

OPERATIONAL EXPERIENCE WITH A KLYSTRON 50KV/30KW INVERTER POWER SUPPLY

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Abstract

We have developed an inverter type high-voltage power supply for an oil-filled klystron modulator [1][2]. The power module produces 38-kJ/sec peak and 30 kJ/sec average power at a 50-kV output voltage. It drives a 1:16 step-up transformer to deliver -350 kV to a 50-MW C-band (5712-MHz) klystron. We obtained an output voltage regulation of around 0.34% (3σ) at 50-kV. So far our experience with the inverter power supply has shown probable adequate long run reliability.

1 INTRODUCTION

X-ray free electron laser (XFEL) based next generation light sources are now coming on-line around the world. In Japan, SPring-8 has such a single-pass XFEL project, the SPring-8 Compact SASE Source (SCSS) [3]. The first project goal will be to generate 60-nm FEL from a 250-MeV energy beam to demonstrate realistic operation by November 2005 [1]. Fig. 1 sketches the layout.

For the SCSS project, the following three key technologies contribute to the overall machine compactness: (1) A high gradient C-band accelerator. The accelerating gradient can be as high as 40-MV/m, thus an accelerator only 10-m long, including Q-magnets and monitors, is enough to reach 250-MeV. (2) An in-vacuum undulator, which enables creating a shorter period undulator. Therefore the required beam energy is lower, again reducing the accelerator size. This also contributes to shortening the FEL gain length. (3) A low emittance beam injector. On the down side, the short undulator period does require a low emittance electron beam.

In view of this, we made a somewhat unconventional choice, a HV (500-kV) pulse DC gun using a single crystal CeB₆ thermionic cathode. This has the potential of generating a very small emittance beam while providing for a long lifetime.

To saturate the FEL lasing in the 9-m long undulator line, a low emittance beam current with peaks as great as

1-kA is required. This high peak current is generated by first compressing the bunch length in the injector and then further by a magnetic-chicane bunch compressor.

The first inverter power supply prototype was delivered in March of 2003 by TOSHIBA Electro-wave Products Co. Ltd, and two more power supplies were delivered in March of 2005 by the NICHICON Corporation.

In this paper, we report on our operational experiences with these high voltage inverter power supplies.

2 CONCEPT

In general, high power klystron modulators, such as those of the common 100-MW peak, 30-kW average power class suffer from many diverse and troublesome problems. Often they are unreliable; produce large electromagnetic noise emissions; are bulky in size as well as being the most expensive component in the accelerator system. The obvious reason being that they typically use many high voltage, high power components (such as the thyatron, high voltage diodes, etc.); and because after all functionally they must generate pulsed high voltages at high currents, stressing all the components. Thus, in spite of the obvious need for improvement, in Japan modulator power supplies have not changed in many years.

2.1 Advantages of the Inverter Power Supply

For the SCSS, "compactness" and "modularity" are among the key design principles. We will use on the order of 60 to 80 klystrons and associated power modulators for the 8-GeV X-FEL main project. Hence the need for unit "compactness" and "modularity" in order to reduce the cost and to keep the system simple. The concepts and technologies that come out of the R&D for SCSS will be transferable not only to large scale accelerators but also to many other potential compact accelerators; we would expect to find applications to industrial, medical and tabletop-size accelerators.

The physical size of the first prototype modulator from TOSHIBA was only 48-cm wide, 42.4-cm high and 68-cm deep. It generates a maximum output voltage of 50-kV and an average power of 30-kJoule/sec; this can drive a 50-MW class klystron at up to a 60-pps repetition rate.

The benefits of the inverter type power supply are;

- (1) Compact in size,
- (2) Minimal and extremely low stored energy. When there is a high-voltage breakdown in the

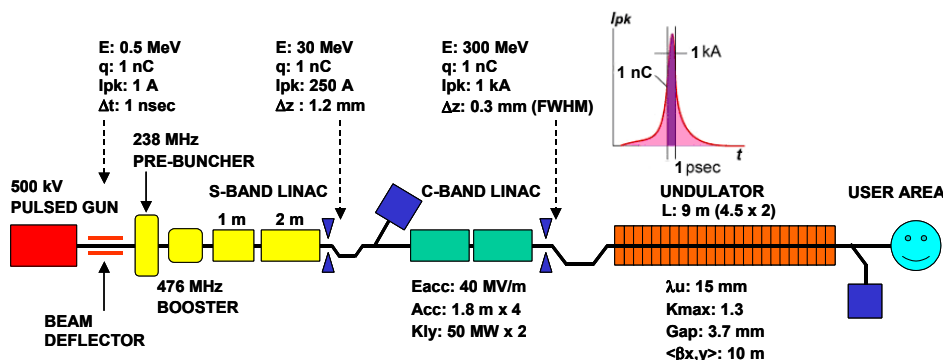


Figure 1: Beam line layout in SCSS for 250 MeV.

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klystron or the thyatron, the energy available for dissipation in the output section of the inverter power supply is limited and thus is less likely to cause circuit component destruction. The estimated stored energy per charging bucket is on the order of 0.2% of the peak PFN stored energy (438 Joule). This should help extend the thyatron lifetime as compared with the usual circuit operation.

- (3) Fully controlled output voltage. An inefficient de'Q-ing circuit is not necessary.
- (4) Fully internal interlocking. This simplifies the overall modulator interlock circuitry, and reduces the labour and expense of assembling and wiring.
- (5) Easy and flexible interface to computer control and communications with the accelerator upper levels.

2.2 Performance Target

From the analysis of SASE-FEL theory, we know that FEL amplification is very sensitive to the electron energy in the undulator. Therefore, pulse-to-pulse stability of the beam acceleration is important. To provide enough rf power and phase stability in the linac, the cathode beam voltage of the klystron should be stable to within $\pm 0.5\%$ of the -350-kV klystron cathode operating voltage. To achieve this we have been developing and improving inverter high-voltage power supplies since the beginning of the SCSS project [3]. The major target performances are summarized in Table 1.

Table 1: Target performance of the inverter power supply

Output voltage range	0 - 50 kV
Average current:	1.5 A
Charge rate	average: >30 kJ/sec
	peak: >37.5 kJ/sec
Output voltage regulation (p-p):	<0.2 %
	<0.04 ¹⁾ %
Power factor at full load:	>85 %
Power efficiency at full load:	>85 %

Note: 1) one NICHICON inverter power supply aimed to realize a voltage regulation of $<\pm 0.02\%$ for the electron gun modulator, which is particularly critical.

3 OPERATIONAL RESULTS

3.1 Overall Performance

Three inverter high voltage power supplies were tested with same modulator and load; a C-band klystron in diode mode (ie. no rf output power) as shown in Fig 2 [1]. A circuit diagram of the experiment is shown in Fig3.

All three drove the C-band klystron cathode up to -350-kV, two at a 60-pps repetition rate, while one of the two NICHICON inverter power supplies was limited to 10-pps [4]. The reason for this limitation was circuit changes that attempted to increase the voltage regulation to better than $\pm 0.02\%$ at 50-kV of the output voltage. This particular inverter will be used for the 500-kV pulsed DC electron GUN. We obtained a flatness of within the design spec of $\pm 0.5\%$ over the full 2.5- μ sec pulse width at klystron cathode voltage of -350-kV from all the inverter power supplies. This is adequate for the SCSS first step C-band rf system. A Fig. 4 and 5 shows typical waveforms (voltages and current) for the inverter power

supply and klystron cathode each using the same modulator.

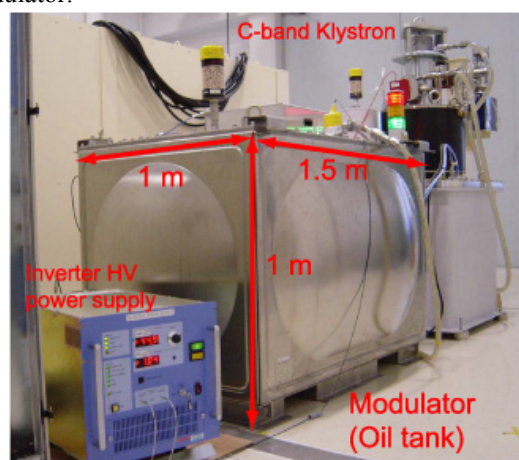


Figure 2. This photograph shows a set of high power rf source for the main linac; an inverter-type high voltage power supply (TOSHIBA, left), the modulator (NICHICON, middle), and the 50-MW C-band klystron (TOSHIBA, right).

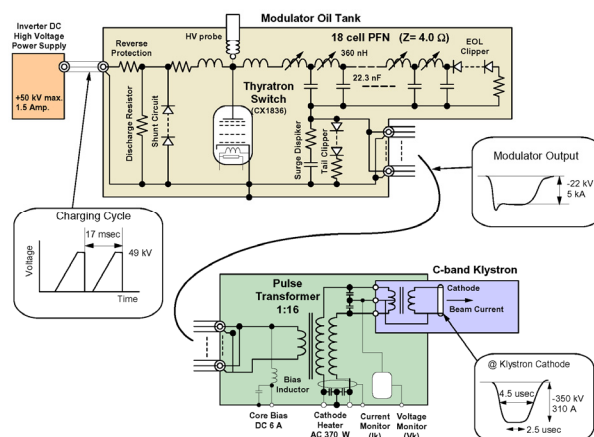


Figure 3. Circuit diagram of the modulator, the pulse transformer and the C-band klystron. In the actual implementation, we use 4 parallel HV coaxial cables for the klystron.

3.2 Voltage Regulation

To measure the voltage regulation, we used a Tektronix AD845 to make histograms of the acquired data, focusing on a narrow window to observe timing jitter and amplitude variations. An example is shown in Fig. 6. Each measured data set accumulated 10^4 shots and the histogram indicates the 3σ limits for the voltage regulation. The usual storage type scope does not show the histogram of the measured data with the 3σ range marked, they only show the visible accumulated trace lines.

We used following simple statistical numerical formula to eliminate (or separate) the background noise from the measured data.

$$D_{sta} = [\sqrt{\{(D_{measure})^2 - (D_{noise})^2\}}] \times 6/D_{mean}$$

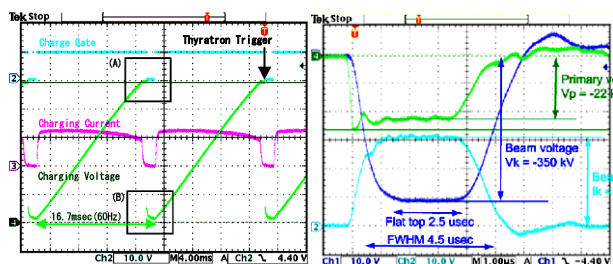


Figure 4: Typical waveforms of the TOSHIBA inverter power supply at 60-pps (left), and klystron (right).

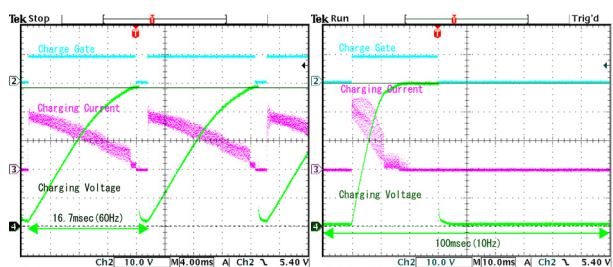


Figure 5: Typical waveforms of a NICHICON inverter power supply (No. 1, left), and klystron (No. 2, right). The second inverter power supply need 30-msec to 50-kV of an output voltage with klystron modulator.

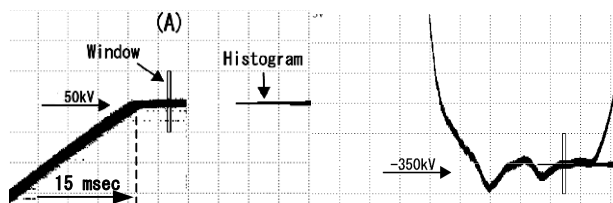


Figure 6: Typical waveforms of the voltage variations TOSHIBA inverter power supply (left), and klystron (right).

Here D_{sta} is calculated variation data at 3σ , D_{meaur} is rms measured data, D_{noise} is the noise level rms while there was no output voltage from the inverter power supply, and finally D_{mean} is an average of the absolute value of the output voltage over 10^4 shots. The acquisition regions for both output voltage and noise data were purposely limited to the narrow horizontal window as shown in Fig 7. As can be seen from this Figure, the noise level was found to be around 28.5-mV in window-B (zero output voltage from the inverter power supply). Figures 8 and 9 show the histograms of the output voltage variations at 50-kV for NICHICON inverter supplies and klystron cathode.

Our results for the 3σ voltage variation measurements of three-inverter power supplies were about 0.34% for the inverter output, and about 0.3% for the klystron cathode voltages, the details are summarized in Table 2.

Table 2: Voltage variations at 3σ for the inverter power supply and klystron.

Inverter model	Inverter	Klystron
TOSHIBA	0.31%	0.25%
NICHICON (No. 1)	0.34%	0.25%
NICHICON (No. 2) ¹⁾	0.38%	0.38%

NOTE: 1) operation at 10-pps.

From these experimental results, we found that limiting factor in the voltage regulation of the modulator was the stability achievable in the voltage regulation of the inverter power supply.

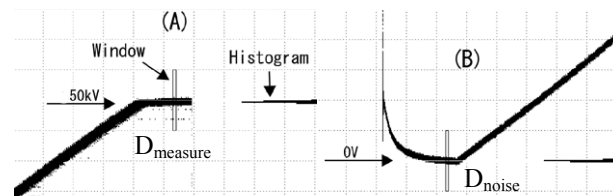


Figure 7: TOSHIBA inverter output voltage variation histogram at 50-kV (a), and zero output voltage from inverter power supply (b). In this case, the noise level is 28.5-mV.

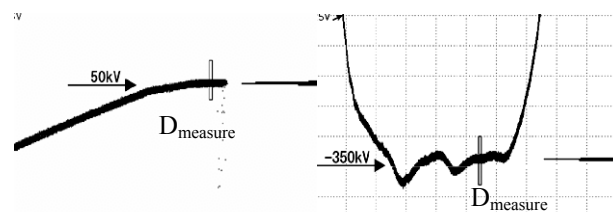


Figure 8: Voltage variation histogram for the NICHICON inverter power supply (No. 1) and the Klystron cathode.

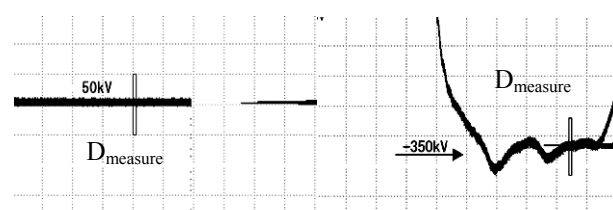


Figure 9: Voltage variation histogram for the NICHICON inverter power supply (No. 2) and the Klystron cathode.

4 SUMMARY

Tests on three prototype inverter power supplies shows good potential for output voltage stability and long-term reliability. All of three successfully drove the C-band 50-MW klystron through the oil-filled modulator. We will try to increase the voltage regulation to better than 0.1% at 3σ . We will try to install the inverter power supply in the same modulator tank at the 8-GeV main SSCS project.

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