ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPS30

DESIGN AND CHARACTERIZATION OF ADJUSTABLE-LENGTH PULSE GENERATOR FOR BEAM KICKER SYSTEM*

B. Nguyen†, B. N. Comiskey, H. J. Gaus III, J. T. Bradley III, E. G. Loftin, E. Huang, H. Patel,
Los Alamos National Laboratory, Los Alamos, USA

Abstract

The contemporary advancement in particle accelerator technology necessitates precise control over beam manipulation for various experimental and industrial applications. One pivotal aspect of this control resides in the generation and modulation of high-voltage pulse to manipulate the trajectory and behavior of particle beams within the accelerator systems. This extensive study delves into the design, development, and characterization of an adjustable-length pulse generator specifically tailored for a beam extraction kicker system, which is employed to navigate the beam out of the photon storage ring. The primary aim of this research is to engineer a versatile and reliable pulse-length modulation mechanism for a high-voltage pulse generation, which can produce adjustable pulses with ultra-fine precision to meet the demanding requirements of beam manipulation within the accelerator setup. The system's design encompasses a meticulous integration of electronic components, waveform shaping modules, and control mechanisms to achieve the desired output.

BEAM KICKER SYSTEM

A beam kicker system deflects the time-selected beam from its circulating or transporting system. The electromagnetic field interact with the selected particles and cause their direction to be diverted [1]. The beam kicker system as illustrated in Fig. 1 consists *of* three main parts, see bullets below:

- **Pulse modulation**: which includes the charging power supply, pulse forming network (PFN), the main switch, the dump switch, and the dump load. The pulse modulator produces a sequence of voltage pulses of a desired amplitude, width, and repetition rate. This voltage pulse will generate an electric field between the electrodes in the deflector [2].
- **Deflector**: The deflector which includes two electrodes with appropriate length generates an electromagnetic field directed at the beam to deflect its direction [3].
- **Termination circuitry**: The termination circuitry absorbs the voltage pulses and support the pulse forming by matching the impedance to avoid the reflection. This can be a short-circuit termination [4].

Other than the above-mentioned parts, the kicker system requires more components for mechanical installation, isolation, and insulation to protect from the high voltage issues. Since the switches are floating at a high voltage level, all its auxiliary circuits such as gate driver circuits, gate-driver power supplies, and gate control circuits should be isolated via a transformer or a digital isolation of the control signals. If a thyratron is used as a switch, its trigger circuits and heater power supplies should be isolated as well [5]. Sensing and protection circuits should be included to monitor the system and shut it down when a fault occurs. The logic interlock should be installed to make sure that the kicker system works in coordination with other systems. In the next section, we will discuss the operation of the kicker system.

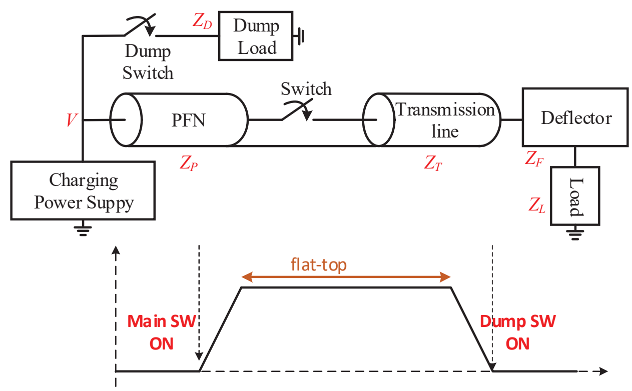

Figure 1: Pulse forming circuit system and the pulse output waveform.

KICKER SYSTEM OPERATION

Although the kicker system can include many more complicated steps related to the overall operation of the particle accelerator. The simplified operation of a beam kicker system can be summarized as follows, assuming that all interlocks are released.

- **Energy charge**: The charging power supply charges the pulse forming network to a voltage level. The charging time is determined by the specifications of the power supplies, the parameters of the PFN, and the additional energy storage components of the modulator. The charging time should be small enough to handle the high repetition rate of the kicker, since the PFN should be charged sufficiently so the next pulse could be released at the proper parameters [6].
- **Rise-time**: Once the PFN is charged, the main switch is triggered ON. The storage energy would release through the transmission line to the deflector and the termination load. The rise time depends on the parameters of the switch and parasitic impedances of the circuit [7].

* This work was supported by Los Alamos National Laboratory's Laboratory Directed Research and Development (LDRD) Program
† email address: bangnguyen@lanl.gov.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPS30

- **Flat-top**: The PFN helps the pulse achieve a flat-top for a period of time. The length of the flat-top is determined by the energy storage in the PFN and the types of the PFN. The dump switch can be used to forcedly reduce this length [8].
- **Fall-time**: When the PFN runs out of energy, or the dump switch is triggered, the pulse would return to zero. The fall-time depends on the impedances of the PFN and related components, similar to the rise-time.

The operation would continue repeatedly as long as the PFN is charged. While the pulse is released from the PFN, it travels through the transmission line toward the load. The impedance of all components in the system should be matched to reduce the pulse reflection. The delay of the pulse traveling through the coaxial cable is depends on the impedance of the cable [4]

DESIGN OF COMPONENT PARAMETERS

The design of a beam kicker system focusses on the specifications and parameters of the devices and components. Key factors are summarized here:

- **Rated voltages and currents**: these basic parameters should be considered first when choosing components and devices for a kicker system. All components and devices should be able to handle the desired voltages and currents.
- **Isolation level**: Since the switches are floating, the auxiliary circuits such as controller, gate driver, heater, and sensing circuits should be appropriately isolated from the main power components.
- **Insulation, clearance and creepage**: A kicker system may operate up to 50 kV or higher, components should be insulated and maintain a safe clearance and creepage A sealed tank with insulating oil can be considered to safely operate the kicker system [9].
- **Radiation resistant**: The deflector and transmission line may be exposed to high radiation, so the radiation resistant should be considered. The fire resistance also need to be taken into consideration if needed [8].
- **Impedance matching**: to hinder the reflection, the impedance of all components in the entire system should be matched.

Other parameters and factors are also critical. Next, we discuss the choices of main components of the kicker system.

- **Capacitor charging power supply**: This power supply usually runs in resonant mode to improve the efficiency. The input source should be universal from 90 VAC to 260 VAC 50/60 Hz then we can use it under any power systems. This power supply should have a power factor correction at its rectified stage to reduce the harmonic emissions back to the grid. The electromagnetic interference (EMI) and radio frequency interference (RFI) should also be low. The voltage and current regulation should be as accurate as possible [6].
- **PFN:** This can be configured by a sufficiently long coaxial cable as Fig. 2 [10]. The cable-type PFN provides low ripple, but it requires low attenuation to control droop. In CERN, an artificial PFN is made of lumped elements as resistors, capacitors and inductors [9].
- **Switch:** Traditionally, a thyratron is used for the power switch since some operate up to 80 kV voltage and 10 kA current. The transition time can be as fast as 20 ns rise time and 2 kHz switching frequency operation. However, the thyratron and vacuum tube devices are becoming obsolete. It is only a closing switch and cannot be forcedly opened. Thyratron operation is limited at the repetition rate of a few kHz [11]. Solid-state semiconductor devices can be an alternative. None the less, there are still many challenges ahead to mature solid-state technology. Recent advances of wide band gap devices such as Silicon Carbide and Gallium Nitride have increased the power handling capacity, the operating frequency, and the reverse recovery of semiconductor power switches [12]. Since these devices can be turned on and off, the design of pulse modulators has more options. We discuss this in SOLID STATE SWITCHES.
- **Deflector:** This is the electrode or the kicker magnet which is installed in the beam line to deflect the beam. The length of the kicker magnet can be calculated based on the deflected angle, the electromagnetic field, and the beam velocity at the installation area [13]. The design of the deflector effects the rise and fall times. The material of this component should be radiation resistant since it is exposed directly to the beam.
- **Load:** The termination load can be designed with impedance matching to eliminate reflections.

Overall, many important factors need to be considered in the design of the kicker system. Further than the above-mentioned components, there are other issues that need to be considered such as beam coupling, grounding, shielding, material and mechanical design [14].

Figure 2: Coaxial cable and ferrite core used as Blumein PFN at LANSCE.

SOLID STATE SWITCHES

With the above-mentioned disadvantages of the thyratron, solid-state switches are commonly employed as an alternative [15]. Traditionally, the semiconductor switches are based on silicon materials (Si) such as IGBTs, MOSFETs. Although an IGBT can handle higher voltage

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPS30

and power when compared to a MOSFET, its operating frequency is only up to a few kHz. MOSFETs can work up into the Mhz, but it has reverse recovery problems. MOSFETs cannot handle high transient voltages or currents. Wide band gap devices offer superior power handling capabilities, low on-resistance, and fast transition response. With their wide bandgap properties, SiC/GaN devices can efficiently handle high-frequency switching and deliver high-voltage pulses, making them ideal for high-power applications like the beam kickers. The use of solid-state switches can offer greater variability in pulse width as the switch can be turned off completely. Inductive voltage adders are a widely used configuration that are used to stack up the voltage pulse for beam kicker applications [4].

CONCLUSION

This paper summarizes the configuration of a kicker system, highlighted key components and factors in the design and installation. In addition, the paper discuss how recent advances on wide-band-gap devices benefits the development of future kicker systems. These devices offer superior power handling capabilities, low on-resistance, and fast transition response. With their wide bandgap properties, SiC/GaN devices can efficiently handle high-frequency switching and deliver high-voltage pulses, making them ideal for high-power applications like the beam kicker.

REFERENCES

[1] H.W. Alvestad *et al.*, "The Lansce Switchyard Kicker Project", *Proceedings of the 2005 Particle Accelerator Conference*, Knoxville, TN, USA, May 2005, pp. 3310–3312. doi:10.1109/pac.2005.1591451

[2] A. Benwell *et al.*, "A 5KV, 3MHz Solid-state Modulator Based on the DSRD Switch for an Ultra-fast Beam Kicker", *2012 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, San Diego, CA, USA, Jan. 2012, pp. 328-331. doi:10.1109/ipmhvc.2012.6518746

[3] F. Bulos *et al.*, "Some Fast Beam Kicker Magnet Systems at SLAC", SLAC, USA, SLAC-PUB--4178, p. 1884, Jan. 1987.

[4] Johannes Ruf *et al.*, "Requirements for an Inductive Voltage Adder as Driver for a Kicker Magnet with Short Circuit Termination" in *Proc. IPAC'21*, Campinas, Brazil May 2021, pp. 3521–3524. doi:10.18429/JACoW-IPAC2021-WEPAB351

[5] B. Morris and R. B. Saethre, "Thyratron stability improvements of SNS extraction kicker system" *2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, San Francisco, CA, USA, 2016, pp. 84–87. doi:10.1109/ipmhvc.2016.8012902

[6] Y.-F. Liu, M. Gu, Q.-B. Yuan, R. Wang, J. Tong, and S. Li, "Development of a MHz Pulsed Power Supply for Kicker Magnet in SHINE", IEEE Trans. Power Electron., vol. 39, no. 4, pp. 4291-4300, Apr. 2024. doi:10.1109/tpel.2023.3347748

[7] B. Goddard *et al.*, "SPS Injection and Beam Quality for LHC Heavy Ions With 150 ns Kicker Rise Time", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 1360-1362. doi:10.18429/JACoW-IPAC2016-TUPMR048

[8] J. Power, B. Blind, and A. J. Jason, "The los Alamos Proton Storage Ring Fast-Extraction Kicker System", *IEEE Trans. Nucl. Sci.*, vol. 32, no. 5, pp. 3021–3023, Oct. 1985. doi:10.1109/tns.1985.4334261

[9] M. Barnes, "Kicker Systems", *CERN Yellow Rep. School Proc.*, vol. 5, p. 229, 2018. doi:10.23730/CYRSP-2018-005.229

[10] C. Tsukishima and S. Nakata, "An Fast Extraction Instrument of Low Charging Voltage with Small Residual Field using Series Blumlein Line Modulators", *IEEJ Transactions on Industry Applications*, vol. 112, no. 9, pp. 891–898, 1992. doi:10.1541/ieejias.112.891

[11] R. Saethre *et al.*, "Thyratron replacement for the spallation neutron source linac extraction kicker PFN system", *2015 IEEE Pulsed Power Conference (PPC)*, Austin, TX, USA, 2015, pp. 1–6. doi:10.1109/ppc.2015.7297034

[12] Y. Chen *et al.*, "Comparative Study on Driving Switching Characteristics of GaN-FET and SiC-MOSFET in Transient High Voltage Pulse Discharge Circuit", *2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE)*, Beijing, China, 2020, pp. 1-4. doi:10.1109/ICHVE49031.2020.9279479

[13] C. R. Rose and D. H. Shadel, "Design of a pulsed-current source for the injection-kicker magnet at the Los Alamos Neutron Scattering Center", *Digest of Technical Papers. Tenth IEEE International Pulsed Power Conference*, Albuquerque, NM, USA, 1995, vol.2, pp. 1432-1436. doi:10.1109/ppc.1995.599818

[14] W. Zhang *et al.*, "Design considerations of fast kicker systems for high intensity proton accelerators", *PPPS-2001 Pulsed Power Plasma Science 2001. 28th IEEE International Conference on Plasma Science and 13th IEEE International Pulsed Power Conference. Digest of Papers (Cat. No.01CH37251)*, Las Vegas, NV, USA, vol. 1, pp. 302–305, 2001. doi:10.1109/ppps.2001.1002052

[15] I. Roth, "Solid-State Thyratron Replacement. Final Report", Diversified Technologies, Bedford, MA, USA, Rep. DOE-DTI-11292, Dec. 2017. doi:10.2172/1414582