PULSED POWER APPLICATIONS IN HIGH INTENSITY PROTON RINGS*

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Abstract

Pulsed power technology has been applied in particle accelerators and storage rings for over four decades. It is most commonly used in injection, extraction, beam manipulation, source, and focusing systems. These systems belong to the class of repetitive pulsed power. In this presentation, we review and discuss the history, present status, and future challenge of pulsed power applications in high intensity proton accelerators and storage rings.

INTRODUCTION

The present and future application of high intensity proton sources includes high-energy physics experiment, nuclear physics experiment, and nuclear engineering such as waste transmutation and sub-critical reactors [1][2][3].

Pulsed power systems in the proton accelerator and storage rings provide fast manipulating capability to inject and extract particle beams. Various applications of pulsed power technology exist at lower power level in other areas of accelerator such as beam instrumentation, source, and RF. In large accelerator facilities, tens to hundreds of pulsed power systems are used, such as in RHIC-AGS Collider-Accelerator Complex of Brookhaven shown in Figure 1.

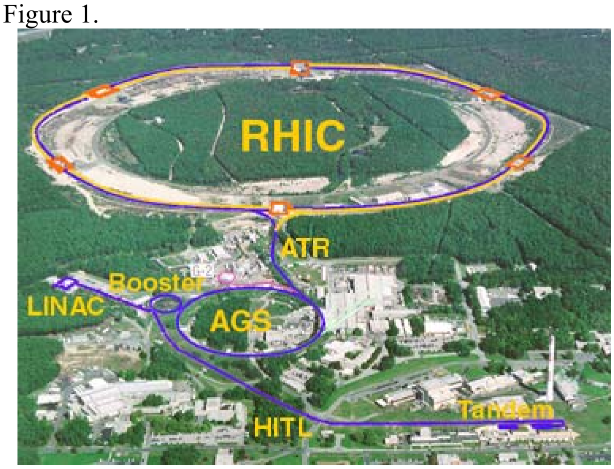

Figure 1. Brookhaven RHIC-AGS Collider-Accelerator complex

Experimental physics and accelerator physics issues of high intensity proton synchrotrons and accumulators were reviewed in [4] and [5]. Physicists wish to have faster and faster kickers with higher, and even higher strength. Other critical factors include low beam impedance design, higher repetition rate, flexible pulse width and operation mode, and high reliability.

In this paper, we are most interested in engineering issues of the pulsed power systems. These include new physics demands, technical challenges, design feasibility, operating environment, development trend, and need to have advanced engineering research.

BRIEF REVIEW OF ACCELERATOR PULSED POWER IN HIGH INTENSITY PROTON RINGS

Among the early pioneers of accelerator pulsed power research and development Dave Fiander of CERN is the most recognized subject expert. In one of his papers published in the late eighties, he gave a though overview of kickers and septa at CERN PS complex [6]. Many of the techniques are still being used today, and the challenges remain.

Typically, pulsed septa and orbit bump power supplies are slow devices in the range of several microseconds to millisecond. This type of system operates in few hundred to few kilo volts range with tens of kilo amperes output capacity. Capacitor discharge controlled by solid state switching device is commonly used topology.

Kickers are fast pulsed systems. Fast kickers usually have a field rise time of tens to hundreds of nanosecond, and a short pulse width from tens of nanosecond to a few microseconds. Slow kickers like beam dump kickers have longer field rise time, and pulse duration are often in tens of microseconds. Most kickers are high repetition rate systems. They run in burst mode with very high pulse repetition rate within the burst or continuous mode with moderate pulse frequency. However the beam storage and collider ring kicker systems might run at low duty factor and low repetition rate. All kicker systems are considered to be repetitive pulsed systems in contrast to single shot systems.

Dr. Paul Smith described some commonly used pulsed power circuitry in his recent lecture given at the CERN Accelerator School [7]. Pulse Forming Network (PFN) or Pulse Forming Line (PFL) with thyratron switch has dominated fast kicker pulse generator design for over forty years. The main circuitry is a simple and effective scheme of power compression.

Engineering issues [8] include material survivability in very high radiation operating environment; availability of kicker magnet and deflector high voltage strength material, high voltage and high power pulsed switching and storage devices, and high voltage pulse transmission system; and high frequency pulsed system shielding and grounding techniques, etc.

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Another important area of development in high voltage and high current kickers is the magnet. Since magnetic field deflection is more efficient than electrical field deflection, use of low impedance kicker magnet could save the straight section length in the proton ring. It is usually the constraint of existing ring or new design with limited straight section length.

CERN's early design of transmission line type magnet with ferrite blocks and parallel plate capacitors have been widely adopted for 25 ohm and 12.5 ohm impedance magnet design. This type of design uses large metal plates to construct capacitors and becomes impractical for very low impedance magnets. Therefore it is necessary to use high dielectric material in low impedance magnet design.

NEW AND PROPOSED SYSTEMS

Significant progress has been made during the last two decades. At the system level, new topologies are used in various designs. At sub-system level, switch mode power supply, programmable logic controller, and digital delay generator have become semi-standard. At component level, solid-state switches and high energy density capacitors are widely applied in pulse generators. High dielectric materials are adapted for energy storage and transmission line magnets.

Around the world, new and advanced pulsed power systems are being built, developed, and proposed for high intensity proton facilities. The newly completed extraction fast kicker system of the SNS accumulator ring at Oak Ridge, the prototype development of extraction kicker of the J-PARC 50 GeV main ring, upgrade of CERN SPS kickers, upgrade of Brookhaven AGS and AGS Booster kickers, NuMi fast kicker at FERMI, and development of AHF 50 GeV ring extraction fast kicker are just a few examples.

ORNL Spallation Neutron Source Accumulator Ring Extraction Fast Kicker System

The ORNL Spallation Neutron Source project is a collaboration of six U.S. DOE laboratories. Brookhaven National Laboratory design and build the accumulator ring and transport line. The extraction fast kicker [9] is a critical system faced many challenges. The SNS accumulator ring layout is shown in Figure 2.

Its peak output power exceeds Giga-Watts, which is an order of magnitude increase than other fast kickers in its class. The pulse rise time is 200 ns, and the reserved beam gap is 250 ns. The specified pulsed current amplitude is about 2400 amperes.

Its pulse repetition rate is 60 pulse-per-second. It will operate 24 hours a day and seven days a week continuously, rather than burst. It will pulse 5.18 million times a day in operation. A five-year operation will accumulate more than 9.33 billion shots. Therefore, all pulsed components and subsystems must have a designed pulse lifetime of multi-billion shots under specified operating conditions. Certainly, it is in the frontier of high repetition rate, long pulse lifetime high voltage pulsed power technology.

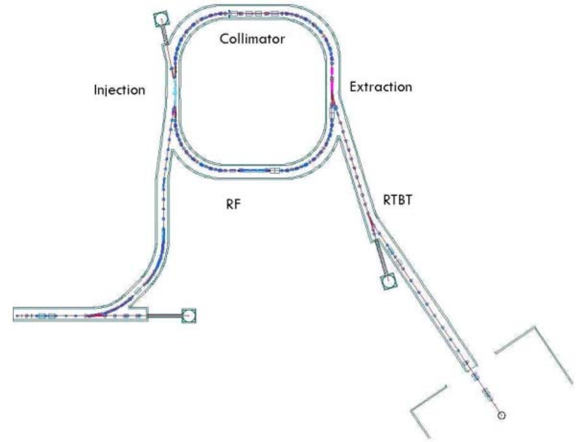

Figure 2. Spallation Neutron Source Accumulator Ring

An important issue in high intensity proton ring is to lower the beam loss, which in turn requires lower beam impedance. Extraction fast kicker occupies a long stretch of the accumulator ring. Its beam impedance might contribute a large portion or even dominate the overall impedance. Therefore, reducing the beam impedance of kicker is critical to the success of the ring design.

To generate the high peak power, modularization is used in this system design. Fourteen identical pulse modulators have been built. Two kicker vacuum tanks contain seven kicker magnet sections each. Fourteen pairs of high voltage pulse transmission cables will connect the high voltage modulators and the corresponding kicker magnet loads. The kicker magnet arrangement is shown in Figure 3.

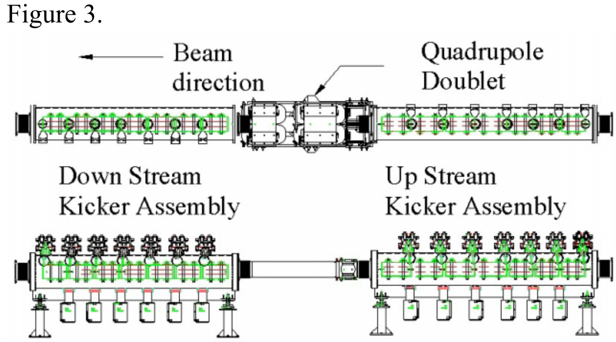

Figure 3. SNS extraction fast kicker magnet arrangement

In SNS design the kicker beam impedance is lowered by providing 25 ohm low resistance termination to each of the fourteen kicker sections and enlarged magnet aperture.

The Blumlein pulse forming topology combined with a 25 ohm low resistance beam impedance termination, a lumped inductance picture frame ferrite magnet, and a full positive reflection of pulse current at kicker magnet is the basic design. It offers a simple pulse compression method with four times more efficiency of matched PFN or PFL approach.

The high intensity proton ring has much higher level of ionized radiations than other accelerator environment. In

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this design, high voltage pulsed power modulators and auxiliary instrumentation and control systems are all located in a dedicated service building. There are no dissipative components, no active devices of kicker system used inside the accumulator ring high radiation area. This minimizes the interruption of beam operation and greatly reduces the personnel exposure to the high residual radiation during routine maintenance.

Brookhaven National Laboratory has successfully developed the fast kicker system. The Applied Power Systems was contracted to do the production work. It has completed the production of fourteen high voltage modulators and their auxiliary systems. All production units were tested well above the specification. Table I lists major component test summary, and Table II lists the production test summary. All high voltage modulators passed tests successfully. The extraction fast kicker system has been delivered to ORNL on schedule and within budget.

Table I. Major component test summary

COMPONENT	HI-POT VOLTAGE	RATED VOLTAGE	OPERATING VOLTAGE
THYRATRON	80 KV	80 KV	35 KV
DIODE STACK	75 KV	72 KV	35 KV
CAPACITOR	100 KV	50 KV	35 KV
CABLE	100 KV	75 KV	35 KV

Table II. High voltage modulator production test summary

75 KV	214 % OF SPEC.	DC	HI-POT	2 MINUTES
35 KV	100 % OF SPEC.	PULSE	60 HZ	16 HOURS
40 KV	114 % OF SPEC.	PULSE	60 HZ	8 HOURS
45 KV	129 % OF SPEC.	PULSE	30 HZ	2 HOURS

Fast pulsed power systems for the LHC

The demanding beam parameters of CERN's LHC machine have required both the development of new pulsed power systems for fast magnetic elements in the LHC itself as well as the upgrade of many existing fast pulsed power systems in the Booster (PSB), PS and SPS proton injector chain. A total of twenty separate kicker systems are required to transfer the beam from the Linac to the LHC, to assure safe beam dumping and to execute aperture and Q measurements. Their positions in the LHC machine and injector chain layout are shown in Figure 4.

The PSB extraction (EK) and recombination (TK) kicker systems, the PS injection (TIK) and extraction (FAK) kicker systems [10] and the SPS Injection (MKP) [10] and Extraction (MKE) [10] kicker systems all required major improvements in rise and fall times and pulse flat top stability. These systems all employ transmission line type magnets pulsed from matched impedance PFNs using thyratron switches. Resonant charging voltages range from 40kV to 85kV. Pulse lengths range up to 2.1µs in the PS Complex, where cable PFNs are employed, and up to 10.5µs in the SPS where lumped element PFNs are used. The development of sophisticated circuit simulation models of all principal elements of these systems has proved indispensable for the optimization of kicker performance. In the PS, for example, accurate modeling of multi-stage thyratrons permitted precise evaluation of the effects of saturating ferrite inductors to reduce the pre-pulse current, which was particularly detrimental to the kick rise time. In the SPS, PSpice™ simulation was used extensively to optimize various PFN modifications to reduce pulse flat top ripple in both the injection and extraction systems. More drastic measures were required to satisfy the injection rise time improvements in the MKP system which included increasing the system's characteristic impedance and installing new magnets with fewer cells to reduce the filling time.

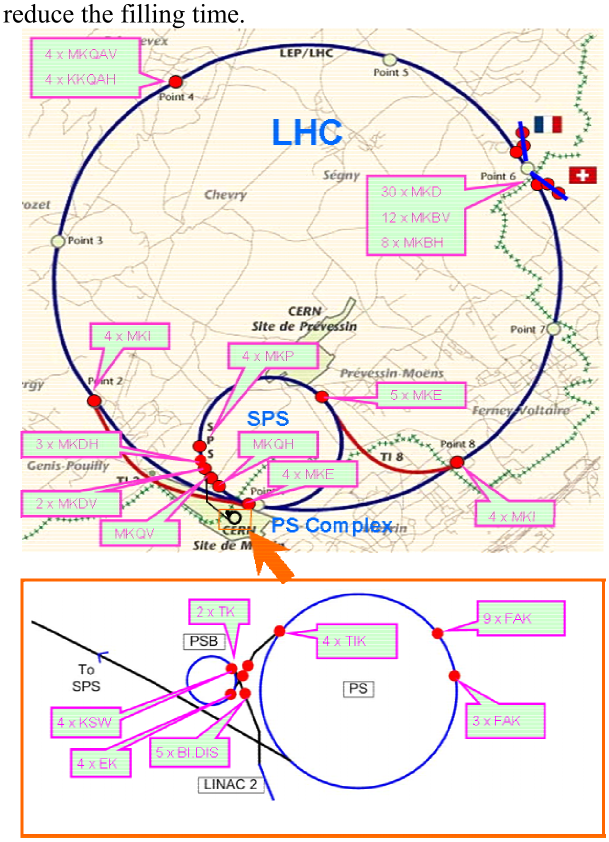

Figure 4. Fast pulsed magnet systems in the LHC chain

Five MKE magnet modules presently installed in LSS4 will extract both a beam for anti-clockwise LHC ring and a beam for the CERN Neutrinos to Gran Sasso (CNGS) target. In 2006 a further four MKE magnets will be installed in LSS6 for beam extraction to the LHC clockwise ring. Ferrite heating will be induced by the high intensity, short bunch length LHC beam and cooling has been implemented to restrict temperature rise to below the Curie temperature [10].

The new injection kicker system for LHC (MKI) [11] comprises four fast pulsed magnets per injection point. Ripple on the field flat top must be less than ±0.5%. To achieve this stringent requirement, the PFN inductances are made of a continuous straight, rigid coil with constant and high precision pitch, surrounded by an Omega shaped aluminum shield (Figure 5).

Frequency dependence of the inductance and resistance of the PFN coil, as well as the effect of distortion during winding have been assessed via electromagnetic simulations. Series production at TRIUMF of the final generators is complete and tests confirm that performance is within specification.

The LHC beam dumping system [11] is essential to protect machine components from damage due to excessive beam losses. The associated pulsed power systems must meet extremely high reliability criteria and extensive safety and redundancy measures have been incorporated. In the critical MKD systems [11] each generator will consist of two parallel discharge circuits, including two switches, with failsafe triggering. The 18.5kA, 90μs flat top pulse will be switched using high reliability Fast High Current Thyristors (FHCT). The expected MKD system failure rate (i.e. fewer than 14 of the 15 generators working) is 1.1 x 10^{-11}/hour.

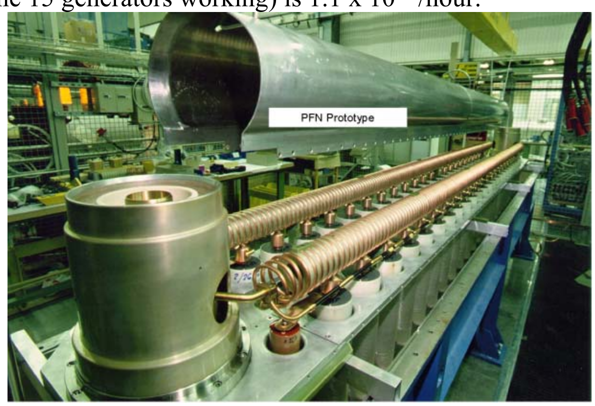

Figure 5. View of opened MKI 5Ω PFN

J-PARC Main Ring Extraction Kicker System Development

J-PARC is a new high intensity proton source, as shown in Figure 6, under construction in Japan. The beam in the J-PARC main ring is accelerated from 3GeV to 50GeV. The harmonic number of main ring is nine. One bucket is left empty to allow field rise time of the extraction kicker. Since the rise time of the kicker field (1.1μs) is not tight, IGBT is used as a main switch instead of thyratron. The flat top duration of the kicker magnetic field is 4.3μs. PFN composed of lumped C and L is adopted instead of PFL (coaxial cable). To operate IGBT and components of PFN in the atmosphere rather than oil, the maximum PFN voltage is limited to 44kV.

Five sets of the kicker magnet inside vacuum tanks are installed in the extraction area. The height, width, and length of the kicker magnet core gap are 100mm, 100mm and 2.4m, respectively. The characteristic impedance of this transmission kicker magnet is 5Ω with ground return structure. Its transmission time is long as compared to high impedance matched load kicker system. To shorten the transmission time in half, the kicker magnet is split into two C-shape transmission type kicker magnets with face to face. We named the magnet as "twin transmission type kicker magnet" [11].

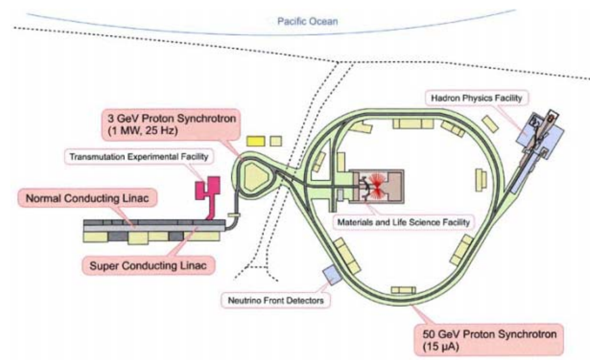

Figure 6. J-PARC layout

This extraction kicker system must be bipolar to serve both beam abort function and fast extraction. The orbit to the abort line has the same angle (6mr) but opposite sign of the normal extraction line. The kicker system adopts the combination of Blumlein pulse forming topology, a transformer and a twin-transmission type kicker magnet as shown in Figure 7. It utilizes the symmetrical structure of Blumlein PFN to generate identical kicks by selectively switching one of the two switches. The IGBT switch (1) is used for normal beam extraction, and switch (2) is used for abort function. When the negative half PFN voltage pulse generated by the turn-on of the switch (1) reaches the right end of PFN (1), the positive current begins to flow from the right to the left in the primary line of the transformer. During beam abort, the positive current flows from the left to the right in the primary line of the transformer. The kicker magnet can generate the magnetic field with the same strength but opposite sign. For the abort extraction during the acceleration, the charging voltage of PFN should correspond to the circulating beam energy. The minimum turn-on voltage of IGBT is nonzero, however, we use programmable trigger system of kicker magnets from one to five according to the circulating beam energy.

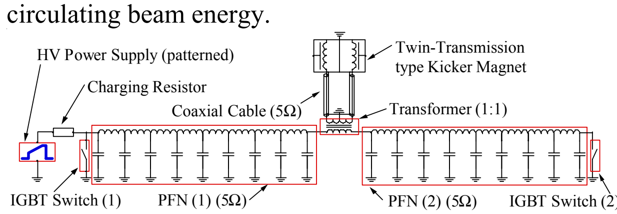

Figure 7. Main schematic of J-PARC main ring extraction fast kicker.

FUTURE R&D

To create faster and more powerful pulsed power systems, with greater flexibility and reliability, new topologies, devices, and technology are needed.

Topologies

The Blumlein pulser is a topology to multiply the output peak power. It can be used in multiple stages, but

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switching speed of multiple switches could cause pulse rise and fall time degradation. The other limitation is lack of flexibility of the pulse length.

The solid-state modulator based on inductive adder technology offers faster rise time, faster fall time, flexible wave shape and pulse length. It is also a topology to boost output voltage from adding multistage low voltage devices at primary side. However, the rise time and fall time slow down with the increased number of primary stages. The core size and power dissipation increase with the current level, pulse rise and fall time, and pulse repetition rate. The AHF extraction kicker prototype is in the frontier of this development.

The idea of using RF source of different frequency to compose the fast pulse has been circulating for years. It is based on the Fourier components of a given pulse shape. The methods of construction differ, but the merits are the same.

High Repetition Rate System

The principle of pulsed power system is to accumulate energy from available primary power source through a relatively long period of time and compress it into a burst or a series of short pulse of high peak power. Typical duty factors of slow pulsed systems such as orbit bumps and septa are in the range of hundredths or thousandths. To achieve high power compression ratio, fast pulsed systems have duty factors in millionths, billionths, or even smaller range. When the pulse repetition rate and duty factor increase, the power rating of the primary power source and the dissipation in the system might become the limitation. Hence, the energy recovery scheme, low dissipative device and material are needed. In particular, the high frequency high permeability low loss magnetic material will help to advance the high repetition rate high duty factor systems.

Device and Subsystem

On the component level, the solid-state switching device with higher voltage rating, high current rating, and switching speed will help to achieve faster pulse rise and fall time. The plasma switching device continues to play an important role in high power fast pulsed system for its high power fast speed switching capability. Its application is limited by lack of ability to switch off and by restricted repetition rate to allow switch recovery.

The low inductance high stability high energy density pulse capacitors are used as primary energy storage in most pulsed power systems. Its reliability and pulse lifetime has been improved by using new technologies. At high energy storage level, the safety of system links directly to device reliability. Method to prevent open and short circuit failures in high power pulsed system is an important issue.

The transmission cables above 100 kV will be helpful in application of higher voltage fast pulsed systems. With continuing trend of high frequency, high current pulse system development, low loss, low impedance, and high bandwidth are desirable characteristics of pulsed cable. At present stage, the frequency range up to Giga Hz, and impedance down to a few ohms are preferable.

CONCLUSION

Accelerator pulsed power systems are on the leading edge of the high repetition rate pulsed power technology. Especially, the new and advanced fast pulsed power systems are state of art in the area of pulse lifetime, system reliability, compactness, high precision pulse shape, and high repeatability. This area is attracting more and more attentions from researchers from various academic fields and countries.

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