PULSED MODULATOR TECHNOLOGY

Hiroshi MATSUMOTO
J-PARC/KEK

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- **LONG PULSE WIDTH (~msec) AND HIGH REP. RATE. (200 Hz)**
- **OUTPUT PULSE VOLTAGE STABILITY**
- **MODULATOR CIRCUIT CONFIGURATION**

MAJOR REQUIREMENT OF THE RECENT MODULATORS

It does not describe all pulsed modulators.

SHORT PULSE MODULATORS

ITEM	J-PARC, INJ./EXT. KICKER MAG.	KEKB INJ. LINAC	LCLS SLAC	SACLA SPring-8	PAL-XFEL PAL
PULSE WIDTH @FLAT TOP:	~1 μsec x 4	~2.5 μsec	~1.5 μsec	~2.5 μsec	~ 4 μsec
PULSE RESPONSE TIME (RISE):	<300 nsec	<1 μsec	<400 nsec	<1 μsec	<1 μsec
KLYSTRON BEAM VOLTAGE STABILITY:	<1000 ppm (< 10^{-3})	<1000 ppm (< 10^{-3})	<40 ppm (<4 x 10^{-5})	<50 ppm (<5 x 10^{-5})	<50 ppm (<5 x 10^{-5})
TIMING JITTER:	<10 nsec	<10 nsec	<1 nsec	<1 nsec	<5 nsec
REPETITION RATE:	25	50	120	60	60

It does not describe all pulsed modulators.

LONG PULSE MODULATORS

MAJOR SPECIFICATION	iBNCT [1)]	OIST	ILC
OUTPUT VOLTAGE [kV]:	-90	-34	-120
OUTPUT CURRENT [A]:	30	37	140
VOLTAGE STABILITY [ppm]:	±<1000	±<500	±<10000
PULES WIDTH @FLAT TOP[msec]:	1.0	1.0	1.65
REP. RATE [pps]:	200	200	5 (10)
AVERAGE POWER [kW]:	540	300	139 (277)
OVER CURRENT ENERGY [J]:	< 20	< 20	< 20

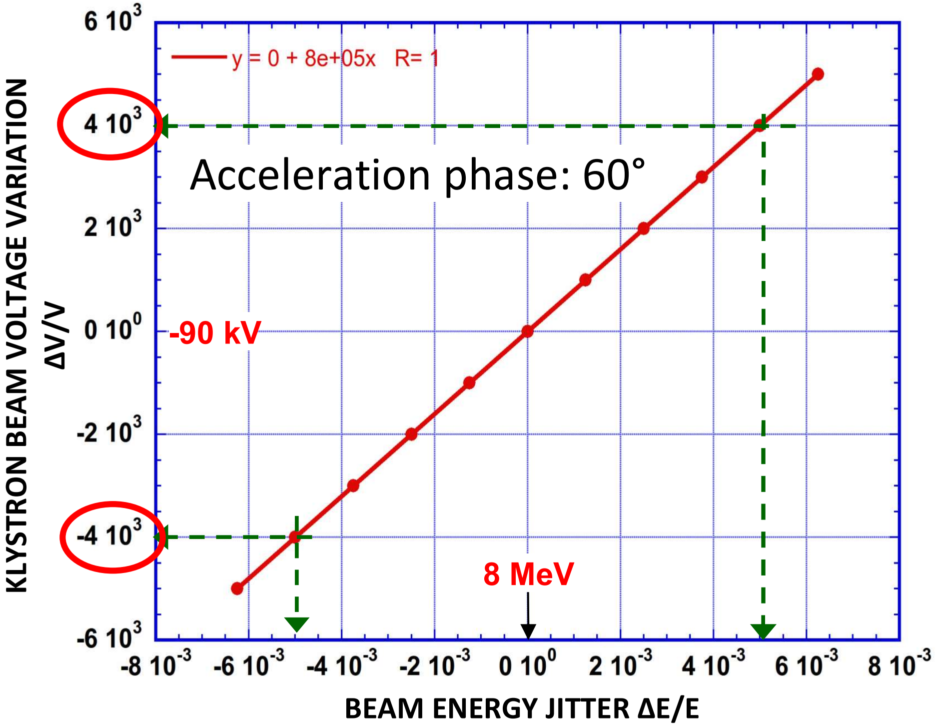
1) THXB01 by Masakazu YOSHIOKA

→ Ongoing operation from 2014

XFEL ACCELERATORS REQUIRED THE HIGH STABILITY OF OUTPUT VOLTAGE AND SMALL TIMING JITTER OF KLYSTRON BEAM VOLTAGE TO PROVIDE 10-4 OF BEAM ENERGY JITTERS.

*Timing jitters: a few μsec will be acceptable.

REQUIREMENT OF KLYSTRON BEAM VOLTAGE STABILITY AND PULSE FLATNESS



$$E_z(\Delta P) \propto \sqrt{P_0} = \sqrt{V_k^{2.5}}$$

$$\left(E_z = \sqrt{P_0 \times R_0} \propto \sqrt{P_0}\right)$$

$$E_z(\Delta\theta) = \frac{\sin\theta_{60} - \sin(\theta_{60} - \Delta\theta)}{\sin\theta_{60}}$$

E_z: Electric field gradient along axis
R_{acc}: Shunt impedance [Ω]

BEAM ENERGY JITTER	MODULATOR VOLTAGE STABILITY
$\pm 5 \times 10^{-3}$	$\pm 4\times10^{-3}$ (TARGET: $\pm 1\times10^{-3}$)

→ Request from the beam loss

1. AN ELECTRIC GRADIENT OF CAVITY

$$E_z(V/m) = \sqrt{P_0 \cdot \sin(\theta_0) \times R_0} \propto \sqrt{P_0 \cdot \sin(\theta_0)} \qquad (1)$$

- P_o [W]: Klystron output rf power
- θ_0 [°]: Acceleration phase @60° for iBNCT
- R_0 [Ω/m]: Shunt impedance

2. Power supply output voltage variation vs fluctuations of P0 and of θ0.

$$P_0 = \eta \times (\underbrace{I_K \times V_K}) \propto V_K^{2.5} \qquad (2)$$

$$I_k = \mu k \times V_k^{\frac{3}{2}}$$

- I_K: Klystron beam current
- V_K: Klystron beam voltage
- μK: Klystron micro perveance
- η: Conversion efficiency from beam current to rf.

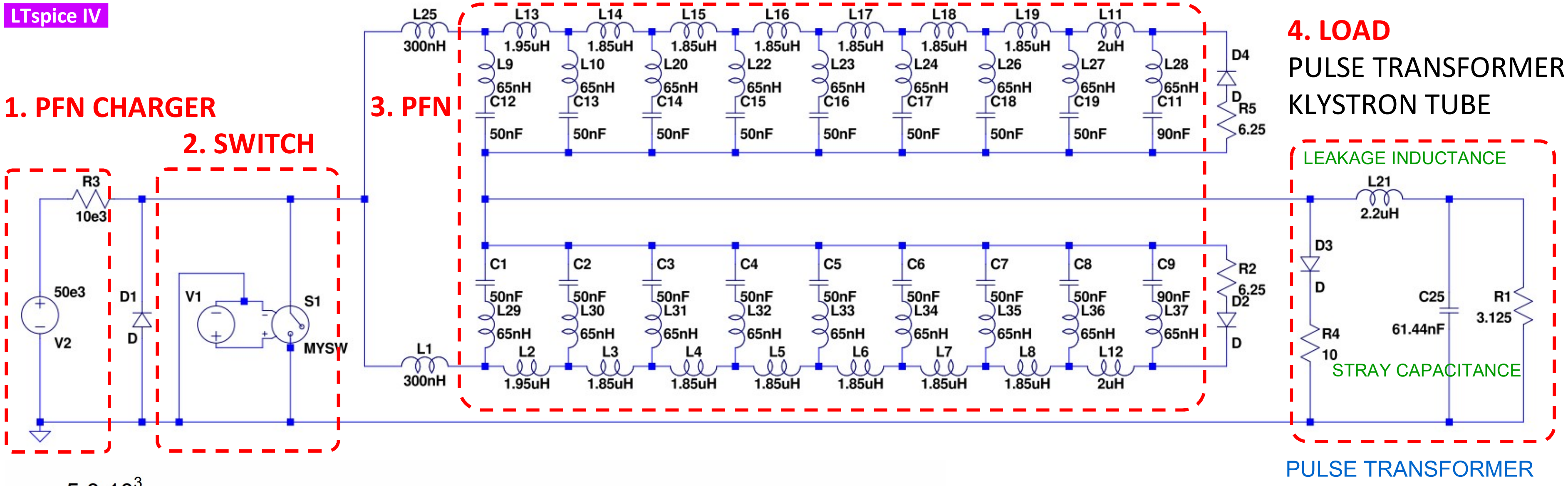
$$\frac{\Delta\theta}{360} = \frac{e}{mc^2} \times \frac{L}{\lambda_0} \times \frac{V}{(\gamma^2-1)^{\frac{3}{2}}} \times \frac{\Delta V}{V_0} \qquad (3)$$

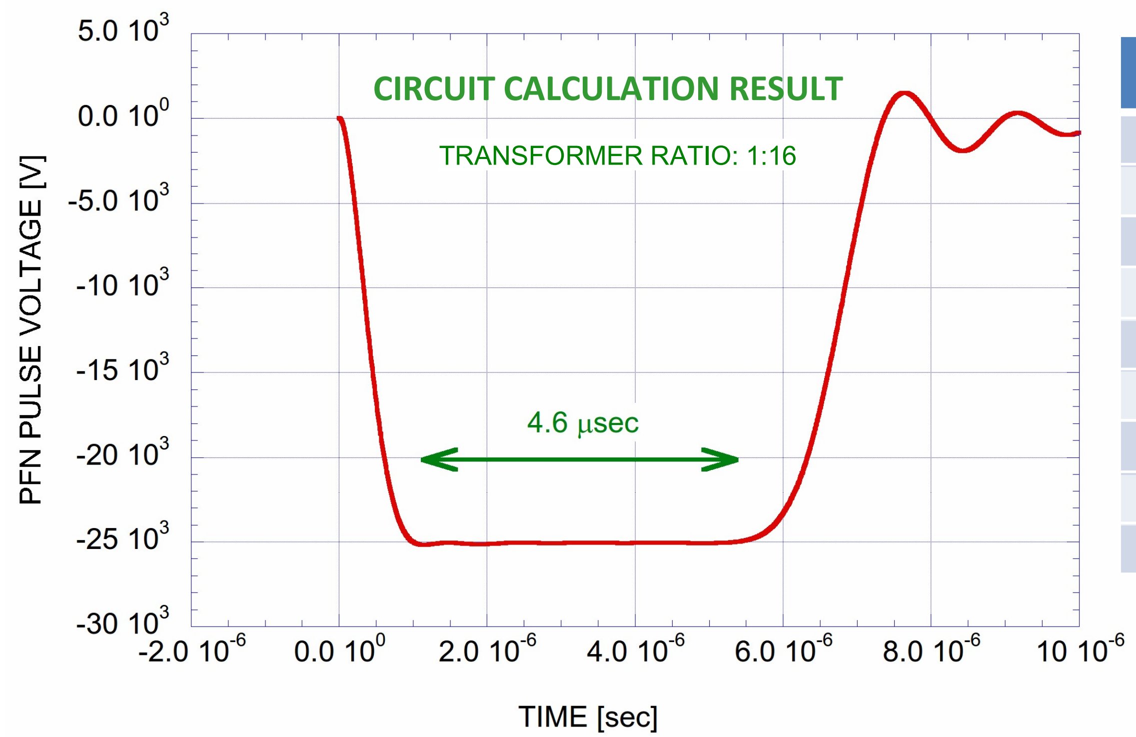
$$\left[\gamma = 1 + \frac{V}{0.511\times10^6}\right]$$

- $\Delta\theta$ [°]: phase change according to HV voltage.
- e [C]: 1.6×10^{-19}, electron charge.
- m [kg]: 9.11×10^{-31}, electron mass.
- c [m/sec] $= 3\times10^8$, light speed.
- L [m]: 2.465, drift length between input and output cavity.
- λ_0 [m]: 0.93, free wave length.
- V_0 [V]: −90kV, HV pulse voltage.
- V [V]: $V_0 \pm \Delta V$, HV pulse voltage change.

TYPICAL CIRCUIT OF SHORT PULSE MODULATOR

LTspice IV





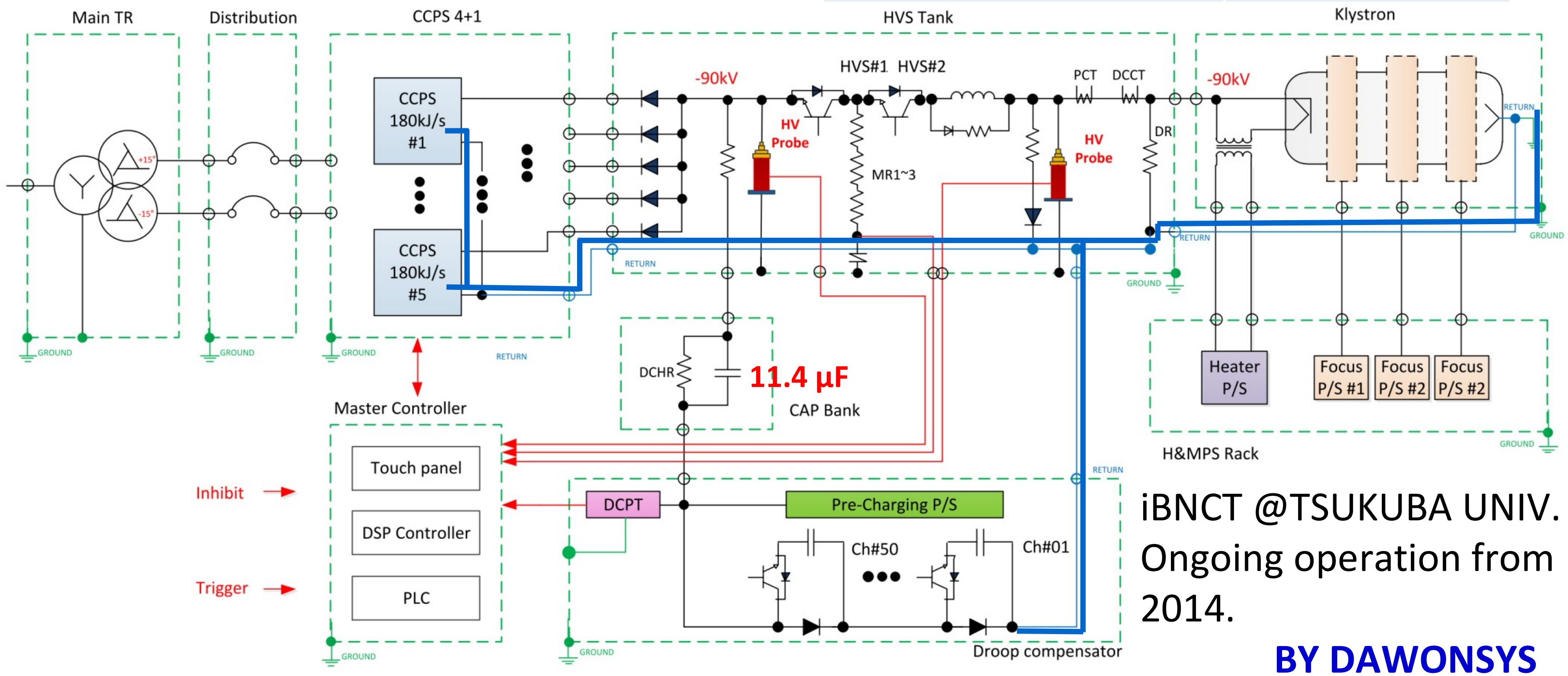
ITEMS	
PFN ENERGY (1/2C*V²):	74 kW (@60 pps)
CHARGING VOLTAGE (MAX.):	50 kV
PFN OUTPUT VOLTAGE:	25 kV
PFN OUTPUT CURRENT:	8 kA
PULSE WIDTH (FLAT TOP):	4.6 µsec
REPETITION RATE:	120 pps
PFN IMPEDANCE:	3.125 Ω
TOTAL CAPACITANCE:	0.98 µF
TOTAL INDUCTANCE:	31.3 µH

NOTE:
PULSE TRANSFORMER LEAKAGE INDUCTANCE : 2.2 µH (@PRIMARY)
LOAD STRAY CAPACITANCE: 61.44 nF (@PRIMARY)

LONG PULSE & HIGH REP. RATE MODULATOR POWER SUPPLY

MODULATOR	PARAMETERS
Output Voltage [kV]:	-90
Output Current [A]:	30
Load Impedance [kΩ]:	3
Pulse Width [msec]:	1
Pulse Flatness @ Top	$\sim 1 \times 0^{-3}$
Repetition Rate [Hz]:	single - 200 (max.)

KLYSTRON	PARAMETERS
Beam Voltage [kV]:	-90
Beam Current [A]:	30
Impedance [kΩ]:	3
Pulse Width [msec]:	1
RF Output Power [MW]:	1.2
Repetition Rate [Hz]:	200 (max.)
Short current limit [J] :	20 (max.)

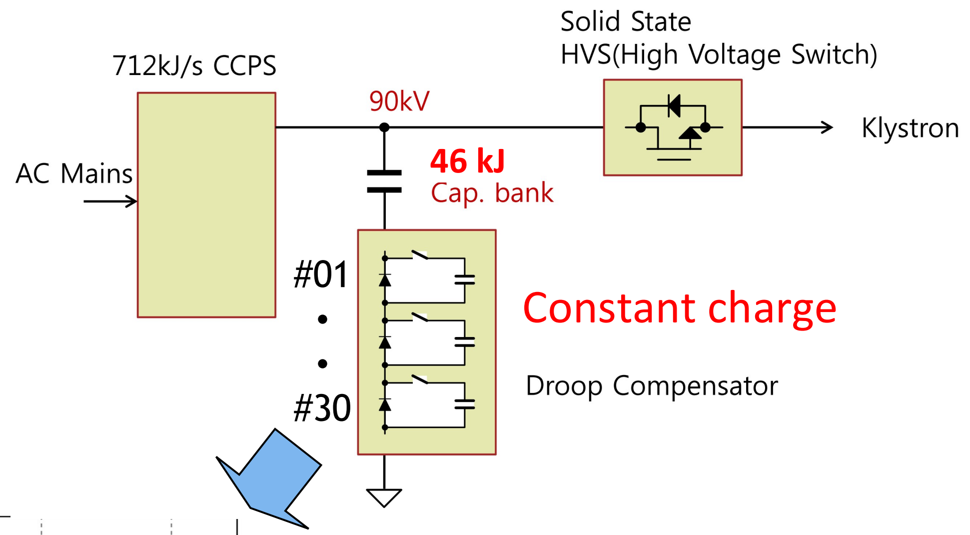


iBNCT @TSUKUBA UNIV.
Ongoing operation from 2014.

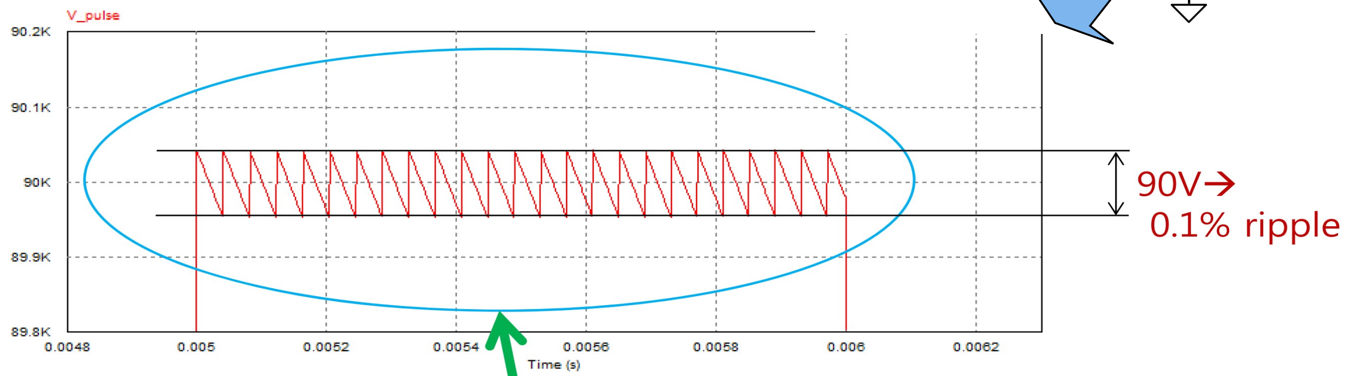
BY DAWONSYS

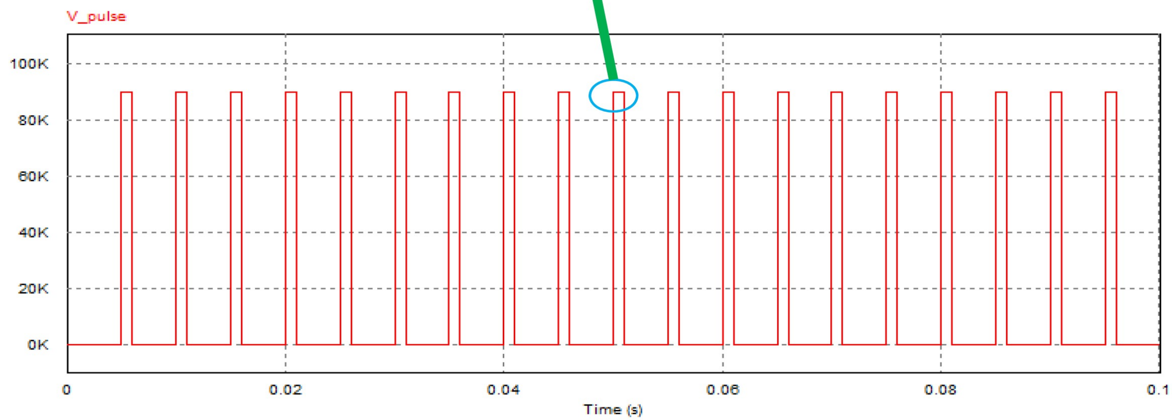
Droop Compensation Circuit for iBNCT at Tsukuba Univ.

48 modules to provide an order of 10^{-4} flat-top at 1 msec pulse width.

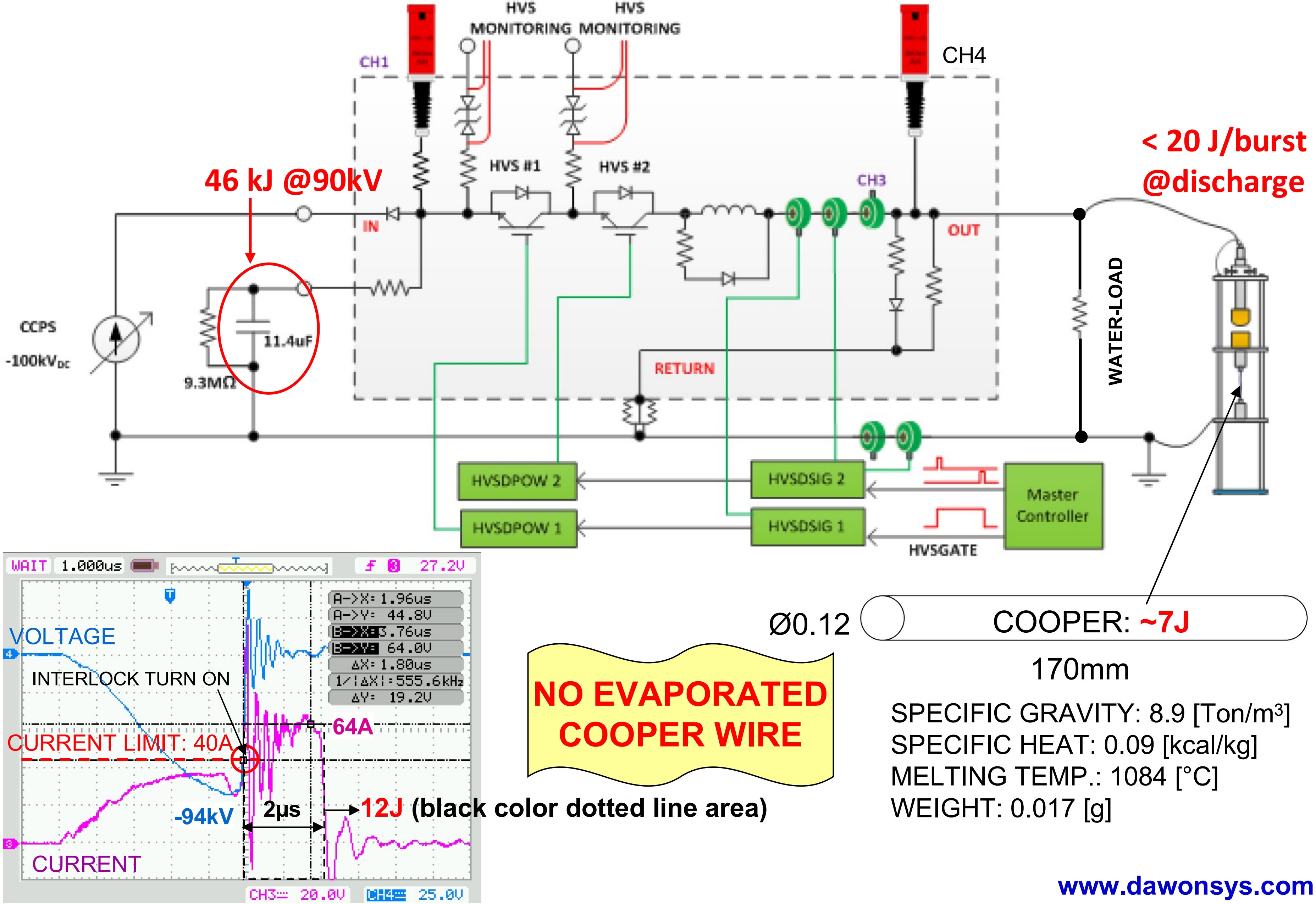


Simulation Result





OVER CURRENT PROTECTION TEST

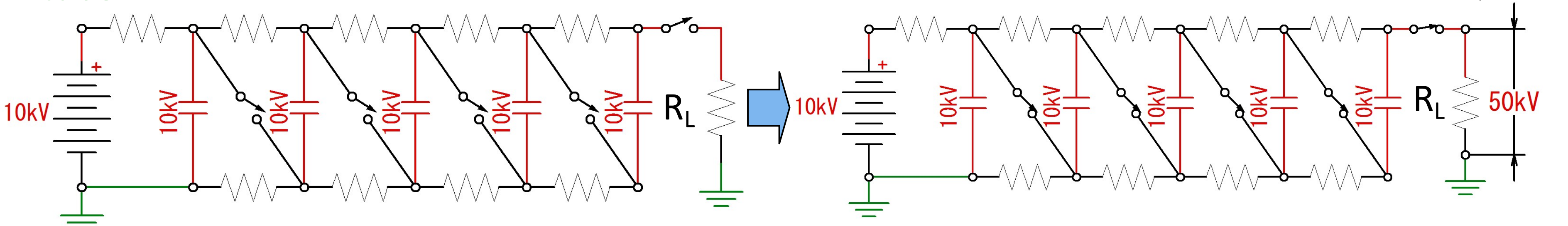


SPECIFIC GRAVITY: 8.9 [Ton/m^3]
SPECIFIC HEAT: 0.09 [kcal/kg]
MELTING TEMP.: 1084 [°C]
WEIGHT: 0.017 [g]

Principle of Marx circuit: Parallel charge ➡ Series output

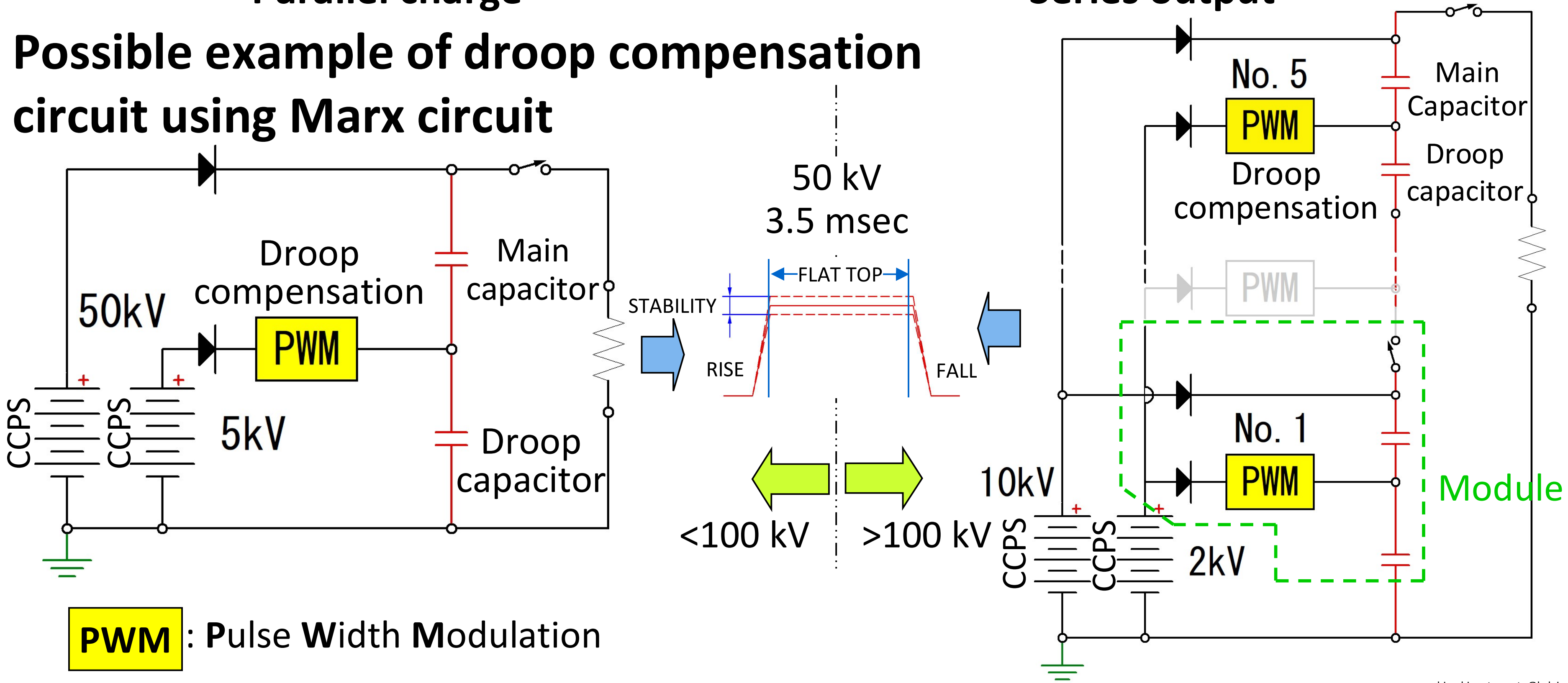
Marx circuit was originally developed to provide high voltage with short pulse using hard switch tube.

Output voltage droop: $V_{CHARGE} \times \exp\left(-t/_{CR}\right)$



Parallel charge **Series output**

Possible example of droop compensation circuit using Marx circuit



PWM: **P**ulse **W**idth **M**odulation

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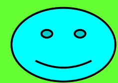
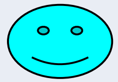
ADAPTABLE APPLICATIONS FOR TWO TYPE OF MARX POWER SUPPLY

MODULATOR TYPE	MAJOR SPECIFICATION	iBNCT	OIST	ILC
	OUTPUT VOLTAGE [kV]:	-90	-34	**-120**
	OUTPUT CURRENT [A]:	30	37	140
	VOLTAGE STABILITY [ppm]:	±<1e3	±<500	±<1e4
	PULES WIDTH [msec]:	1.0	1.0	1.65
	REP. RATE [pps]:	**200**	**200**	5 (10)
	AVERAGE POWER [kW]:	**540**	300	139 (277)
	SHORT CIRCUIT ENERGY [J]:	<20	<20	<20
MAIN ENERGY BANK + CONST-CHARGE DROOP COMPENSATOR				 1,3)
MAIN ENERGY BANK + CONST-CHARGE DROOP COMPENSATOR				 1)
MARX (MAIN + FINE)		 2)	 2)	 1)

Practical level (iBNCT) — Under development (OIST, ILC)

NOTE:

1) Not easy to provide charging voltage of -120 kV from CCPS.
2) IGBT switching loss is very large at 200 pps of rep. rate.
3) There are many number of circuit elements.

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2. CURRENT PERFORMANCES OF MODULATOR

- PAL-XFEL@PAL
- SACLA@SPring-8
- BNCT@Tsukuba Univ.

SHORT PULSE MODULATOR STABILITY TEST RESULTS

by POSCO ICT (DONG-A HI-TECH STAFF), Matsumoto.
Discussion with Lee-san, Son-san, Jang-san and Kim-san.

No thyratron work

CONTENT	PAL-XFEL		(Vk & Ik)/CCPS	SACLA		(Vk & Ik)/CCPS
Digital scope	Tektro (1st)	Tektro (2nd)		Tektro	Lecroy	
CCPS VOLTAGE (STD) [ppm]:	8 @100KHz	8 @100KHz		8 @100KHz	12 @100KHz	
GND fluctuation for CCPS [ppm]:	5 @100KHz	6 @100KHz		8 @100KHz	8 @100KHz	
Beam voltage Vk (STD) [ppm]:	31 @100KHz	27 @1MHz	3.9 (1st), 3.4 (2nd)	24 @1MHz	32 @1MHz	3 and 2.7
GND fluctuation for Vk [ppm]:	28 @100KHz	19 @1MHz		16 @1MHz	26 @1MHz	
Beam current Ik (STD) [ppm]:	not measure	49 @1MHz (41)	6 (2nd), 5 (cal.)	25 @1MHz	32 @1MHz	3.1 and 2.7
GND fluctuation for Ik [ppm]:	not measure	38 @1MHz (29)		18 @1MHz	32 @1MHz	

Four CCPS (each 30 kJ) operate in parallel. **Single CCPS (35 kJ) operate.**

( ): calculated value of stability for Ik using eq. 1.

MEASUREMENT CONDITIONS

- PAL-XFEL and SACLA@SP8 use same configuration as shown in Fig. 1.
- GND fluctuation measured before start charging of CCPS and before tur on Thyratron at PAL-XFEL and SACLA@SP8.
- PFN charging voltage: 42 kV (44 kV for 5% positive mismatched conditior at PAL-XFEL and 48 kV (nominal) at SACLA@SP8.
- Measurement time: 3 min. at PAL-XFEL and 2 min. at SACLA@SP8.

COMMENTS:

- A stability of Ik is worth than Vk, because of as following relation;

$$Ik = \mu P \times V_k^{1.5} \propto V_k^{1.5} \qquad (1)$$

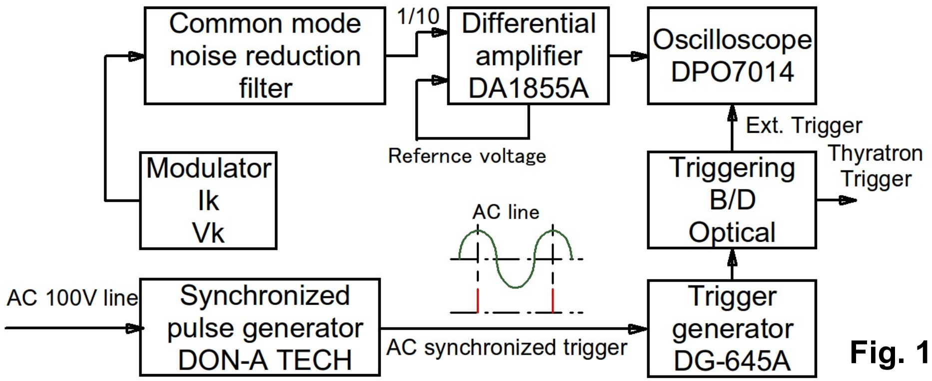


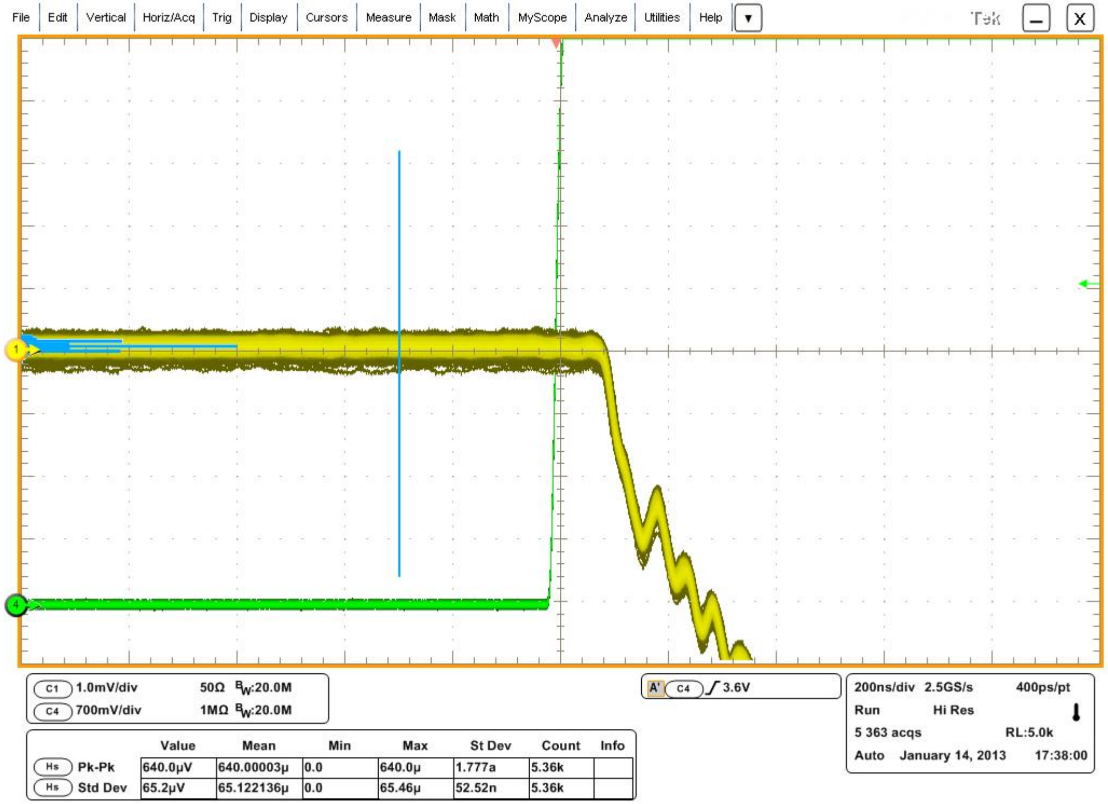
Fig. 1

- ATF modulator provide an acceptance level (50 ppm) for PAL-XFEL at PFN voltage of 42 kV. Need a long run operation at 44 kV (5% positive mismatched condition).
- A measurement equipment of ATF modulator will better to more improve such as the cable length (shorter is better) and also cable quality to provide the EMI shield.
- A current return circuit between thyratron and plus transformer will be improved such use as new plus transformer deigned by Jang-san.
- From experimental result at SACLA, EMI noise resistance of Lecroy digital scope worse than Tektro. (commented by Dr. Inagaki of SACLA)

Stability Measurement of PFN Voltage(Vpfn)

By POSCO ICT/PAL-XFEL

➢ **Stability Measurement of Beam Current(Synchronized)**



PFN Voltage : 42 [kV]

Persistence time : 3 [min]

Repetition Rate : 60 [Hz]

Trigger Thyratron : Synchronized

DA1855A : 23.39 [V]

Standard deviation : 65.2 [μV]

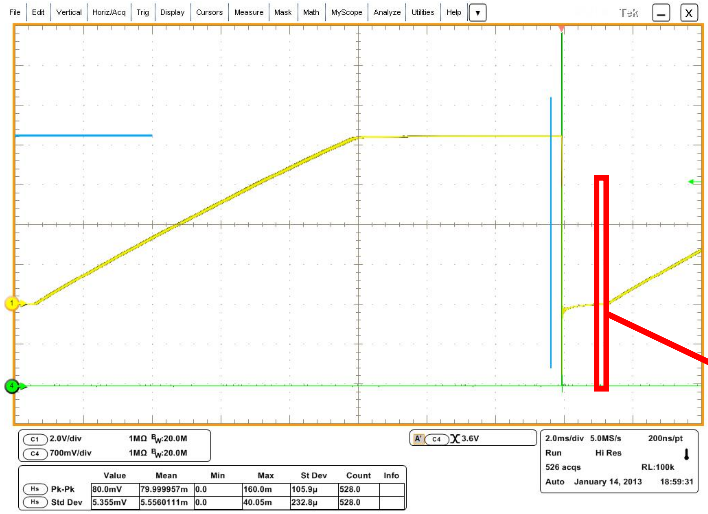
Peak Voltage : 0.64 [mV]

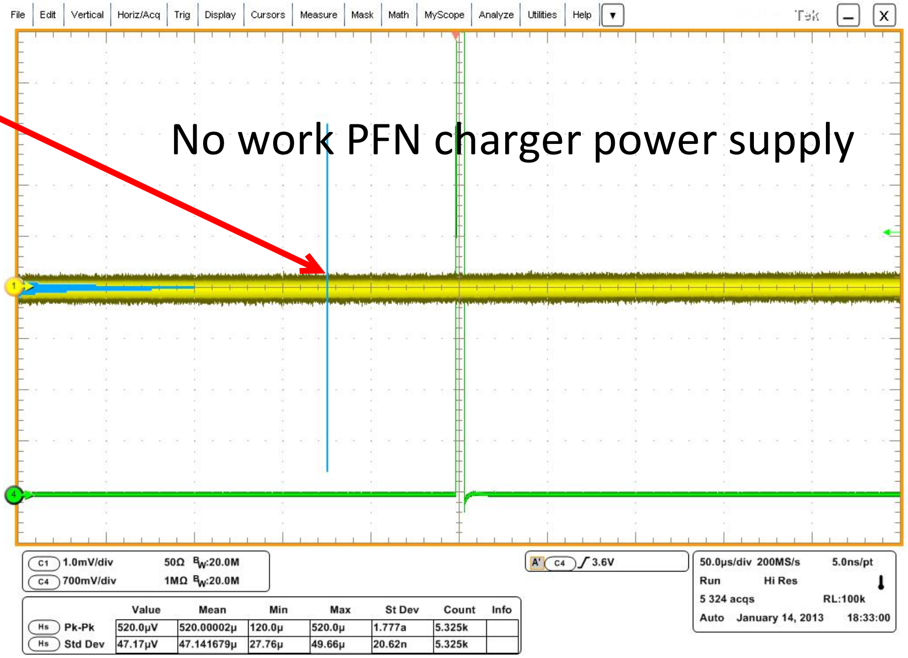
Output Stability :

65.2/8.4004 = 7.76 [ppm]

Noise Measurement of PFN Voltage

By POSCO ICT & PAL-XFEL



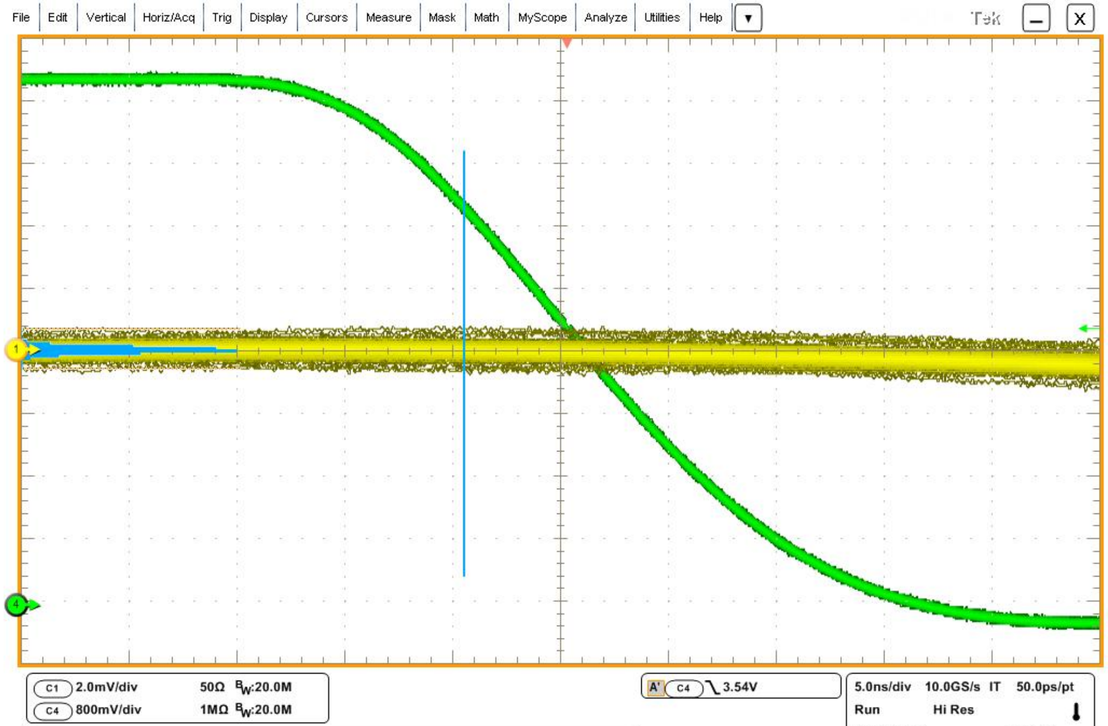


- **PFN Voltage : 42 [kV]**
- **Repetition Rate : 60 [Hz]**
- ***Standard deviation* : 47.17 [µV]**
- **PFN Voltage Noise : 5.62[ppm]**

Stability Measurement of Beam Voltage(Vk)

By POSCO ICT/PAL-XFEL

➢ **Stability Measurement of PFN Voltage(Synchronized)**



	Value	Mean	Min	Max	St Dev	Count	Info
Hs Std Dev	112.1μV	112.1812μ	0.0	134.3μ	131.0n	2.323k	
Hs Pk-Pk*	1.28mV	1.2800001m	0.0	1.28m	54.22a	2.323k	

PFN Voltage **: 42 [kV]**

Persistence time : 3 [min]

Repetition Rate **: 60 [Hz]**

Trigger Thyratron **: Synchronized**

DA1855A **: 42.056 [V]**

Standard deviation **: 112.1[μV]**

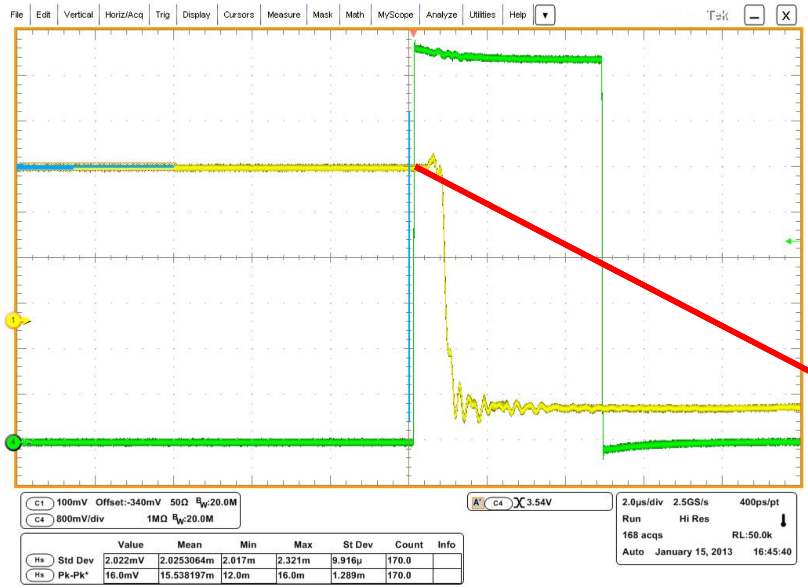
Peak Voltage : 1.2[mV]

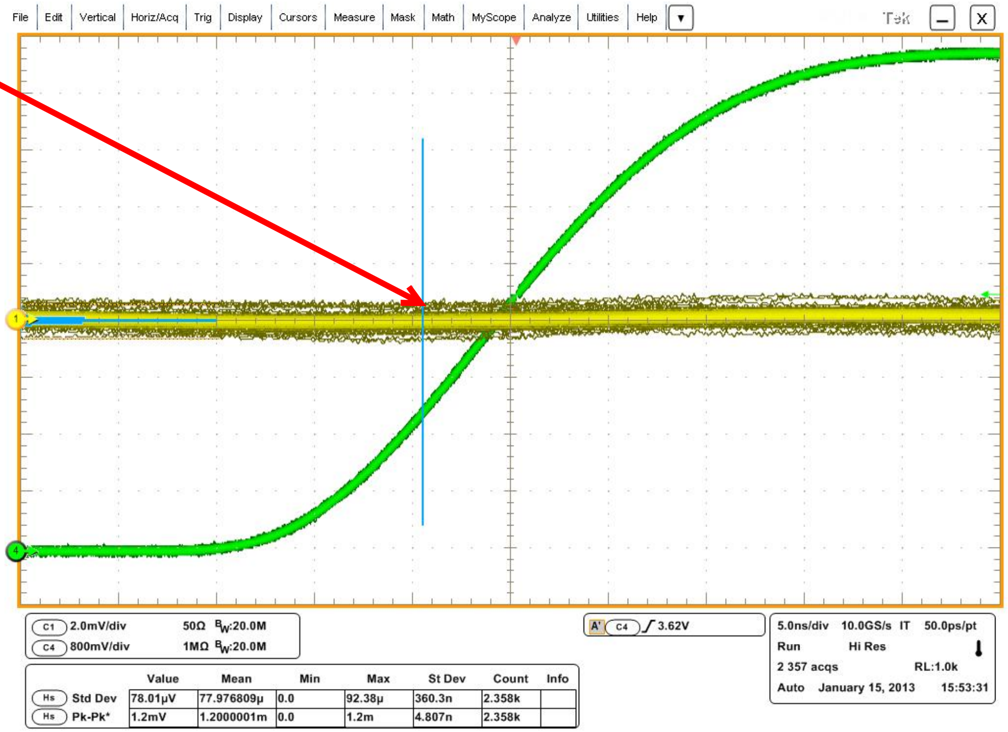
Output Stability **:**

112.1/42.056 = 26.7 [ppm]

Noise Measurement of Beam Voltage

By POSCO ICT/PAL-XFEL

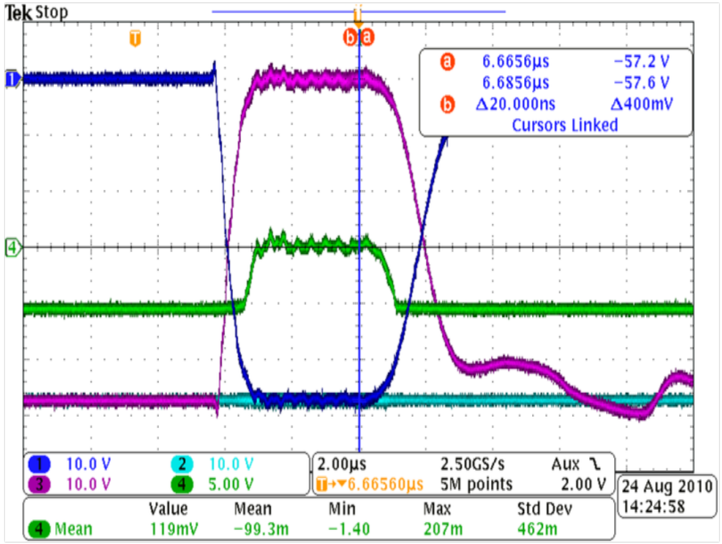


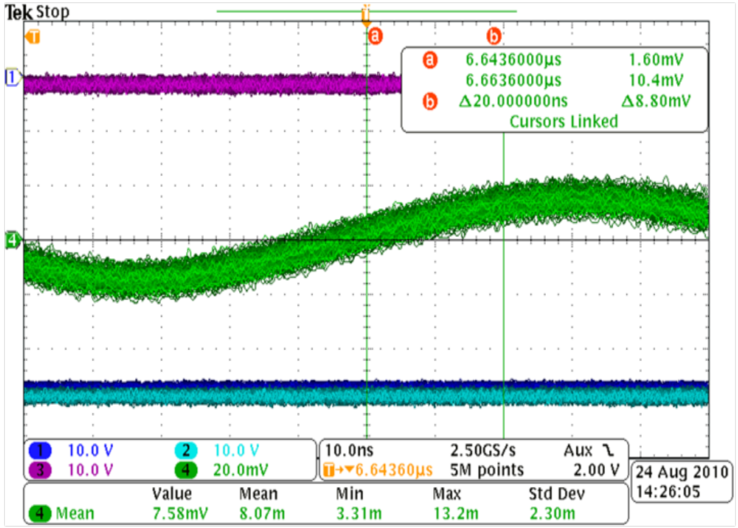


- **PFN Voltage : 42 [kV]**
- **Repetition Rate : 60 [Hz]**
- ***Standard deviation* : 78.01 [µV]**
- **PFN Voltage Noise : 18.5 [ppm]**

Pulse Stability Measurement Example

By Chaofeng Huang @SLAC

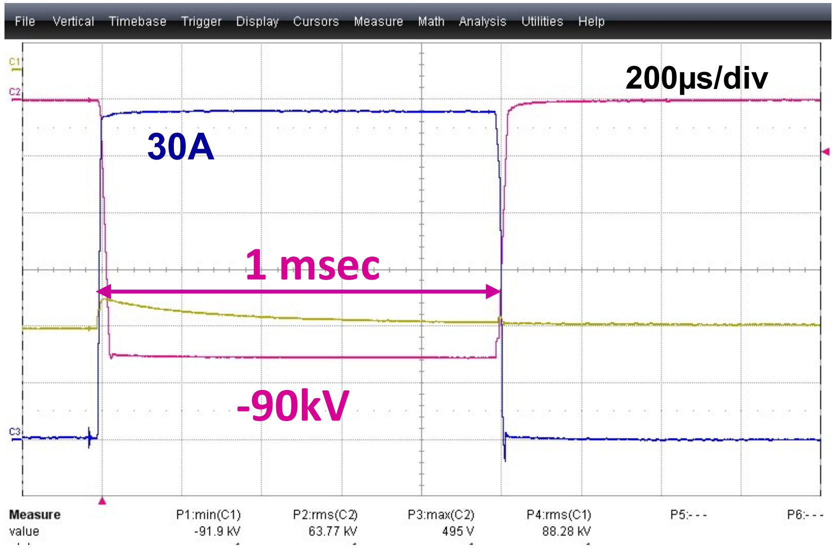


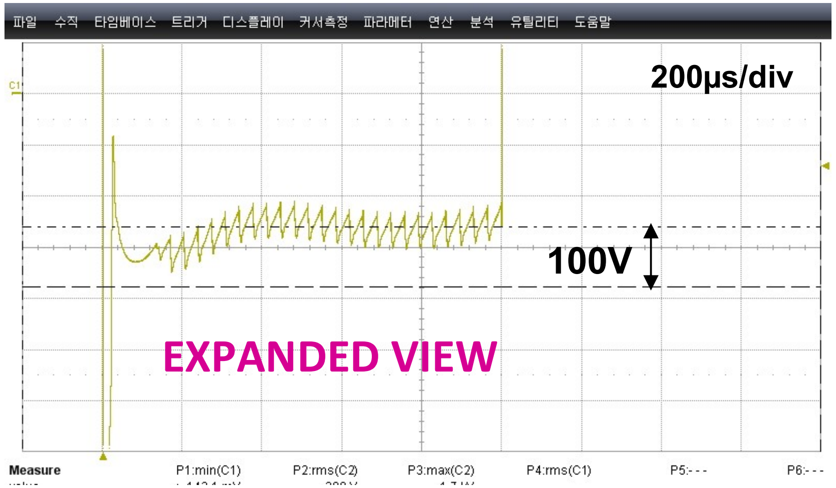


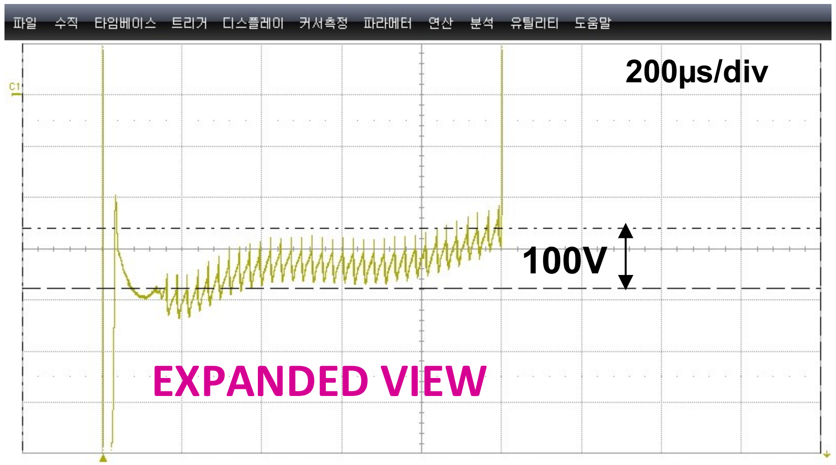
Ch1---Linac PFN modulator 28-2 Klystron negative pulse, which is about 57.4V between cursor a and b
Ch2---Offset voltage
Ch3---Differential signal
Ch4---Output signal

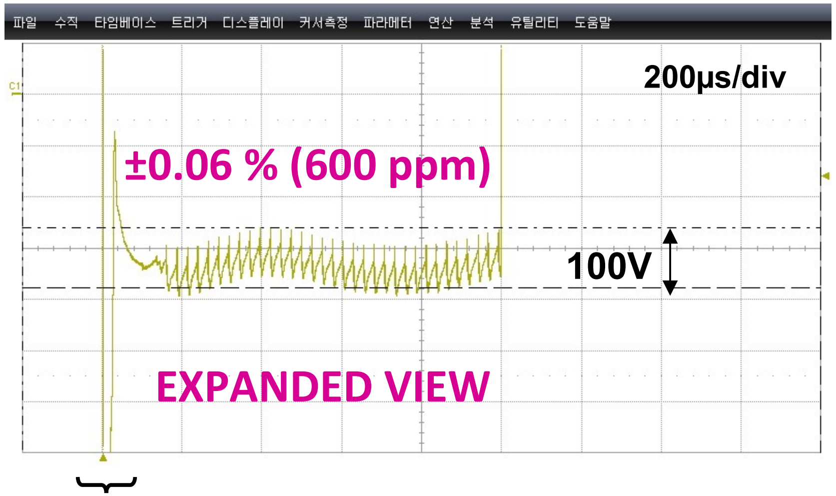
Modulator 28-2 running at 60Hz. 1000 sample wave-forms
The pulse stability is about **40.1ppm** (2.30mV/57.4V)

OUTPUT PULSE WAVEFORM ADJUSTMENT FOR iBNCT@TSUKUBA UNIV.





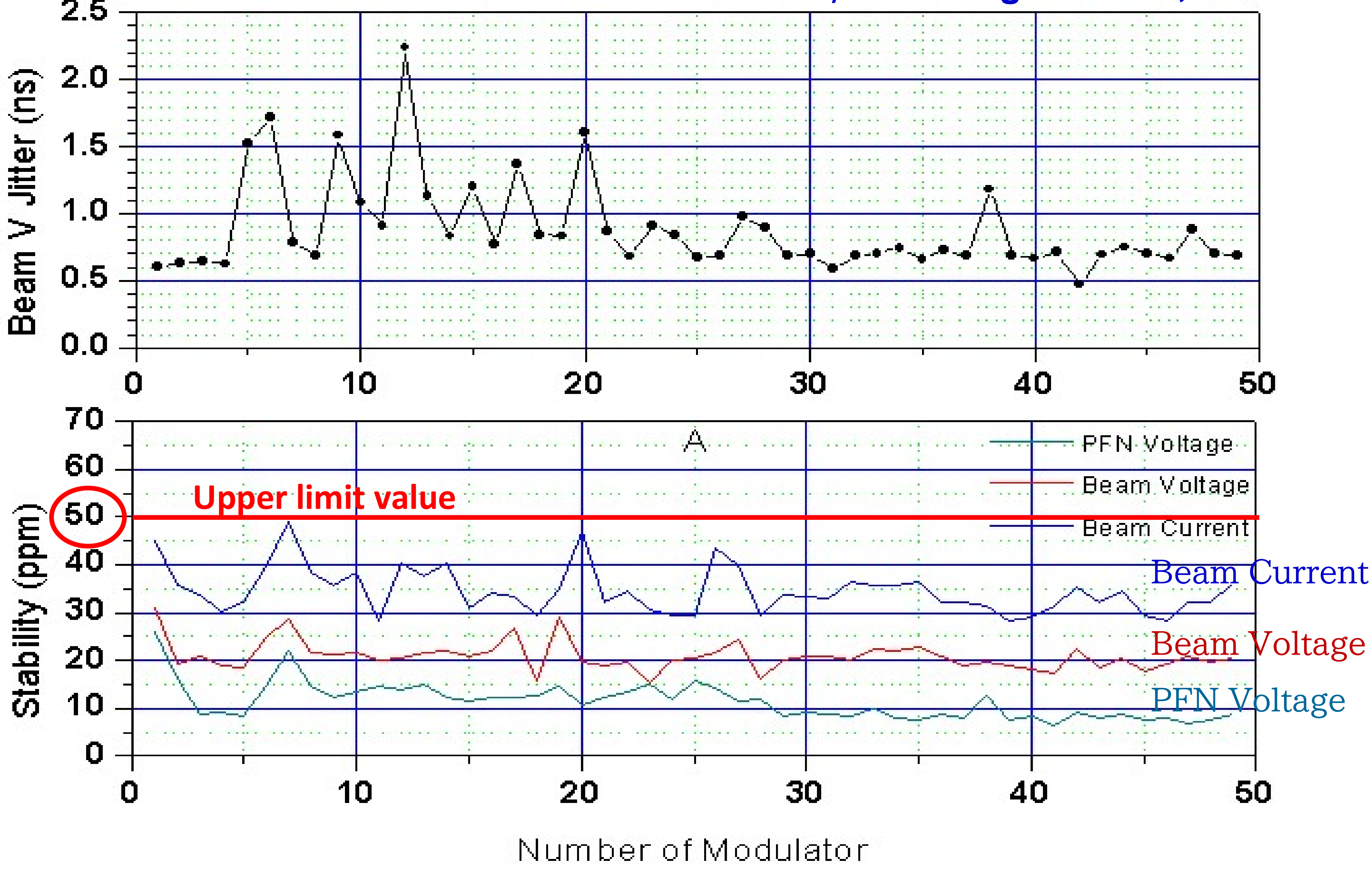




Fake signal due to monitor sircuit.

Stability Measurement

By **Dr. Heung-Soo Lee, PAL-XFEL**



3. FOR FUTURE PERFORMANCE IMPROVEMENT

- THYRATRON TUBE IMPROVEMENT.
- USE SOLID STATE SWITCHING DEVISE.

by Dr. Jong-Seok Oh, NFRI

Potential of existing thyratron tubes

Wagner Model CH1191; 1600 tubes for 10 years since 1964
This data analysis includes only 35% tubes since 1985.
1964-1984 : 46 kV, 4.2 kA, 3.8 us, 360 pps → 5.7 A
1985-1994 : 46 kV, 6.3 kA, 5.4 us, 120 pps → 4.1 A

20 tubes are still active in 1994 with ages between 75 ~ 120 kHours!

Wide distribution of age and lifetime profile. The quality does not reach the industrial products.

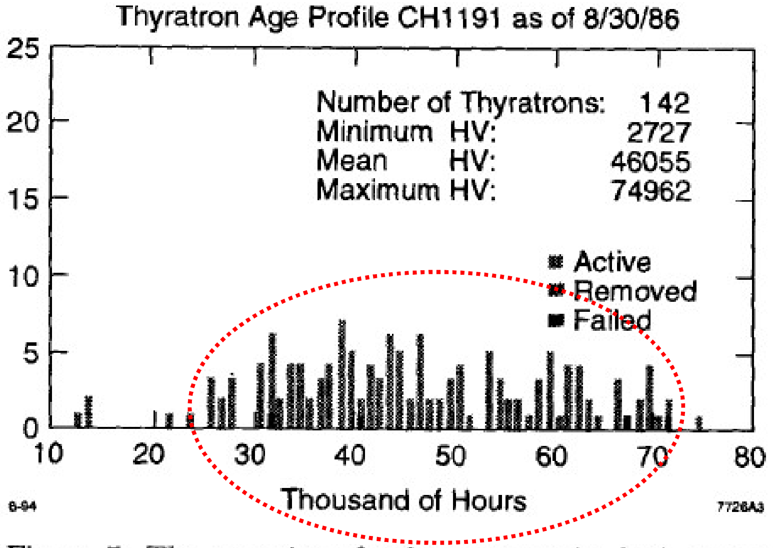


Figure 7. The quantity of tubes versus the high-voltage running-time hours.

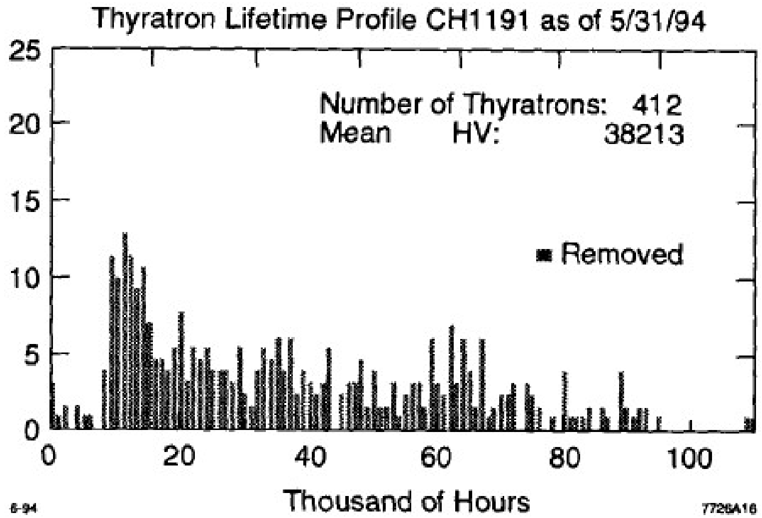
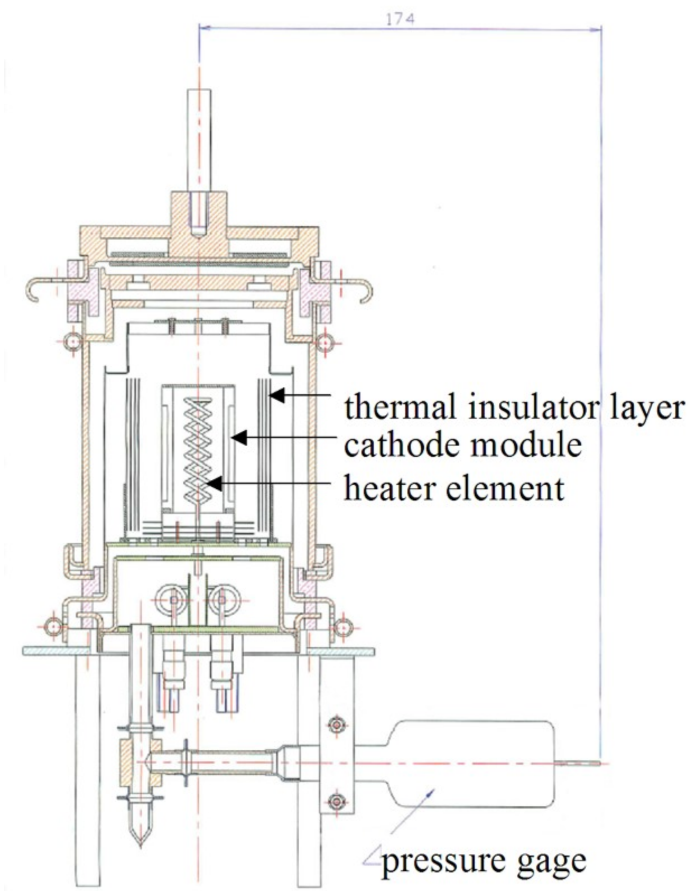


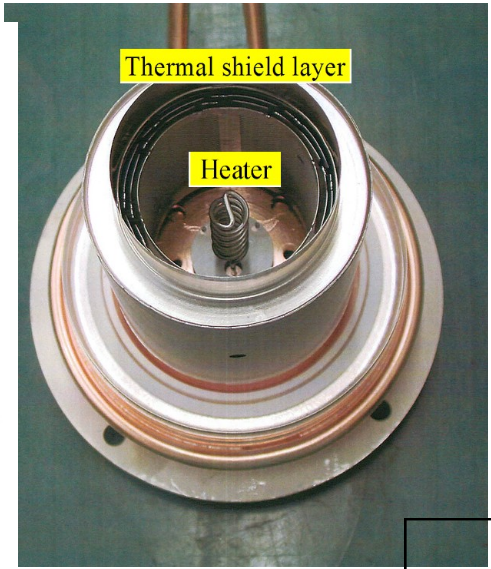
Figure 8. The quantity of tubes versus the high-voltage running-time hours at the time of removal from the linac modulator.

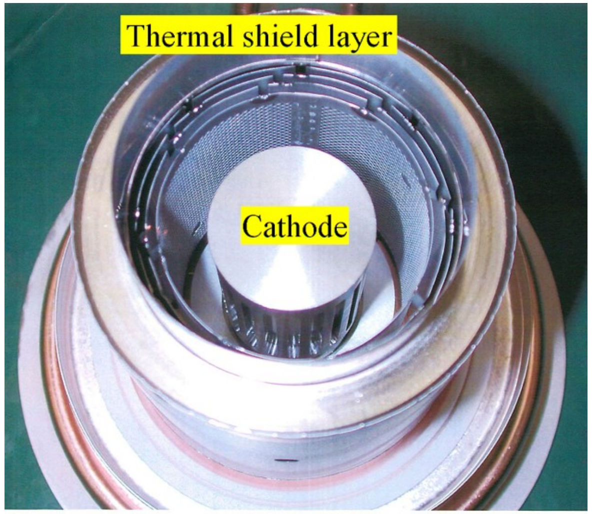
Reference : David B. Ficklin Jr., A History of Thyratron Lifetimes at the Stanford Linear Accelerator Center, SLAC-PUB-6543, December 1994

NEW THYRATRON DEVELOPMENT

Many thyratrons die due to several common causes coming from the circuits used and operational environments rather than any intrinsic problems with the **device itself**. Many of the cause depends on the poor mechanical structure. So, we collaborated with TOSHIBA to develop the new thyratron tube, which **mechanical structure has same concept as klystron tube** as can be seen in Figure. (Proceedings of LINAC 2006, Knoxville, Tennessee USA, "R&D OF THE LONG-LIFE THYRATRON-TUBE", H. Matsumoto, J. S. Oh and W. Namkung



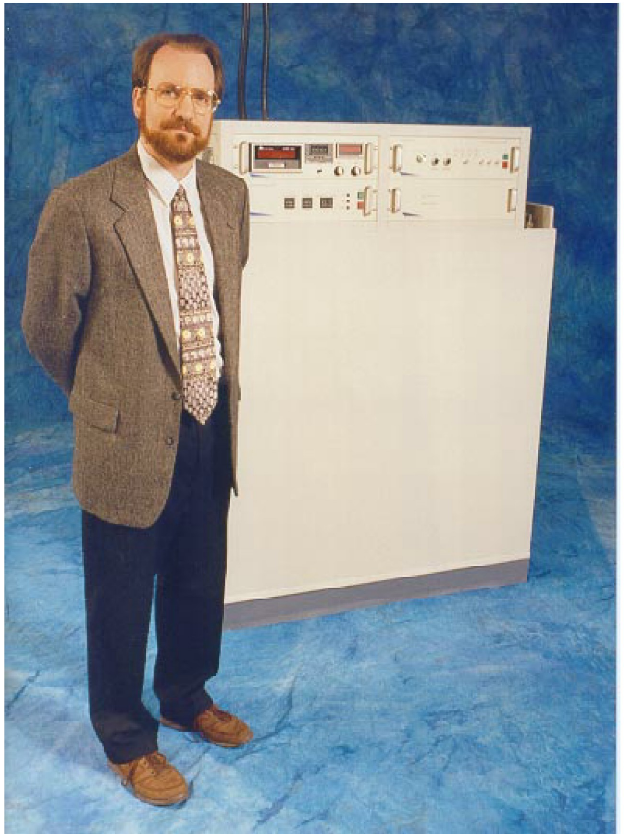




Ongoing operation from 2006 at TOSHIBA

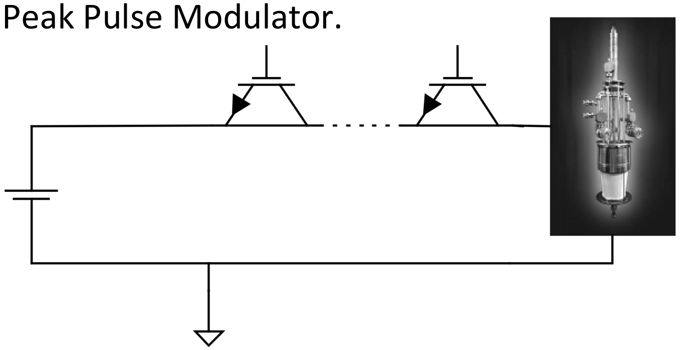
Item	Parameters
Anode voltage (kV):	24.0
Heater current (A):	65.5
Reservoir voltage (V):	3.1
Reservoir current (A):	6.7
Repetition rate (pps):	50
Operation load resistor (W): load capacitor (nF):	24.0 9.35

USE SOLID STATE SWITCHING DEVISE

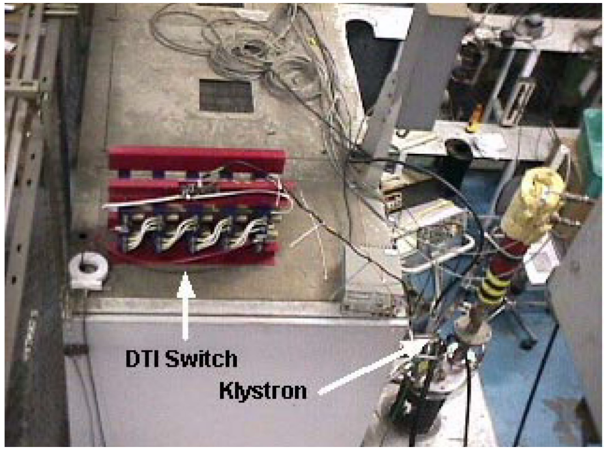


DTI's HVPM 100-500 100 kV, 50 MW Peak Pulse Modulator.

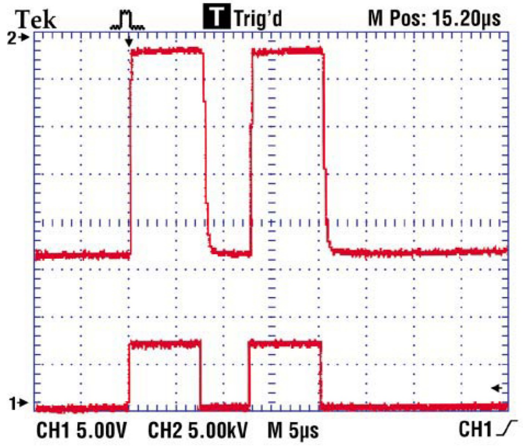
The next generation of linear colliders will require an order of magnitude leap in pulsed power to millions of volts at thousands of amperes, delivered at much higher efficiency than is presently available. The current technology base of thyratrons, PFNs, etc., is inherently limited in scaling to meet these new requirements. Diversified Technologies, Inc. (DTI), has had tremendous success since 1993 in the application of high voltage IGBT devices to large, high-voltage and high-current modulator systems. DTI has sold commercial solid-state modulators capable of 20 to 160 kV and 150 to 2000 A for customer applications ranging from RF tube testing to ion-implantation. This technology is rapidly becoming the preferred alternative to conventional vacuum tube modulators and switches for future accelerator designs. (Proceedings of the 1999 Particle Accelerator Conference, New York, 1999)



Cathode Modulator / Crowbar Replacement.



45 kV, 30 a DTI Solid State Switch with Klystron at SLAC.



SLAC Prototype 45 kV, 30 A Switch Result @ 22 kV, 80 a Into Resistive Load.

USE SOLID STATE SWITCHING DEVISE

ScandiNova

K2-4 FOR S-BAND AT 80 MW-LEVEL, 400kV / 500A / 4,5μs / 60 Hz

PAL 포항가속기연구소 Pohang Accelerator Laboratory

K2-4 FOR POHANG ACCELEATOR LAB, KOREA

KLYSTRON VOLTAGE AT 400kV, 4.5us

SUMMARY

1. Stability and its timing jitter of the klystron beam voltage was achieved smaller than **50-ppm** and **5-nsec**.

2. However, an EMI leak will be limit the performance improvement. We should study the EMI leak from the modulator.

3. Thyratron tube has potential for the long life time such as **75 ~ 120 kHours.** However, it has wide distribution of age and lifetime profile. The quality does not reach the industrial products.

4. A new concept thyratron tube, which has same mechanical concept as klystron show the good performances since 2006.

5. Performance and availability of solid state modulator is practical level. However, cost seems expensive than the existing modulator using thyratron tube.

Both of the thyratron tube and the solid-state modulators will be needed, is my personal opinion.