The Advanced Photon Source 352-MHz RF Systems

(…….*A Case for Solid State?)*

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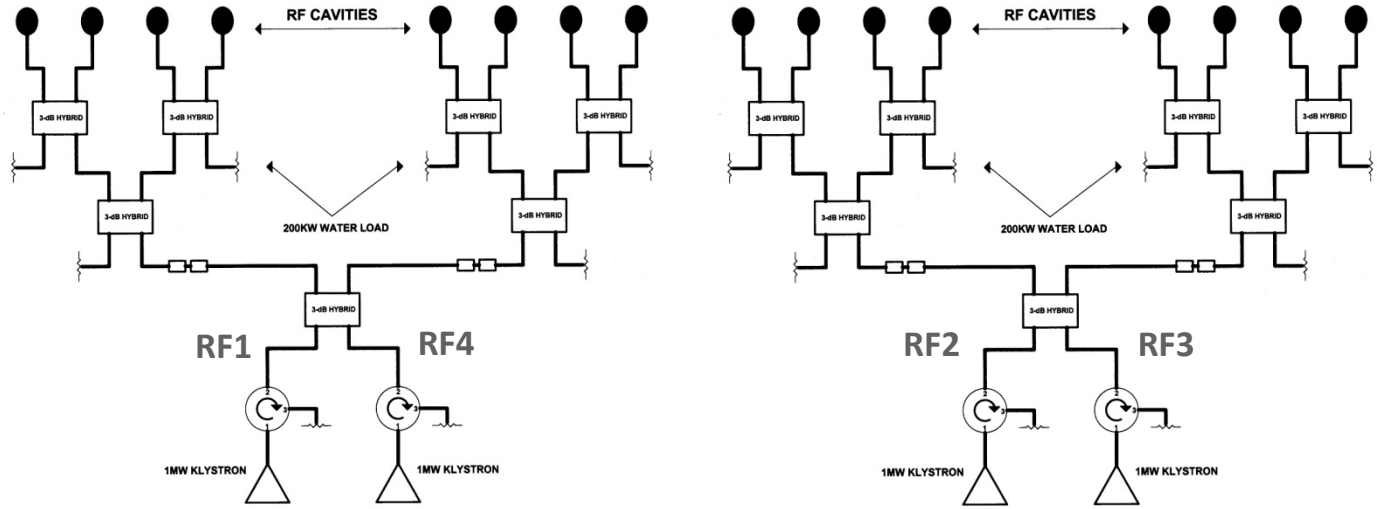
Outline

- APS RF System Topology
- Concepts for Solid State RF Power at APS
- SOLID STATE RF POWER AT APS?……*what would we get for all that cost and effort?*

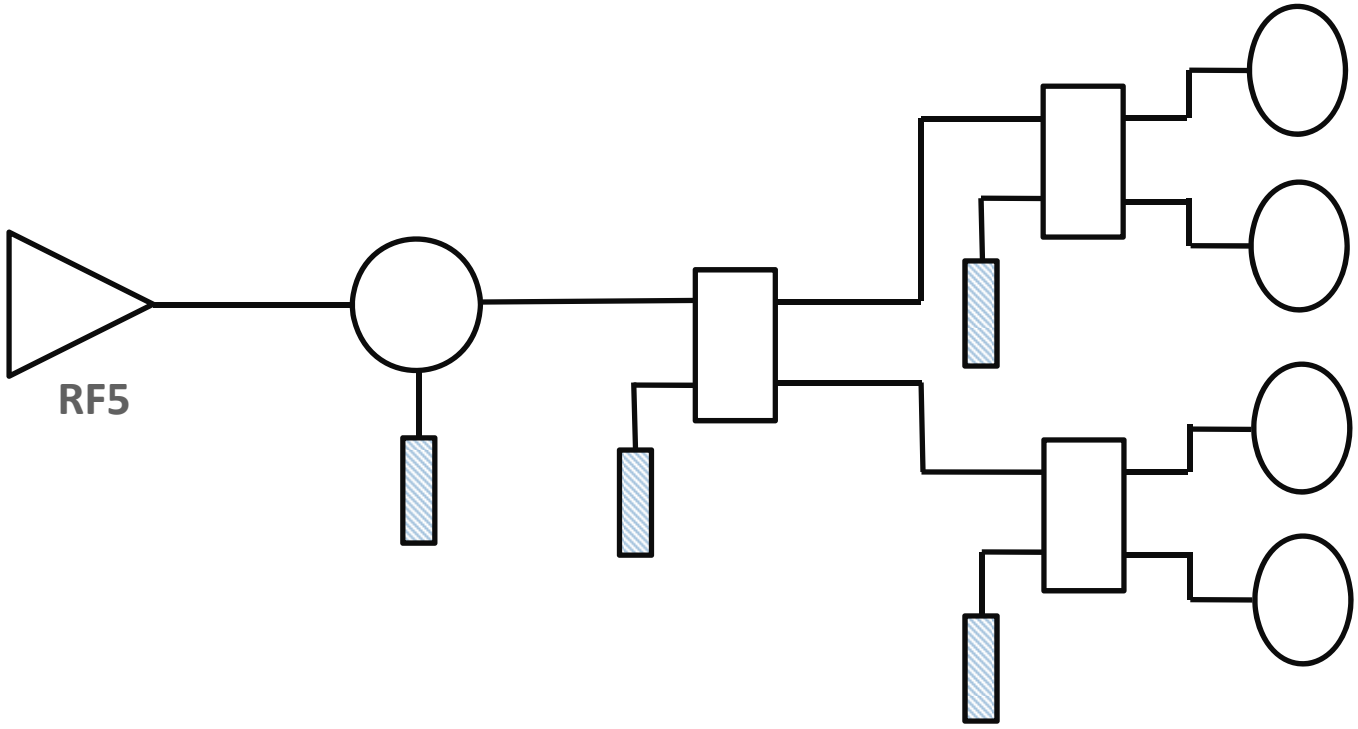
APS Storage Ring RF Topology

- Waveguide switching system provides twelve modes of operation with different combinations of rf systems
- Routine storage ring operation is 103mA maximum stored current in “top-up” mode
- Requires two klystrons driving storage ring, each operating at ~ 675kW CW
- “Offline” rf stations are in diode, 70kV@5-6A

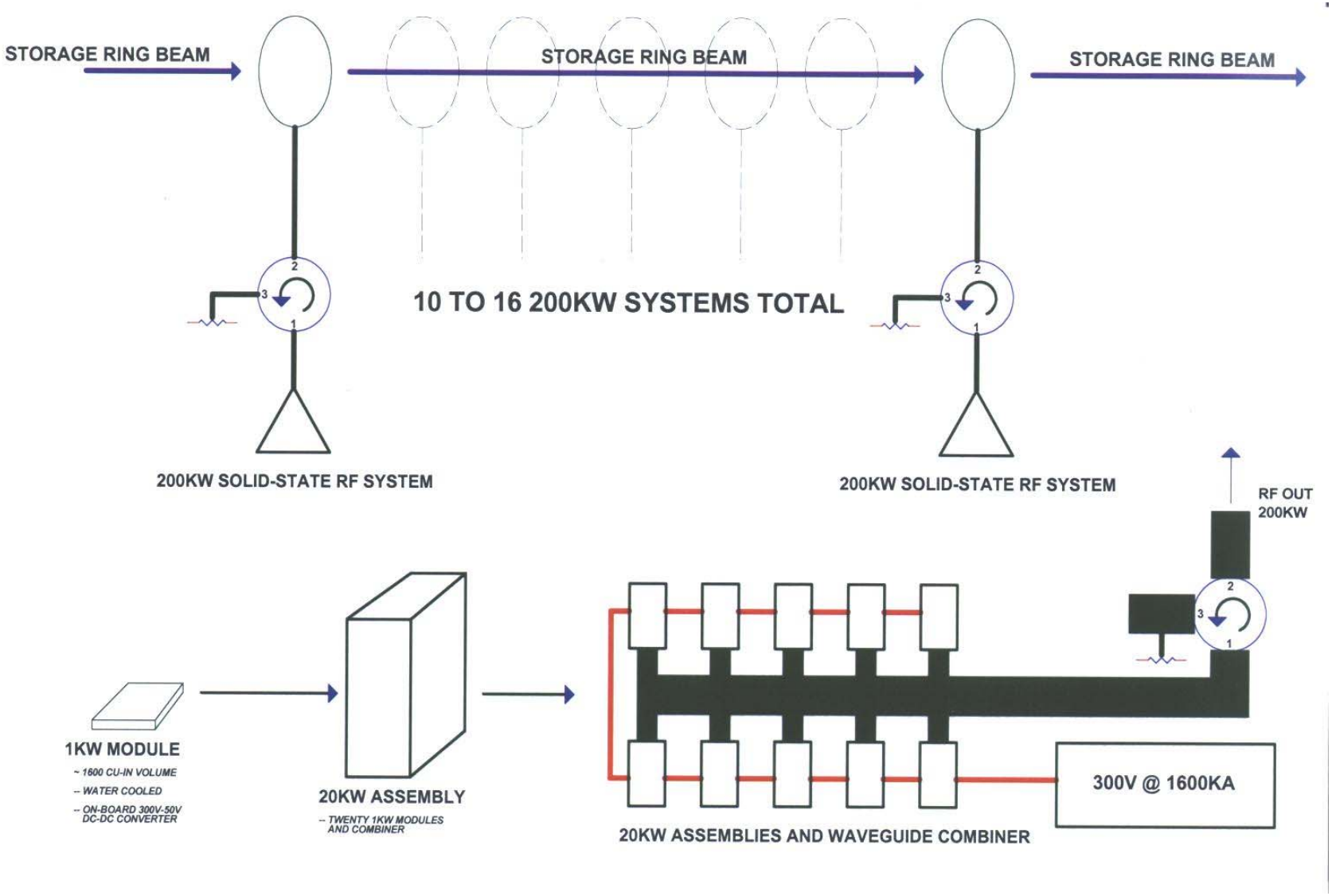


APS Booster RF Topology

- Uses one 1-MW klystron (RF5) operating at 400kW peak, ~ 120kW average power
- Waveguide switching system allows storage ring station RF3 as a back-up to RF5

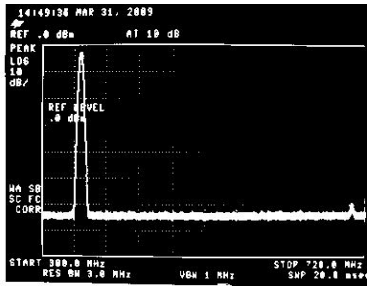


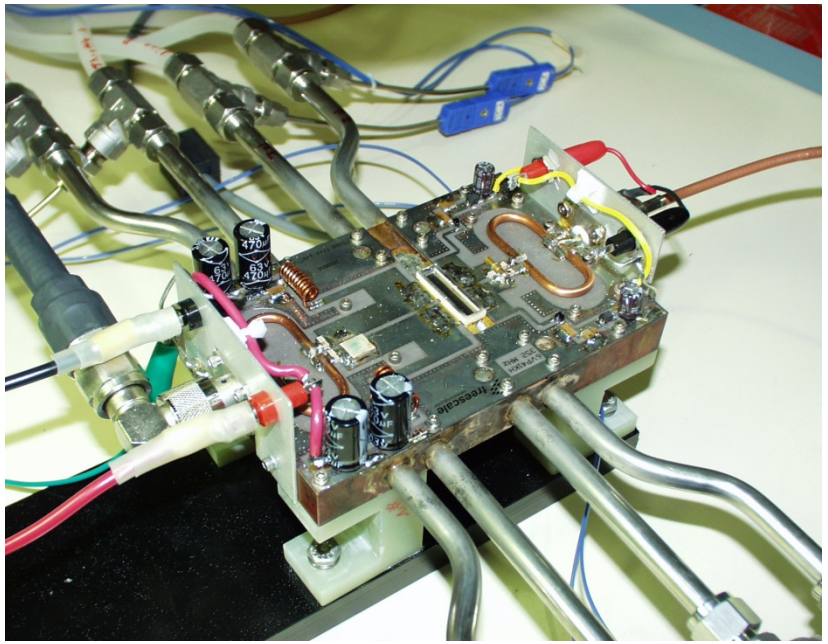
APS Solid State RF Concept

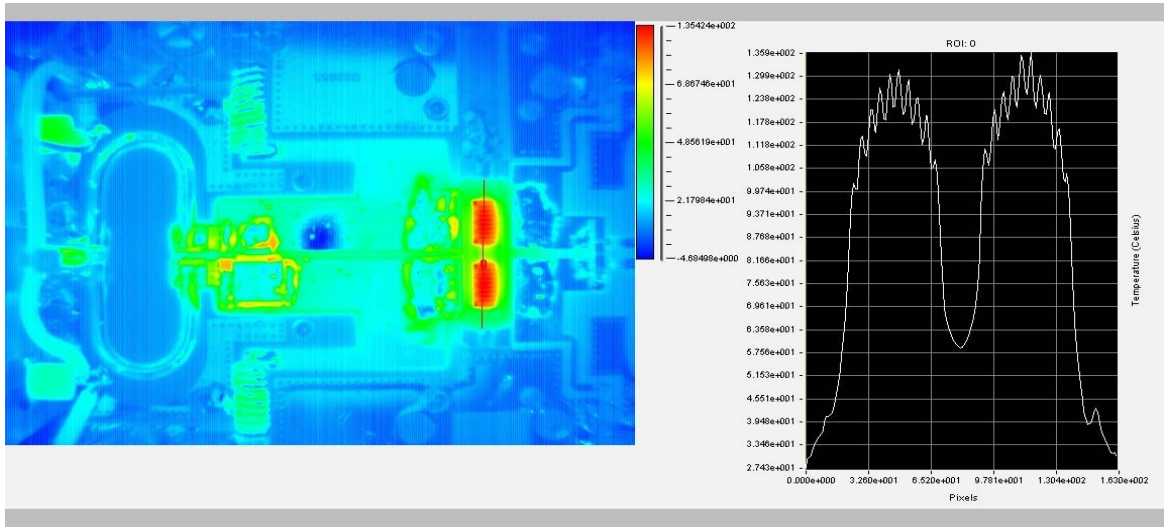


APS 352-MHz 1kW Amplifier Testing

- Vd = 49.26V
- Id = 30.65A
- Pdc input = 1509.82 watts
- RF output = 1000 watts
- Eff = 66.2%
- RF input = 8.32 watts
- RF gain = 20.79dB



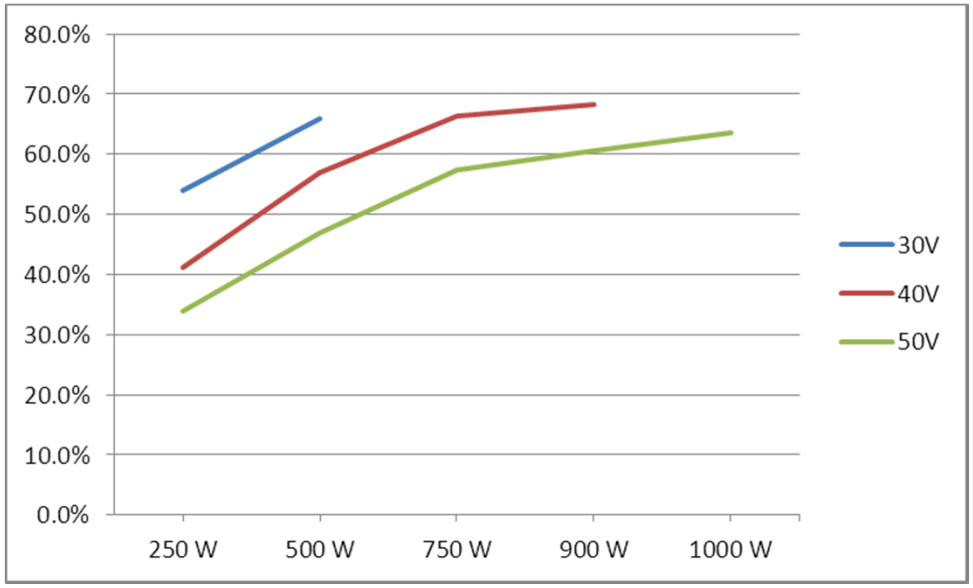


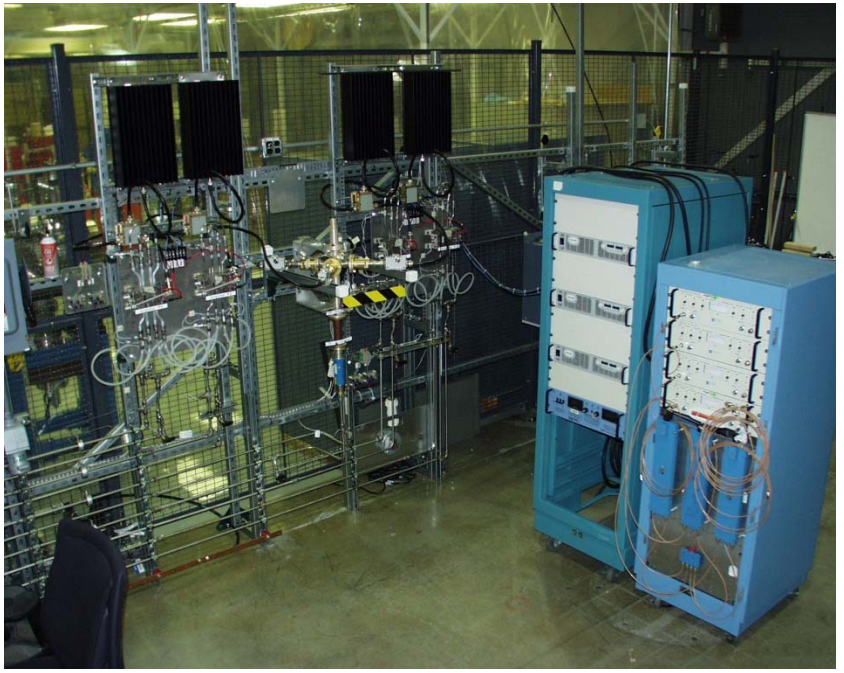


APS 352-MHz 4kW Demonstration

Produced 3.45kW CW

Demonstrated advantage of drain voltage control to improve efficiency at intermediate power ranges:





Why Consider Solid State RF Power for APS?

(the standard answers……)

- **Improved Operating Efficiency**
- **Improved Reliability**
- **Lower Maintenance Costs**

(other pressing concerns……)

- **Cleaner RF Power**
- **Future Availability of 352-MHz/1MW CW Klystrons**

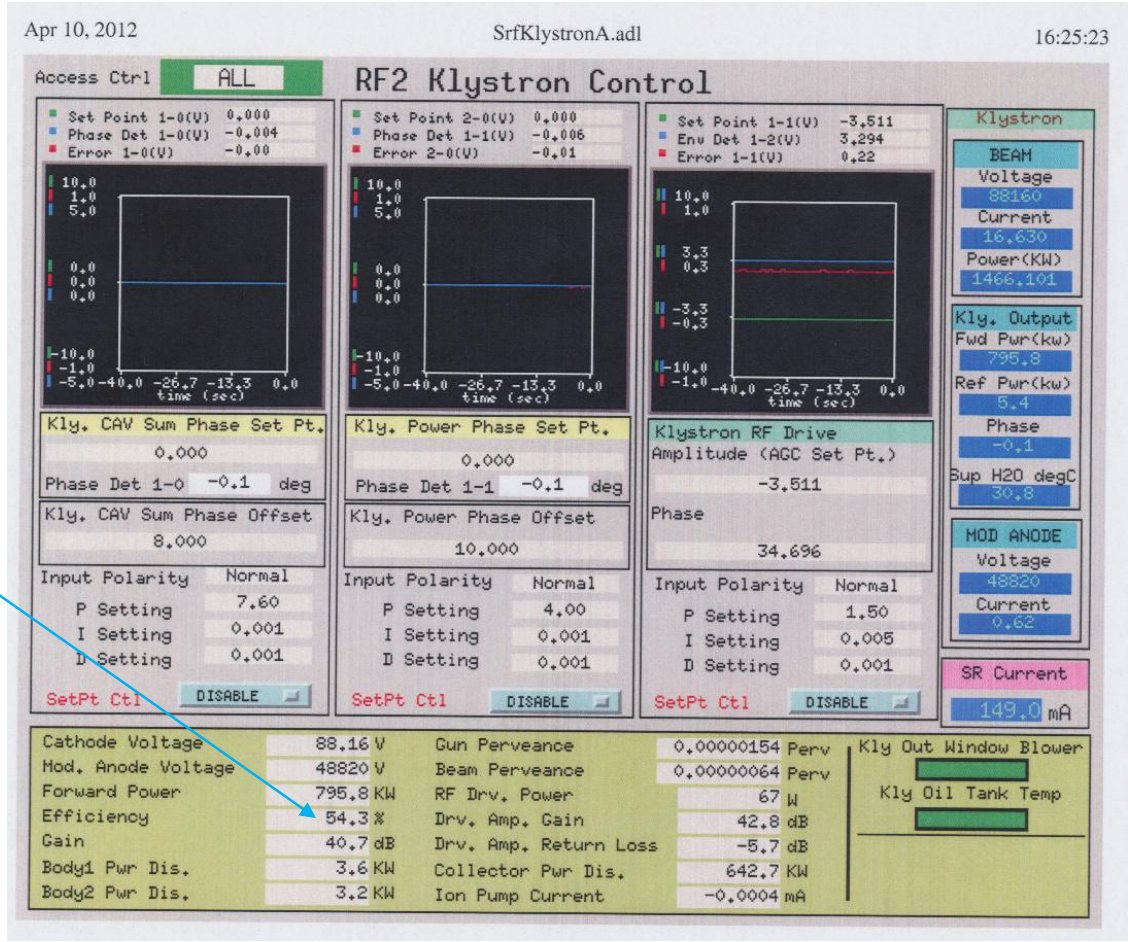
Improved Efficiency? ✓

- **SR RF system efficiency poor (≈ 30%) at injection**

  → *≈ 350kW klystron rf output*

- **Improves to ≈ 55% with 150mA stored beam**

- **Booster % efficiency is *very poor* due to low average rf power: ≈ *16%***



A solid state amplifier system with efficiency optimization could improve average storage ring rf system efficiency by ≈ 10-15% …… ***But 200kW IOT's could do it too***

Improvements in Reliability?

- RF downtime and mean time to fault (MTTF) since 2010:
  - → FY2010: 0.31%, 307.8 hours
  - → FY2011: 0.10%, 490.6 hours
  - → Run 2011-3: 0.11%, 769.0 hours

- ***Latest run, Feb 1, 2012 to April 25, 2012:***
  - → Total rf system downtime = *0.047%*

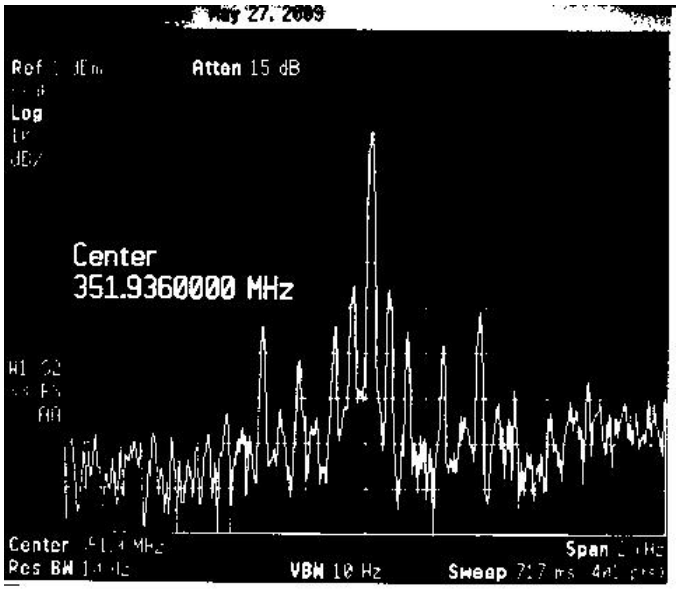
APS facility downtime 0.27% with 287 hours MTTF

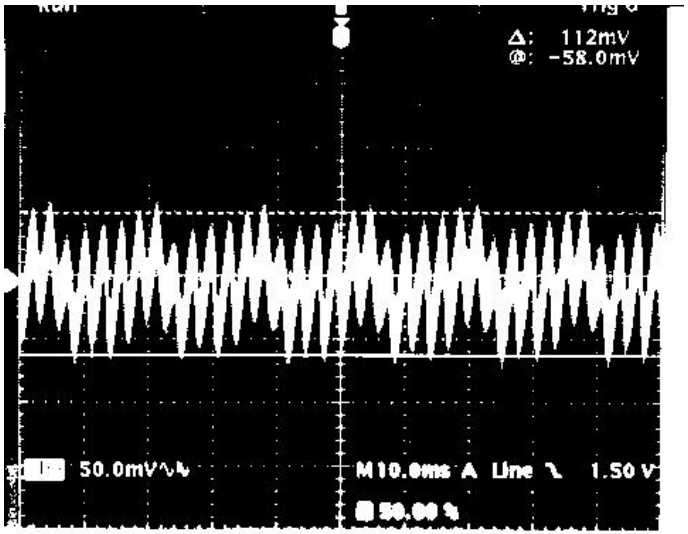
The argument for solid state in terms of rf system reliability is not strong

Cleaner RF Power?

- The APS Short Pulse X-Ray (SPX) Upgrade will require a significant reduction in phase and amplitude noise on the storage ring rf
- The major source of noise has been identified as 360Hz and other ac line harmonics on the klystron HVPS output
- LLRF Adaptive feed-forward compensation techniques are being developed to address the problem in the present rf systems…….

The 352-MHz/1kW solid state amplifiers tested at APS have demonstrated very low uncorrected noise





352-MHz/1MW CW Klystron Availability?

- **Only one supplier remains: *Thales***
- **Cost per unit has increased ≈ 300% since 1992**
- **The number of sockets worldwide for these klystrons is shrinking (12?.....15?) *How long will they be available?***
- **Other capable suppliers exist, but NRE would be significant**

APS 352-MHz Klystron Inventory

- Operating klystron hours as of 4/25/12:

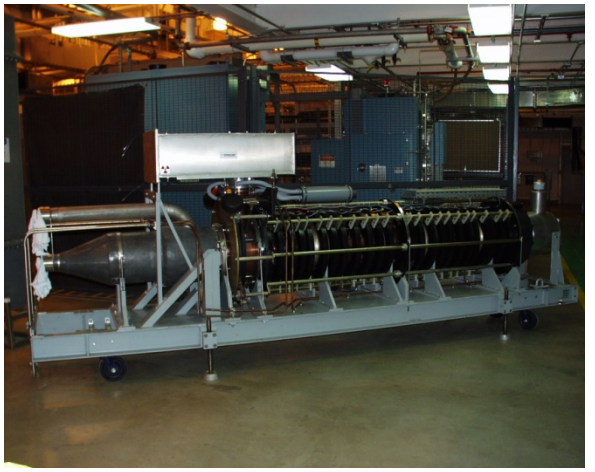
  → ***RF1 ---- Thales s/n 089043 ---- 11,076 hr***

  → ***RF2 ---- Thales s/n 089036 ---- 13,638 hr***

  → ***RF3 ---- EEV s/n 01 ---------- 71,754 hr***

  → ***RF4 ---- Thales s/n 089030 ---- 43,174 hr***

  → ***RF5 ---- Thales s/n 089026 ---- 62,033 hr****



Average klystron lifetime at APS is ≈ 64k hours

……but higher output power required for 150mA operation will shorten lifetime

*** Longest Thales lifetime at APS to date**

APS 352-MHz Klystron Inventory

- **Spares:**
  - → *Thales s/n 089024 ---- rebuilt, FAT on Aug. 30, 2004*
  - → *Thales s/n 089029 ---- rebuilt, FAT on Dec. 8, 2003*
  - → *Thales s/n 089033 ---- rebuilt, FAT on Feb.6, 2007*
  - → *Thales s/n 089048 ---- new, at factory for repair, FAT June 2012*
  - → *Thales s/n 089054 ---- new, FAT 11/16/12*
  - → *Thales s/n 089055 ---- new, FAT 11/15/11*
  - → *E2V (Los Alamos) s/n 01 ------ retuned, tested to 1MW June 10, 2011*
  - → *E2V (Los Alamos) s/n 005 ---- retuned, tested to 1MW, June 10, 201*
  - → *Philips (CWDD) s/n 73201.55 ---- retuned, tested to 1MW, Feb 10, 2011*

Retired klystrons that still function:

- → *Thales s/n 089041 ---- retired May 3, 2010 at 56,360 hours (sideband instabilities, high body losses, x-rays)*
- → *EEV s/n 01 ---------- retired Jan.11, 2012 at 77,725 hours (no issues)*

Do we have enough spares to last APS lifetime?

Solid State Challenges at APS

- **Cost!**

  → The cost of solid state power, plus reconfiguring 352-MHz rf topology to one 200kW amplifier per cavity (x12 or 16) would require a complete redesign of waveguide, LLRF, ac power, water, and interlock systems – *even at $5/watt for SS power, the total cost could exceed $30-$40M*

- **Physical Constraints**

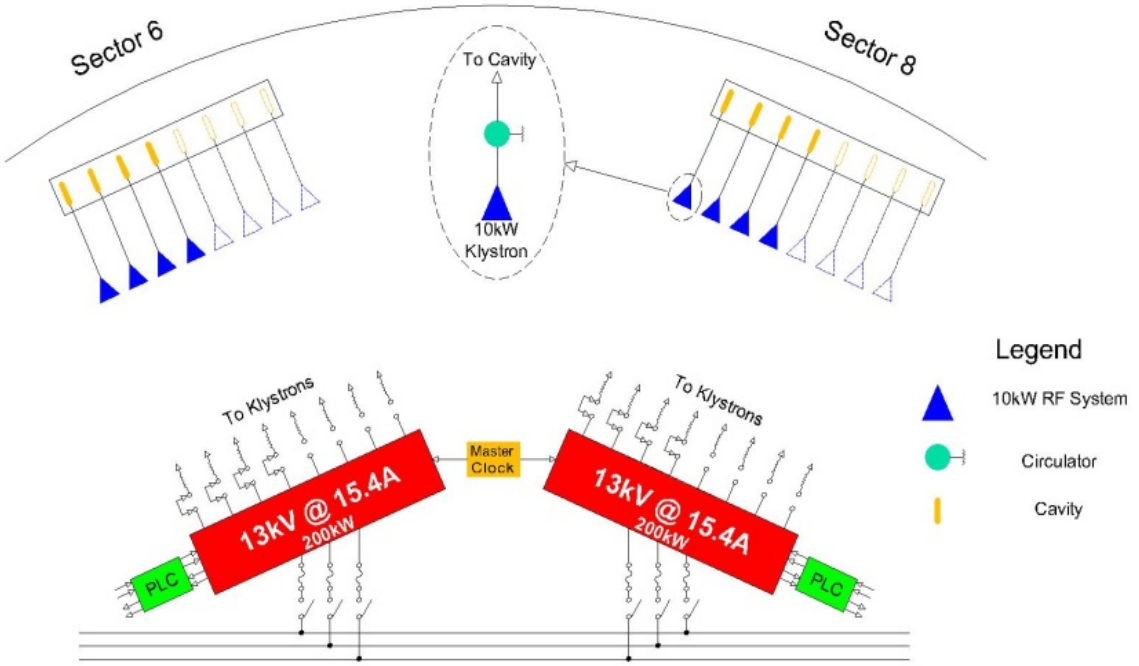
  → Existing klystron rf systems produce ≈ 950 watts per sq-ft of floor space……..*a solid state system must fit in the existing building*

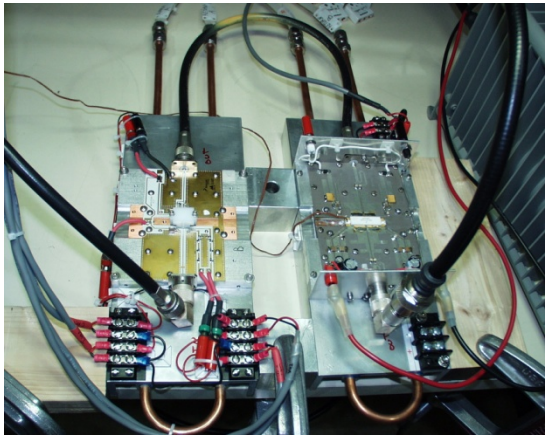
- **Interruption of APS Operations**

  → Reconfiguring 352-MHz HLRF topology alone could require many months of dark time

Solid State for SPX?

- SPX conceptual design calls for 10kW CW power at 2.815GHz using klystrons
- 10kW CW at S-band is possible with solid state
- Power -vs- cost break point between solid state and existing klystrons appears to be at ≈ 3-4kW CW
- SPX S-band CW power costs estimated at ≈ $55/watt for solid state and ≈ $20/watt for klystrons

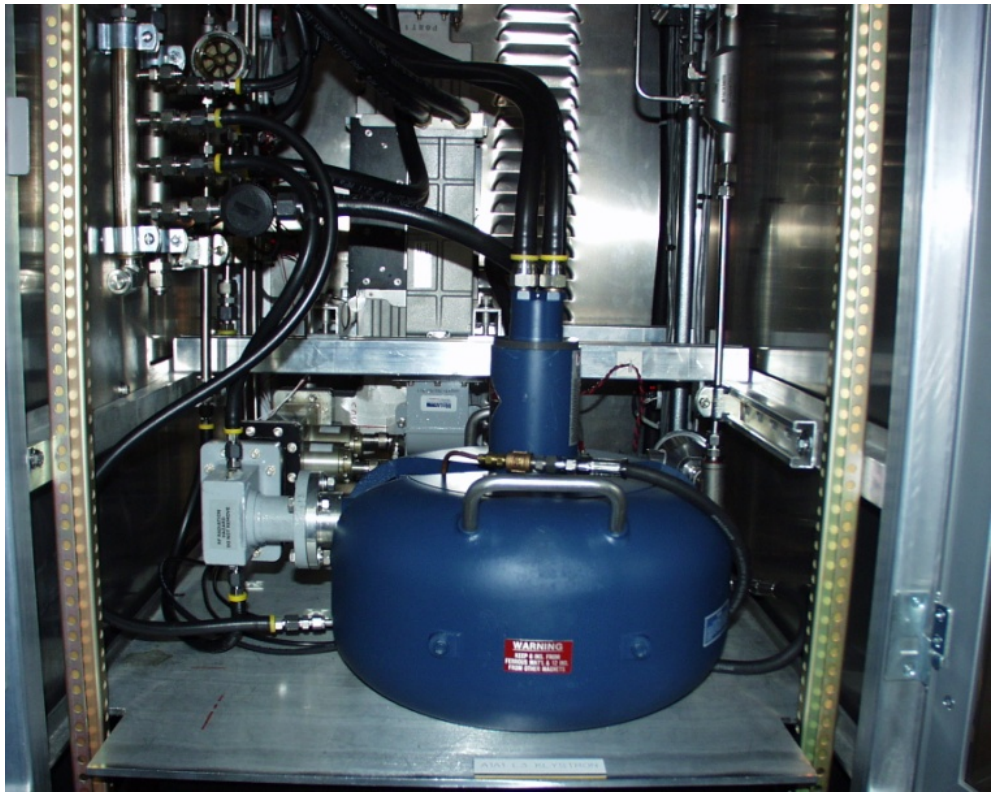




2.815GHz/150 WATT CW DEMONSTRATION AT APS

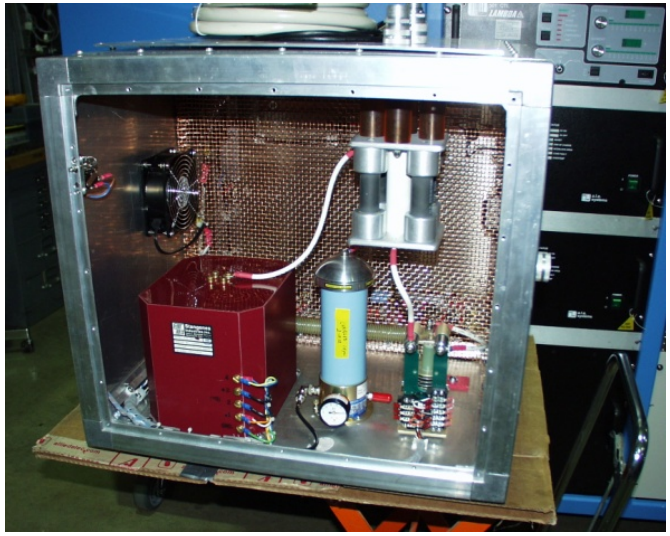
L-3 2.815GHz/5kW CW Klystron

- 1-5/8” EIA coaxial output
- Permanent magnet focus
- Mod-anode gun, but will be operated in diode mode
- Requires 12kV @ 1.295A
- RF gain ~ 42dB
- Efficiency not so hot (≈ 32%), *but no focus supplies needed*
- Stable operation to full power



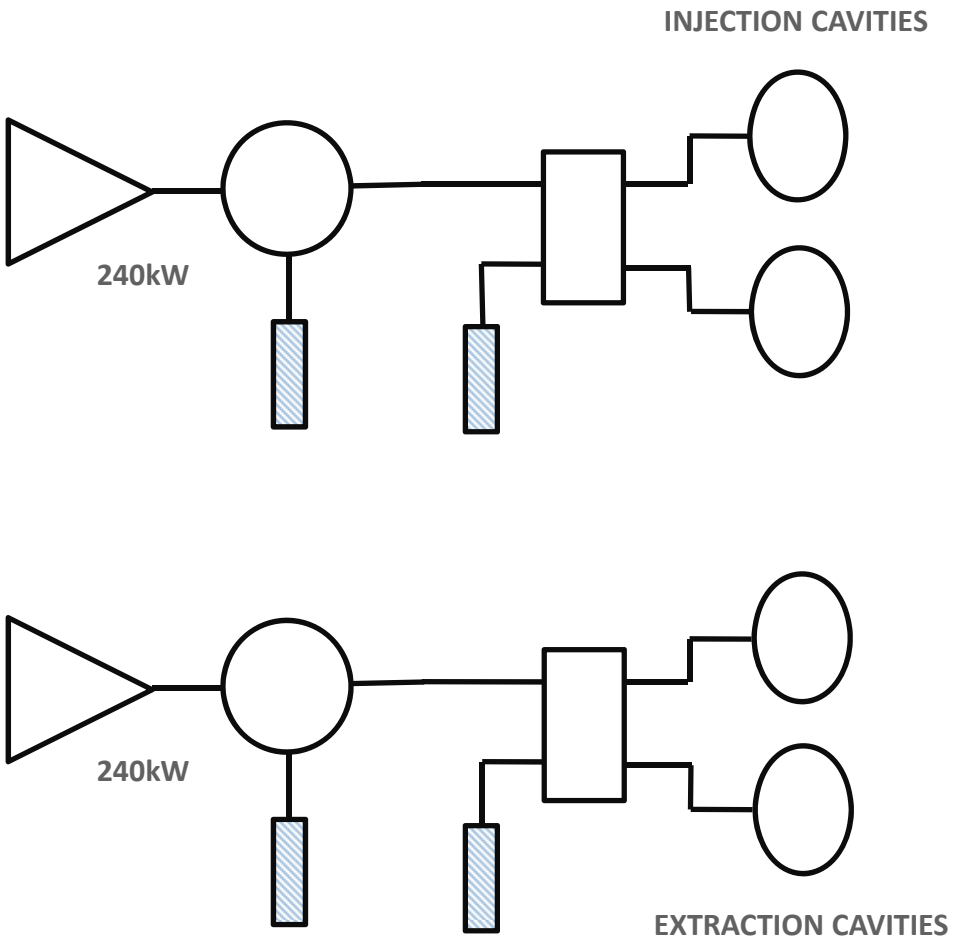
SPX-0 2.815GHz/5kW CW Amplifier System

- Utilizes L-3 L4442 PM-focus klystron
- 50kW output isolator and RF load
- Includes waveguide shutters between klystron and isolator input port
- Ultra-low ripple HVPS for minimal phase and amplitude noise on output



Solid-State Booster at APS?

- **Seems most "do-able" cost-wise:**
  ≈ $4-6M??
  → ***Would not affect SR rf systems***
- **Less disruption to APS operations**
- **Assuming 60% overall efficiency, would reduce ac line load by ≈ 600kW**
- **May fit in available space due to 90^{o} orientation of APS booster rf**
- **Two 240kW systems would provide 80kW of headroom over present booster operating point**

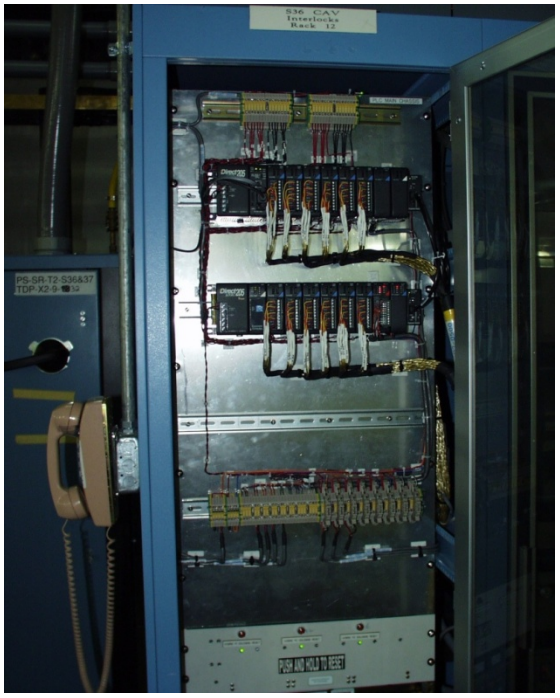


Reliability Upgrades Since 2010

Upgrade of RF Interlock Systems

- **Replacement of all original process meter relay logic rf interlock systems with PLC's was completed**
  - → *Simplified system wiring, reducing intermittents*
  - → *Eliminated process meters and associated failures*
- **Only two rf system trips attributed to PLC interlock systems since 2005!**
- **Eliminated at least 2-3 trips/year from old interlock systems**

ORIGINAL INTERLOCK SYSTEM AT SECTOR 36 CAVITY LOCATION



PLC INTERLOCK SYSTEM INSTALLATION AT SAME LOCATION

Reliability Upgrades Since 2010

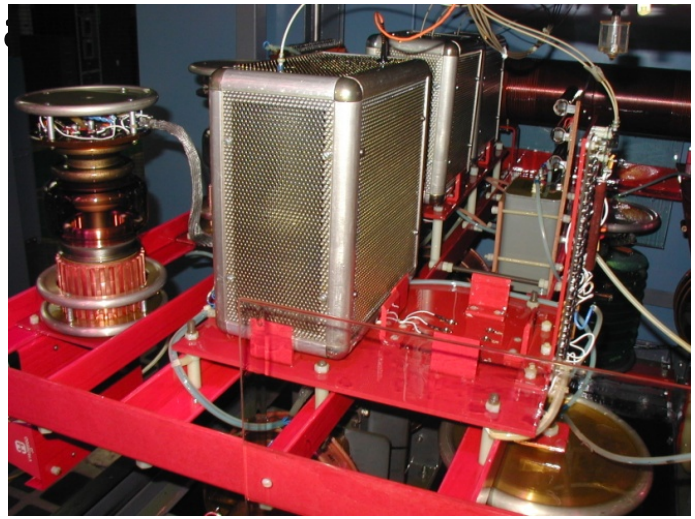
Replacement of Original 13.2kV Fused-Disconnect Switches

- Original switch would fail and stick in open or closed position
- Typically 2-4 failures per year
- Significant downtime to make repairs
- No failures with new switch!
- See Gian Trento talk

NEW 13.2kV SWITCHES BEING PREPARED FOR INSTALLATION

Enhanced High-Voltage Power Supply Maintenance

- **Detailed visual inspection of mod-anode regulator tank components**

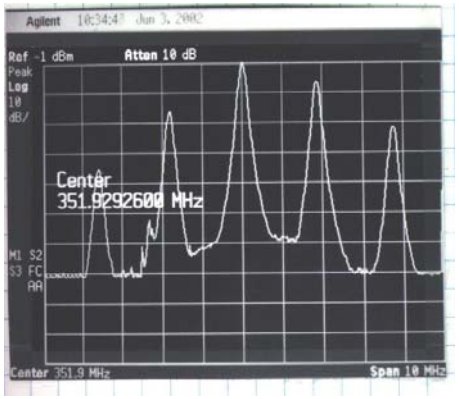


- **Tests on T-R set oil to detect arcing**
- **See Gian Trento talk**

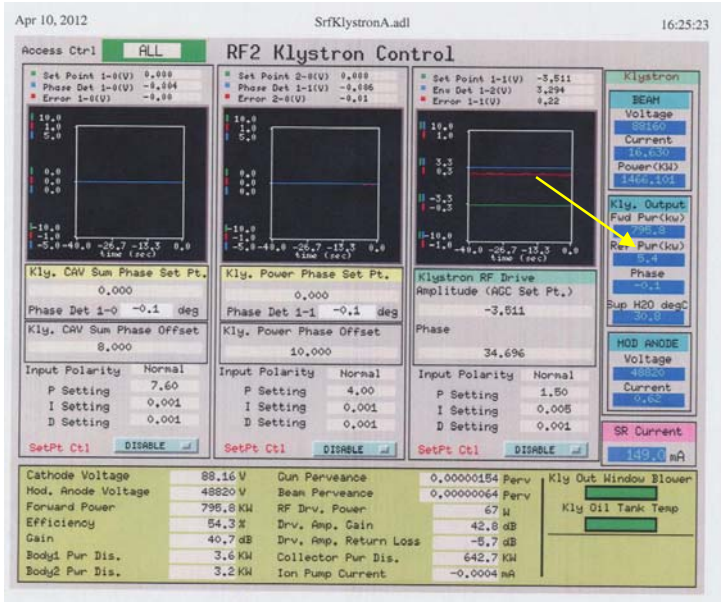
RF1 HIGH VOLTAGE POWER SUPPLY CONTROL RACKS

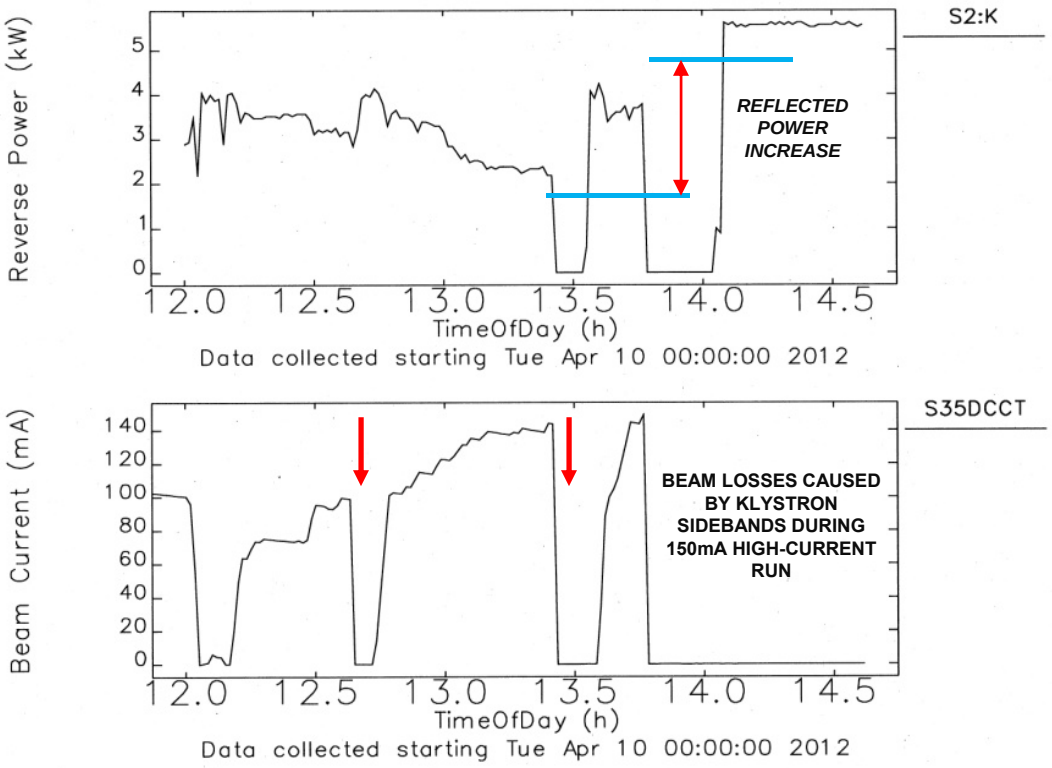
Major Klystron Issues

Klystron Sidebands



- Remains an issue with Thales TH2089A klystrons
- Ability to adjust circulator bias is critical to achieve stability
- 1-2kW increase in reflected power is typically effective
- ≈ 2-3% efficiency penalty





Major Klystron Issues

Gun Arcing

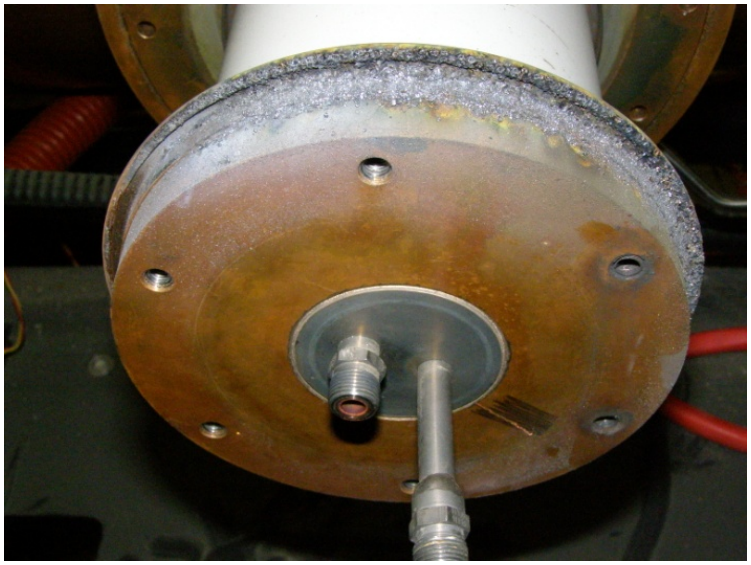
- Typically caused by barium deposition over time
- Causes random crowbar trips
- All klystrons have developed this problem to some degree
- "Spotknocking" the klystron gun is very effective
- Extends useful life of older klystrons
- *A spotknocking power supply system is essential to maintain system reliability*

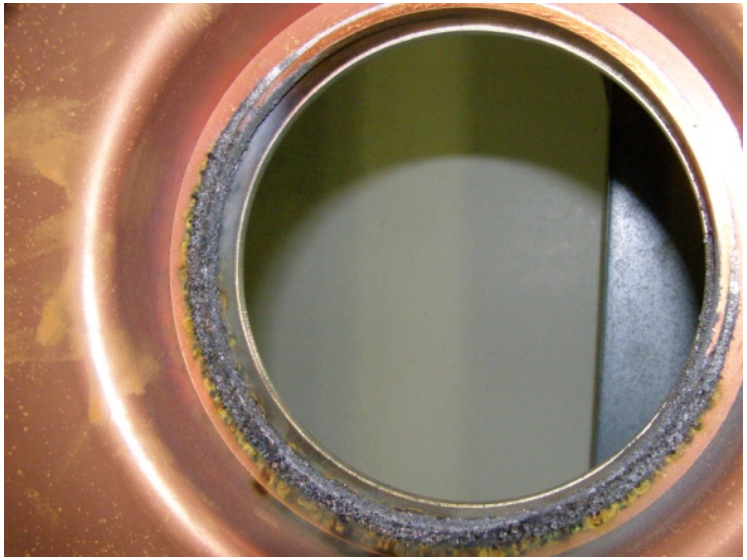
125kV/10mA SPOTKNOCKING POWER SUPPLY WITH PANTAK CABLE SET AND HIGH VOLTAGE JUNCTION BOX

*Last But Not Least……*Hardware Failures for CWRF2012!

Booster Input Coupler -- Waveguide Transition Arcing

- Arcing damage caused by degraded rf contact with waveguide transition matching post
- Coupler had to be replaced after 17 years of service!
- Same problem seen on one other coupler, but not as bad; coupler contacts will be cleaned and a new matching post will be installed
- One coupler will be disassembled for inspection every shutdown from now on

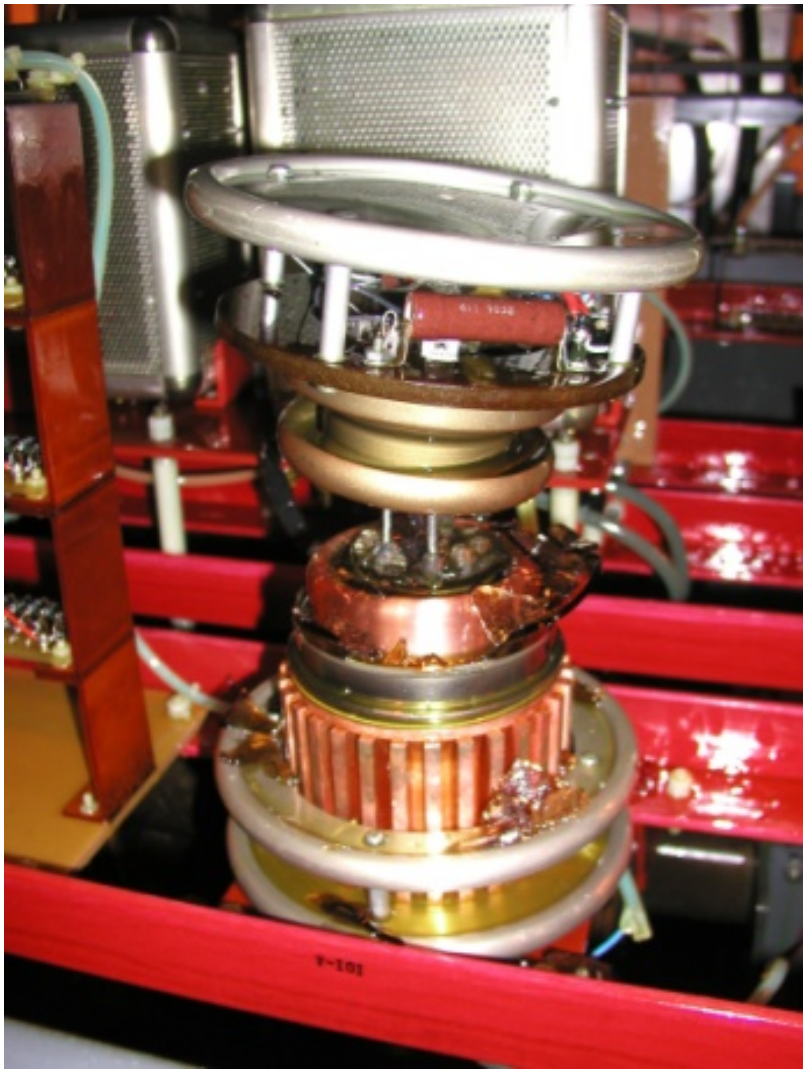




Hardware Failures for CWRF2012

Destroyed TH5188 Tetrode

- Crowbar failed to fire due to accidental disconnection of fiber optic cable
- The tetrode took it very hard
- Very loud noise, very upsetting to people
- On the bright side…….*no other damage occurred*



TETRODE IN HVPS MOD-ANODE REGULATOR TANK