ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB324

PIP-II 800 MeV PROTON LINAC BEAM PATTERN GENERATOR*

H. Maniar, B. Chase, Fermi National Accelerator Laboratory, Batavia, USA
J. Dusatko, SLAC National Accelerator Laboratory, Menlo Park, USA
S. Khole, D. Sharma, Department of Atomic Energy, Mumbai, India

Abstract

The Beam Pattern Generator is the system that synchronizes the beam injection and the RF systems between the PIP-II LINAC and the Booster. The RF frequencies of these two accelerator systems are not harmonically related. Synchronization is accomplished by controlling two MEBT beam choppers, which select 162.5 MHz beam bunches from the LEBT and RFQ to produce an appropriate reduced beam bunch pattern that enables bucket-to-bucket transfer to the Booster RF at 46.46 MHz (84th Harmonic). This chopping pattern also reduces the beam current to an average of 2 mA over the Booster injection, matching the Linac nominal beam current. The BPG also generates the RF frequency/ phase reference which the Booster will phase lock to during injection. The BPG is fully programmable, allowing for arbitrary beam patterns with adjustable timing parameters, having a fine adjustment resolution of ~ 38 ps. The latter is accomplished using digital signal processing techniques. The paper discusses the design of the BPG, its construction, test results and operational experience after being integrated into the PIP2 IT test accelerator and concludes with a discussion of system's performance and future plan.

INTRODUCTION

Proton Improvement Plan -II

To facilitate the next generation of neutrino experiments, Fermilab is building a Continuous Wave RF, 800 MeV, superconducting H- LINAC PIP-II replacing the existing 400 MeV copper LINAC [1]. The primary goal of PIP-II is to increase the available proton power for neutrino experiments to 1.2 MW. Figure 1 shows the proposed infrastructure upgrade for PIP-II at Fermilab.

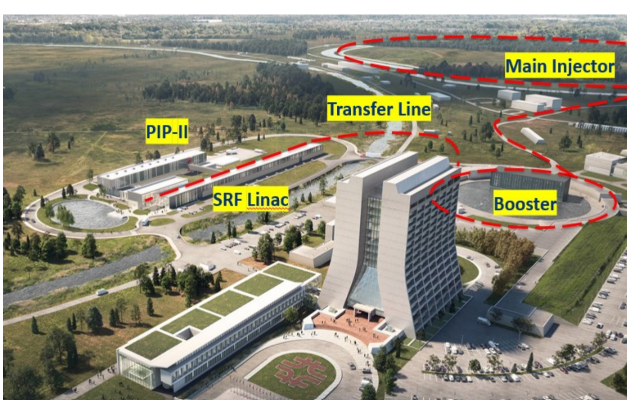

Figure 1: Fermilab PIP-II infrastructure rendering.

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

PIP2 Injector Test (IT) is a test accelerator at Fermilab. PIP2 IT is now operating as an SRF accelerator with beam transported to the high energy beam absorber and acceleration demonstrated through both the half wave resonator (HWR) and single spoke resonator (SSR) cryomodules. PIP2 IT also consists of two ion sources, a low energy beam transport (LEBT), a radio frequency quadrupole (RFQ), and a medium energy beam transport (MEBT).

Beam Pattern Generator

One of the key capabilities of the PIP-II Linac is to deliver defined beam bunch patterns to multiple bunch targets to meet injection or experiment requirements. The Beam Pattern Generator (BPG) is the system that determines the bunch pattern as requested by experiment or by the Booster injection, and provides 1) drive to the MEBT Fast Kickers, 2) the capability to drive the LEBT Chopper, 3) the injection RF signal which the Booster will lock too and 4) a sync pulse for the Booster to generate the Booster revolution marker. The BPG generates a trigger synchronized with the 162.5 MHz and 650 MHz RF based on an external trigger from a source such as a non-RF based clock system. Figure 2 shows system diagram for BPG used at Fermilab PIP2 IT.

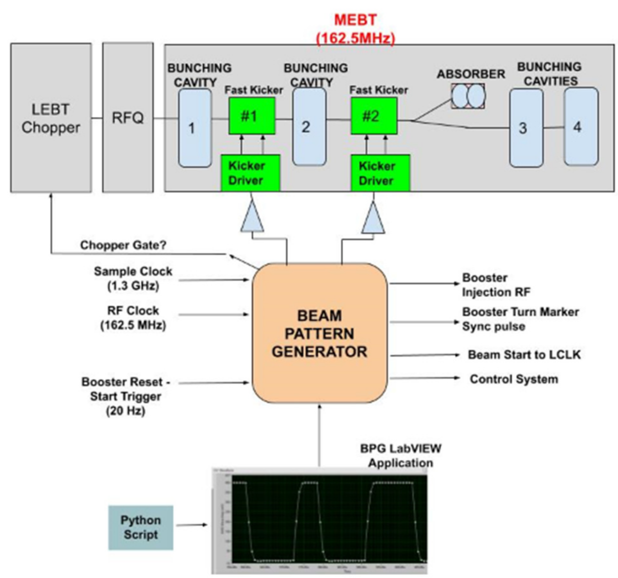

Figure 2: BPG System Diagram.

The BPG and MEBT Fast Kickers are designed to produce a beam pattern at the output of the MEBT in any requested sequence of 162.5 MHz bunches over some time period that is repeated at the 20 Hz machine repetition rate. This arbitrary beam pattern can contain information that span the frequency range from 20 Hz to 81.25 MHz. Fine

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB324

time adjustment with fast rise times increase the bandwidth up to 650 MHz and therefore the systems must maintain an extremely flat amplitude and phase response. The two Fast Kickers are constructed with a pair of spiral coils designed to match signal propagation with the 2.1 MeV beam velocity and give a transverse electrostatic kick to the beam bunches away from the central orbit to be captured by the beam absorber.

The new Booster injection is more complicated because of the longer 550 µs injection period, 20 Hz machine operation and the requirement for synchronized bucket to bucket beam transfers between the two machines. The 162.5 MHz fundamental Linac RF and the Booster RF frequencies are not harmonically related requiring a beam pattern with the exact pattern derived from intersection of 162.5 MHz bunches from the RFQ and a set acceptance angle of the Booster RF buckets at the injection energy. Two of the 82 Booster buckets will have no beam injected into them to provide a kicker gap to reduce beam loss. For the injection scheme to work, the BPG must also provide RF signal with the proper frequency and phase angle for the Booster RF to lock to during the injection period. The BPG must also provide a revolution marker to identify the position of the gap buckets.

SYSTEM DETAILS

BPG system has been tested on bench and at PIP2 IT with MEBT and Fast Kickers with beam and has met all the design requirements of generating waveform beam pattern.

Hardware

Figure 3 shows Beam Pattern Generator chassis, currently being used at PIP2 IT.

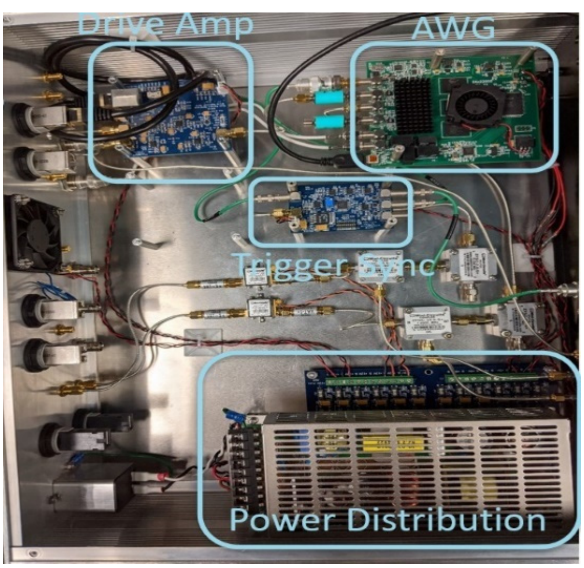

Figure 3: BPG Chassis.

- Arbitrary Waveform Generator (AWG) [2]: Prototype BPG uses 2-channel, 2.5 GSPS/ch WavePond AWG with 1.3 GHz external clock input and provides 750 mVpp, 50 Ω DC coupled outputs.
- Drive Amplifier: This circuit translates single ended 750 mVpp AWG output to 0-1.3 V signal output to kicker electronics.
- Trigger Synchronizer: This circuit receives trigger from timing system and samples trigger to the 162.5 MHz RF clock.

Software

A python script generates a binary file in CSV format where "0" represents the beam bunch allowed to pass through and "1" represents the beam bunch to be kicked out. Each element represents a period of 6.15 ns. This CSV file is an input for BPG LabVIEW application, which generates beam pulse patterns for AWG running at 1.3 GHz clock rate. Key features of this application are adjustable channel delays, rising edge delay, falling edge advance, and phase flip. Both channel delays can be adjusted independently and has ~ 38 ps of time resolution for each value of rising/ falling edge adjustment. Figure 4 shows BPG LabVIEW application generating a 10 µs beam pattern where channel 2 is delayed by 1 µs compared to channel 1.

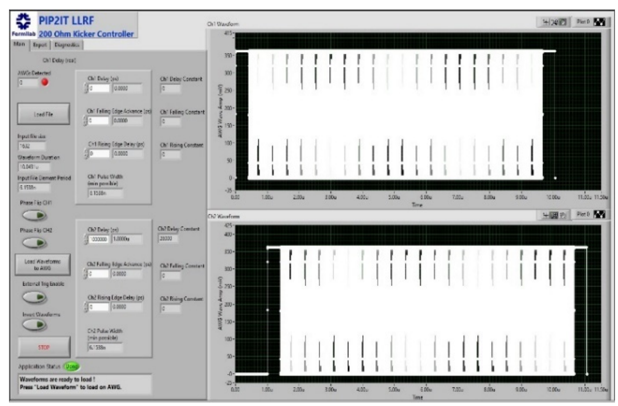

Figure 4: BPG LabVIEW application.

Synchronization

Synchronization is not the key function of BPG but is critical to machine operations and to understand how the required precision is achieved for other functions of BPG. An external trigger from any external source, e.g. a non-RF based clock system, used as input in a synchronizing circuit that will create an output trigger that is precisely aligned with the 162.5 MHz and the 1300 MHz RF. Sub 1300 MHz period alignment is done so that the trigger maintains the setup and hold time requirements of the AWG input circuit. The AWG has output triggers that can now go back to the distributed clock system and any other system that needs precision timing. With this synchronization system the outputs of the AWG channel are stable with respect to the RF and all other AWG channels to the level of the jitter specs of the AWG which is on the order of picoseconds.

Digital Signal Processing

There are many fine timing resolution and precision requirements for the output waveforms and sampling theory tells us that these requirements can be met with the

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB324

relatively low clock rate of 1.3 GSPS. This sample rate allows the generation of a 650 MHz bandwidth signal with exact timing and amplitude within the limits of bandwidth and the resolution of the DACs. To get a timing resolution of ~ 38 ps, all signal processing is done at a virtual rate of 26 GSPS which allows the desired resolution. Final signals are digitally filtered to below the 650 MHz Nyquest frequency, then down sampled to 1.3 GSPS. These signal arrays are loaded into AWG waveform memory and the output of the DACs are run through an analog reconstruction filter. While bandwidth limited, the resolution of ~ 38 ps and amplitude information is faithfully preserved in the analog signal output.

TEST RESULTS

Figures 5 and 6 shows BPG output waveforms. As shown in Fig. 5, channel 2 (green) is delayed by 1 µs as compared to channel 1 (yellow) for a 10 µs pattern. This is the output waveform of BPG channels for the pattern shown in Fig. 4. By default, the BPG generates 6.15 ns (1/162.5 MHz) wide pulses for beam kick and beam pass patterns. This can be adjusted using rising edge delay or falling edge advance parameters.

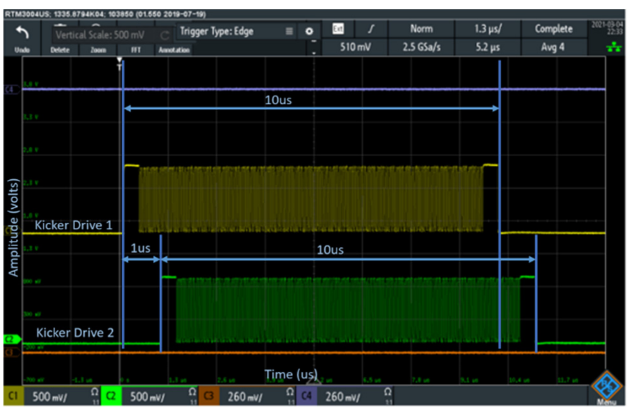

Figure 5: BPG output channels.

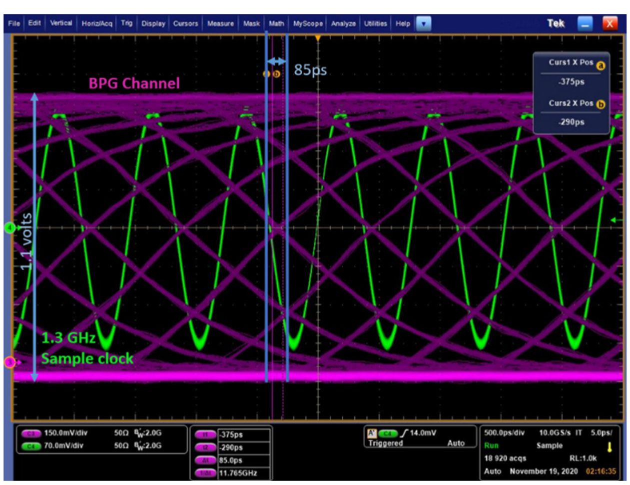

Figure 6: BPG output channel with infinite persistence.

Figure 6 shows one of the BPG output channel (magenta) measured over few minutes span with infinite persistence, triggerd on 1300 MHz sample clock (green). It measured ~ 85 ps peak to peak of electronic jitter and system dispersion tested on bench for both BPG output channels.

SUMMARY

Key features of BPG includes beam pattern for the Booster injection, generate Booster revolution marker, drive the MEBT Fast Kickers and create an output trigger, precisely aligned with the 162.5 MHz RF clock. All features of BPG has been tested with PIP2 IT MEBT and generated beam pattern up to 550us. Beam intensities and bunch patterns mimicking that expected for PIP-II are demonstrated and validated. Beam Pattern Generator is a key component to demonstrate that the beam characteristics for PIP-II are achievable. Based on PIP2 IT experience, several new features have been added and software bugs been fixed. The flexibility of the BPG allows amplitude modulation in any symbol structure up to the Nyquist limit of 81.25 MHz and given this symbol information along with the known transfer function of the RF/cavity system optimal filters provide the theoretical best Signal to Noise Ratio (SNR) with great rejection microphonic and other disturbances. Future development plans for the BPG involves development of a custom BPG circuit board with 4 channel outputs and an EPICS-based controls interface for the PIP-II Linac.

REFERENCES

[1] V. Lebedev, “The PIP-II Reference Design Report”, Fermi National Accelerator Laboratory, Batavia, USA, Rep. FERMILAB-DESIGN-2015-01, Jun. 2015.

[2] Wavepond Dax22000, `https://www.chase-scientific.com/index.html`