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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Burgeoning Worldwide Interest in New Accelerator Based Photon Sources

- Coherent X-ray FELs
  - SLAC LCLS II
  - Los Alamos MaRIE 50 keV (concept)
    - Materials under dynamic loading and irradiation extremes at the microstructure scale
  - Pohang FEL
- Compton gamma-ray sources
  - Lawrence Livermore MEGa-ray at 250 MeV
    - Nuclear material detection
    - Material assay
- Medical imaging, security inspection, and nuclear material detection

Photon Requirements and Facility Definition Driven by Scientific Needs and Applications

- Large parameter space for accelerator design – beam parameters, physical size, efficiency, reliability, etc
- Ultimately choice of RF frequency becomes the key question
  - Availability of RF sources
  - System reliability
  - Cost
  - Available physical space
- S, C, and X-band klystrons are the sources under consideration

S-Band Klystrons Now Define the State of the Art for High Peak Power & Reliability

- SLAC 5045 Klystron
  - > 800 installed on SLAC linac since 1984
  - 2.856 GHz
  - 65 MW peak, 45 kW avg.
  - 350 kV beam voltage
  - 3.5 μs pulse width
  - 180 Hz PRF
  - 8 A/cm^2 cathode current density
  - 45% efficiency
  - > 80 ,000 hr MTBF
- 150 MW version built for DESY

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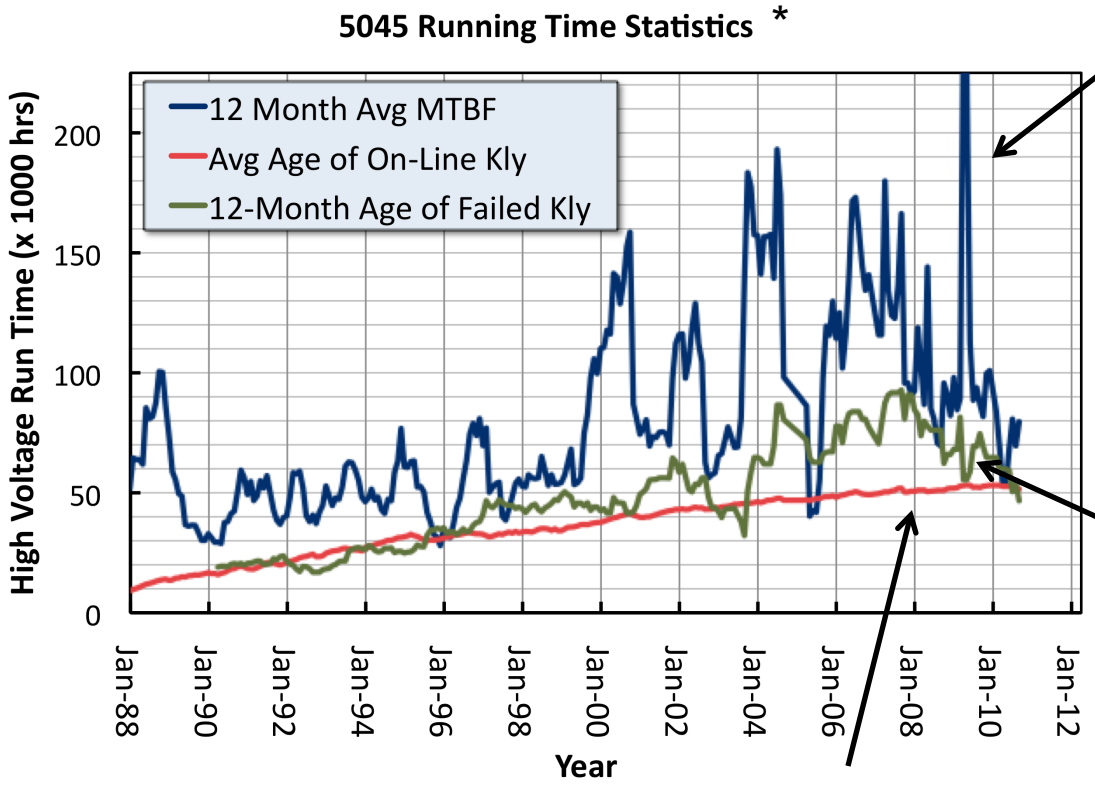
Large Number of Tubes (800) and Decades of Hard Operation Have Provided Excellent Statistics



12 Month Avg MTBF: total HV hours accumulated on all klystrons during the previous 12 months divided by the total number of failed klystrons during the same period – **80-90,000 hr**

12 Month Age of Failed Klystrons: total accumulated HV hours for all 5045 klystrons failed during the previous 12 months divided by the number of failed klystrons during the same period- **65-70,000 hr**

Average Age of On-Line Klystrons: total accumulated HV hours to date of the 245 currently installed 5045 klystrons divided by 245- **52,000 hrs**

** Ref. MPOC142 Jensen, et al*

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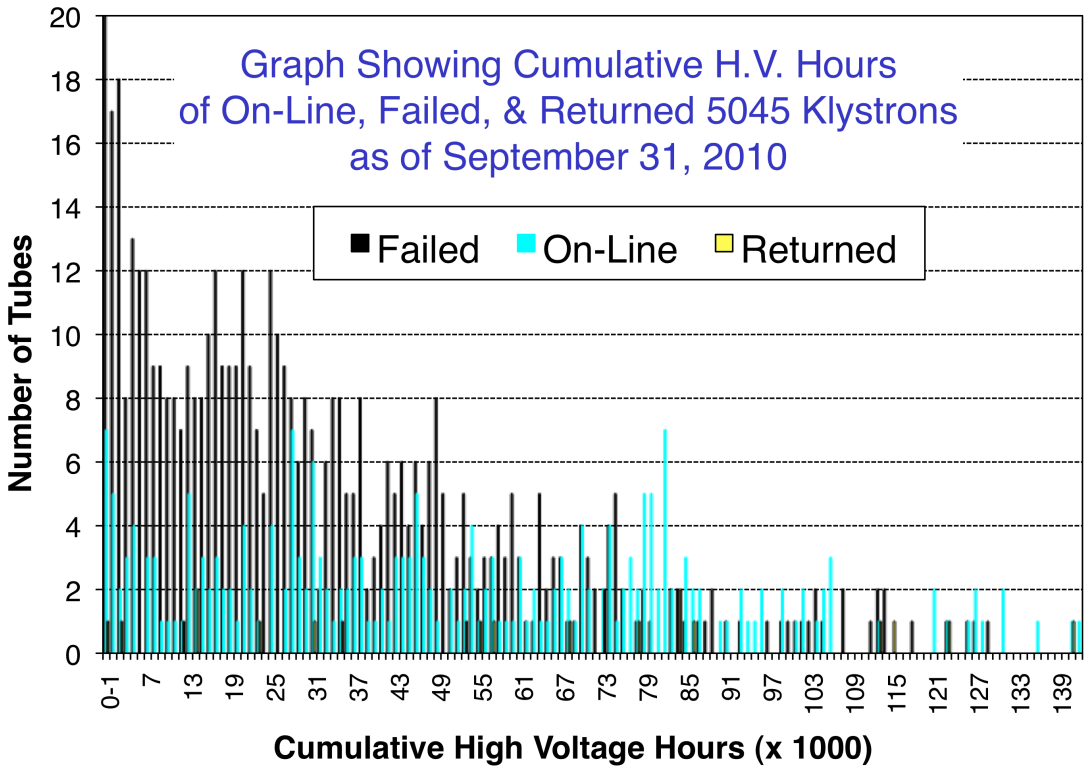
Some 5045s Are Very Long-Lived



- 43 klystrons have exceeded 100K hrs
- 22 are still on-line
- Three > 140K hrs
- Failure modes
  - Cracked/punctured windows
  - End-of-life cathodes
    - Low emission
    - Gun arcing
    - Gas bursts

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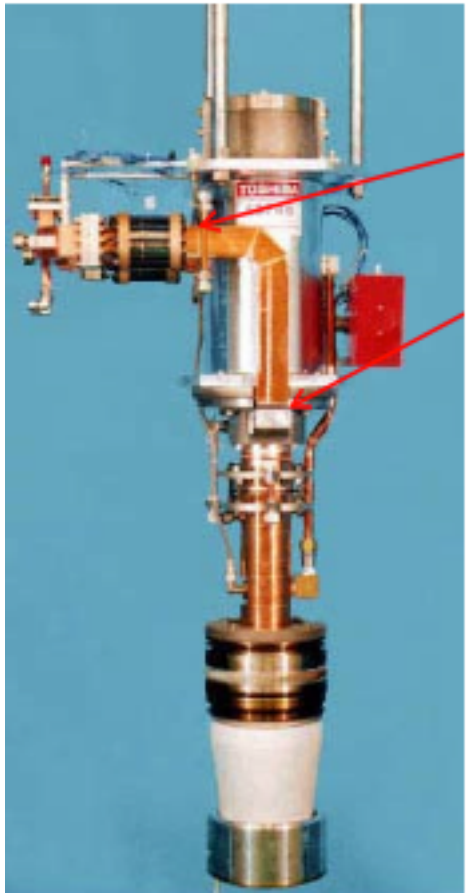
C-band Klystrons – 66 Toshiba E37202 Klystrons Operating at SPring-8 SACLA*



Two Windows

Traveling Wave output cavity

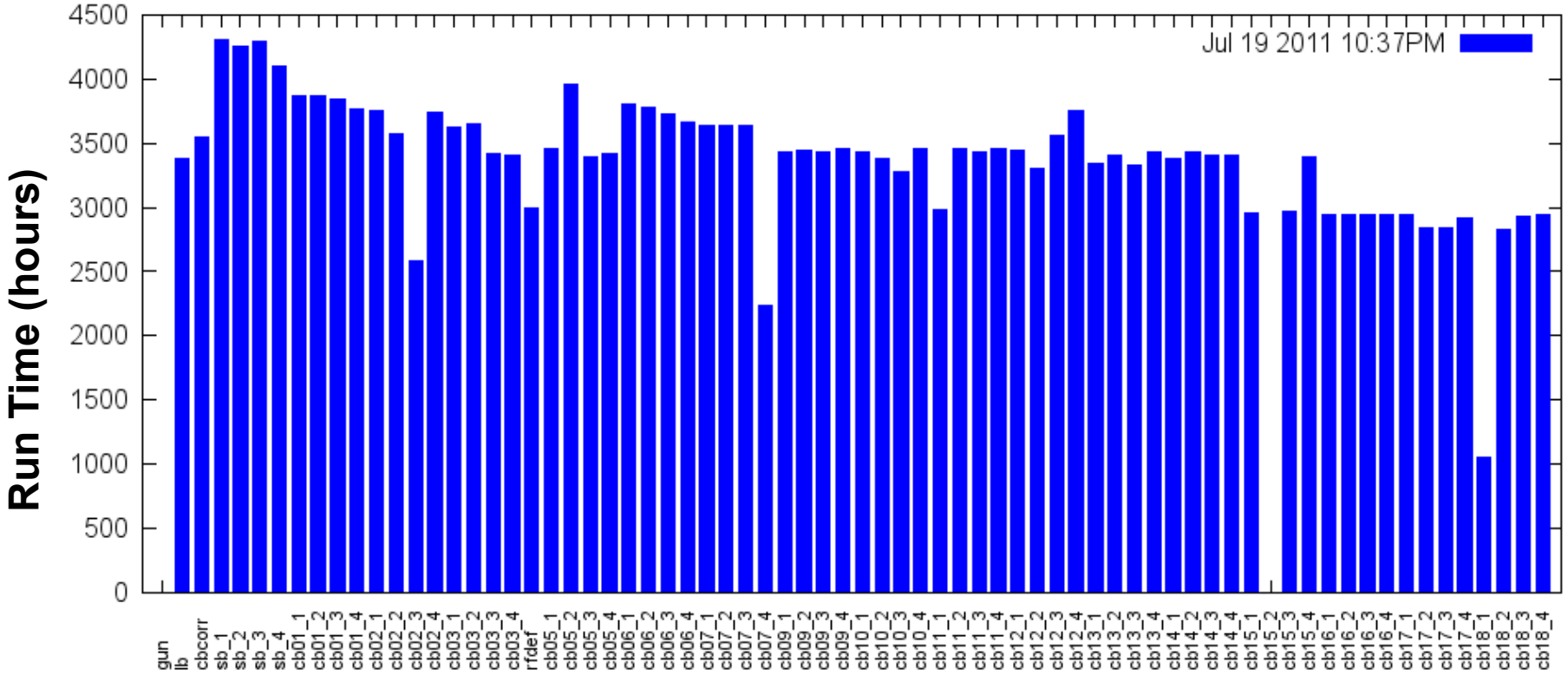
Toshiba E37202 Ratings

	Maximum	Typical @ SACLA
Peak Power	50 MW	30-40 MW
Beam Voltage	350 kV	300-330 kV
Pulse Width	2.5 μs	2.5μs
PRF	60 pps	10-60 pps
Efficiency	44%	40%
Frequency	5.712 GHz	5.712 GHz

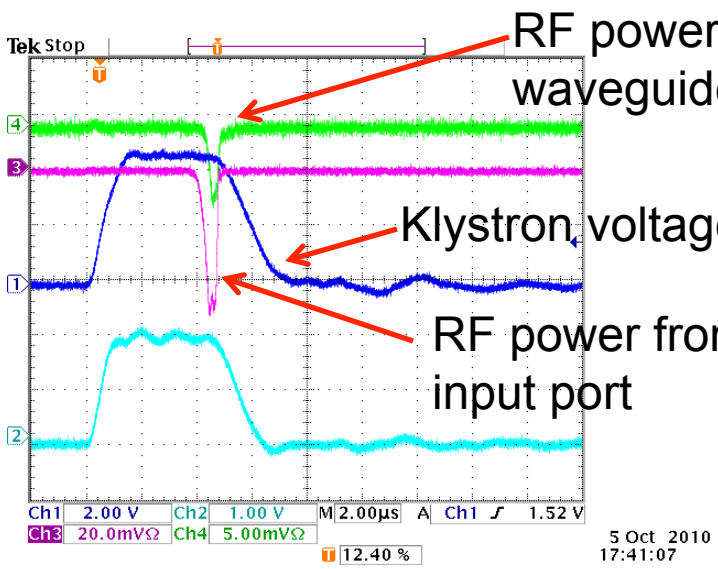
** SACLA data provided by T. Inagaki*

Run Time Statistics for Toshiba E37202 at Spring-8

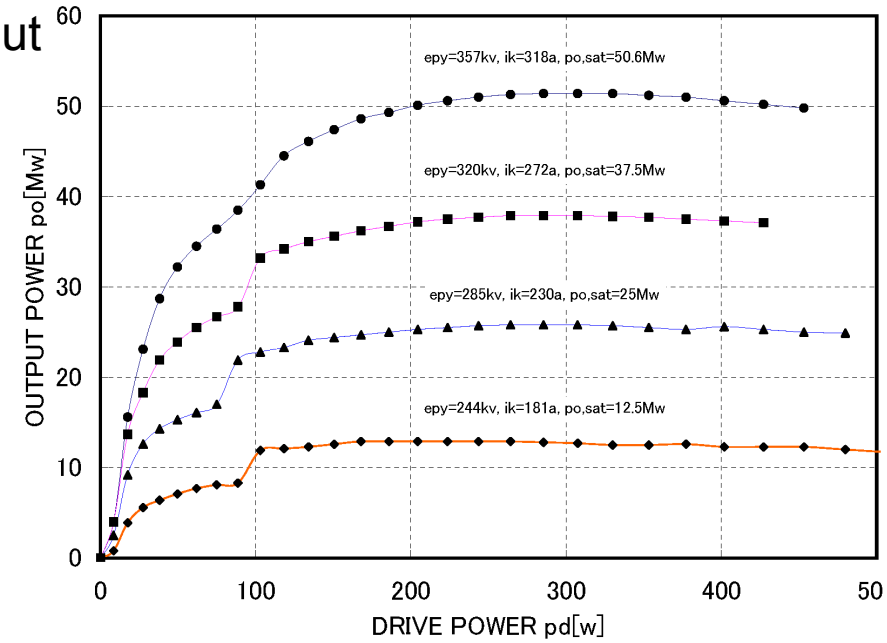
- 5 Months of Accelerator Operation from Oct. 2010
- 66 klystrons with 3000-4000 operating hours
- 1 failure at 1200 hours



Several Abnormal Characteristics Observed in E37202 Performance

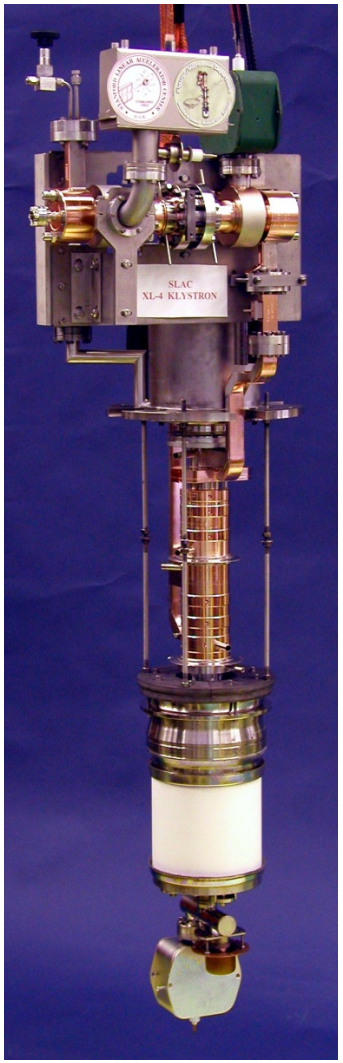


- 30 out of 70 klystrons exhibit > 10 GHz oscillation late in the HV pulse, with NO RF drive
- Couples to input and output
- No oscillation > 230 kV
- Not an operational issue



- 4 klystrons out of 70 have discontinuities in the P_{drive}-P_{output} power curve
- Output is unstable at <100 W drive
- Multipactor suspected
- Non-issue-normal operation > 200 W drive

X-Band Klystrons –SLAC XL4 & XL5



Parameter	Maximum
Peak Power	50 MW
Beam Voltage	440 kV
Beam Current	350 A
RF Pulse Width	1.5 μs
PRF	60 Hz
Freq. XL4/XL5	11.424/12.0 GHz
Perveance	1.2 μP
Efficiency	~ 40%
Focusing solenoid	4.6 kG/23 kW

X-band Development Program Produced 3 Distinct Series of Klystrons: XC, XL, PPM

X-band Klystron Design and Performance Specifications

	Solenoid Focused		PPM Focused (6 Tubes)				Solenoid
Tube Name	XC (8 Tubes)	XL1-**XL4** (26 Tubes)	**XL-PPM**	**75 XP-1**	**75 XP-3**	**75 XP3-4**	**XL5** (5 Tubes)
Freq. (GHz)	11.424	11.424	11.424	11.424	11.424	11.424	12
Peak Pwr (MW)	**100**	**50**	**50**	**75**	**75**	**75**	**50**
RF Pulse Length	1 μs	1.5 μs	1.5-2.4μs	2.8 μs	3.2 μs	1.6 μs	1.5 μs
Beam Voltage (kV)	440	440	490	490	490	506	440
Beam Current (A)	520	350	190	257	257	257	350
μP	1.8	1.2	0.6	0.75	0.75	0.75	1.2
Achieved	51 MW @ 1 μs & 60 Hz	50 MW @ 1.5 μs & 60 Hz	50 MW @1.5-2.4 μs	79 MW @ 2.8 μs & 10 Hz	75 MW @ 1.6 μs & 120 Hz	75 MW @ 1.6 μs & 120 Hz	50 MW @ 1.5 μs & 60 Hz
Notes	Low efficiency	In product-tion	Gain instability	Spurious oscillation	Excessive intercep-tion	Air cooling limited P_{avg}	In production

More than 30 XL4 & XL5 Klystrons Have Been Built

- XL4s routinely power test stands for high gradient experiments and testing RF structures
- Several have logged >10,000 hours but mostly below 35 MW
- One XL4 powers the LCLS phase space linearizer – has run 25,000 hr at 20-25 MW at 60 and 120 Hz
- LCLS X-band deflection cavity will also require an XL4
- Preparing to conduct a life test on a new XL4
- During testing at full spec 50 MW, 1.5 μs, 60 Hz, no breakdowns observed during 24 hr heat run

XL Klystron Is a Solid Design with a Growing Track Record

- Small number of tubes (~30) and widely variable operating conditions => insufficient run time statistics for a meaningful MTBF calculation
- With increased operating experience and incremental improvements will likely become more widely use in accelerator applications
- Effort underway to transfer design of the XL5 to industry for production

Klystron Reliability Summary

	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

Conclusions

- S-band klystrons have a well established track record for high reliability in hard operation
- C-band klystrons have only recently been chosen for large accelerators
  - Maturity is low
  - Infant mortality is low with operation at 60-80% of max power level
- X-band klystrons
  - Extensive R&D history but operational maturity is low
  - Solid design with growing track record
  - Incorporated into operational facilities
  - Design being transferred to industry