Accelerator Laboratory

Solid-State Modulator for Klystron

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Table of Contents

1. PFN type Modulator with a Solid-State Switch

- Development of 45 kV SI-thyristor Switch
  In co-operation with NGK, Sumitomo Hevay Industries, Komatsu.

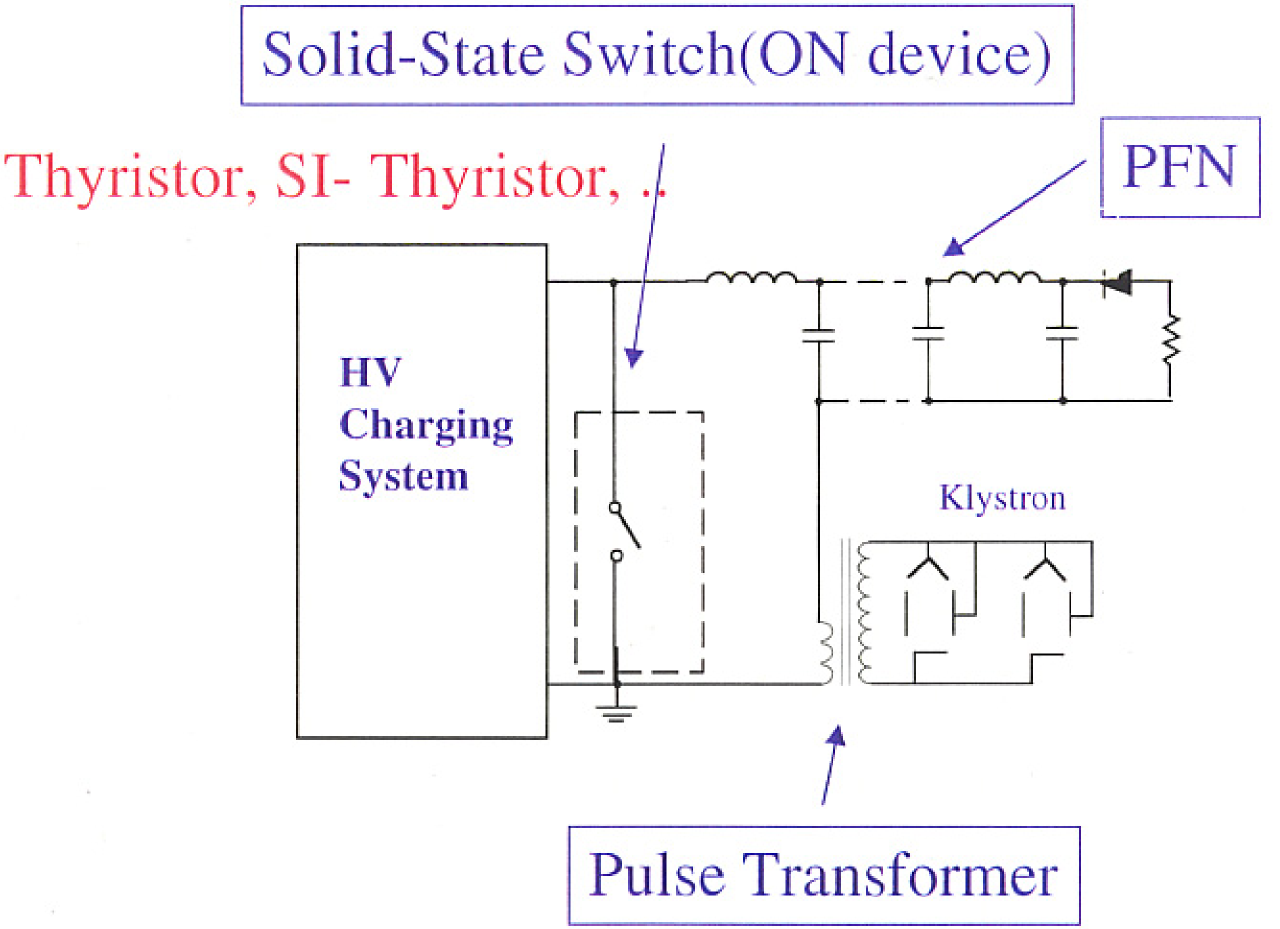
2. Direct Switching type Modulator with Solid-State IGBT Switches

- Development of a pulse generator using multiple pulse modulators stacked in series
  In co-operation with Mitsubishi Electric Co.

3. Summary

PFN-type Modulator with a Solid-State Switch

To replace a thyratron tube



Solid-State Switch(ON device)

Thyristor, SI- Thyristor, ..

PFN

Pulse Transformer

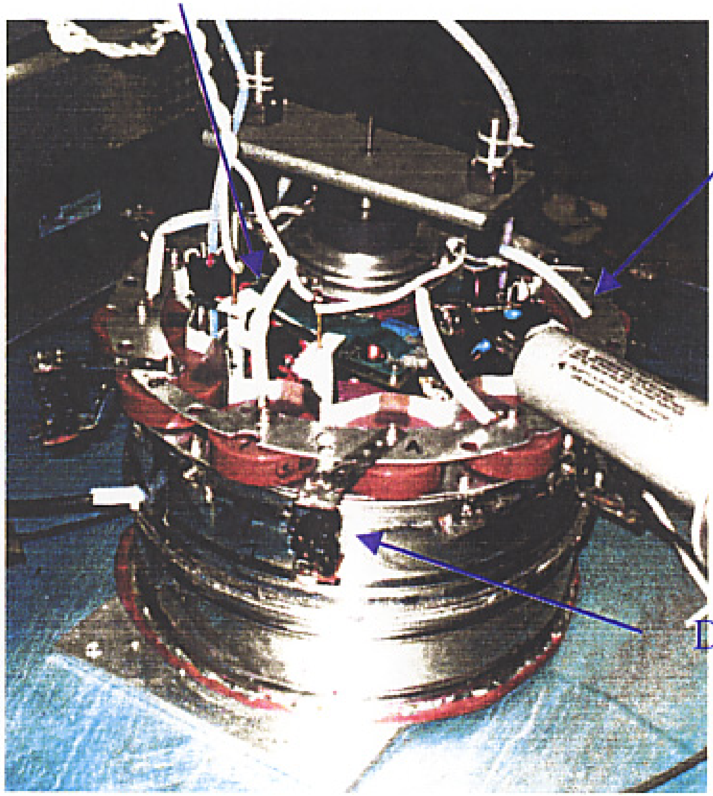
45kV Solid-State Switch Specifications

• Hold-off voltage	45 kV
• Peak current	6,000 A
• Pulse width	6 μs
• Repetition rates	50 pps
• Device	SI-Thyristor[NGK : RS1600PA40T1(4kV)]
• Connection	15 devices in series
• Insulation	Oil
• Cooling	Forced oil cooling

- As a first step in the solid-state switch development, we designed a solid-state switch to meet the requirements of approximately one hundred-megawatt peak power klystron modulators for the KEKB injector linac or the Accelerator Test Facility(ATF) linac.

Measurement of Fast Turn-on Characteristics Using a Low Inductance Test Circuit

SI-Thyristor and Gate driver circuit

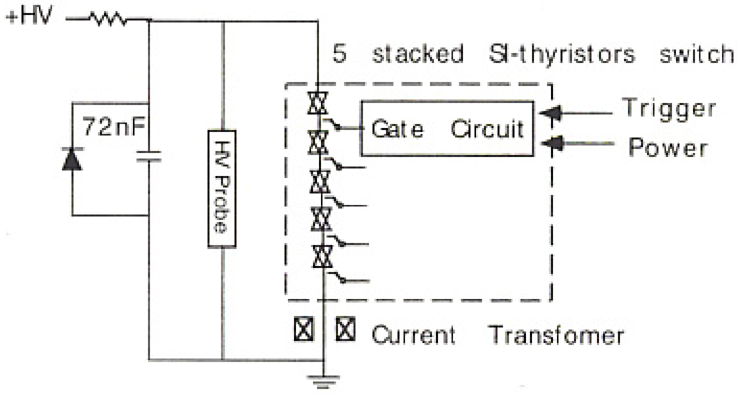


Capacitor

Diodes

Photography of the test circuit

Circuit inductance(~136nH)



Equivalent circuit

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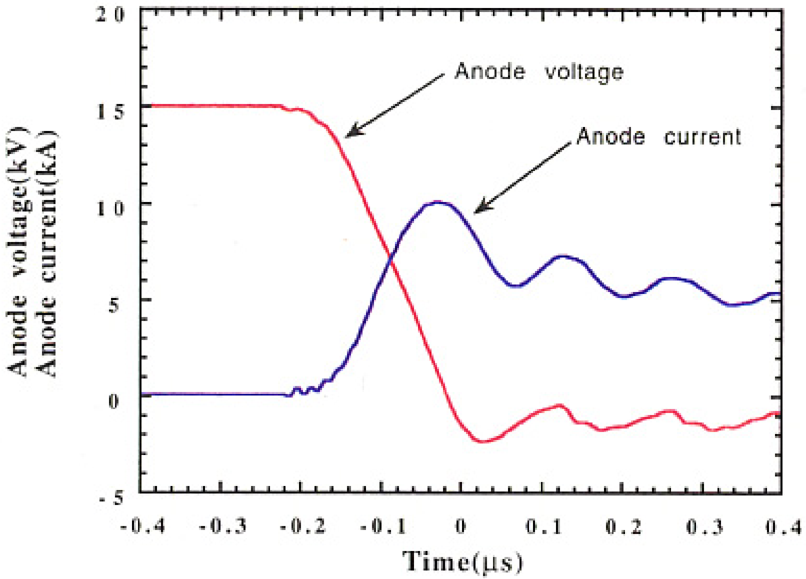
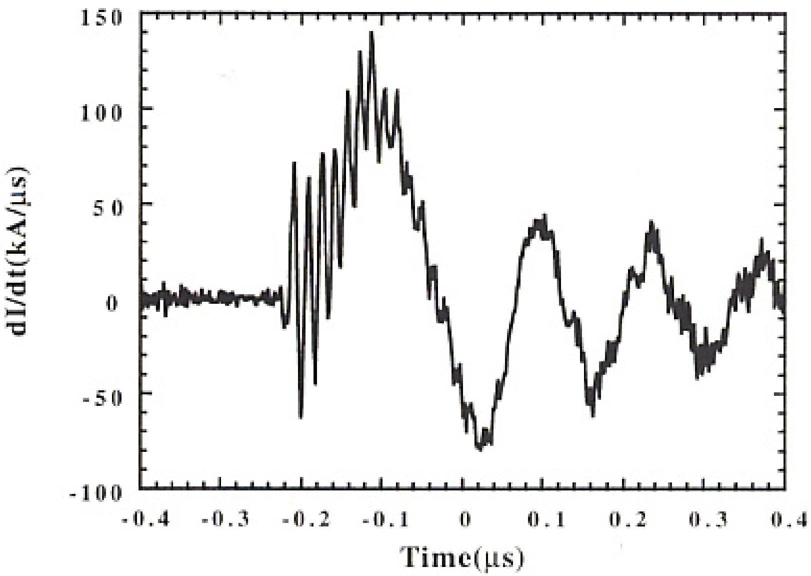
Switching waveforms and dI/dt waveform





- Peak current	10kA
- Peak dI/dt	110kA/µs
- Switching time(90-10%)	128ns

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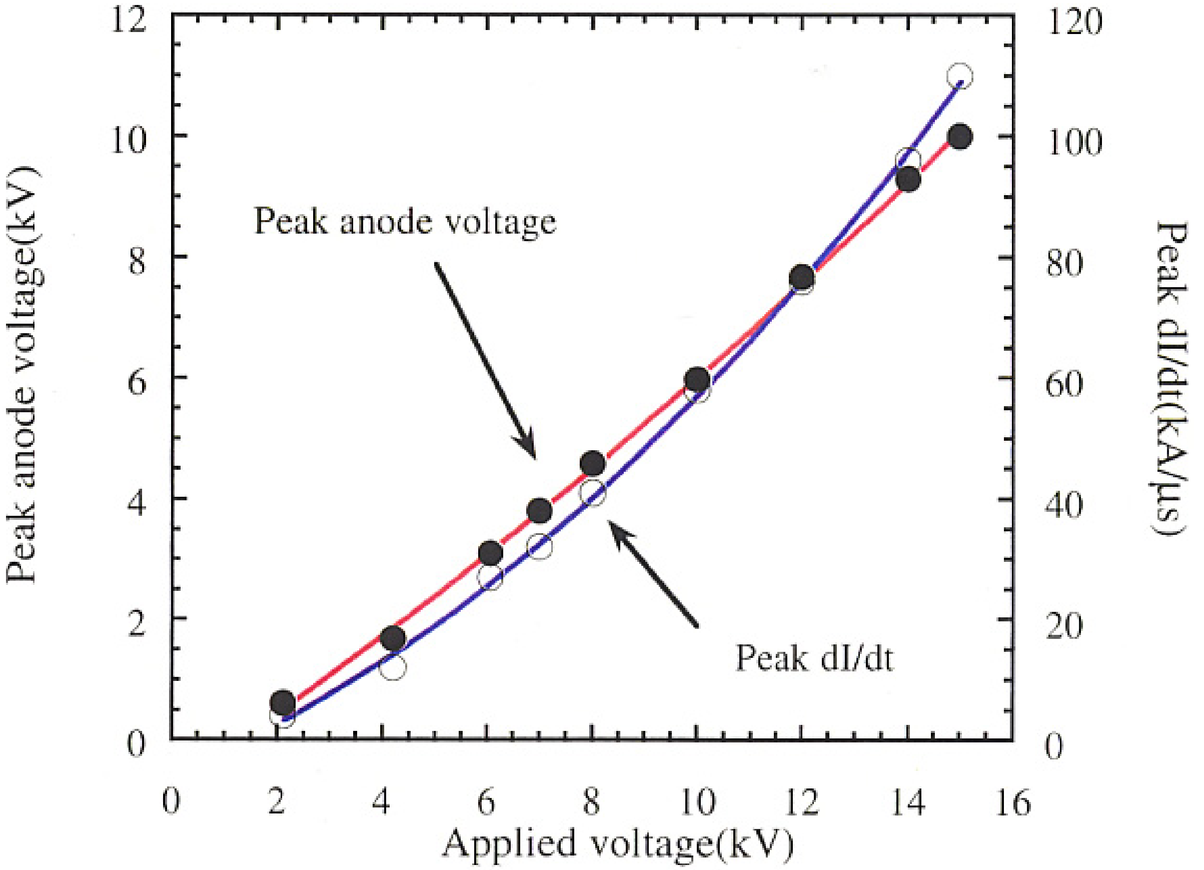
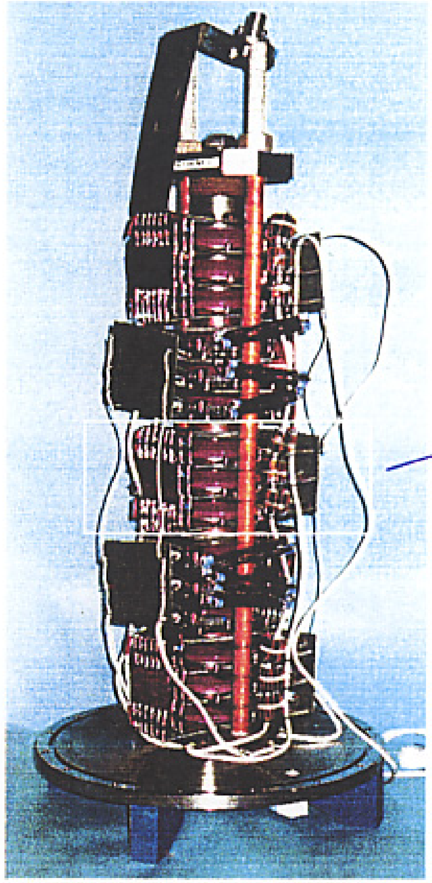
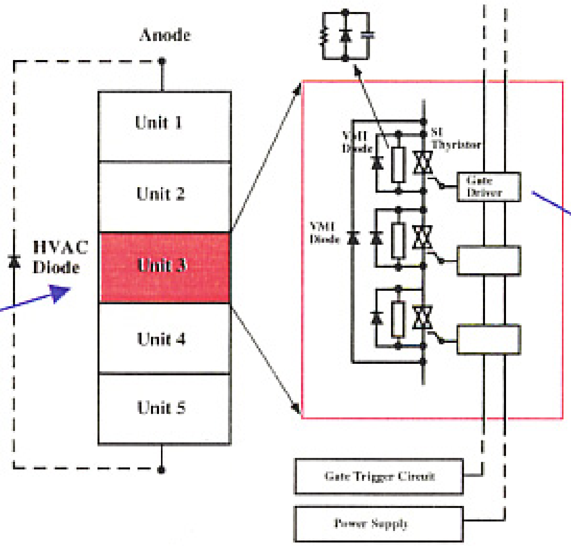
Peak anode current and dI/dt as a function of applied voltage



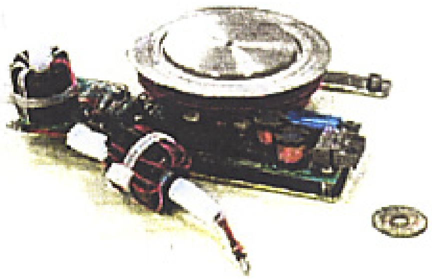
45kV Solid-State Switch



Switch assembly



Basic circuit diagram



Gate driver circuit
and
SI-thyristor

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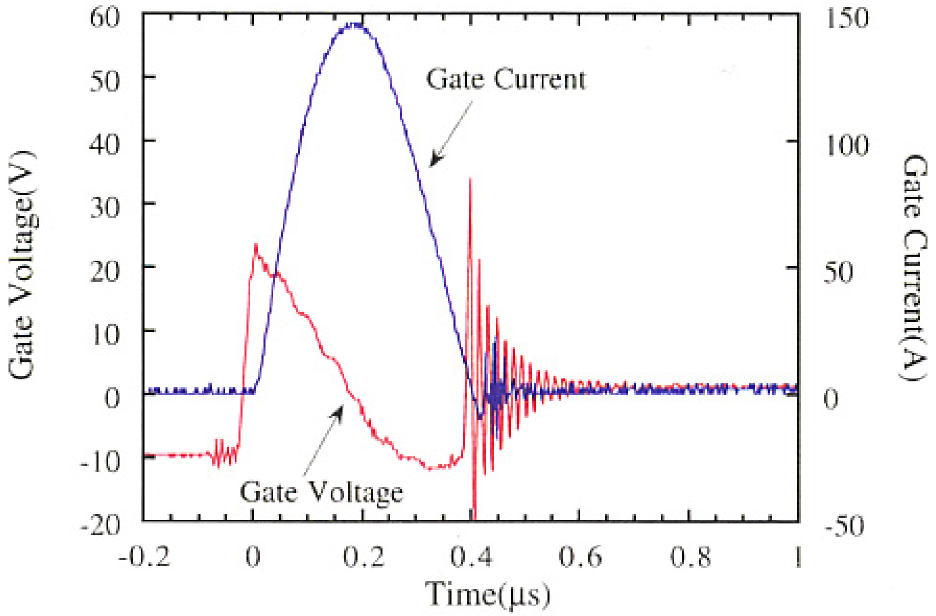
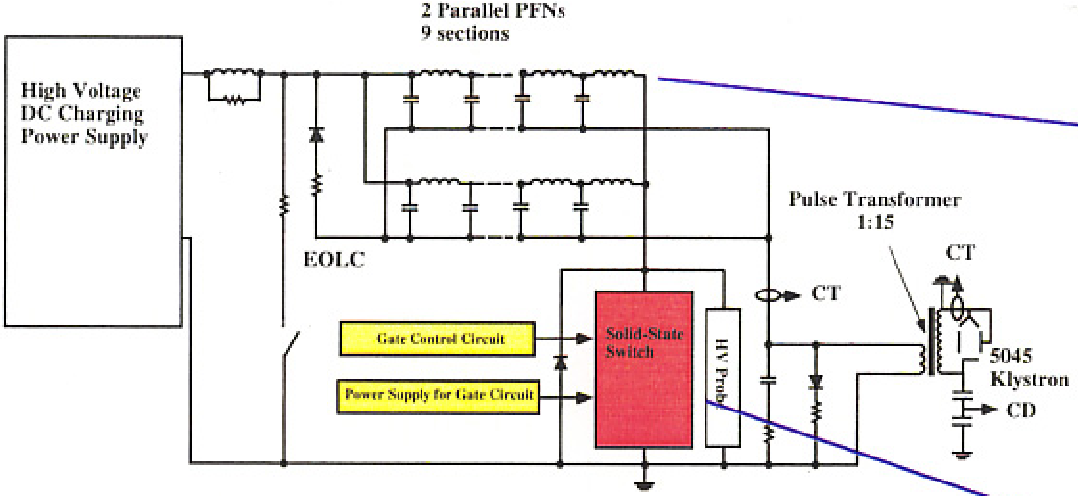
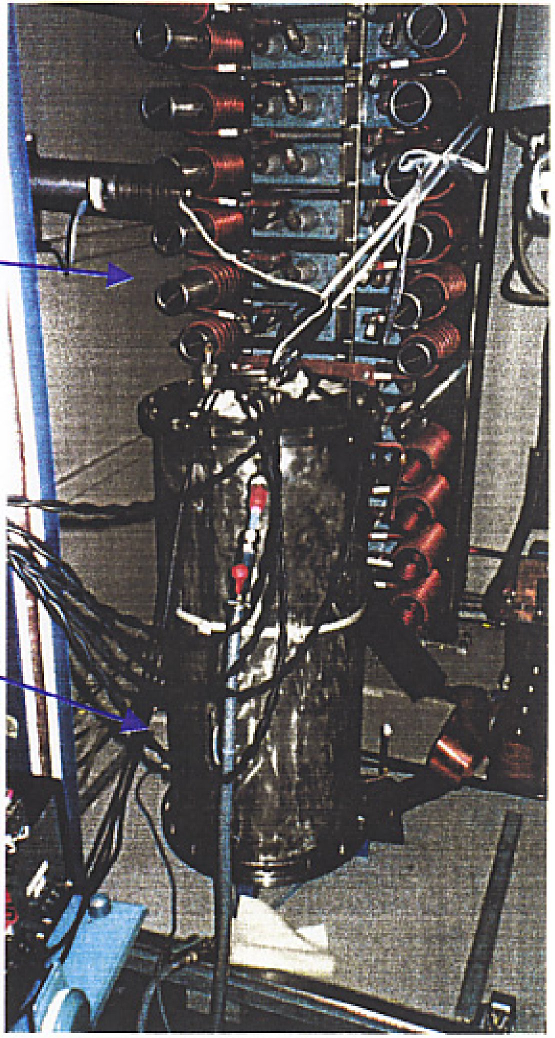
Gate Voltage and Current Waveforms



- The SI-thyristor is a normally-on type device. To make a hold-off state, a bias voltage of –10 V is applied between the gate and cathode electrodes. A gate circuit driving large gate current with a short rising time is essential to obtain a fast switching time of the device. Thus, it is important to reduce the total inductance in the gate circuit and to apply much higher voltage to the gate.

Test Circuit





Operation Parameters

• Peak output power	136 MW
• Hold-off voltage	45 kV
• Peak current	6 kA
• Pulse width	6 μs
• Repetition rates	25 pps
• di/dt	10 kA/μs

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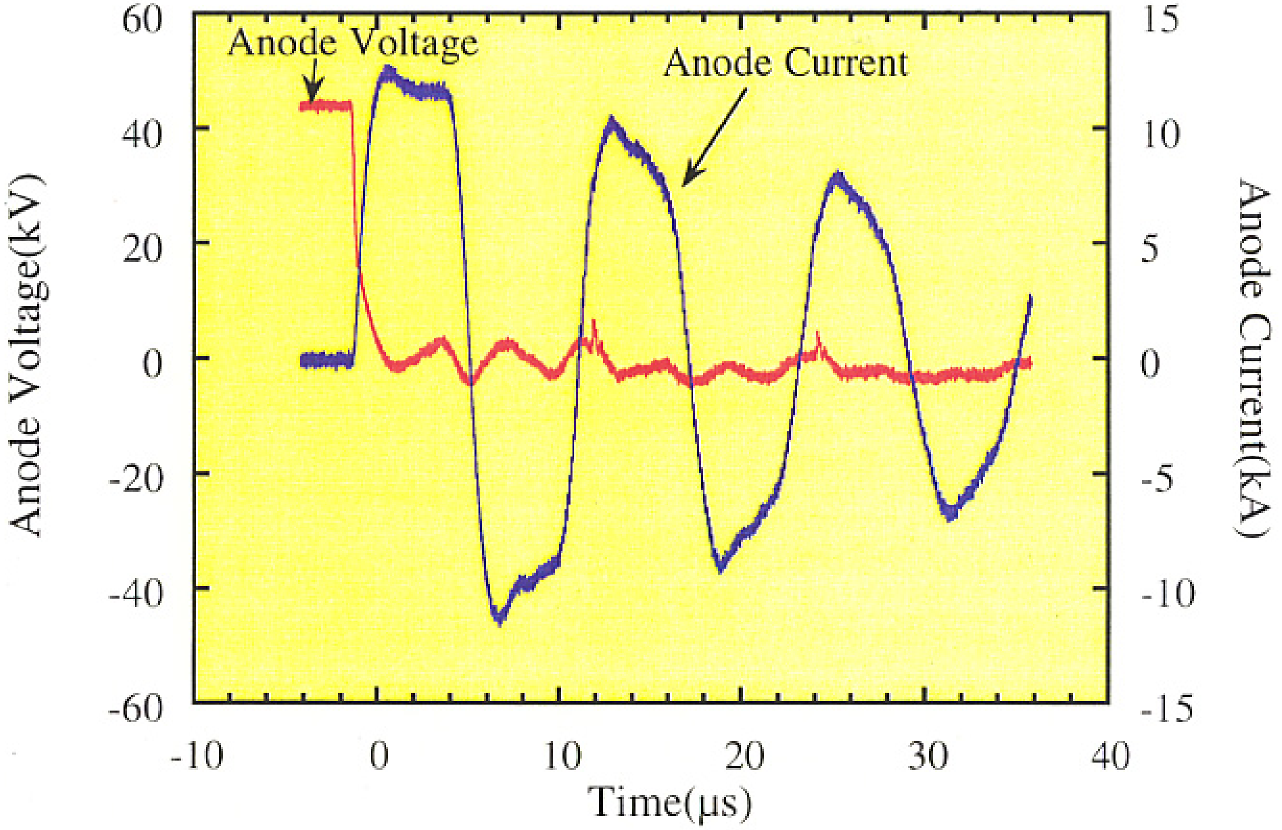
Dead-Short Circuit Test



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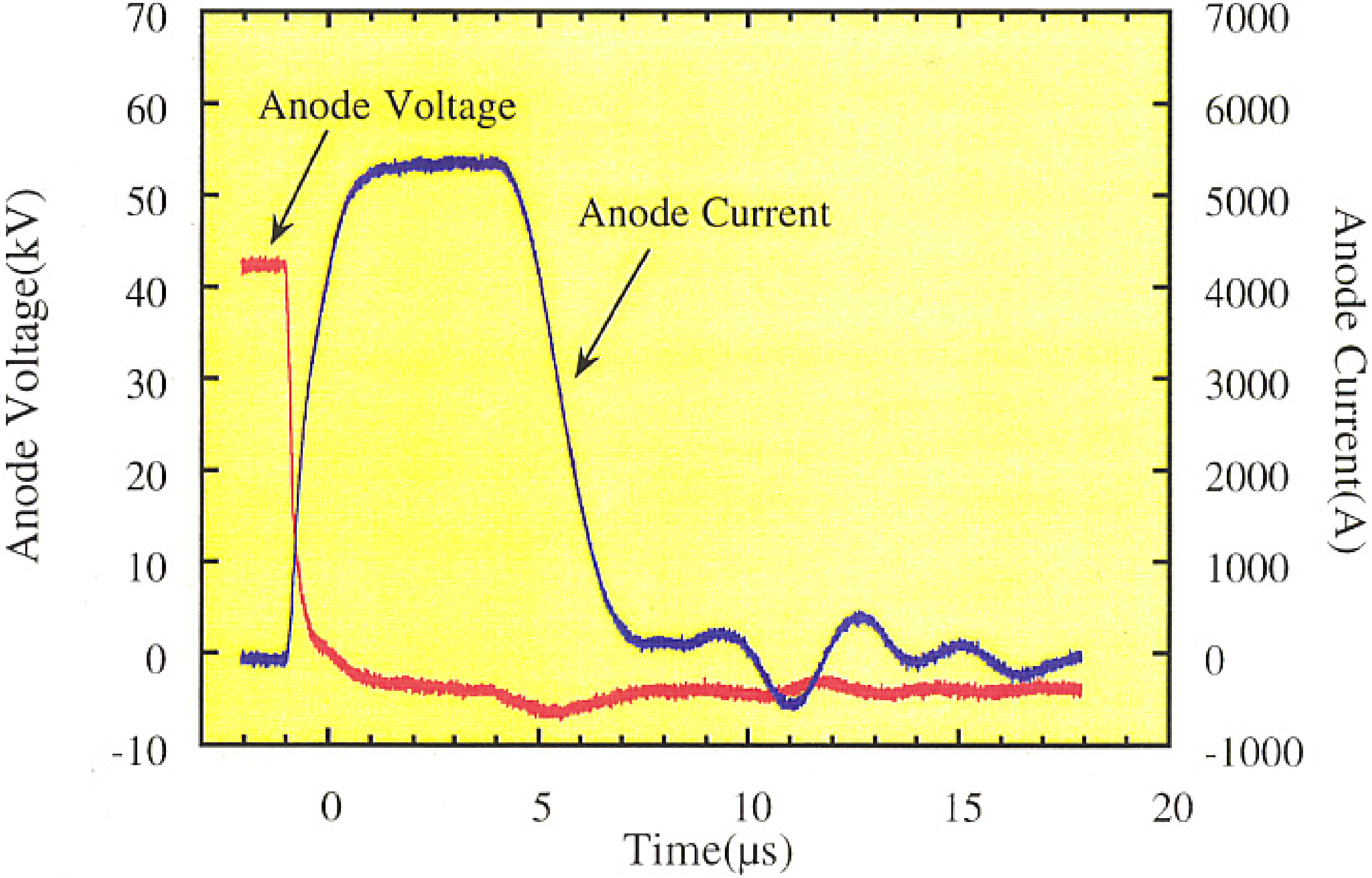
Switching Waveform



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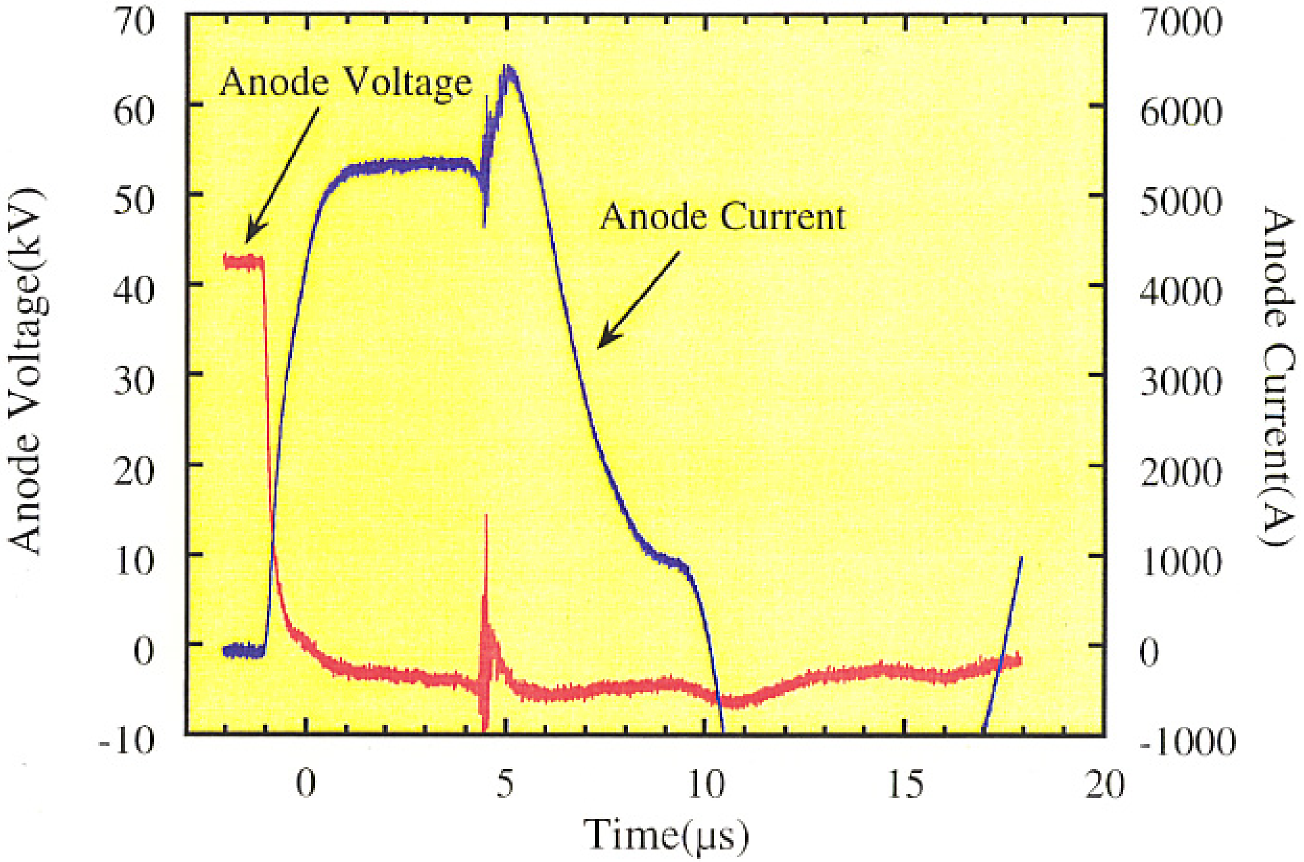
Klystron Arc-down



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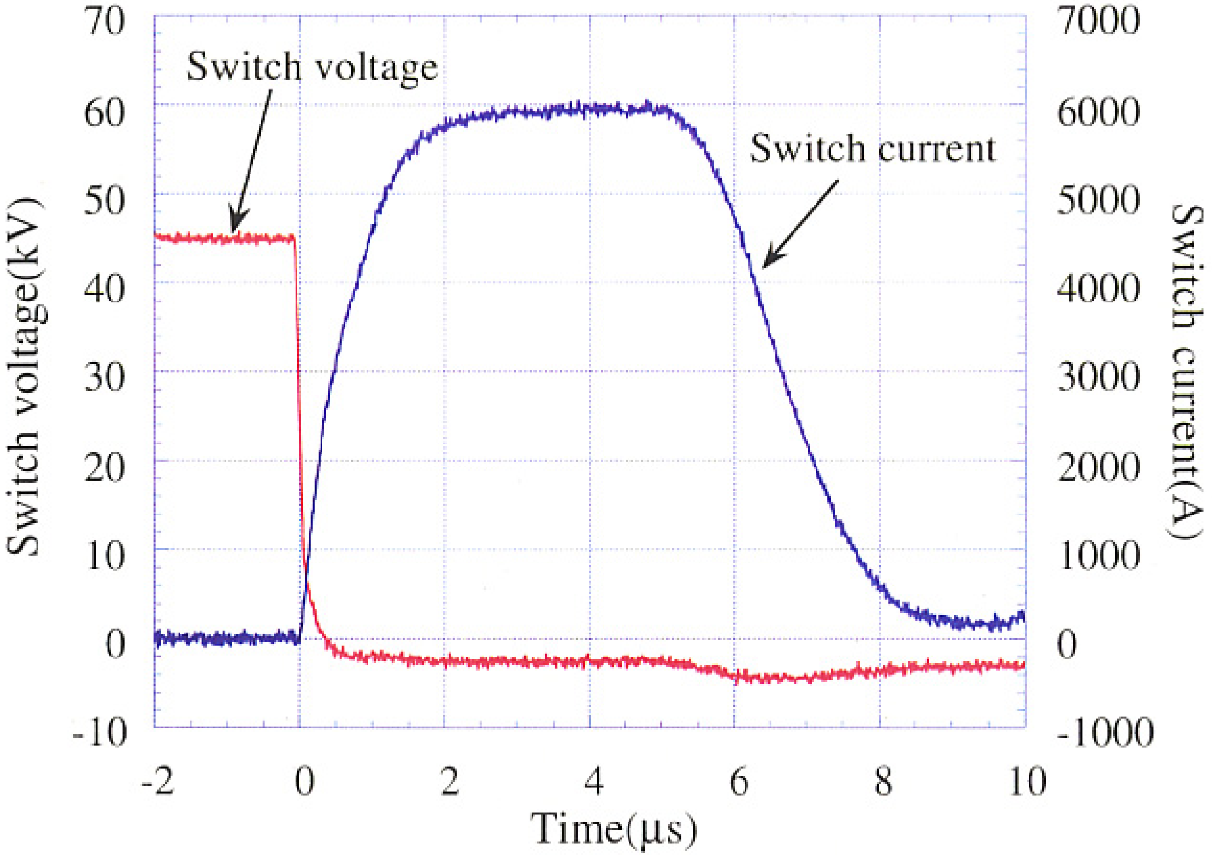
Typical switch voltage and current waveforms (Solid-State Switch, PFN:45kV)



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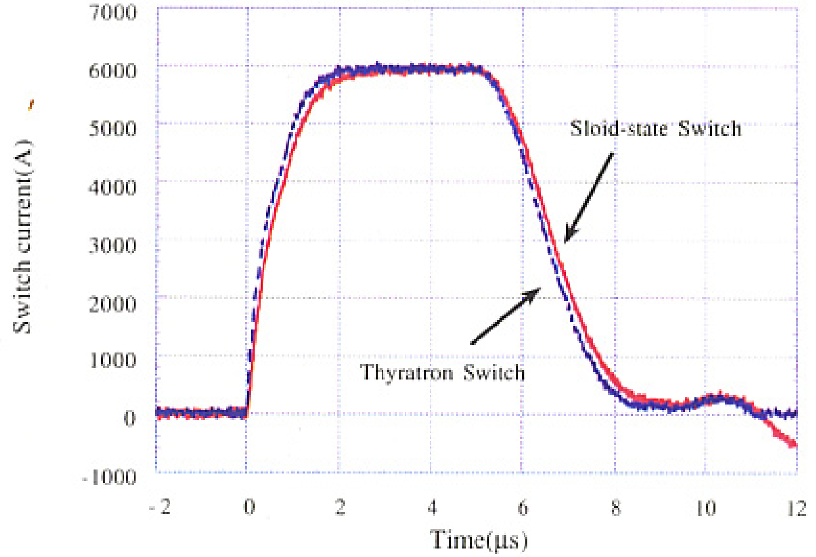
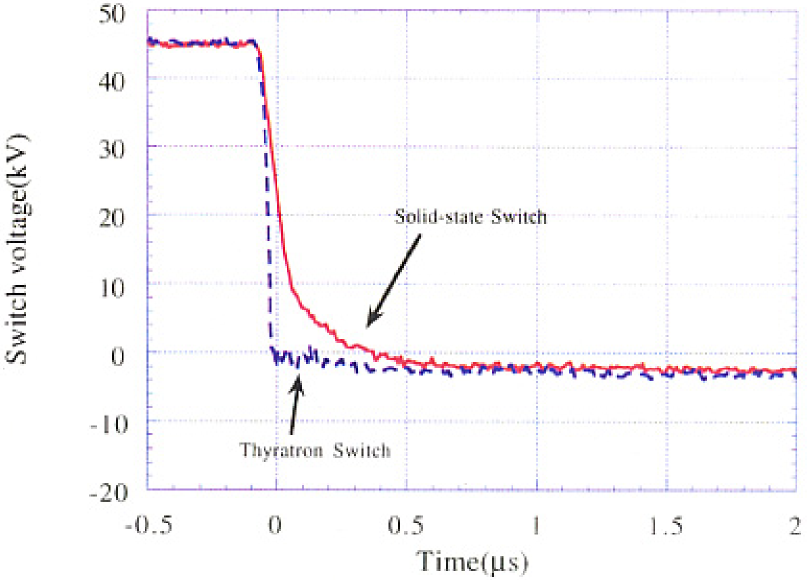
Switching current and voltage waveforms (Solid-State Switch vs. Thyratron Switch)

Switching Current



Thyratron : EEV CX1536

Switching Voltage



Thyratron Switching Time(90-10%): 40 ns
Solid-State Switching Time(90-10%): 208 ns

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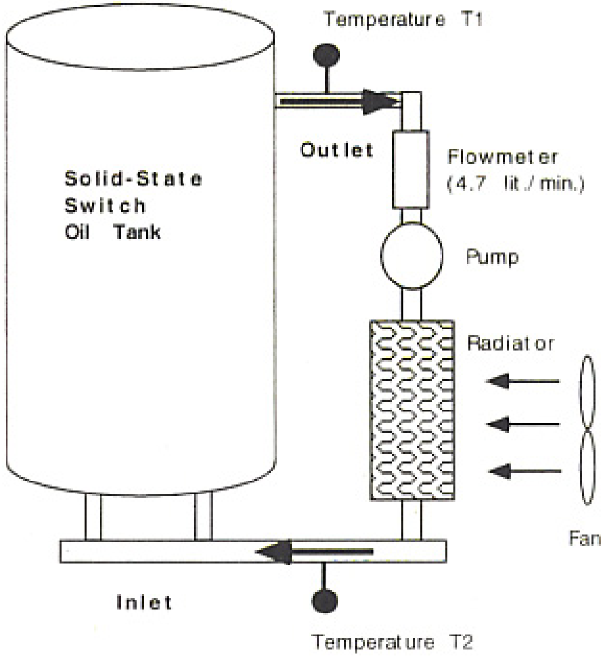
Switch Losses vs. PFN Voltage

- **Measurement of switch losses by means of calorimetry**

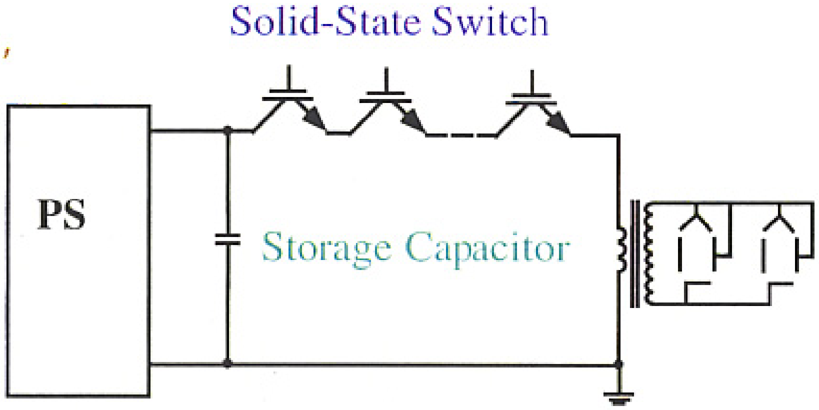
PFN Voltage (kV)	PFN Stored energy (J/pulse)	Switch Losses (J/pulse)	Details of switch losses		
			Balance resisters (J/pulse)	Gate Circuits (J/pulse)	Devices (J/pulse)
20	162	9.4(5.8%)	0.98(10.5%)	0.8(8.5%)	7.6(81.0%)
30	365	21.3(5.8%)	1.92(9.0%)	0.8 (3.8%)	18.6(87.2%)
40	648	32.8(5.1%)	2.77(8.5%)	0.8 (2.4%)	29.2(89.1%)
45	820	41.1(5.0%)	3.10(7.4%)	0.8 (2.4%)	37.2(90.7%)



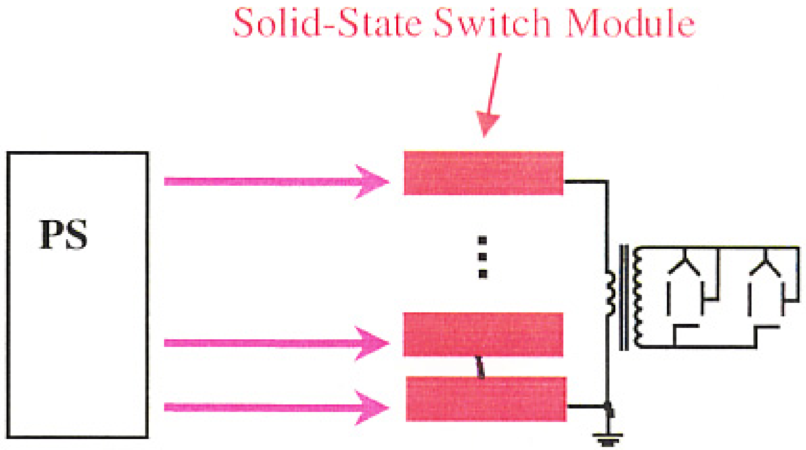
130 W/°C

Direct switching type modulator

- **Series Switch Topology**



- **Adder Topology**



- **Flexible**

  Active waveform control
  - Pulse width
  - Pulse flatness

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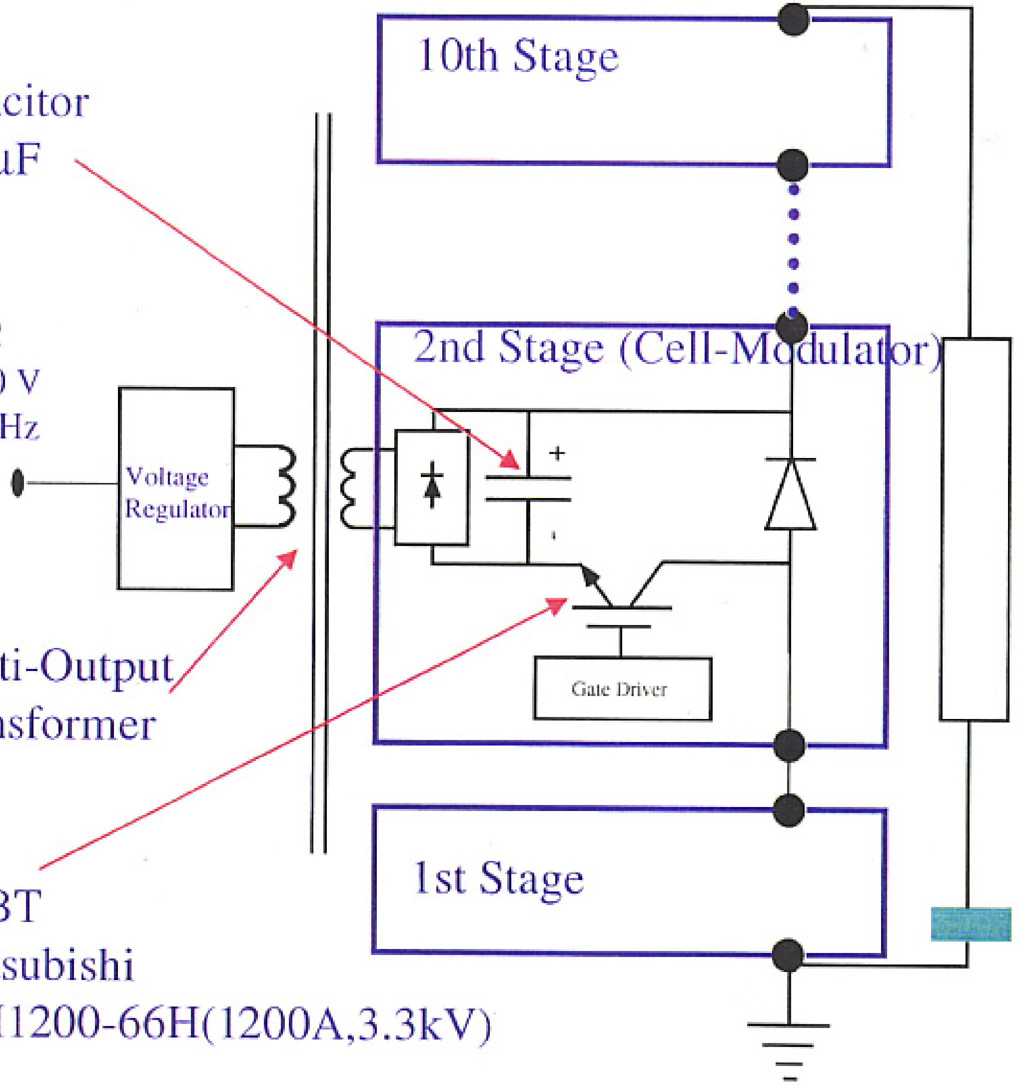
10-Stage Test Modulator Circuit



Capacitor
17.3µF

AC
100 V
50 Hz

Multi-Output
Transformer

IGBT
Mitsubishi
CM1200-66H(1200A,3.3kV)

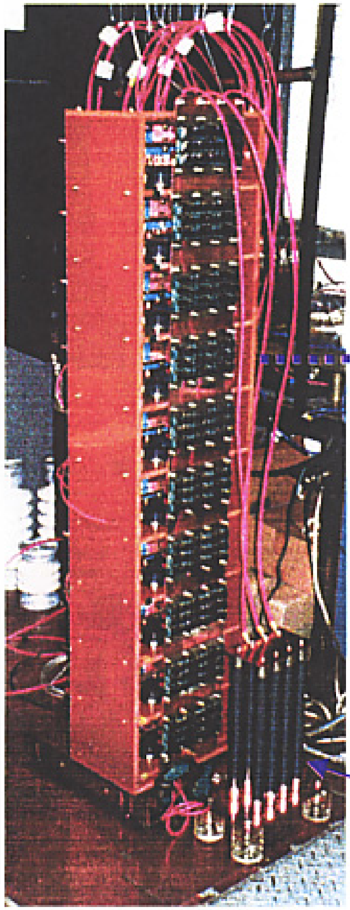
Max. 20 kV

Parameter	**Value**
Output Voltage	20 kV
Output Current	2.9 kA
Pulse width	3 µs
Number of Cell-Modulator	10
Repetition Rate	5 Hz

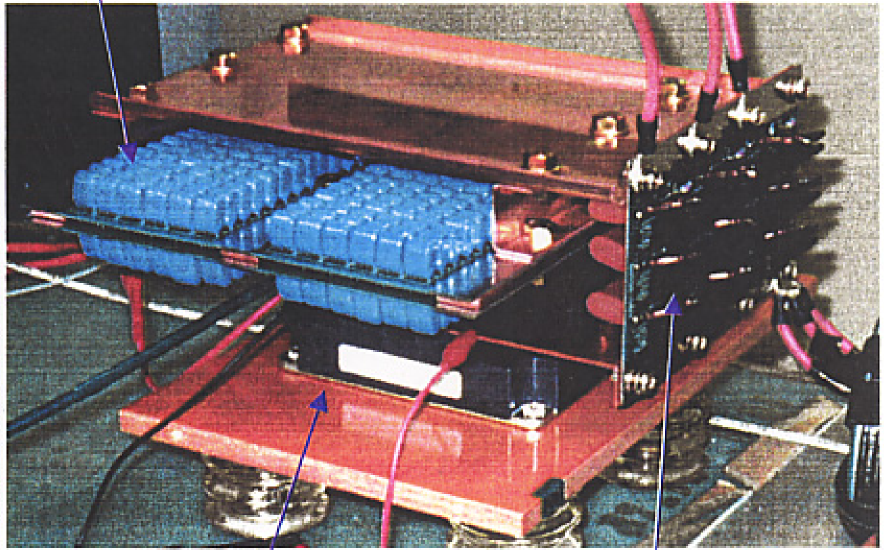
Resistor
Load

CT

10-Stage Test Modulator



Resister Load



Energy Storage Capacitors

Cell-Modulator

IGBT

Bypass-Diodes(Freewheeling diodes)

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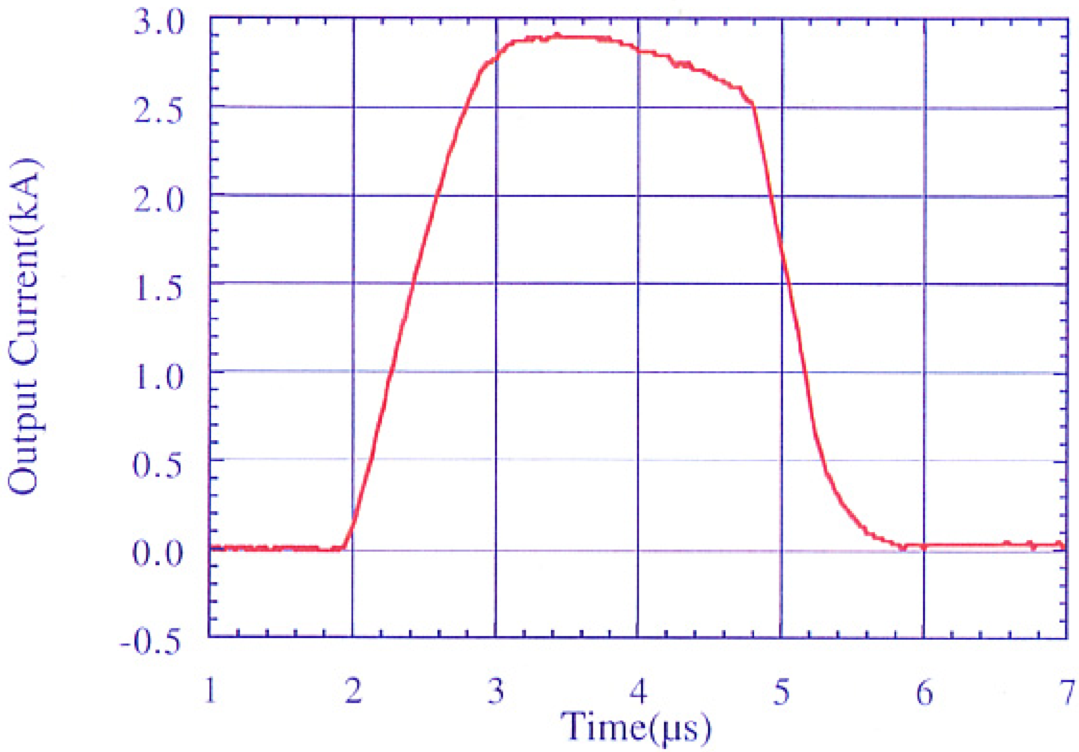
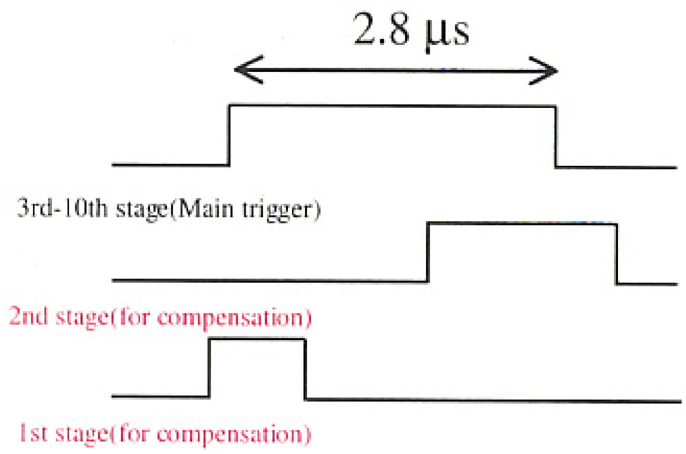
10-Stage Test Modulator
(17 kV, 2.9 kA Output Pulse)



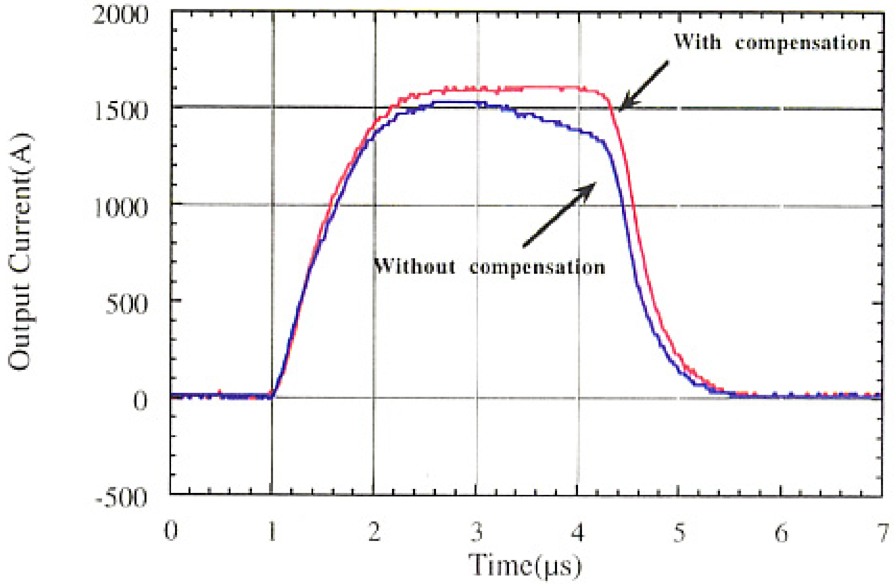
IGBT: CM1200HB-66H(1200A, 3.3kV)
Applied Voltage: 1.7 kV/stage, Repetition rate: 2 Hz
Storage Cap.=17.3 μF(film), Resistor Load=5.2 Ω

Active Waveform Control

- **With appropriate triggering of IGBT modules, output waveform can be controlled. (PWM method, Timing-control method).**
- **Adding small energy near pulse end increases useful pulse width.**



Trigger Timing Chart



- Test by timing-control method

  Operated 10 modules using 2 modules as a waveform compensation module at each stage voltage of 1 kV.

IGBT: CM1200HA-66H x 5 + CM1200HB-66H x 5
Applied Voltage : 1 kV/stage, Repetition rate: 2 Hz
Storage Cap.=17.3 μF, Resistor Load=4.1 Ω

Summary

- A compact solid-state switch using SI-thyristors was designed and tested with a klystron pulse modulator. We have demonstrated that the switch can reliably operate at a 43 kV hold-off voltage, a 5.4 kA peak current, a 6 μs pulse width, and 25 pps, and can withstand load faults.
  Successfully operated for 57 hours(5 M shots)

- A direct switching type modulator using individual pulse modulator stacked in series, is being studied. A ten-stage test modulator has been built and has been successfully operated at 20 kV and switched up to 2.9 kA.