps the the RF Drive signal itself. \rightarrow Action of the loop chain on the signal without the compensation \Rightarrow Pass-band response







HARDWARE CHARACTERIZATION - MODELING



For simulation purposes: need a model reliably describing the filter action to be used to benchmark measurements and validate impedance model.

→Fit with **Resonator** model based on test-stand measurements:

Not accurate enough to describe the filter steadystate transfer function.

Working on a better fit and beam-based measurements to gain information about transient beam loading behaviour.



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HARDWARE CHARACTERIZATION - BEAM - BASED MEASUREMENTS

Measurements in Single RF at injection (160 MeV): transient state. Scans in intensity to evaluate beam loading through the demodulated I and Q components. Time needed at injection to compensate beam loading is inversely proportional to the -3 dB BW.



Single RF

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Double RF





CONCLUSIONS

- PSB Finemet RF System introduces large broad-band longitudinal impedance
- Fast and slow RF feedback action required to reduce beam loading effects
- Unstable behaviour at low intensity happening in Closed-Loop and Single RF operation
- LLRF modular cavity control system acting on multiples of the revolution frequency
- TEST-STAND MEASUREMENTS
 - Small effects of harmonics and frequencies on Transfer Function (TF) parameters
 - Consequential change in the TF at higher multiples of fs
- INJECTION TRANSIENT MEASUREMENTS
 - No effect from bunch length at h = 1
 - Effect from peak current and bunch length at h = 2
- MODELING
 - Previous model does not accurately reproduce the steady-state behaviour
 - Transient behaviour to be included





References

- [1] Courtesy of Mauro Paoluzzi, CERN
- [2] H. Timko et al., Phys. Rev. Accel. Beams, vol. 26, 2023.
- [3] Courtesy of Marco Niccolini, CERN
- ISBN: 978-3-95450-182-3.
- Proton Synchrotron Booster", in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 907-910.
- •[6] Courtesy of Diego Barrientos, CERN
- [7] Courtesy of John C. Molendijk, CERN

•[4] M.E. Angoletta et al., "Control and Operation of a Wideband RF System in CERN's PS Booster", in Proc. 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, paper THPAB141, pp. 4050-4053,

• [5] D. Barrientos, S. C. P. Albright, M. E. Angoletta, A. Findlay, M. Jaussi, and J. C. Molendijk, "A New Beam Loading Compensation and Blowup Control System Using Multi-Harmonic Digital Feedback Loops in the CERN







Back-Up Slides

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CONTEXT - FINEMET CAVITY SERVO-LOOPS

N => 19 S<u>etp</u>oint M => 20 M = 20 FS Swing -> 4.25 ms Per cavity FS = 8kV * sqrt(2) [6] C42 C18 H1-typ = 8kV total SoftRFSwitch **IQ**reg H1 / cav = 8/3 kV ~FS/4 RF R 8kV-step -> 4.25 / 4 ~1 ms. WrSP MHz100 SP_I (18:0) lout (18:0) SP_lin (18:0) SP_Qin (18:0) Qout (18:0) C24 '1' ce SP_Q (18:0) -7// C25 '0' round_cy testl (18:0) testQ (18:0) loopCtrl: 0 = No Drive 1 = Test Drive oopControl (OpenLoop Demodulator 2 = Setpoint Drive (Open Loop) DriveZero DSP_RF_Ena 3 = Closed Loop C2 control_bypassDSPE na timOnWhileDSPOff timOnWhileDSPOff RF_Rst control_bypassTiming info_timingOn RF_Clk FirmTiming (31:0) firmTimSel_on (12:8) TimingSel or firmTimSel_off(4:0) vectorDeMod_RdData (31:0) mTimingSel off vectorDeMod_Addr (5:2) RFOutO fRange RFDisByOOR FOutOfRange RFDisByOOF VMERdD vectorDeMod_WrDone vectorDeMod_WrData (CLNotPermFault VMEWr vectorDeMod_RdMe vectorDeMod_RdErro VMERdE vectorDeMod_WrMe vectorDeMod_WrE rro VME WrE RF_CII 4 DSP48 ADCAtt RFin (15:0) l_n (18:0) C30 enableCIC Q_n (18:0) 11 C26 RateOut plx mu Λ f_MO FrevM (31:0) Hxl (15:0) LO HxQ (15:0) RF_Rs N => 16 C21 1Q reg **Cavity Rotate Control** WrCavRot locCavRotCos (15:0) cavRotCos (15:0) cavRotSin (15:0) locCavRotSin (15:0) DspSample N => 16 C17 IQreg Loop Rotate Control WrLoopRot loopRotCos (15:0) locLoopRotCos (15:0) loopRotSin (15:0) locLoopRotSin (15:0) RF_Clk RF_Rst N => 16 C34 ------VME Addr (7:2) VMEWrData (31:

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VMERdMem







CONTEXT - FINEMET CAVITY SERVO-LOOPS

Electrical delay : < 1 us between LLRF and Finemet Field regulation using DSP with T = 10 us Fixed frequency Clock with $f_{fix} = 122.7$ MHz



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Modulator:











- Optimised span around each revolution harmonic: \rightarrow Resolution Band-Width = 104 Hz
- Excitation signal sweep time : 600 ms
- Notch filter like frequency response

When the VNA sweep passes by the set revolution frequency the servoloop response is maximal and the RF drive output increases to compensate the emulated beam loading.

| | 600 ms VNA signal | | | |
|--------------------------|-----------------------------------|----------------------|------|---|
| | | RF CAVITY DRIVE sign | nal | |
| | | | | |
| · · · · | TRIGGER starting at | | OSCI | LLOSCO |
| 1.00 V/div -3.800 V 2 | DE50 10.0 mV 6.00 mV | | | Tbase -80 200 m 2.5 MS 1.25 |





HARDWARE CHARACTERIZATION - BEAM - BASED MEASUREMENTS

Measurements in Double RF at Flat-Top (1.4 GeV cycle): sector with accelerating RF off and servoloops not active. Static induced voltage.



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