A Review of Klystron History and Performance at CEBAF

Richard Nelson - 6/27/18

"This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177."

Outline

- Brief lab history
- Problems, Failures and course corrections
- Additional purchases & rebuilds
- Pushing power to higher levels
- Current & Future klystron use

The Beginning

- CEBAF - Continuous Electron Beam Accelerator facility was launched ~1984
- Design warm design was changed to superconducting
- Klystrons: the go-to device: 5 kW CW, 1497 MHz (1 per SC cavity)

Spec Developed & Prototypes Ordered

- Varian, Thomson CSF, Raytheon
- Received prototypes were similar (2 of 3)
- Varian design was adapted from 2 kW air-cooled PM troposcatter klystron
  - Water-cooled collector, higher voltage, +mod anode
  - Collector rated for full beam power
  - Efficiency remained low at 32%

Varian VKL7811W - Litton/L3 L4941

- 11.6 kV @ 1.3A nominal
- 1.6 cm^2 cathode (0.81A/cm^2)
- Type-M dispenser cathode
- Typically 1-2 watt drive
- Coaxial output (1-5/6 non-EIA coaxial w/Marman clamp)
- Isolated collector for body current monitoring
- Requested: 20k hour life, 3 times rebuildable
- Warranty: 600 hour / 1 year warranty (150k hour cathode expected from accelerated vendor testing)

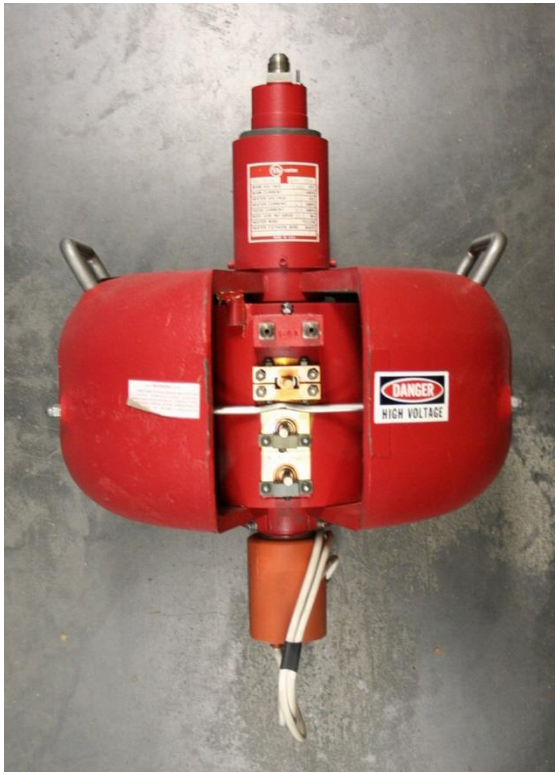
JLab RF Power

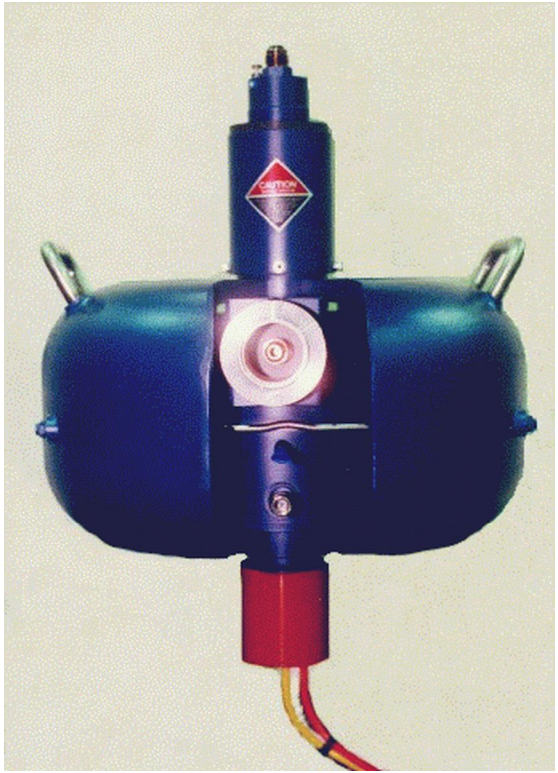
- Only klystrons were only considered (the logical choice for the time)
- 5kW saturated power
  - Required 340, bought 350
  - Supplemental purchases: 120 for spares, FEL, upgrades, non-rebuildable tubes
  - 3 rebuild contracts so far
- Also in use:
  - 80 x 13 kW klystrons (12 GeV upgrade)
  - 4 IOTS running 499 & 748,5 MHz
  - FEL klystrons: 2 x 100 kW + 25 x 8 kW
  - 4 x SSAs for beam extraction to halls

Buying the Klystrons

- Competitively bid - options for 25/50/100% from one or more vendors
- Price advantage and delivery capabilities went to Varian for 350 units
- Three year production period (manufactured, received, tested, & installed as RF zones and SRF became available)
- Initial operation at reduced voltage for commissioning periods
  - 4 HV settings via transformer taps
  - ** Heater power was set to nameplate values **
  - Contributing to early – and ongoing problems
- Some rebuilt even before leaving the factory

Red Klystron, Blue Klystron





Klystron Protection

- Overload detection and series limiting resistor (fuse)
  - Typically 3 strikes to resistor failure (cheap fuse)
- Ignitron-based crowbar installed, then removed
- Tubes will generally survive multiple arcs
  - Older tubes may have emission flat line with require hours to recover
- Initial failures were high – but not directly from arcing

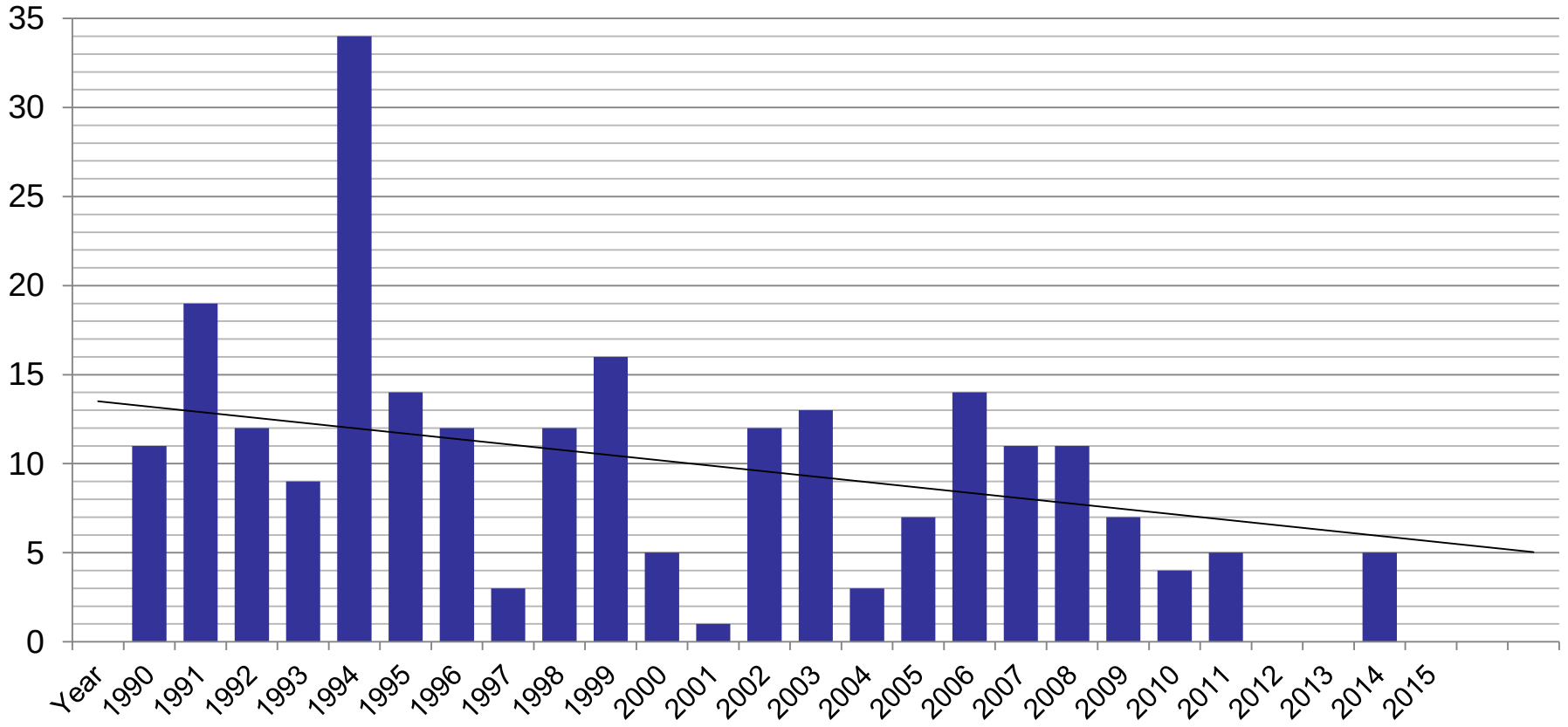
Operating Modes

- Reduced power using transformer taps
  - 3,4,5 kW (for C20 cryomodules)
- Other stopgap mode
- Reach power levels as needed; keep AC power down
- Added: switch selectable autotransformer (500V steps)
- Rebuilt CMs needed 6.5 kW - boost supply to existing HV PS
- Upcoming rebuilt CMs need 8 kW: rebuild power supply completely
- 12 GeV upgrade: new 13 kW design solenoid tube
  - 1 switchmode PS per 2 tubes. Still no crowbar.

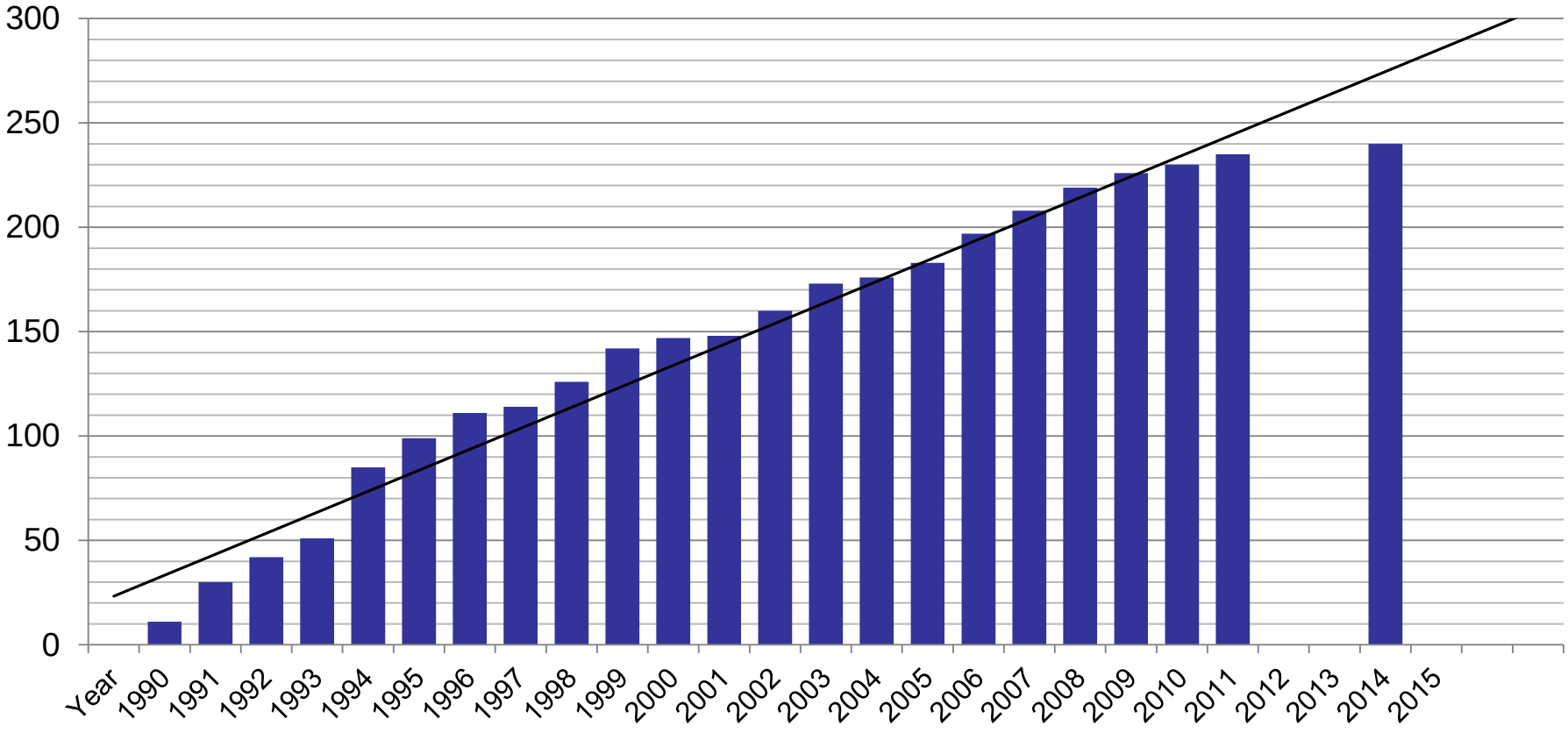
How We've Fared

- Based on requested 20k hour life
  - Anticipated failures was 100 failures/year based on operating hours
- Repair contracts to date: 3
- Most early failures were catastrophic
  - MA ceramic leakage & heating
  - Internal on mod anode ceramic
- Thermal runaway without limiters
- Leakage still most common failure
  - Still usable with reduced output
  - Of 340 installed, >50 are limited

Failures by Year



Cumulative Failures



Klystron Failures: The Early Years

Year	Klystron Filament Hrs	Cum Klystron Filament Hrs	Klystron Failures	Cum Klystron Failures	Avg Klystron Fil. Hrs / Failure	Cum Avg Klystron Fil. Hrs / Failure
1990	40,000	40,000	0	0	0	0
1991	150,000	190,000	11	11	13,636	17,273
1992	365,000	555,000	19	30	19,211	18,500
1993	390,000	945,000	12	42	32,500	22,500
1994	700,000	1,645,000	9	51	77,778	32,255
1995	2,268,000	3,913,000	34	85	66,706	46,035
1996	2,187,000	6,100,000	14	99	156,214	61,616
1997	2,546,000	8,646,000	12	111	212,167	77,892
1998	2,626,000	11,272,000	3	114	875,333	98,877
1999	2,277,000	13,549,000	12	126	189,750	107,532
2000	2,424,000	15,973,000	16	142	151,500	112,486
2001	2,538,000	18,511,000	5	147	507,600	125,925
2002	2,032,000	20,543,000	1	148	2,032,000	138,804
2003	2,309,600	22,852,600	12	160	192,467	142,829
2004	2,715,456	25,568,056	13	173	208,881	147,792
2005	2,657,232	28,225,288	3	176	885,744	160,371
2006	2,343,600	30,568,888	7	183	334,800	167,043
2007	2,077,440	32,646,328	14	197	148,389	165,717

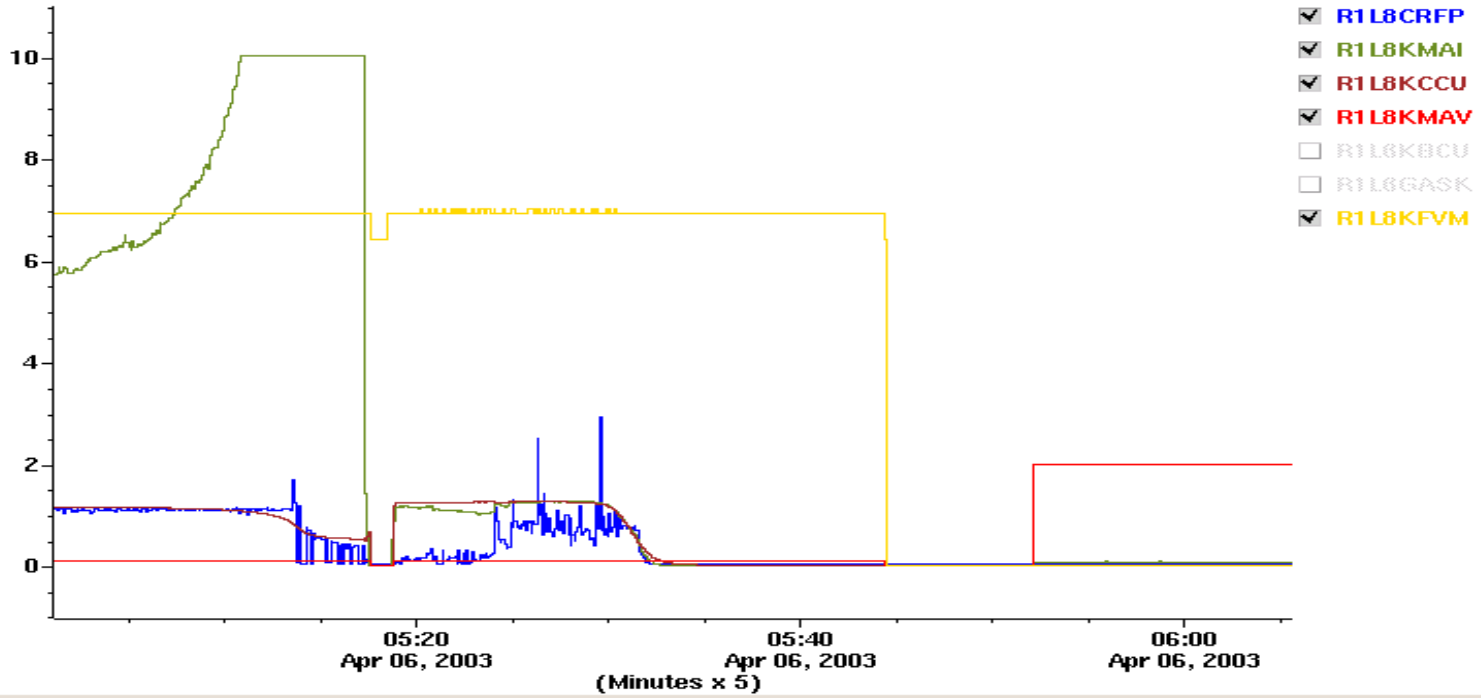
Failure Types

- Early: catastrophic – arcing (external) hard failures
- Increasing leakage flowed by thermal runaway due to mod anode ceramic leakage – went to air hot
- Rarely cathode EOL
    - MIRAM curves were early thought to be a good predictor of aging
    - Automated script to produce curves – not useful for predicting life
    - Manual monitoring & action

The 1995 Repotting Game

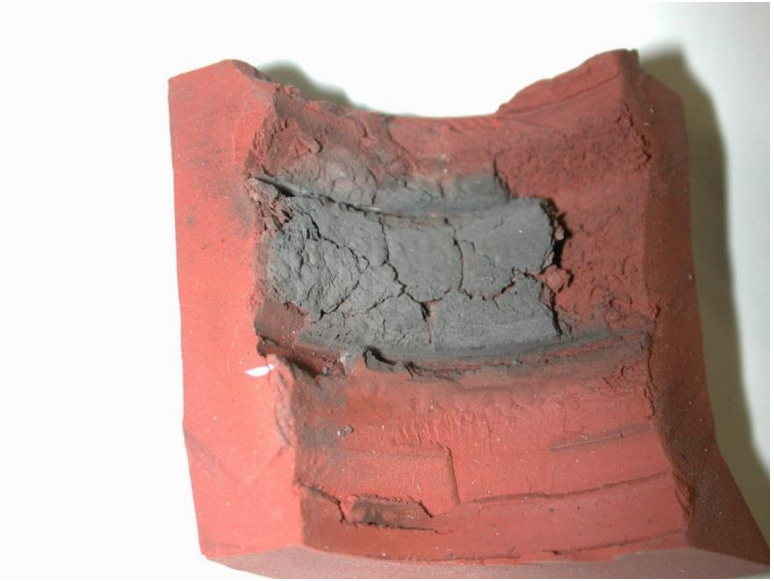
- Degraded potting the result of?
  - Temperature?
  - Curing process?
  - Material itself?
  - Considered running with no potting on gun
  - First repair contract switch materials
    - Better thermal characteristics
  - All removed and repotted -- still failures
  - MA current monitoring ***not*** continuous (or easy)
  - Added live monitoring & later active controls

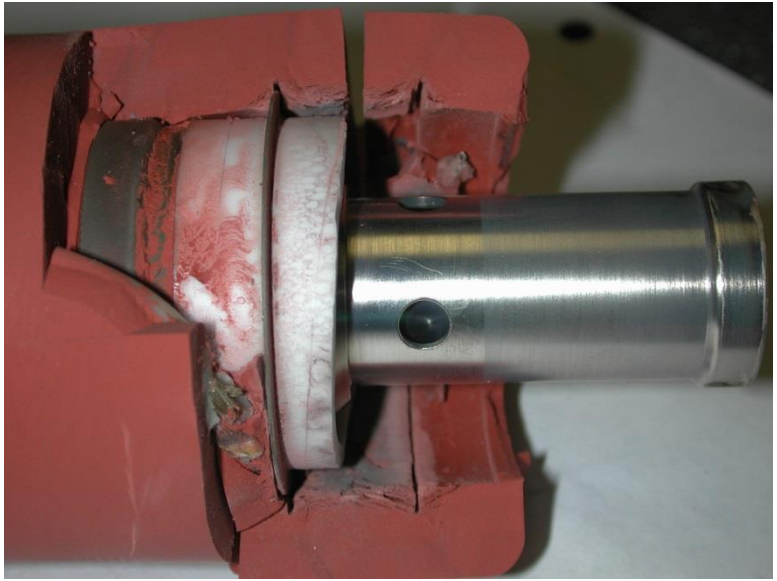
Thermal Runaway



- Thermal runaway on mod anode current (KMAI)
- Cathode current (KCCU) drops as KMAI rises. Fracture.

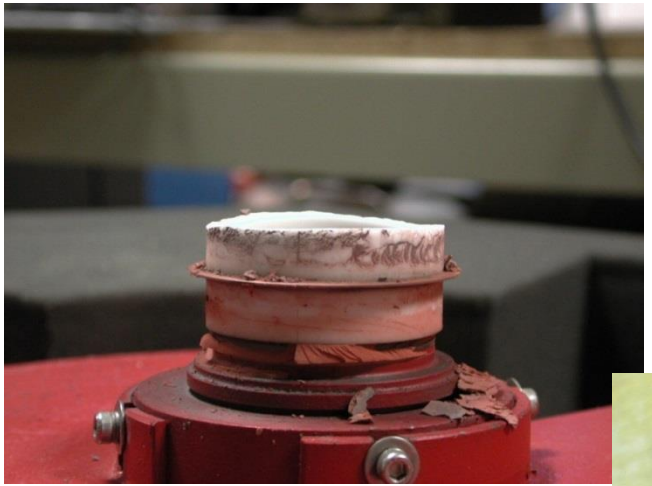
Degraded Potting

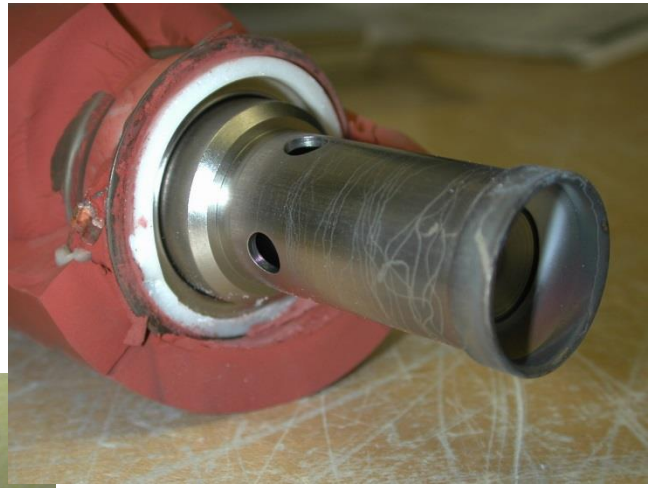




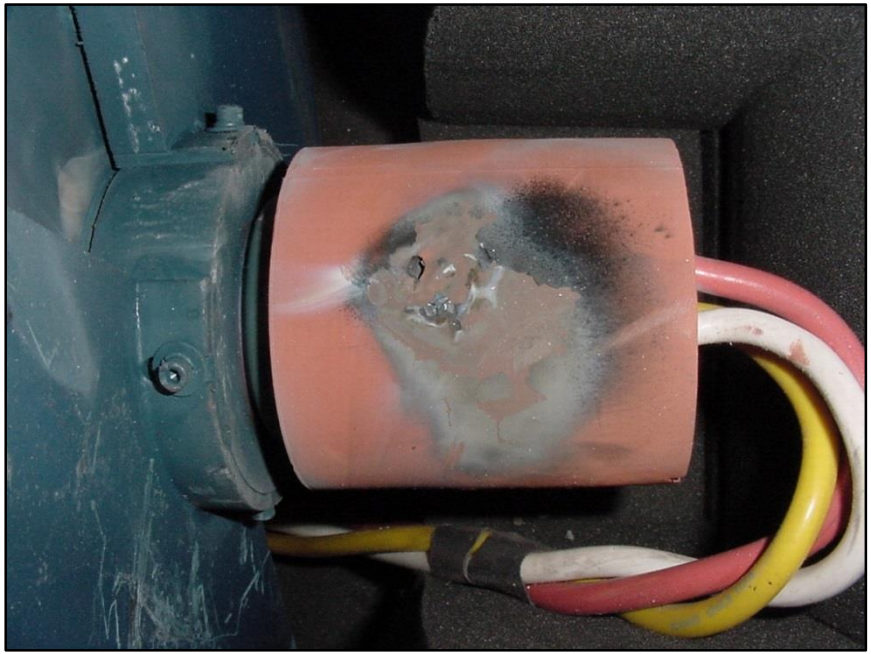
Potting degradation due to high ceramic temperature

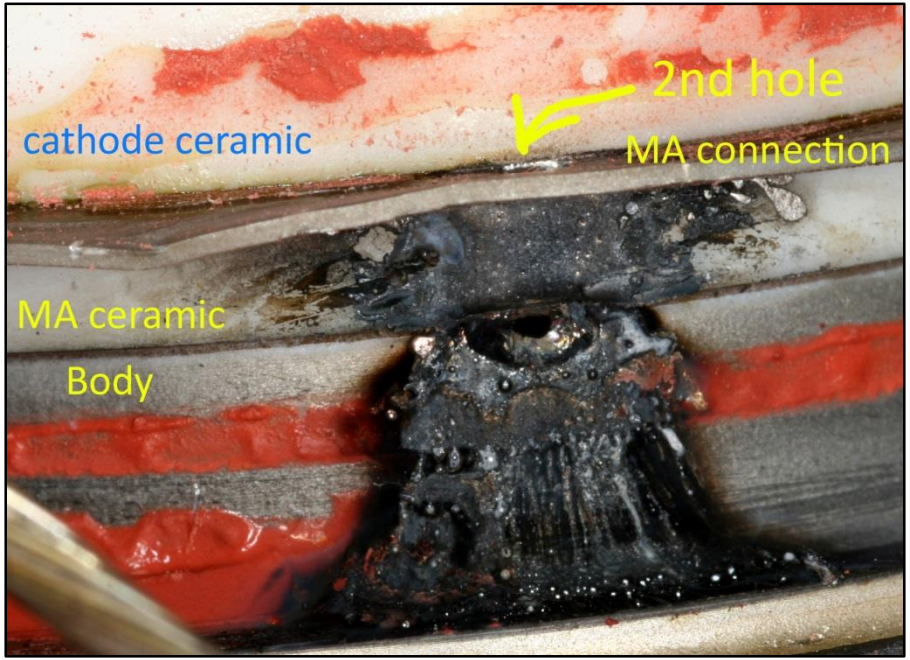
Fractured Ceramic





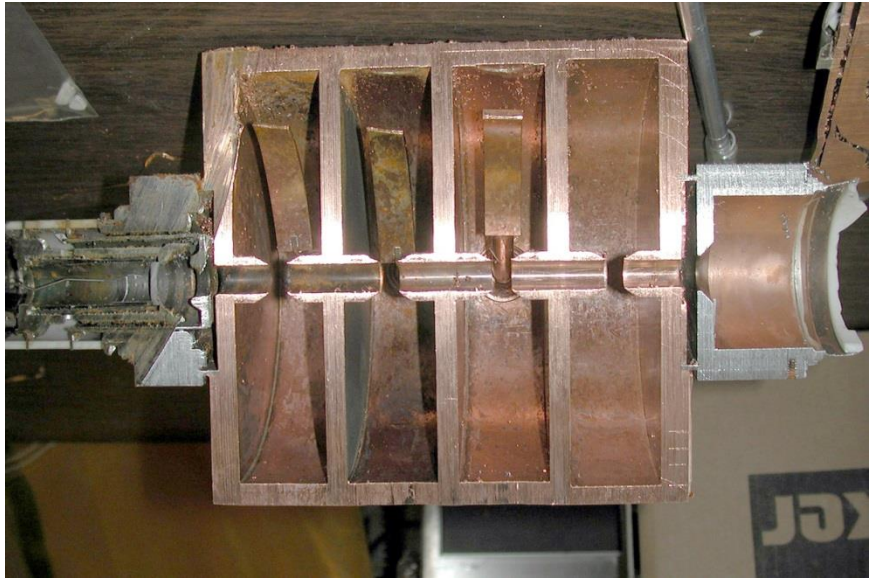
External Arcs

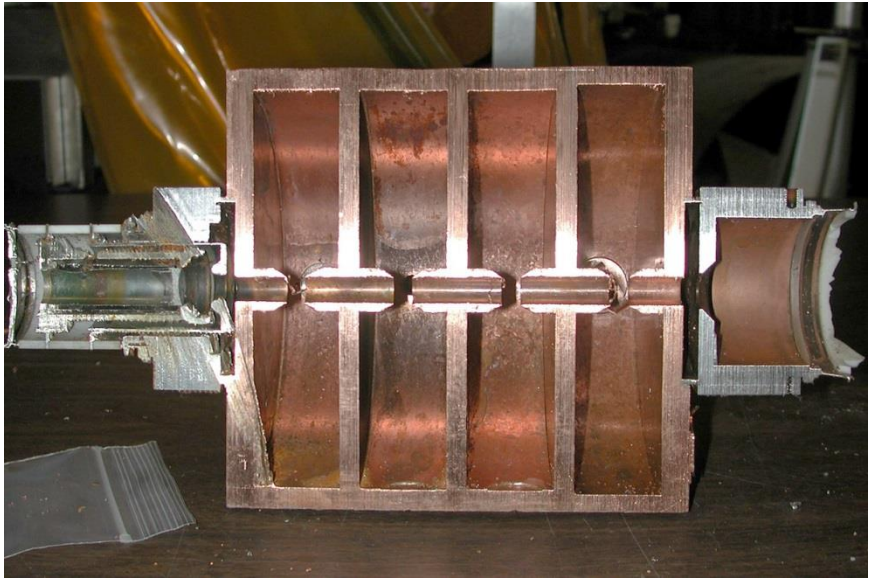




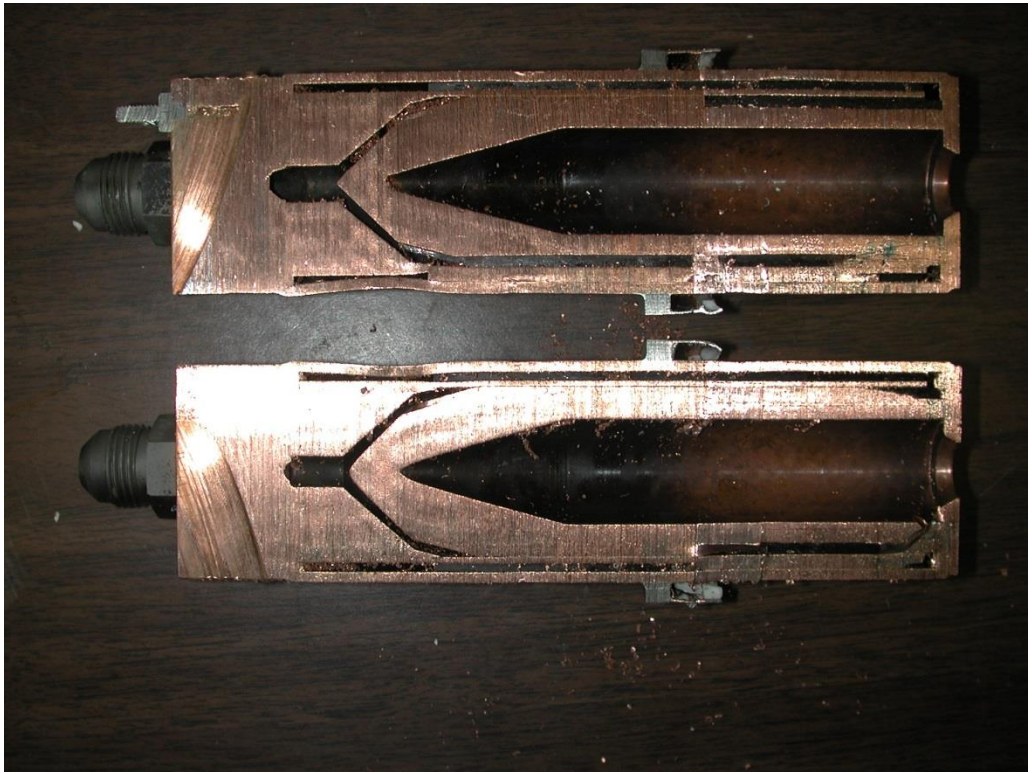
Repairable or Not?

Body

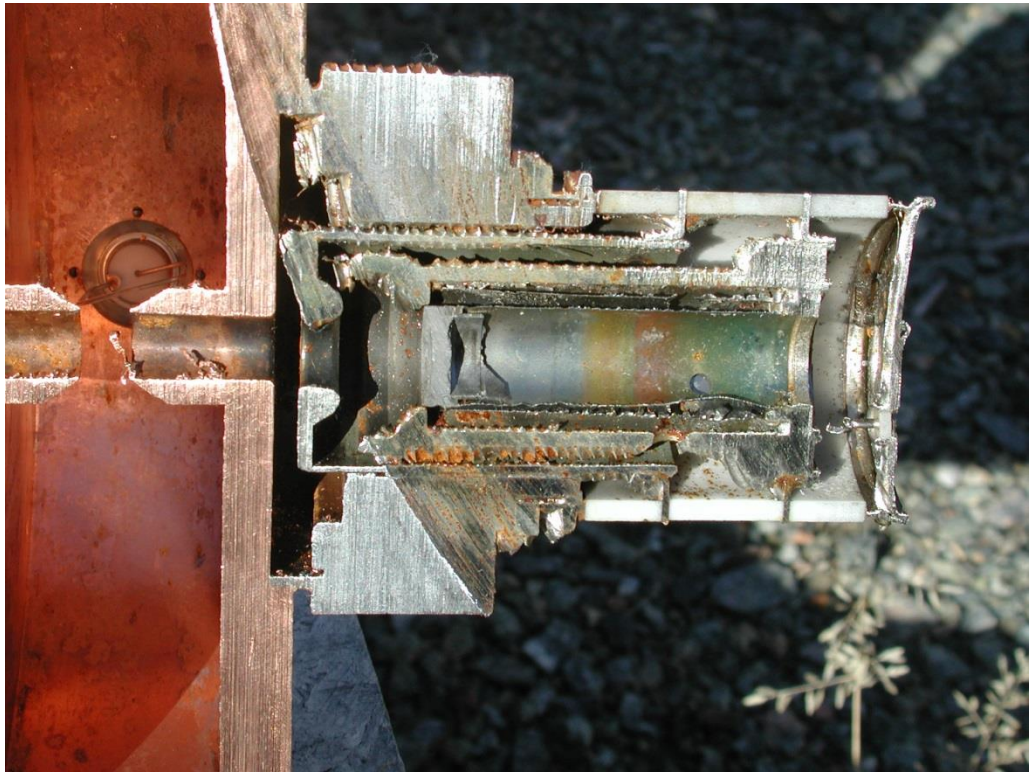




Collector



Gun



Changes to Gun Design

- Problem due to barium deposits on ceramic interior
- Gun revise to try and minimize deposition
- Internal vents relocated
- Ceramic length rearranged to increase path length on critical surface

Gun Stalk & Ceramic Changes

Other Rare Failures

Connectors

Repair Contracts

- Initial contract included most failure type
  - Gun/cathode, collector, windows, etc.
  - Gun replacement dominated
  - Later contracts simplified repair types: BER option
    - Working tubes failed to be rebuilt
    - Lifetime not as good, costs increased
    - 50% cost of new set as ceiling
    - Long dry period with no repairs and new tubes
    - FEL mothballed for 16-24 additional spares

Failure Analysis Report

Summary of Analysis:

This unit was returned for Major Repair - Electrical Evaluation was waived.

1. The inner connector was not returned with the unit. The tube passed the vacuum check.

2. The collector coolant flow was slightly restricted when checked using the new specification (25psi max @ 8.0gpm). After acid flushing the collector pressure was within the specification.

3. Internal evaluation indicates the tube is a candidate for major repair.

Note: Major Repair attempt failed 11/1/07. This unit failed electrical test after two major repair efforts. The tube is not suitable for any further rework.

Repair Action:

- Changed from MAJOR REPAIR 11/07/07.
SCRAP - This unit is not suitable for additional rework.

Comment: Original build, not previously repaired, not at air

Klystron Population

- TJNAF and CEBAF : 4 GeV→6 GeV→12 Ge
  - Assumed a robust 6 GeV Machine
  - 1st test at 6 GeV killed 1 tube per day for 9 days…
- 4 halls, up to 200 uA design
- 420 klystrons

Installed Klystrons

4 5 kW klystrons

8 x 13 kW klystrons

Other Notes

- Reduced failures, average 165k hours between failures)
- Determined 0.6 failures per week running
- 50+ weak units (what's a "failure"? Not dead, not a failure)
  - Catastrophic failures checked, weak tubes rising
  - High mod anode current still most common reason
- Data sheet gone from CPI web site some years back
- Recently Scrapped duds (decided we'd accumulate more for rebuilding, if optioned
- New tubes on order again (finally)
- That 13 kW has seen 3 failures in a few years
  - Same gun, different problems

Klystrons Still Our Choice

Pros

- Proven solution
- Long life
- Easy replacement
- Fits our sockets

Cons

- Moderate / variable efficiency
  - Input power remains constant
- Rising replacement cost (like most things)
- “Dangerous” high voltage (…always touted by SSA proponents)
- Long lead 9 months plus

Operation

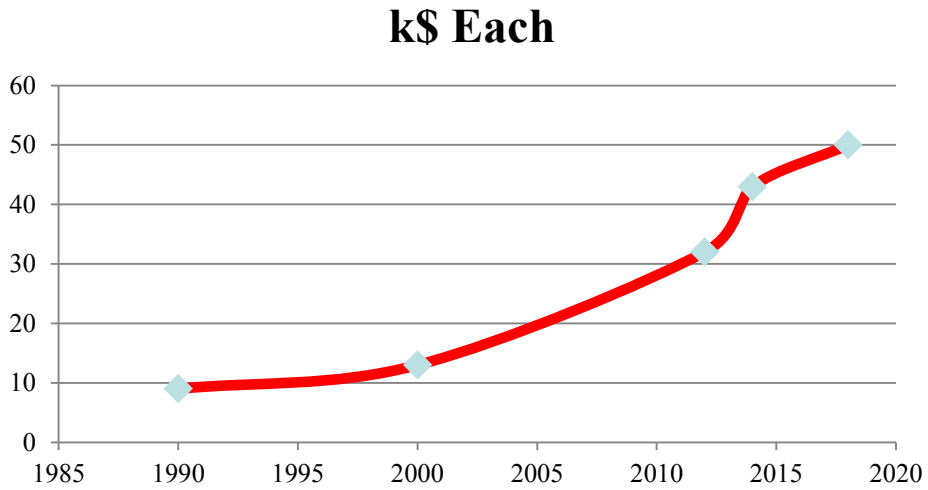
- History
  - 4 GeV design, run at 6 GeV (C20 CM)
  - Klystrons purchased as 5 kW
    - 350 Varian, 120+ Litton/L-3
  - Run to 8 kW in FEL (LERF)
  - Little more power, raised 480V 2.5 – 5%
  - Added boost supply to 6.5 kW for refurbished CM (C50)
  - Multiple repair contracts
    - PendEl, L-3, CPI
- Limited duty most common failure/limit
  - Shuffles, replacements, actual fresh replacements

Klystron Health

- 0.63 failures per week of operation (.28 more recently)
  - How many weeks running (13-32), how many failures?
- Can expect rate to increase as EOL approaches
  - When? Not readily predictable
- Few spares on hand so robbed FEL of 16
- > 50 poor tubes currently being used
- Affects gradient available
- 20 per year replacement contract funded
  - 4 option years depending on budget

Future – Continue to Supply RF

- Continue buying present klystrons
  - … unless requirements change or sources disappear
  - 2 vendors – for now
  - Prices continue to rise



Replacing the Klystron?

- Considered, discussed, nothing planned
- Considered paying more using energy savings
  - No options for klystrons that would fit
- SSA
  - Availability improving. Cost & size are concerns
  - Transistors not popular at 1.5 GHz
- Magnetron
  - Ongoing SBIR and other work
  - Amplitude & phase adjustment, device lifetimes?
  - Custom device – no mass market savings

Summary

- Lots installed
- Failure rate (0.3/week of operation)
- Running: 27 weeks suggests 8 per year (and growing…
  - 20 new purchased (per year)
  - 50 weak presently installed
  - 8-16 fresh 8 kW per year for C75 upgrades
  - Many years to catch up
- If JLEIC launches, klystrons and SSAs likely
- Finally! New replacements in the pipeline.

Thank You

"OK, we haven't run out yet, but we ***really*** should buy more klystrons. No, I don't know when they'll fail…"