Care and Feeding of the APS 352-MHz/1MW CW Klystrons

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10/3/08

General Performance Specifications

- Operating frequency = 351.93MHz nominal
- RF Power Output = ~ 1.2MW CW typical, *1.3MW CW absolute maximum*
- Cathode voltage = 101kV max
- Beam current = 21A max
- Mod-anode voltage = 0 - 85kV
- Mod-anode current = 10mA DC/20mA peak maximum
- Efficiency = 60% typical, 65% absolute maximum
- RF Bandwidth = ~ 200kHz at 1dB points
- RF Gain = ~ 42-45dB, *dependent on cavity tuning*
- RF drive power at saturation + ~ 40-90W, *dependent on cavity tuning*
- Maximum reflected power at output flange = 20kW
- Heater power = 0 - 25V @ 25A maximum
- Body power dissipation = 20kW *absolute maximum*
- Output cavity power dissipation = 30kW *absolute maximum*

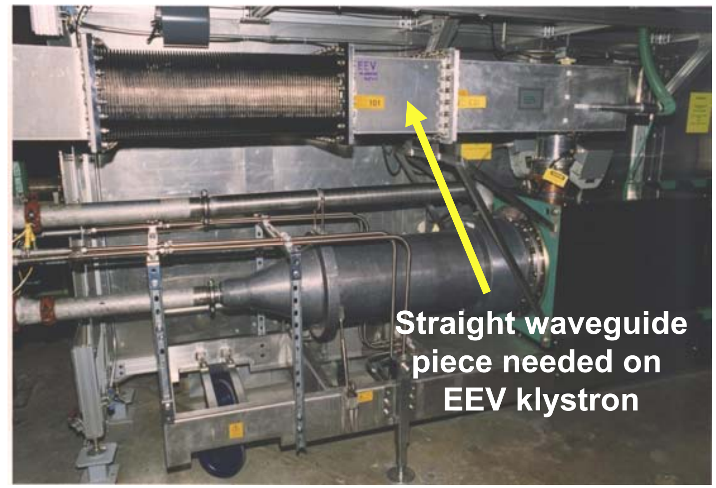
Thales TH2089A and EEV K3513A

- **Both klystrons are essentially the same in terms of electrical specifications, but differ slightly in length:**

The EEV

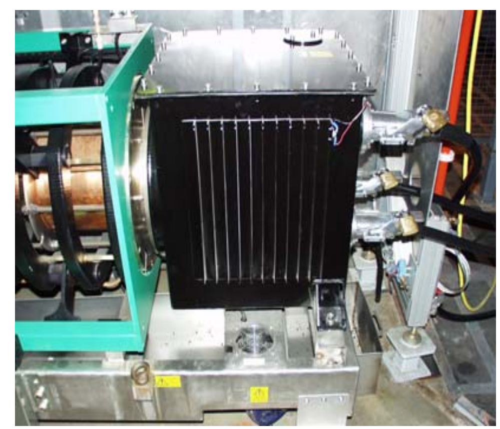
is slightly shorter than

the Thales



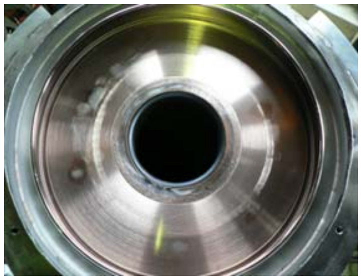
Thales Pantak connections are outside of the garage

EEV Pantak connectors are inside of the garage



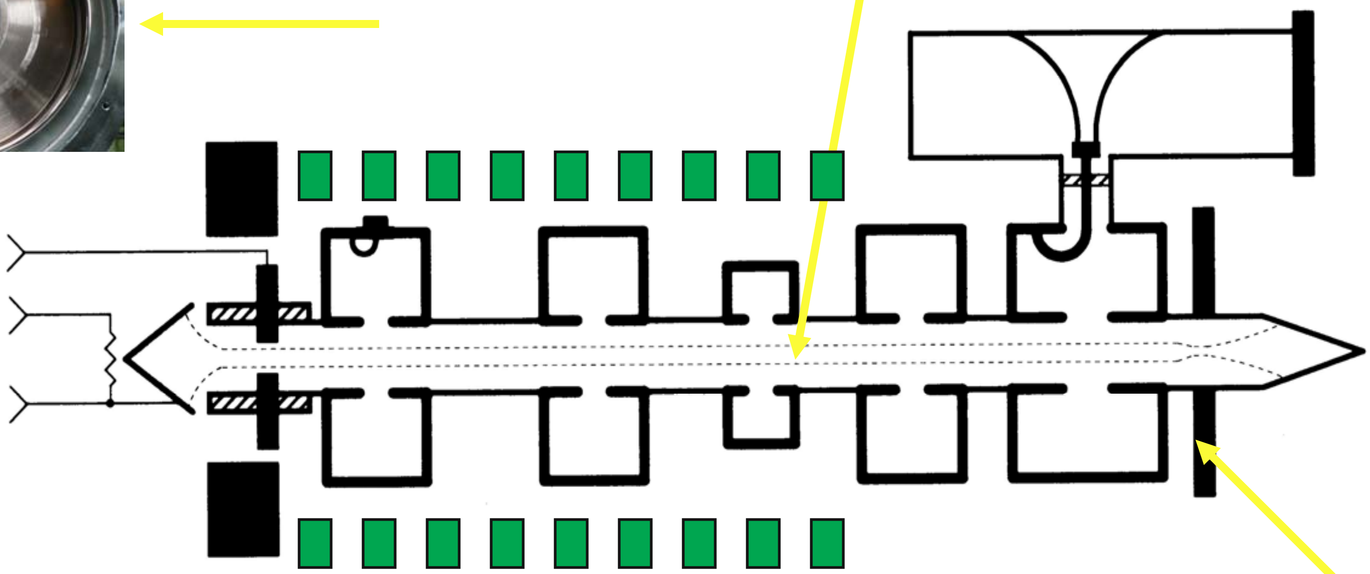
Klystron Fundamentals

- Electron beam from gun is launched and magnetically confined to avoid contact with klystron structures:



View of drift tube at first cavity input

Approximate profile of focused dc (no rf) beam



Large gun focus magnet helps launch beam into drift tube with minimum interception

Air-cooled solenoid coils generate 300 gauss focus field along length of klystron

Large focus magnet at collector inlet to over-focus beam and generate space charge forces which distribute the beam over a wider area of the collector

Electron Gun and Mod-Anode Control

- The modulating anode element allows for dc control of the klystron beam power relatively independent of cathode voltage.

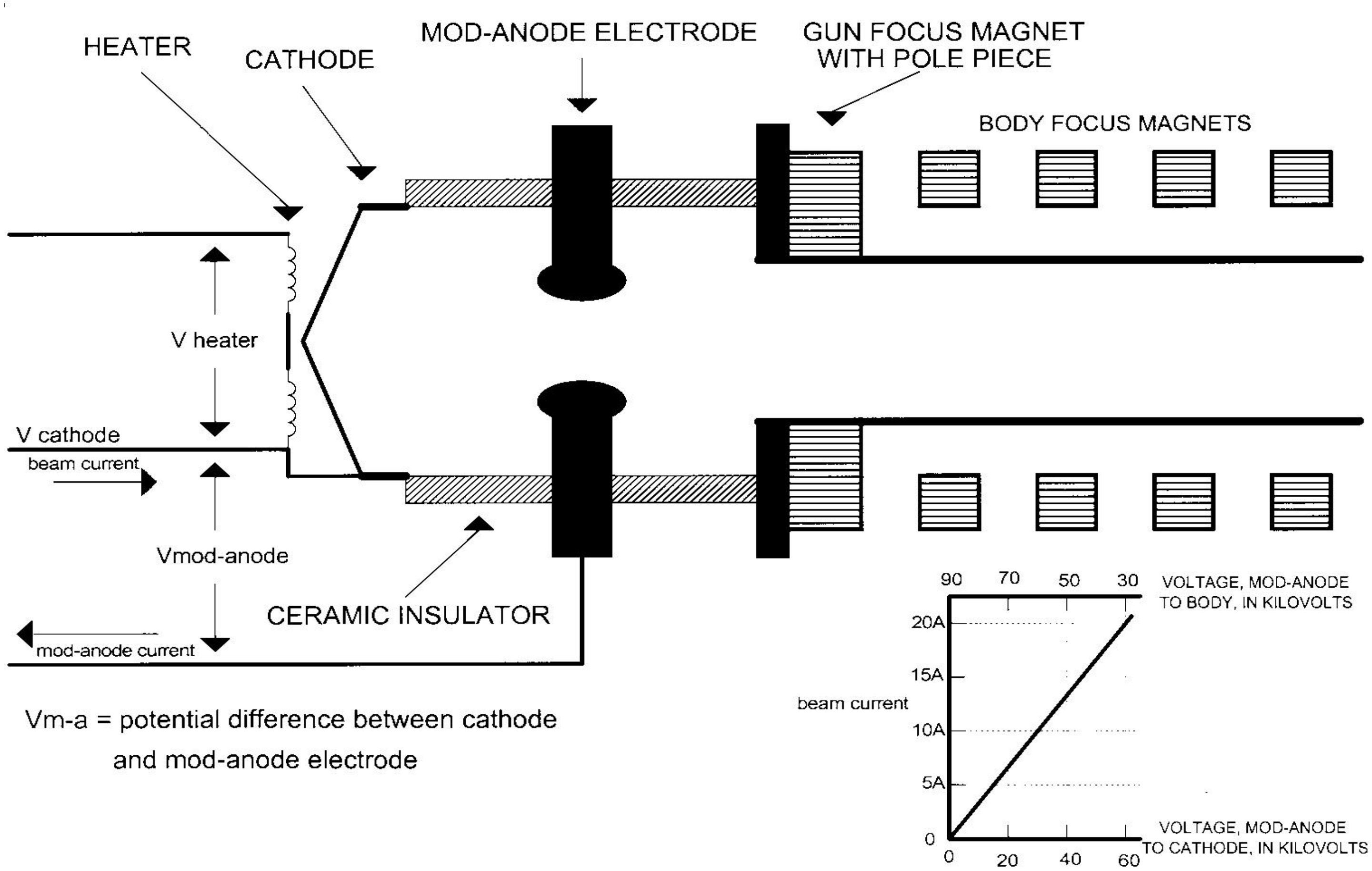


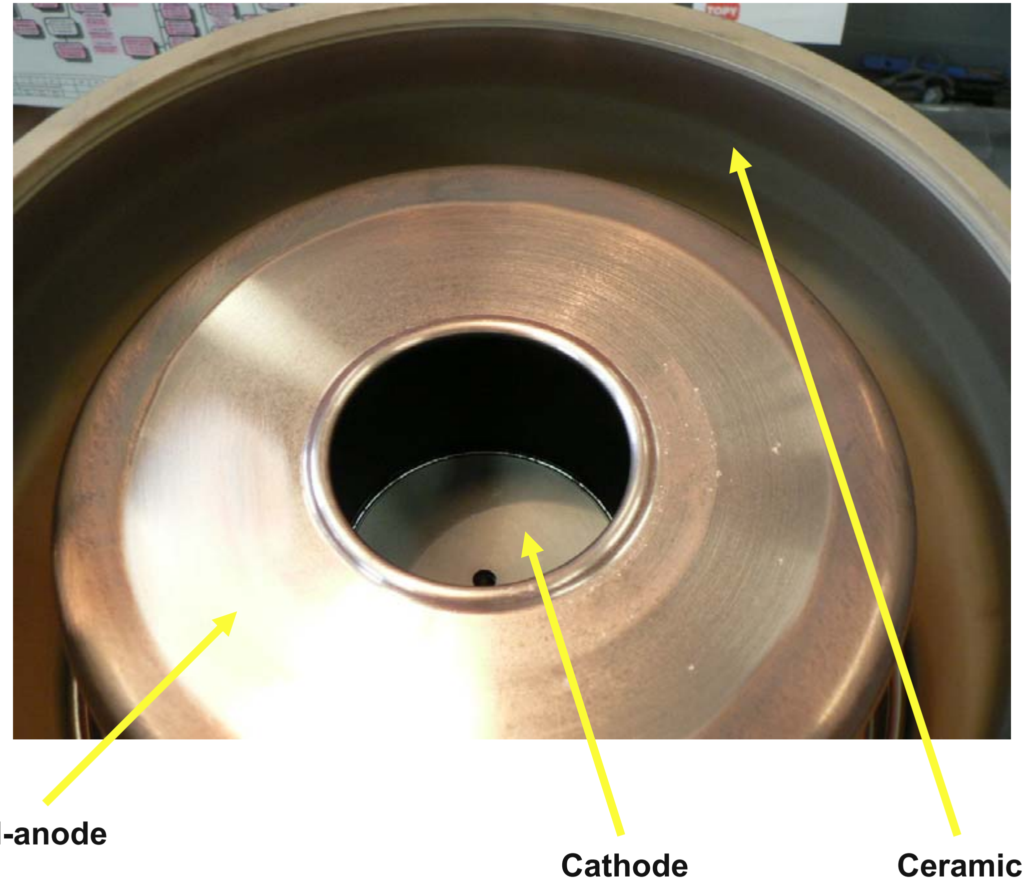
Photo of Actual TH2089A Mod-Anode and Cathode

• Cathode assembly and emitting surface can be seen through beam hole in the mod-anode electrode.

• **Under normal conditions, the mod-anode intercepts very little beam.**

→ *Typical mod-anode current is 0.1-3mA depending on beam power and rf output.*

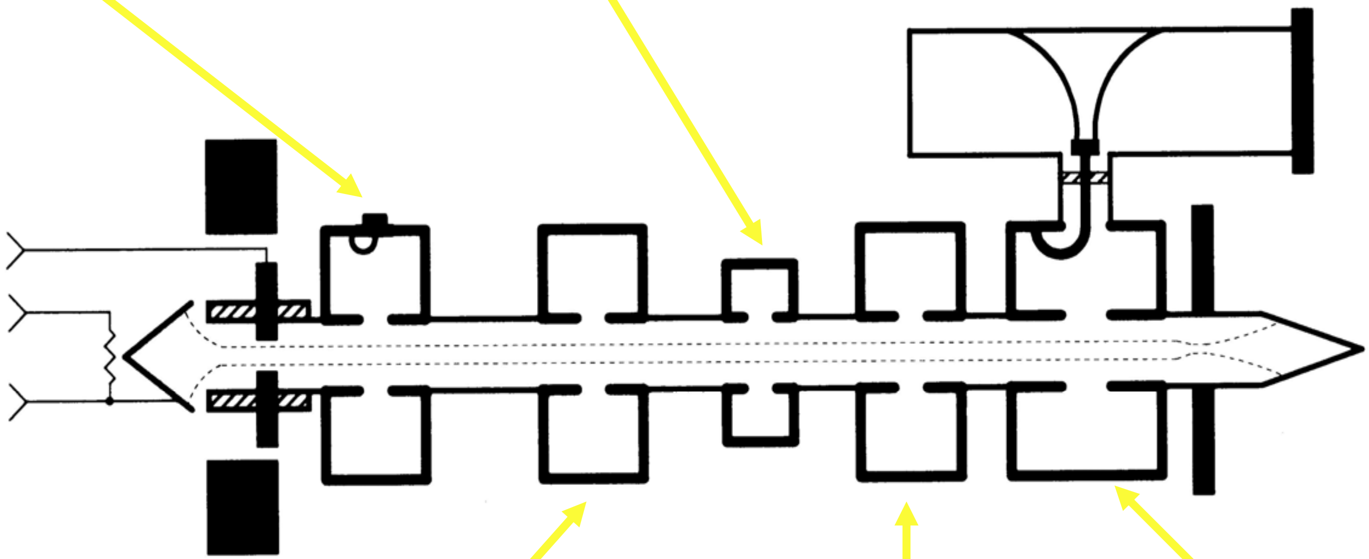
→ *Excessive mod-anode current can be a sign of sideband instabilities (“back-streaming” electrons) or excessive barium deposition on the gun ceramics.*



TH2089A Klystron RF Cavities and Typical Tuning Points for Operation at 351.93MHz

Input cavity
Fr = 351.36 MHz

Cavity #3 (second harmonic)
Fr = 692.3 MHz



Cavity #2
354.65 Fr = MHz

Cavity #4
Fr = 359.1 MHz

Output cavity
Typically tuned to operating frequency

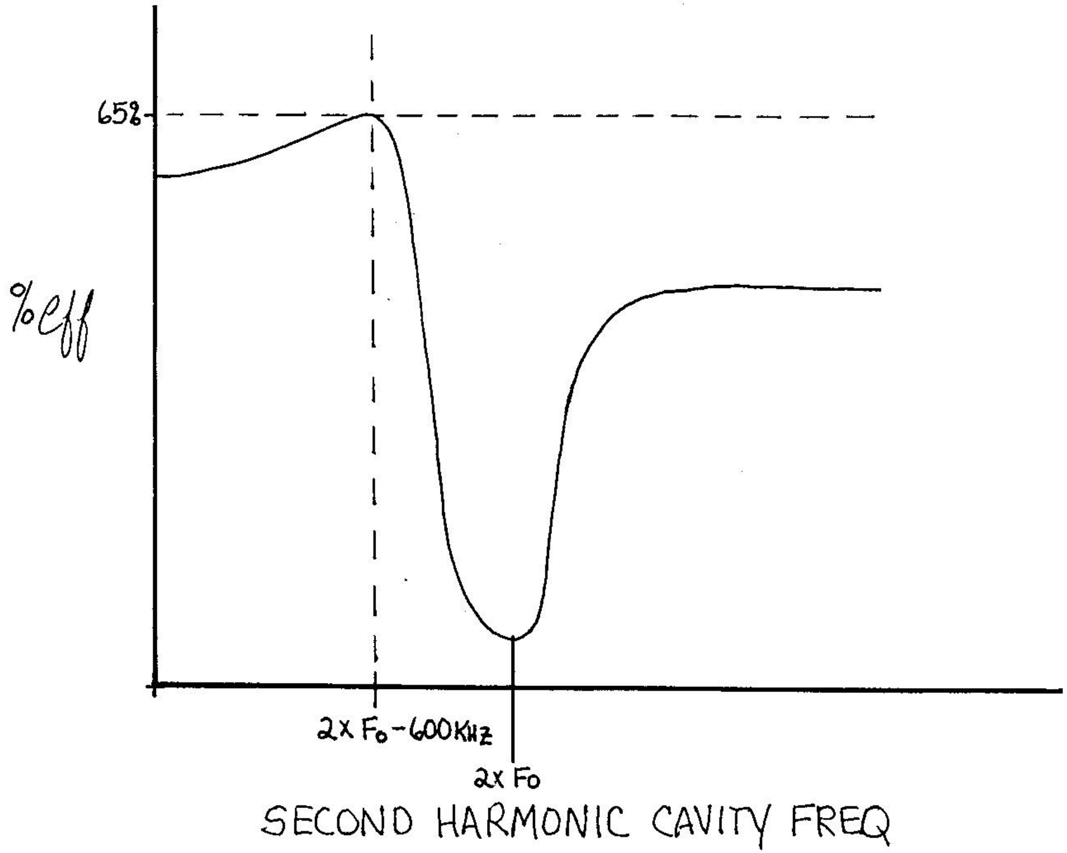
These cavity frequencies produce the best performance in terms of efficiency and stability

The Second-Harmonic Cavity Increases Efficiency

- A properly tuned 2nd-harmonic cavity increases peak current in the bunches, thereby increasing dc-to-rf conversion efficiency.

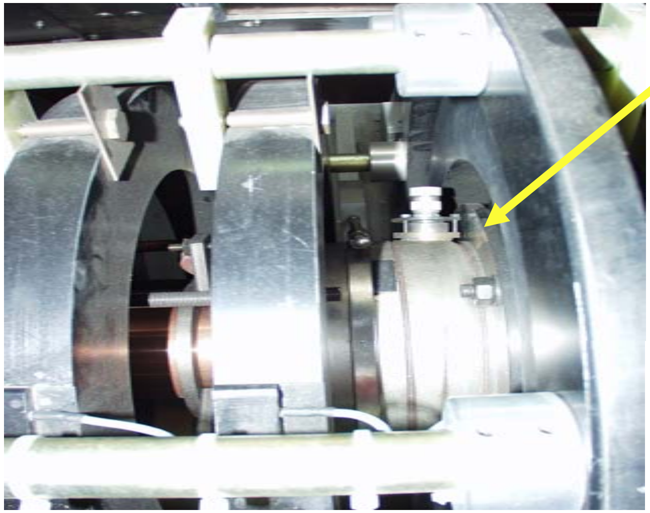
- 2nd-harmonic cavity tuning is critical……….*efficiency drops drastically if the cavity is tuned too close to 2 x Fo!*

  → *This is what happened to one of our EEV klystrons when the cavity tuning nuts came loose and the cavity detuned!*

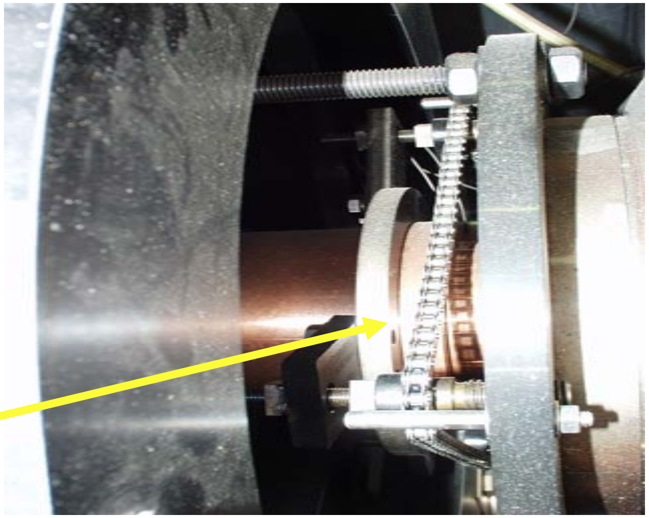


Klystron Cavities

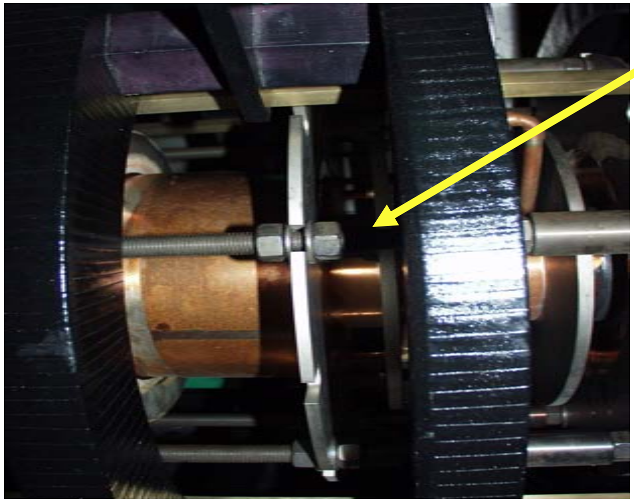
- Cavities are tuned by compressing or pulling on bellows sections in drift tube between cavities:



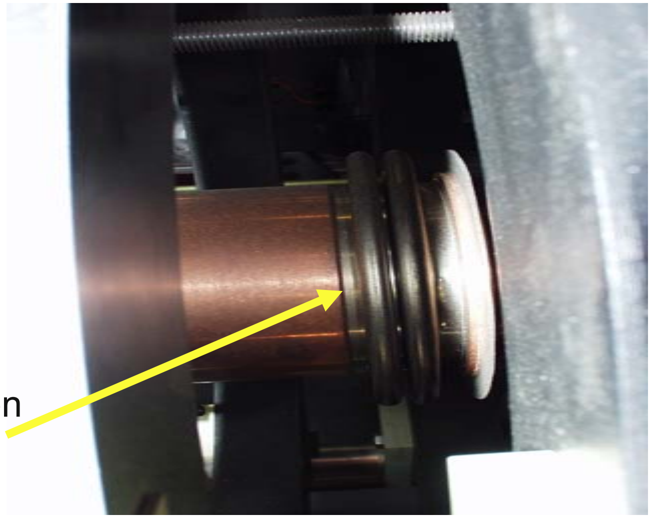
TH2089A 2nd harmonic Cavity with pickup loop



Chain drive mechanism for tuning cavities on TH2089A



Nut-nut system for tuning Cavities on EEV klystrons



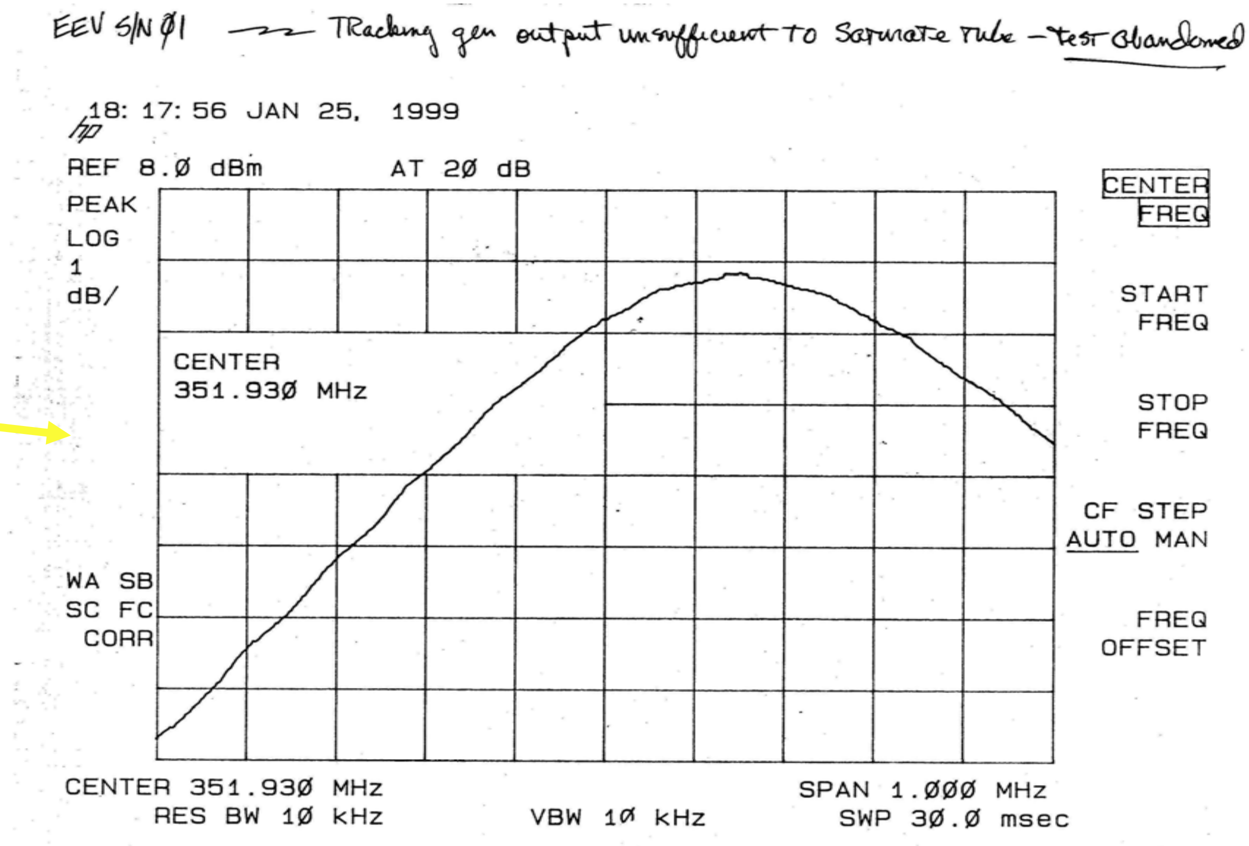
Bellows section between cavities on beam pipe

Klystron RF Bandwidth

- These klystrons are fairly narrow-band: 1-dB RF bandwidth is ~ 200kHz.

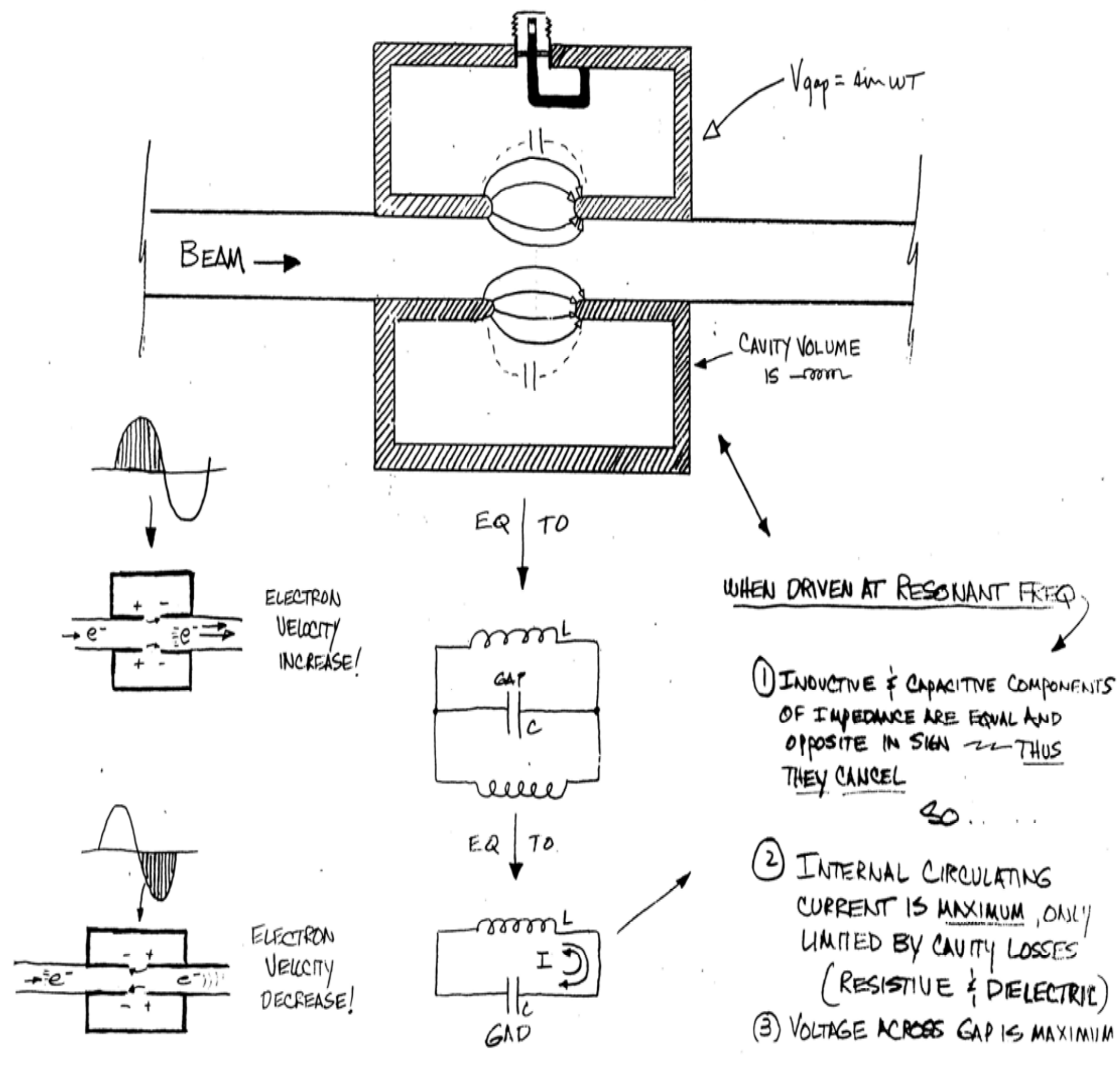
  → This is why the Philips klystron must be retuned from 352.21MHz to APS frequency if we are going to use it as a spare.

Swept response of EEV 01 using a spectrum analyzer tracking generator to drive klystron



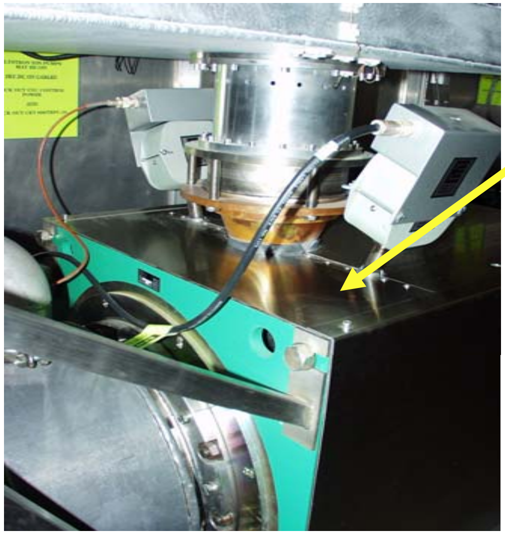
Electron Velocity Modulation by Cavity Gap Voltage

- The electrons group in bunches as they move down the drift tube.
- The dc kinetic energy of the beam will be converted to rf power when the bunches pass through the output cavity, which extracts the beam energy.
- The more cavities involved, the greater the peak current in each bunch, which increases rf gain and output.

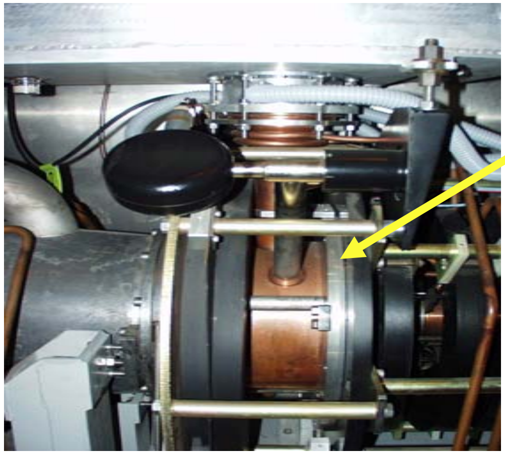


Klystron Output Cavity

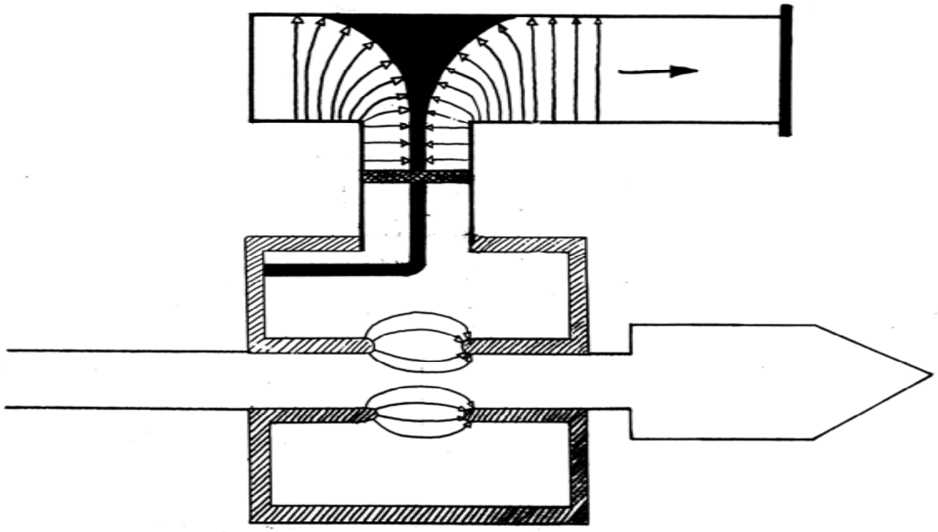
- Converts kinetic energy of bunched electrons to rf power:

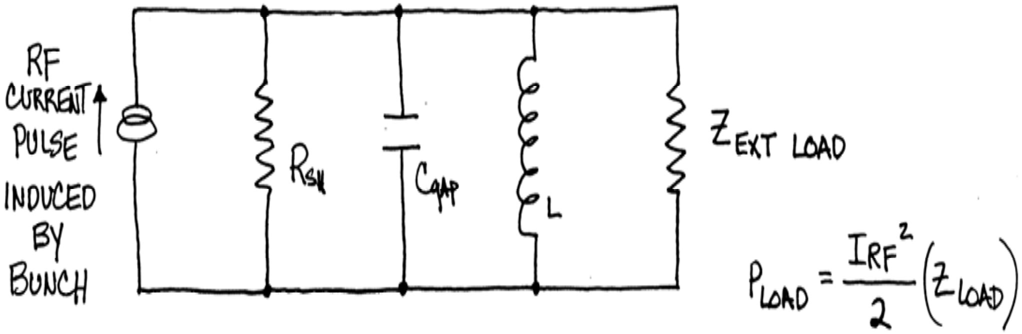


EEV K3513A



Thales TH2089A

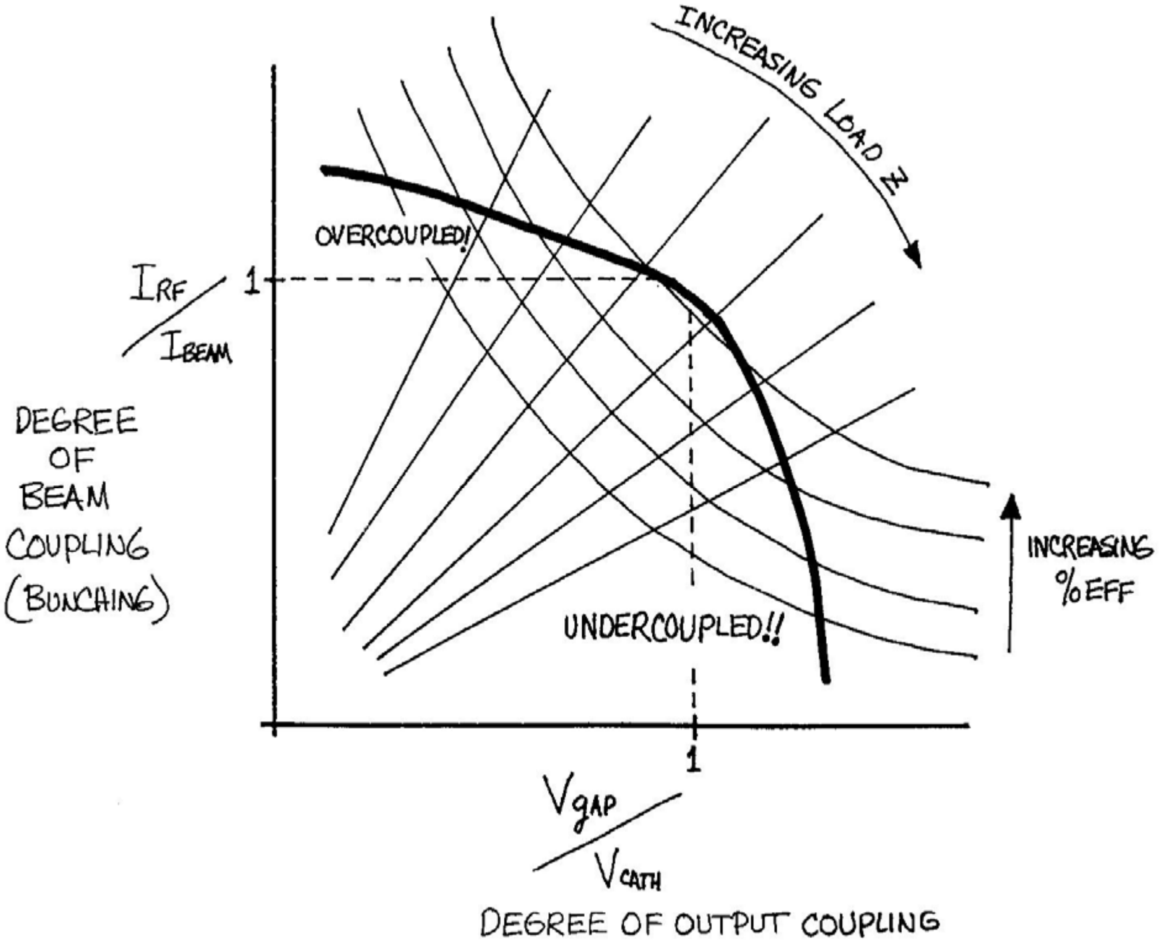




Output Cavity Match Can Influence Efficiency and Stability

- TV klystrons typically utilize a variable output coupler for optimization of efficiency and bandwidth, *but under-coupling can cause arcing and instability!*

- Our klystrons use a fixed output coupler, but output cavity coupling can be influenced by changes in output match.



Output Cavity Effect On Operating Efficiency

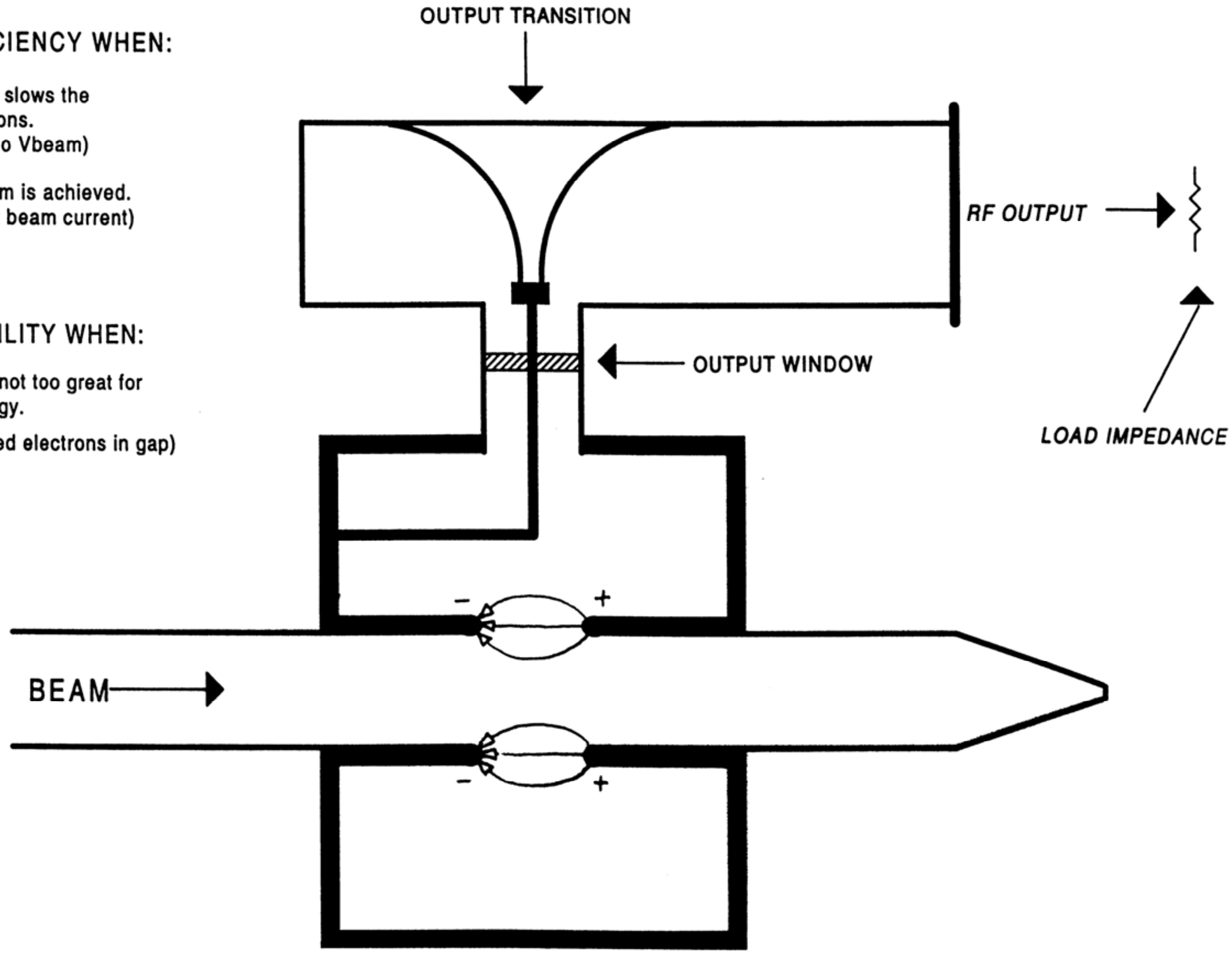
YOU HAVE PEAK EFFICIENCY WHEN:

1. Output gap retarding field slows the greatest number of electrons. (Vrf approximately equal to Vbeam)
2. Peak rf current in the beam is achieved. (peak rf current = 1.414 x beam current)

YOU HAVE BEST STABILITY WHEN:

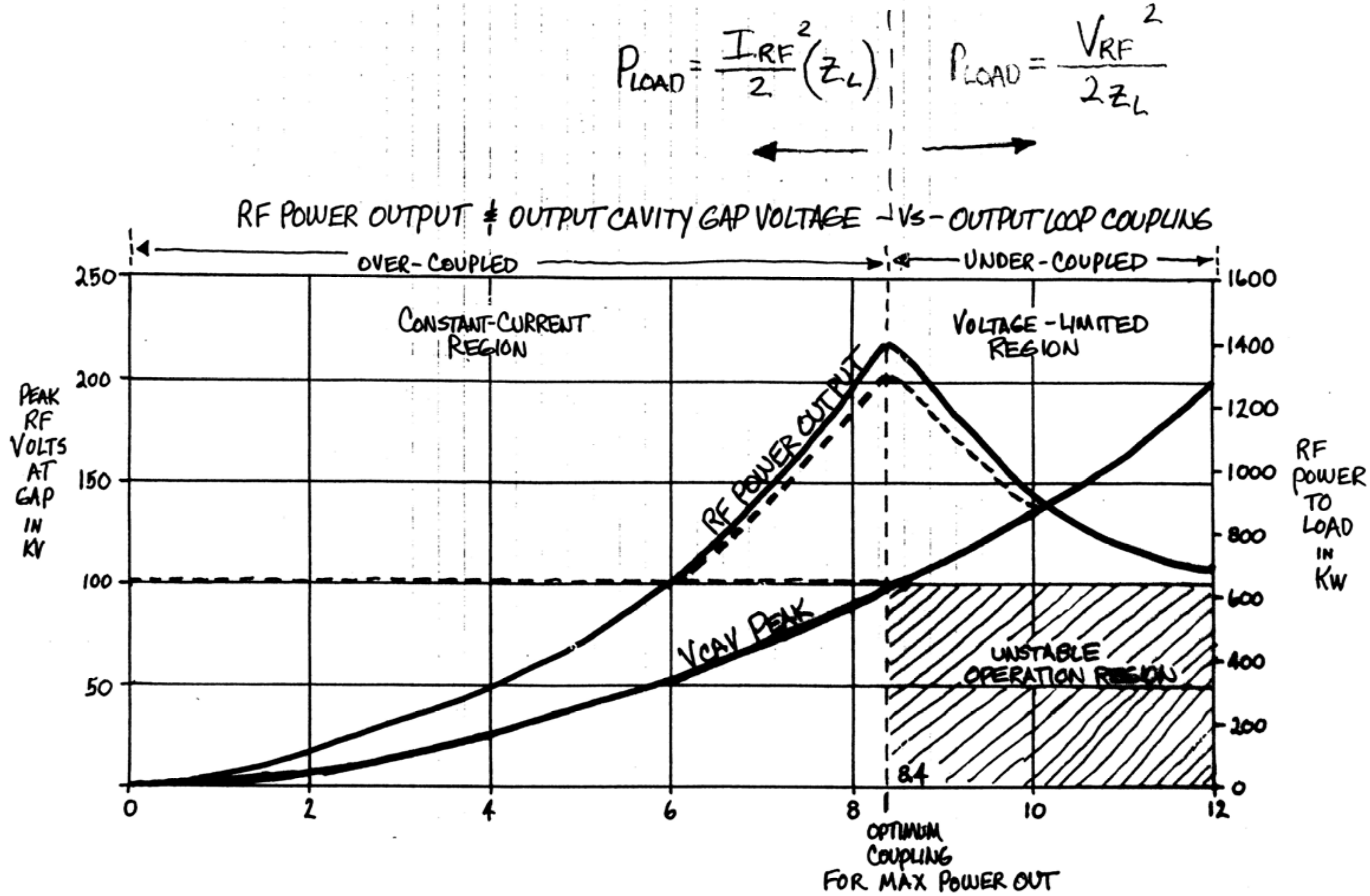
Output gap retarding field is not too great for a given beam energy.

(not too many slowed or stopped electrons in gap)



Output Cavity Match Can Influence Efficiency and Stability

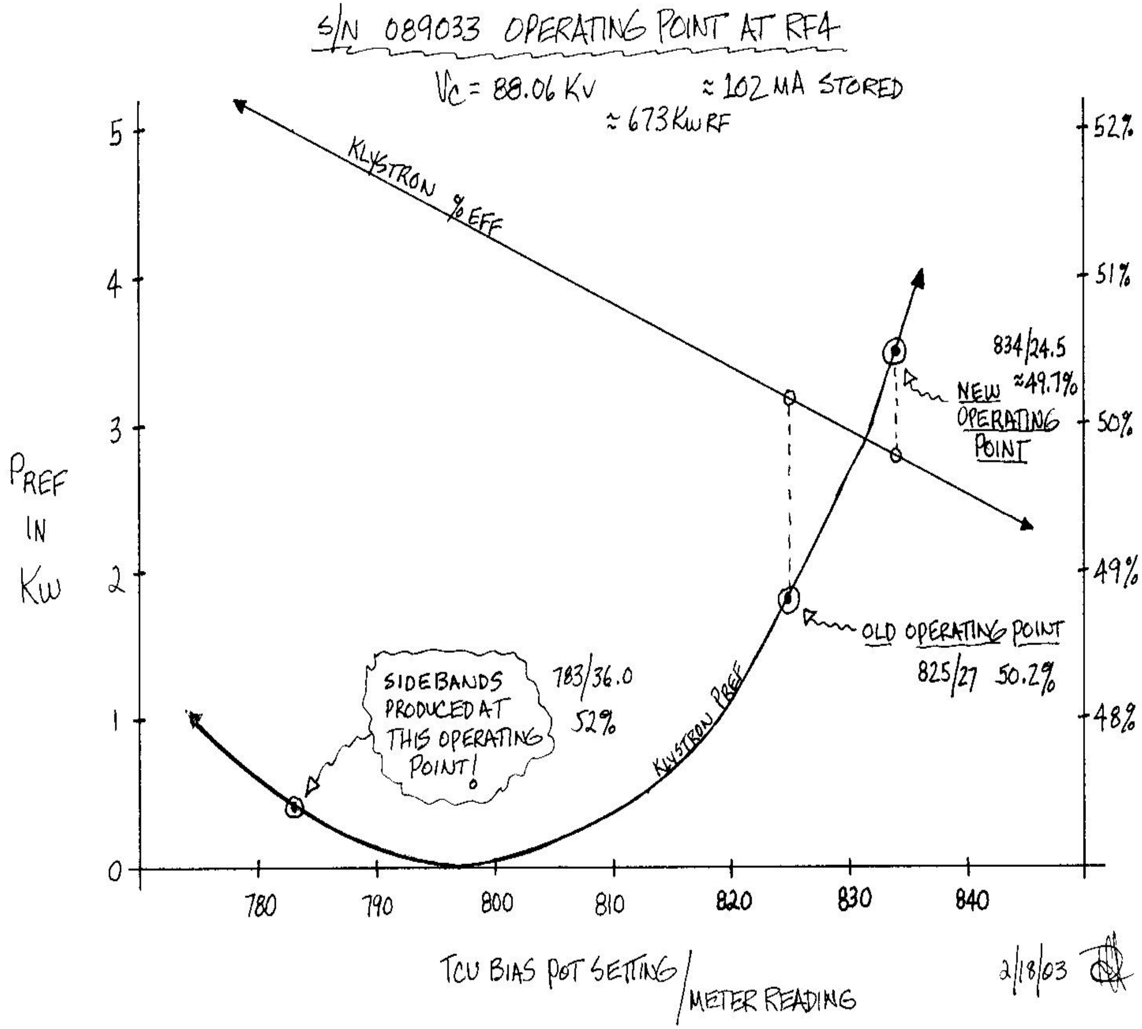
- Operating efficiency peaks at the theoretical optimum output coupling point.



Adjusting Circulator Bias For Best Stability

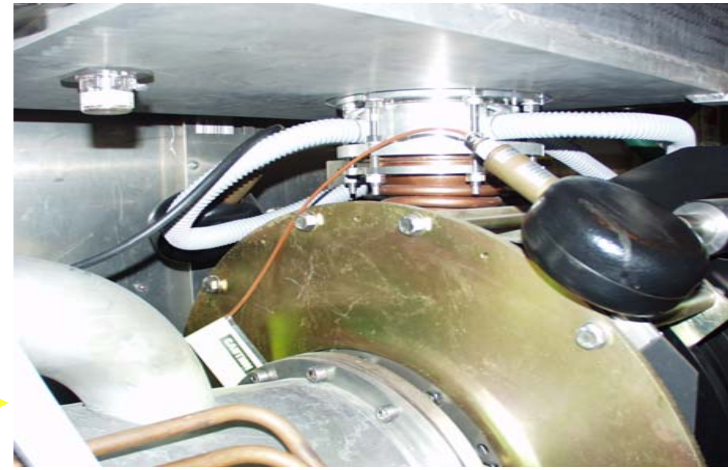
- Sideband instabilities can be caused by excessive output cavity gap voltage, which results in slow electrons in the output cavity gap being accelerated toward the gun when the rf voltage reverses polarity.

- Adjusting the circulator bias for increased reflected power lowers gap voltage slightly, trading efficiency for stability.

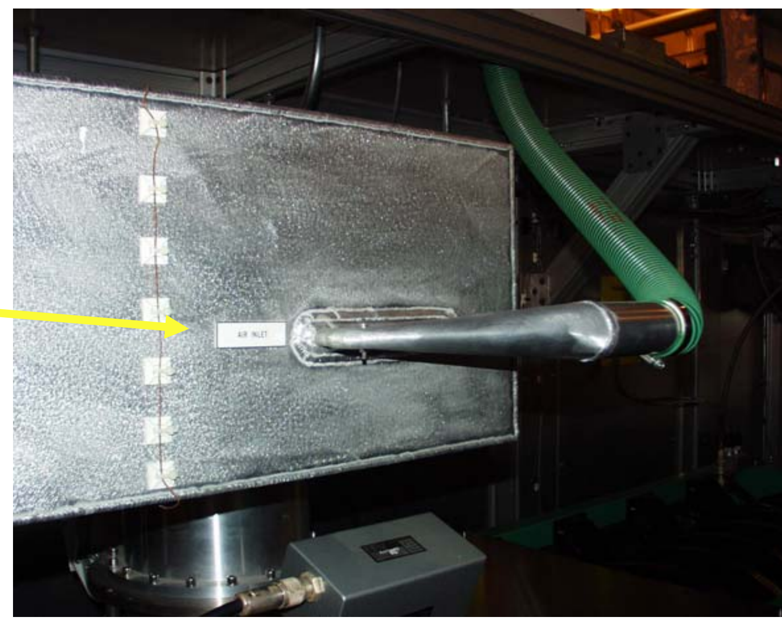


Output Cavity Window Cooling

- Thales TH2089A cooling air is supplied to window ceramic by four hoses at the surface of the output window



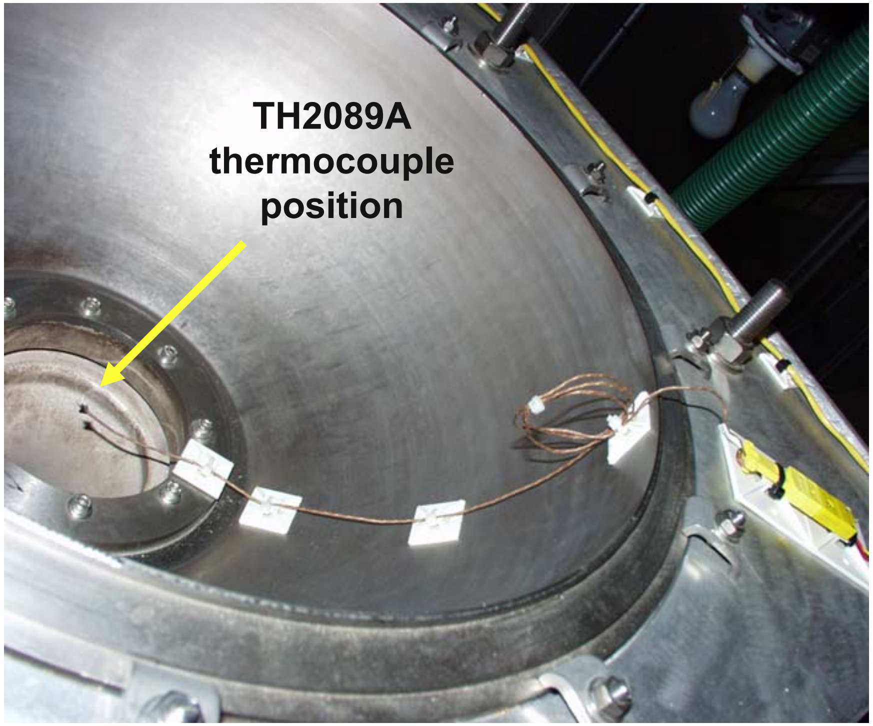
EEV K3513A window cooling air is supplied by one hose that blows into the hollow T-bar output coupler in the waveguide and directed down to the window ceramic surface.

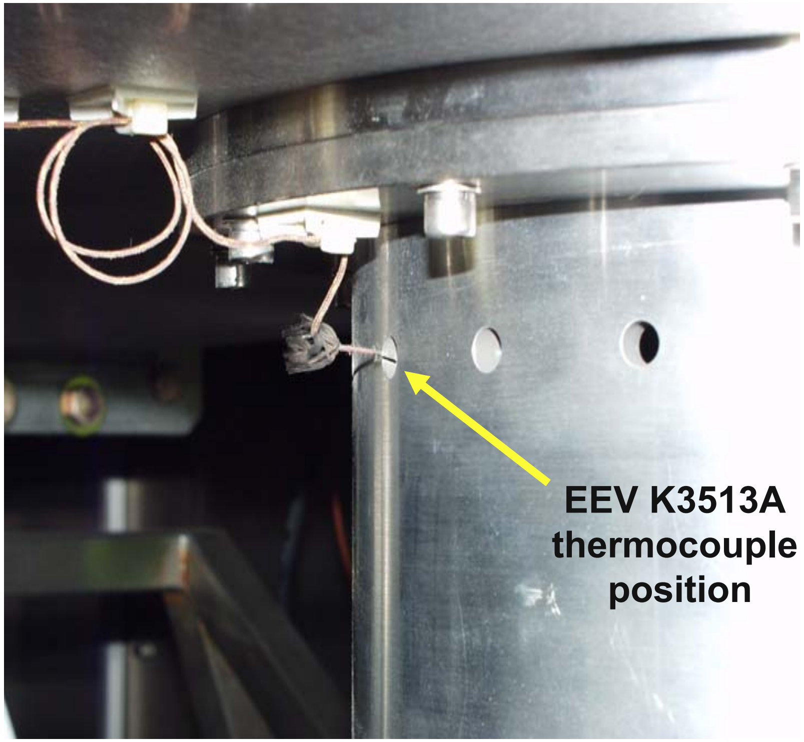


KEEP THE WINDOW AIR FILTERS CLEAN!

Measuring Output Window Temperature

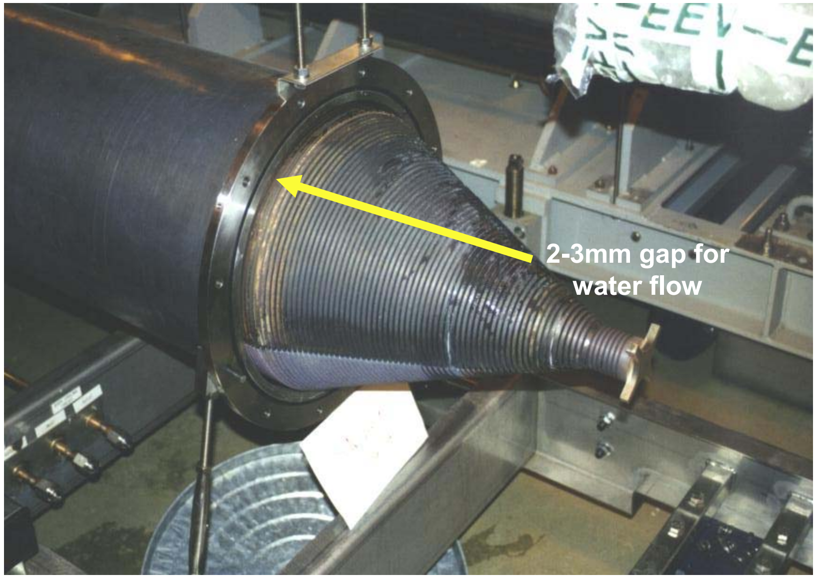
- Measured by thermocouples positioned in the output air flow from the window
  - → *Typical window exhaust air temperature at 1.1MW rf output power is ~ 55º C*
  - → *Interlock the rf drive on window air temp at 75ºC!*





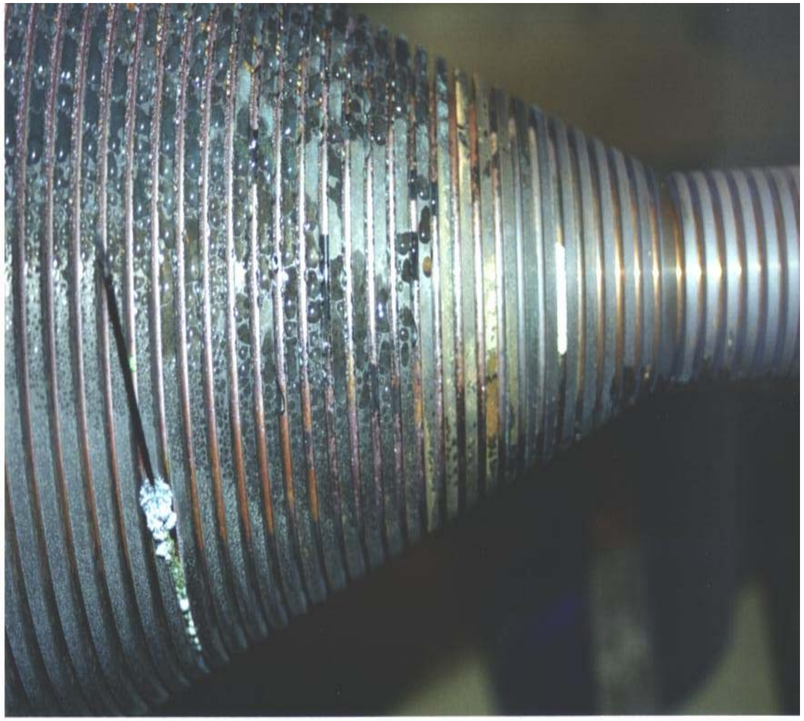
“Hypervapotron” Cooling of Collector

- Hundreds of times more efficient in removing heat than standard laminar water flow.
- Grooves and fast water velocity (2-3M/sec) over the grooves promote the creation of steam bubbles in the grooves, which are then absorbed by the fast laminar water flow.



Collector with portion of boiler removed

Maintaining the 2-3mm spacing between the boiler and collector surface is critical!
Any disruption of water flow will lead to a hot spot that can run away!



Groove depth and width are critical.

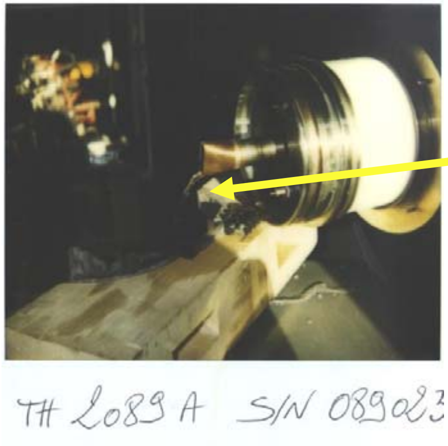
Collector Failure due to Foreign Material Obstructing Water Flow

- Pipe thread cuttings clogged collector grooves and resulted in a hot spot which grew steadily worse due to ion-focusing.
- The ultimate result was the total loss of the klystron due to loss of klystron vacuum.

Foreign material found between collector and boiler

Distorted collector due to melting

Overheated appearance on collector



A real surprise at the factory when they opened the tube!

Melting on interior of collector

Preventive Maintenance Topics

- Long life and trouble-free operation from super-power CW klystrons depends heavily on proper routine maintenance and troubleshooting techniques, such as:

  → Check condition of oil and Pantak connections

  → Perform cathode emission tests to determine proper cathode heat operating point

  → Monitor body losses and efficiency for performance degradations

  → Monitor for onset of instabilities, such as sidebands and cavity multipactors

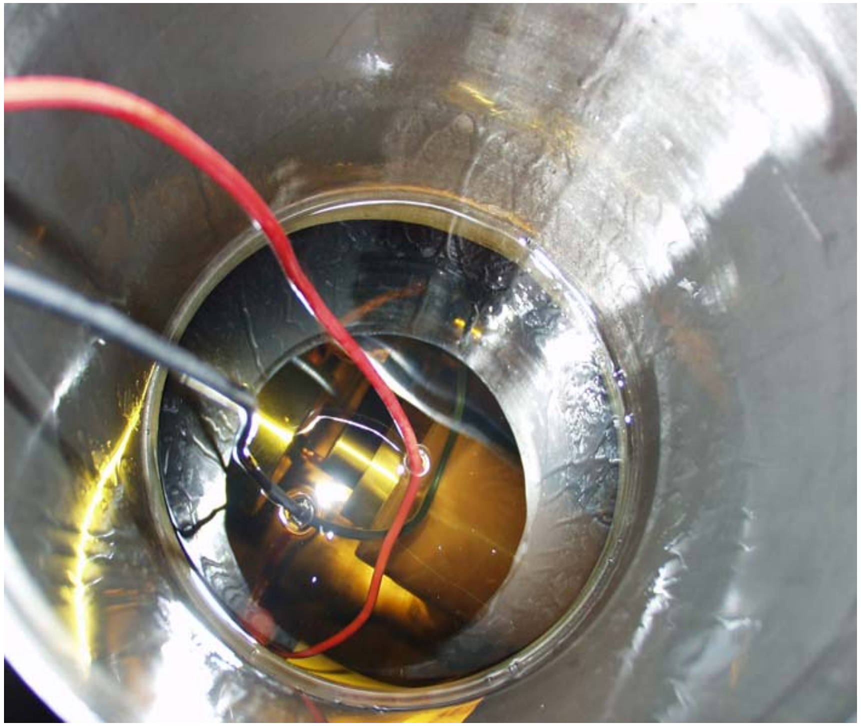
  → Routine gun spotknocking to monitor dc conditions in gun

  → Check focus magnet connections routinely for loose or poor connections

  → Routine checks for oil and water leaks

Checking Condition of Oil

- Perform breakdown tests on oil at every shutdown – *must pass 30kV*
- Check color of oil – new oil is clear, x-rays cause the oil to darken …….
  but if there is any foreign material in the oil or it is very dark, the tank must be removed and cleaned, and the oil replaced.



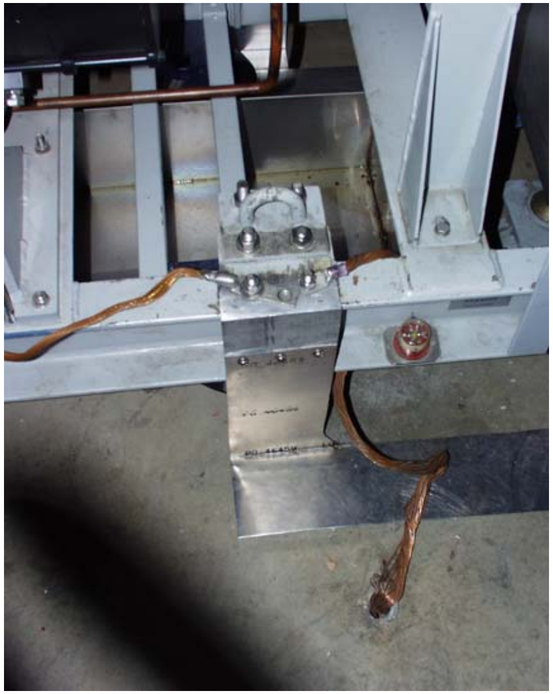
View of normal oil inside Thales tank

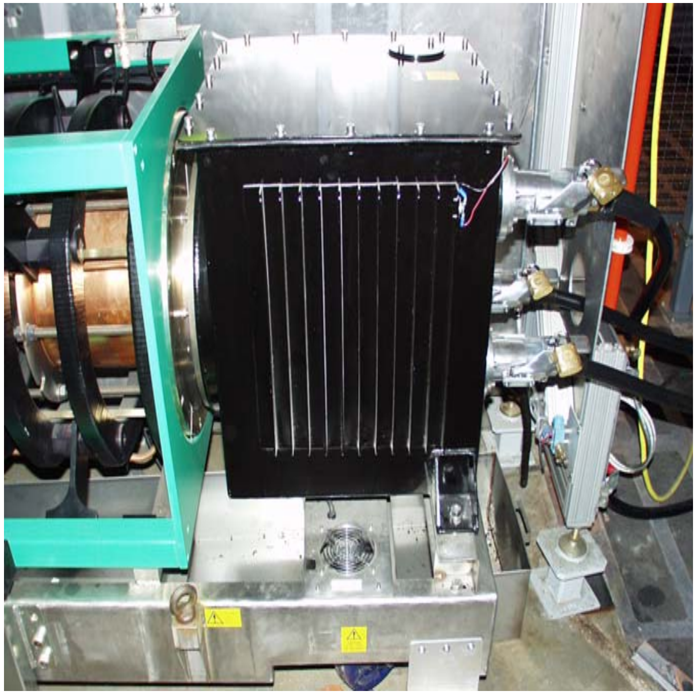
Ground-stick terminals inside tank before entering!

Checking High-Voltage and Ground Connections

- Clean and re-grease all Pantak plugs and sockets
  → NOTE: *If any oil is detected inside the Pantak socket when the plug is removed, the socket and/or gasket are leaking and must be replaced!*

- Check all ground connections for tightness



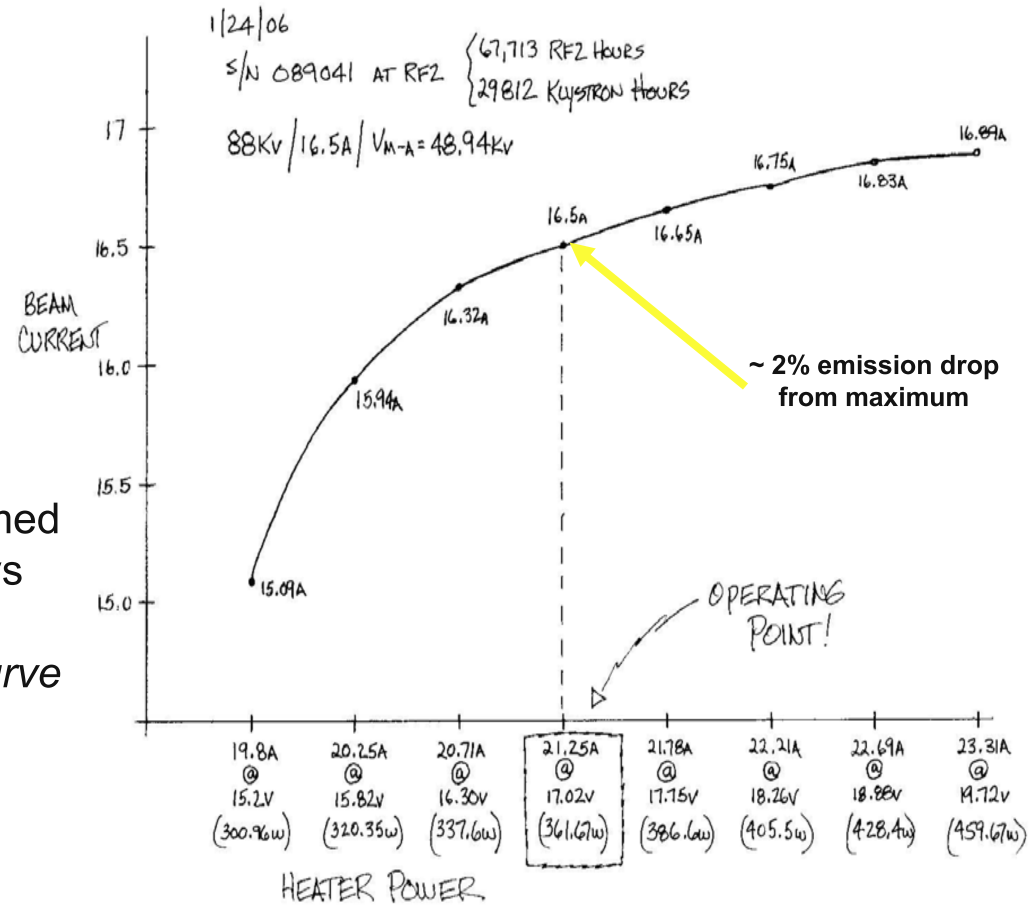


Cathode Emission Tests

- The factory heater power operating point is determined during initial testing at the factory under full-power (~ 92kV @ 20A, 1.1MW rf) operating conditions.

However…….you <u>will not</u> require that much cathode heat because we do not operate at full power.

→ Excessive cathode heat causes premature depletion of barium from the cathode and risks excessive barium deposition on the gun elements (arcing!)



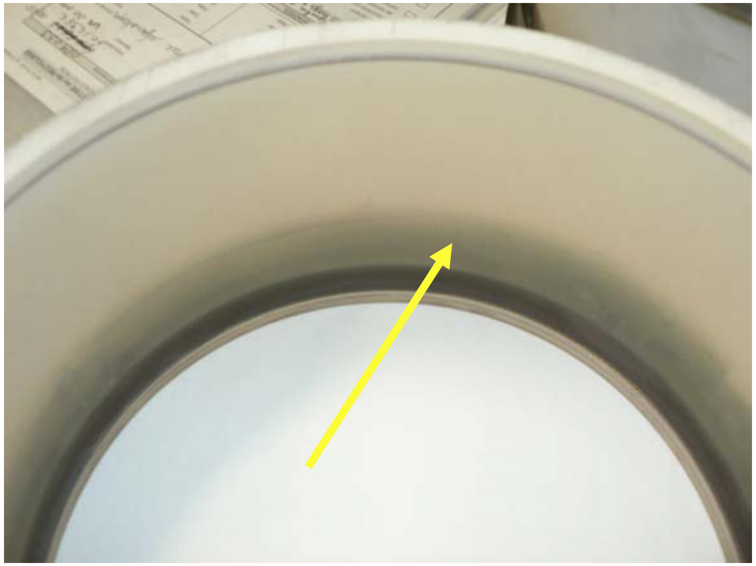
- An initial emission test should be performed on new tubes after approximately 30 days of operation to allow time for cathode impurities to be cleaned off……..*if the curve does not show a sharp knee as heater power is reduced, the new cathode is still in the cleaning process!*

- Emission tests should be conducted approximately every two years in order to keep up with cathode aging.

Result of Excessive Barium Deposition in Cathode

- Barium deposition can be caused by defective crowbar systems that allow more than 20J of energy in gun arcs, excessive cathode heating, or simply old age.

- Barium deposition onto the gun components and rf cavity nosecones can be the cause of gun arcing and unstable rf operation.



Excessive barium on gun ceramic

Excessive barium on cathode whenelt electrode

<u>*Excessive Body Losses Can Be Very Dangerous!*</u>

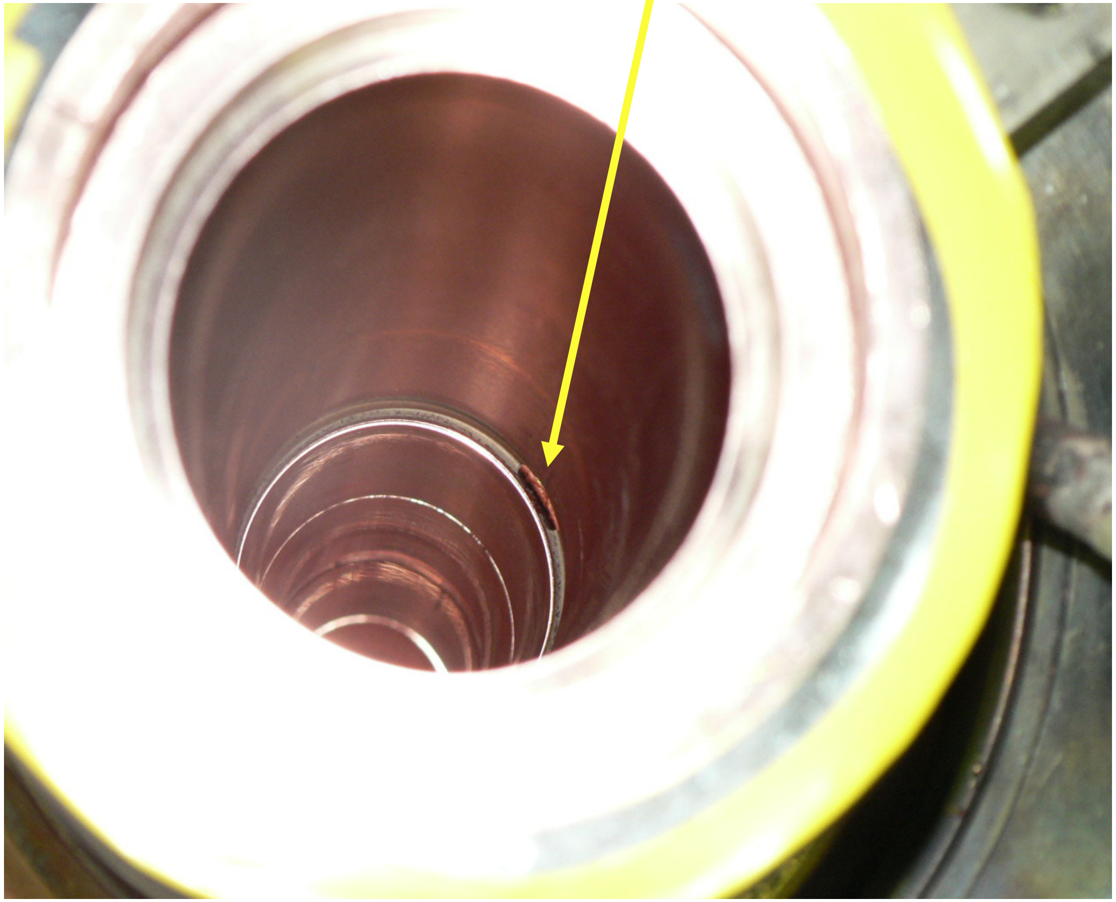
- **Typical body losses are much lower than the maximum allowable values:**

→ *Body power ~ 1-3kW at 1.1MW RF output*

→ *Output cavity power ~ 2-3kW at 1.1MW output*

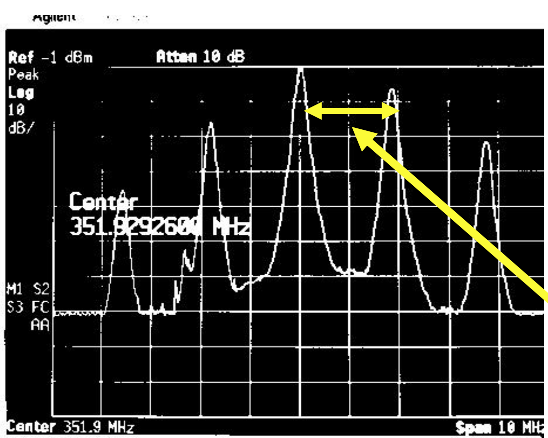
MAKE SURE YOUR BODY POWER INTERLOCKS ARE SET PROPERLY!

<u>Remember</u>…………..due to the transit time of water, there is significant delay in detecting high water temperatures!

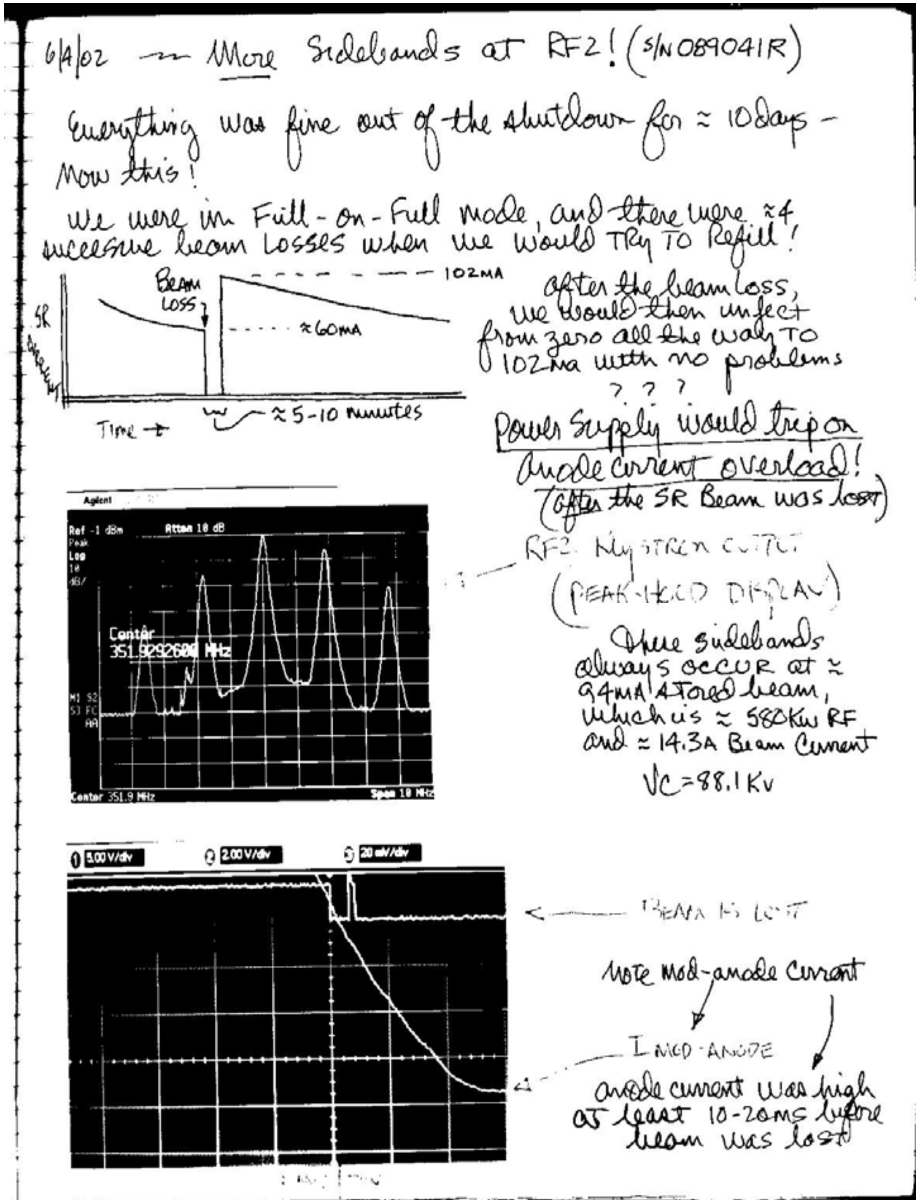


Klystron Sideband Instability

- Thought to be caused by "backstreaming" electrons from the output cavity gap
- Produces very strong sidebands at Fc +/- the difference in Fr between cavity #1 and cavity #2
- Almost always accompanied by excessive or very erratic mod-anode current and possibly erratic vacuum activity
- Usually remedied by cavity tuning or adjusting output match.



Fc +/- ~ 1.8MHz


6/4/02 — More Sidebands at RF2! (S/N 089041R)

Everything was fine out of the shutdown for ≈ 10 days — Now this!

We were in Full-on-Full mode, and there were ≈4 successive beam losses when we would try to Refill!

after the beam loss, we would then inject from zero all the way to 102MA with no problems ? ? ?

Power Supply would trip on Anode current overload! (after the SR Beam was lost)

RF2 Klystron output (Peak-hold display)

These sidebands always occur at ≈ 94MA stored beam, which is ≈ 580Kw RF and ≈ 14.3A Beam Current

Vc = 88.1Kv

Beam is lost

Note Mod-anode Current

I mod-anode

anode current was high at least 10-20ms before beam was lost

Gun "Spotknocking"

- Involves using a high-voltage/low-current power supply with less than 20 Joules stored energy to "knock" barium deposits off of gun electrodes.
- Has been successfully used to reduce gun arcing in old klystrons.
- Can be a useful diagnostic tool to trend gun leakage current over time, and also to help determine if chronic crowbar events are klystron or crowbar-related.
- Refer to RF Technical Note on spotknocking, ***<u>and do not exceed 200 watts dissipation on gun ceramics!</u>***

1/13/06 — {Spotknocked RF2 Klystron (S/N 089041) — in response to numerous un-explained CB Firings}

Anode - Body Ceramic		Anode - Cathode Ceramic	
10kV — Ø	No Sparks	10kV — Ø	
20kV — Ø		20kV — Ø	
30kV — Ø		30kV — Ø	
40kV — Ø		40kV — Ø	
50kV — Ø		50kV — 30µA	
60kV — 10µA		60kV — 120µA	
70kV — 20µA	Sparks at ≈75kV	70kV — 450µA	Sparks!
80kV — 50µA		80kV — 1.27mA	Spark!
90kV — 90-100µA		83kV — 1.78mA	Spark!
93kV — 130µA	Several Sparks	85kV — 2.4mA	Sparks tapered off and ended
99kV — 110µA	Several Sparks		

Backed Down to 90kV, and Leakage Current was now ≈30µA

An improvement but overall, Very little activity

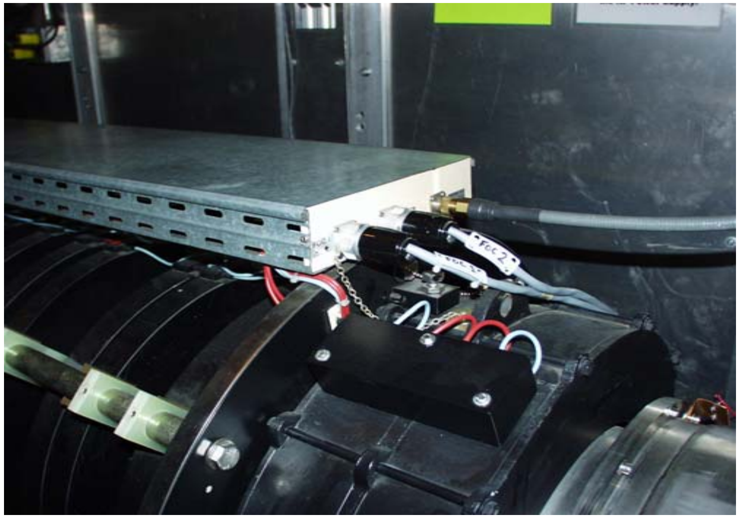
Backed Down to 60kV, and leakage current is now 60µA

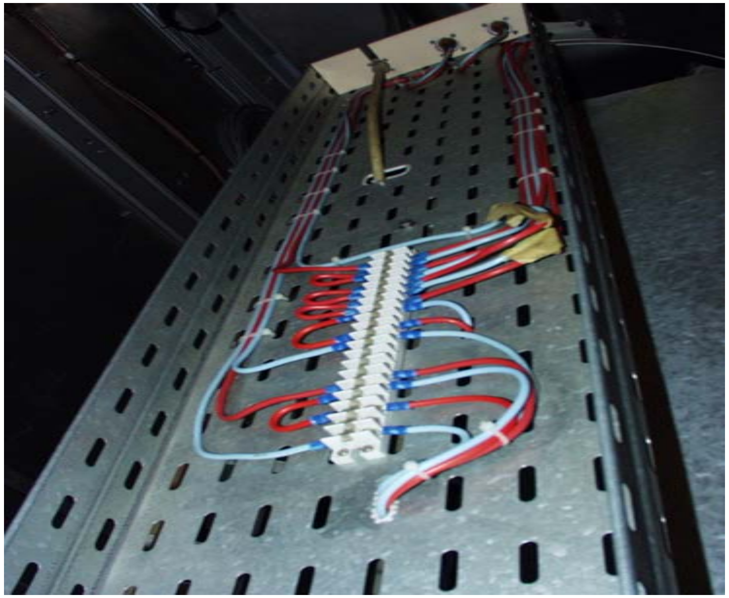
An improvement — but overall, Very little activity at normal operating voltages

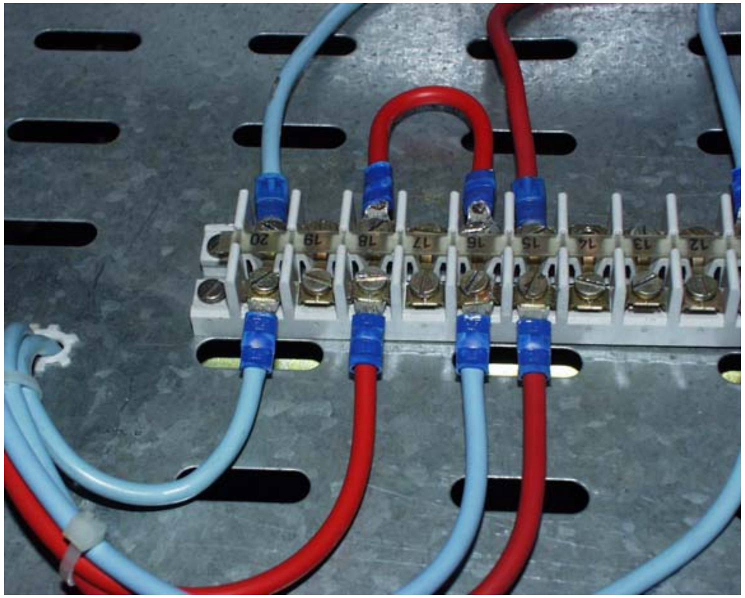
Considering the age of this klystron (and its history): 32K hrs, the spotknocking process was remarkably quiet!

Checking Focus Magnet Connections

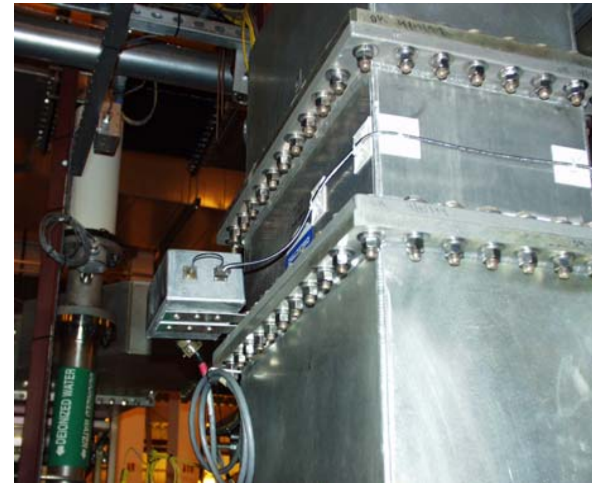
- Visually check focus magnet connections on TH2089A klystrons for loose screws or overheated crimp lugs.
  - → *Note: Some TH2089A's have 100-watt resistors in the magnet junction box to adjust current in individual coils when needed to optimize focusing.*



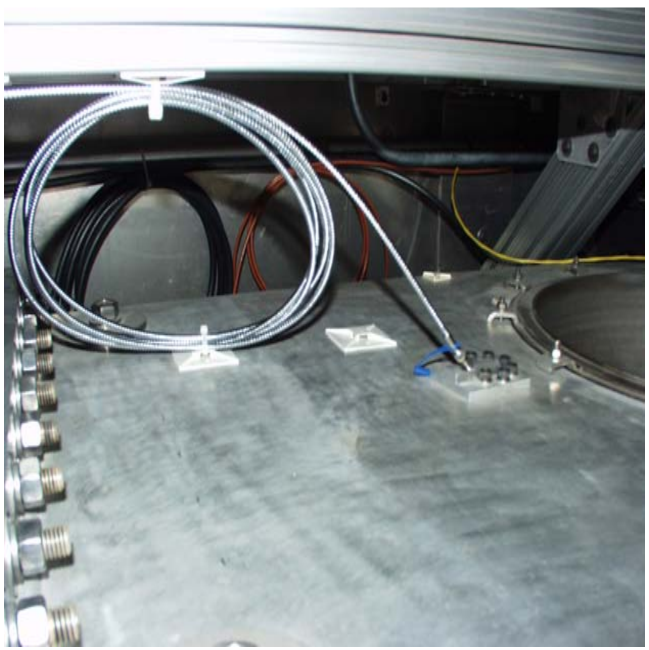


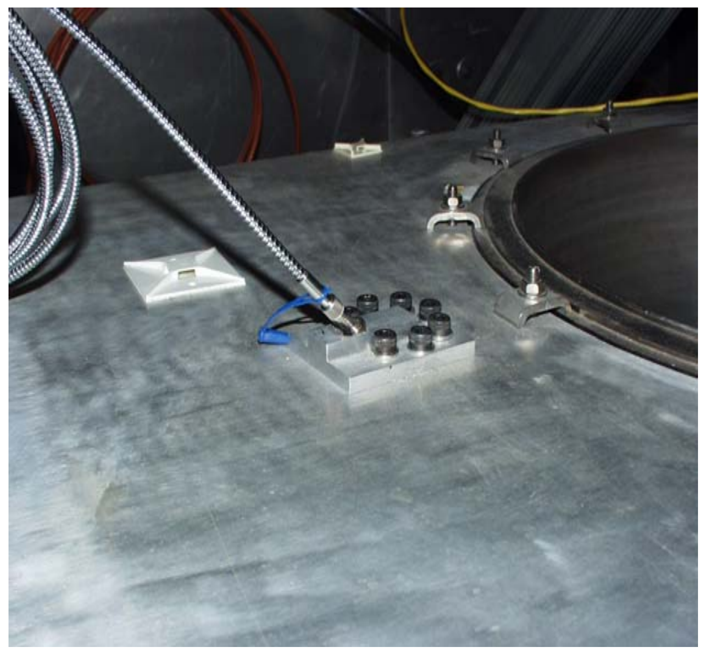


Output Window Arc Detection



- Fast arc detection is *critically* important to prevent window damage!
  - → *Test arc detectors routinely at the input of the fiber optic cable!*
  - → *Verify that the fiber-optic cable is connected to the view port!*





Common Water Leak Locations on the TH2089A and K3513A

- **Over time, minor water leaks can occur at the following body water circuit fittings:**

K3513A body and output Cavity inlets and outlets	TH2089A oil tank water jacket	TH2089A body-1 water circuit
		

Routinely check these connections for tightness!
Replace gaskets if leaks persist!