

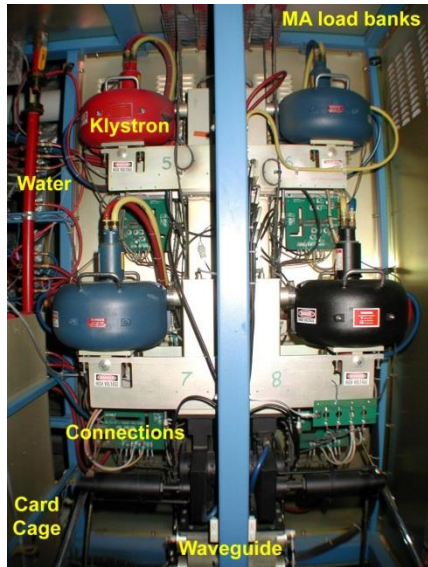
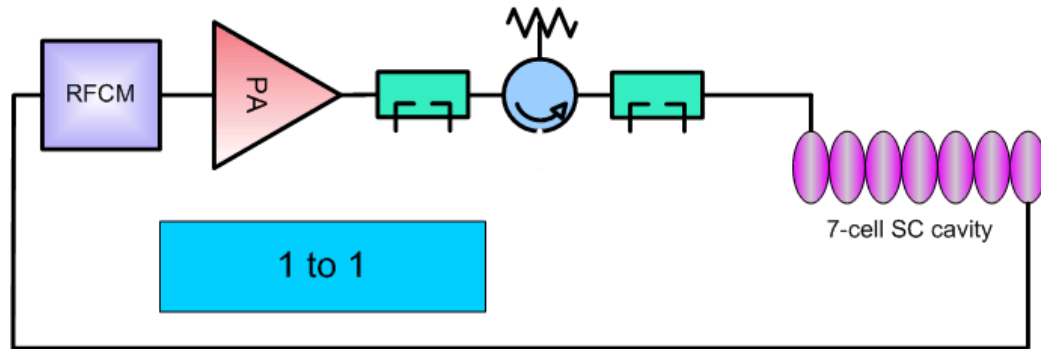
RF Power Klystrons & 20 Year Look

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7/15/15



RF Power



klystrons

8 x 13 kW klystrons

Why A klystron?

- Best (only) choice at the time - 1988
- Easy to use: Input (drive), output (to CM), power source (CPS)
- High gain
- Moderate efficiency, when operating saturated
 - We don't run there
- Existing design tweaked for frequency and power
- 2kW became 5kW (later 8), 1.3 GHz to 1.497 GHz
- Water-cooled (most heat dumped into water)
- 33% efficient (rated power)
- A custom solution for our requirements

RF Power

- Only klystrons were considered
- 5kW saturated power using klystrons
 - Up to 8 kW (FEL & OL04)
 - 42¼ cryomodules + capture = 340 klystrons
 - Initial purchase: 350
 - 24 in FEL zones, 4 for cavity testing
 - 1 prototype in FEL buncher
 - Supplemental purchases: 120 for spares, FEL, 10 for OL02 R100 upgrade
 - Rebuilds along the way
- 4 x 1 kW SSAs for separation
- IOTs: 4 for separation (499 & 748.5 MHz)

12 GeV Upgrade

- 80 cavities = 80 klystrons
- Higher efficiency, higher power
 - Purchase: 84 including first article
 - Also considered IOT & SSA
 - IOT concerns
 - » None built for 1.497 GHz
 - » Some in service at 1.3 GHz
 - » Higher cost, lower gain (high drive required - 100W preamp vs 0.1 – 2 W)
 - IOT advantages: efficiency
 - SSA: Advancing, but not there yet (cost, size, capabilities)

How We've Fared

- Original spec asked for minimum 20k hour life
- Anticipated failures: 100 failures/yr. Didn't happen
- Repair contracts (3)
- Rebuild *up to* 3 times
- Early fails: catastrophic not cathode depletion
- Internal leakage on ceramic
- Thermal runaway (mod anode effects)
- Leakage still most common fail
 - Imposes limits on tube



Klystron Failures: Part 1

| 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 |

Klystron Failures: Part 2

| Year | Failed | Weeks Running |
|--------|---------|---------------|
| FY2008 | 9 (11?) | |
| FY2009 | 11 | |
| FY2010 | 7 | |
| FY2011 | 4 | |
| FY2012 | 5 | |
| FY2015 | 5 | 18 |

240

Klystron Procurement Times

- Recent: R100 upgrade klystron buy (10 pcs)
 - Req entered: 10/1/12
 - Signed/Bid: 10/3/12 - 12/20/12
 - Placed: 12/21/12
 - 1st received: 5/30/14
 - Last received: 8/26/14
 - 5.4 months ARO for 1st (8 mo from start)
 - Time to 10th unit: 8.3 mo ARO (11 mo from start)
 - Maximum delivery rate?

Klystron Pros & Cons

Pros

- Proven solution
- Long life
- Fits our sockets
- Easy replacement
- High gain
- High output power

Cons

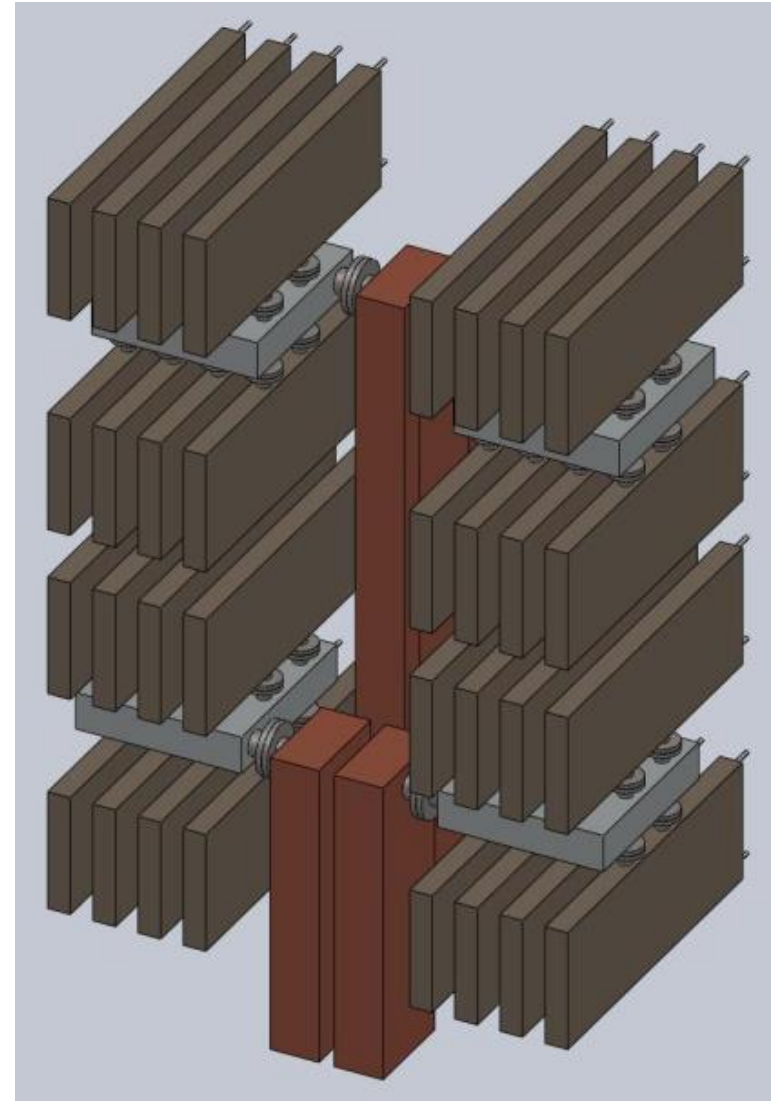
- Moderate / variable efficiency
 - Input power remains constant
- Rising replacement cost (like most things)
- “Dangerous” high voltage (...always touted by SSA proponents)

SSA (Solid State Amplifiers)

- Evolving, prices dropping, power per device up though 1.497 GHz not a mainstream frequency
 - Transistors developed for large markets – we're a small user
- Generally higher efficiency (more constant)
- Complex designs (multiple stages, splitters, combiners, etc.)
- Soft failure modes (gradual power loss)
- “Safe low voltage operation” (50V/400A)
- Major hardware changes to drop in
- At \$11/w, 88k\$ per device X340 units = 30M\$

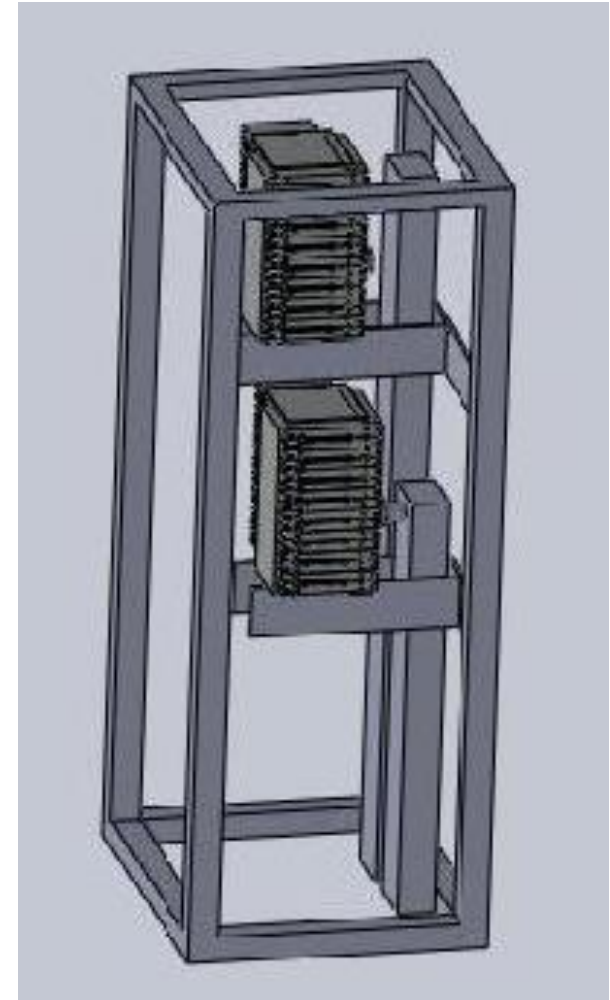
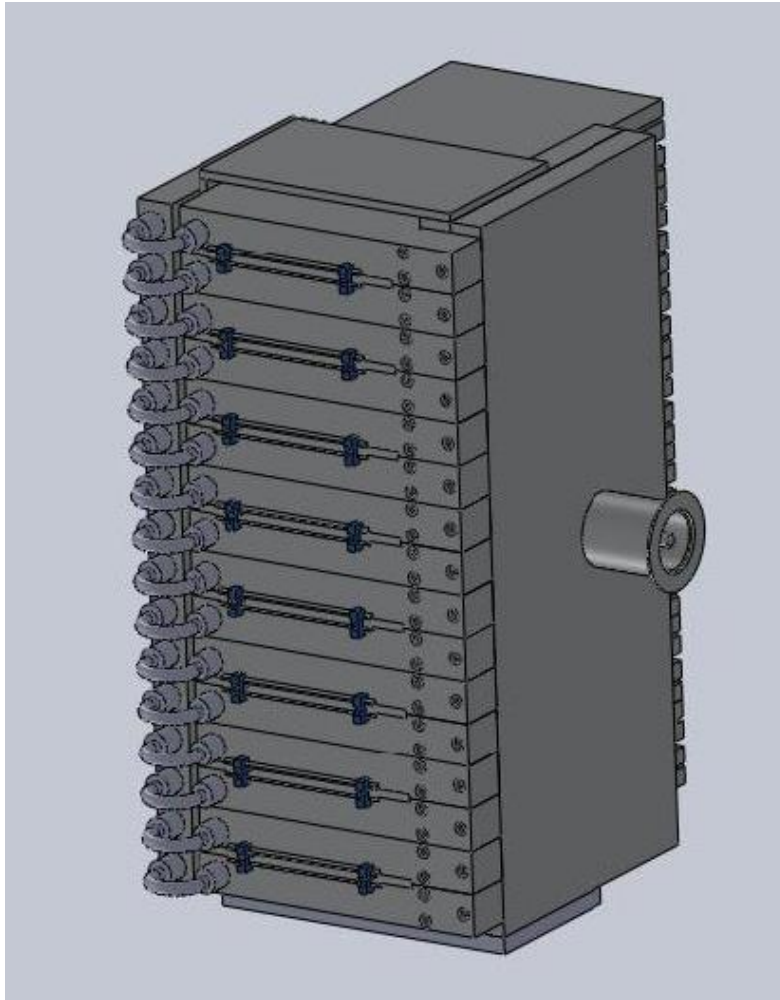
SSA SBIR Efforts

- Several attempts over 10+ years
- Nothing usable yet
- Price, unknown
- SBIR companies typically not production capable, nor are developing an “Innovative” design

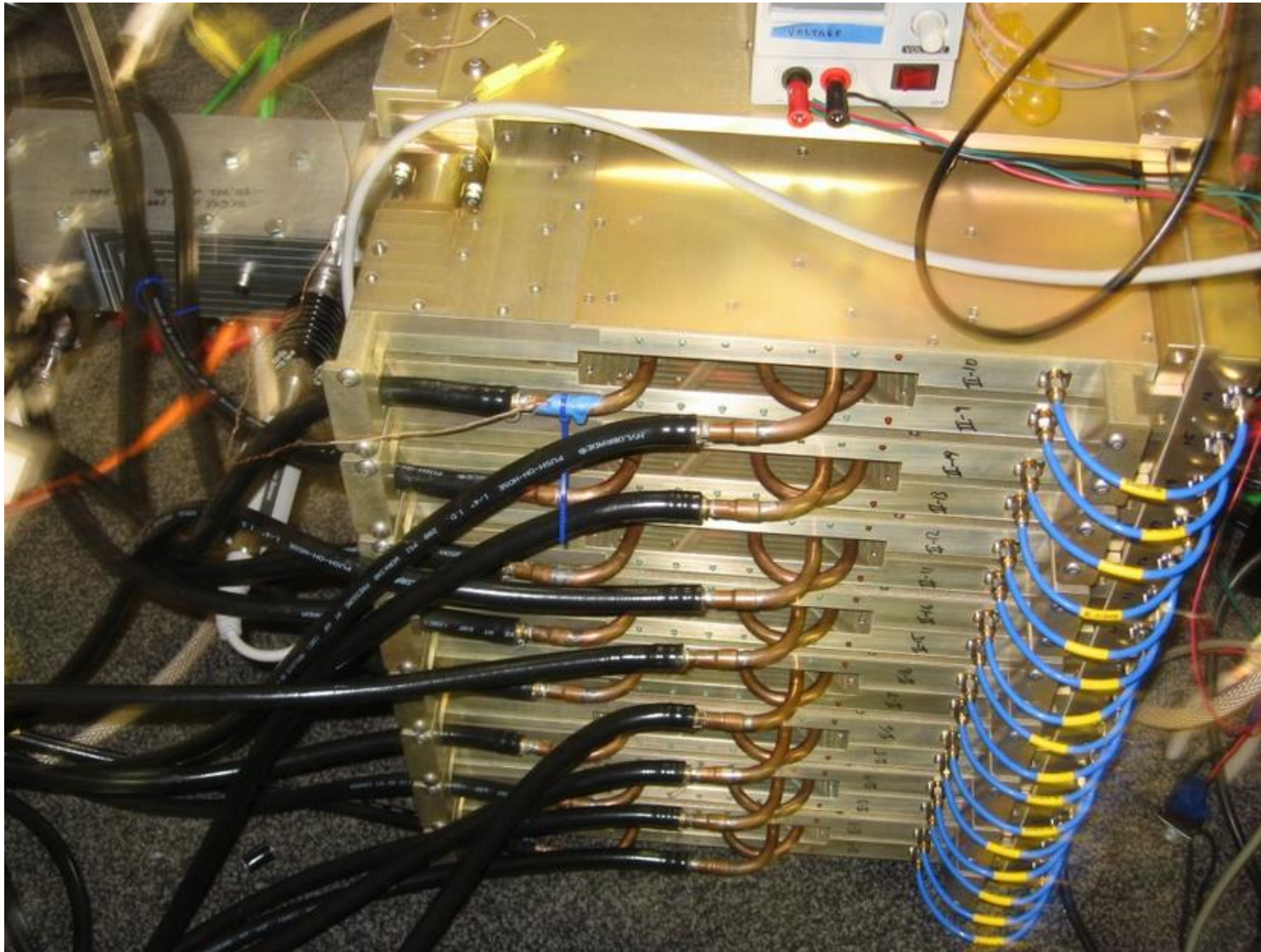


SBIR: Design to Fit Our Space

Multi-module amplifier could be installed in our HPA



SBIR SSA

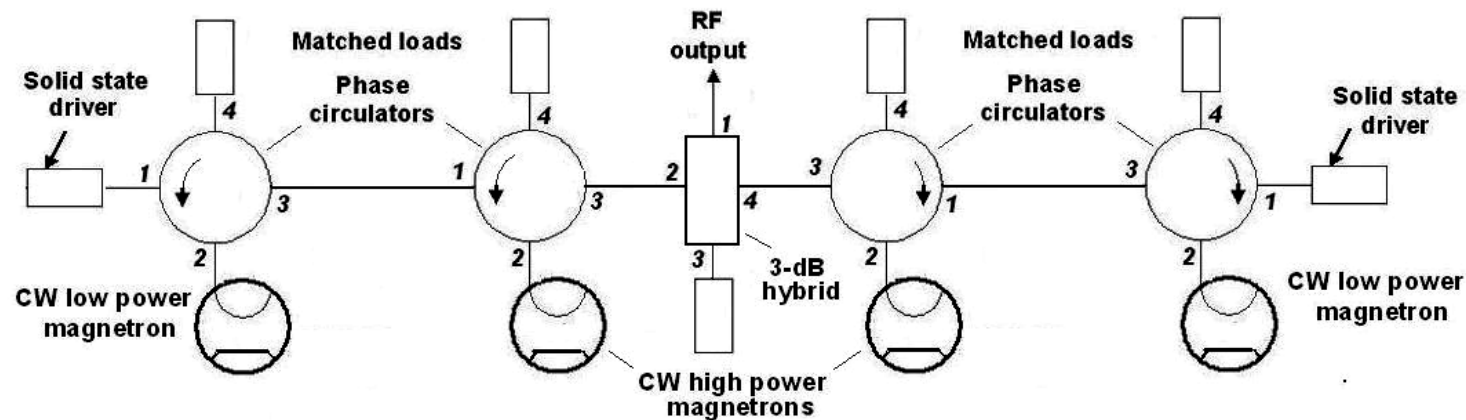


Magnetrons

- Research being done here at JLab and looking with multiple approaches
- It's an oscillator - industrial cookers, radar
 - Cost-effective power with high efficiency
- As an amplifier, more complex system (multiple magnetrons, waveguide components, etc.)
- Injection locking for frequency control, hybrid combining to adjust power? Modulated HV and magnetic?
- Not a drop-in replacement for our klystrons
- Significant changes – a new system (as with SSA)

Other Magnetron Comments

- Shorter life (than klystrons or SSA)
- Applicability based on requirements
- Individual devices may cost less per watt, but additional hardware adds significant expense



Muons, Inc.



Fermilab

MEIC RF Power (H. Wang)

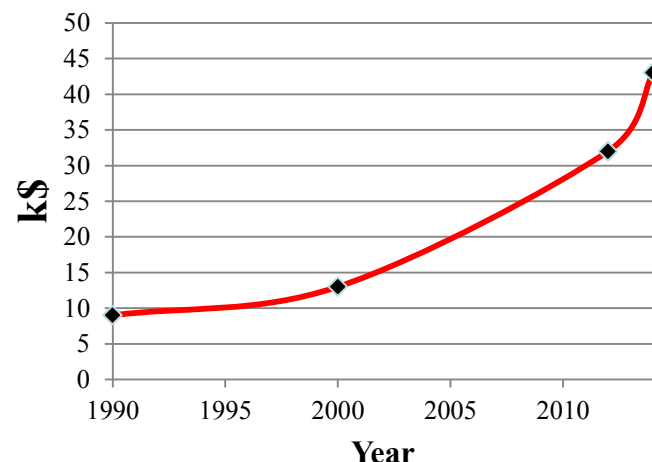
| | CEBA F 12GeV | E- Ring PEP-II 10GeV | Ion-linac Pb 60MeV/u | Booster | Ion-Ring Pb 40GeV/u | | CC- ERL Cooler 55MeV | Crab (16+6)X 2MV |
|--|-----------------------------|---|-------------------------------------|----------------|------------------------------------|-----------|---|---------------------------------|
| Frequency (MHz) | 1497 | 476.3 | 162.5 /325 | 0.6-1.3 | 1.2-1.3 | 952.6 | 476.3 /952.6 | 952.6 |
| Duty Cycle (%) | cw | cw | 0.5 | ramp | ramp | cw | cw | Cw |
| Cavity | sc 2K | nc | nc | nc | nc | sc 2K | nc/sc 2K | sc 2K |
| Max Peak Power(MW) | 2.76 | 12.79 | 42 | | 0.36 | 0.73 | 0.12 | 0.0023 |
| Average Power (MW) | 2.76 | 12.79 | 0.46 | 0.084 | 0.36 | 0.73 | 0.12 | 0.0023 |
| Klystron DC-RF Efficiency (%) | 35-51 | 67 | 50-60 | na | na | 50-60 | 50-60 | 50-60 |
| Magnetron DC- RF Efficiency (%) | 80-90 | 80-90 | 80-90 | na | na | 80-90 | 80-90 | 80-90 |
| DC Power Save (MW) | 3.4-3.8 | 3.1-4.9 | 0.26-0.35 | na | na | 0.41-0.55 | 0.07-0.09 | 0.0013- 0.0017 |



Future – Continue to Supply RF

- Continue buying present klystrons
 - ... unless requirements change
 - 2 vendors (one hasn't built it since our original buy)
 - Prices on the rise

| | | |
|----------------|--------------|---------------|
| 1990 | \$9k | Varian |
| 2000 | \$13k | L-3 |
| 2012 | \$32k | L-3 |
| 2014 | \$43k | L-3 |
| 2016-35 | TBD | ?? |



- Monitor options for alternate tech with major system changes
- Monitor integrity of other components

Klystron Health

- 2009 snapshot: 0.63/week of operation (.28 later)
 - How many weeks, how many failures?
- Expect rate to increase as EOL approaches
 - When?
 - Metrics not available to predict
- Spares: 12 on hand
- Installed: 16 poor (limited) tubes
- Cost: increasing
 - 20 per year proposal wasn't funded
- Arne suggests 500k\$/year (~10 units per year)
- A good start – but start soon



Thank You

OK, we haven't run out yet, but we really should buy klystrons... crying wolf?



"Crying wolf"
refers to the action
of crying
but instead of
tears,
a wolf
comes out.



lefthandedtoons.com