Accelerator Laboratory

KEK Bouncer-type Modulator

M. Akemoto, H. Honma, H. Nakajima, T. Shidara, S. Fukuda

High Energy Accelerator Research Organization(KEK)

2007 High Level RF EDR Kickoff Meeting

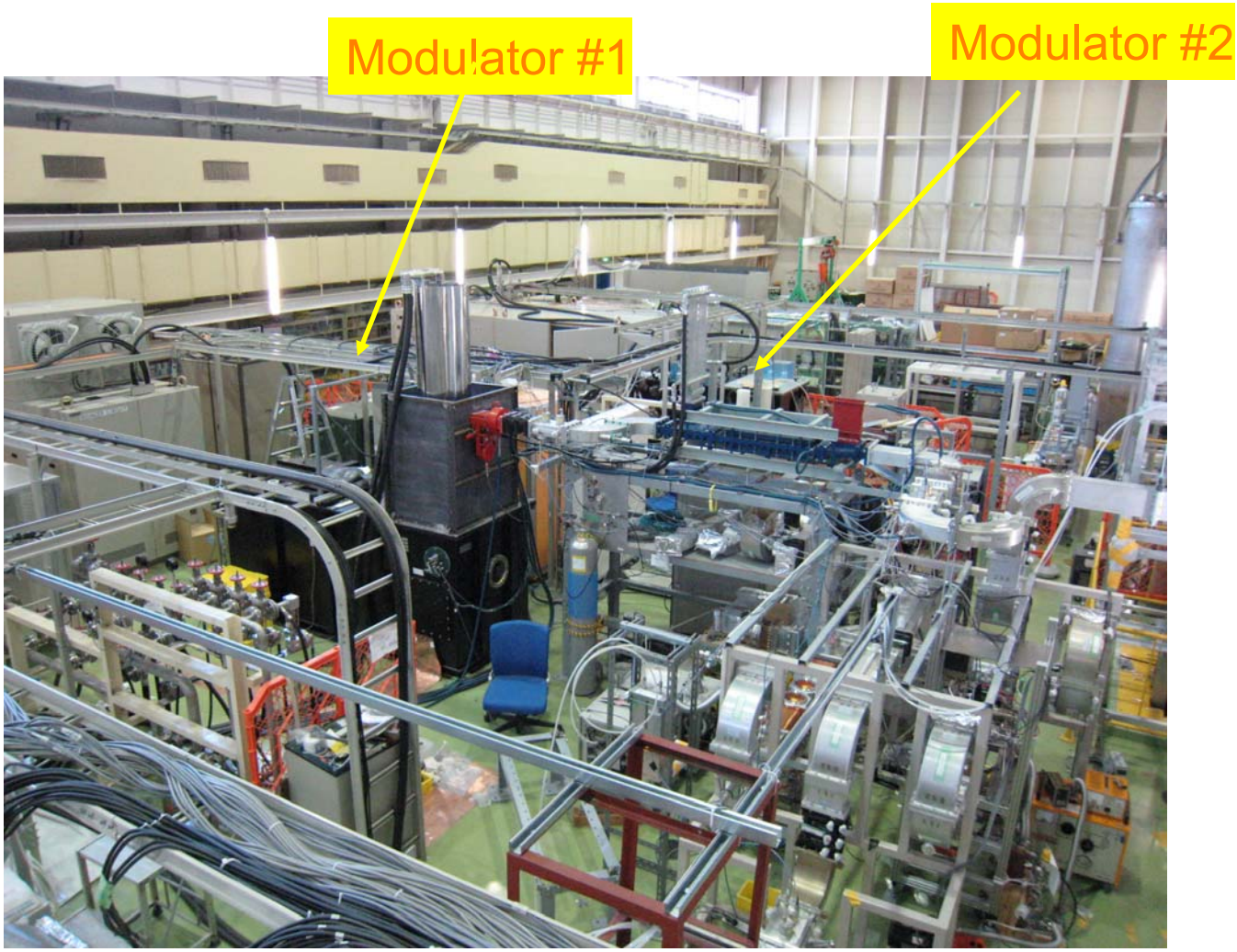
Oct. 2, 2007

Accelerator Laboratory

Table of Contents

Accelerator Laboratory

Present Status on STF



STF Klystron gallery

Accelerator Laboratory

5 MW Single-Beam Klystron

Specifications (TH2104)

• Operating Frequency	1.3 GHz
• RF Pulse Width	1.5 ms
• Peak Output Power	5 MW
• Beam Voltage	124 kV
• Beam Current	92 A
• Micro-Perveance	2.1
• Repetition Rate	5 pps
• Efficiency	46 %

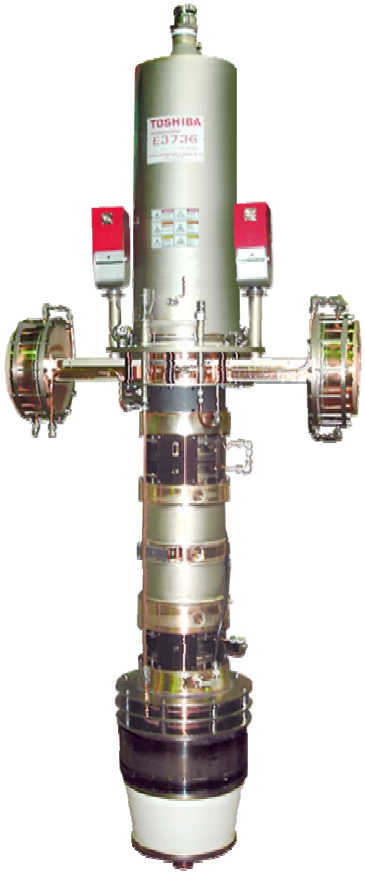
TH2104A

Accelerator Laboratory

10 MW Multi-Beam Klystron

Specifications (Toshiba E3736)

- Operating Frequency 1.3 GHz
- RF Pulse Width 1.5 ms
- Peak Output Power 10 MW
- Number of Beams 6
- Beam Voltage 120 kV
- Beam Current 140 A
- Micro-Perveance 3.4
- Repetition Rate 5 pps
- Efficiency 60 %



Toshiba MBK

Accelerator Laboratory

STF Modulator #1

•To rapidly start the project and reduce its cost, the first modulator was converted from a klystron modulator system obtained from the Power Reactor and Nuclear Fuel Corp (PNC).

•The PNC modulator had been originally designed and built about 10 years ago for the positron factory project at PNC.

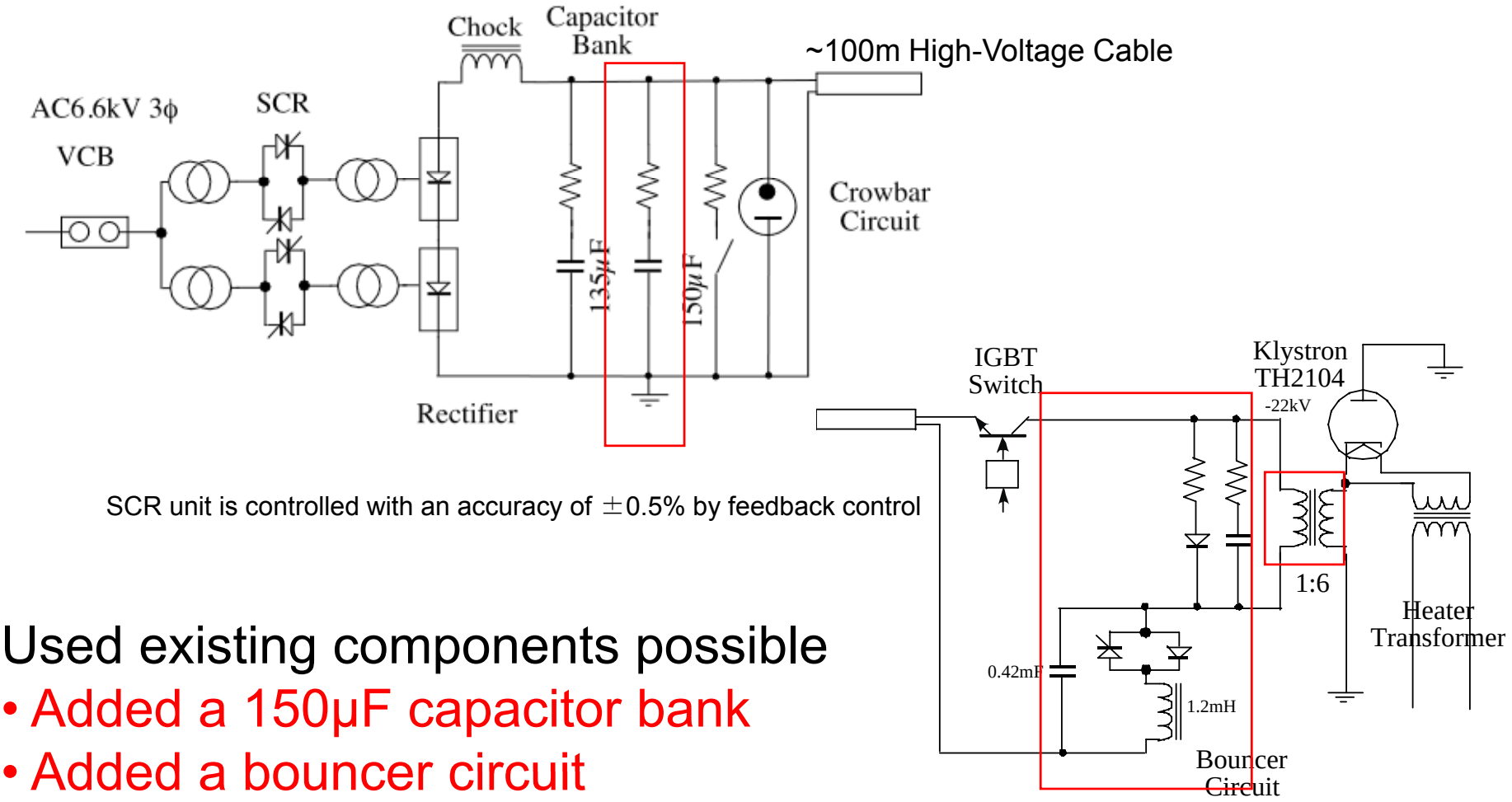
•It was first time that we built a bouncer-type modulator.

Design parameters of STF Modulator #1

• Peak Output Power	12.0 MW
• Secondary Output Voltage	130 kV
• Secondary Output Current	92 A
• Pulse Flat-top width	> 1.5 ms
• Rise time(10-90%)	< 0.1 ms
• Flatness	±0.5%
• Repetition Rate	5 pps
• Pulse Transformer Ratio	1:6

Schematic Circuit Diagram of STF Modulator#

Accelerator Laboratory



SCR unit is controlled with an accuracy of ±0.5% by feedback control

Used existing components possible

- Added a 150μF capacitor bank
- Added a bouncer circuit
- Exchanged a new 1:6 pulse transformer

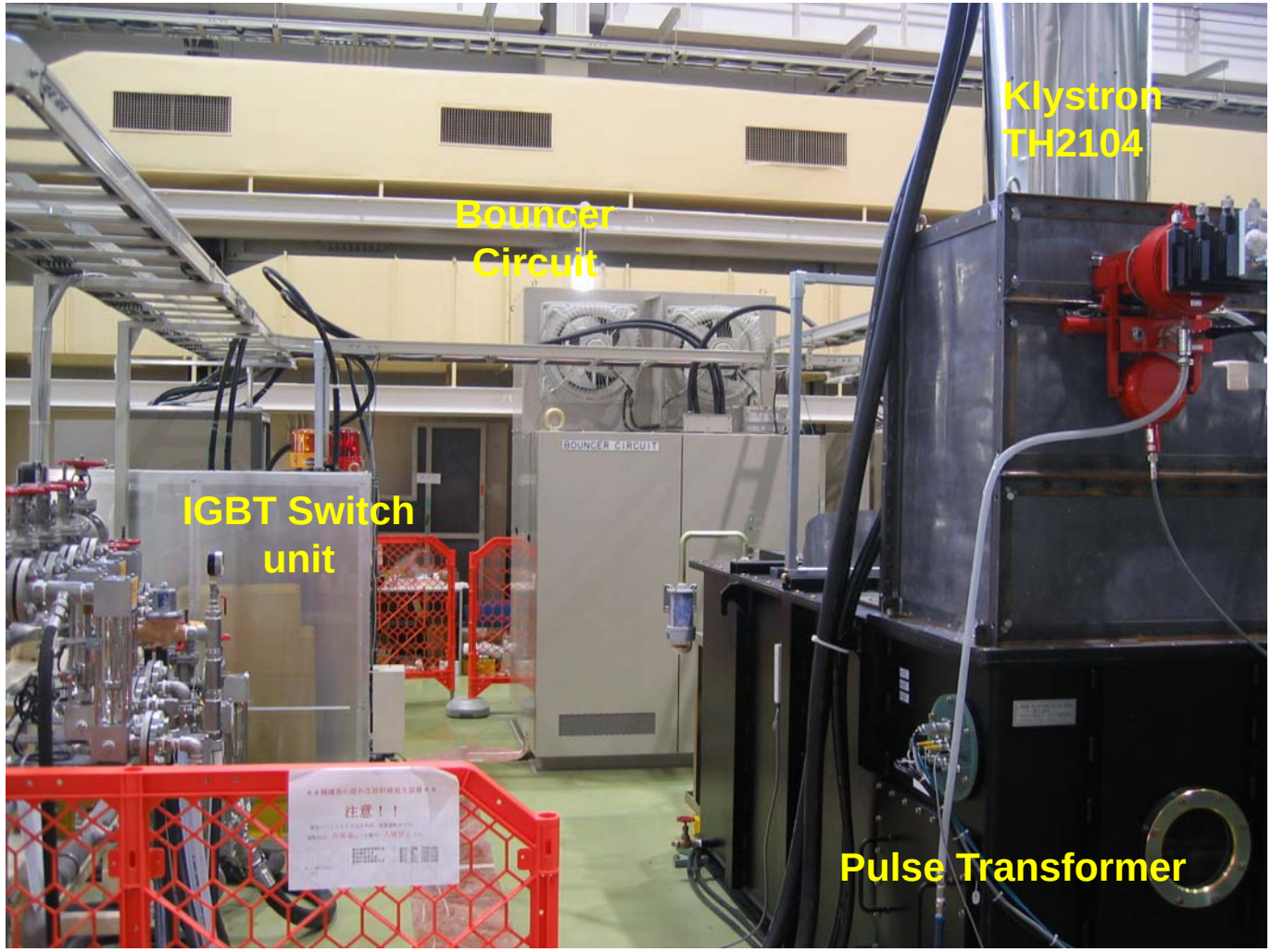
Accelerator Laboratory

STF Modulator#1

DC Power Supply(Tent House)

Accelerator Laboratory

STF Modulator#1



Klystron Gallery

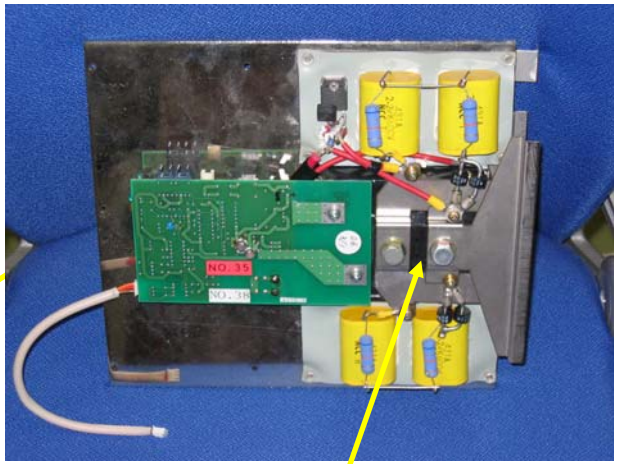
Accelerator Laboratory

IGBT Switch

36 IGBT plug-in boards in series

Switch assembly

Trigger: Optical fiber cable



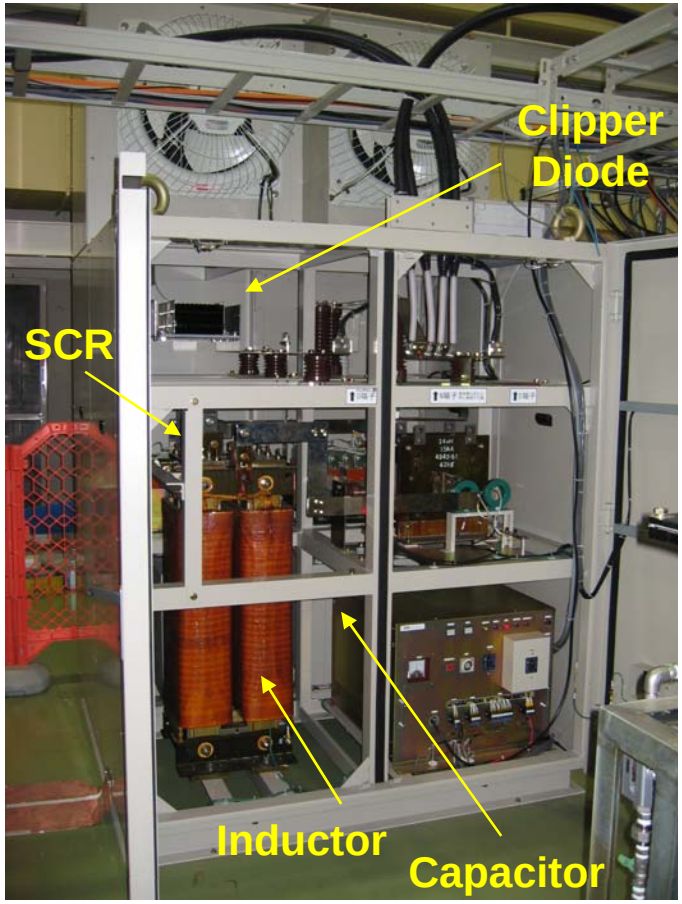
IGBT Driver Board

IGBT
Mitsubishi CM600H-24H
Rated Voltage : 1200V
Rated Current : 600A

Accelerator Laboratory

Bouncer Circuit for STF Modulator #1

Bouncer unit



Inside of Bouncer Circuit

Accelerator Laboratory

Pulse Transformer for STF Modulator #1

Specification of Pulse Transformer

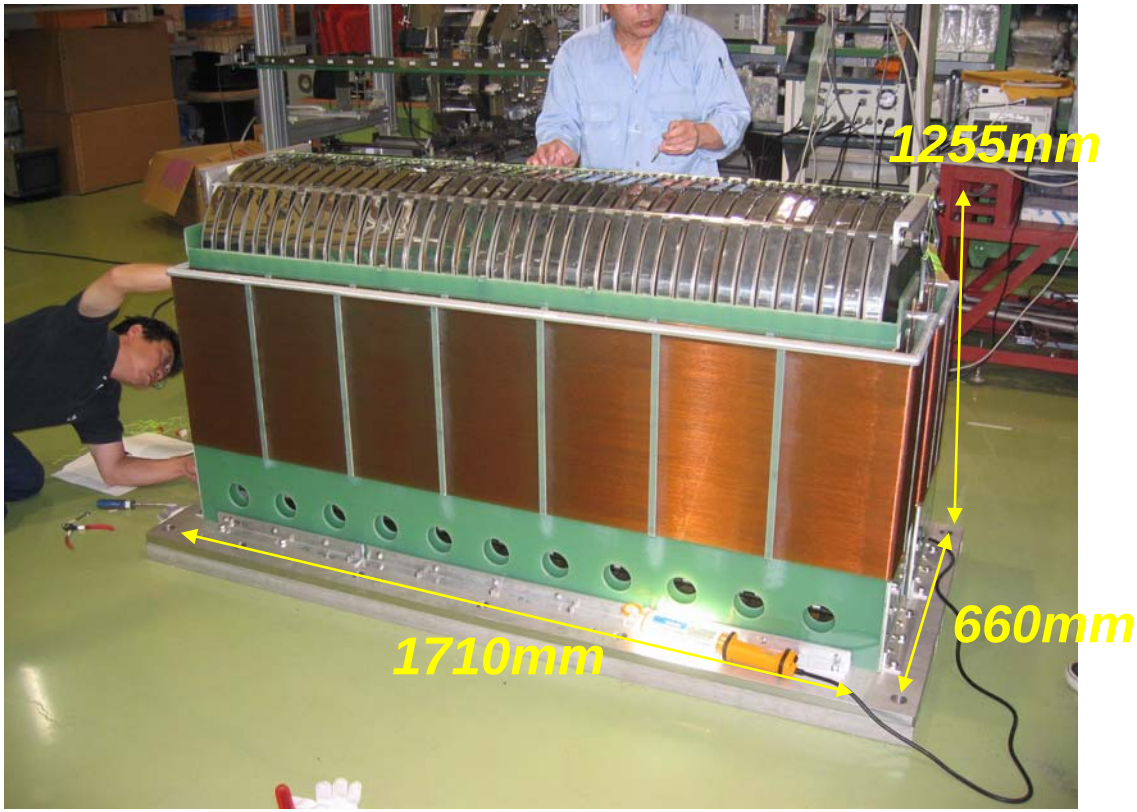
- Primary voltage
  21.7 kV
- Primary current
  552 A
- Primary impedance 36.8Ω
- Secondary voltage 130 kV
- Secondary current 92 kV
- Secondary impedance
  1413 Ω
- Flat-top pulse width 1.5 ms
- Rise-time(10-90%) 40μs
- Pulse droop < 3%
- Step-up ratio 1:6

Features

- Core comprises 39 subcores.
- Reuse 25 subcores that were used in the JHF to reduce its cost.
- Core material is 0.22mm thick silicon steal ribbon.
- DC bias
- Auto winding-type
- Size of the tank
  2.9 m(W) x 1.2 m(D) x 1.3 m(H)
- Total weight weight including the oil
  9.1 tons (core 4.4 tons)
- Heater transformer is isolation transformer-type.

Accelerator Laboratory

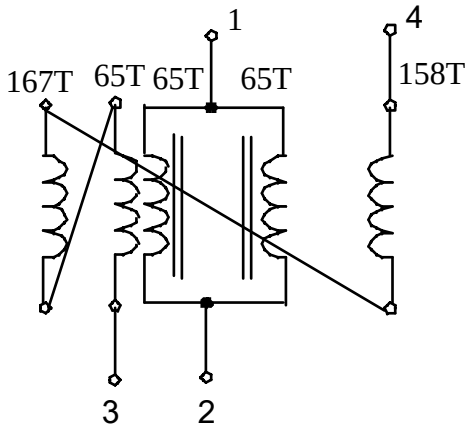
Pulse Transformer for STF Modulator #1



Core-and coil assembly

Design parameters
(in the secondary side)

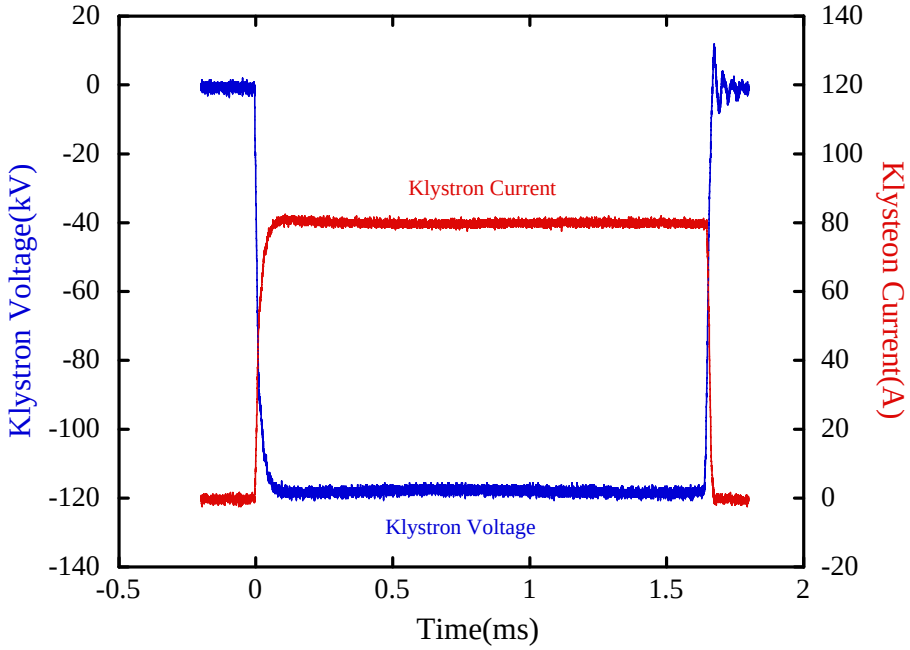
- Primary inductance : 60 H
- Leakage inductance : 20 mH
- Distributed capacitance : 570 pF



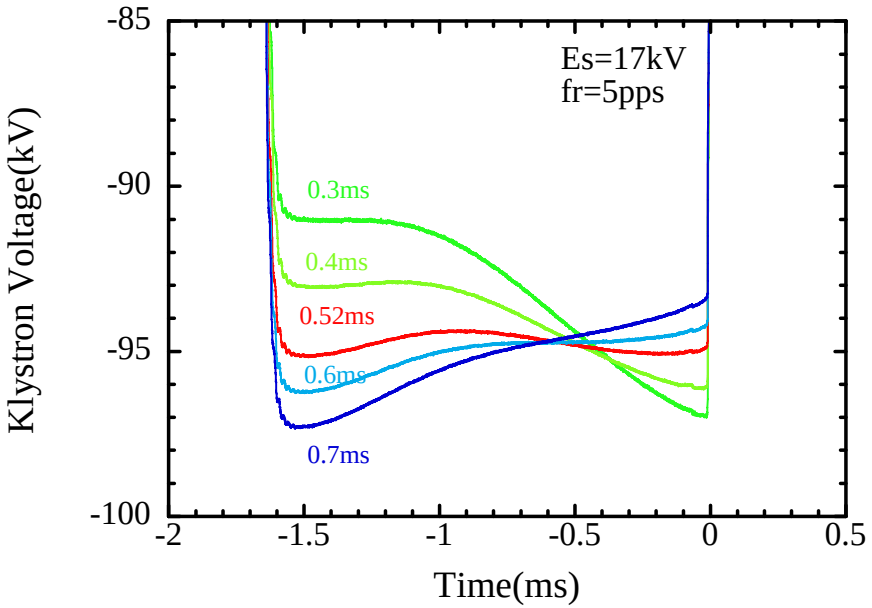
Schematic winding diagram

Accelerator Laboratory

Klystron voltage and current waveforms



Bouncer Timing Optimization



Es=21.5kV, Pw=1.7ms, fr=5pps
Peak voltage=120 kV, Peak current = 81A
Rise-time(10-90%)=33μs
Output rf power=3.9 MW

Es=17kV, Pw=1.7ms, fr=5pps
Flatness=0.8%(p-p)

Klystronl voltage is limited at 21.5 kV because each device voltage becomes 950V due to circuit inductance.

Accelerator Laboratory

STF Modulator#2

- New modulator capable of driving a 10 MW MBK klystron
- Based on TESLA/FNAL design.
- More compact and highly reliable modulator design
- Test operation has been finished.

Features :

(1) Pulse Transformer

Use a 1:15 step-up ratio to realize a more compact switch, which can be used in higher rated voltage and current devices such as IEGT(Injection Enhanced Gate Transistor) in the future

(2) DC Power Supply

Use four 50 kW switching power supply in parallel

(3) Capacitor Bank

Use high energy density SH(Self-Healing)type capacitors

(4) Main Switch

Use a highly reliable conventional IGBT device, which is the same as the device used in STF modulator #1

(5) No crowbar

Eliminate a crowbar circuit by reinforcing the IGBT switch protection

Accelerator Laboratory

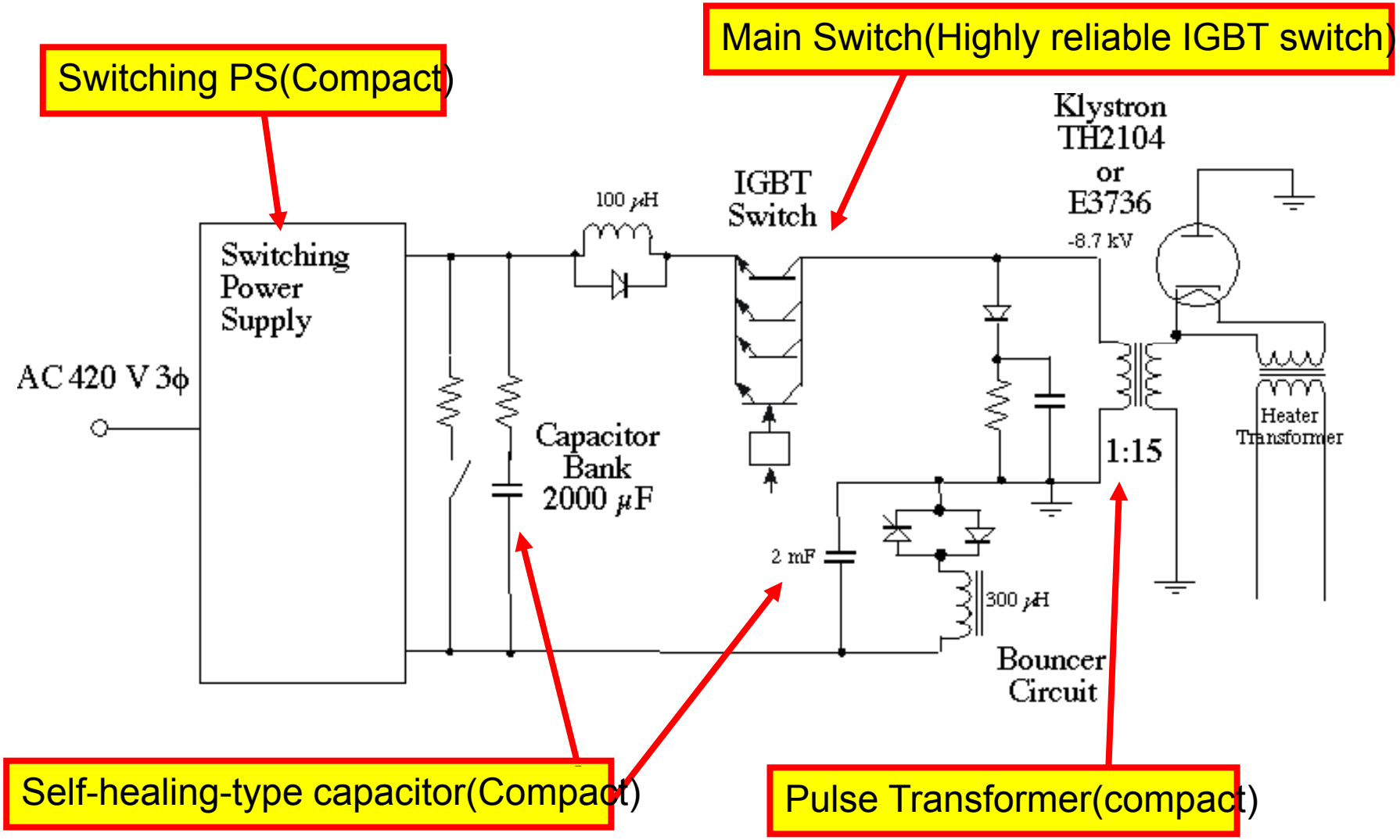
Design Parameters of STF Modulator#2

• Peak Output Power	16.8(12.0) MW
• Secondary Output Voltage	120(130) kV
• Secondary Output Current	140(92) A
• Pulse width	1.7 ms
• Flat-top width	> 1.5 ms
• Rise time(10-90%)	< 0.1ms
• Flatness	±0.5%
• Repetition Rate	5 pps
• Pulse Transformer Ratio	1:15
• Capacitor Bank	2000 μF<20%droop>
• LC Bouncer	
Inductance	2.0 mH
Capacitance	0.3 mF
• Main Switch	
Voltage	8.8(9.5) kV
Current	2100(1380) A

( )=5MW Single Klystron

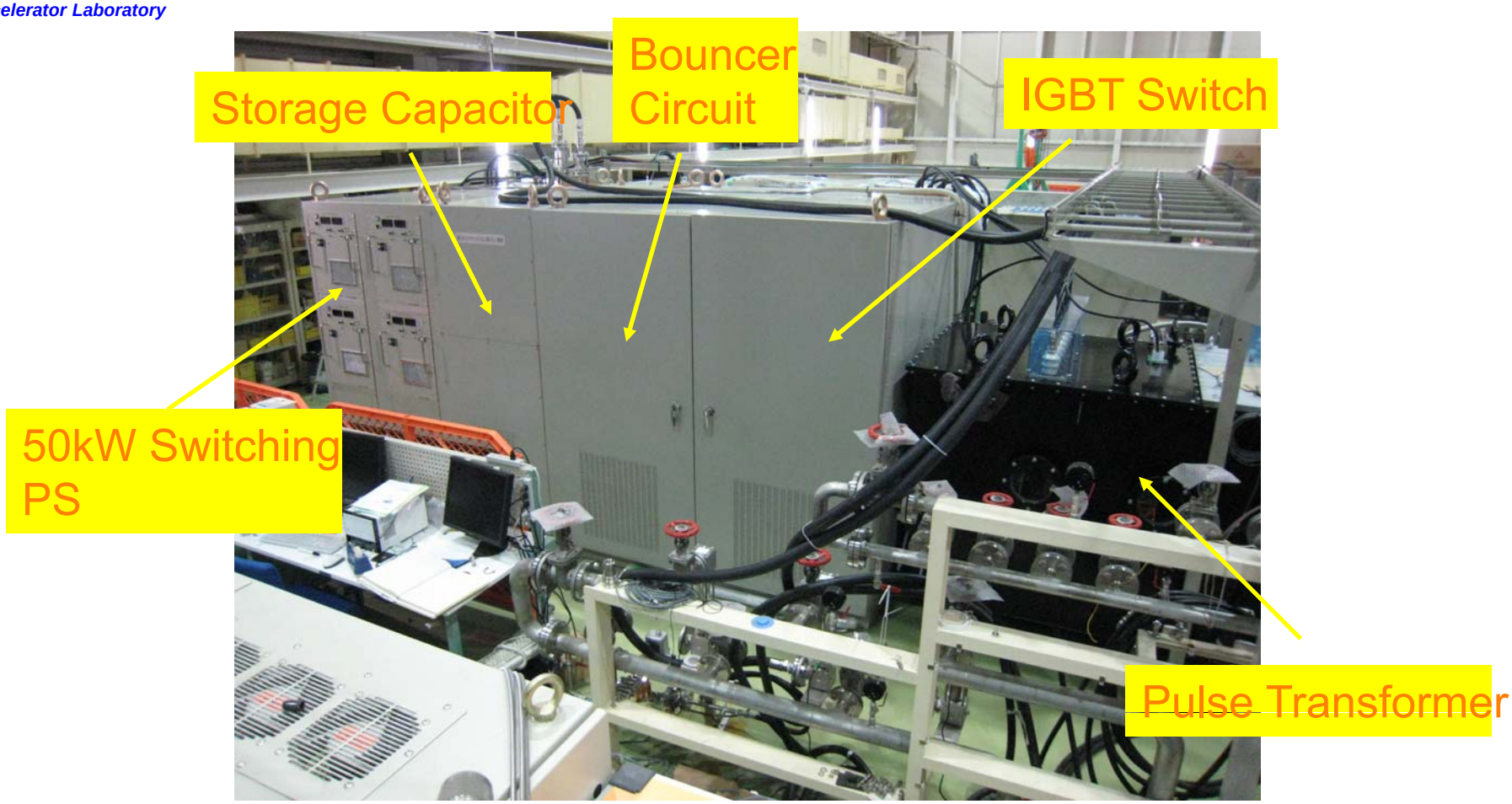
Accelerator Laboratory

Schematic Circuit Diagram of STF Modulator #2



Accelerator Laboratory

Overview of STF Modulator #2



The size of the main cabinet is 4.2m wide x 2.2m deep x 2.2m high

Accelerator Laboratory

DC Power Supply

Specifications

- 4 switching power supplies operation in parallel
- Input voltage: 420 V, 3 phase, AC
- Output voltage：10 kV
- Charging rate：200 kJ/s
- Switching frequency: 20 kHz
- Repetition rate：5 Hz
- Voltage regulation：< 1% at 5 Hz
- Cooling：Water cooling

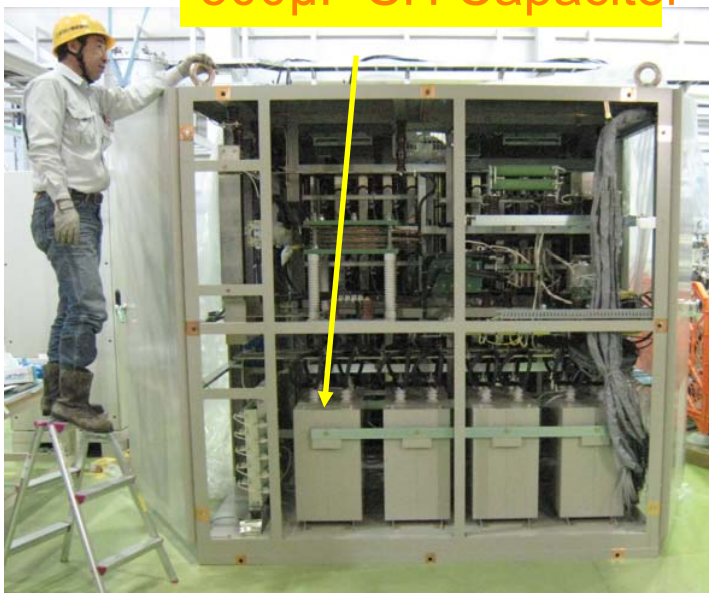
Four 50 kW switching power supplies

Accelerator Laboratory

Capacitor Bank

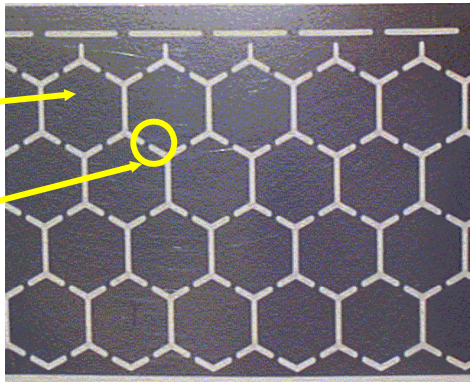
Features:

- **4 SH capacitors in parallel**
- **Capacitance: 500 μF**
- **Rated voltage: 11 kV DC**
- **Metallized PP films**
- **Form a small segmented metallization pattern to prevent a catastrophic failure that may arise from an internal high energy discharge.**
- **Design dielectric strength : 300V/μm**
- **Design Lifetime : 100,000 hours at 5 pps**
- **Size : 68 cm W x 25 cm D x 68 cm H**
- **Energy density : 270 kJ/m^3**
- **Developed by Nichicon Co.**



Before breakdown

After breakdown



Capacitor structure

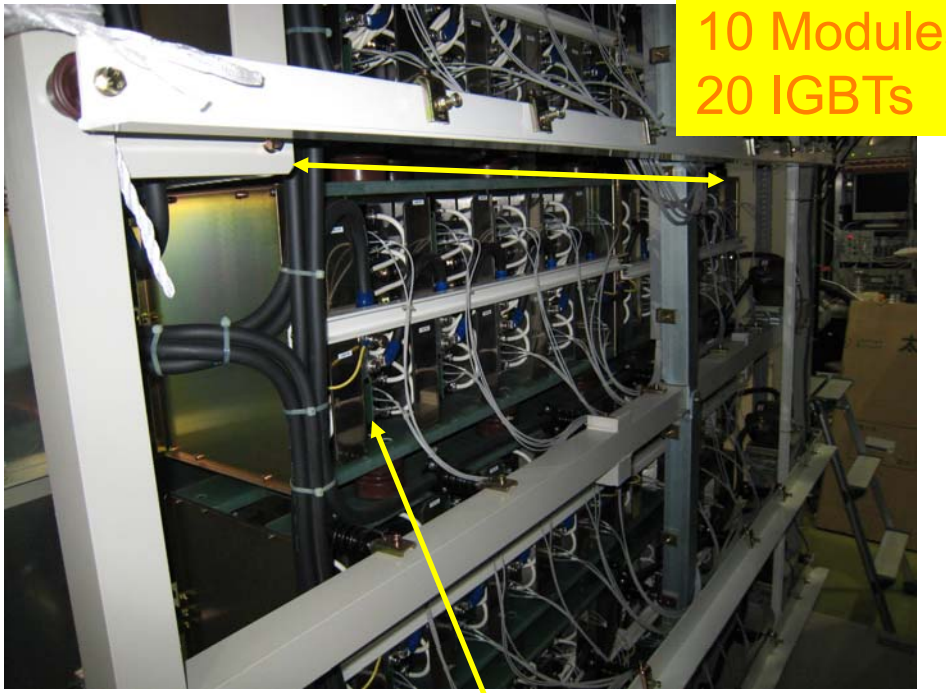
Accelerator Laboratory

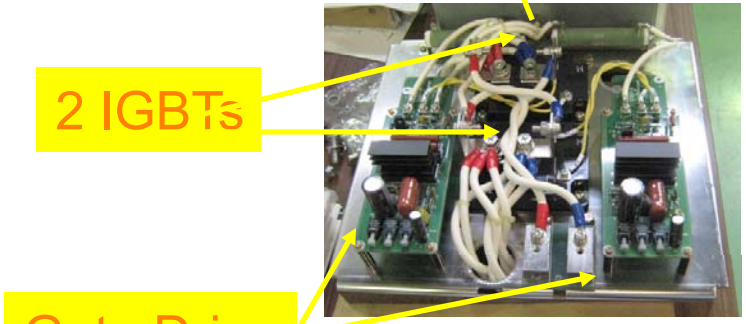
Main Switch

- **Device : Mitsubishi IGBT**

  CM600H-24H 1200V, 600A

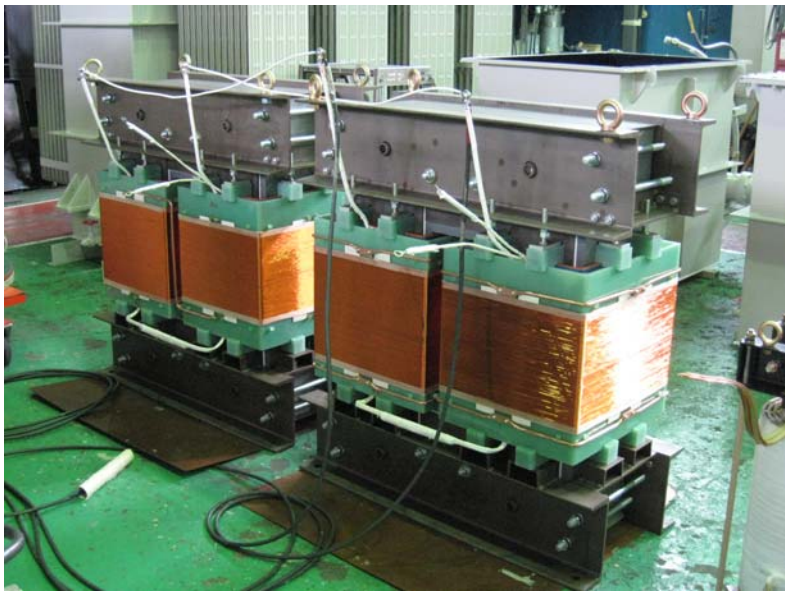
- **Structure : 20 series and 4 parallels**
- **Gate signal : optical fibre cable**
- **dc power for the gate drive circuit is fed through the main line.**
- **To detect the short-circuiting of the device, each device voltage is measured; a device is decided to have shorted if its voltage is less than 50 V when the switch turns off, the device is decided to be short. In such situation, the switch is rapidly stopped to protect it.**
- **Has fast over-current protections for each IGBT module, the primary and secondary of the pulse transformer.**





Accelerator Laboratory

Pulse Transformer for STF Modulator #2



Core-and coil assembly

Features;

- Optimized for a rise-time of ~ 100 μs
  Leakage inductance ~ 39 mH
- Divided into two transformers
  One for full withstanding voltage
  The other for half withstanding voltage
- Laminated core
- Material is 0.3 mm thick silicon steal ribbon
- DC bias
- Iso winding
- Heater transformer is isolation transformer-type

Size of the tank

- 2.2m W x 1.1m D x 1.4m H

Design parameter (in the secondary)

- Primary inductance : 92 H
- Leakage inductance : 36 mH
- Distributed capacitance : 844 pF

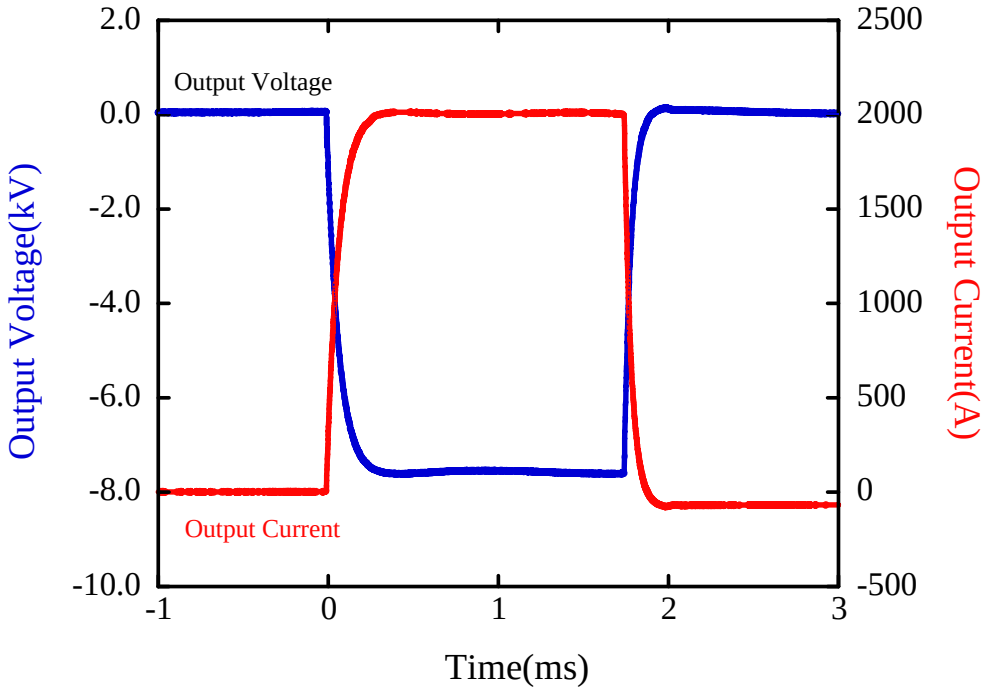
Total weight : 8.3 t

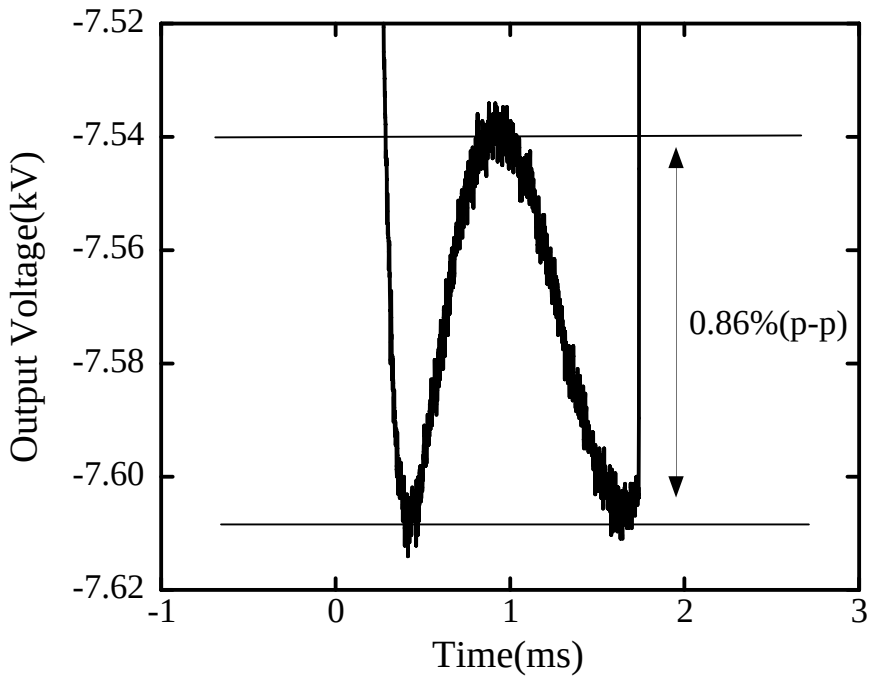
- Two pulse transformer : 2.3 t x2
- Tank : 1.5 t
- Oil : 2.2 t

Accelerator Laboratory

Output Voltage and Current Waveforms

Dummy load : 3.8 Ω + 200 μH Reactor in the primary side



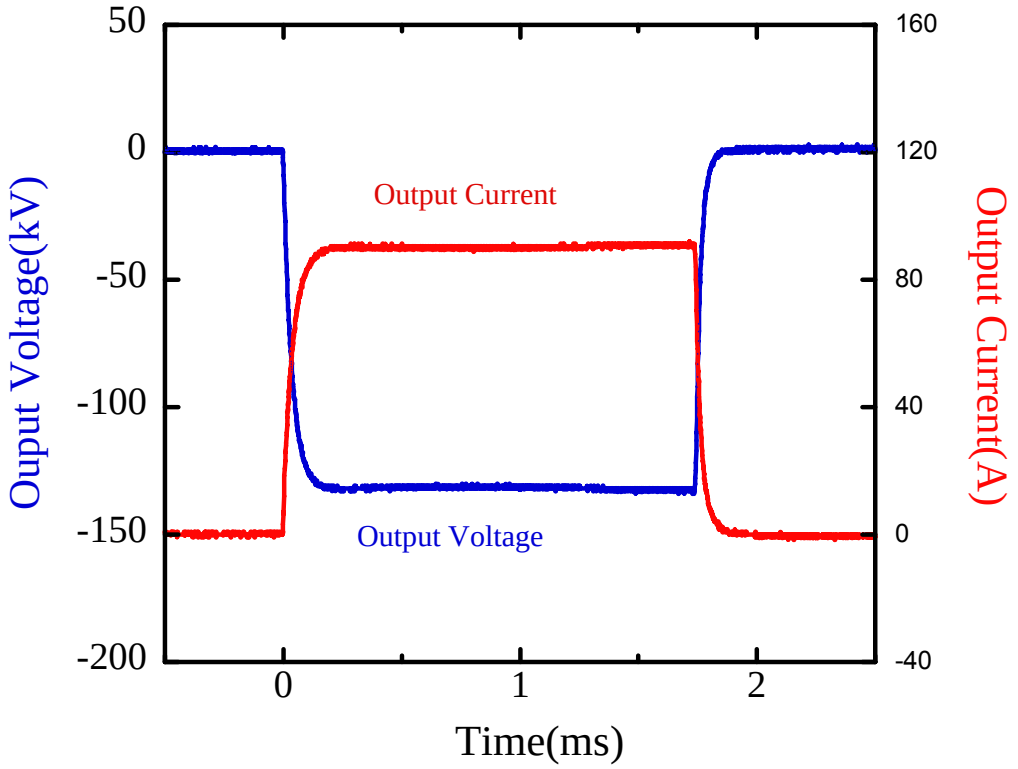


Es=9.1 kV, Pw=1.75 ms, fr=5 pps
Peak pulse voltage = -7.57 kV, Peak pulse current = 2009 A

Accelerator Laboratory

Output Voltage and Current Waveforms

Dummy load : 1400 Ω resistor in the secondary side of the pulse transformer



Es=10 kV, Pw=1.75 ms, dc bias=5 A, Bouncer trigger timing= 0.4 ms
Peak pulse voltage = 133 kV, Peak pulse current = 90 A, Rise-time(10-90%)= ~130 μs

Compact IEGT Switch Development

Accelerator Laboratory

9kV, 2100 A, 1.7 ms, 5Hz

Main Switch for modulator #2

Comparison of IEGT and IGCT

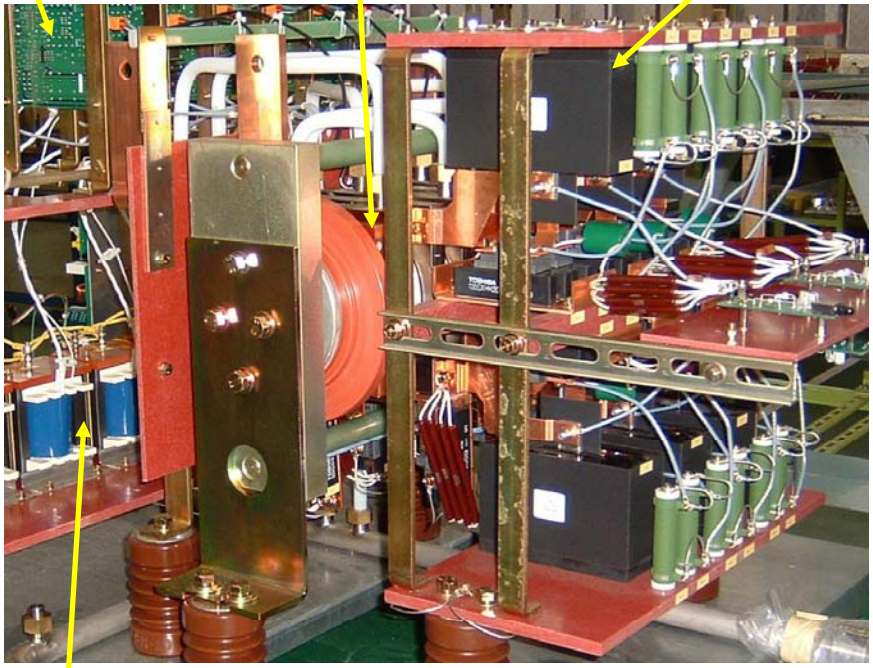
Device	ＩＥＧＴ ST2100GXH24A (toshiba)	ＩＧＣＴ 5SHY35L4511 (ABB)
Voltage	4.5kV	4.5kV
Turn-Off Current	5500A	3800A
RMS Current	2100A	2200A
di／dt	5000A／μs	1000A／μs
Outline	φ125mm post 26.5mm t	φ85mm post 26.5mm t
Gate	Voltage Drive 20W Power	Current Drive 100W Power

ＩＥＧＴ (Injection Enhanced Gate Transistor)

Gate Driver

6 stack IEGTs

Snubber Circuit



Transformer for gate driver PS

IEGT Switch Assembly

Trigger: Optical fiber cable

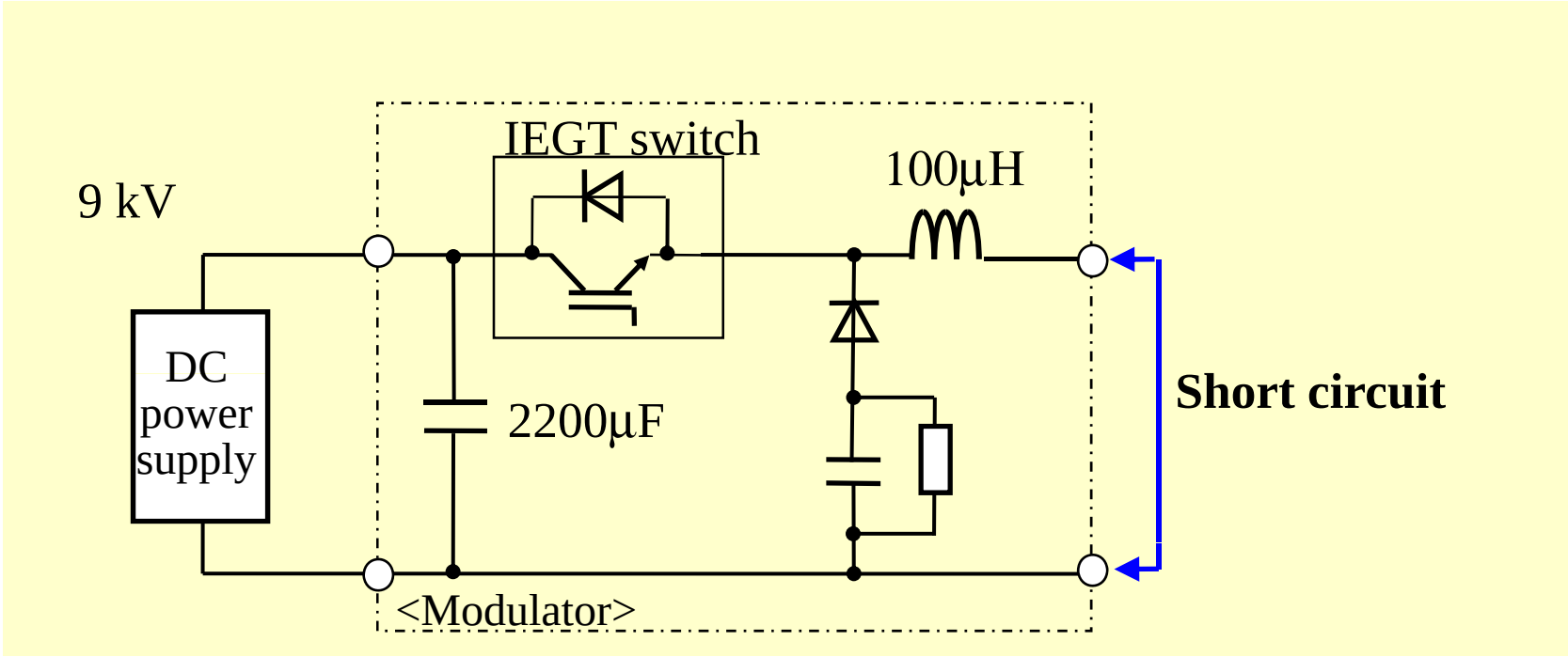
Size：900 mm W x 920 mm D x 685 mm H

Cooperation with TMEIC(Toshiba-Mitsubishi Electric Industrial Systems Corporation)

Accelerator Laboratory

IEGT Tern-off Test

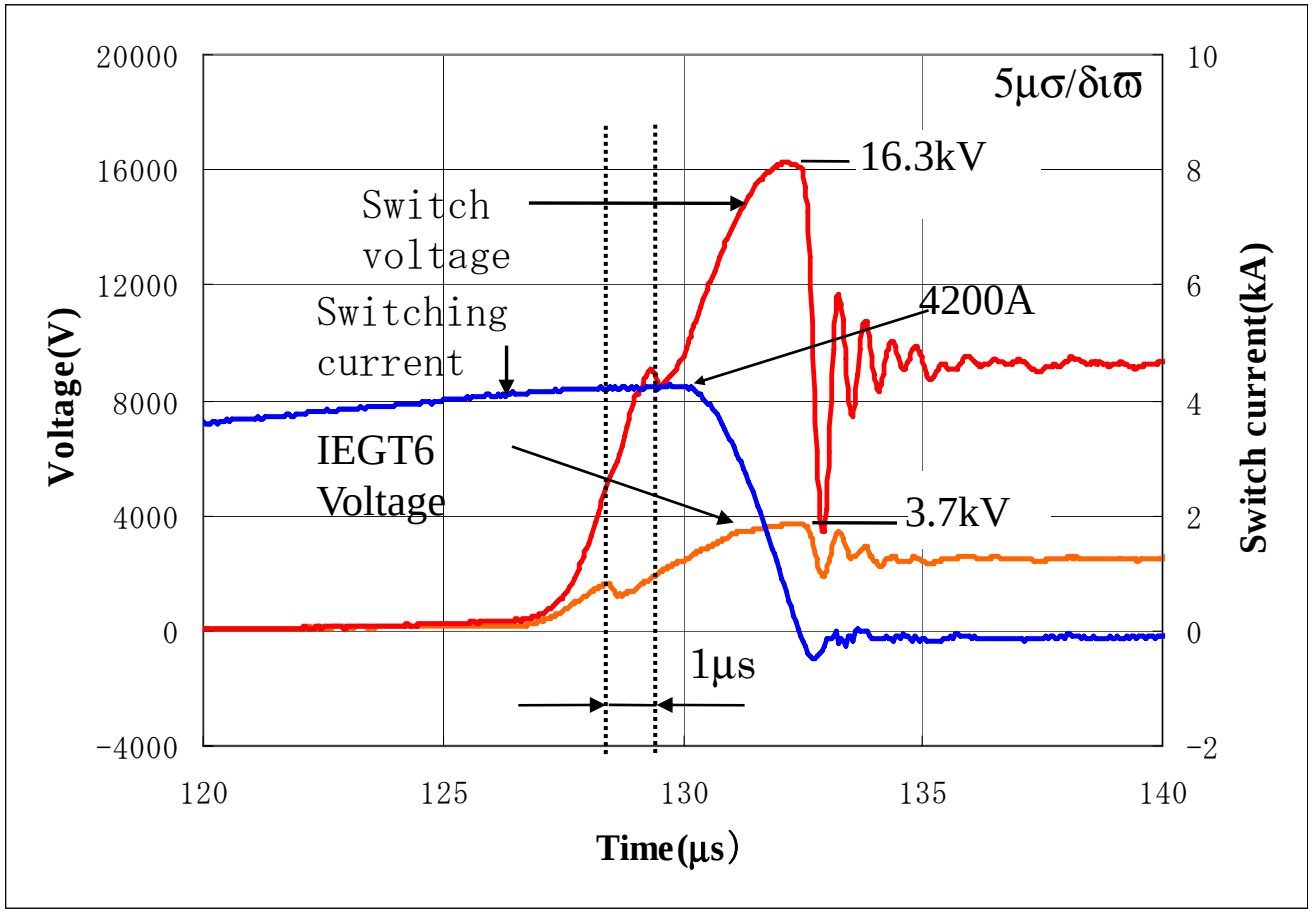
In case of the short-circuiting in the primary side of the pulse transformer



This test is very hard condition for the switch.

Accelerator Laboratory

IEGT Turn-off Test Result



The data show the switch was able to turn off at 9 kV, 4200A and the transient voltage of the switch was 16.3 kV(< 27 kV).

Over-current detection level : 2520A

Accelerator Laboratory

Summary

•It was the first time that KEK built a bouncer type modulator. Two bouncer-type modulators for STF have been built at KEK.

•The first modulator has converted from an old klystron modulator system to start up the project quickly. Pulses with a peak voltage of 120 kV, a peak of current of 81A, a width of 1.7 ms, a rise time of 33μs(10-90%), a flat-top width of 1.5 ms within 0.8%(peak to peak) were successfully generated at 5 pps and the output rf power then reached 3.9 MW. This modulator is used for a high power test of the coupler for the cavity.

• The second modulator capable of driving a 10 MW klystron is now complete and will be used for high power test of a 5 MW klystron.

• High-power test of IEGT switch has been performed in cooperation with TMIC and the results show very good performance