High Power Solid-state Switch for Replacement of Thyratron for Kicker & Klystron Modulator

R&D Status

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Disadvantages of Thyratron Compared to Solid-State Switch

1. Lifetime
- Unpredictable life span , Short average lifetime

2. Fault Characteristic

3. Maintaining characteristics
(Rise time, On-state resistance and so on)
- It is difficult to maintain these characteristics consistently over the life of the Thyratron

4. Additional Power Supplies
- It is needed that cathode heater and the reservoir heater are supplied from independent power supplies

5. Jitter / Delay Time Drift

Associated with Reliability

6. Heating Time

7. Cost (Operation, Installation)

8. Repairable

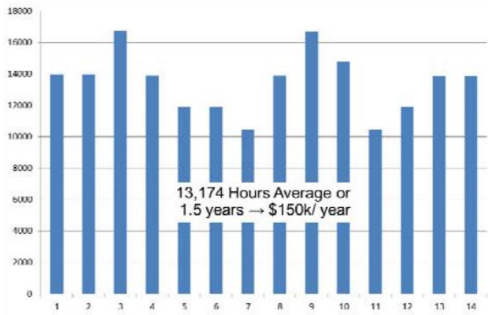
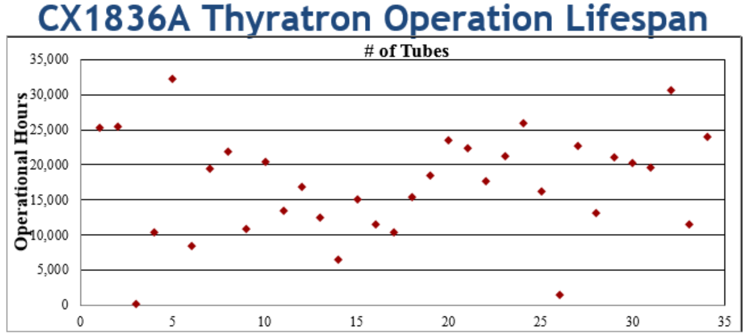
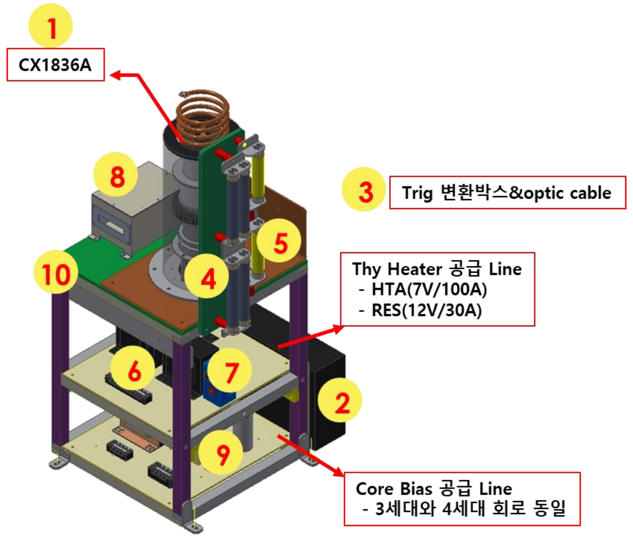
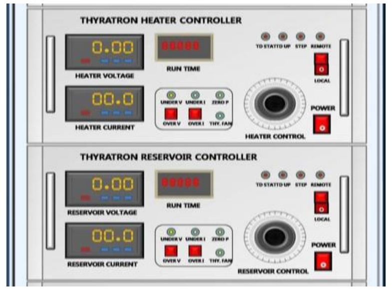


Figure 5. Average thyratron life versus kicker position



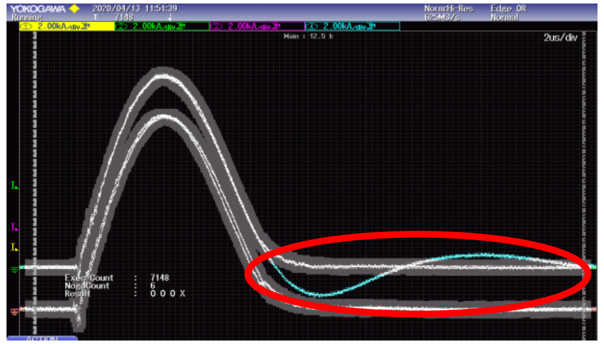


Thyratron Stand



Reservoir & Cathode Heater Power Supply


Mis-firing Fault


Reverse Conducting Fault

KERI KOREA ELECTROTECHNOLOGY RESEARCH INSTITUTE

PAL POHANG ACCELERATOR LABORATORY

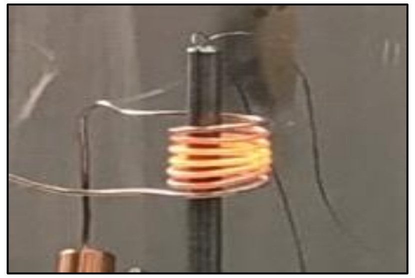
PAL (Pohang Accelerator Laboratory) and KERI (Korea Electrotechnology Research Institute) Collaboration

Korea Electrotechnology Research Institute
(KERI)

KERI
KOREA ELECTROTECHNOLOGY RESEARCH INSTITUTE

PAL

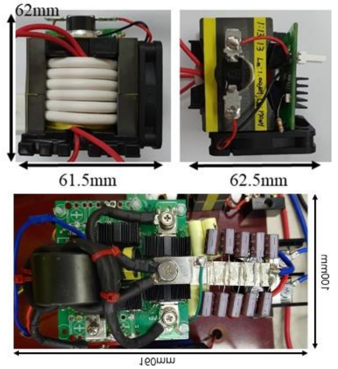
Pohang Accelerator Laboratory
(PAL)



Induction Heating Power Supply

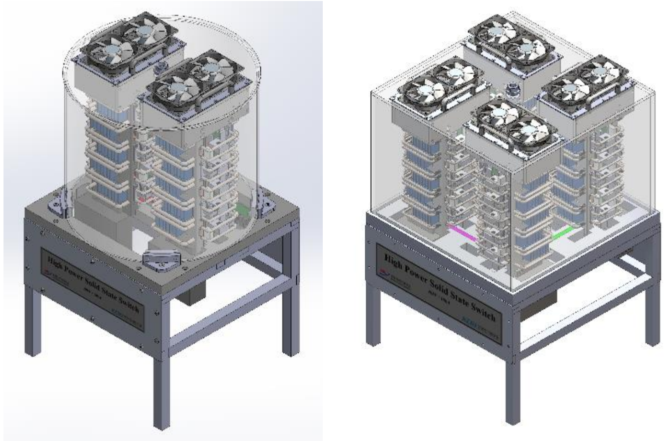
NEG Coating Power Supply
(5kV, 1.5A)

Nano-Second Pulse Modulator
For Pseudo Single Pulse Mode
(40kV, 40ns]



Enhancing Thyratron Performance through Power Supply Research

16kV, 10kA Solid-State Switch and Kicker Modulator



Replacement of Thyratrons with Solid-State Switches: (20kV, 10kA), (50kV, 10kA) Ratings

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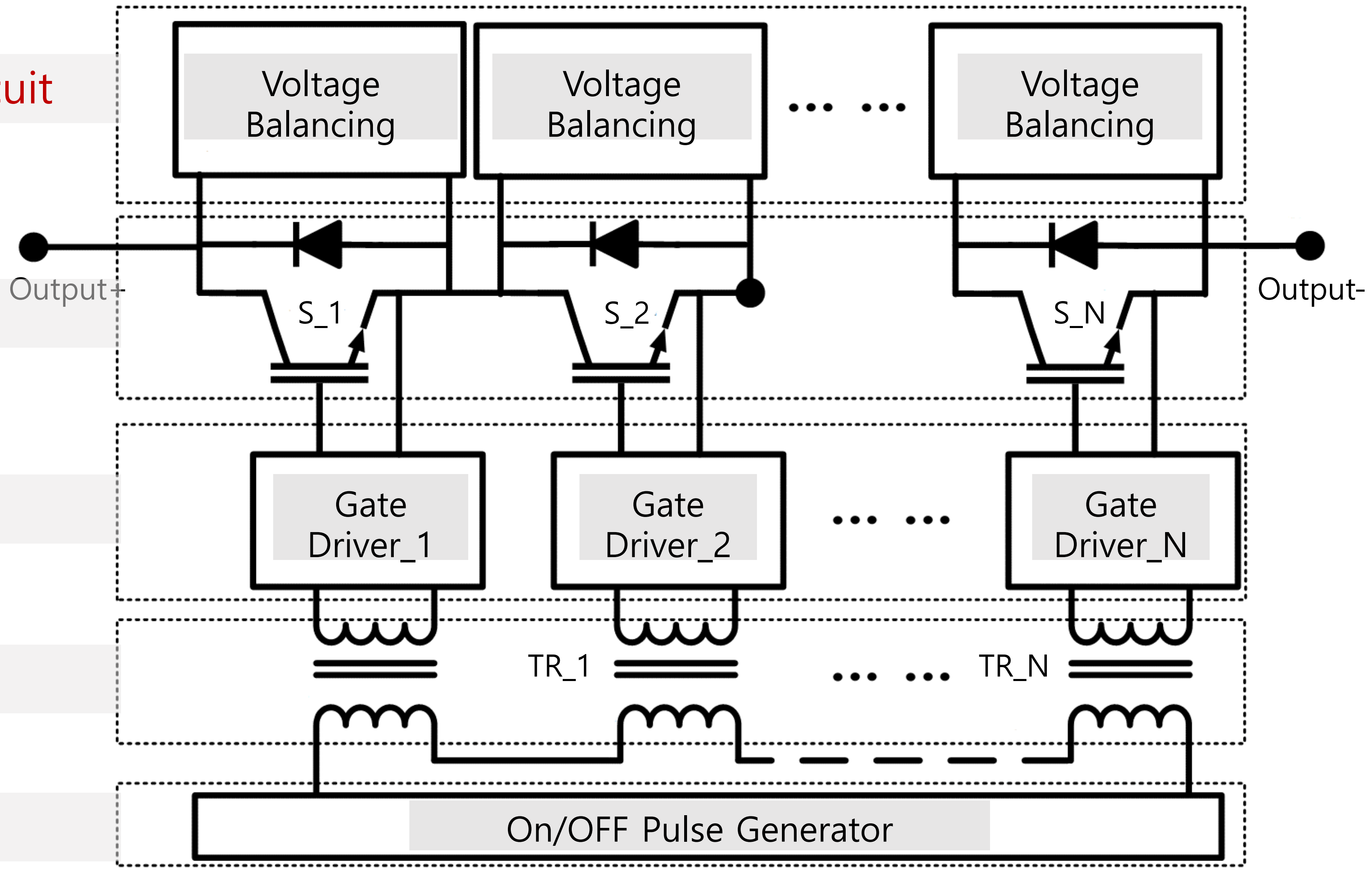
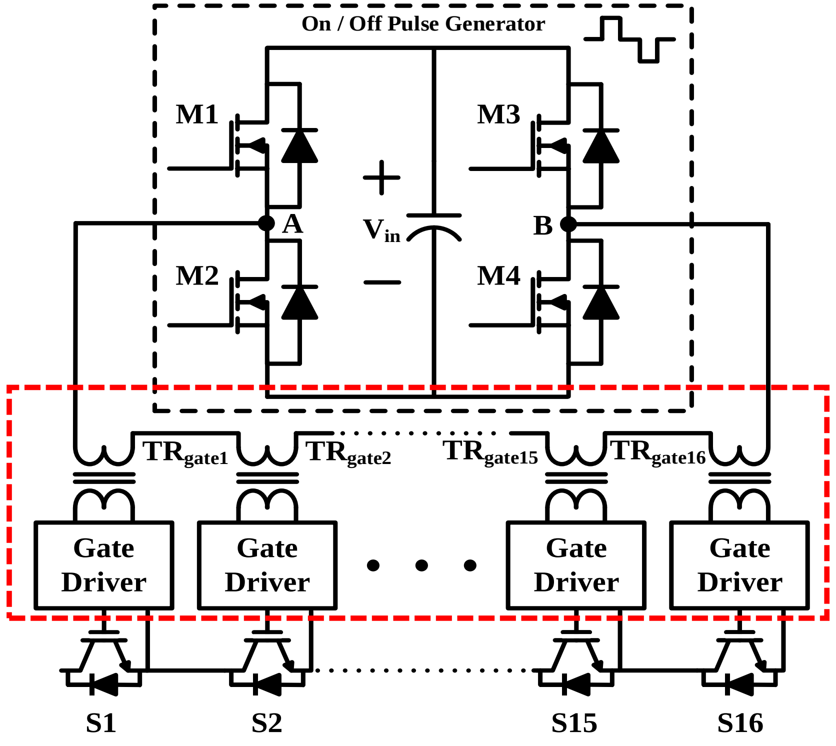
Key Technological Elements for the Development of High-Power Solid-State Switches

1. Voltage Balancing Circuit
2. Switch & Structure
3. Gate Drive Circuit
4. Gate Powering
5. Control Circuit



Development of Synchronous Operation & High Current Driving Technologies for Switch

1) Design of Switch Synchronous Operation Scheme

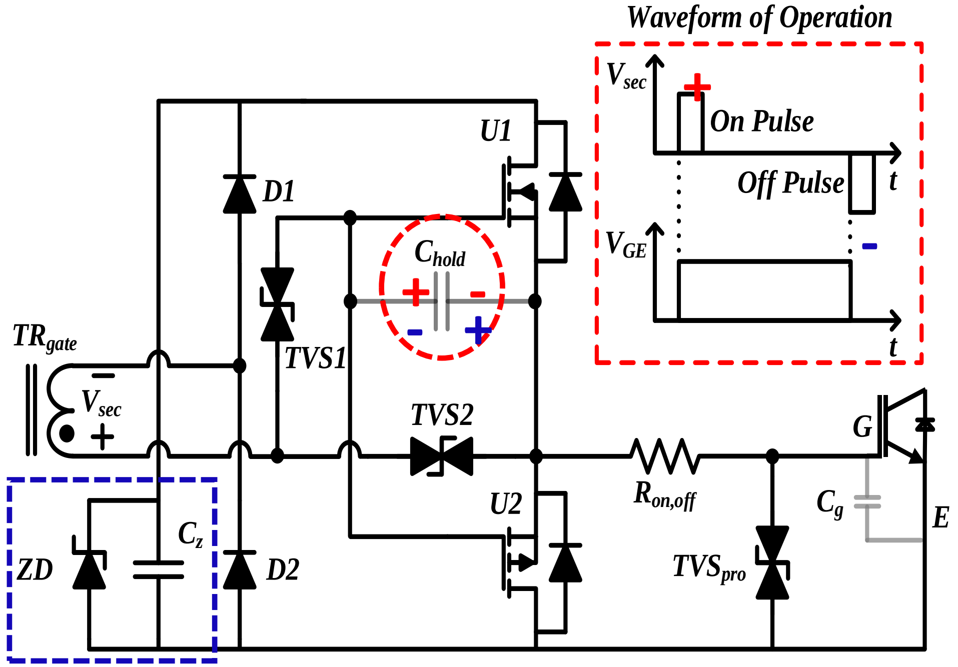


- Simultaneous Supply of Isolated Driving Power & Signal using a Transformer

(vs. Multiple High-Voltage Insulated Power Supplies + Opto-Coupler Driving)

→ Reduced Implementation Cost of Driving Circuit and Precise Synchronous Operation

2) Design of Gate Driver for Switch in High Current Operation

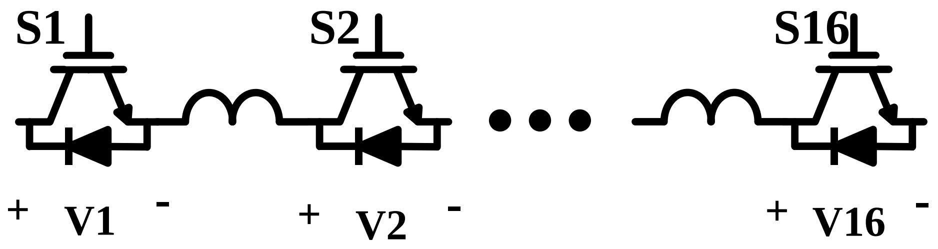


- Long Pulse Driving Method using Short On/Off Pulse → Gate TR Size ↓
- On/Off Pulse Rectification Circuit → Simplified High-Voltage Insulated Driving Power Supply
- Gate Charge Equalization & Minimization → Optimized synchronous operation and High current driving

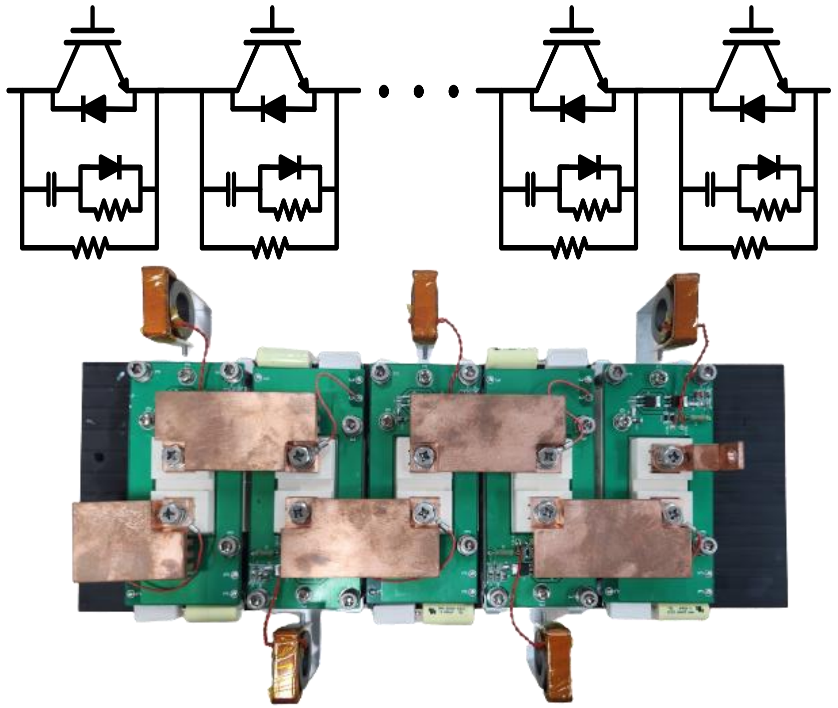
Design of Voltage Balancing Circuit & Inductance-Reducing Series-Stacking Structure

- Considerations for Component Series-Tacking→ Voltage Balancing & Inductance Reduction for Achieving Fast Current Rise Rate

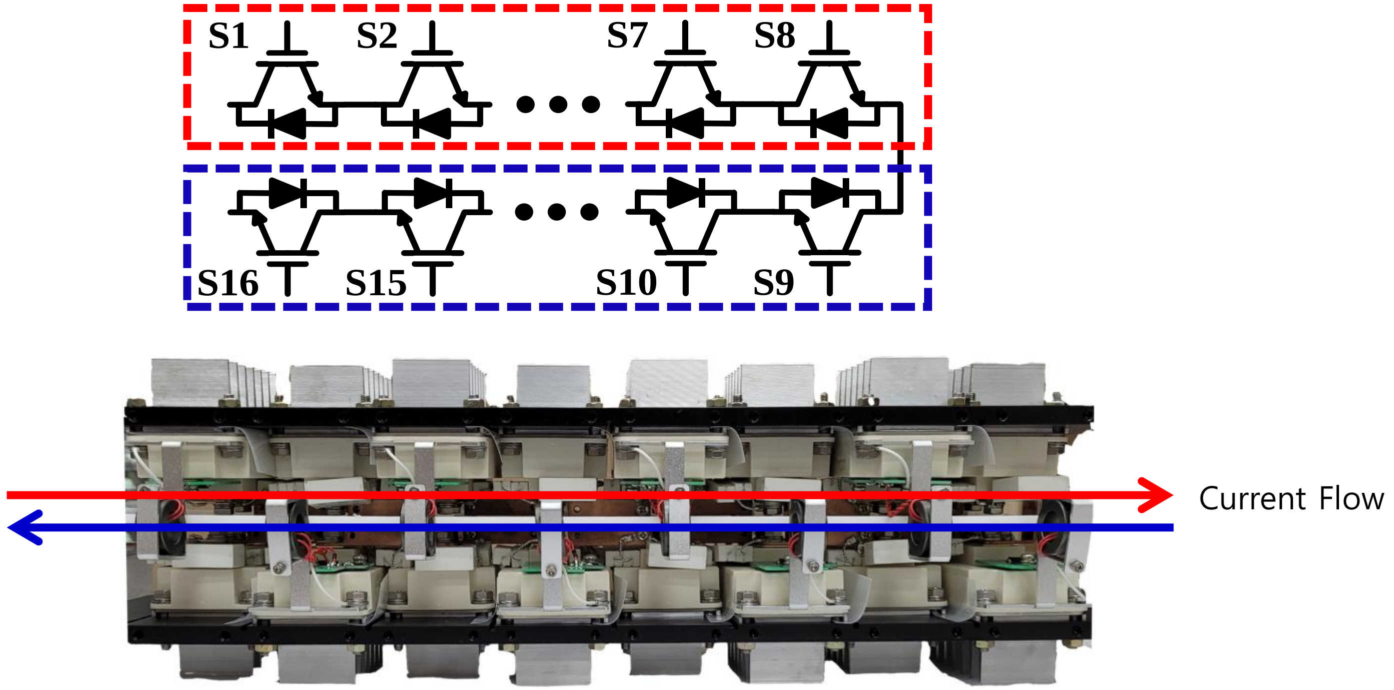
3) Design of Voltage Balancing Based on RCD Snubber



4) Design of Inductance-Reducing Series-Stacking Structure

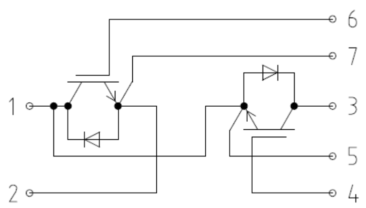
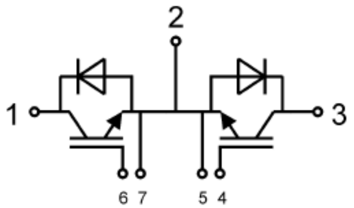
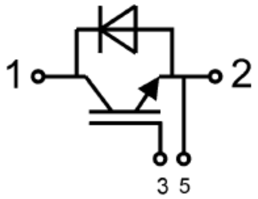
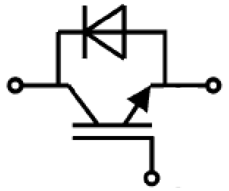


<Photo of Switch Stacking Circuit and Fabrication based on RCD Snubber>



<Photo of Inductance-Reducing Stacking Structure and Fabrication>

Selection of Optimal Stacking Components under Pulse Operation Conditions

Part Name	FF450R12KT4	SKM600GM12E4	**SKM900GA12E4**	**FZ600R17KE4**	T0960VC17G
Photo					
Structure					
Manufacturer	INFINEON	SEMIKRON	**SEMIKRON**	**Infineon**	IXYS
DC Voltage/Current Ratings	1200V(×2) / 450A	1200V / 600A(×2)	**1200V / 900A**	**1700V / 600A**	1700V / 960A
Pulse Current Rating	900A @ 1ms	1800A(×2)	**2700A**	**1200A @ 1ms**	1920A @ 1ms
Review Results	Internal Gate Drive Line Issues in Switch		**Ease of Stacking Structural Design**		Price and Stacking Structure

Switch Specifications for Kicker Modulator

<CX1836A (E2V)>

Existing Kicker				Newly Fabricated Kicker		
Min	Typical	Max		Min	Typical	Max
		50	Peak Forward Anode Voltage (kV)			35
		<10	Peak Inverse Anode Voltage (kV)			35
		10	Peak Anode Current (kA)			10
			Rate of Rise of Anode Current (kA/μs)			>100
		10	Average Anode Current (A)			2
10			Cathode Heating Time (min)	15		
10			Reservoir Heating Time (min)	15		
0		40	Ambient Air temperature (℃)	0		40
	200	350	Anode Delay Time (ns)		100	250
	3	10	Time Jitter (ns)		1	5
	20		Recovery time (μs)			

<The Specifications of Thyratrons>

<CX1154C (E2V)>

	Min	Typical	Max
Peak Forward Voltage (kV)			16
Peak Inverse Anode Voltage (kV)			13.5
Peak Operating Current (kA) @ 6μs			10
Rate of Rise of Anode Current (kA/μs)			6
Average Anode Current (A)			0.37
Ambient Air temperature (℃)	0		40
Anode Delay Time (ns)			100
Time Jitter (ns)			2

<The Required Specifications for Thyratron Replacement>

Switch Specifications for Klystron Modulator

<CX1836A (E2V)>

CX1836A (PAL-XFEL)				L4888 (PLS-II)		
Min	Typical	Max		Min	Typical	Max
		50	Peak Forward Anode Voltage (kV)			55
		<10	Peak Inverse Anode Voltage (kV)			<10
		10	Peak Anode Current (kA)			15
			Rate of Rise of Anode Current (kA/μs)			25
		10	Average Anode Current (A)			8
10			Cathode Heating Time (min)	15		
10			Reservoir Heating Time (min)	15		
0		40	Ambient Air temperature (℃)	0		40
	200	350	Anode Delay Time (ns)		400	
	3	10	Time Jitter (ns)		10	
	20		Recovery time (μs)			

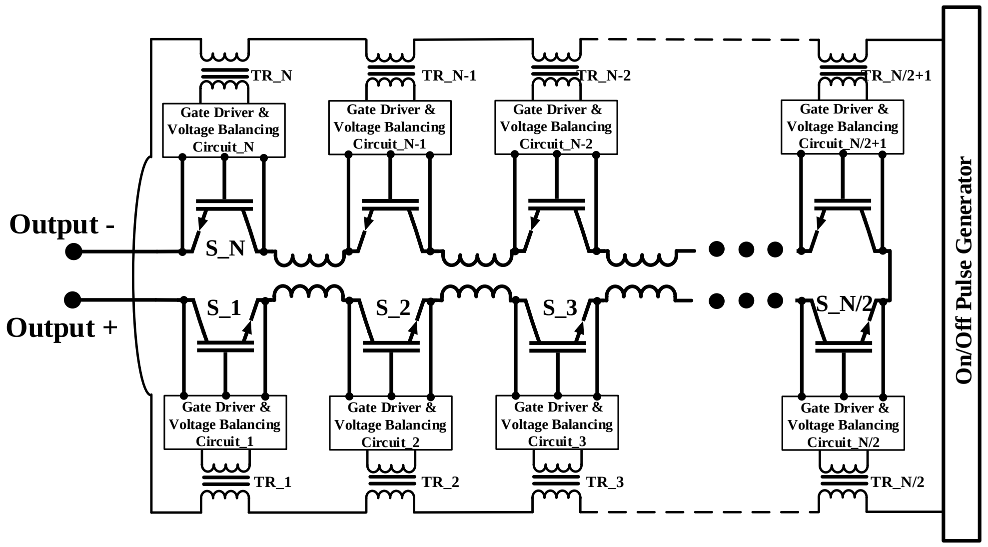
<The Specifications of Thyratrons>

<L4888 (E2V)>

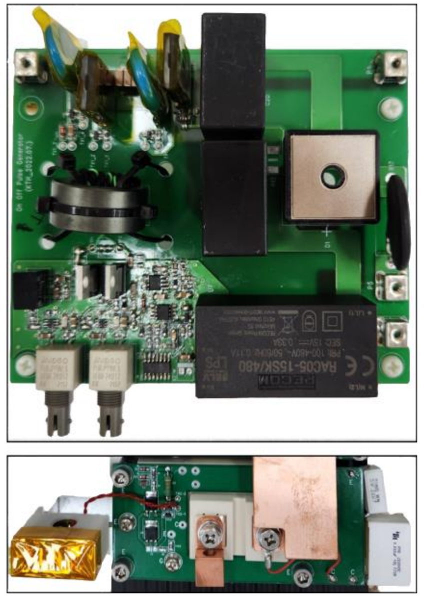
	Min	Typical	Max
Peak Forward Voltage (kV)			46
Peak Operating Current (kA) @ 10μs			8.5
Non-Repetitive Peak Current (kA) @ 10μs			17
Rate of Rise of Anode Current (kA/μs)			10
Average Anode Current (A)	0.64 @10Hz	3.83 @60Hz	7.66 @120Hz
Ambient Air temperature (℃)	0		40
Anode Delay Time (ns)			200
Time Jitter (ns)			1

<The Required Specifications for Thyratron Replacement>

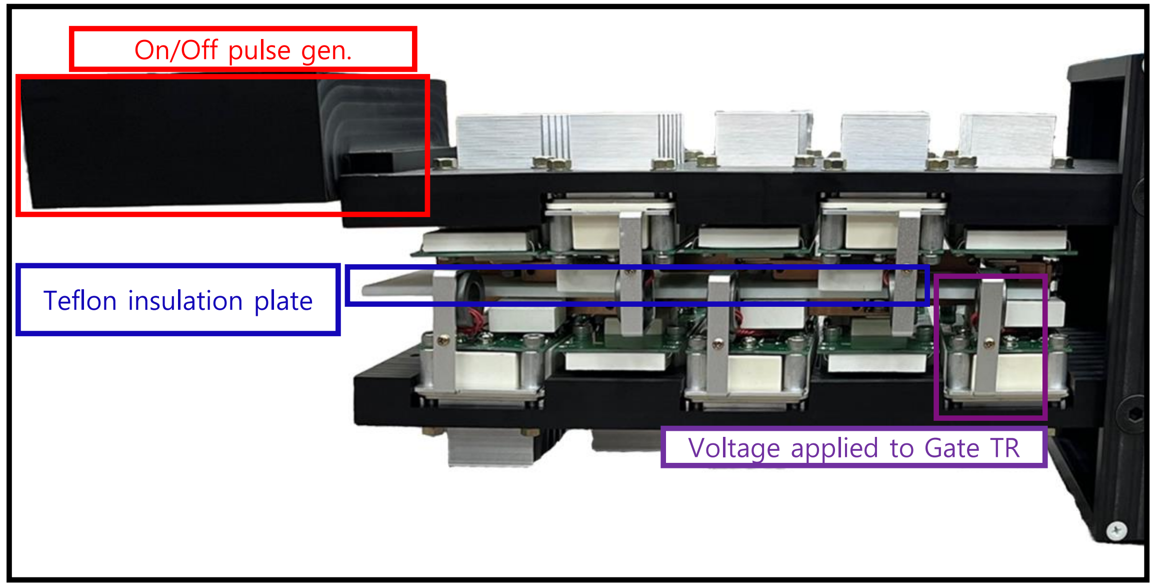
Design of Solid-State Switch Unit Modules for Multi-purpose Use



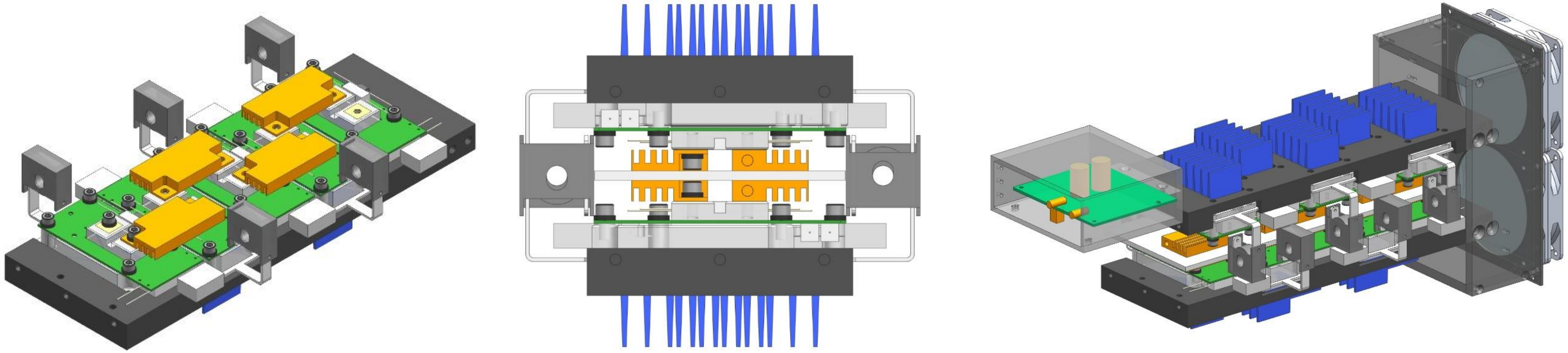
<Circuit diagram of the unit module>



<On/Off pulse gen. & gate drive circuit>

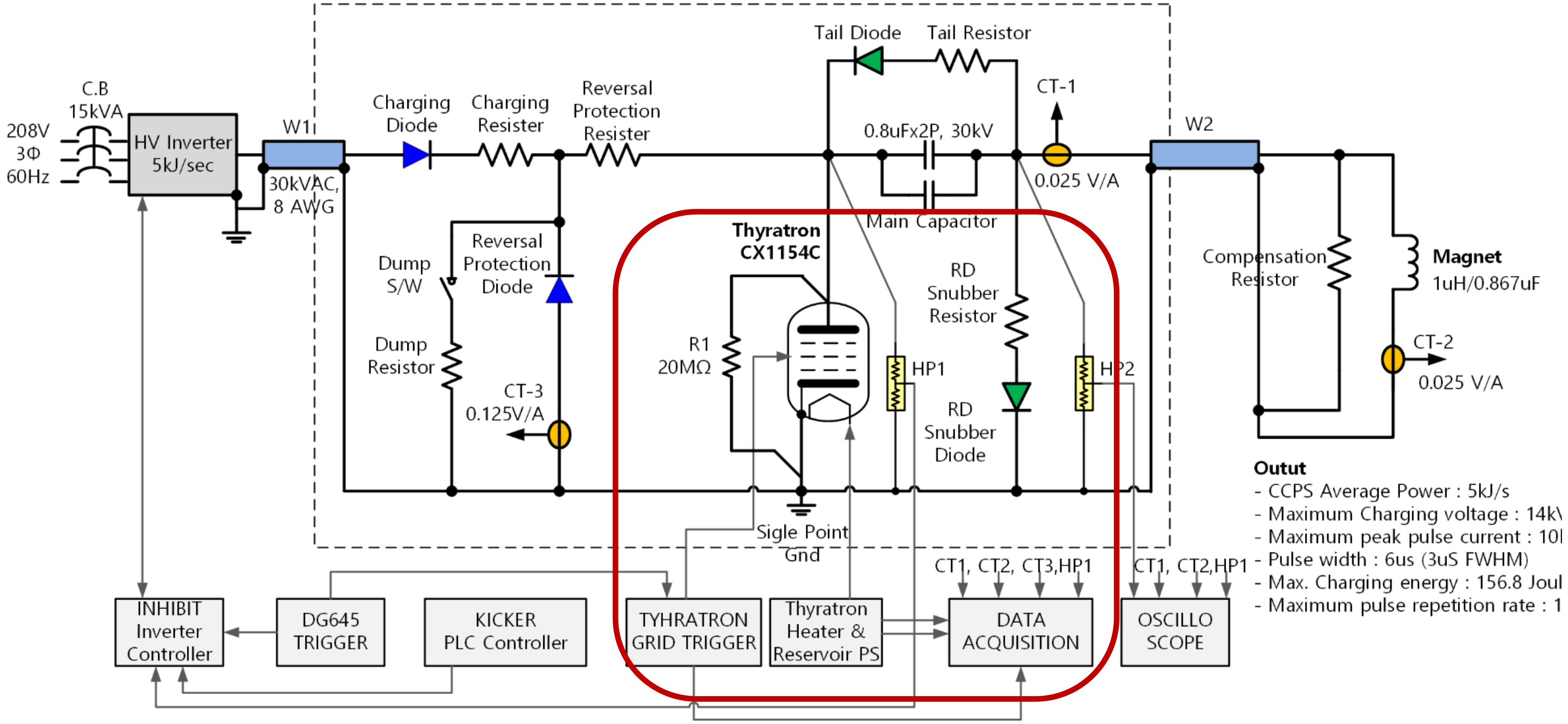


<Implemented unit module>



<Circuit and structure for the development of IGBT-based high-power switch unit module >

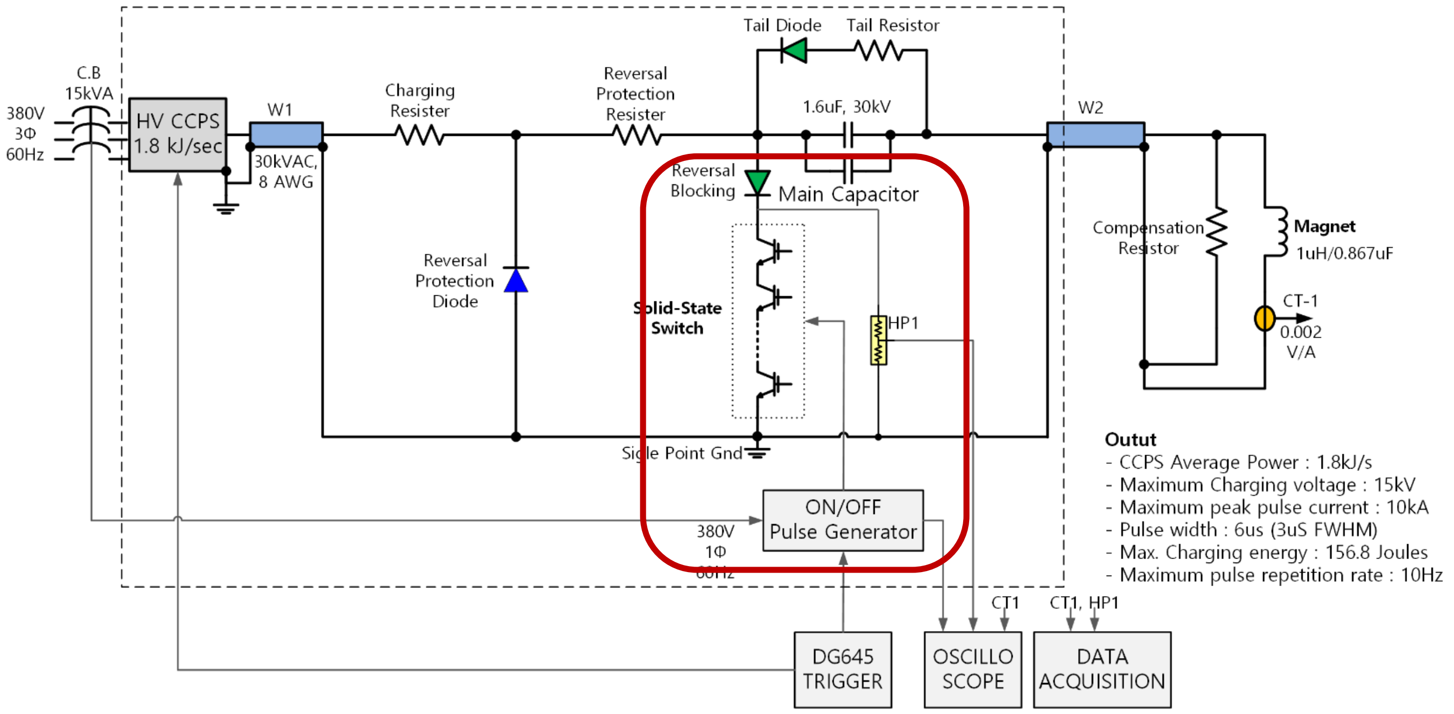
From Thyratron to Solid-State Switch Kicker Modulator Conversion



<Current Kicker Modulator Configuration>

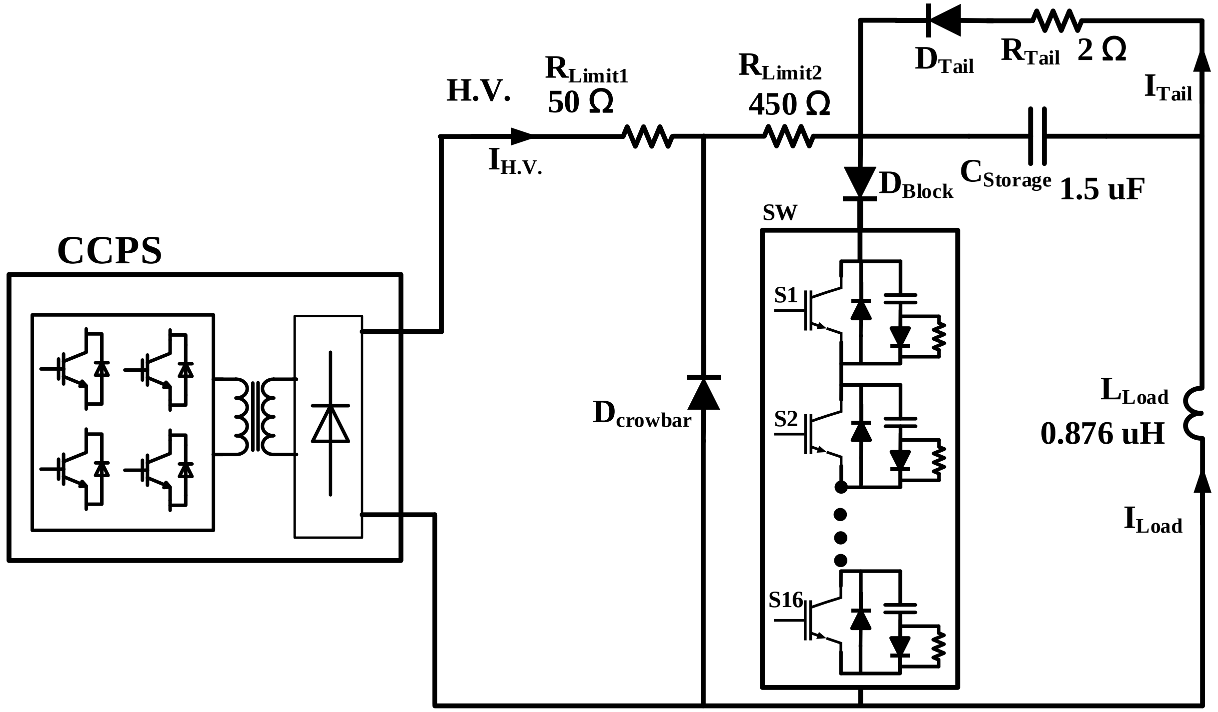
1. Remove power supplies for Thyratron drive.
2. Remove Snubber Circuit for Thyratron.
3. Remove auxiliary circuit for Thyratron.
4. Add Reverse Current Blocking Diode for Solid-state Switch

(5. Replace Tail Resistor for Energy Recovery with an Inductor.)



<Configuration Diagram of Kicker Modulator with Solid-State Switch>

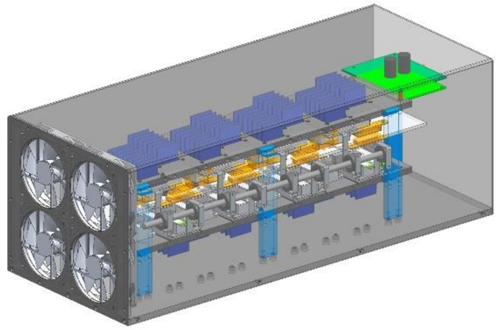
Optimizing In-house Design and Fabrication of a Solid-state switch-based kicker modulator.



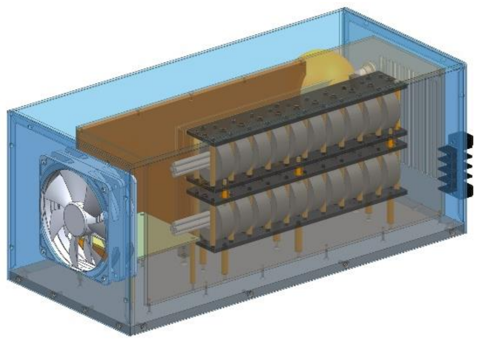
<Circuit Design for Solid-state based Kicker Modulator>

1. Charging Resistor (R_{Limit1})	Peak Current	Peak Voltage	Pulse Energy	Average Power
	100A	5,000V	0.4J	20W
2. Reversal Resistor (R_{Limit2})	Peak Current	Peak Voltage	Pulse Energy	Average Power
	100A	16,000V	1.4J	50W
3. Reversal Diode ($D_{crowbar}$)	Peak Current	Peak Voltage (V)	Average Current	RMS Current (A)
	80A	20,000V	0.1A	1A
4. Tail Resistor (R_{Tail})	Peak Current	Peak Voltage	Pulse Energy	Average Power
	4,400A	9,000V	110J	1,053W
5. Tail Diode (D_{Tail})	Peak Current	Peak Voltage	Average Current	RMS Current
	4,400A	20,000V	0.3A	26A
6. Main Capacitor ($C_{Storage}$)	Peak Current	RMS Current	Peak Voltage	Peak Reversal Voltage
	13,000A	60A	16,000V	-8,000V
7. Reverse Blocking Diode (D_{Block})	Peak Current	Peak Voltage	RMS Current	Reverse Recovery Time
	13,000A	16,000V	60A	< 100ns

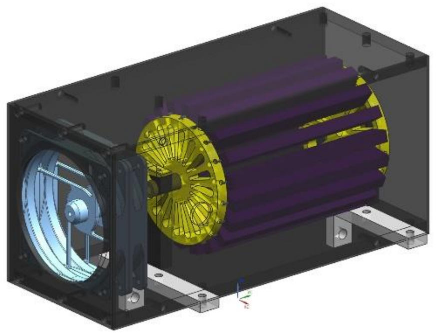
<Simulation Analysis Results of Component Operating Conditions>



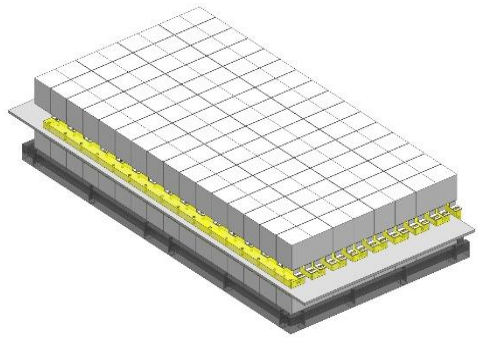
<High Power Switch based on IGBT>



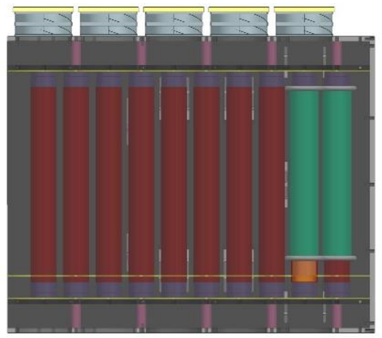
<High Precision High Voltage Capacitor Charger>



<High Voltage Blacking Diode>



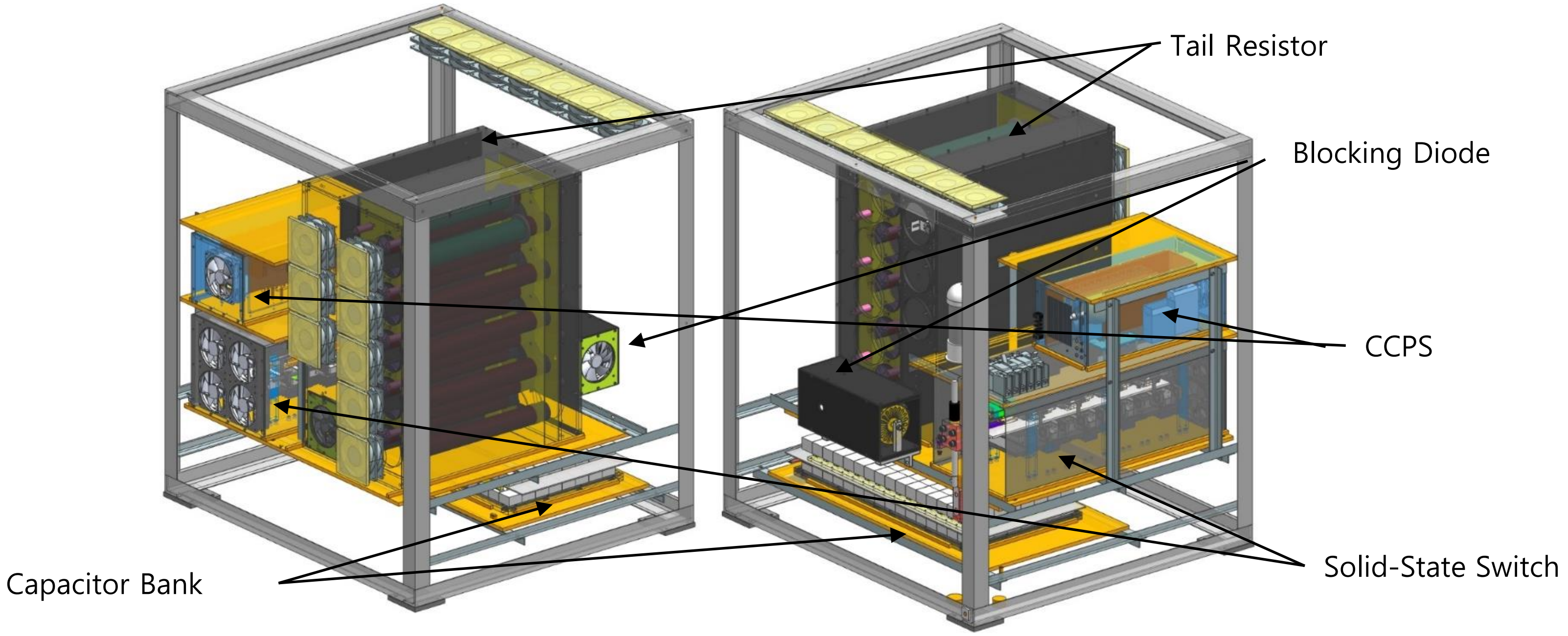
<High Voltage Capacitor Bank>



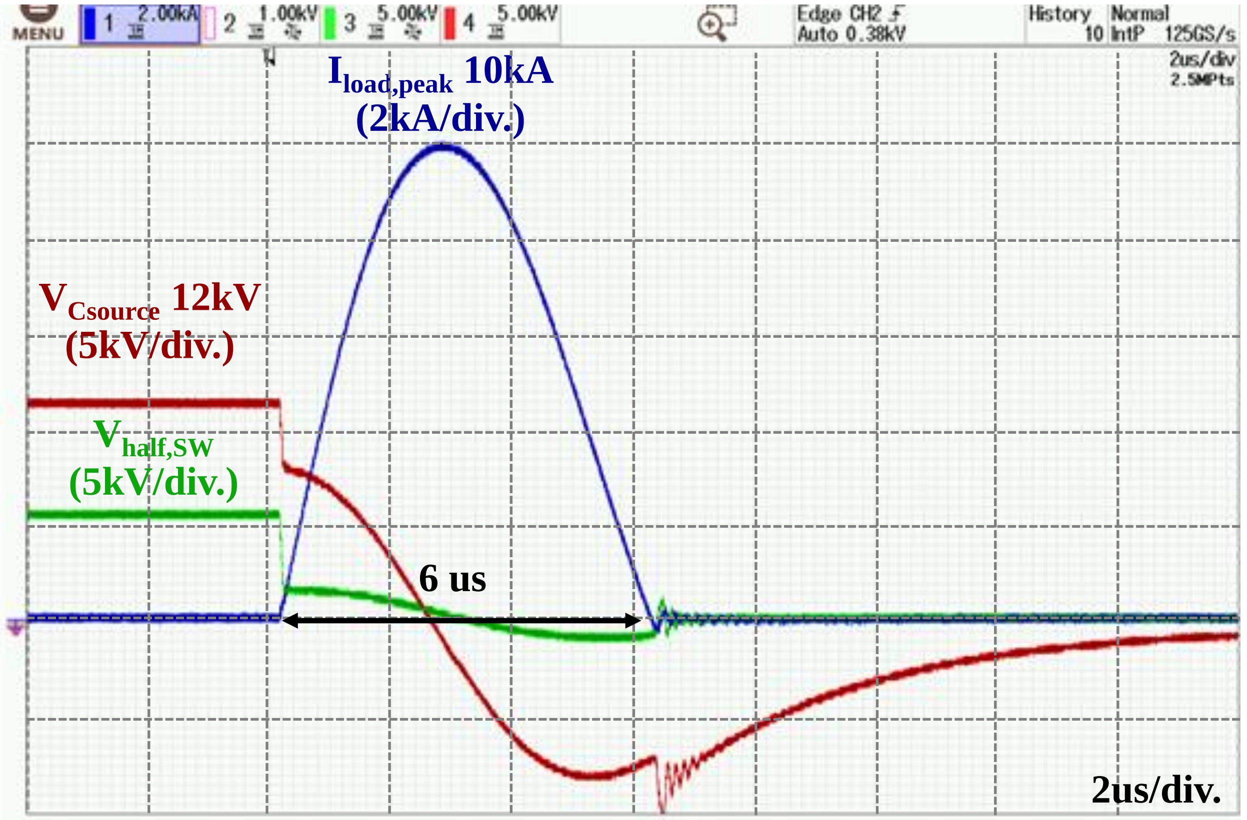
<Reversal Diode & Tail Diode>

Fabrication and Testing Results of the Kicker Modulator

<Developed kicker modulator system>

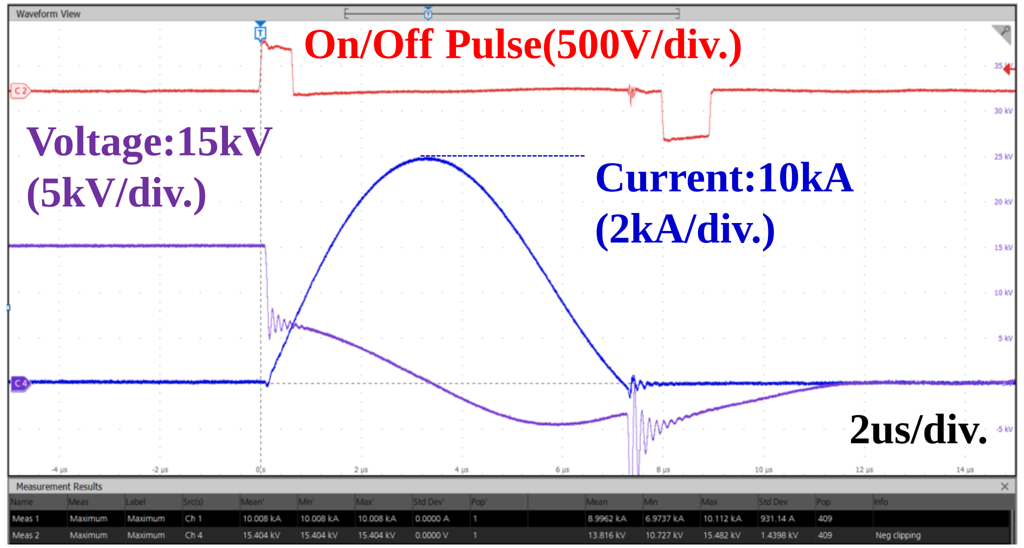


<Detailed modeling of the Solid-State based accelerator Kicker Modulator>

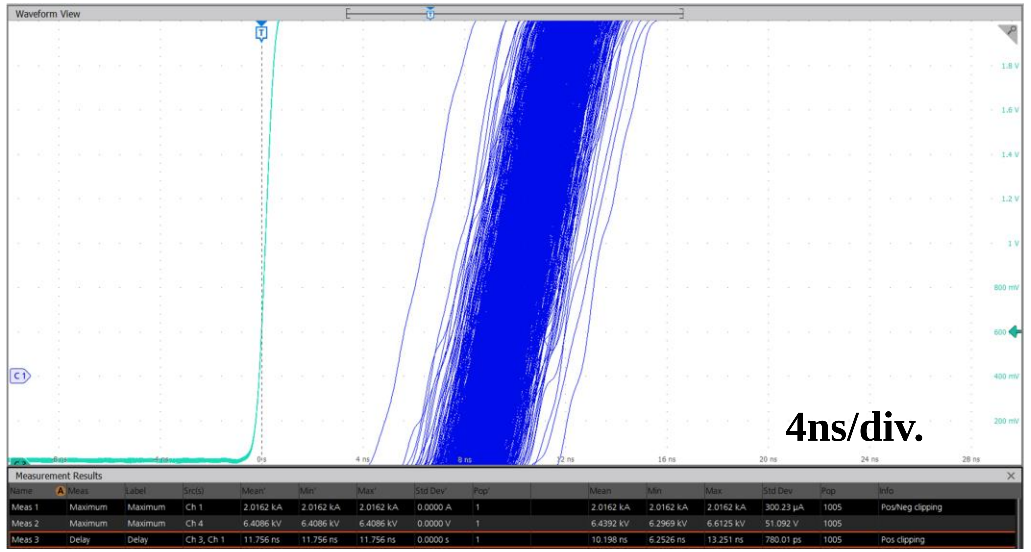


<Experimental waveforms>

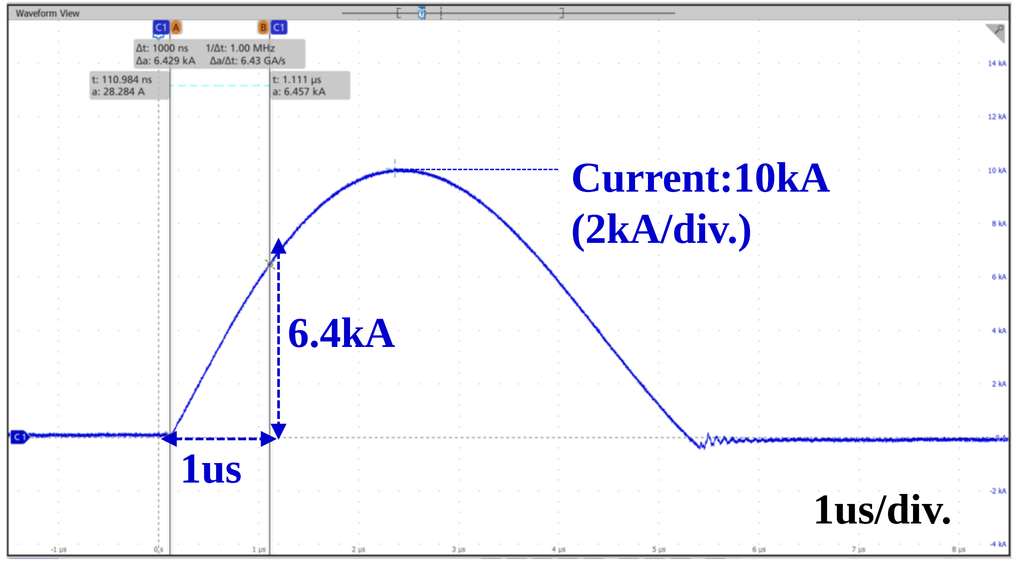
Performance Verification Test Results and Certification



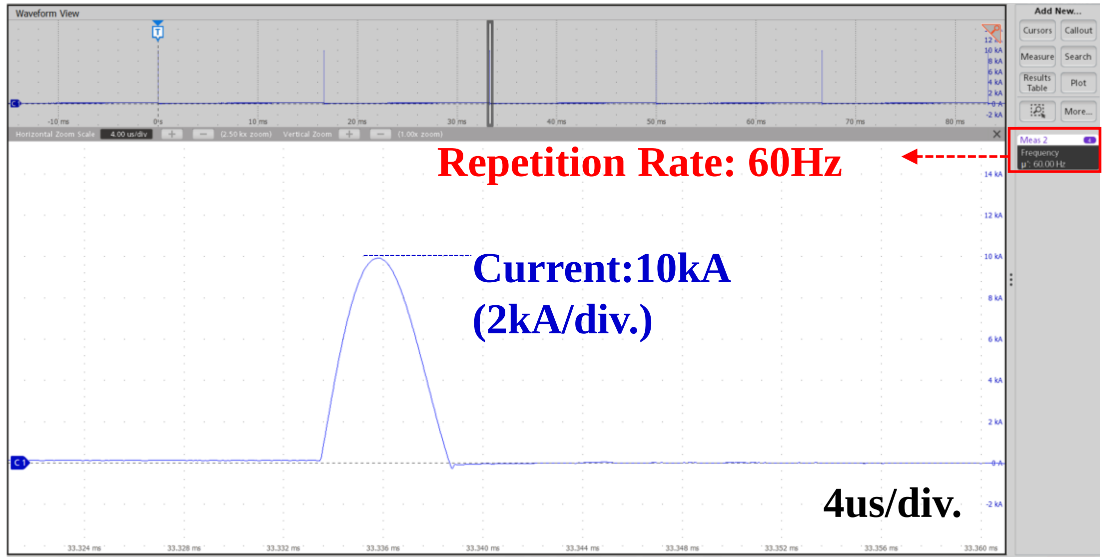
<Maximum 15kV Voltage and 10kA Current Performance>



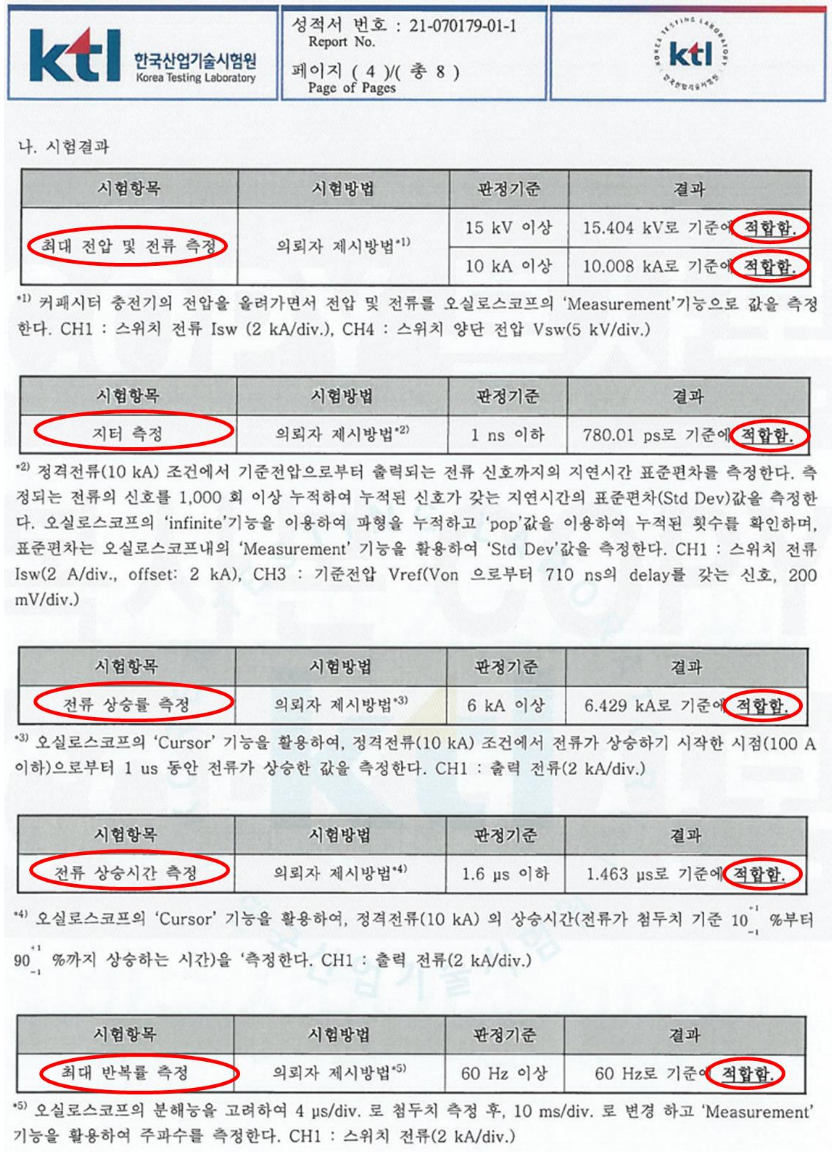
<Jitter Standard Deviation 780ps Performance>



<Max Current Rise Time 6.4kA/us Performance>



<Maximum Repetition Rate of 60Hz Performance>



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성적서 번호 : 21-070179-01-1
Report No.

페이지 (4)/(총 8)
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나. 시험결과

시험항목	시험방법	판정기준	결과
최대 전압 및 전류 측정	의뢰자 제시방법*1)	15 kV 이상	15.404 kV로 기준에 적합함.
		10 kA 이상	10.008 kA로 기준에 적합함.

*1) 커패시터 충전기의 전압을 올려가면서 전압 및 전류를 오실로스코프의 'Measurement'기능으로 값을 측정한다. CH1 : 스위치 전류 Isw (2 kA/div.), CH4 : 스위치 양단 전압 Vsw(5 kV/div.)

시험항목	시험방법	판정기준	결과
지터 측정	의뢰자 제시방법*2)	1 ns 이하	780.01 ps로 기준에 적합함.

*2) 정격전류(10 kA) 조건에서 기준전압으로부터 출력되는 전류 신호까지의 지연시간 표준편차를 측정한다. 측정되는 전류의 신호를 1,000 회 이상 누적하여 누적된 신호가 갖는 지연시간의 표준편차(Std Dev)값을 측정한다. 오실로스코프의 'infinite'기능을 이용하여 파형을 누적하고 'pop'값을 이용하여 누적된 횟수를 확인하며, 표준편차는 오실로스코프내의 'Measurement' 기능을 활용하여 'Std Dev'값을 측정한다. CH1 : 스위치 전류 Isw(2 A/div., offset: 2 kA), CH3 : 기준전압 Vref(Von 으로부터 710 ns의 delay를 갖는 신호, 200 mV/div.)

시험항목	시험방법	판정기준	결과
전류 상승률 측정	의뢰자 제시방법*3)	6 kA 이상	6.429 kA로 기준에 적합함.

*3) 오실로스코프의 'Cursor' 기능을 활용하여, 정격전류(10 kA) 조건에서 전류가 상승하기 시작한 시점(100 A 이하)으로부터 1 us 동안 전류가 상승한 값을 측정한다. CH1 : 출력 전류(2 kA/div.)

시험항목	시험방법	판정기준	결과
전류 상승시간 측정	의뢰자 제시방법*4)	1.6 μs 이하	1.463 μs로 기준에 적합함.

*4) 오실로스코프의 'Cursor' 기능을 활용하여, 정격전류(10 kA) 의 상승시간(전류가 첨두치 기준 10^{+1}_{-1} %부터 90^{+1}_{-1} %까지 상승하는 시간)을 '측정한다. CH1 : 출력 전류(2 kA/div.)

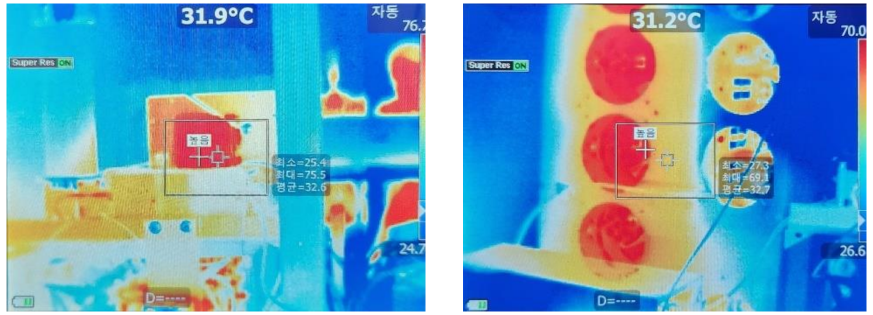
시험항목	시험방법	판정기준	결과
최대 반복률 측정	의뢰자 제시방법*5)	60 Hz 이상	60 Hz로 기준에 적합함.

*5) 오실로스코프의 분해능을 고려하여 4 μs/div. 로 첨두치 측정 후, 10 ms/div. 로 변경 하고 'Measurement' 기능을 활용하여 주파수를 측정한다. CH1 : 스위치 전류(2 kA/div.)

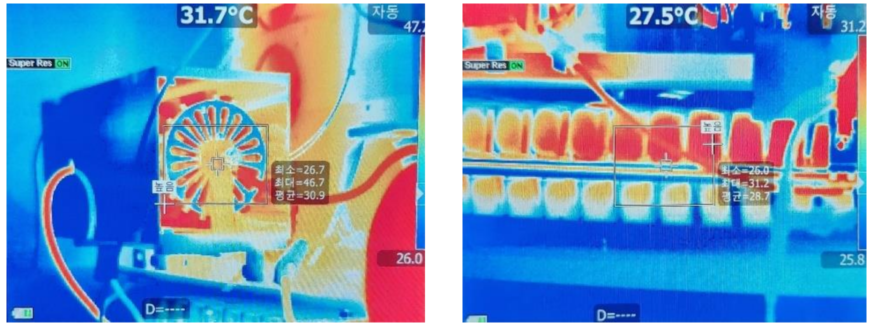
<Korea Testing Laboratory (KTL) Certified Test Report>

Reliability Testing of Solid-state Switch and Test Results

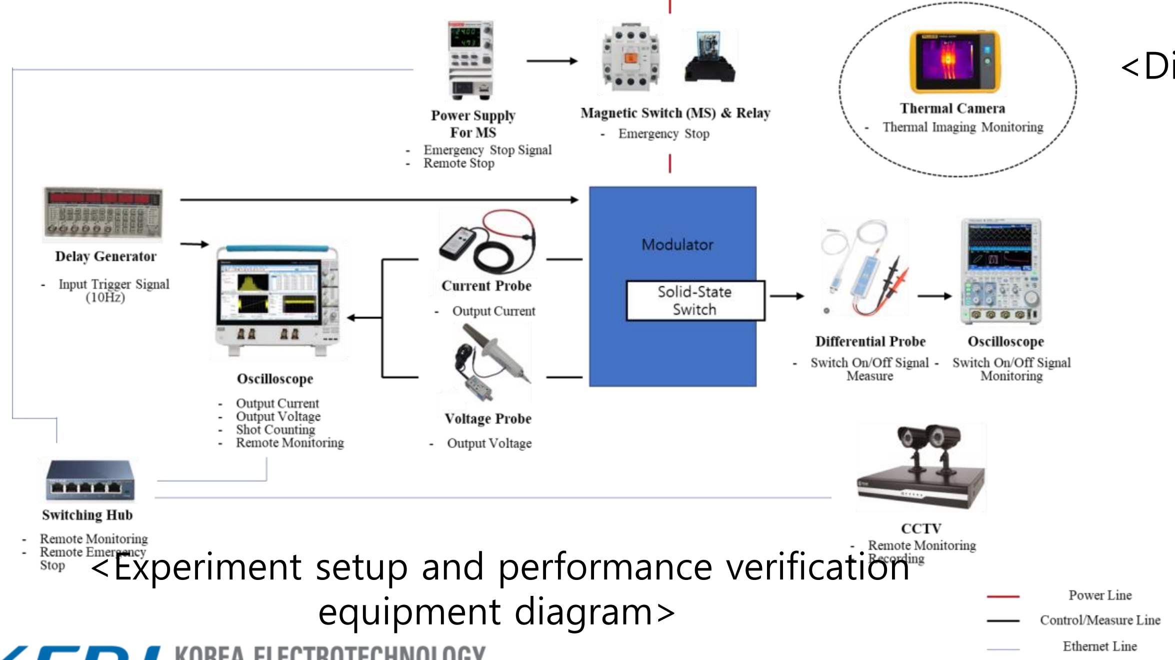
<Reliability Test Set-up>



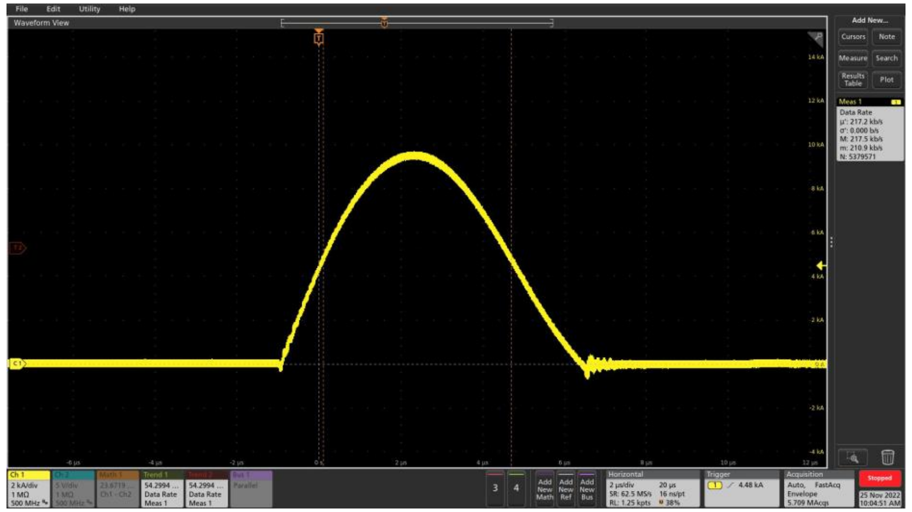
<Switch & Tail Resistor Temperature Measurement Results>



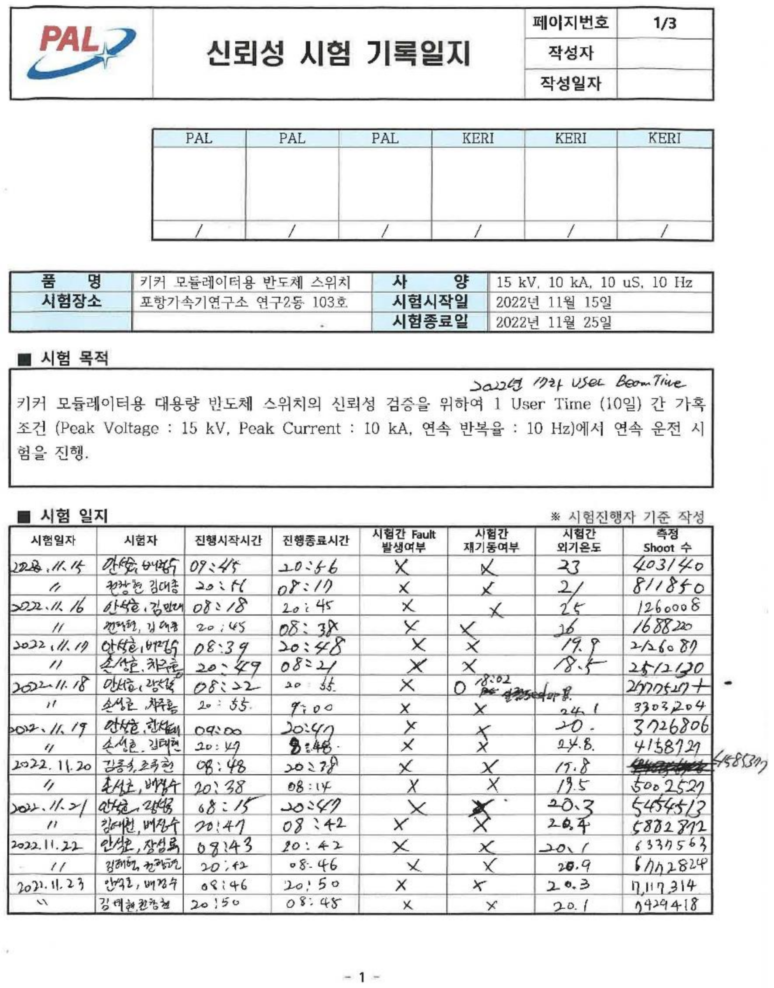
<Diode & Capacitor Module Temperature Measurement Results>



<Experiment setup and performance verification equipment diagram>



<Accumulated Output Current Waveform of 5 million Shots>



신뢰성 시험 기록일지

페이지번호	1/3
작성자	
작성일자	

PAL	PAL	PAL	KERI	KERI	KERI
/	/	/	/	/	/

품 명	키커 모듈레이터용 반도체 스위치	사 양	15 kV, 10 kA, 10 uS, 10 Hz
시험장소	포항가속기연구소 연구2동 103호	시험시작일	2022년 11월 15일
		시험종료일	2022년 11월 25일

■ 시험 목적

키커 모듈레이터용 대용량 반도체 스위치의 신뢰성 검증을 위하여 1 User Time (10일) 간 가혹조건 (Peak Voltage : 15 kV, Peak Current : 10 kA, 연속 반복율 : 10 Hz)에서 연속 운전 시험을 진행.

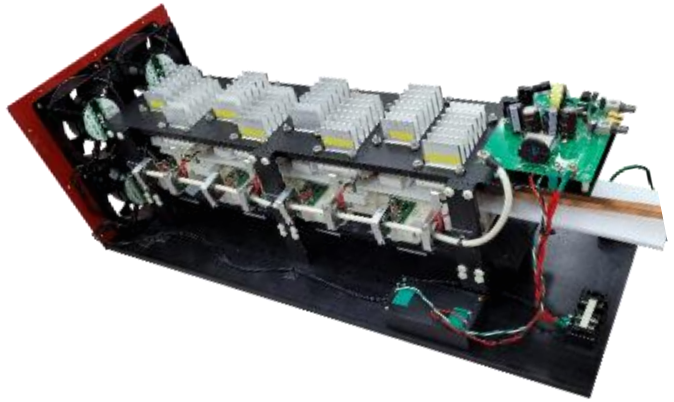
■ 시험 일지 ※ 시험진행자 기준 작성

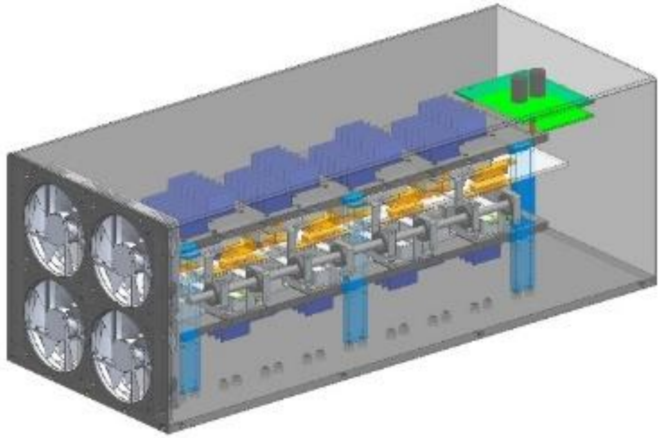
시험일자	시험자	진행시작시간	진행종료시간	시험간 Fault 발생여부	시험간 재기동여부	시험간 외기온도	측정 Shoot 수
2022.11.15	[illegible]	09:45	20:56	X	X	23	403140
〃	[illegible]	20:56	08:17	X	X	21	811850
2022.11.16	[illegible]	08:18	20:45	X	X	25	1260008
〃	[illegible]	20:45	08:38	X	X	26	1688220
2022.11.17	[illegible]	08:39	20:48	X	X	19.9	2126087
〃	[illegible]	20:49	08:21	X	X	18.5	2512130
2022.11.18	[illegible]	08:22	20:55	X	O 18:02 [illegible]		2977527
〃	[illegible]	20:55	9:00	X	X	24.1	3303204
2022.11.19	[illegible]	09:00	20:47	X	X	20.	3726806
〃	[illegible]	20:47	8:48	X	X	24.8	4158727
2022.11.20	[illegible]	08:48	20:38	X	X	15.8	4585317
〃	[illegible]	20:38	08:14	X	X	19.5	5002527
2022.11.21	[illegible]	08:15	20:47	X	X	20.3	5454513
〃	[illegible]	20:47	08:42	X	X	20.4	5882872
2022.11.22	[illegible]	08:43	20:42	X	X	20.1	6337563
〃	[illegible]	20:42	08:46	X	X	20.9	6772824
2022.11.23	[illegible]	08:46	20:50	X	X	20.3	7117314
〃	[illegible]	20:50	08:48	X	X	20.1	7429418

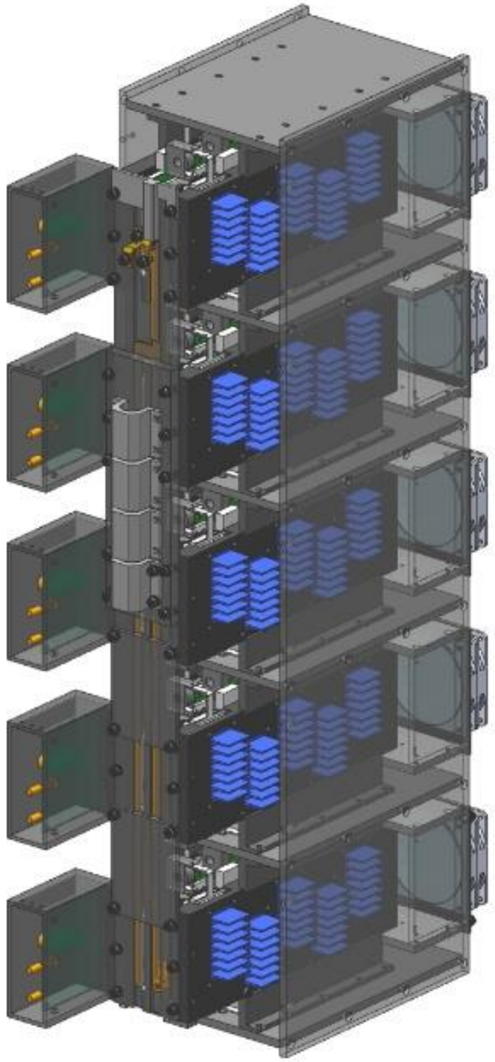
- 1 -

<Reliability Test Log>

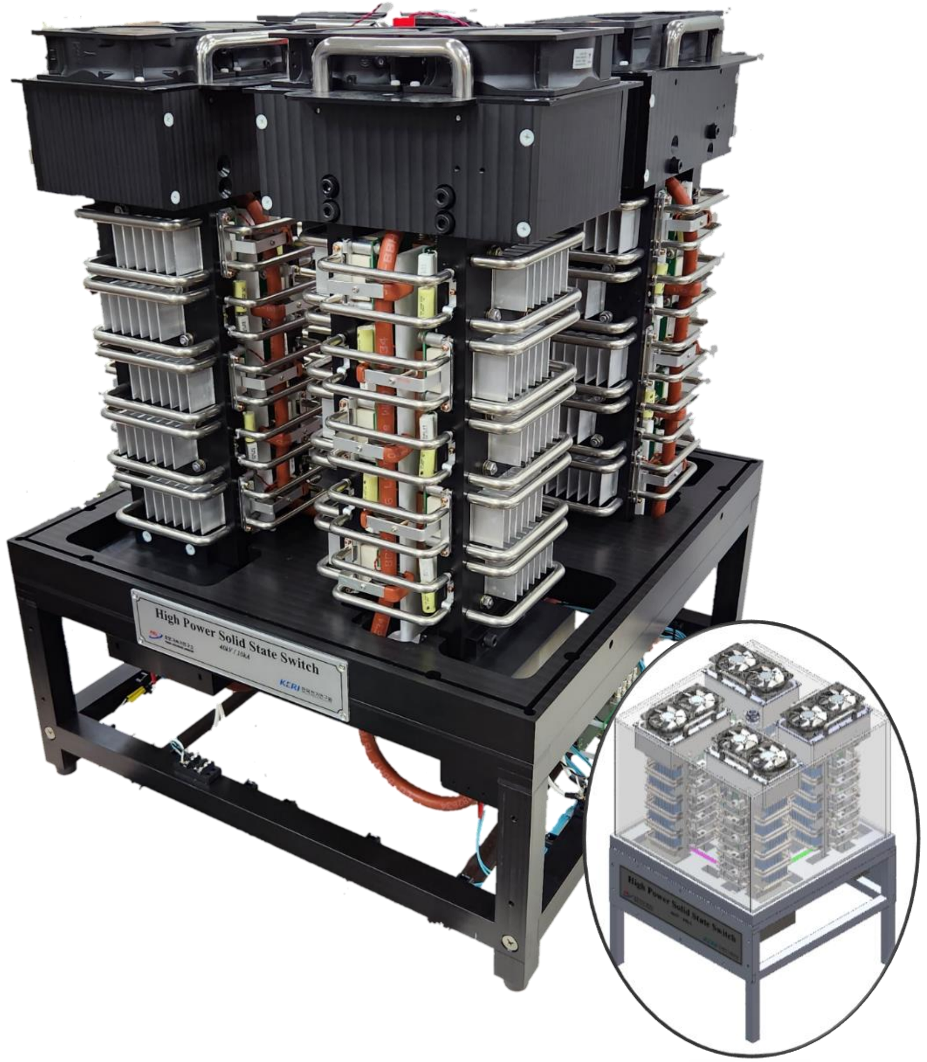
Solid-state switches Developed thus Far.





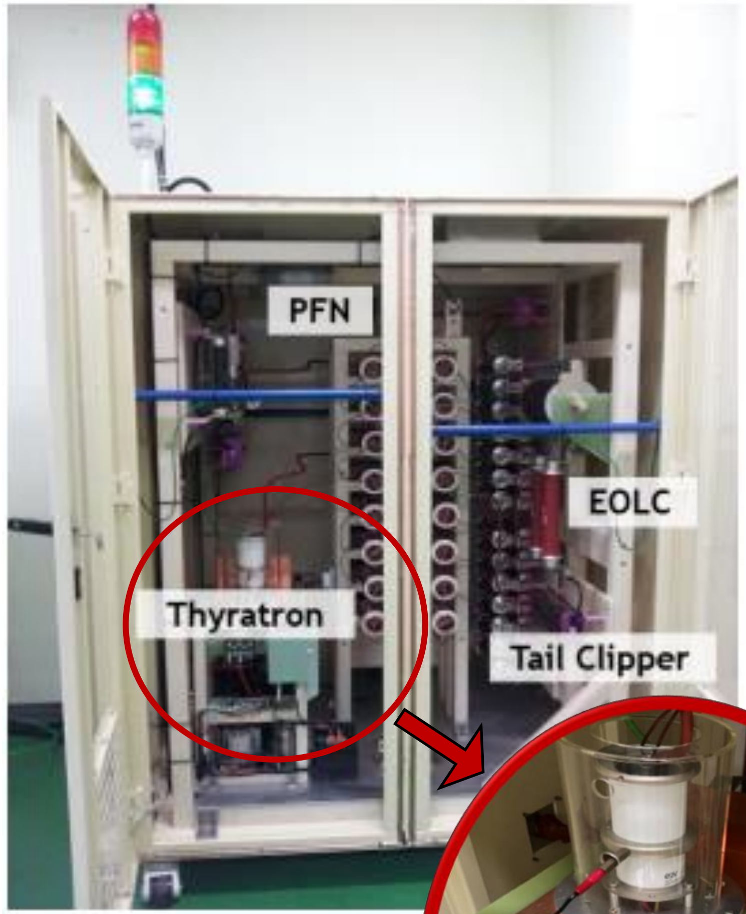


<15kV,10kA & 50kV, 10kA Solid-State Switch Prototypes>
(PAL Kicker & Klystron Modulator)



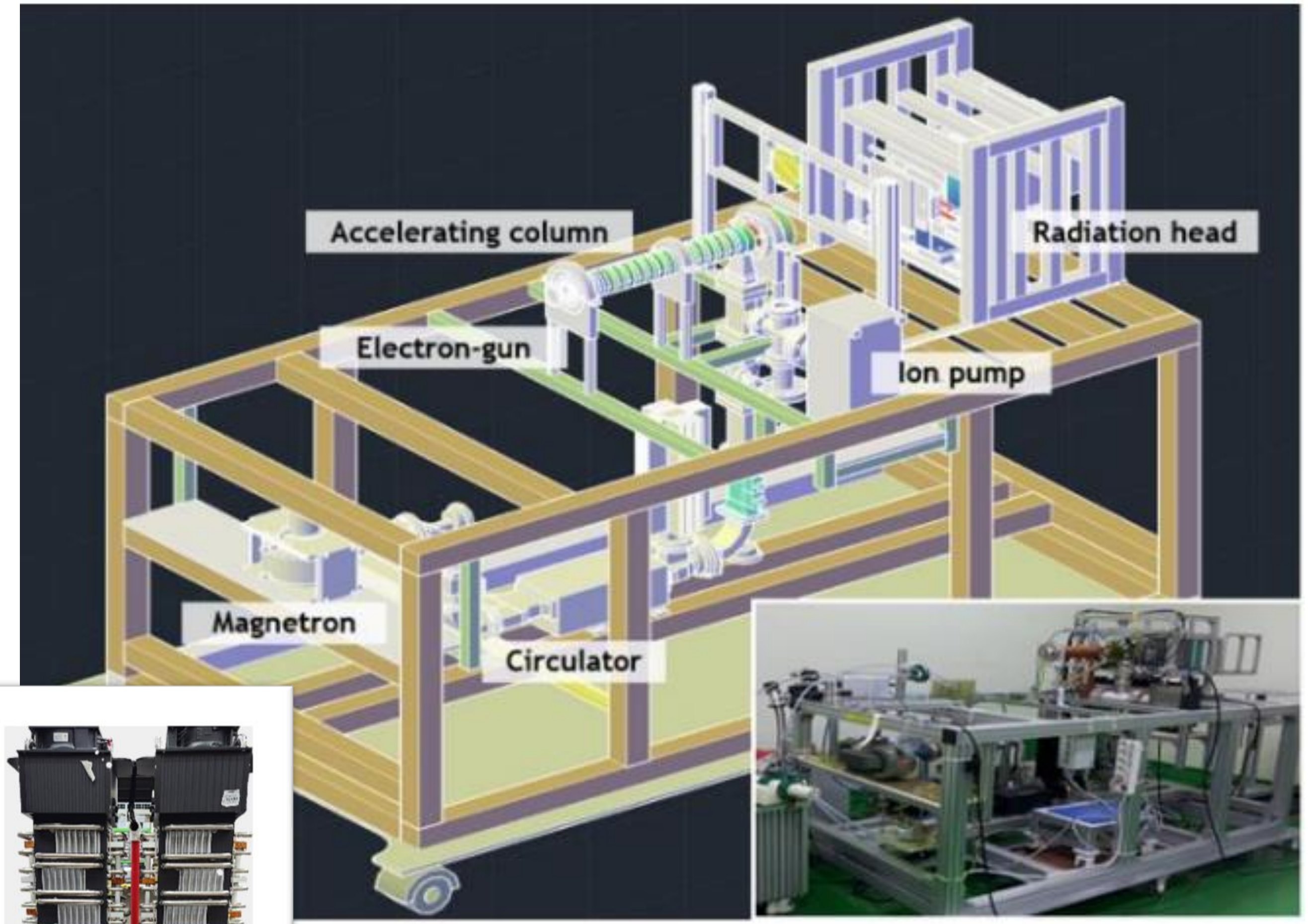
<25kV,10kA & 50kV, 10kA Solid-State Switch (Packaging)>
(4GSR Kicker & Klystron Modulator)

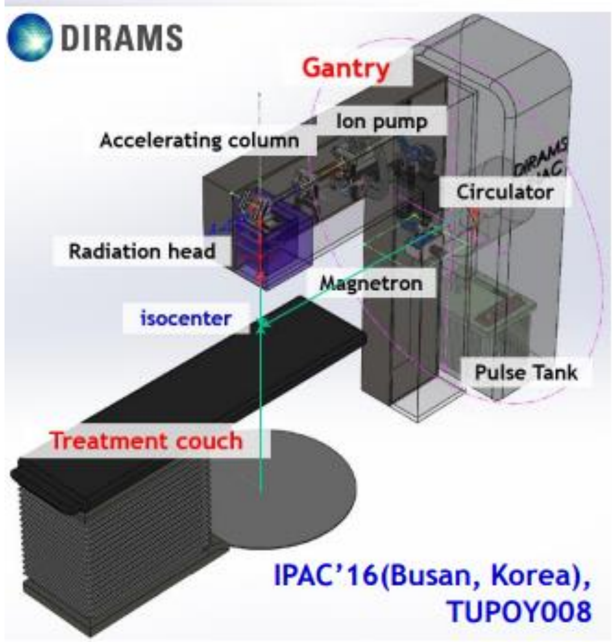
Application to the Modulator for DIRAMS' LINAC-based Experimental Animal Irradiator



<6MW PFN Type Pulse Modulator>

<E2V CX1154C Thyratron>

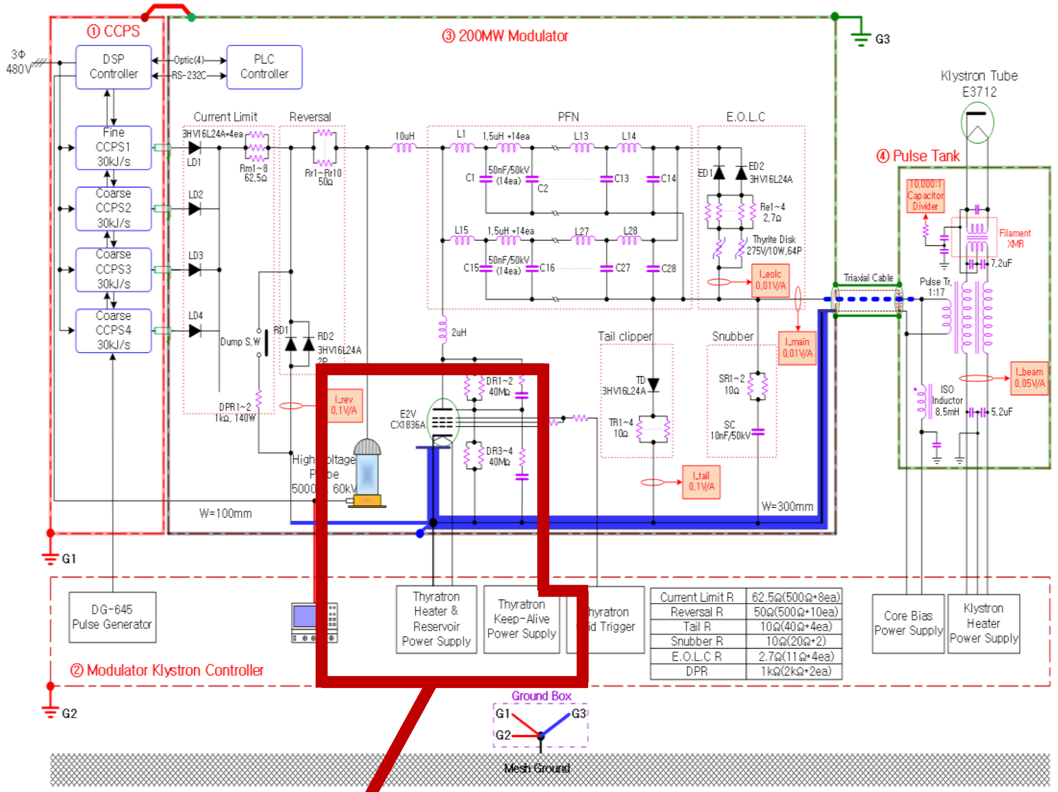




<6MeV C-band Medical LINAC>

- Dirams is a radiological research institution in South Korea
- PAL & KERI are currently underway in replacing the thyratron switch of the Pulse Modulator in the Experimental Animal Irradiator with a solid-state switch.
- Initial experiments completed, final implementation testing in progress

Future Plans



<200MW PFN Type Klystron Modulator>

<PAL Injection Test Facility Gun, Injector, Klystron& Modulator>

<E2V CX1836AX>

- The PAL Injection Test Facility is a facility that simulates and allows experimentation with the actual LINAC components such as the gun, injector, klystron, and modulator, which were used during the construction of PAL-XFEL. Currently, it serves as a facility for testing devices and beams.
- The plan is to utilize the Solid-State Switch for long-term reliability testing by replacing the Thyratron with it.

Thank you for listening to my presentation.

If given the opportunity, I would like to share our developed switch and technology and have the chance to discover its shortcomings together, so that we can work on improving them collaboratively.

Thank you

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