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

СИСТЕМЫ ПИТАНИЯ ВЫСОКОВОЛЬТНЫХ КИКЕРОВ НА ОСНОВЕ ТИРАТРОНОВ

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

The first part of the report is dedicated to the beginning of TPI-thyratrons use in relatively low-power kickers, the second application in powerful kickers.

- Проанализированы результаты наработки на сроке службы ТПИ-тиратронов с ненакаливаемым катодом – pseudospark switches (PSS) в кикерных устройствах ускорителей, дано описание конструкций и электрических схем питания мощных кикеров, рассматриваются результаты испытаний устройств с тиратронами ТПИ-типов на рабочее напряжение до 75 кВ, предназначенными для установок НИКА (ОИЯИ), а также для модернизации ускорителя У70 в НИЦ «Курчатовский институт» – ИФВЭ. Первая часть посвящена началу применения ТПИ-тиратронов в относительно маломощных, вторая применению в мощных кикерах.

Applied Pulsed Switches

- Normally high-power thyratrons and spark gaps have been used as the switching components. In particular, for CERN-made accelerators in IHEP (Protvino) working gas pumped spark gaps were utilized.
- In the recent time there have been many reports on application of solid state-switches in kicker. 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/).

Статистика сроков службы тиратронов с накаливаемым катодом (SLAC)

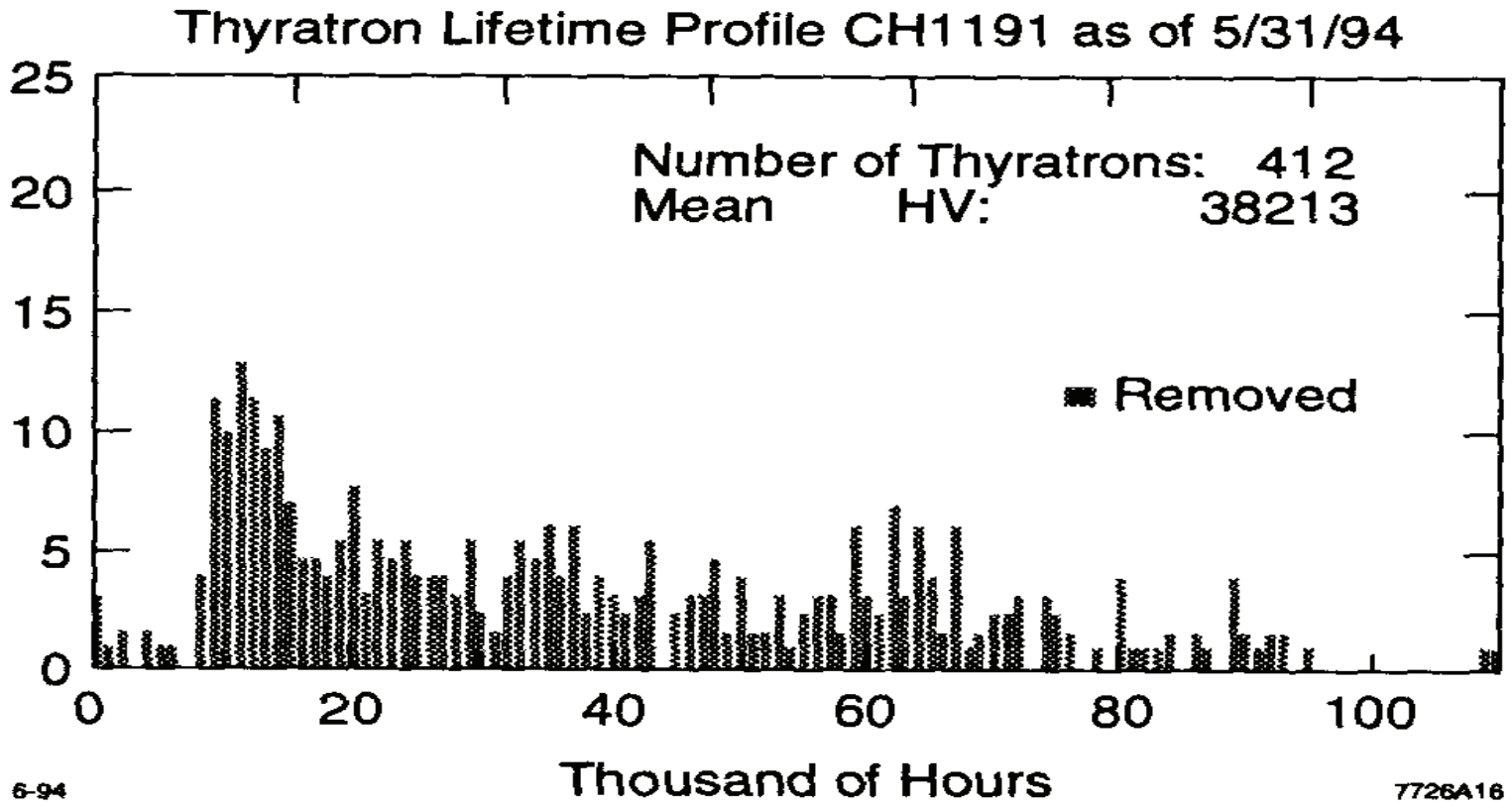


Figure 8. The quantity of tubes versus the high-voltage running-time hours at the time of removal from the linac modulator.

Truly classic thyratrons ensure many years of reliable operation of accelerators. However, this is not always justified.

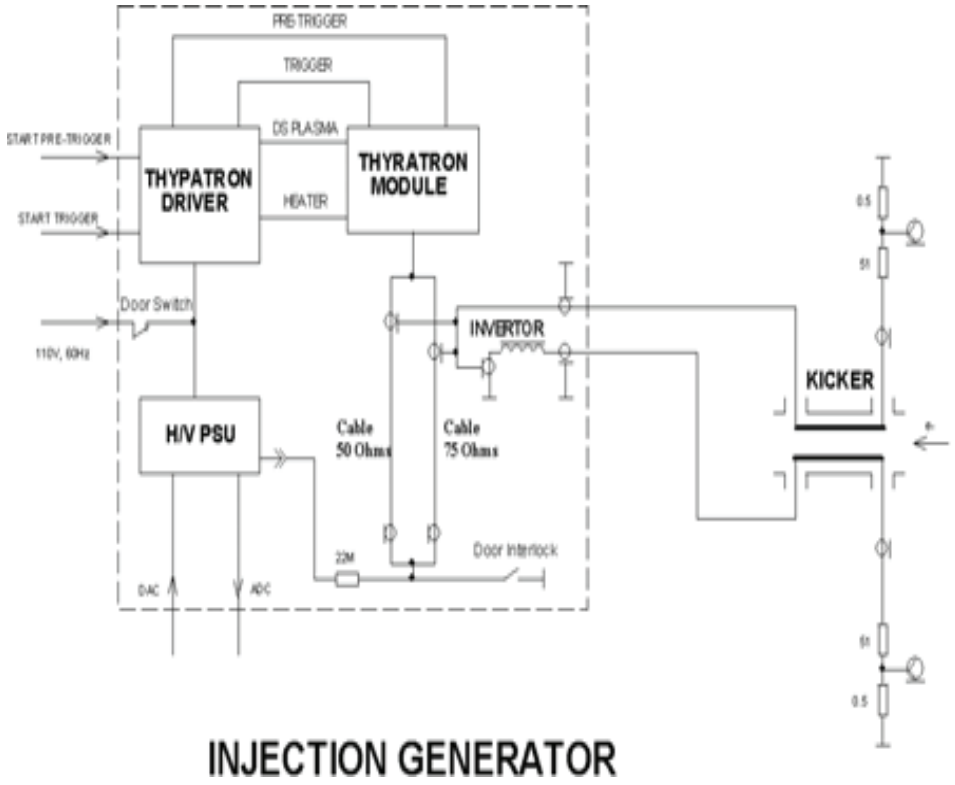
Тиратроны с ненакаливаемым катодом Pseudospark Switches Serial

Competition with solid-state devices compel the developers of thyratrons create designs devoid of such shortcomings of classical thyratrons as the presence of powerful heat chains, low reliability, and high cost.

System of high-voltage nanosecond generators for injection-extraction kickers for the Duke University FEL complex

- 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. The booster has 19 electron bunches at most, with the possibility of their pass-by in the SR FEL with a maximal frequency of 25 Hz. Operation in the main ring carried out in a few regimes: 2, 4 and 8 bunches. The aim of this is to inject the beam from the linear accelerator to the booster with minimal losses; to extract the beam in bunches from the booster and to inject it to the main ring. 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: TPI1-1k/20 in the booster generators and more power TPI3-10k/25 in the main ring generators. These PSS successfully compete with the traditional “hot thyratrons” and surpass them in jitter and rate of switching.

System of high-voltage nanosecond generators for injection-extraction kickers for FEL complex of the Duke University



INJECTION GENERATOR

Parameters of the **injection** generator with TPI1-1k/20

Pulse duration, ns	106
Maximal amplitude, kV	15
Pulse front time at the level of (0.1-0.9), ns	8
Pulse decay time at the level of (0.1-0.9), ns	8
Maximal pulse repetition rate, Hz	2
Output impedance, Ohm 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

Parameters of the Extraction Generator with TPI1-1k/20

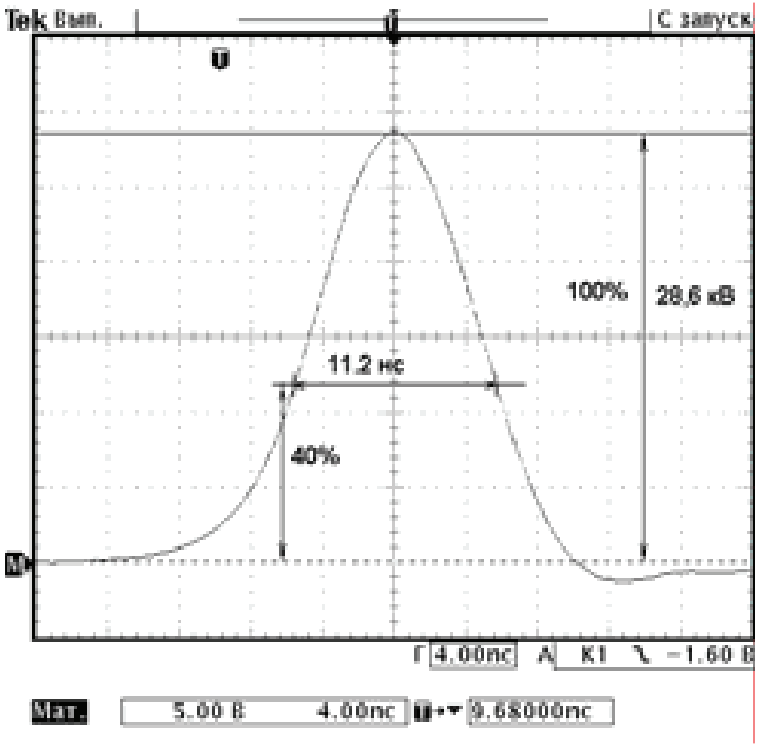
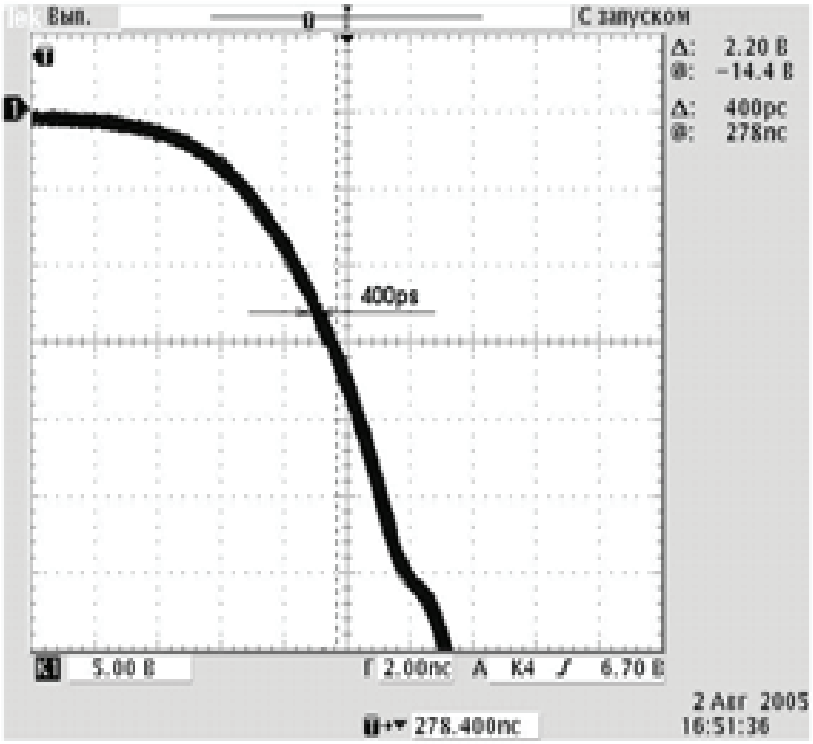


Figure 2: Oscillogram of a summed-up pulse on the extraction kicker with a 50 Ohm load.

Pulse half-amplitude duration, ns	10
Maximal amplitude, kV	22
Front duration at the level of (0.1-0.9), ns	10
Fall duration at the level of (0.1-0.9), ns	10
Maximal pulse repetition rate, Hz	25
Output impedance, Ohm	50
Switch type	TPI1-1k/20
Type of the forming line	Blumlein
Voltage tuning range, kV	4 -20

TPI–thyratron's jitter of the injection generator pulse



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. Fig. 5 and 6 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%.

Parameters of the generator for injection for the kickers of the ring

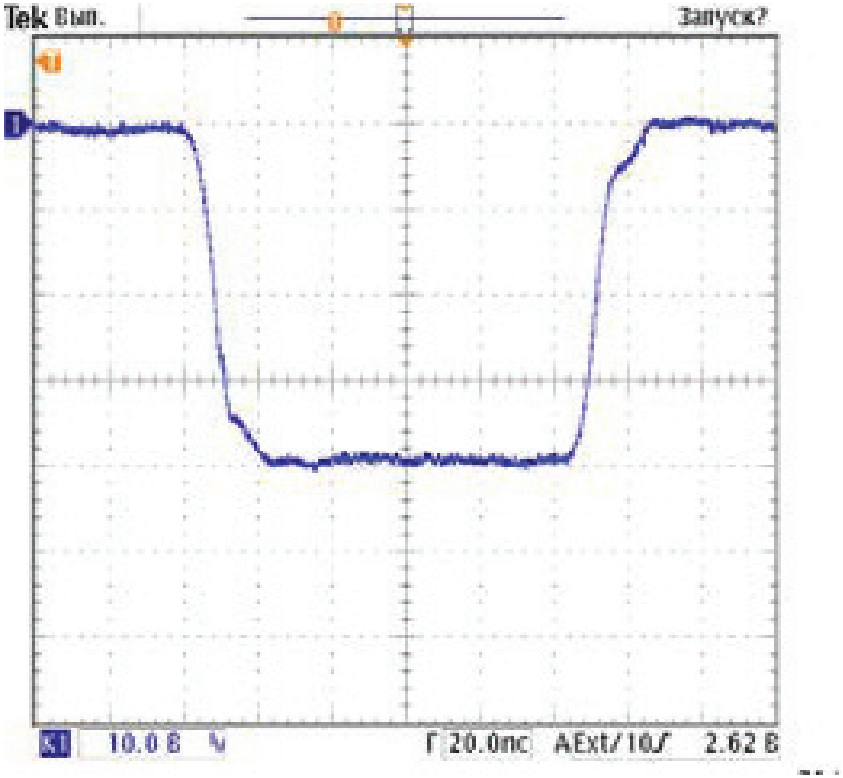


Figure 4: Panoramic oscillogram of a pulse on the injection kicker

Charge voltage PFN (Blumlein), kV	30
Output voltage (kicker pulse amplitude), kV	30
TPI maximal current (at 30 kV)	4.8 kA
Output resistance, Ohm	12.5
Pulse duration (double path over each PFN section), ns	50
Front duration at the level of 0.1-0.9	30
Fall duration 0.1-0.9	30
Jitter (pick-to-pick), ns	<1

Advantages

This design applies one pseudo-spark switch, TPI1-10κ/25, to power both plates of each of the kickers. The pseudo-spark switch works at maximal current as high as 5 kA and maximal anode voltage as high as 30 kV.

Such a design offers the following advantages:

1. No jitter between the kicker plates.
2. Only one TPI driver is required.
3. Each generator to power the corresponding kicker is designed as a separate module and is compactly arranged in a special cabinet.

Status of the kicker's thyratrons on January 2014

Serial number	Thyratron type	Hours of operation	Number of pulses	Pre-ionize voltage drop	Current status
27	TPI1-1K/20	~5,900	~1,200,000	250V, 18mA	In storage
23	TPI1-1K/20	~15,000	>10,400,000	314V, 10mA	In operation
	TPI1-1K/20	>20,000	~12,000,000	330V, 10mA	In operation
	TPI1-1K/20	>20,000	~12,000,000	293V, 10mA	In operation
61	TPI3-10K/25	~11,500	~5,600,000	372V, 10mA	In storage
62	TPI3-10K/25	>13,300	~9,300,000	344V, 10mA	In operation
63	TPI3-10K/25	>20,000	~12,000,000	389V, 10mA	In operation
64	TPI3-10K/25	~760		~171V, 10mA	In storage
65	TPI3-10K/25	~7,000	~1,900,000	417V, 12.5mA	In storage
180	TPI1-10K/20	>7,700	>6,000,000	364V, 10mA	In operation

Condensed statistics (as of August, 2016) on operation of TPI1-1k/20-thyratrons in FEL installations

ТПИ1-1к/20 Serial number	Life cycle	Hours of operation	Number of pulses	Current status	Special feature
47	From the date of launching of the system in 2005	30,000	32,000,000	In operation	Operated at low voltage down to 6.5 kV
23	Since February 2009	22,650	16,600,000	In operation	Anode voltage is changed in wide range
48	From the date of launching of the system in 2005 until July 2014	21,800	14,000,000	In operation	
285	Since November 2014	5,260	3,500,000	In operation	Anode voltage is changed in wide range

ТПИ1-10к/25 Serial number	Life cycle	Hours of operation	Number of pulses	Current status	Special feature
62	From the date of launching of the system in 2005 until August 2014	15,000	14,000,000	Out of order: heater short	
63	From the date of launching of the system in 2005	28,600	18,600,000	In operation	Operated at low voltage down to 7 kV.
180	Since June 2011	15,170	12,300,000.	In operation	Anode voltage is changed in wide range
181	Since July 2016			In operation	

According to the latest data from October 02, 2018, you can add another 5,000 hours of work to these dates.

Results of operation

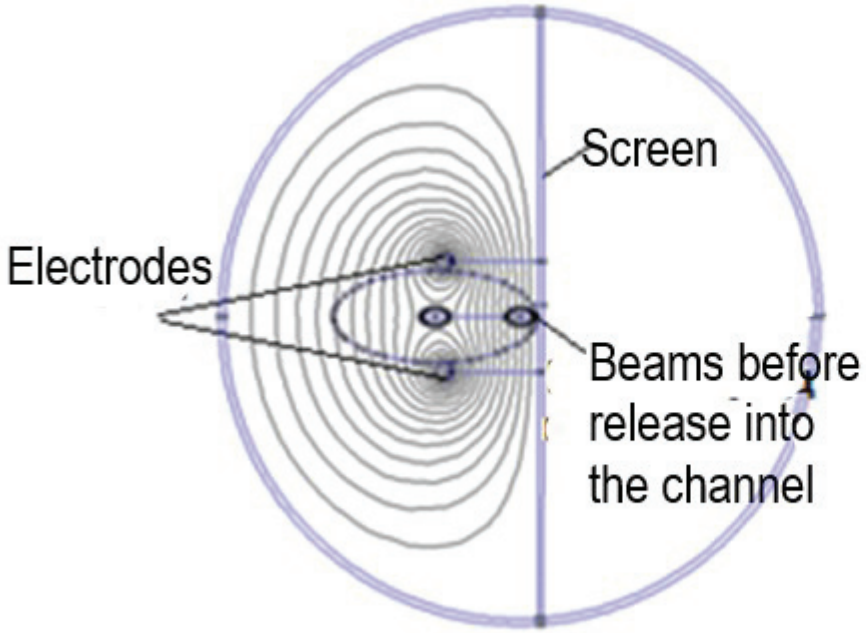
- The choice of switches of the TPI-type ensures the specified requirements for generators: jitter no more than 0.8 ns; rise and fall time of pulses from 4-5 ns; irregularity of the “shelf” for a long pulse (100 ns) - no more than 5%. There is the possibility of a fivefold adjustment to the output voltage while maintaining the shape of the pulses. In addition: - the design is significantly simplified by using one switch to power both kicker plates and a large switching current (up to 10 kA). The reliability of generators and manufacturability during assembly is quite high. At the accelerator complex, almost no self-breakdown (pre-fire) are observed.
- Generators have been operated at the FEL complex at Duke University, USA, North Carolina since 2005. Since the beginning of the regular operation of the system, more than 35,000 hours have been gained. During this time, the main problems were with the reliability of the drivers, which are now virtually eliminated. To reduce the tendency of the voltage drop in the thyratron on the preionization electrode to flow from the flowing direct current, instead of a constant one, “quasi-permanent” preionization is introduced, with a low-current ignition pulse preceding the launch of the thyratron by no more than 1 ms.

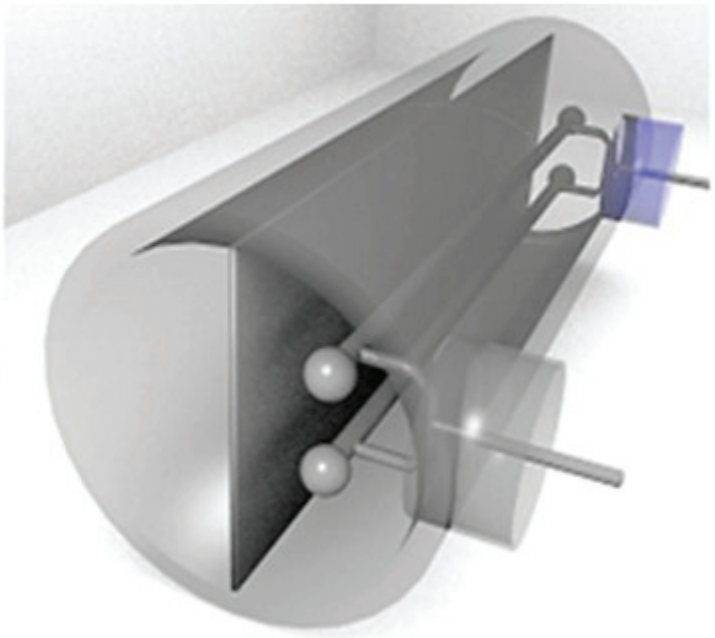
New Developments for NICA Projects

- It is important to note that TPI-switches in addition to the above properties - high reliability, long lifetime, short time jitter, have a record time of recovery electrical strength. They are capable of operating at either polarity of operating voltages, have small dimensions and relatively low cost.
- TDI-type thyratrons are used as crowbars, providing a unipolar impulse and protection of the unit elements, eliminating dangerous overvoltages.
- 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 (BINP). 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.

Kicker configuration

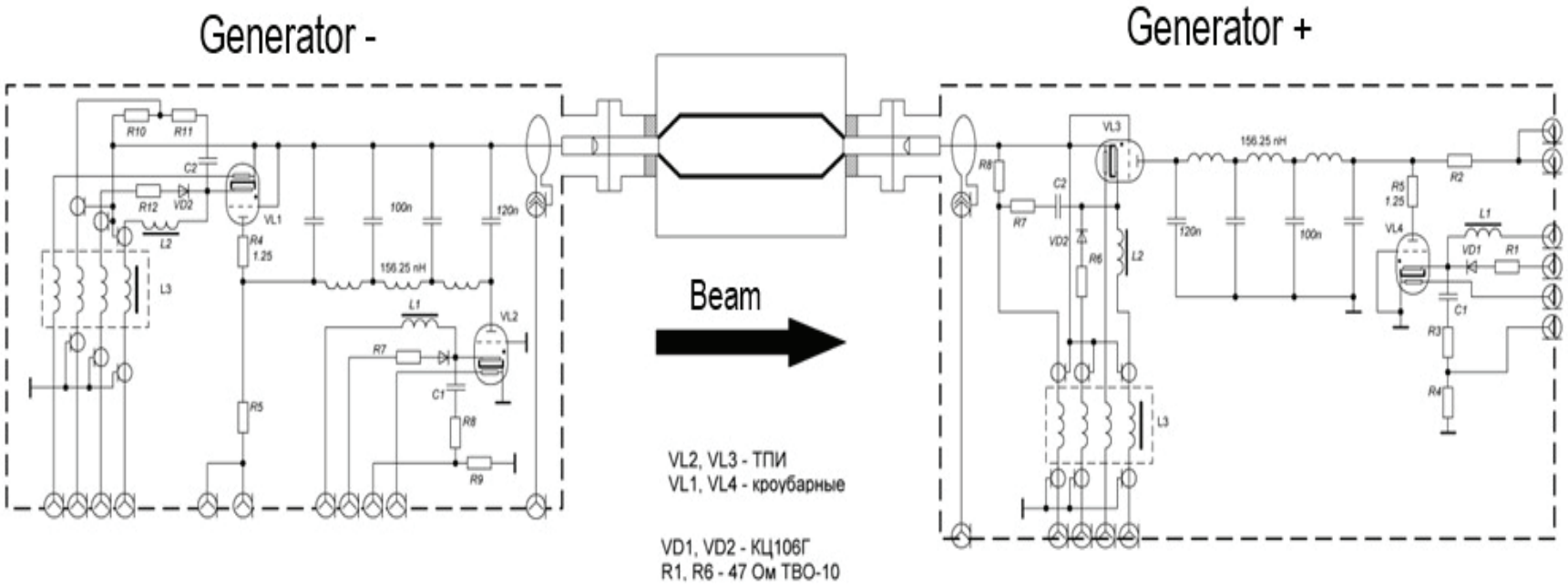
The kicker is a construction, consisting of one pair of conductors connected in parallel and a grounded shield, replacing the second pair of conductors with an opposite current direction, symmetrical with respect to the center of the beam discharged into the channel. Electrodes and the screen are placed into a vacuum chamber.

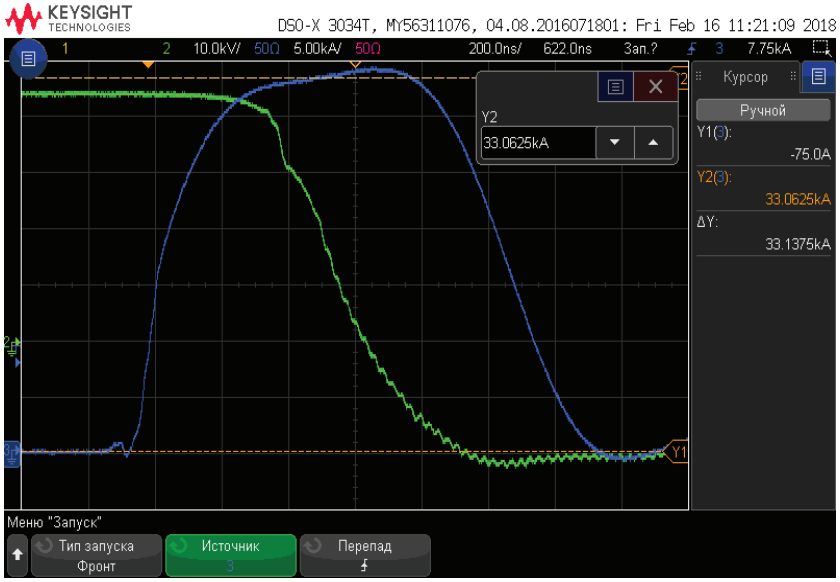




Kicker supply schematic

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





Oscillograms of current and voltage pulses during testing (200 ns/div)

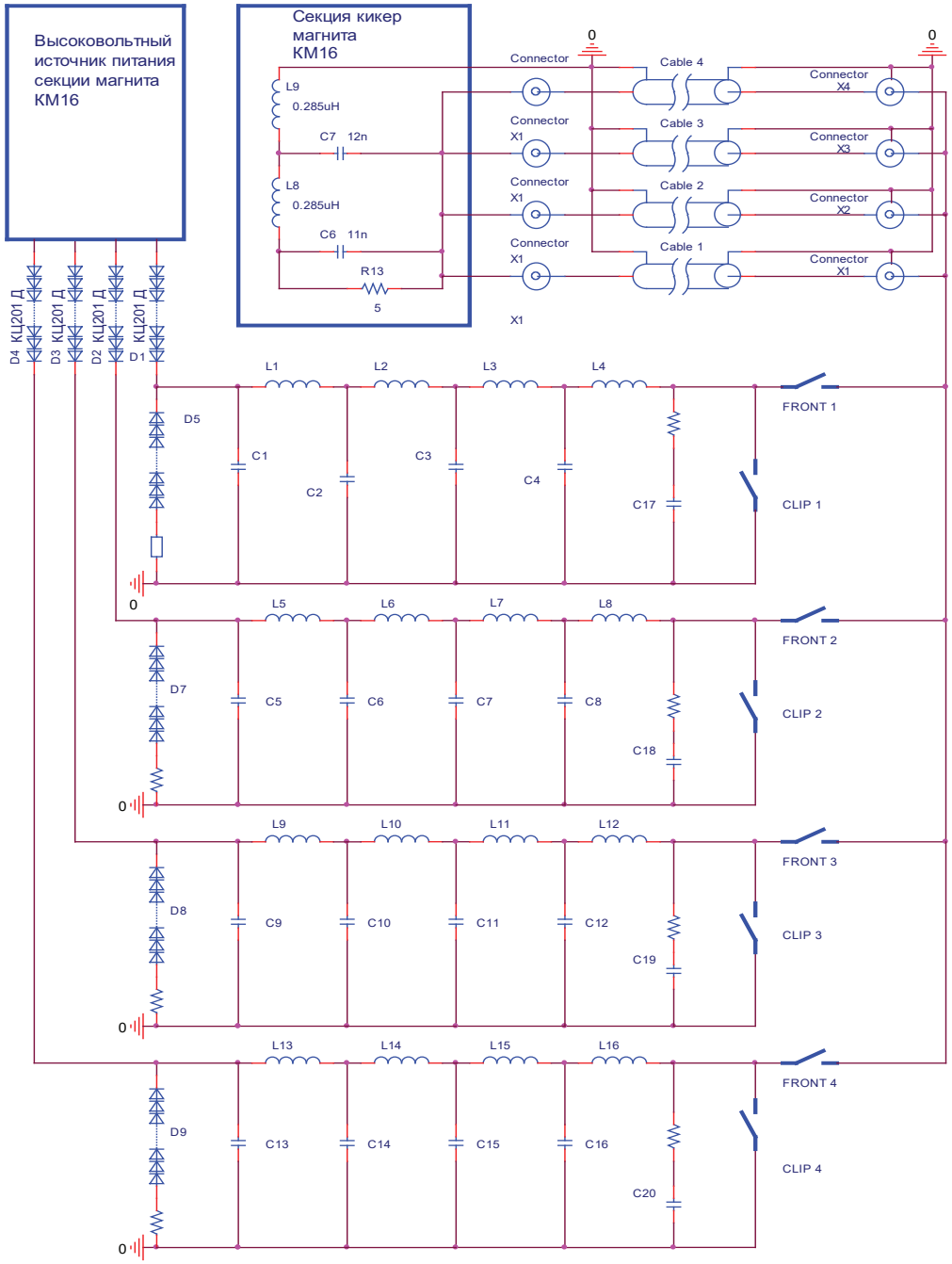
Oscillograms of current and voltage (500 ns/div.)

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

U70 Accelerator Kicker Magnet Supply Upgrade

- 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). In this case, the beam will be released in four portions 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.

Circuit schematic of beam release by discharge of pulse forming networks (PFN) onto a single load (one section of U70 accelerator kicker magnet).



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

Thank you for attention!

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