EVALUATION OF PERFORMANCE, RELIABILITY, AND RISK FOR HIGH PEAK POWER RF SOURCES FROM S-BAND THROUGH X-BAND FOR ADVANCED ACCELERATOR APPLICATIONS*

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Abstract

Historically linear accelerator development and the choice of frequency have been driven by the availability of RF power sources. This is also true at the present time and is particularly significant as new accelerators are being conceived and planned over a wide frequency range for FEL light sources and other applications. This paper evaluates the current state of the technology for high peak power RF sources from S-band through X-band including reliability and the facility risk incurred for applications demanding high availability and decades-long operation.

INTRODUCTION

With the recognition of the scientific utility and practical applications of both coherent and incoherent x-ray and gamma-ray light sources and the successful operation of the LCLS at SLAC, there is burgeoning interest worldwide in the development of new accelerator based photon sources. The photon requirements and corresponding facility definition driven by the varied scientific needs and for specific applications such as materials assay using nuclear resonance fluorescence [1] encompass an enormous parameter space for the accelerator design. These parameters include, for example, accelerator gradient, physical length, RF power to beam conversion efficiency, number of electron bunches per macropulse, RF frequency, emittance, wakefield intensity, pulse repetition frequency, and structure filling time. The accelerator design and optimization and its dependence on these parameters and others, particularly the choice of RF frequency, is described in a recent paper by F. Wang [2]. Other factors that must be taken into consideration in the accelerator and facility design are the available physical space, cost, and reliability. Ultimately the choice of accelerator RF frequency becomes the key question. The answer is driven by both the above listed factors and the availability of reliable RF power sources, usually klystrons, at the frequencies of interest. Since the accelerator driven light sources now operating and under consideration include S, C, and X band frequencies, this paper evaluates the current state of the technology for high peak power RF sources from S-band through X-band for applications demanding high availability and decades-long operation.

S-BAND KLYSTRONS

Since the 1960s the evolving mission of the SLAC Two-Mile Accelerator has pushed the development of S-band (2.856 GHz) klystrons such that they now define the state of the art. The SLAC 5045 klystron has been the workhorse for the linac since the 1980's and continues to be so today, powering the LCLS which uses 1/3 of the linac and FACET which uses the remaining 2/3. The details of the 5045 development have been described elsewhere [3]. The 5045 operates at 65 MW peak power for 3.5 μs and an average power of 45 kW. The 5045 has been operated as high as 100 MW at pulse lengths shorter than 3.5 μs.

A total of 245 SLAC 5045s are required to power the SLAC linac and more than 800 of these tubes have been installed on the linac. This large number of tubes coupled with hard, 25+ year operation provide excellent accumulated running statistics for evaluating tube reliability. The detailed evaluation of the statistical data is presented at this conference and is briefly summarized below [4]. The 5045 run time statistics are shown below in Fig. 1.

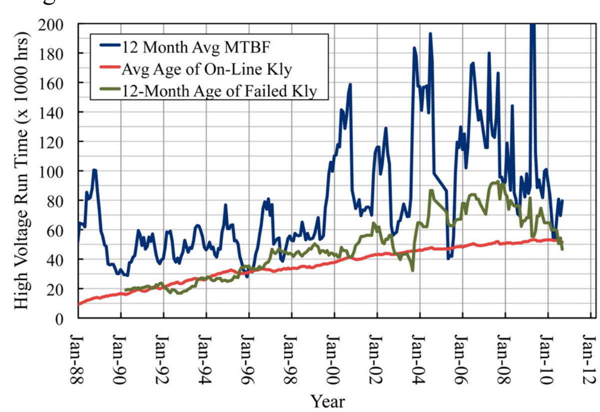

Figure 1: Run time statistics for the SLAC 5045 klystron.

Metrics relevant to the discussion of 5045 reliability include:

Average Age of On-Line Klystrons: total accumulated high voltage hours to date of the 245 currently installed 5045 klystrons divided by 245.

12 Month Age of Failed Klystrons: total accumulated high voltage hours for all 5045 klystrons failed during the previous 12 months divided by the number of failed klystrons during the same period.

12 Month Average MTBF: total high voltage 5045 klystron hours accumulated on all klystrons during the previous 12 months divided by the total number of failed klystrons during the same period.

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Cumulative MTBF: total accumulated high voltage hours on all klystrons since the beginning of time divided by (total number of failed klystrons since the beginning of time plus 50% of klystrons in evaluation at the data point date).

The *Average Age of On-Line Klystrons* in 2010 is 52,000 hours. Twenty-two klystrons have exceeded 100,000 hours and several have exceeded 140,000 hours. The *12 Month Age of Failed Klystrons* is around 65-70,000 hours. The *12 Month Average MTBF* now averages about 90,000 hours.

Fig. 2 plots the cumulative MTBF from 1984 through 2010, which is approaching 55,000 hours. Note that this plot includes the "learning curve" from the early days of 5045 production when performance problems were identified and engineering changes and production improvements were implemented.

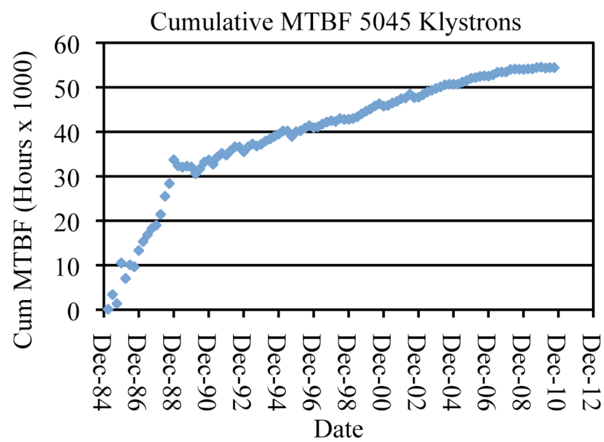

Figure 2: Cumulative MTBF for 5045 klystrons.

The most common failure modes are cracked or punctured vacuum windows and end-of -life cathodes that produce low emission, internal gun arcing, and gas bursts. [4]. A more robust window design could lead to increased 5045 lifetime in the future.

C-BAND KLYSTRONS

The SPring-8 Angstrom Compact Free Electron Laser (SACLA) in Japan has pioneered the use of C-band RF accelerator technology. The accelerator uses 66 C-band (5.712 GHz) Toshiba E37202 klystrons with the maximum and typical ratings reported by SACLA in Table 1.

Table 1: Toshiba E37202 Ratings

	Maximum	Typical @ SACLA
Peak Power	50 MW	30-40 MW
Beam Voltage	350 kV	300-330 kV
RF Pulse Width	2.5 µs	2.5 µs
Repetition Rate	60 pps	10-60 pps
Efficiency	44%	40%

SACLA has provided to the author all the C-band data reported in this paper on the performance of the 66 C-band klystrons [5]. High voltage operation began in Oct. 2010 and over a period of approximately 5 months one klystron out of 66 failed. The klystrons were operated for 3,000-4,000 hours at 10-60 pps.

The run time data are shown in Fig. 3 below. Two additional C–band klystrons (not shown below) have operated for 9,000 hours since 2005 in the 250 MeV test accelerator at 20-30 pps for about 8 hours per day at 20 MW and 40 MW. So far no problems or emission degradation have been observed.

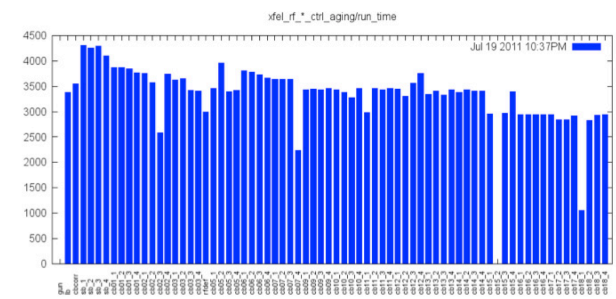

Figure 3: Run time hours for Toshiba E37202 klystrons. CB15-2 had a damaged pulse transformer and is not in use. CB18-1 failed after 1179 hours of operation.

The trip rate due to RF breakdown at the accelerator, klystron high voltage discharge, and thyratron discharge is about 2 per hour at 10 pps. The trips are distributed as follows: RF breakdowns 48%; klystron high voltage discharges 6%; and thyratron discharges 46%.

With the failed klystron, a scenario occurred where after several high voltage discharges, the vacuum pressure in the tube increased until finally the ion pump failed. The high voltage operating time was 1179 hours. The exact cause of the failure has not yet been investigated.

There have been some unexpected characteristics in the tube performance. Four klystrons out of 70 have discontinuities in the P_{drive} vs. P_{output} power curve. When the input power is less than 100 W the output power is unstable. Multipactor is suspected as a possible cause since the discontinuity appears at the same input power level. However since normal operation requires input power greater than 200 W this instability is not an issue.

Thirty klystrons out of 70 exhibit self-oscillation with no RF input drive at 230 kV. The oscillation occurs almost at the end of the 2.5 µs flat-top of the high voltage pulse. The oscillation appears to be above 10 GHz and couples power to both the input port and the output waveguide and has occasionally caused damage to low-level RF components. Increasing the focusing magnetic field suppresses the oscillation but causes a loss in output power. No oscillation is observed above 230 kV and since the typical operating voltage is 300-330 kV this is not a problem operationally. These abnormalities are under investigation to improve the reliability.

X-BAND KLYSTRONS

High power X-band klystrons were developed at SLAC during the late 1980's through the early 2000s as part the intensive R&D effort for an X-band linear collider. The evolution of the SLAC X-band klystron is nicely described by Vlieks [6]. The development program produced three distinct series of klystrons: the XC (100 MW), XL (50 MW), and the PPM (periodic permanent magnet focused, 75 MW). The XL 50 MW series has emerged as the tube of choice for advanced accelerator applications. The XL4 is used to power LCLS X-band structures for beam phase space linearization and transverse deflection and is the source under consideration for the 250 MeV X-band linac for Lawrence Livermore National Laboratory's MEGa-ray initiative. Two versions have been developed: the XL4 at 11.424 GHz and the XL5 at 12 GHz [7]. The XL performance parameters are shown in the table below.

Table 2: XL Klystron Parameters

Parameter	Maximum
Peak Power	50 MW
Beam Voltage	440 kV
Beam Current	350 A
RF Pulse Width	1.5 µs
Repetition Rate	60 Hz
Freq. XL4/XL5	11.424/12.0 GHz
Perveance	1.2 µP
Efficiency	40%
Focusing solenoid	4.7 kG/23 kW

Approximately thirty XL4 and XL5 klystrons have been produced. Most are employed as sources for driving accelerators, testing RF structures, and powering high gradient breakdown experiments. Several have logged more than 10,000 hours of operation, but mostly below 35 MW. The XL4 powering the LCLS linearizer has operated for 25,000 high voltage hours at 20-25 MW with 100 ns pulse length at 60 and 120 Hz PRF. A life test at full specifications on a new XL4 will commence shortly. After the new XL klystrons are high voltage and RF conditioned up to full operating voltage and power they are subjected to a 24 hour heat run during which time no RF or HV breakdowns are observed. At the present time because of the small number of tubes produced and the widely variable operating conditions, there are insufficient run time statistics to establish meaningful MTBF numbers. That said, the XL klystron appears to be a solid design with a growing track record. There is reason to believe that with increased operating experience and incremental improvements, the XL klystron will become more widely used in accelerator applications. There is currently an effort underway to transfer the design of the XL5 to industry for production. If the XL klystron is to be used in a facility requiring many tubes operating 24/7, one should consider developing a PPM or superconducting alternative to the 23 kW solenoid focusing magnet.

SUMMARY

The relative maturity and reliability of klystrons are indicated in the table below.

Table 3: Klystron Maturity

	S-Band SLAC 5045	C-Band Toshiba E37202	X-Band SLAC XL4/5
Peak Power max	65 MW	50MW	50 MW
# of tubes	> 800	68	30
Operating Hours	>25 x10^6	284,000	< 100,000 (estimated)
Reliability	>80,000 hr Average MTBF over 3 yrs	Insufficient operating experience for MTBF, but infant mortality is low.	Insufficient operating experience for MTBF calculation

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