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# POWER SUPPLY SYSTEMS OF HIGH-VOLTAGE KICKERS ON THE BASIS OF TPI- AND TDI- THYRATRONS

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*Abstract*

This report is a survey of lifetime tests with cold-cathode TPI-thyratrons, or pseudospark switches (PSS) in kickers of various accelerators. Descriptions of design and electrical circuits of power kickers as well as lifetime, test results of devices utilizing 25 and 75 kV TDI- and TPI-thyratrons in injection and extraction kickers of the FEL (the Duke University, USA), NIKA installations (JINR) and accelerator U70 in Kurchatov's Institute – IPHE are presented.

## INTRODUCTION

High-voltage kicker power supplies, both existing and under construction in new MegaProjects, are subject to the most stringent requirements. As for operation of the kickers high current (about 10s of kiloamperes) at load impedance of several Ohm are required, the operating voltage should be as high as 100 kV, pulse duration of 0.2-5 µs, rate of current rise higher than 100 kA/µs, timing instability (jitter) less than 10 ns. The time interval between pulses depending upon the quantity of injected bursts for every switch can be from tens of microseconds up to several seconds. The switches should be able to operate both positive and negative voltages.

Normally high-power thyratrons and spark gaps have been used as the switching components. In particular, for CERN-made accelerators in NRC "Kurchatov Institute"-IHEP working gas pumped spark gaps were utilized. In the recent time there have been many reports on application of solid state-switches in kicker [1-3]. However gas-discharge thyratrons are still in demand. For example it is known that in the international project – FAIR accelerator (Facility for Antiproton and Ion Research) Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany) classical thyratrons will be used to drive kicker magnets. The company TeleDyn-e2v reported the fact that it won contract to supply 30 thermionic cathode, deuterium hollow anode thyratrons CX2593X, featuring 4 high-voltage gaps, operating voltage up to 100 kV (https://www.e2v.com/news/e2v-thyratrons-to-drive-kicker-magnets-at-fair-accelerator/).

Application of thyratrons to deliver average current 5-10 A at the expense of heating power up to several hundreds of watts [4, 5], like CX2593X and CX1925, is not quite reasonable, especially in kicker drivers, operating at frequency up to 60 Hz. The toughest competition with solid state switches makes the thyratron designers to elaborate solutions without shortcomings inherent in classic thyratrons as power heater circuits, insufficient reliability and lifetime, high costs. Cold cathode thyratrons have been designed in Germany, USA, France, Russia and other countries [6]. To date TDI- and TPI-type pseudospark switches operating at voltages up to 150 kV, used in various pulsed power application, including free electron lasers, accelerators [5, 7, 8]. In kicker drivers TPI-switches are capable of operating at either polarity of driving voltages, feature record low recovery time, small outline dimensions and relatively low cost.

TDI-type thyratrons are used as crowbars, providing a unipolar impulse and protection of the unit elements [9], eliminating dangerous overvoltages.

## CIRCUIT AND TEST OF TPI-THYRATRONS DRIVEN KICKERS

### *System of High-Voltage Nanosecond Generators for Injection-Extraction Kickers for FEL Complex of the Duke University*

A 1.2 Gev booster-synchrotron was created in order to increase the electron beam current in the main ring of the free electron laser SR FEL [7]. This works considers a system of nanosecond generators of beam kick pulses on the injection and extraction kickers of the FEL booster as well as a kicker system to inject the beam into the main ring of the SR FEL. In the nanosecond generators, energy is switched to the load with the use of the Pseudo-Spark Switch (PSS, thyratrons with a cold cathode) of the TPI-family (see Tables 1, 2 and 3).

Table 1: System Specifications of Injection Generator with TPI1-1k/20

| | |
|---|---|
| Pulse duration, ns | 106 |
| Maximal amplitude, kV | 15 |
| Pulse front time (level of 0.1-0.9), ns | 8 |
| Pulse decay time at the level of (0.1-0.9), ns | 8 |

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| | |
|---|---|
| Maximal pulse repetition rate, Hz | 2 |
| Output impedance, Ohm<br>The output is two 50 Ohm cables, each powering its plate of the kicker. | 25 |
| Type of the forming line | single |
| Voltage tuning range, kV | 4 - 10 |

Oscillograms of pulses on the kicker plates are given below (Fig.1). The obtained minimal jitter of the operating pulse generator pulse equals 400 ps.

Table 2: Parameters of the **Extraction** Generator with TPI1-1k/20

| | |
|---|---|
| Pulse half-amplitude duration, ns | 10 |
| Maximal amplitude, kV | 22 |
| Front duration (level of 0.1-0.9), ns | 10 |
| Fall duration (level of 0.1-0.9), ns | 10 |
| Maximal pulse repetition rate, Hz | 25 |
| Output impedance, Ohm | 50 |
| Type of the forming line | Blumlein |

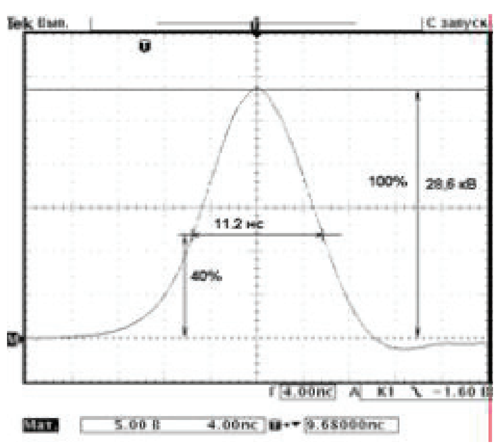


Figure 1: Waveform of a summed-up pulse on the extraction kicker with a 50 Ohm load.

Table 3: Parameters of the Generator for **Injection** for the Kickers of the Ring

| | |
|---|---|
| Charge voltage PFN (Blumlein), kV | 30 |
| Output voltage<br>(kicker pulse amplitude), kV | 30 |
| TPI maximal current (at 30 kV), kA | 4.8 |
| Pulse duration (double path over each PFN section), ns | 50 |
| Front duration at the level of 0.1-0.9, ns | 30 |
| Fall duration 0.1-0.9, ns | 30 |
| Jitter (pick-to-pick), ns | <1 |

Unlike the injection generator, the PFN by the Blumlein scheme is used in the extraction generator as the storage line. The minimal front obtained at TPI1-1k/20 was of the order of 9 ns to 10 ns. Since the beam size at extraction is certainly less than 1 ns, the bell-shaped pulse is quite admissible especially because the extraction pulse jitter is ±200 ps.

Figure 1 show an oscillogram of a summed-up pulse (positive and negative) between both plates of the extraction kicker. The pulse amplitude turned out to be 28.6 kV and the residual amplitude of the kick of neighboring separatrices was no more than 40% (Table 4).

Table 4: Status of the Kicker's Thyratrons on January 2014

| Serial # | Type | Hours × 1000 | Pulses, million | Current status |
|---|---|---|---|---|
| 27 | TPI1-1K/20 | ~5,9 | ~1,2 | S |
| 23 | TPI1-1K/20 | ~15,0 | >10,4 | O |
| | TPI1-1K/20 | >20,0 | ~12,0 | O |
| | TPI1-1K/20 | >20,0 | ~12,0 | O |
| 61 | TPI3-10K/25 | ~11,5 | ~5,6 | S |
| 62 | TPI3-10K/25 | >13,3 | ~9,3 | O |
| 63 | TPI3-10K/25 | >20,0 | ~12,0 | O |
| 64 | TPI3-10K/25 | ~0.76 | | S |
| 65 | TPI3-10K/25 | ~7,0 | ~1,9 | S |
| 180 | TPI1-10K/20 | >7,7 | >6,0 | O |

*: S - In storage ; O - In operation

** According to the latest data from October 02, 2018, one can add 15,000 hours of operation more to these readings.

## *New Developments for NICA Projects and U70 Accelerator Kicker Magnet Supply Upgrade*

For the accelerator complex NICA (JINR, Dubna) a kicker, providing release of protons and ions into the channel, connecting the buster-synchrotron and storage ring "NUCLOTRON" is being designed by the Institute of Nuclear Physics SB RAS. The kicker is driven by a nanosecond generator with supply voltage up to 50 kV and current up to 30-32 kA. To release particles into the bypass channel, a rather high value of a pulsed (500 ns) magnetic field of 0.17-0.18 T is required with a uniformity of about 1-2% and a leading edge of less than 500 ns. The load of the generator is a pair of rod kicker electrodes, comprising the inductance of the order of 600 nH. The kicker is a construction, consisting of one pair of conductors connected in parallel and a grounded shield, replacing the second pair of conductors with an opposite current direction, symmetrical with respect to the center of the beam discharged into the channel (Fig. 2). Electrodes and the screen are placed into a vacuum chamber.

In order to optimize the kicker supply circuitry various modes were simulated. As a result a supply circuit of a single pair of kicker electrodes with inductance 600 nH by 2 pulse forming lines with either polarity of output pulses, connected from opposite ends was chosen (Fig. 3 shows line of negative polarity).

The lines are switches by thyratrons TPI1-10k/75 (VL2 and VL3) with maximum anode voltage up to 75 kV. This supply circuit reduces effective inductance of the kicker as much as in two times,which allows obtaining necessary rate of pulse rise. The additional thyratrons (VL1, VL4)

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in the circuit serve to dissipate pulses, reflected from the load.

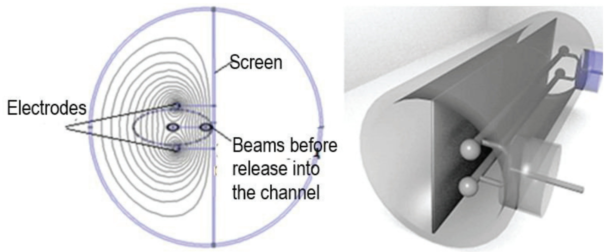


Figure 2: Kicker configuration.

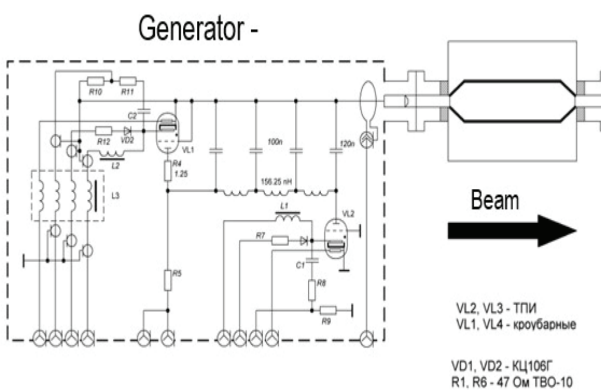


Figure 3: One half of kicker supply schematic.

The oscillograms below (Fig. 4) show the results of the first tests of one half of the (right) power circuit of the kicker of the release.


Figure 4: Oscillograms of current and voltage pulses during testing (200 ns / div).

Current pulse in the load (kicker inductivity analogue) is shown in blue, anode voltage of the crowbar thyratron with respect to the earth is shown in green. Current amplitude is 33 kA, rise time is less than 500 ns. The plato instability is explained by insufficient match of pulse forming network cells, which will be eliminated at the final assembling of kicker with generator.

A somewhat different kicker driving circuit is being designed in IHEP (Protvino), where the upgrade of power supply system for the shock magnet of the U70 accelerator has recently been started. The essence of the upgrade is the study of the possibility of obtaining multiple output of protons per one accelerator cycle (8 sec).

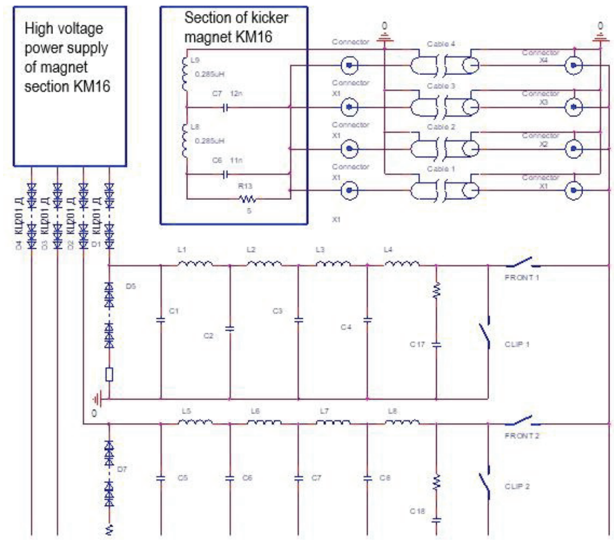


Figure 5: Circuit schematic of beam release by discharge of pulse forming networks (PFN) onto a section of U70 accelerator kicker magnet).

In this case, the beam will be released in four portions (Fig. 5) within 100 µs. The pulse forming networks are discharged each through their own switch, in turn within gap of 20-30 microseconds. This circumstance imposes special requirements on the parameters of switches. The switches in this case should have a recovery time less than 20 microseconds.

As the switches it is planned to use 75 kV thyratrons TPI1-10k/75 and TDI4-100k/75.

Power supply parameters:
PFN operating voltage – 60 kV
Load current – 7 kA
Crowbar switch current – 17 kA
Pulse duration 0.2- 1.25 µs
Rate of current rise 100 kA/ µs
Timing instability (jitter) 10 ns
Time interval between single switch pulses 8 s

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