

***Pulsed Power Systems in Large Accelerator Complex***

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# PULSED POWER SYSTEMS IN LARGE ACCELERATOR COMPLEX\*

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## Abstract

Large particle accelerator complexes use pulsed power systems for injection, extraction, beam manipulation, source, and focusing systems. Most of 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.

**Keywords:** Accelerator power supplies, accelerator magnets, pulse power systems, pulse modulation.

## INTRODUCTION

Application of particle accelerators has grown into many areas such as high-energy physics research, nuclear physics research, material science research, medical research and treatment facility, nuclear waste transmutation, and sub-critical reactors. Existing large accelerator complexes such as CERN, FERMI, Brookhaven's Collider-Accelerator Complex, and KEK consist of a combination of linear and circular accelerators and storage rings. New ones under construction and proposed future facilities expand the

energy range as well as size of the facility. Typical large complex may occupy thousand acres of land.

Pulsed power systems in accelerator complexes 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 radio frequency system.

## GROWTH OF ACCELERATOR PULSED POWER SYSTEMS

In the field of particle accelerator research the premier meeting is Particle Accelerator Conference (PAC). It started at 1965. Over last four decades, number of pulsed power related research reported in the conference has been growing steadily. For example, kicker is a typical fast pulsed power system. Number of paper with kicker in its keyword or text was zero in 1965. At second PAC, there were only four papers used kicker as keyword and ten papers had kicker in their text. Since then, this number has been rising fast. At PAC 2005, 185 papers were related to kicker. Statistics of "kicker" associated papers reported at PAC from 1965 to 2005 is listed in Table I. Figure 1 shows the growth chart.

Number of Kicker Related Papers at PAC

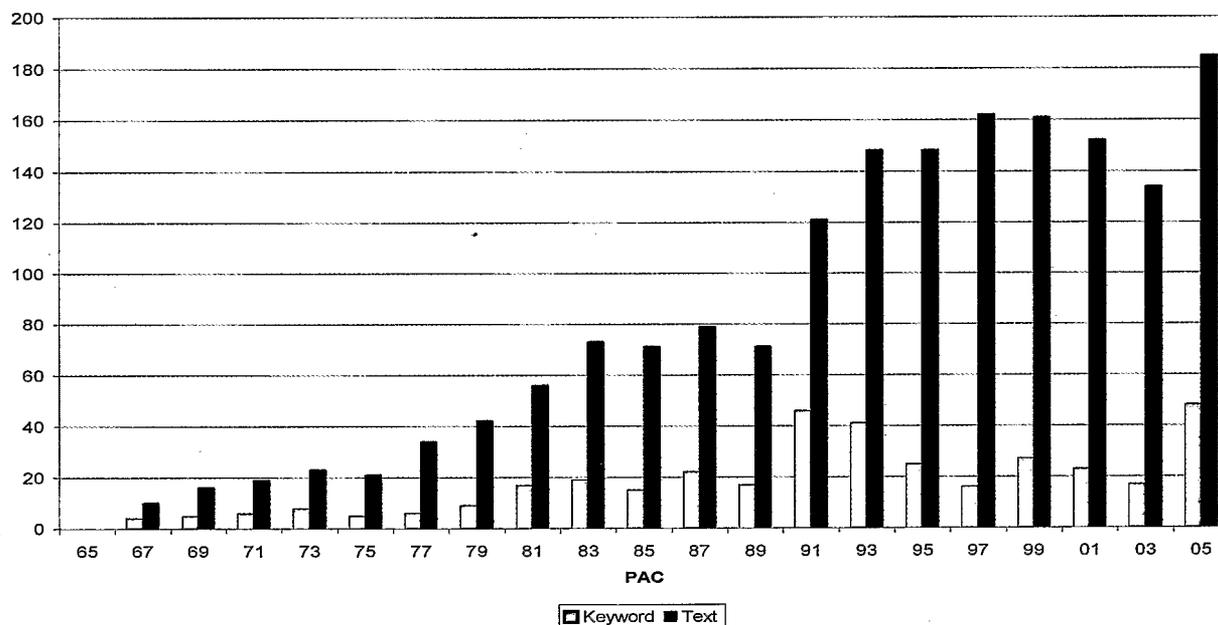


Figure 1. Statistic of kicker related papers reported at PAC from 1965 to 2005.

Table I. Statistics of kicker related papers reported at PAC from 1965 to 2005.

PAC	Kicker (Keyword)	Kicker (text)
65	0	0
67	4	10
69	5	16
71	6	19
73	8	23
75	5	21
77	6	34
79	9	42
81	17	56
83	19	73
85	15	71
87	22	79
89	17	71
91	46	121
93	41	148
95	25	148
97	16	162
99	27	161
01	23	152
03	17	134
05	48	185

Similar trend is found in European Particle Accelerator Conference (EPAC). This conference series was started in 1988. Statistics of kicker related research at EPAC is in Table II, and the plot is given in Figure 2.

Number of Kicker Related Papers at EPAC

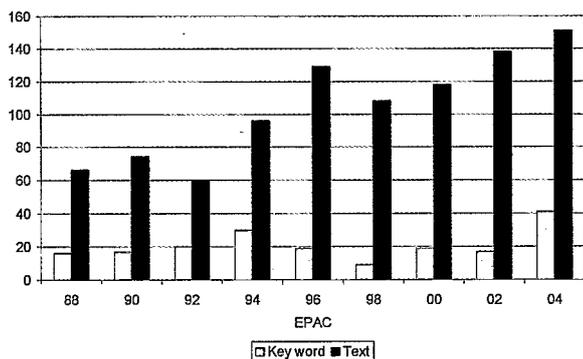


Figure 2. Statistic of kicker related papers reported at EPAC from 1988 to 2004.

Table II Statistics of kicker related papers reported at EPAC from 1988 to 2004.

EPAC	Kicker (Keyword)	Kicker (Text)
88	16	66
90	17	74

92	20	60
94	30	96
96	19	129
98	9	108
00	19	118
02	17	138
04	41	151

This trend is partially due to growing need of beam transfer systems between multiple accelerators and experimental facilities in large accelerator complexes. Another factor is growing number of accelerators and light source facilities.

### APPLICATION OF PULSED POWER SYSTEM IN ACCELERATOR

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 3.

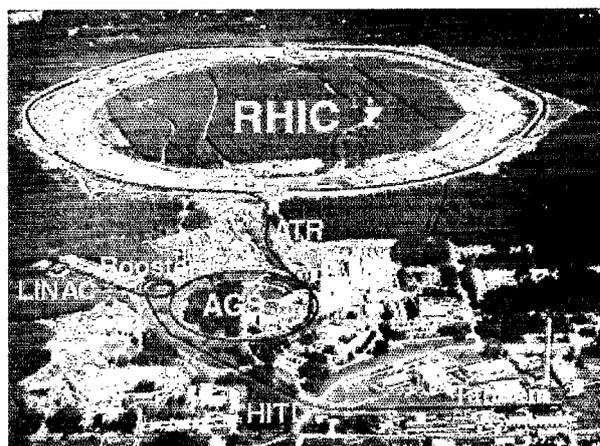


Figure 3. Brookhaven RHIC-AGS Collider-Accelerator Complex

Major research areas of accelerator pulsed power system include pulsed power generator or modulator system, control and diagnostic system, measurement techniques, computer aided simulation of circuit behavior and electromagnetic field, pulsed power device, and magnet or deflector system.<sup>1)</sup>

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 thorough overview of kickers and septa at CERN PS complex.<sup>3)</sup> 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.<sup>4)</sup> Pulse Forming Network (PFN) or Pulse Forming Line (PFL) with thyatron 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 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.<sup>5)</sup>

In recent years, solid-state modulator technology has made great advancement. Massive parallel and serial solid-state devices are used to construct high power fast pulse generators. Voltage sharing and current sharing among devices, high voltage transient, simultaneous turning on or turning off all devices, interference of parasitic inductance and capacitance, and etc. have been major obstacles of the conventional solid-state modulator development. A new topology inductive-voltage-adder is based on transformer coupling. It has the advantage of placing all solid stage devices at primary side of the transformer, which is at ground potential and adding up the voltage at secondary side of transformer to provide high voltage output pulse. This technology has been demonstrated successfully in fast kicker and RF modulators.<sup>6)</sup>

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.<sup>7)</sup>

## NEW ACCELERATOR COMPLEXES AND PULSED POWER 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 large accelerator complexes. The newly completed extraction fast kicker system of the SNS accumulator ring at Oak Ridge, the development of extraction kicker of the J-PARC 50 GeV main ring, LHC pulsed power systems, upgrade of CERN SPS kickers, and NuMI fast kicker at FERMI are just a few examples. In addition, there are several new light source projects are going on in Europe and Asia as well.

### J-PARC Pulsed Power 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.

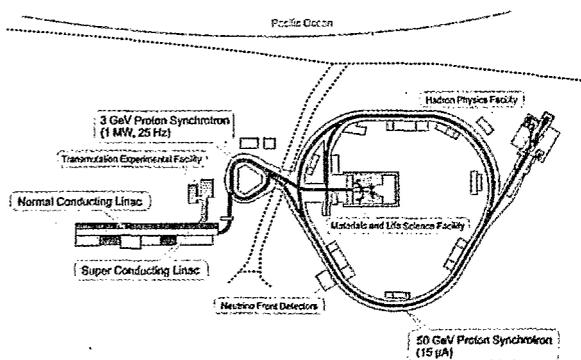


Figure 6. J-PARC layout (Photo courtesy of J-PARC)

The extraction kicker of 3 GeV RCS ring is constrained by limited straight section length. An 80 kV, 8 kA fast kicker system development has been reported. Proposed RCS injection bump system requires a peak current of more than 32 kA, and a <1% waveform tracking error at 0.268 kA per ms current slaw rate that is well above comparable systems in its category. J-PARC main ring extraction kicker is a dual



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.

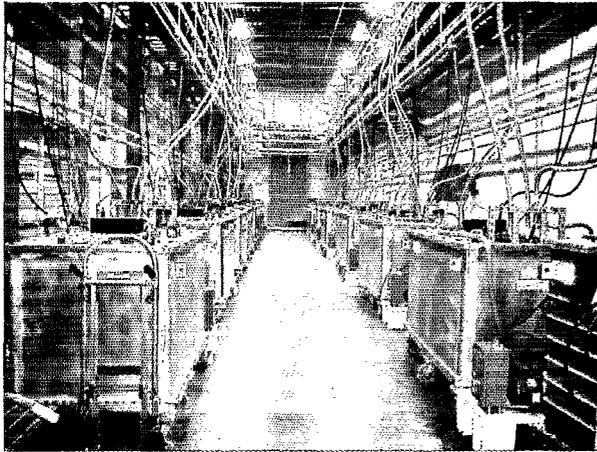


Figure 6 High voltage modulators of SNS Extraction Kicker System installed at ORNL.

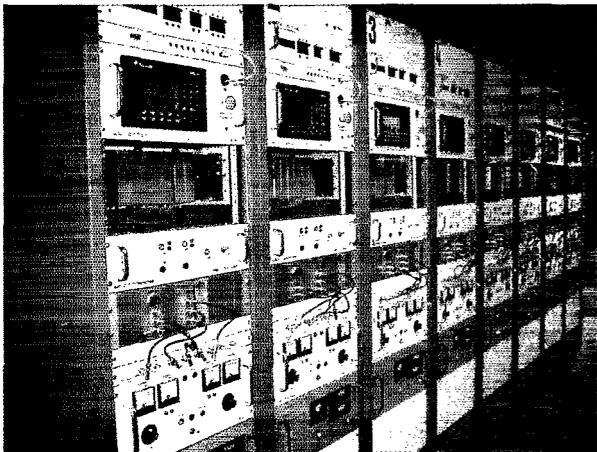


Figure 7 Control racks of SNS Extraction Kicker.

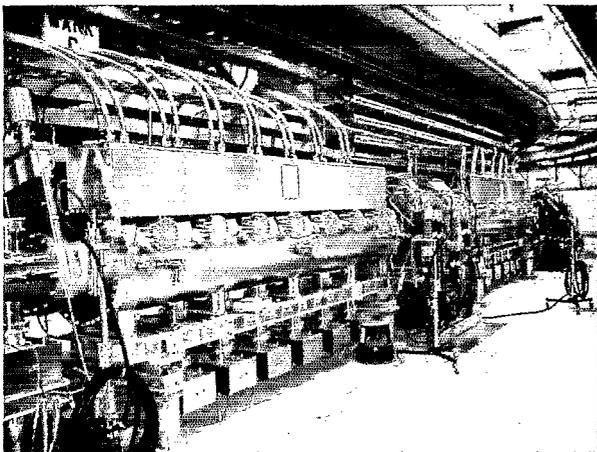


Figure 8. SNS extraction fast kicker magnet inside SNS ring

Brookhaven National Laboratory has successfully developed the fast kicker system. The extraction fast kicker system has been delivered to ORNL on schedule and within budget. The system has been commissioned and is operational.

## ACCELERATOR PULSED POWER SYSTEM R&D

Pulse rise/full time and deflection strength are critical parameters in accelerator pulsed power design. Other factors such as low beam impedance design, higher repetition rate, flexible pulse width and operation mode, and high reliability can be critical as well.

One popular used topology is Blumlein pulser. It is a voltage multiplier. It can be used in multiple stages, but 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 class of kicker development.

Faster and stronger kickers could reduce the size and cost of the accelerator or damping rings. An example is evolution of International Linear Collider damping ring design. It is linked to future advancement of fast kicker technology. From original TESLA design of a 17 km long damping ring to KEK proposed a 3 km long damping ring, development of kicker is a critical factor. The extraction kicker rise time and fall time are around 20 ns in the 17 km damping ring design. These parameters have to be shortened to 2.8 ns in 3 km damping ring design. To achieve this ambitious design goal, several groups are competing on kicker development. New switching devices, such as FID, have made this development possible. The pulse modulation topology associated with FID switch is non-conventional.

Compression ratio is one of the critical measures of pulsed power efficiency. 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.

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.

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