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A LOW LEVEL RF SYSTEM FOR THE FERMILAB TEVATRON*

K. Meisner, H. Edwards, J. Fitzgerald, and Q. Kerns

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K. Meisner, H. Edwards, J. Fitzgerald, Q. Kerns
*Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois, 60510

Abstract

This paper discusses the design philosophy, hardware, and operation of the Fermilab Tevatron low level RF system. Plans to extend the system for colliding beams physics are also presented.

INTRODUCTION

Basic design goals were established for the Tev low level RF (TLLRF) system in late 1982.
1) The TLLRF system would provide the correct RF frequency without the use of beam feedback loops to facilitate Tevatron accelerator commissioning with very low beam intensities.
2) The system would allow synchronous transfer of Main Ring (MR) accelerator beam into Tev RF buckets.
3) The system would allow programmed control of beam momentum (radial position) as a function of time and/or Tev ramp energy.
4) The system would provide active damping of beam coherent synchrotron oscillations.
5) The system hardware would be configured to facilitate expansion required for Fermilab colliding beams high energy physics.

All of the goals relevant to the Fermilab fixed target physics program have been realized and hardware implemented to date will be described. System modifications necessary for colliding beam physics are in construction and planning stages and will also be discussed.

LOW LEVEL RF OSCILLATOR

Q. Kerns realized the small range of ≈ 1023 Hz in Tev RF frequency between 150 Gev and 1 Tev offered the possibility of accurate frequency programming. A strategy for this was developed from fundamental equations.

$$F_{rf} = \frac{h\beta c}{2\pi R} = \frac{hc}{2\pi R} - \frac{hc}{2\pi R} \times (1-\beta)$$

In the first term;

$$1\text{st} = \frac{hc}{2\pi R} = \frac{hc}{2\pi(R_o+\Delta r)} = \frac{hc}{2\pi R_o(1+\Delta r/R_o)} \approx \frac{hc}{2\pi R_o} - \frac{hc}{2\pi R_o} \times \frac{\Delta r}{R_o}$$

R_o is the centered or "best" beam orbit in the Tevatron, and Δr is an orbit variation from R_o. Neglecting terms of $(\Delta r/R_o)^2$ and higher powers in the expansion introduces only .0053 Hz error per cm. Δr. In the 2nd term; let $R = R_o$, to give $(hc/2\pi R_o)(1-\beta)$. This introduces only .01 Hz frequency error per cm. Δr. Then approximate $(1-\beta)$ by $1/2\gamma^2$. This introduces another error of at most (at E = 150 Gev) .01 Hz. The original equation becomes;

$$F_{rf} \approx \frac{hc}{2\pi R_o} - \frac{hc}{2\pi R_o} \times \frac{\Delta r}{R_o} - \frac{hc}{2\pi R_o} \times \frac{1}{2\gamma^2}$$

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

The worst error from all approximations per cm. Δr is only .0253 Hz when E = 150 Gev. The term $hc/2\pi R_o$ is thought of as the RF frequency of a centered beam as the beam energy approaches infinity, or as β approaches 1. For convenience this term is called F_∞.

The value of F_∞ depends only on R_o, and has been set to 53.104736 Mhz after a measurement of the Tevatron orbit length.[1] The strategy becomes: Use a very stable fixed frequency oscillator at F_∞ and accurately add or subtract two difference frequencies (dF) in the audio range.

DIGITAL PHASE SHIFTER/FREQUENCY MODULATOR ELECTRONICS

Hardware which performs audio frequency addition and/or subtraction from F_∞ is packaged in double wide NIM modules. Refer to Figure #1, a functional block diagram of dF module electronics. A dF module splits an input RF signal into quadrature phase vectors, amplitude modulates each vector appropriately, and sums the resultants to generate an RF output which is phase shifted with respect to the input. As phase shifters, the modules have 360 degree range in 4096 steps for .0879 degrees phase setting resolution. The modules can be clocked to advance or retard the input signal phase at a dF rate of +/- Fclk/4096. The dF module output RF changes are phase continuous, and internal digital logic allows dF = 0.0 Hz. The module initial phase can be digitally preset. The versions of these modules used in the TLLRF system are called dF1 and dF2. The dF1 module receives Fclk from an external source and subtracts dF1 from F_∞ to program the RF frequency as a function of Tev beam energy. The dF2 module internally generates Fclk proportional to the sum of two analog inputs and adds or subtracts dF2 (depending on the desired beam position Δr) from the dF1 output RF frequency. Each module has a dF range of +/- 1200 Hz and a dF frequency setting resolution of .3 Hz.

dF MODULE PROGRAMMING

A module called the K/I^2 GENERATOR receives the Tev magnet current program in digital form from a Camac 169 MDAT receiver module.[2] The K/I^2 module converts the input I_{Dig} to Tev energy by $E(\text{Gev}) = 225.799 * I_{Dig}(\text{KA})$, computes $dF1 = F_\infty/2\gamma^2$, and outputs a clock pulse to the dF1 module external clock input. I_{Dig} updates at a 720 Hz rate and one Lsb is .07629 amps. The dF2 module receives an analog radial position program (RPGM) from a Camac 160 curve generator module.[3] RPGM input scaling is $F_\infty(\Delta r/R_o)$, or -53.1 Hz (for +1mm. outside Δr) per volt. The dF2 module also receives a gated tuning voltage from a phase detector comparing Tev and MR cavity fanback RF signals. The tuning voltage closes a phase lock loop and effects synchronous beam transfer at Tevatron injection. The F_∞/dF1/dF2, K/I^2, phase lock loop, and controls hardware contributed to successful beam acceleration to 512 Gev in the Tevatron on July 3, 1983.

BEAM Φs FEEDBACK SYSTEM

A system to detect and damp beam coherent synchrotron oscillations has been implemented to improve Tev operation.[4] Refer to Figure #2 overall system functional block diagram. The Tev cavity fanback RF sum signal and a detected beam RF signal at 53 Mhz are each heterodyned to 8.83 Mhz in the Φs system front end electronics (8.83 Mhz oscillator, mixers, and band pass filters). These signals input to matched 8.83 Mhz SSB crystal filters with a bandwidth of 2 Khz and generate two continuous RF signals with a relative phase which represents the beam to cavity voltage acceleration angle. This phase is detected and differentiated to give dΦs/dt, which is proportional to beam momentum oscillations around the synchronous particle momentum. The Φs system is also called a "global Δr" system, since dΦs/dt oscillations are equivalent to oscillations in the beam closed orbit length. The dΦs/dt error signal is multiplied by a gain curve (ERGN1) from a Camac 160 and inputs to a voltage controlled phase shifter to provide negative feedback and damping of beam synchrotron oscillations.

BUNCH SPREADER

The bunch spreader module introduces small amplitude phase modulation on the Tev cavity RF to increase the bunched beam momentum spread and enhance slow spill duty factors. The module outputs $V\cos(2\nu_s t)$, where the output amplitude is controlled remotely and the output frequency tracks Tev beam energy and approximates twice the beam synchrotron oscillation frequency. Another remote input allows an output frequency vernier adjustment of +/-10 Hz. Four trigger inputs from remotely controlled Camac 177 modules initiate variable length gates which enable the module output. The output always begins at 0 degrees and stops at 0 or 180 degrees.

FLAT TOP OSCILLATOR

An oven controlled crystal oscillator (TFTOSC) serves as an alternative LLRF source for the Tevatron. The module output frequency tracks Tev energies between 376 Gev and 1 Tev and matches the dF1 output frequency within ≈1 Hz via an input from the K/I^2 generator. The TFTOSC output is phase locked to the F_∞/dF1/dF2 oscillator output, switched in to drive the Tev RF cavities, and then released from lock to assume its own programmed frequency with an (exponential) time constant of .11 sec.

SYSTEM MODIFICATIONS FOR COLLIDING BEAMS HEP

New functionality in all Fermilab RF systems is required to accommodate colliding beams HEP. The Tev RF system must simultaneously accelerate proton and antiproton bunches, provide proton to antiproton bunch displacement (cogging) for collision point azimuthal control, and correctly place beam bunches injected from the MR into appropriate Tev proton or antiproton RF buckets (transfer cogging). Additionally, the Tev LLRF system should provide damping of coherent synchrotron oscillations for each individual bunch. These requirements will necessitate accurate control of proton and antiproton RF cavity relative phase and frequency. dF modules driven by a common Fclk source and placed as shown (dotted) in Figure #2 facilitate this control. Additional hardware to achieve cogging includes two new beam synched clock systems, a cogging phase detector which measures bunch relative displacement in units of Tev RF buckets, and a control module to decide which manipulation to perform depending on the active machine cycle type. The Φs feedback system will be extended to include an antiproton detector and electronics to separately monitor and damp coherent oscillations of each antiproton bunch. Work on these modifications is in a prototype construction stage. Detailed designs and progress reports for cogging control and extensions to the Φs system are complex enough to justify a separate article at a later date.

SUMMARY

The Tev LLRF system has satisfied machine operation requirements from initial implementation and Tevatron accelerator commissioning to the present. Hardware expansion and improvements continue as Tev operational requirements evolve. The challenges presented by the Fermilab colliding beams HEP project are becoming better understood in detail and hardware solutions to realize new system functionality are progressing well.

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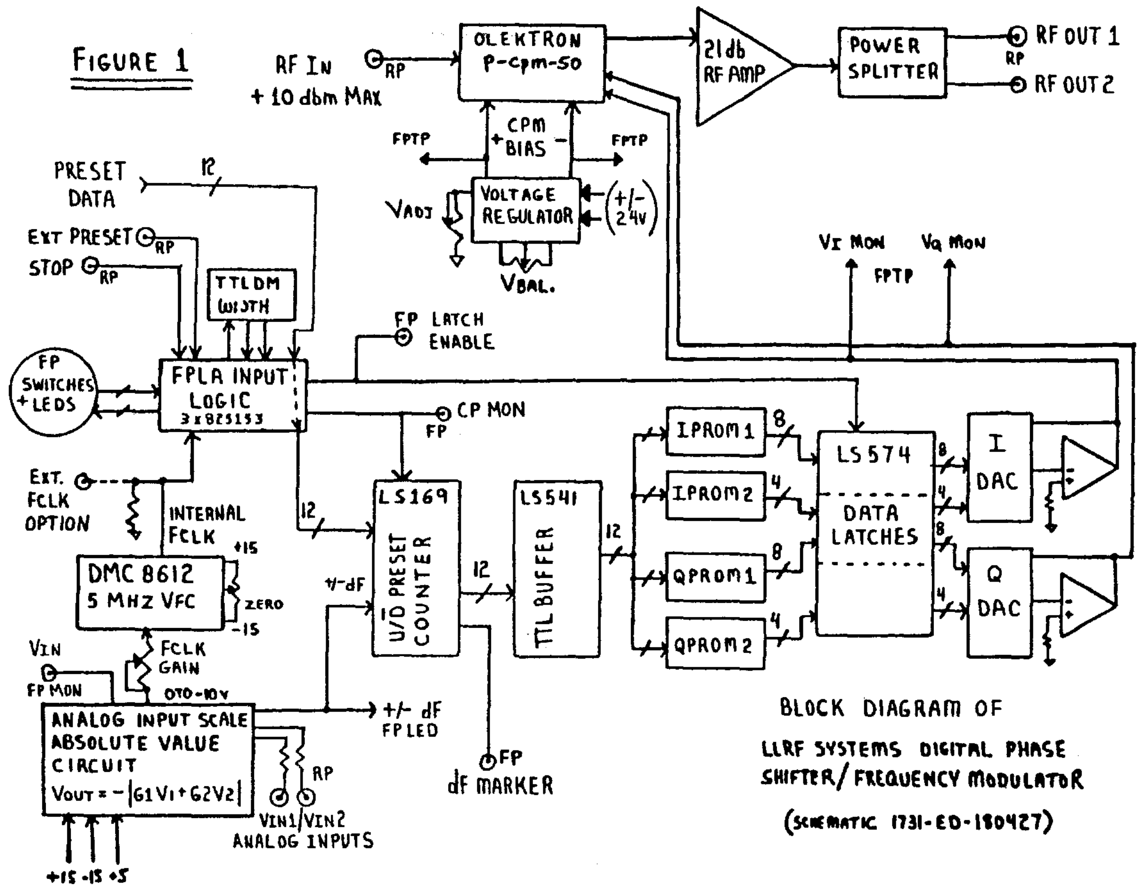
FIGURE 1



BLOCK DIAGRAM OF
LLRF SYSTEMS DIGITAL PHASE
SHIFTER/FREQUENCY MODULATOR
(SCHEMATIC 1731-ED-180427)

TEV LLRF SYSTEM
BLOCK DIAGRAM

FIGURE 2