The Advanced Photon Source RF Systems

-- Performance and Upgrades – 2012-2014

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RF Group
ASD Seminar
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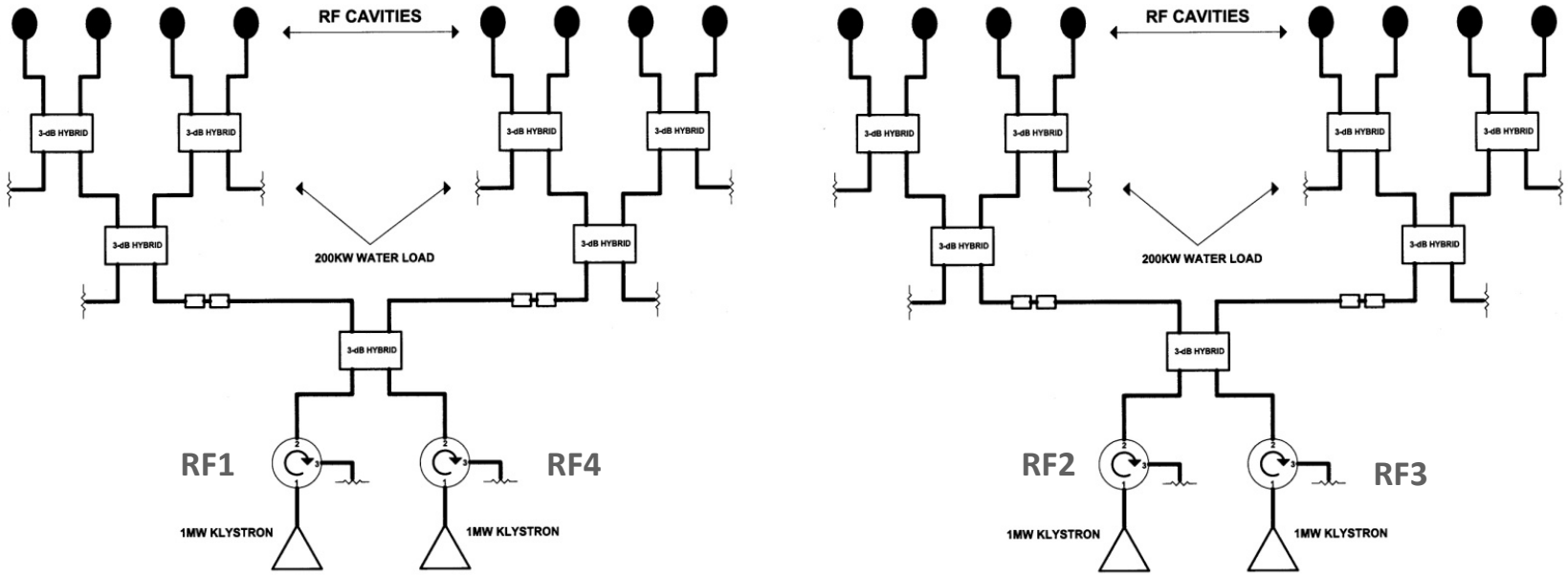
APS Storage Ring RF Topology

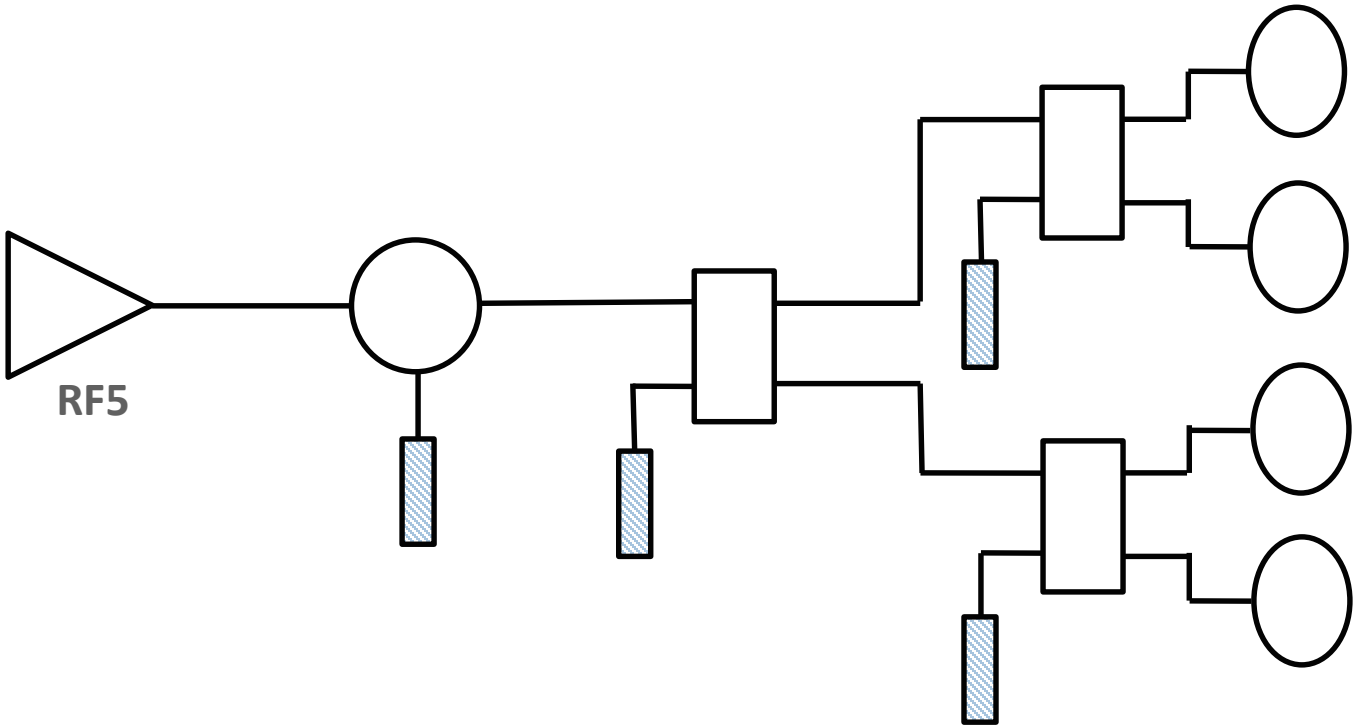
- **Waveguide switching system provides twelve modes of operation with different combinations of rf systems**
- **Routine storage ring operation is 103mA maximum stored current in “top-up” mode**
- **Requires two klystrons driving storage ring, each operating at ~ 675kW CW**
- **“Offline” rf stations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



APS Booster RF Topology

- **Uses one 1-MW klystron (RF5) operating at 400kW peak, ~ 120kW average power**

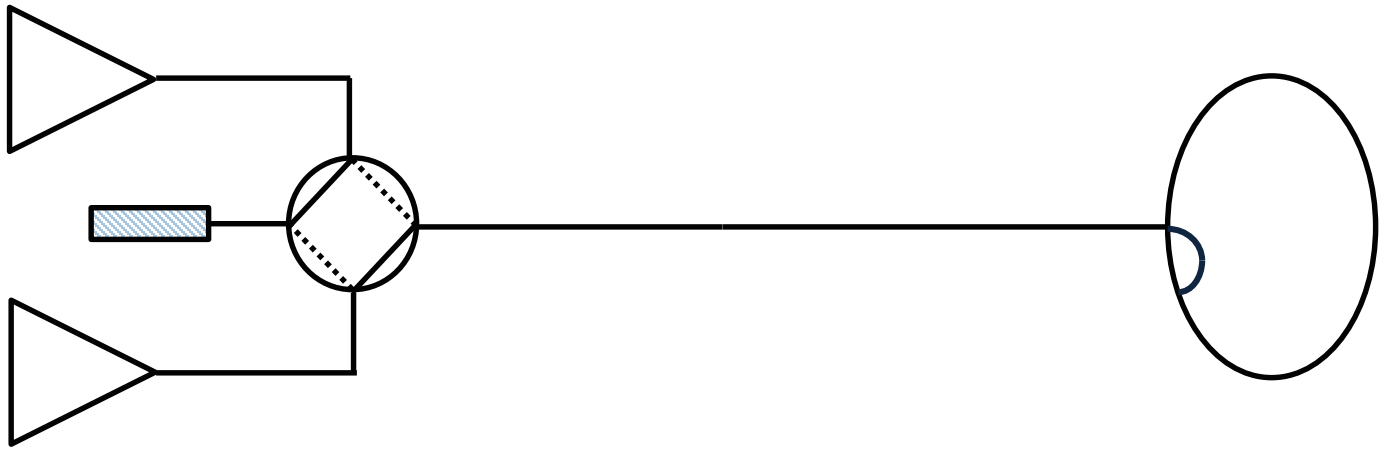
- **Waveguide switching system allows storage ring station RF3 as a back-up to RF5 -- *successfully tested on 7/15/14***



PAR Accumulator Ring -- RF System Topology

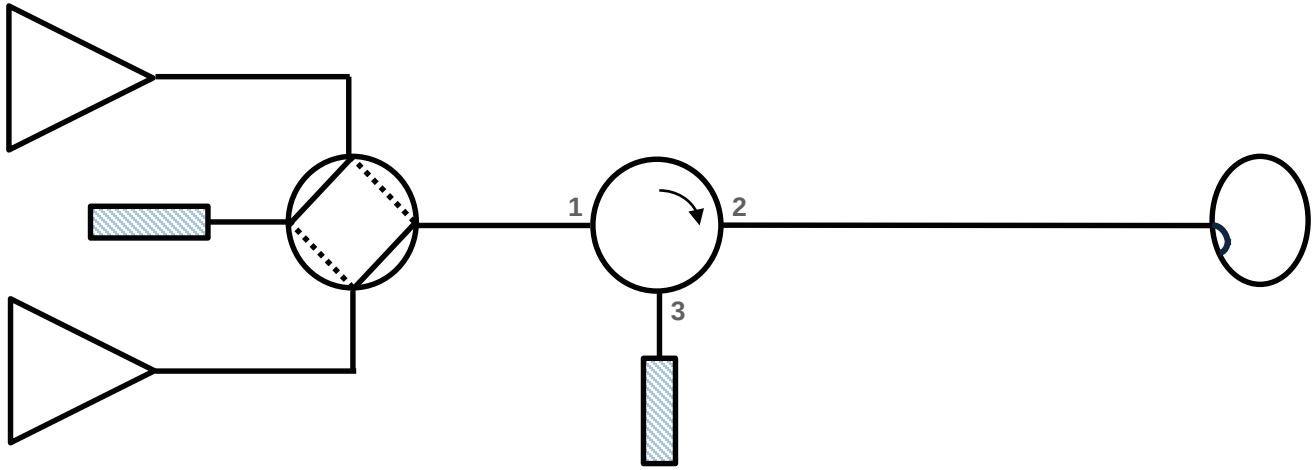
Fundamental System

- 9.77 MHz
- 4kW CW
- YU-106 triode
- Grounded grid
- Main/backup power amplifiers



Harmonic System

- 117.3 MHz
- 3kW peak
- 3CX3000A7 triode
- Grounded grid
- Main/backup power amplifiers



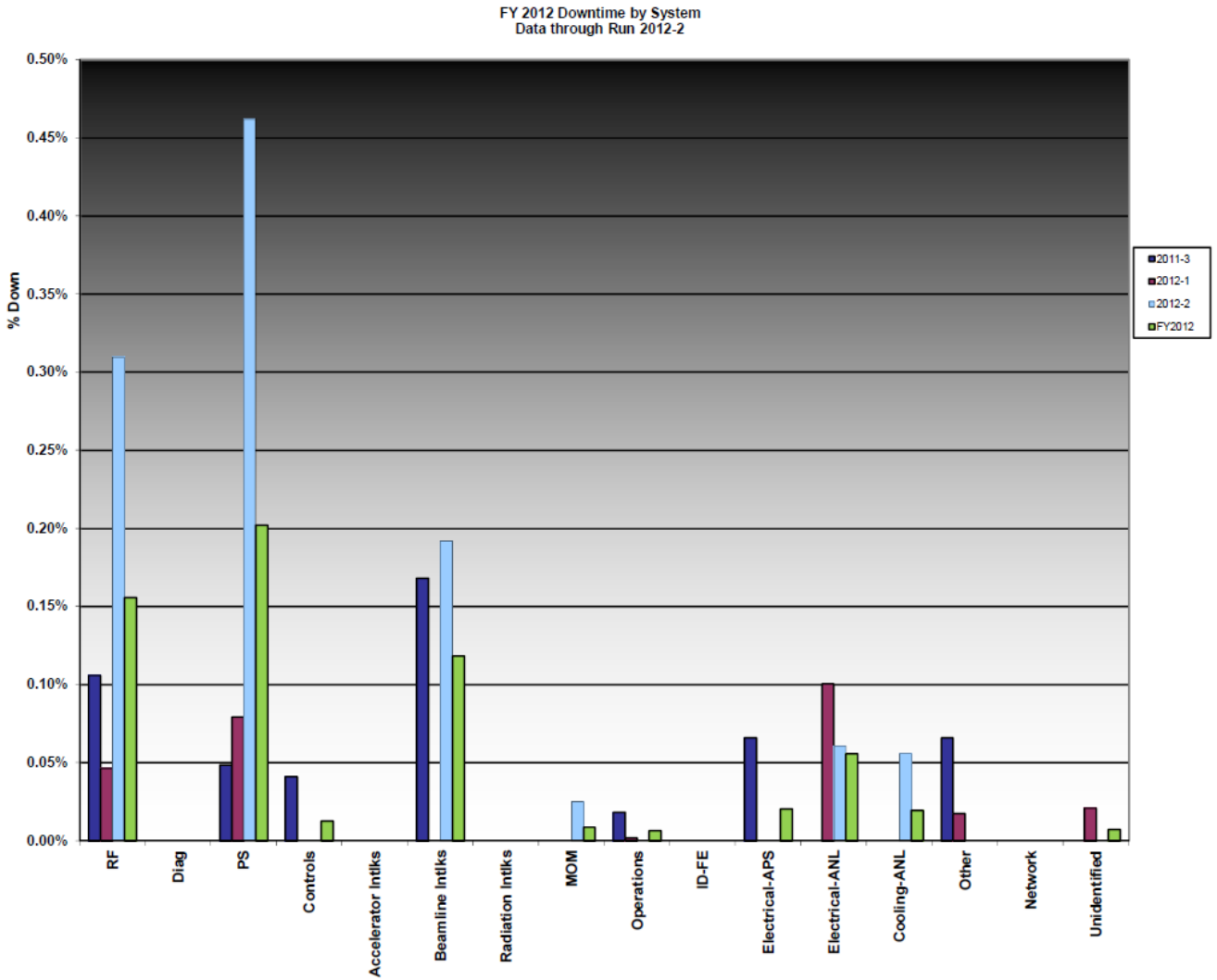
RF System Reliability Statistics

RF System Downtime – FY2012

Main RF Downtime Causes:

→ 24v linear power supply failed in rf power monitor

→ Focus magnet power supply tripped on RF2, and operator error in closing 13.2kV switch



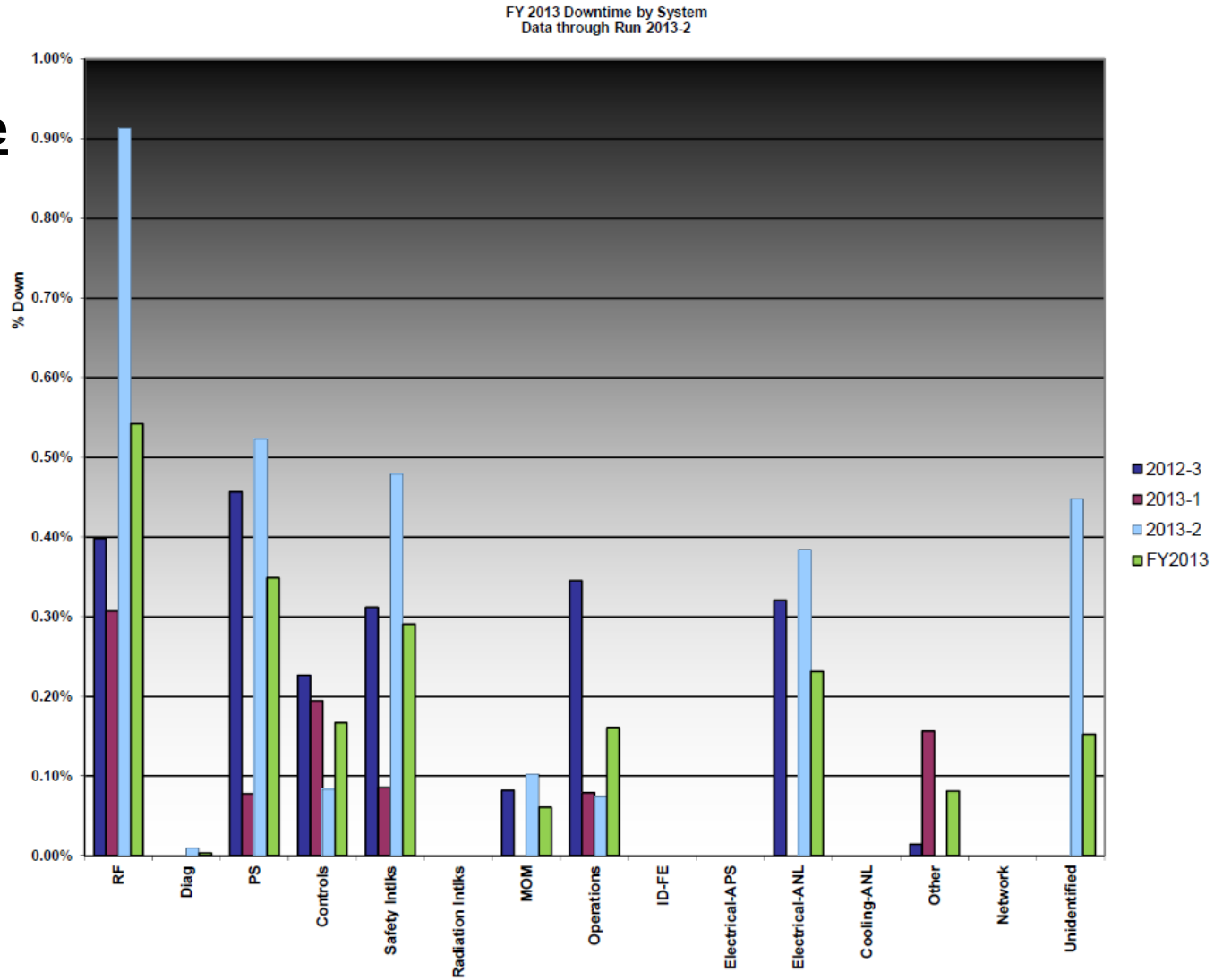
RF System Downtime – FY2013

Main RF Downtime Causes:

→ Sector 38 rf cavity vacuum problem

→ Intermittent failures of LLRF VXI crate power supply

→ Intermittent loss of mod-anode voltage regulation at RF2



RF System Downtime – FY2014

Main RF Downtime Causes:

→ RF3 crowbar trips

→ RF3 klystron sidebands

→ Intermittent access door interlock switch

→ Vacuum trips at Sector 37 rf cavities

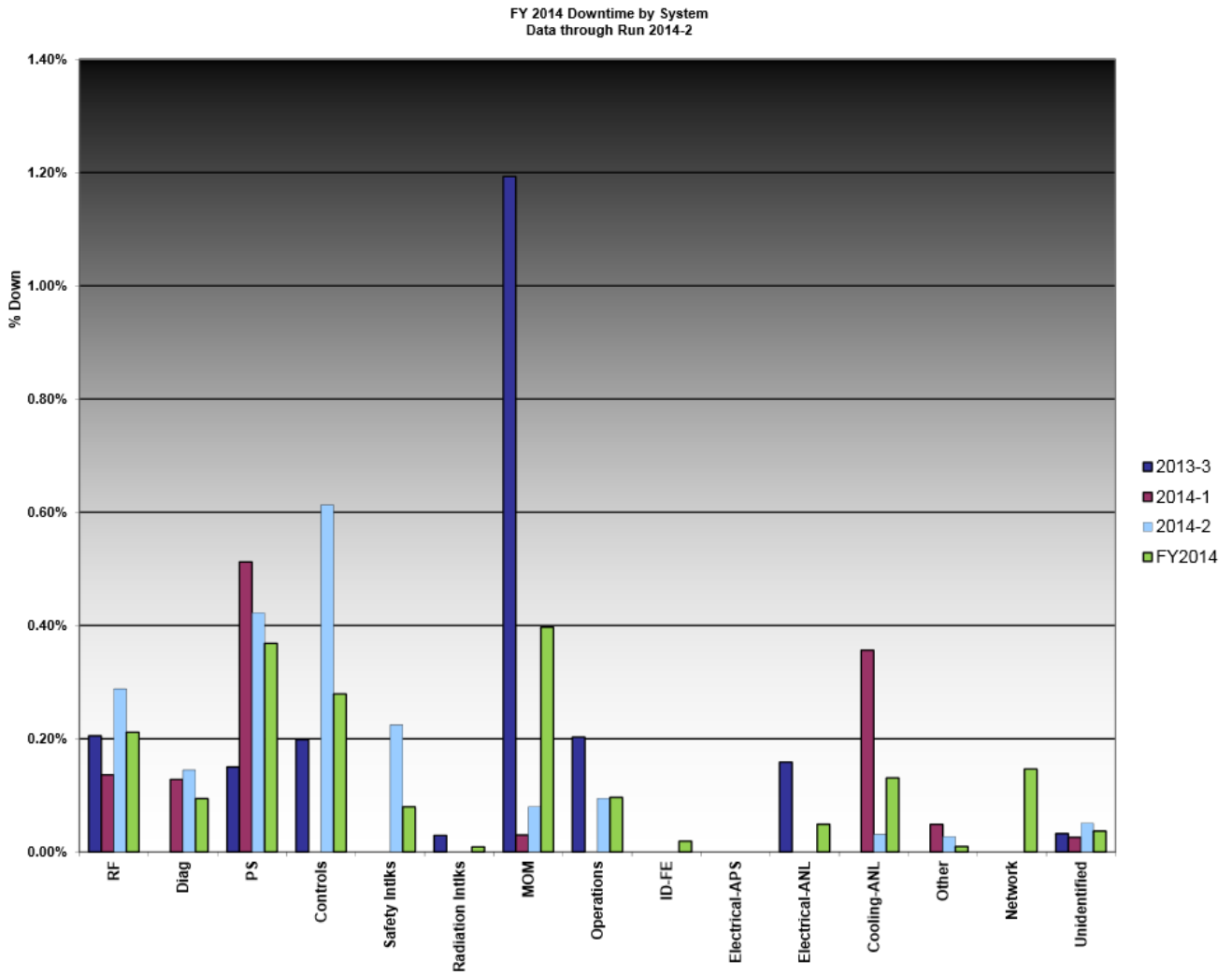
→ Intermittent hv cable

→ Klystron instabilities and waveguide arcing at RF3

RF:

→ 0.21% downtime

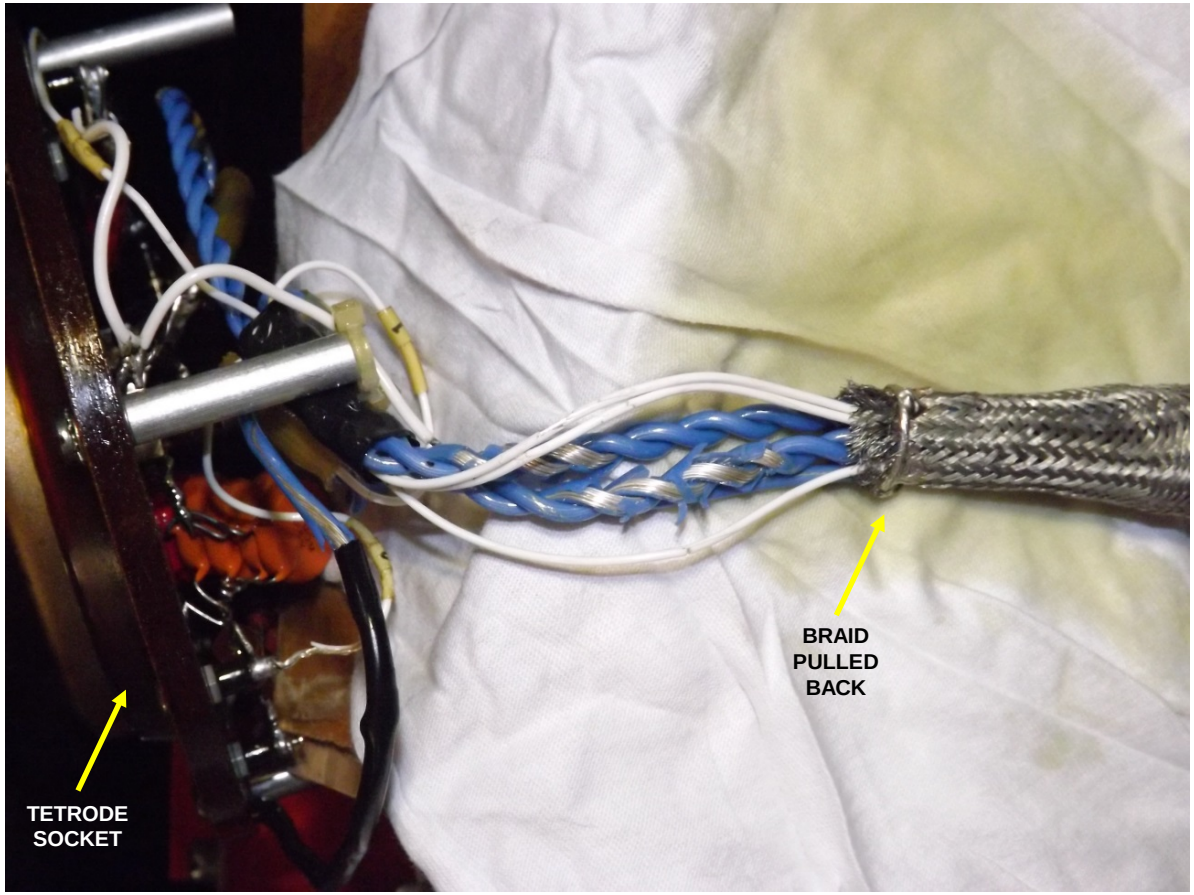
→ 544.5 hours Mean Time Between Faults



RF System Problems and Hardware Failures

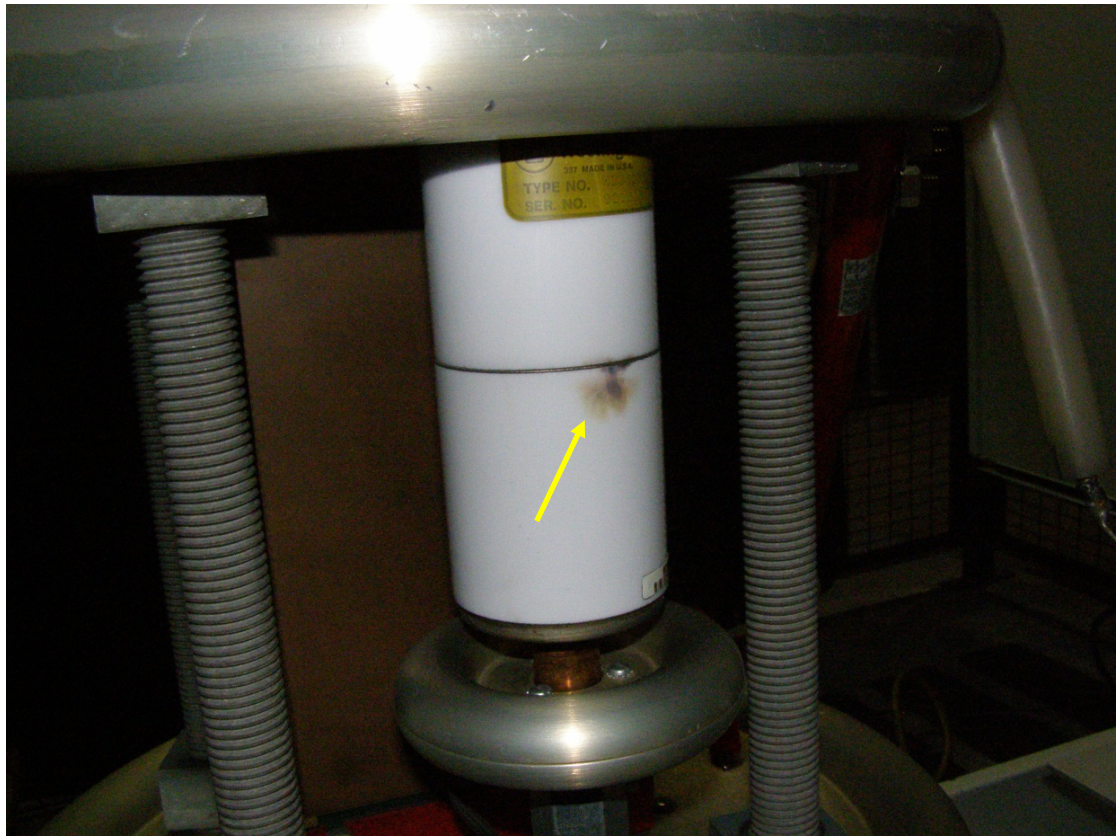
Intermittent Loss of Mod-Anode Voltage Regulation – *cause of many beam losses*

- 18 years of X-rays from tetrodes damaged teflon wire used to feed heater power to the tetrodes
- Caused intermittent short circuit of heater power
- Damage found in all rf stations
- Wiring was replaced



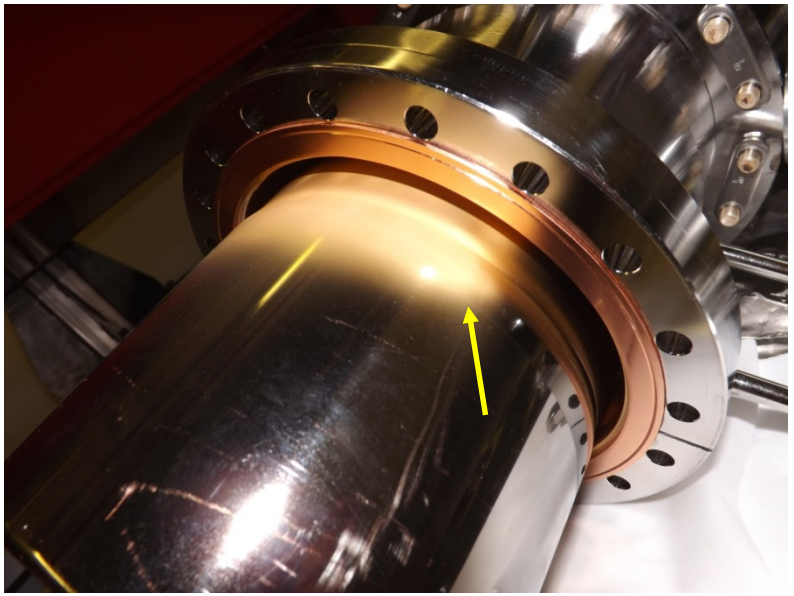
Cause of Crowbar Trips – *Failed 50kV Vacuum Switch*

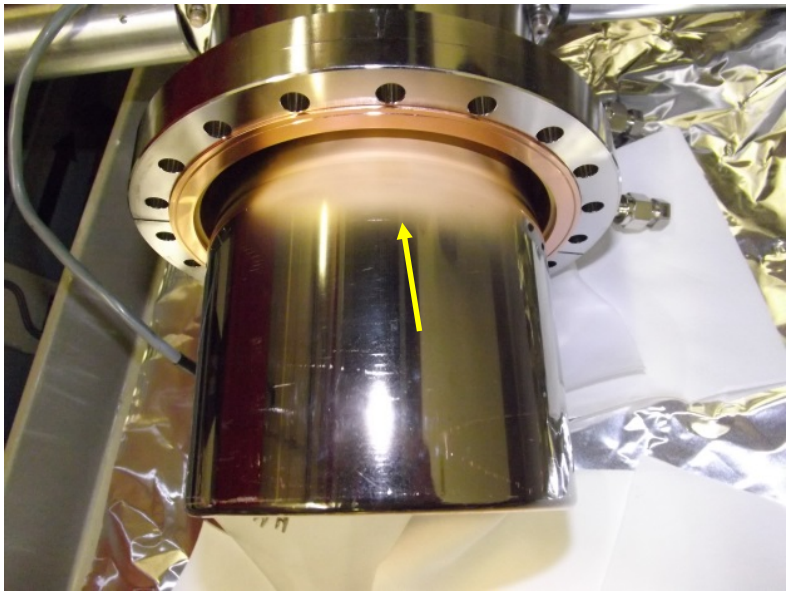
- Two 50kV switches used in series at low end of crowbar test wire
- Switch breaks down in open position, causing intermittent crowbar trips
- No longer available from original manufacturer – found second source

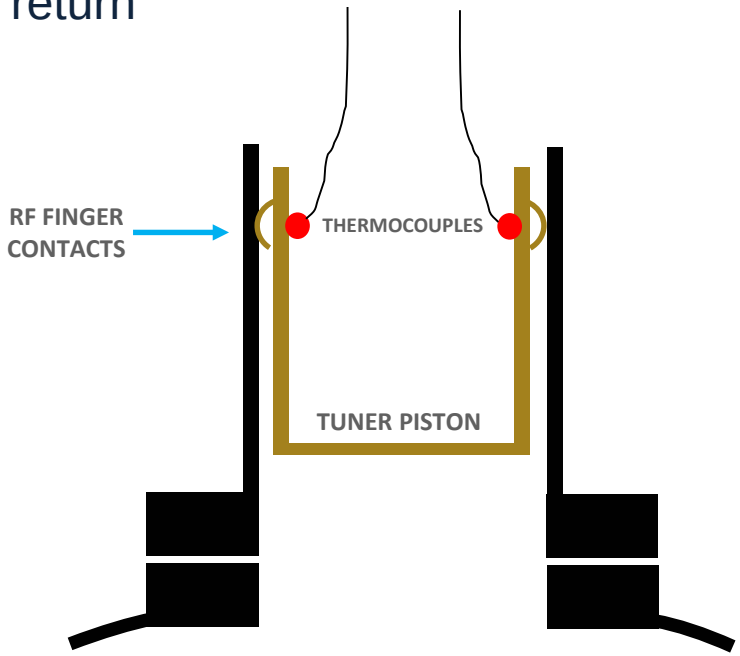


Sector 36/Cavity #3 “Hot Tuner”

- RF Finger temperature suddenly 25-40ºC warmer with hybrid fill pattern – *but normal with 324 singlets*
- Tuner inspection at shutdown shows “plating” on piston……*gold?*
- Tuner was replaced…….problem didn’t return

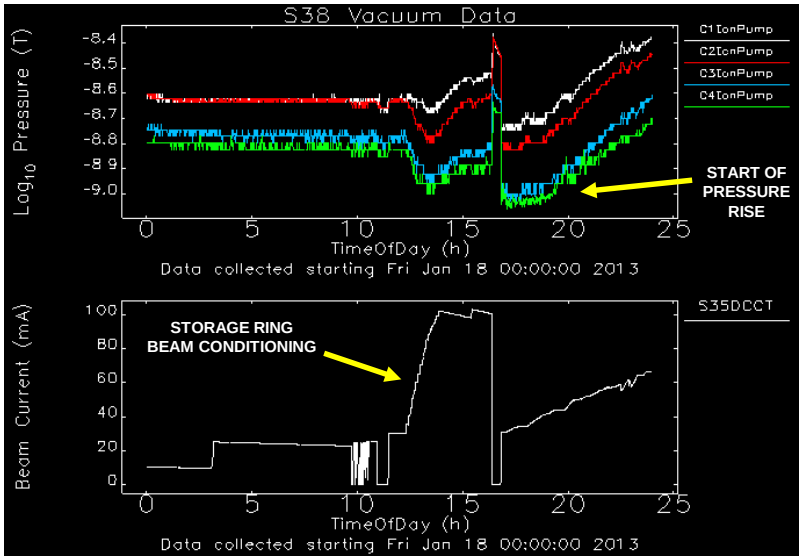


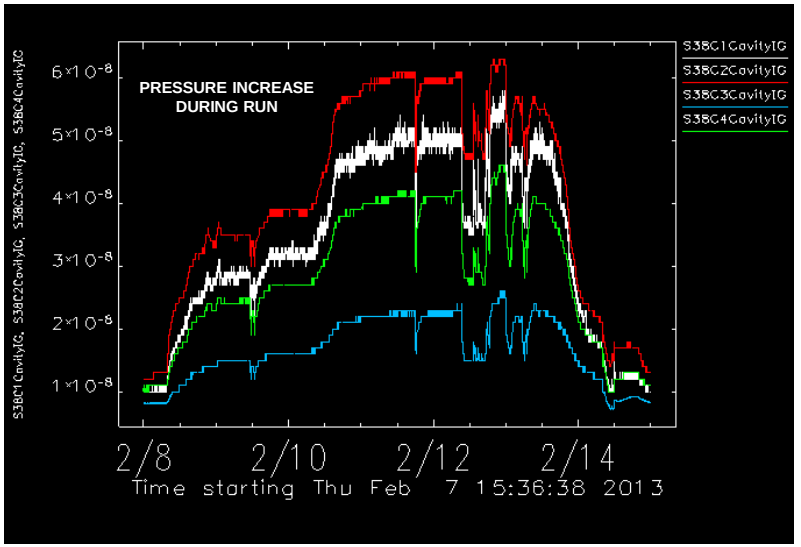




Sector 38 RF Cavities – *Mysterious Vacuum Problem*

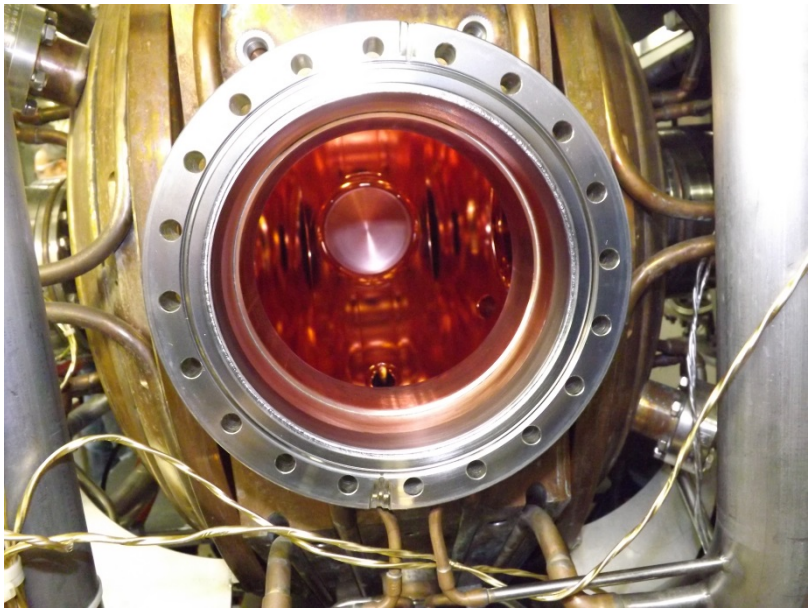
- Vacuum pressure in entire sector of cavities started to rise suddenly at the end of post-shutdown beam conditioning -- *highest pressure in cavity 2*
- Pressure continued to rise as the run progressed, and vacuum interlock trip points had to be raised to stay in operation
- Multiple helium leak tests showed no leaks from atmosphere
- Residual gas analyzer indicated traces of chlorine and fluorine
- Tried conditioning during shutdown, but pressure eventually increased to the point that we could not run rf

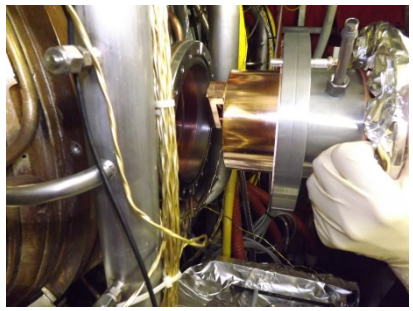




Sector 38 RF Cavities – *Mysterious Vacuum Problem*

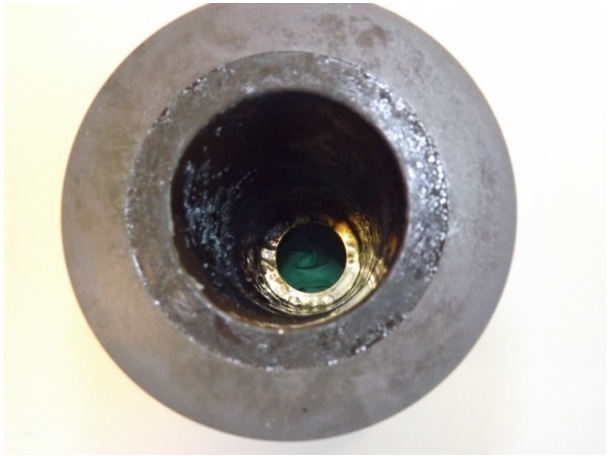
- Parts were *"shot-gunned"* – Couplers, tuners, and HOM dampers were removed from cavities 1 and 2 – *all parts except for one HOM damper were replaced with new components*
- Vacuum pressure quickly returned to normal levels -- low-mid E-9 Torr
- Cavities were re-conditioned back to operating levels in approximately three days
- Pulled parts were installed in RF Test Stand cavity individually to determine which component was outgassing
- Cavity #2 tuner was the source of gas

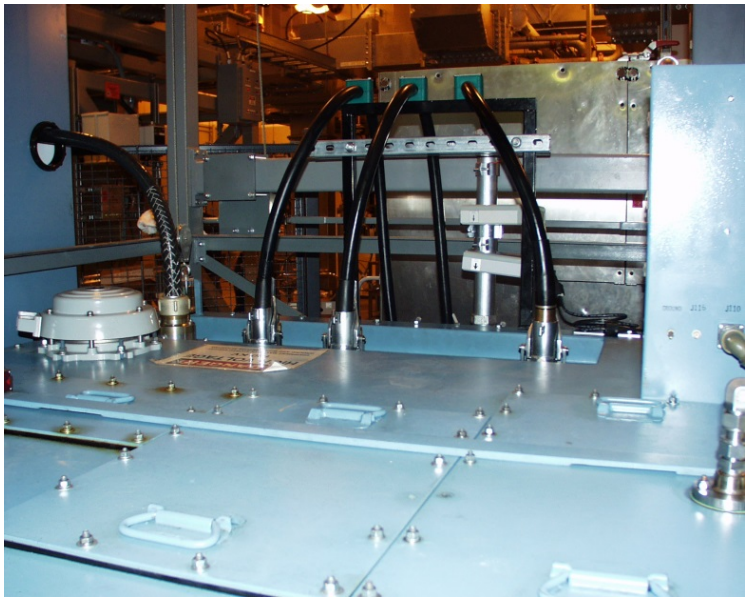




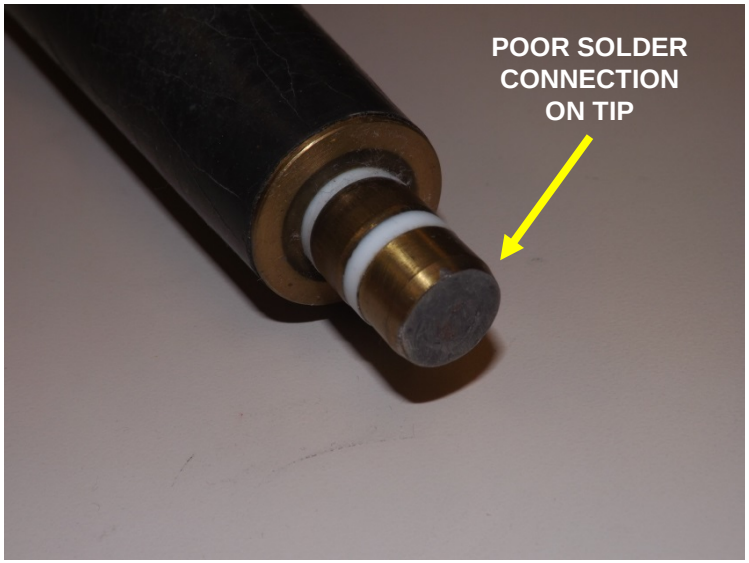
High-Voltage Cable/Socket Failures

- **Connector arcing causes crowbar trip and damage to plug and socket**





- **Causes:**
  - → **Plug insertion force too low**
  - → **Foreign objects in socket**
  - → **Insufficient insulating grease**
  - → **Intermittent contacts on plugs**



Multiple Problems with RF3

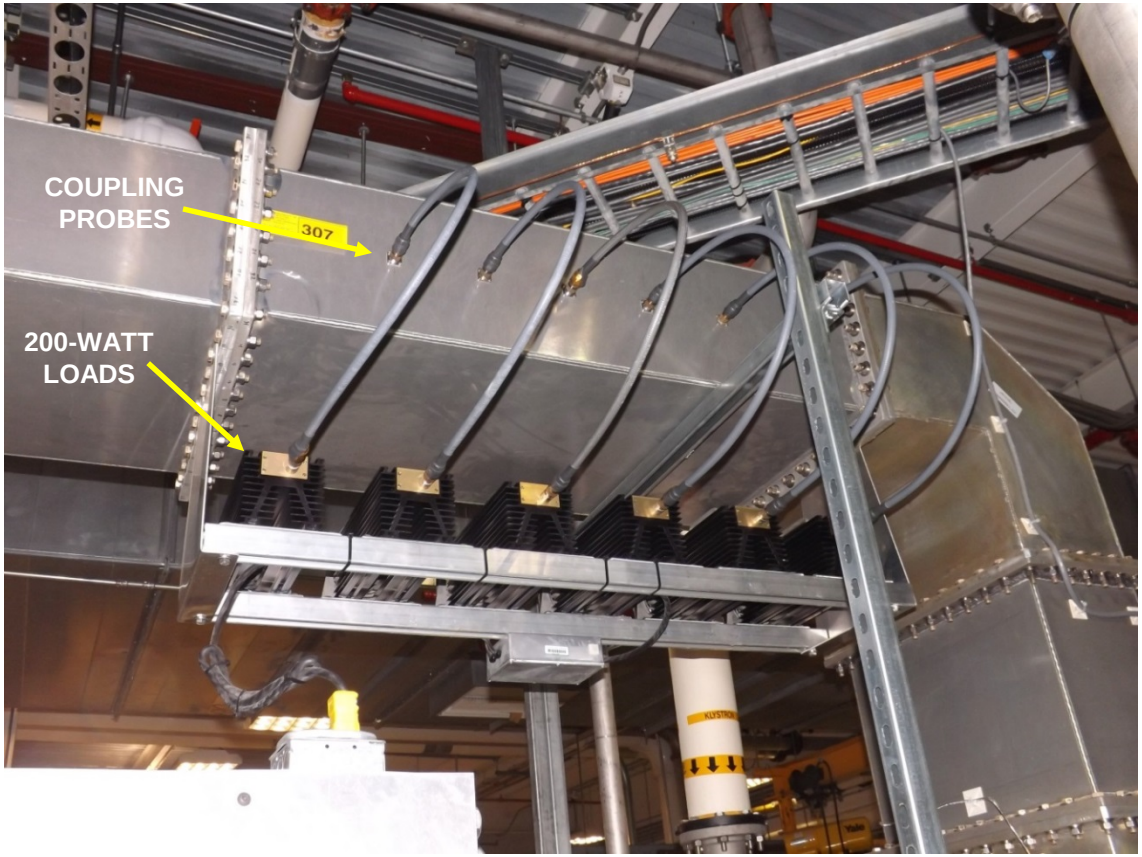
Trouble Started With a Klystron Change!

- **Longest living klystron at APS was retired at RF3:**
  - → EEV K3513 s/n 01
  - → Retired at 81,209 filament hours
  - → 14 years of service with no problems or instabilities
- Replaced with rebuilt spare
- Immediate issues with poor efficiency, crowbar trips, and sideband instabilities
- RF3 was unavailable for an entire run while troubleshooting was in progress
- Multiple causes found:
  - → *Significant cathode voltage readback error*
  - → *Intermittent HV connectors*
  - → *Waveguide arcing*

EEV s/n 01 REMOVED FROM RF3

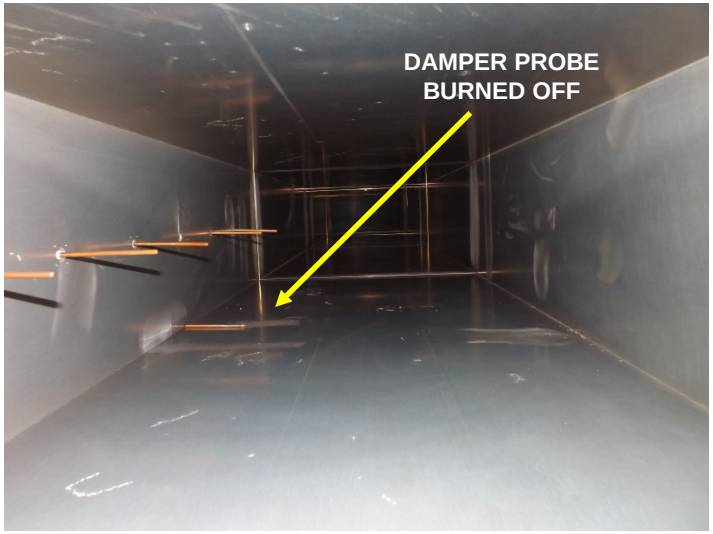
Waveguide Arcing at RF3

- Using the EEV klystron, the system would run at ≈ 700kW for almost an hour, then trip on waveguide arc
- Loud noises coming from the 2nd-harmonic damper
- After four or five arc trips to gather data, we shut the system down
- Waveguide was dismantled for inspection during the maintenance shutdown



2nd HARMONIC DAMPER AT RF3

Waveguide Arcing at RF3



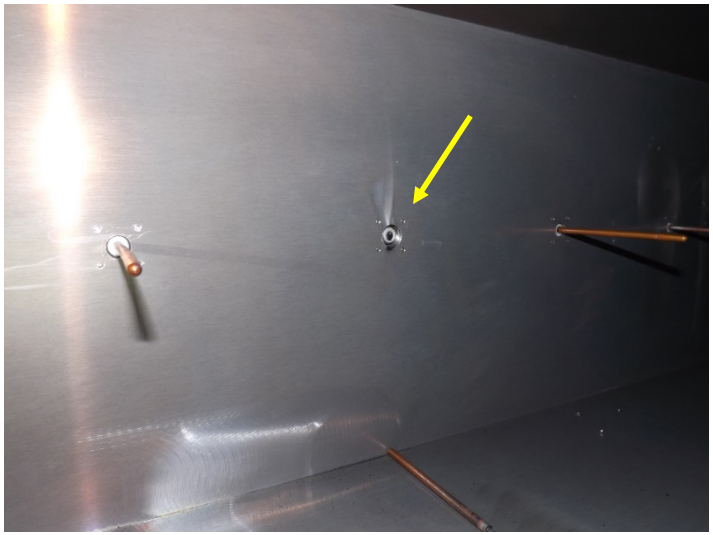
ARCING DAMAGE TO
HARMONIC DAMPER PROBES

Severe damage to harmonic damper pickup probes

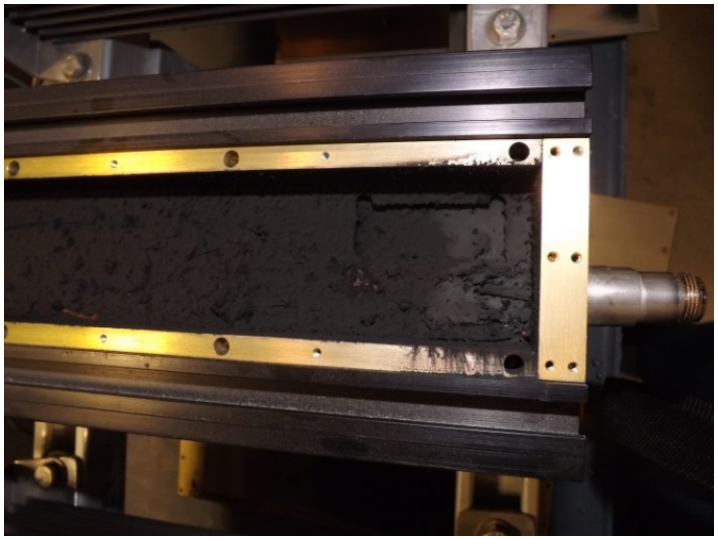
and

terminating loads

ALL SIX HARMONIC DAMPER
LOADS DESTROYED



<u>Cause</u>:
Excessive 2nd harmonic output from klystron



EEV s/n 01 Caused Waveguide Arcing at RF3

- EEV s/n 01 was brought out of retirement and re-installed in RF3 to help troubleshoot system
- Klystron produced excessive 2nd-harmonic power…..why?
- Klystron rf cavity tuning nuts were found to be loose on cavities 3 and 4
- EEV s/n 01 retired *permanently!*
- Replaced with new Thales klystron s/n 089048
  - → *Efficiency at 650kW output is ~ 4-5% lower than other Thales klystrons*
  - → *Some sideband instabilities, but avoidable with careful adjustment*

EEV s/n 01

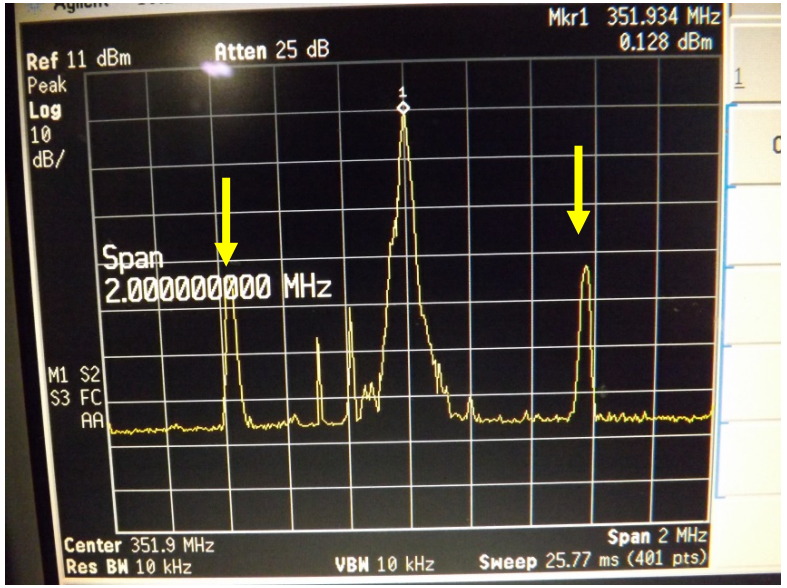
Klystron Sideband Instabilities

- **A common problem with Thales TH2089A**

- Two types:

→ *Back-streaming electrons* -- Thought to be caused by back-streaming electrons from the collector accelerated towards the cathode by output cavity gap voltage. Sideband frequency is typically 351.93MHz ± the difference between resonant frequency of cavity 1 and cavity 2: ≈ 2.2MHz

→ *Cavity multipactor* – Caused by multipactor in the first or second rf cavities. Sideband frequency is typically 351.93MHz ± 1MHz or less



- Sidebands can exist at fixed frequencies, or drift in frequency randomly

- Can be controlled by careful adjustment of cathode voltage, output match (circulator bias), and rf drive level

Shorted MOV in Mod-Anode

- The shorted MOV effectively reduced the plate load resistance of one tetrode from 225kΩ to ≈ 22kΩ

- The power dissipated by the tetrode began to heat the 400 gallons of oil in the tank……until the system tripped on a “mod anode overtemp” fault

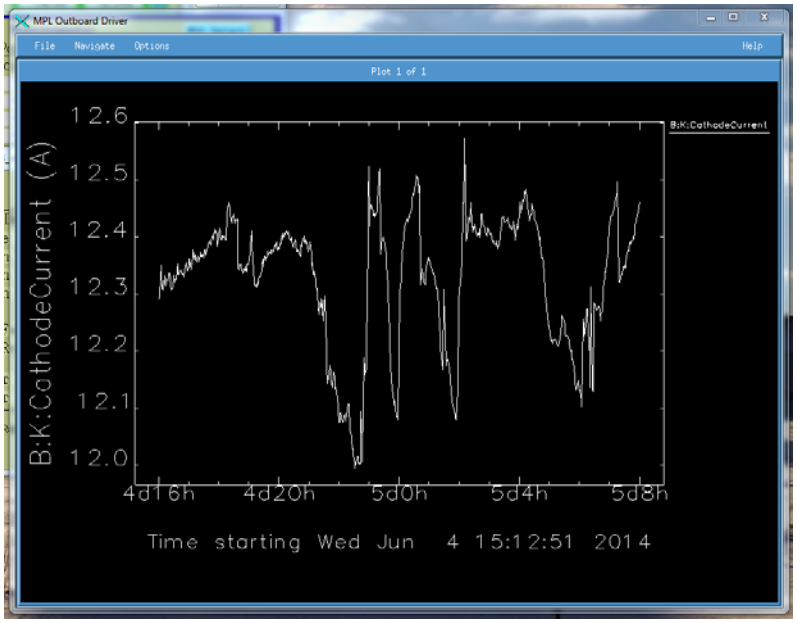
Failed Banana Plug Connection in RF3 Transformer-Rectifier Set

- During routine maintenance, trace chemical analysis of the T-R set oil detected chemical markers for arcing in the oil
- Problem traced to a partially-inserted banana plug used as the bottom connection to a rectifier stack, located under 3,000 gallons of insulating oil
- The plug eventually overheated and began arcing under load

DAMAGED PLUG AND MATING SOCKET

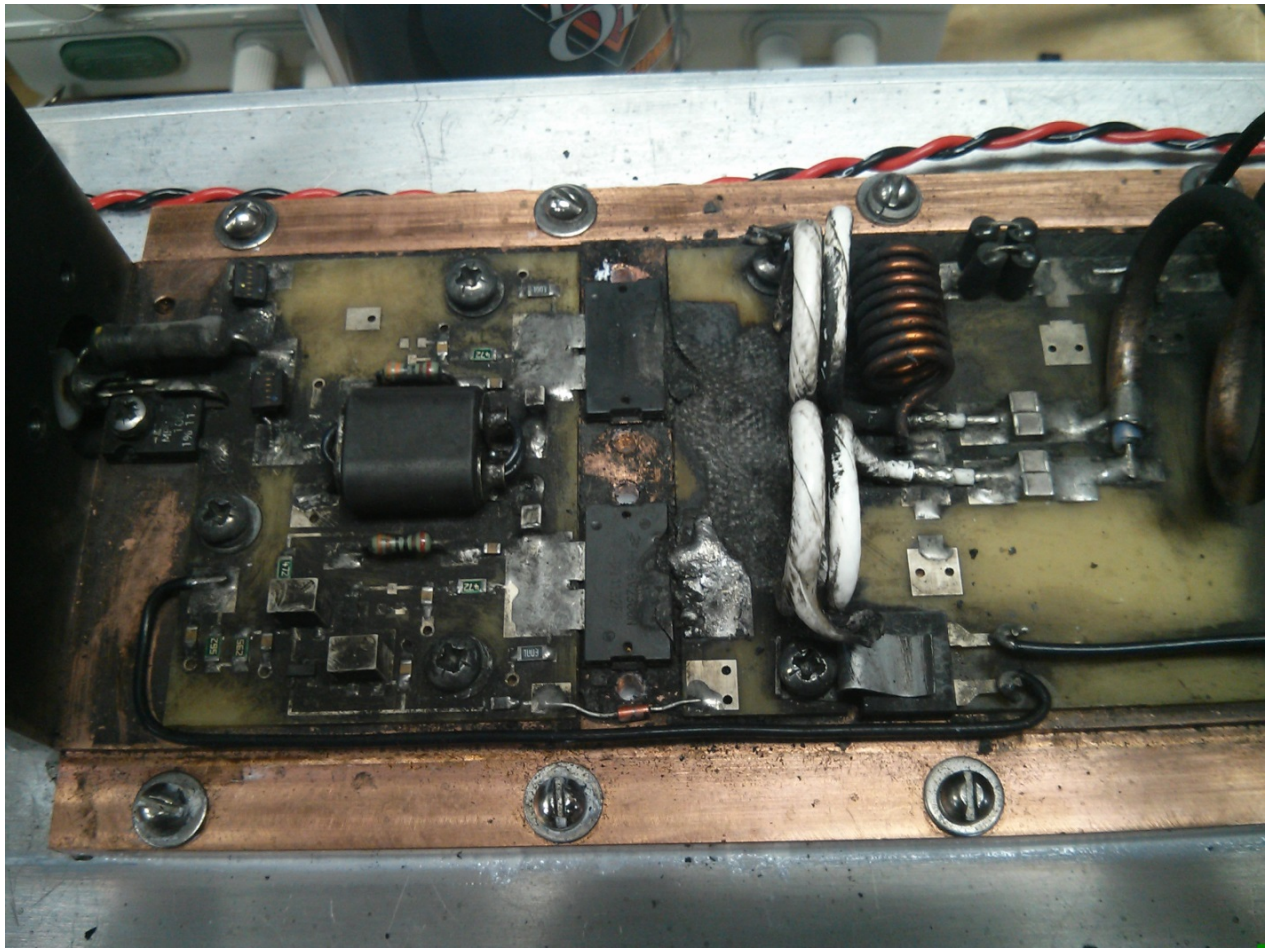
Failure of Re-tuned Philips YK1350 Klystron in RF5

- Retired from CWDD project in 1995
- Re-tuned from 352.21MHz to 351.93MHz in 2009 and tested to 1MW cw in test stand with no problems
- Installed at RF5 in January 2014
- Operated normally for first run of 2014 with no problems
- Coming out of the May 2014 maintenance shutdown, the klystron beam current became unstable
- All attempts to stabilize the gun perveance were futile
- The Philips klystron was removed from RF5 in June 2015 -- the original klystron was re-installed

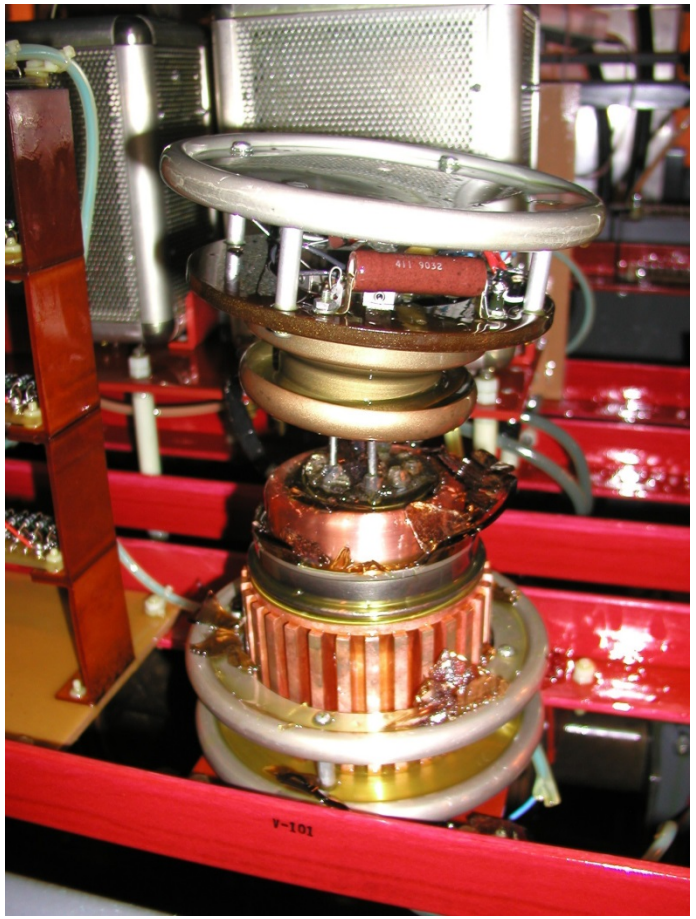


Harmonic PAR Driver Amp Failure

- 117.3MHz/500-watt cw commercial amplifier
- Failed during bench testing into load
- Input and output leads were disconnected with dc power applied
- Suspected instability in design
- Not repairable



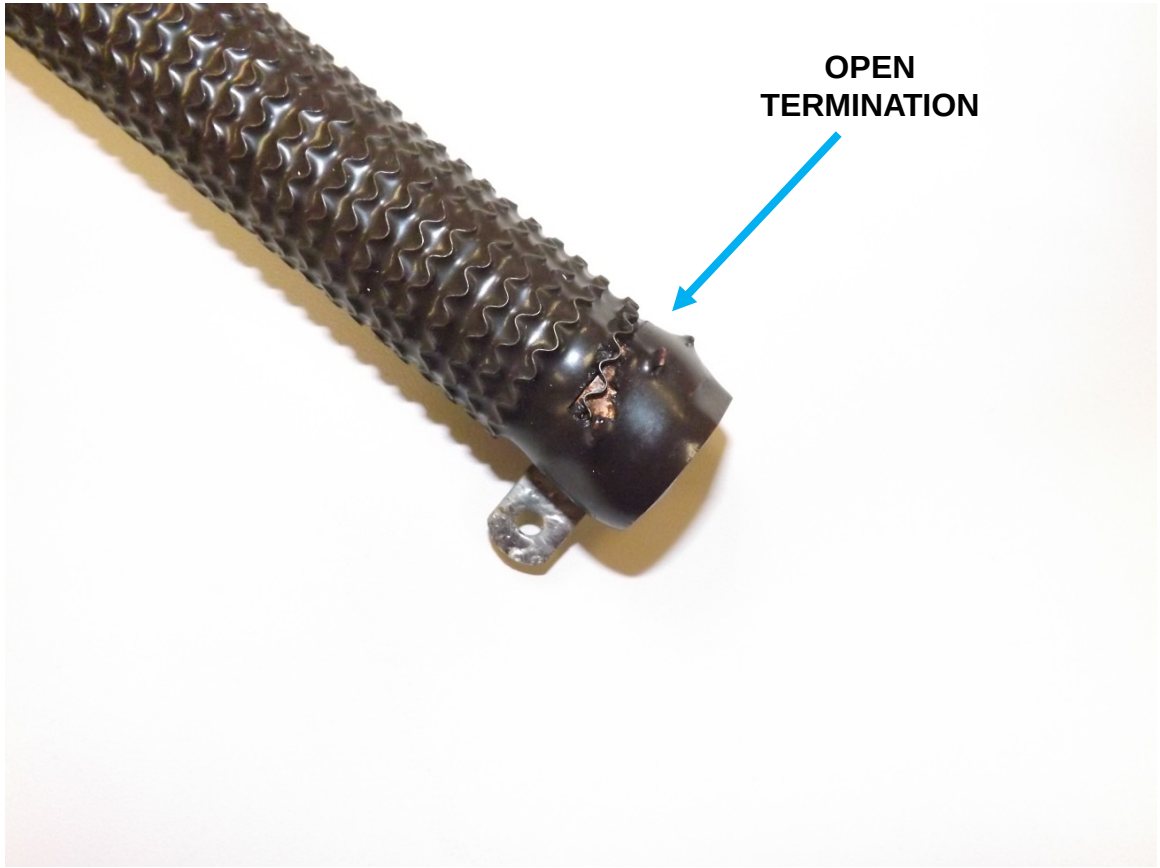
Destruction of a Mod-Anode Tetrode Tube Due to a Malfunctioning Crowbar



CROWBAR FAILED TO FIRE IN RESPONSE TO A HIGH VOLTAGE FAULT

T-R Set Resistor Failure

- Found during routine measurement of RF4 capacitor bank
- Measured 7.5µF rather than expected 8.1µF
- Found resistor in series with capacitor open on one end
- Failed due to age, temperature, crowbar event stress, oil…….???



Potential Problem?

-- *Water in 13.2kVAC and 1400VAC Underground Conduits*

- Conduits run between outdoor transformer pads and rf building
- Cables are almost 20 years old
- Possible failure due to freeze-thaw stress?

RF System Upgrades and Improvements

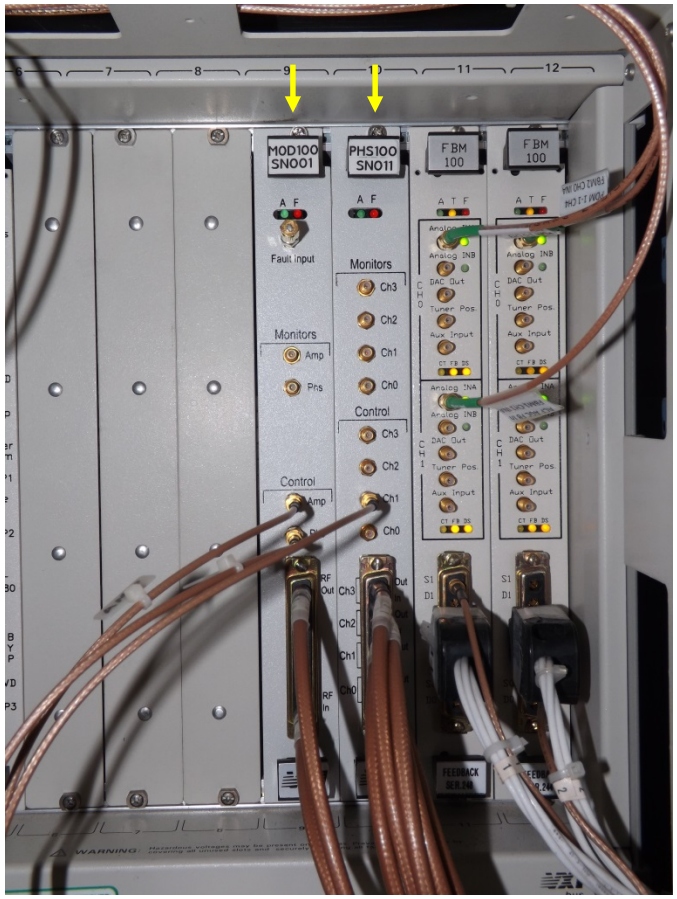
RF System Hardware Upgrades 2012-2014

REPLACEMENT OF ORIGINAL T-R SET FILTER BANK CAPACITORS

NEW PLC CONTROL SYSTEM TO REPLACE ORIGINAL OBSOLETE CONTROLS

RF System Hardware Upgrades 2012-2014

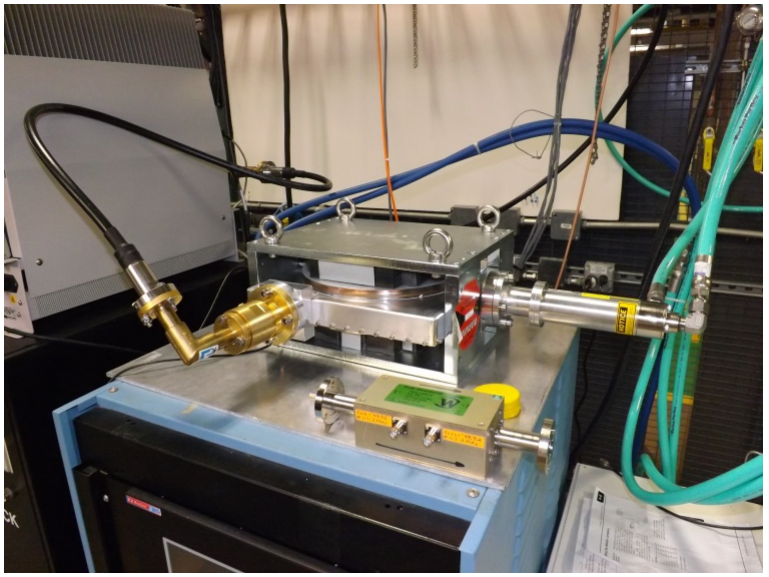
NEW KLYSTRON DRIVER AMPLIFIERS TO REPLACE OBSOLETE ORIGINAL UNITS

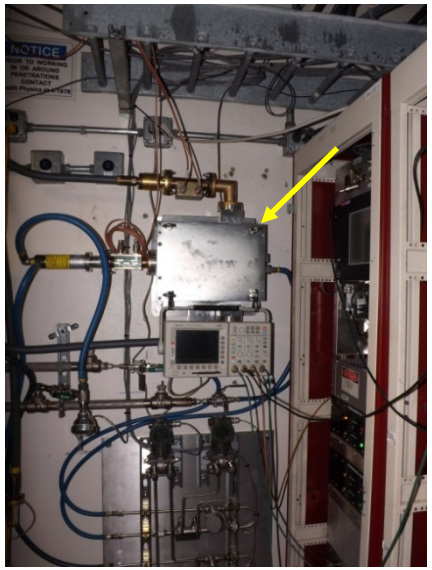


NEW 352MHz MODULATOR AND PHASE SHIFTER LLRF BOARDS

RF System Hardware Upgrades
2012-2014 -- Harmonic PAR Output Isolator

- 117.3MHz/4kW average rating
- Provides >20dB isolation between amplifiers and cavity
- Amplifiers can be tuned for best efficiency with minimum effect on cavity resonance
- Cavity can be operated off-resonance for physics reasons without stressing amplifiers with reflected power
- Switch to back-up amplifier now causes minimal change in cavity tuning loop operating point



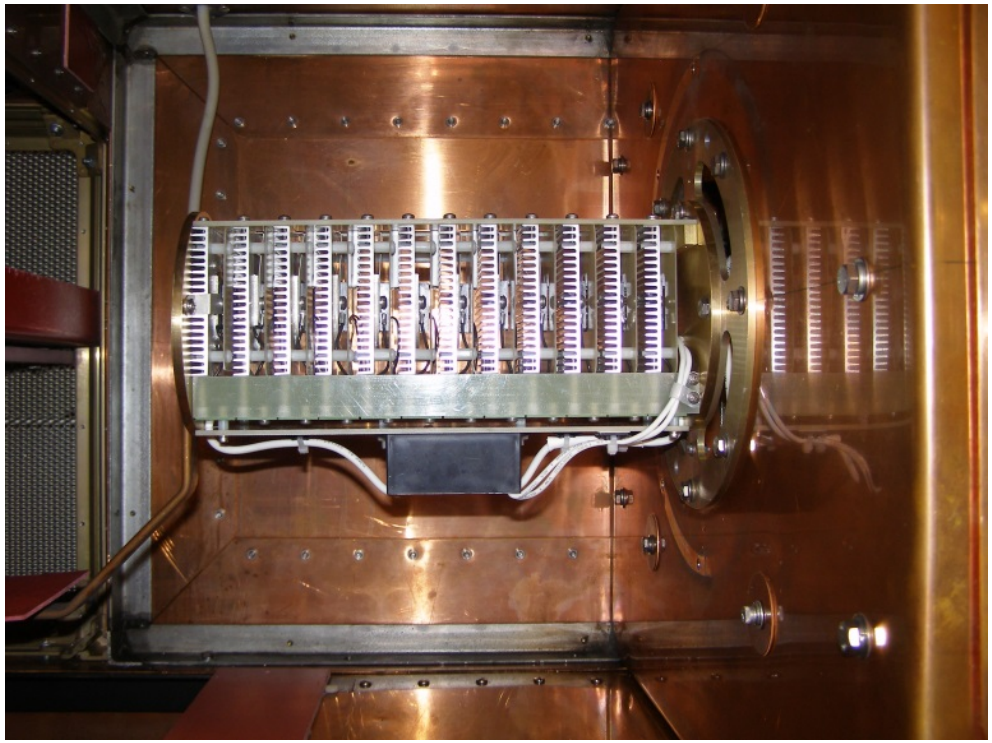


FULL POWER TEST

ISOLATOR INSTALLED

Conversion to Solid State High Voltage Switch in Linac Modulators

- Presently installed in four out of the six Linac modulator systems
- Replaces expensive consumable thyratron tube
- Provides improved performance, reduced complexity, improved reliability, and long-term operating cost savings

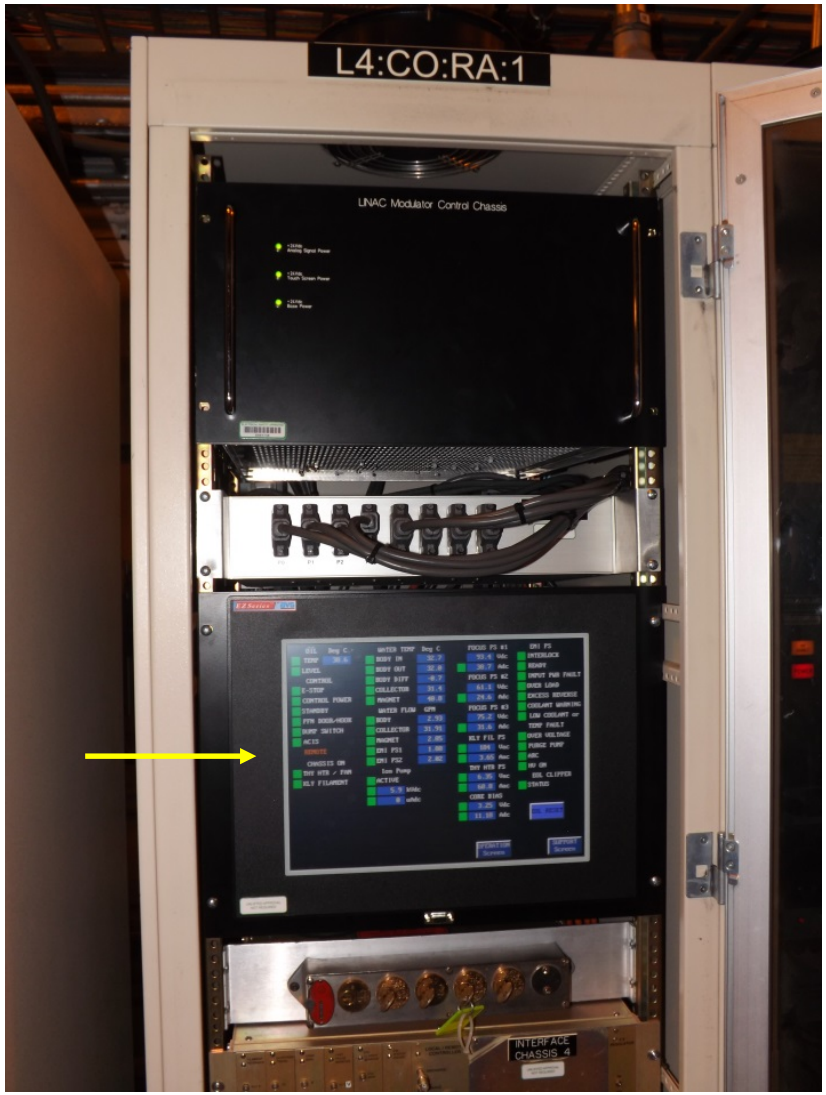


Replacement of Linac Modulator PFN Capacitors

- Presently installed in four out of the six Linac modulator systems
- Replaces original capacitors that have reached the end of their expected operating lifetime
- Provides improved performance and long-term reliability

Replacement of Linac Modulator PLC Control Systems

- Project completed at all six Linac modulators
- Replaced obsolete and un-supported cathode ray tube touch screen monitors with LCD touch screens
- Provides improved reliability and long-term serviceability



Updated Harmonic PAR Cavity Tuner Power Supplies

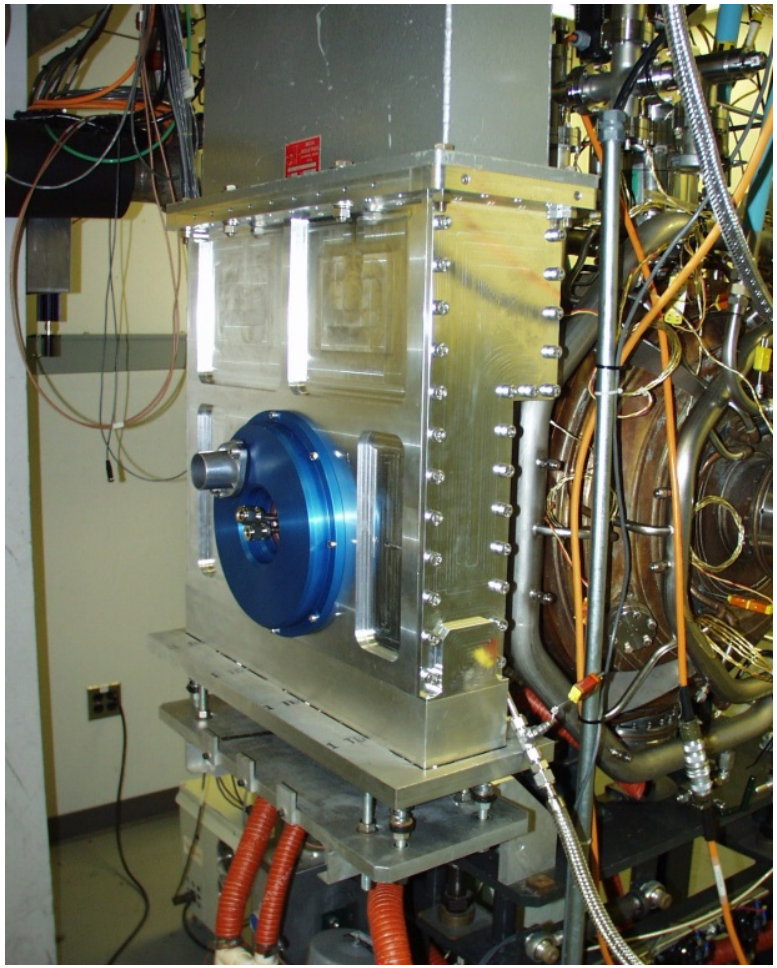
- Replaced 20 year old analog linear transistor amplifiers

- New amplifiers utilize Class-D switching amplifier technology
- Much greater efficiency, reducing heat load and space requirements in racks
- Provides improved current waveform reproduction, and improved reliability
- Main/standby switching capability to shorten recovery time in the event of an amplifier failure

Collaboration with CERN –
A New Storage Ring Cavity Input Coupler

- Design goal for APS is 200kW cw power handling capability
- Prototype reached 200kW cw in APS RF Test Stand
- Evidence of minor arcing on ceramic noticed after test:

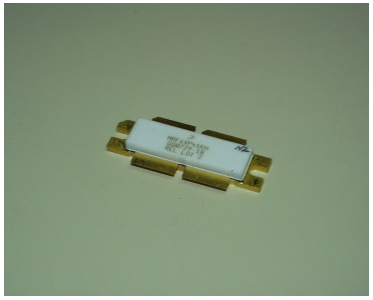
- Analysis underway to determine the cause of the arcing and solve the problem



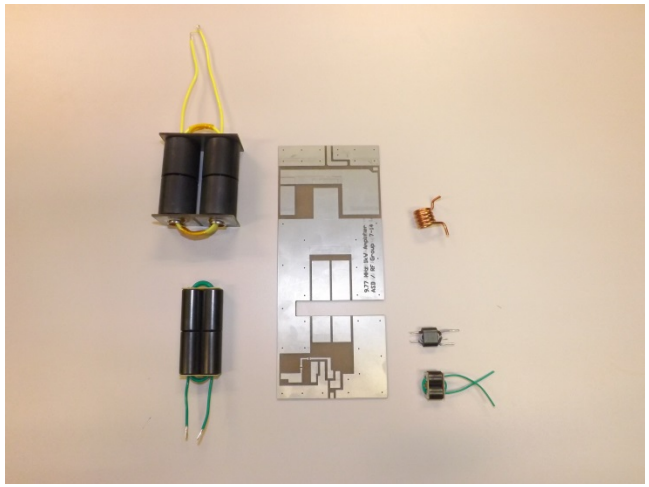
COUPLER AND WAVEGUIDE TRANSITION INSTALLED ON TEST STAND CAVITY

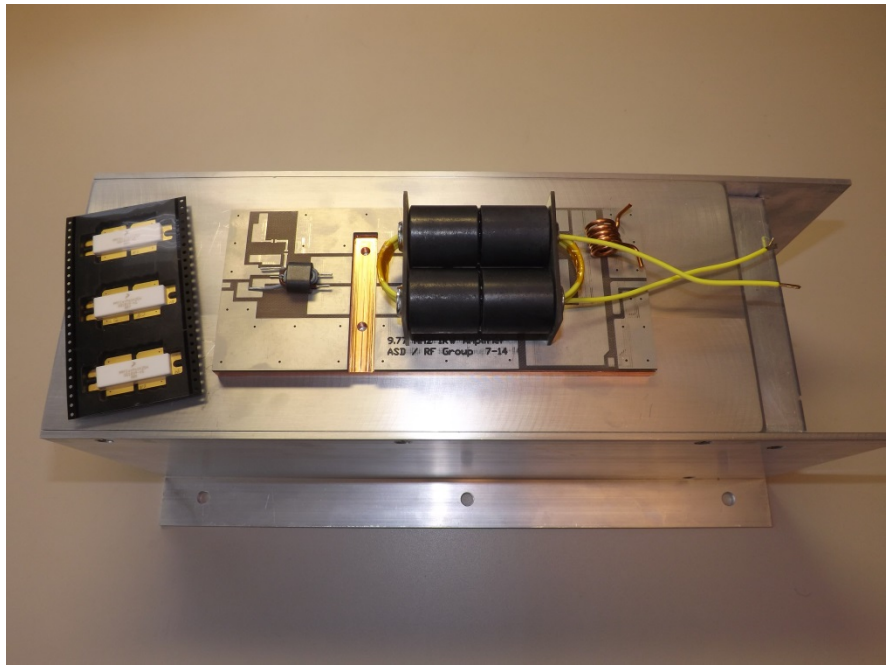
Solid State RF Power Development at APS –
New 9.77MHz/1kW Driver Amplifier for PAR

- Design to replace 20-year old drivers
- Uses one Freescale 1.25kW push-pull LDMOS transistor package



- Broadband transformer matching for simplicity
- Air cooling





The RF Group

The people who did all this work:

- Roy Agner
- Mike Douell
- Mike Drackley
- Bruce Epperson
- David Jefferson
- Tim Jonasson
- George Kotsiopoulos
- Mark Moser
- William Yoder
- Ali Nassiri
- Tim Berenc
- Dave Bromberek
- Alex Cours
- Eddy Goel
- Art Grelick
- Hengjie Ma
- David Meyer
- Terry Smith
- Gian Trento
- Geoff Waldschmidt