ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR39

REVIEW OF KNOWN EXTRACTION KICKERS

H. Gaus III, B. Nguyen, B. Comiskey, J. Bradley III, E. Loftin
Los Alamos National Laboratory, Los Alamos, United States

Abstract

The following paper embarks on an in-depth exploration of extraction kickers employed at some of the most renowned particle physics and neutron science facilities worldwide. Specifically, we delve into the extraction kickers utilized at the Spallation Neutron Source (SNS), Fermi National Accelerator Laboratory (Fermilab), Los Alamos Neutron Science Center (LANSCE), and delve into the novel inductive adder structures. These facilities represent the forefront of scientific research, housing state-of-the-art technologies and extraction kicker systems that play a fundamental role in advancing our understanding of particle physics, neutron science, and related domains. Throughout the paper, we will investigate the design principles, operational intricacies, and technological innovations associated with these extraction kickers. By analysing existing research and scholarly works, we aim to provide a comprehensive overview of the unique challenges and advancements encountered at each facility. Furthermore, we seek to uncover the contributions made by these extraction kickers in enhancing the precision and reliability of experiments, elucidating the mysteries of the subatomic world, and propelling scientific discovery forward.

INTRODUCTION

Kickers play pivotal roles in the operation of modern linear and ring-based accelerators, both in terms of beam steering, selection and guidance; and in terms of diagnostics. In LINACs (Linear Accelerators), kickers are used to provide fast steering and directional control of the accelerated beams. In rings, kickers are used to inject and extract beams. In both LINAC and ring-based accelerators, kickers can play vital roles in beam diagnostics via introduction of short, controlled perturbations to the beam trajectory.

This review will focus on the design principles, operational intricacies, and technological innovations associated with these extraction kickers. By analysing existing research and scholarly works, the aim is to provide a comprehensive overview of the unique challenges and advancements encountered at each facility. Furthermore, the underlying narrative is to uncover the contributions made by these extraction kickers in enhancing the precision and reliability of experiments, elucidating the mysteries of the subatomic world, and propelling scientific discovery forward.

LANSCE – PSR FAST KICKER

The fast extraction kickers in the LANSCE proton storage ring (PSR) use coaxial cables in a Blumlein configuration as a means of delivering a 50 kV bipolar pulse to the storage ring kicker structures.[1] These kickers are triggered by a set of thyratrons. The FX2535 receives the fire pulse and triggers the CX1725 thyratron which closes the circuit to deliver the 50 kV pulses. After the pulse has been sent out of the kicker modulator tank, it is directed via strip line to the storage ring and is finally terminated at a 50-ohm load comprised of four 200-ohm resistors in parallel. The electrical components are all insulated with Diala dielectric oil to provide increased electrical hold off for arcing. The kickers run at a rep rate of 24 Hz during production and have a gap of 108 ns. The rise/fall time for these kickers are 50 ns and 60 ns respectively and have a pulse flat top that is unique to each kicker.[2] SRFK71 experiences a pulse flat top length of 250 ns where SRFK81 experiences a flat top of 360 ns.[3] These pulses are made possible using the H- beam chopper located in the low energy beam transport section of the LINAC.

As far as reliability is concerned, the LANSCE PSR kickers have worked for over 40 years, however newer and more efficient technology is widely available and is used worldwide. Vacuum tube thyratrons are considered obsolescent, have become increasingly hard to source, and have been almost completely replaced by solid state switches. In addition, the kickers are currently limited by the length of the Blumlein cable [e.g., Fig 1].

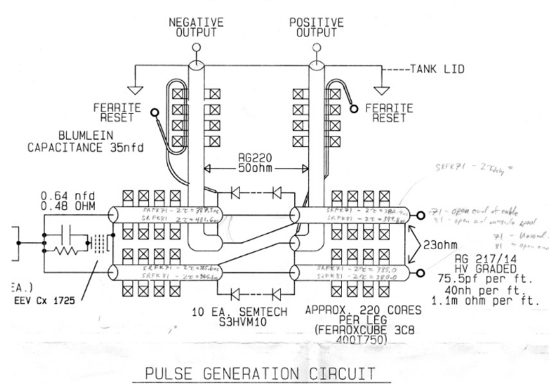

Figure 1: LANSCE fast kicker Blumlein Schematic.

Pulse length is controlled by the length of this cable which in turn means that the experiments and beam manipulations that can be performed are also limited, as kicker pulse duration cannot be altered dynamically. In the future it would be ideal to have a modular design for the kickers that would be capable of changing the pulse length easily and without requiring hardware changes. The key parameters of LANSCE fast-extraction modulators for PSR kicker are summarized in Table 1.

LA-UR-24-24553

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR39

Table 1: Fast Extraction PSR Kicker Parameters

Parameter	Value	Reference
Particle Species	Protons	1, 2
Particle Energy	800 MeV	1, 2
Beam Current	46A	3
Impedance	50 Ω	1
Voltage Amplitude	±45 kV	Measured 2008
Load Impedance	50 Ω	1
Current Amplitude	±900 A	Measured 2008
Current Rise Time (5%-95%)	51 ns	Measured 2008
Pulse Jitter	≤ 5 ns	1
Pulse length (flat top)	329 ns	Measured 2008
Rep rate	20 Hz	Measured 2008

FERMILAB – FAST KICKERS

Fast Kickers at Fermilab transfer beams between accumulation rings, accelerating rings, and target beamlines. The kicker magnet structures are segmented with built-in distributed capacitances to create at traveling wave magnet.[4] They are terminated with a matched impedance to eliminate reflections. This construction allows them to present a pure impedance to a matched driver, resulting in fast rise and fall times.

The Main Injector Ring and associated Recycler Ring Injection kickers' performance is relevant to the requirements of the LANSCE PSR extraction kickers. In 2013, the recycler ring injection kickers were upgraded to achieve kicker field rise and fall times of < 57 ns.[5] To achieve this field risetime at the magnet, the kicker modulator system produces current risetimes of 15 ns on a 1.6 µs flattop pulse of 25 kV, 1 kA into a 25-ohm load. The chosen topology was a floating thyratron switch and the resistive termination mounted at the traveling wave magnet. The pulser performance parameters are given in Table 2.

The quality of the fields within these kickers depends in part on cable quality. Two 50-ohm cables are used in parallel to match the 25-ohm impedance of the traveling wave magnet structure and its termination load. Cable impedance variations within the pulse forming cables and within the 45 m of coax separating the modulator from the magnet can degrade the flatness of the pulse. Cable dispersion can cause the pulse to spread out, increasing the rise and fall times. The +/- 1% voltage stability requirement on the 1.6 µs flat top is met by using an improved version of RG220/U coax cable with more consistent impedance (+/- 0.4 Ohm) for voltage stability. More stable impedance is achieved by imposing tighter requirements on the center conductor dimensions and surface roughness.[5] Lower cable dispersion is achieved by bonding two foil layers to the polyethylene core under the cable's outer conductor braid [5] which can be thought of as presenting a smoother and more uniform surface than braided copper to the smaller wavelengths within the dielectric.

Table 2: Recycler Ring Injection Kicker Performance

Parameter	Value	Reference
Impedance	25 Ω	5
Voltage Amplitude	25 kV	5
Load Impedance	25 Ω	5
Current Amplitude	1000 A	5
Current Rise Time (10%-90%)	15 ns	5
Pulse length (flat top)	1.6 µs	5
Flat Top Amplitude Regulation	± 1.0%	5
Rep rate	15 Hz	5

The quality of the fields within these kickers depends in part on cable quality. Two 50-ohm cables are used in parallel to match the 25-ohm impedance of the traveling wave magnet structure and its termination load. Cable impedance variations within the pulse forming cables and within the 45 m of coax separating the modulator from the magnet can degrade the flatness of the pulse. Cable dispersion can cause the pulse to spread out, increasing the rise and fall times. The +/- 1% voltage stability requirement on the 1.6 µs flat top is met by using an improved version of RG220/U coax cable with more consistent impedance (+/- 0.4 Ohm) for voltage stability. More stable impedance is achieved by imposing tighter requirements on the center conductor dimensions and surface roughness.[5] Lower cable dispersion is achieved by bonding two foil layers to the polyethylene core under the cable's outer conductor braid [5] which can be thought of as presenting a smoother and more uniform surface than braided copper to the smaller wavelengths within the dielectric.

SNS – FAST KICKER

The SNS extraction kicker was reviewed for its parameters to decide if it would meet the specifications of the LAMP PSR upgrade project. SNS uses 13 separate modulators and magnets to provide beam extraction from the SNS accumulator ring. This setup allows for a robust design with discrete components, leading to low down time. The gap (amount of time between pulses) in the SNS ring is ~250 ns. Compared to the ring at LANSCE this is very long, allowing for a relatively long rise time of ~150 ns [6]. In addition, the SNS extraction kicker has a very long fall time of ~16.6ms which is several orders of magnitude longer than the extraction kicker currently used at LANSCE. Where the SNS kicker excels is with its jitter. The jitter of the SNS extraction kicker is ~2 ns which is very low and attributable to their solid-state switching system [6]. The SNS kicker also has a suite of built in

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR39

diagnostics that help maximize the overall lifetime of the discrete components. A multitude of temperature monitors in key locations allows real-time monitoring of the system [7]. An oil circulation system also assists with cooling and leads to longer component life cycles [7]. The separation of the extraction system into 13 separate magnets allows for lower kicking force needed per kicker. The kickers operate at 35 kV and 2.5 kA with an output impedance of 25 ohms [8]. The kicker also has an output pulse with a 750 ns non-variable pulse width [9]. A lower kicking force eases voltage and current requirements, in turn making it easier to find components. The kicker modulators are built from off the shelf capacitors and inductors making repairs quick and relatively easy. The maximum rep-rate for the kicker is 60 Hz [8]. The SNS extraction kicker is a robust design that has operated for several years. The long rise and fall times of the SNS kickers make their use impractical for the future ring here at LANSCE but there are some lessons learned that could be used to improve the system eventually deployed for LANSCE. The use of oil circulation to reduce temperature as well as the use of strategically placed temperatures sensors could be useful in detecting problems before they lead to damaged components. The key parameters of the SNS kickers are summarized in Table 3.

Table 3: SNS Extraction Kickers Main Parameters

Parameter	Specification
Maximum extraction rate	60 Hz
Pulse flat-top length	> 700 ns
Pulse rise time	200 ns (1% - 95%)
Pulse fall time	< 16.6 ms
Kicker magnet inductance	695 nH to 789 nH per section
Operating voltage	~ 35 kV per section
Operating current	~ 2.5 kA per section
Beam Impedance Termination	~ 25 Ω

INDUCTIVE VOLTAGE ADDER KICKER

The conceptual design of a solid-state, inductive voltage adder pulse generator [10] for extraction kicker using wide-band-gap semiconductor devices involves several key components and considerations to achieve optimal performance and reliability. Wide-band-gap semiconductor [11] devices are at the heart of this pulse generator design. These devices offer superior power handling capabilities, low on-resistance, and fast transition response. With their wide bandgap properties, wide-band-gap devices can efficiently handle high-frequency switching and deliver high-voltage pulses, making them ideal for high-power applications like the beam kicker [12]. The pulse generator operates based on the concept of inductive adder. It utilizes a pulse transformer with multiple primary windings to add up the voltage at the secondary winding. The transformer is designed to handle high currents and high frequency operation to generate the desired 50 kV voltage pulses at high repetition rate [13]. Careful consideration is given to the transformer's core material, winding configuration, and physical dimensions to ensure efficient energy transfer and minimal energy losses. To achieve fast and precise control of the pulses, a high-speed switching mechanism is employed. Wide-band-gap semiconductor devices, known for their excellent switching speed, are utilized as the main switches in the pulse generator. These devices can handle the high voltage and current requirements of the system while offering fast and efficient switching characteristics [14].

The pulse generator's control circuitry is responsible for generating and shaping the desired pulses. A pulse shaping circuit is employed to control the rise and fall times of the pulses, ensuring that the beam kicker receives well-defined and accurately timed pulses [15]. This circuitry may involve additional components such as capacitors and resistors to shape the waveform precisely. The pulse generator is typically integrated into a larger control system that manages the operation of the entire beam kicker. It includes interfaces for external control signals, synchronization with other systems, and monitoring of various parameters such as pulse duration and repetition rate. These interfaces ensure seamless integration into the overall beam control infrastructure. The conceptual design of a solid-state, inductive-adder pulse generator for a beam kicker using wide-band-gap semiconductor devices encompasses careful selection of components, efficient energy transfer with inductive adder mechanism, precise pulse generation and shaping, robust voltage regulation and protection, and seamless integration with the overall control system. This design enables the generation of high-voltage, high-frequency pulses with precise timing and control, crucial for beam kicker application.

CONCLUSION

In summary, this literature review has surveyed the kicker systems in use at LANSCE, Fermilab and SNS, provided performance summaries, and identified key features of their operation.

REFERENCES

[1] D. W. Hudgings and A. J. Jason, "Los Alamos Proton Storage Ring Extraction System", in *Proc. PAC'81*, Washington D.C., USA, Mar. 1981, pp. 2791-2794.

[2] G. P. Lawrence, R. A. Hardekopf, A. J. Jason, P. N. Clout, and G. A. Sawyer, "Los Alamos High-Current Proton Siorage Ring; A Status Report," IEEE Trans. Nucl. Sci., vol. 32, no. 5, pp. 2662–2665, Oct. 1985. doi:10.1109/tns.1985.4334011

[3] C. Wilkinson et al., "Comparison of beam transport simulations to measurements at the Los Alamos Proton Storage Ring," Office of Scientific and Technical Information (OSTI), Oct. 1997. doi:10.2172/537345

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR39

[4] J. Dinkel and R. Reilly, “An Upgraded Proton Injection Kicker Magnet for the Fermilab MIR”, in *Proc. PAC'95*, Dallas, TX, USA, May 1995, paper WAA05, pp. 1236-1238.

[5] C. C. Jensen, “Kicker Pulsers for Recycler Nova Upgrades”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3324-3327. doi:10.18429/JACoW-IPAC2015-WEPTY027

[6] B. Morris and R. B. Saethre, “Final Conversion of the Spallation Neutron Source Extraction Kicker Pulse Forming Network to a High Voltage Solid-State Switch”, in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 240-242. doi:10.18429/JACoW-NAPAC2019-MOPLO03

[7] Y. Tan and R. Saethre, “The Recent Improvements of the SNS Extraction Kicker Power Supplies,” in 2022 IEEE Int. Power Modulator and High Voltage Conf. (IPMHVC), Jun. 2022. doi:10.1109/ipmhvc51093.2022.10099421

[8] J.-L. Mi *et al.*, “SNS Extraction Kicker Power Supply Control”, in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, paper TUPLT187, pp. 1568-1570.

[9] J. Mi *et al.*, “SNS Extraction Kicker System and First Article BPFN Test.”, in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper TUPLE068, pp. 2652–2654.

[10] J. Ruf, M. J. Barnes, T. Kramer, and M. Sack, “Improvements of a Branch Module for an Inductive Voltage Adder Based on Measurements and Circuit Simulations,” in 2022 IEEE Int. Power Modulator and High Voltage Conf. (IPMHVC), Jun. 2022. doi:10.1109/ipmhvc51093.2022.10099414

[11] Y. Chen, J. Du, L. Feng, J. Xiao, J. Zhang, and Y. He, “Comparative Study on Driving Switching Characteristics of GaN-FET and SiC-MOSFET in Transient High Voltage Pulse Discharge Circuit,” in 2020 IEEE Int. Conf. on High Voltage Engineering and Application (ICHVE), Sep. 2020. doi:10.1109/ichve49031.2020.9279479.

[12] D. G. Woog, “Inductive Adder for the FCC Injection Kicker System,” Unspecified, 2020. doi: 10.25534/TUPRINTS-00011726

[13] T. W. Hardek, “PSR Switchyard Kicker System Improvements”, in *Proc. PAC'91*, San Francisco, CA, USA, May 1991, pp. 872-875.

[14] S. Guo et al., “3.38 Mhz operation of 1.2kV SiC MOSFET with integrated ultra-fast gate drive,” in 2015 IEEE 3rd Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Nov. 2015. doi:10.1109/wipda.2015.7369298

[15] E. J. Gower and J. S. Sullivan, “Analog amplitude modulation of a high voltage, solid state inductive adder, pulse generator using MOSFETs,” in Proc. MODSYM-02, Hollywood, CA, USA, in MODSYM-02. IEEE. doi:10.1109/modsym.2002.1189479