X-Band Klystron Development at SLAC

Presented by A. E. Vlieks

RF Source development: An obvious byproduct of a Linear new Collider

- In Russia, 14 GHz. Klystrons
- In Germany, two programs.
    - S-band and
    - L-band –TESLA
- U.S and Japan collaboration.
    - X-band development by KEK and SLAC.
    - Later-an alternate C-band Klystron development by KEK
- 2-Beam Accelerator development at CERN and LLNL. LLNL started with X-band and a Induction LINAC. CERN worked on 30 GHz. LINAC structures.

100 MW klystron scaled from S-band to X-band…11.424 GHz:

Some considerations:

•Design at higher beam voltage than S-band Klystron to reach 100 MW.

- •Design will have higher output cavity peak fields

•Use a gun quite similar to the S-band gun.

•Design will have higher areal beam compression than S-band Klystron.

•Design windows for max. bandwidth and free of ghost modes

The development of SLAC X-band Klystrons can be divided into three families:

- •XC Series-find out problems
- •XL Series-solutions
- •PPM Series-include economics for Collider

Design Parameters for first 3 XC Klystrons

Frequency	11.424 GHz.
Pk. Output Power	100 MW
Rf Pulse Width	1 μs.
Beam Voltage	440 KV
Beam Current	520 A
Beam areal Compression	190:1
Max. Gun Surface Gradient	308 KV/cm
Cathode diameter	8.9 cm (3.5”)
Focusing Field	≈ 6kG

XC-1

• 5 cell Klystron with single reentrant output cavity.

• Had thin fragile windows

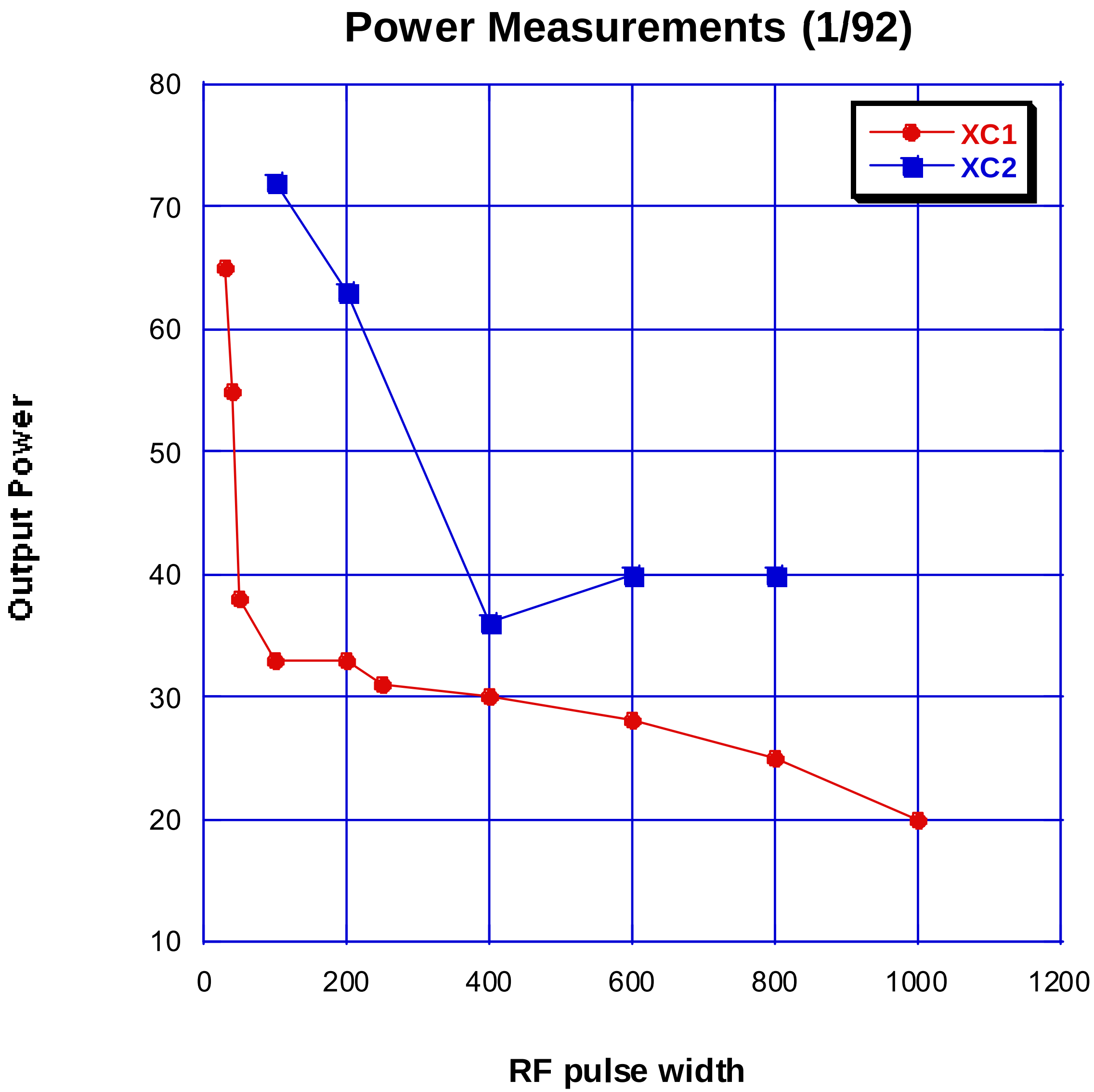
• Reached 65 MW at 30-40 ns but suffered from RF breakdown at wider pulse widths.

•Used in Binary Pulse Compression tests (BPC) and Crossed field Amplifier tests.

•Eventually failed during BPC tests

XC2: In order to reduce the peak fields in the output cavity, a two-cell iris-coupled cavity was designed. With this tube, peak power was generated at narrow pulse widths (100-200 ns) of 72 MW. Tube was extensively used for Binary Pulse Compression tests (38MW, 800 ns) , SLED-II .
Original window design used 0.8 mm window ceramics. Later, this was changed to a thicker, more robust design (3.7 mm) .

XC3: Similar to the XC2 but with an improved magnetic field profile. Performed about the same as XC2 and was used to power a X-band TW Resonant Ring. The Ring was used extensively to test and improve high power ceramic windows. It had a power gain of 10 and operated up to 300 MW with 800 ns pulses.



Power Measurements (1/92)
Output Power
RF pulse width
XC1
XC2
80
70
60
50
40
30
20
10
0
200
400
600
800
1000
1200

XC2-F

Ran from 4/91-1/92

Failed due to broken window.

XC2-G

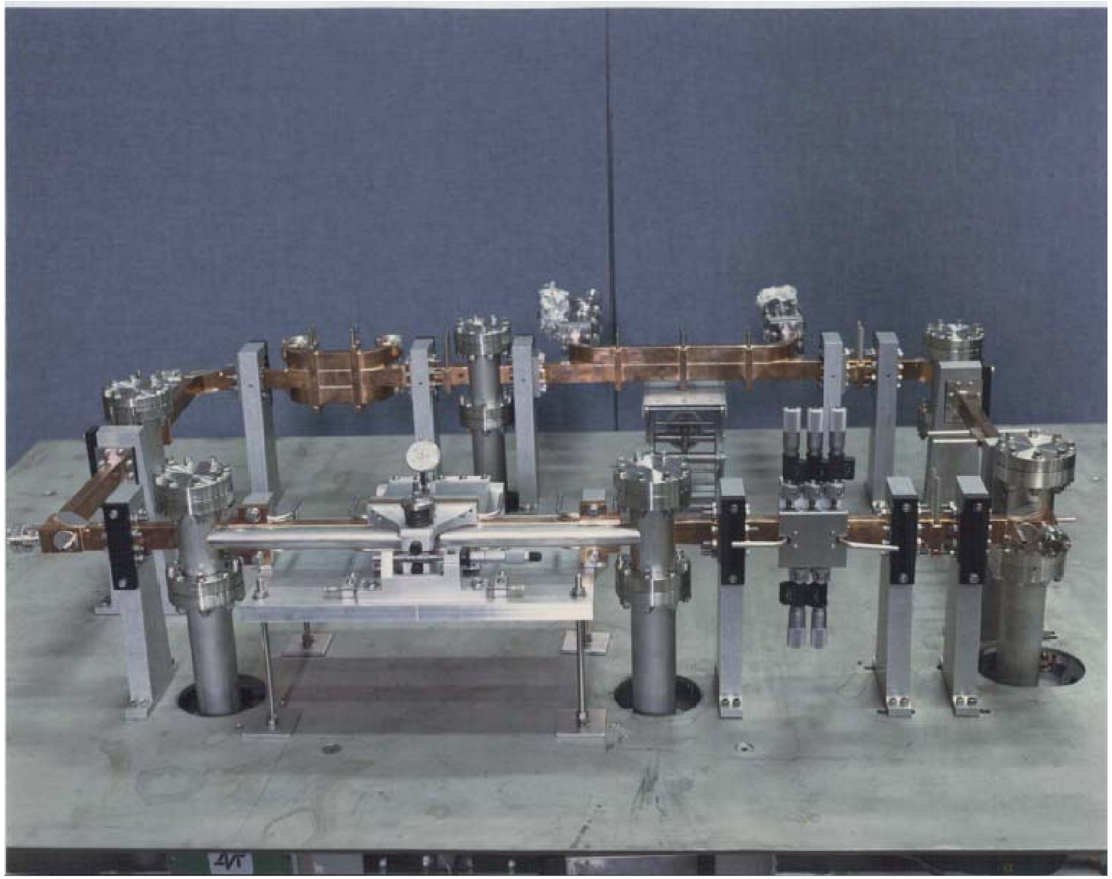
Ran from 4/92-7/95

Used extensively in SLED-II testing.

Used in resonant Ring testing

Failed due to gun failure

Traveling Wave Resonant Ring



It became clear that there were four obstacles to overcome in order to develop a viable tube design. These were:

- Fragile windows
- Output Cavity- beam erosion
- Output Cavity -RF breakdown
- High gun fields and beam compression ratio

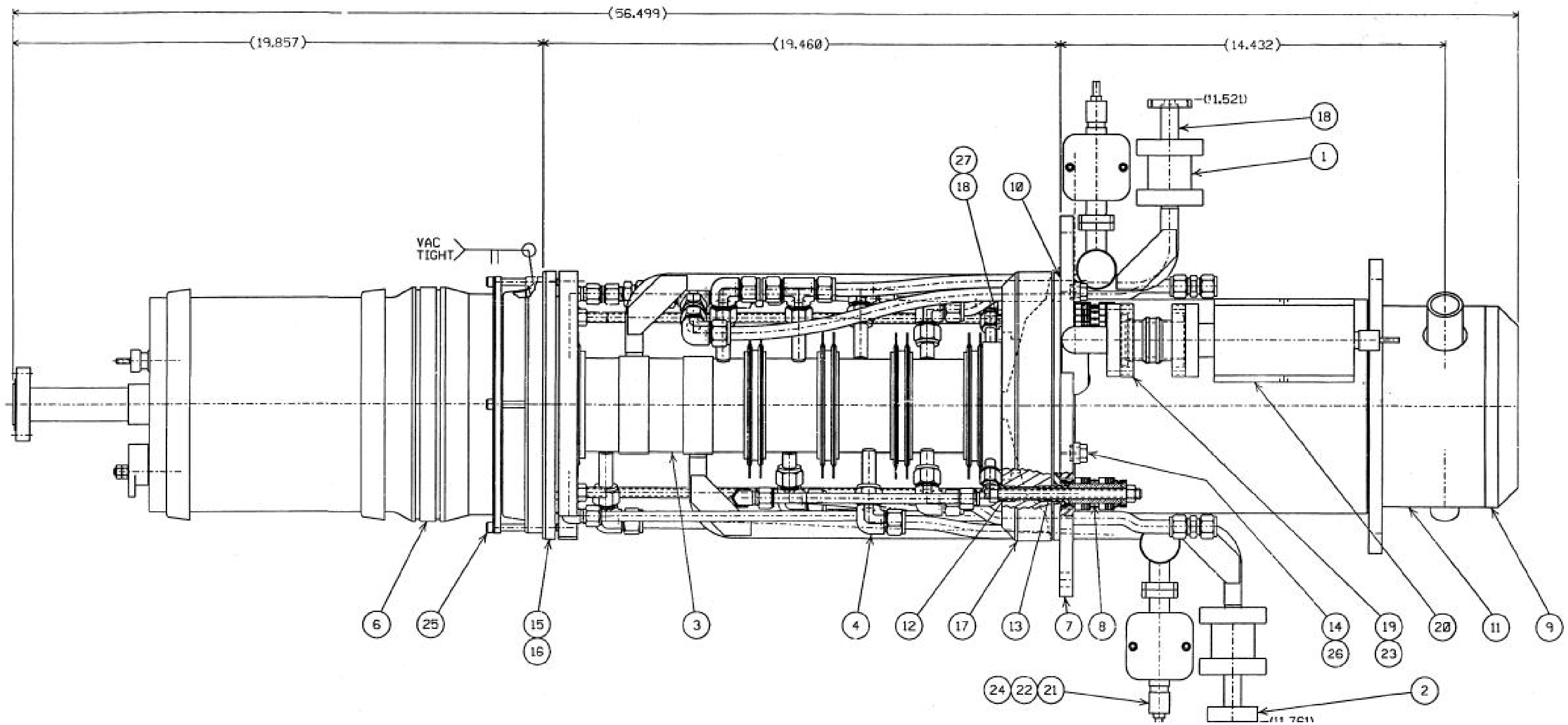
Test a new Gun design-XBT1

Study RF breakdown in Output Cavity-XC4

XBT1

Purpose: Verify beam transmission and agreement with gun code (EGUN) using reduced beam compression.

Used 4 isolated sections with decreasing drift tube diameter.



XBT1 Parameters and Results

Beam Voltage -440KV

Beam Current- 555 A

Measured/Calculated μPerveance-1.93/1.90

Drift tube diameters (mm)- 10.5, 9.0, 8.0

Beam diameter (mm)- 6.4

Tailpipe interception-0.5%,

First drift tube Interception- 21mA

XC4 was a test vehicle to test RF breakdown and gun performance. It was **built without windows** but with internal output loads.

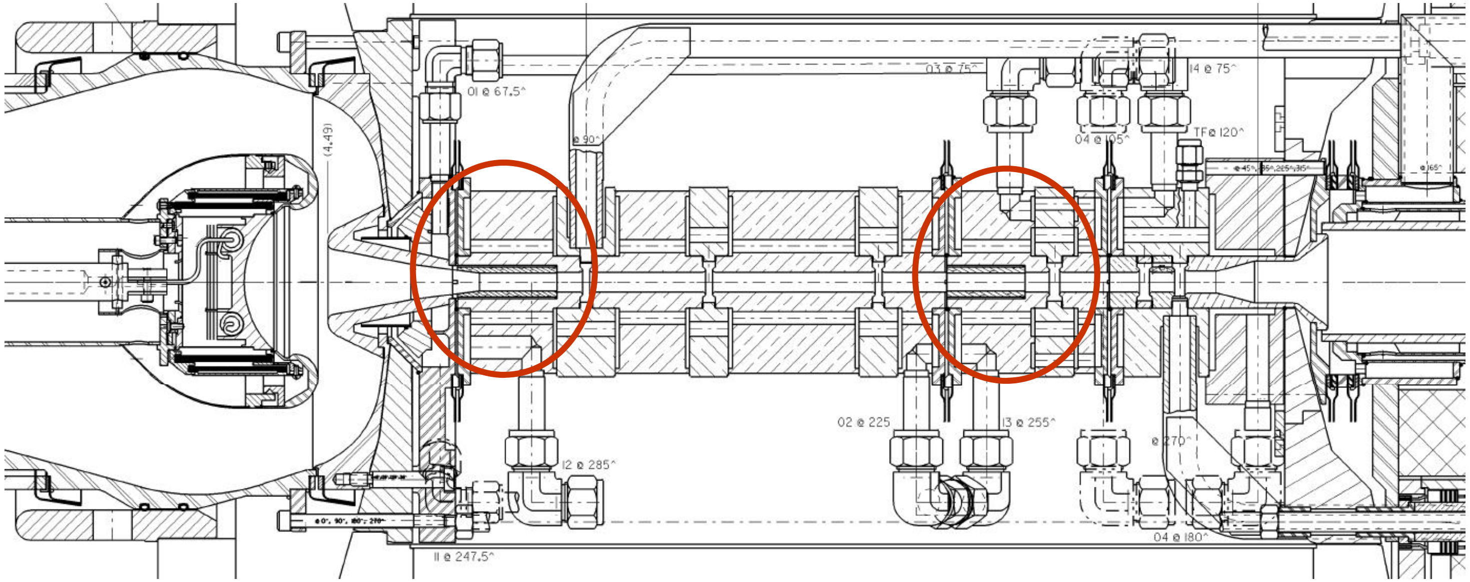
In addition, **Beryllium beam scrapers** were installed in front of the penultimate cavity and the input cavity to reduce erosion in the cavities and drift tube by beam interception.

The goal was to see how the tube would perform without breaking windows during testing and without excessive beam interception.

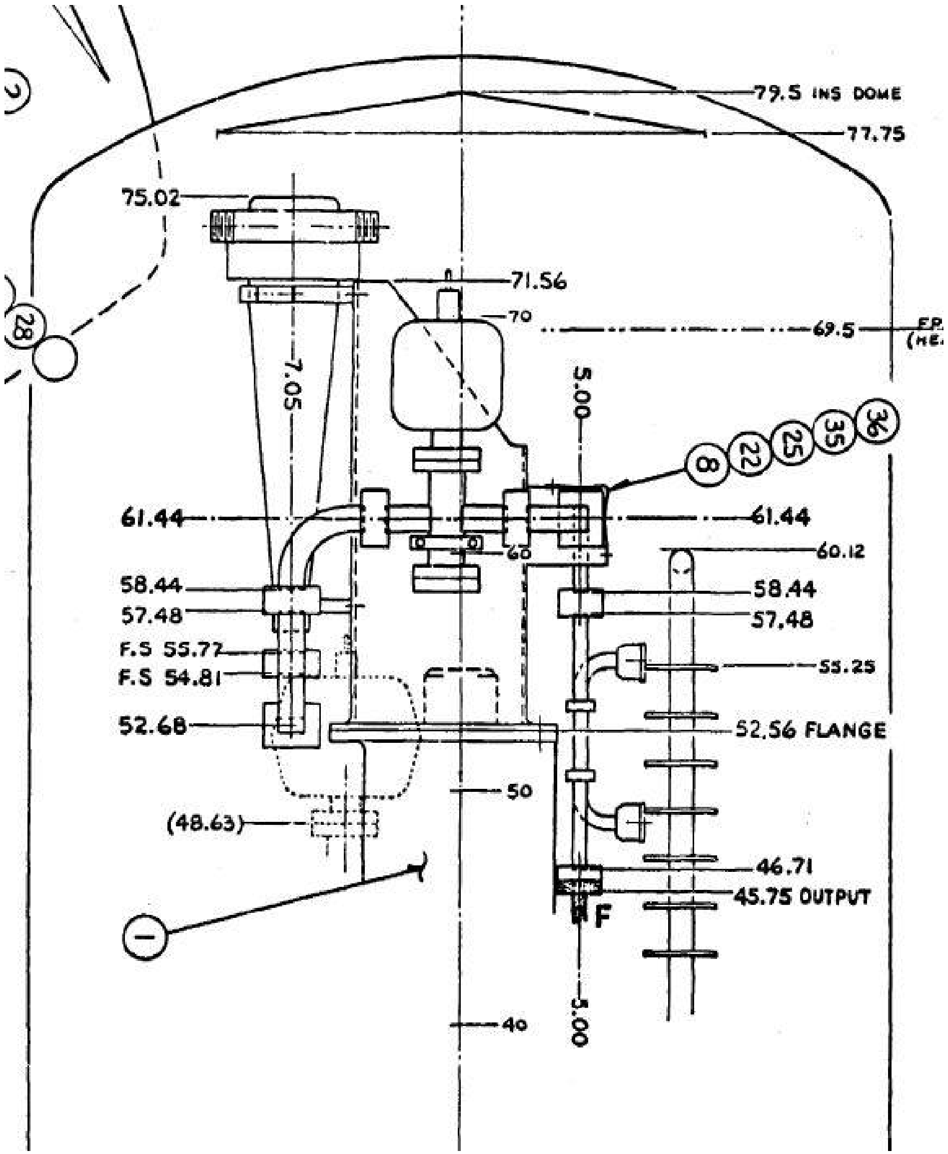
Pulse breakup was still evident during testing. On autopsying the tube it was discovered that the damage did not occur in the output cavity gaps but in the **asymmetric inductive coupling iris.**

A new output cavity design was necessary!!

XC-4 with BeO beam scrapers



XC4 with RF Load in Bake Station



The remaining XC Klystrons, XC5-XC8

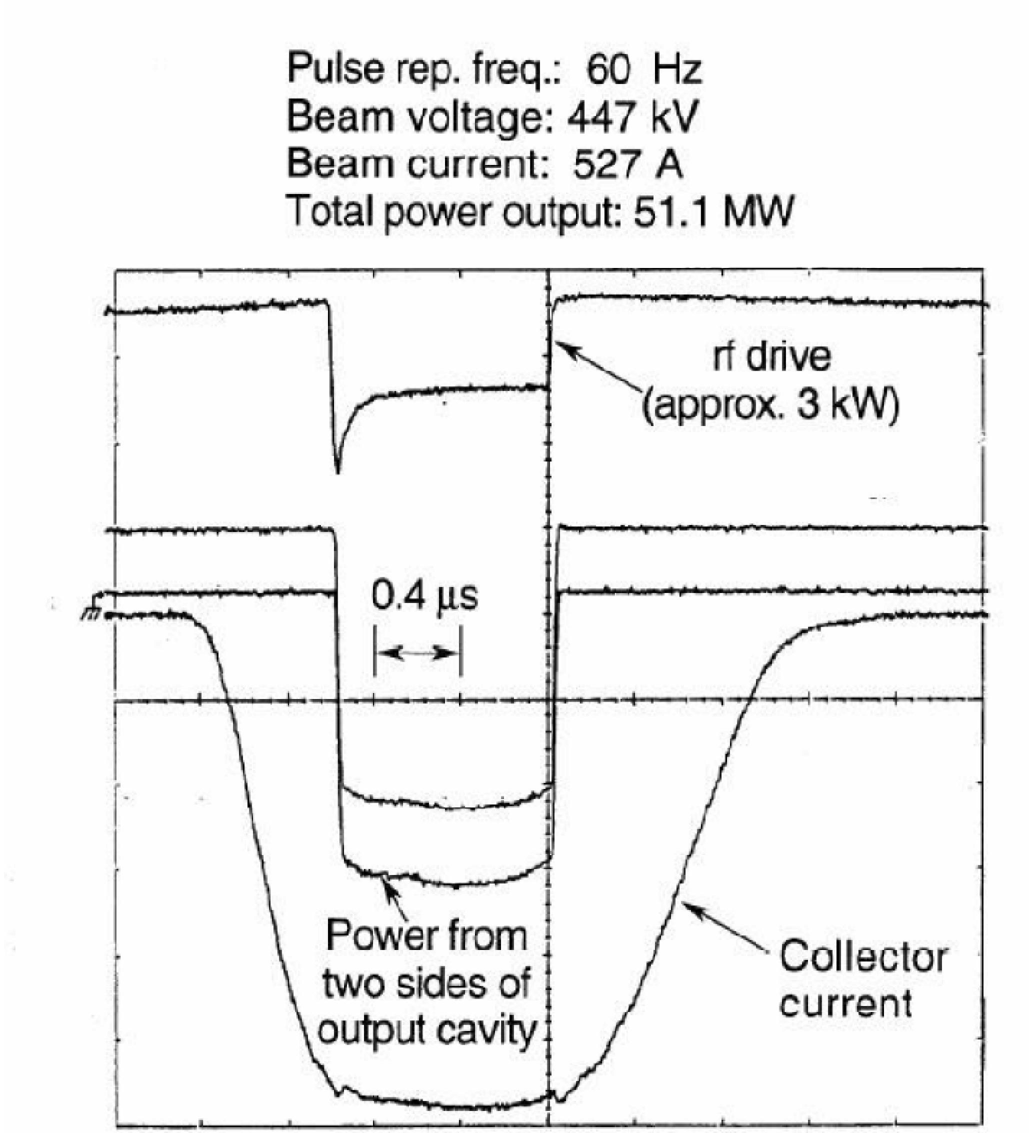
Two changes were made:

Symmetric multiple cell output cavities were designed (except XC-6) and the (XBT1) new lower beam-compression ratio gun was used. The down-side was a high peak cathode current-loading (25A/cm^2)

XC5, XC7 were designed using traveling wave output structures. XC5 produced 52 MW with 1μs pulses.

The principle design code during this development was CONDOR.

XC5- with TW Output Cavity



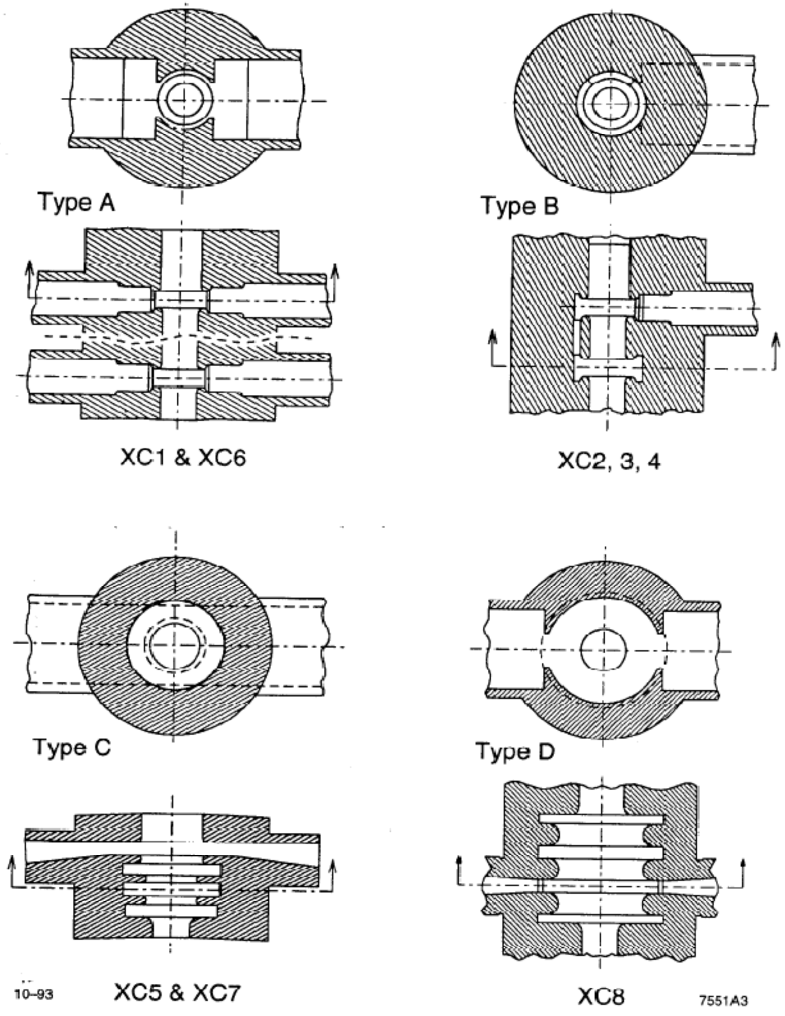
XC-6:

XC6 was an unusual Klystron. It was designed with 2 isolated output cavities and 4 waveguides.

It Produced nearly 90 MW at 200 ns.

It was not repaired after a gun ceramic puncture because of a change in program.

XC-Series Output Cavities



XL series:

It was clear that the XC klystrons were limited in performance by fragile windows and excessive beam interception in the output cavity.

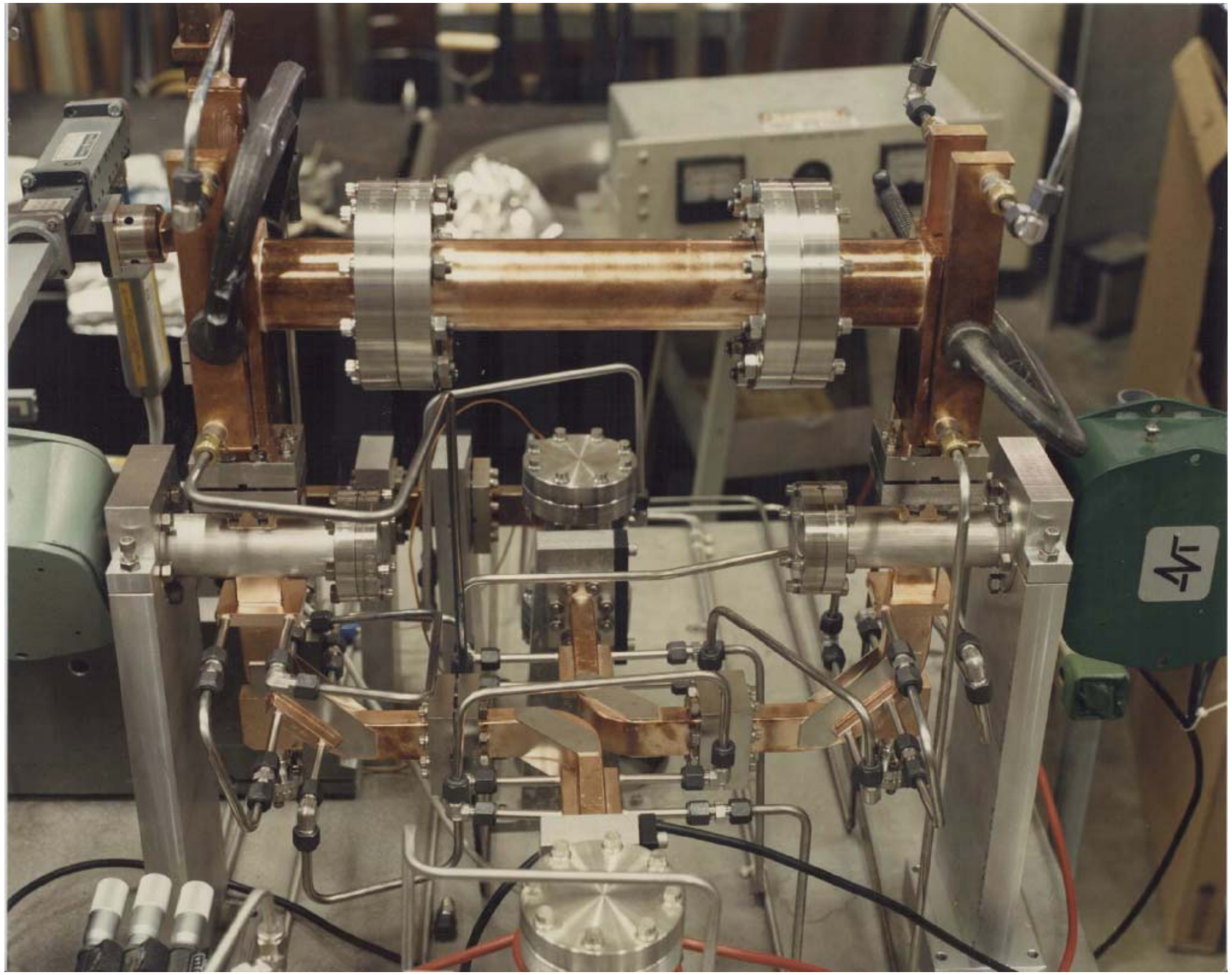
A more efficient, more reliable klystron could be developed if the perveance and output power were lower and if the operating mode for the windows was the circular TE01 rather than theTE11 mode.

> One of the problems with the TE11 mode is that the Electric fields cross the ceramic/metal periphery which often has rough, sharp edges due to a braze fillet. Windows usually were failing due to overheating and arcing at this interface.

A new family of Klystrons was begun. **The 50 MW, 1.2 microperveance klystron.**

- •A beam tester was built to verify the new gun design-
- •The X-band Traveling Wave Resonant Ring was modified for the new windows and window coatings

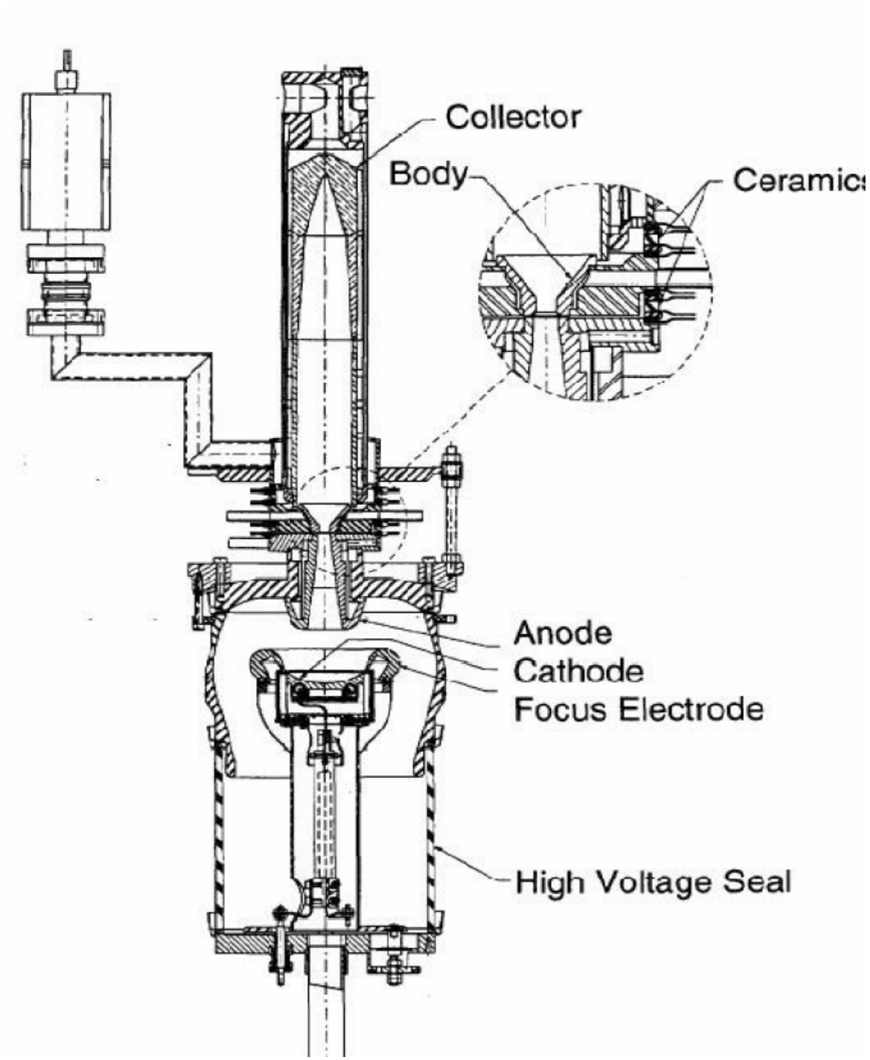
Resonant Ring with window test adapter



XL design Parameters

Beam Voltage	440 KV
Beam Current	350 A
Peak Output Power	50 MW
RF Pulse width	1.5μs
Cathode Diameter	71.4 mm
Beam areal compression	125:1
Peak Cathode loading	12.8 A/cm^2
Magnetic field	0.47 T
μPerveance	1.2

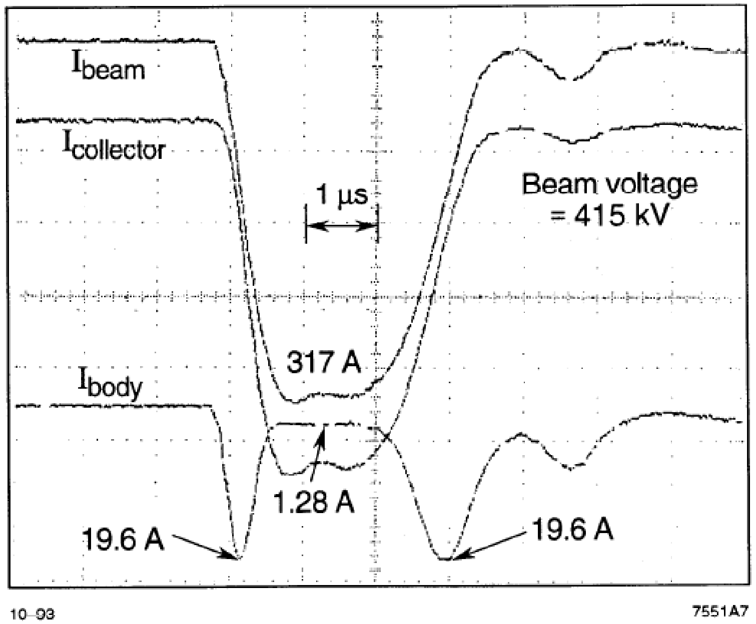
XL- Diode



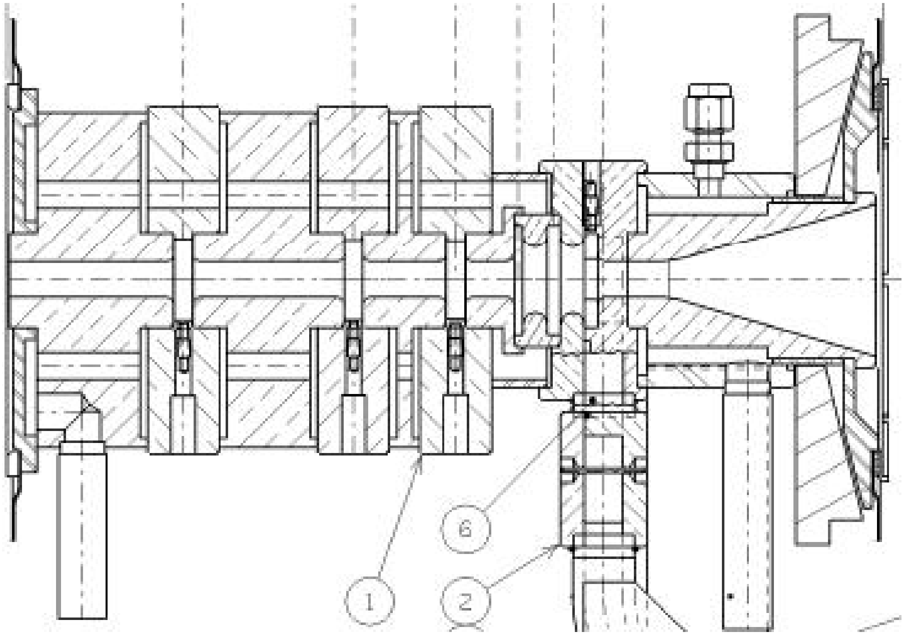
Collector
Body
Ceramics
Anode
Cathode
Focus Electrode
High Voltage Seal

Beam Diode Measurements

- Measured μPerveance- 1.2
- 99.5% Transmission



XL1- This Klystron had 3 gain cavities, 3 “penultimate” or buncher cavities and a 3-cell output “extended Interaction” cavity operating in the π mode.



XL-1 and XL-2 showed improved performance over its XC predecessors. In the first set of tests XL-1 was able to reach 58 MW at 250 ns. At wider pulse widths, however, a 17 GHz oscillation appeared, but could be removed by squeezing the beam to a smaller diameter.

It reached its design power of 50 MW, with a 1.5 μs pulse width for a beam voltage of 413 KV.

The 17 GHz. Oscillation was attributed to a TE11 trapped mode in the equal gap-width penultimate cavities. **This was modified in XL-2. Otherwise, XL-2 was the same as XL-1**

Simulations using “CONDOR” predicted 62.5 MW for XL1 instead of 58 MW

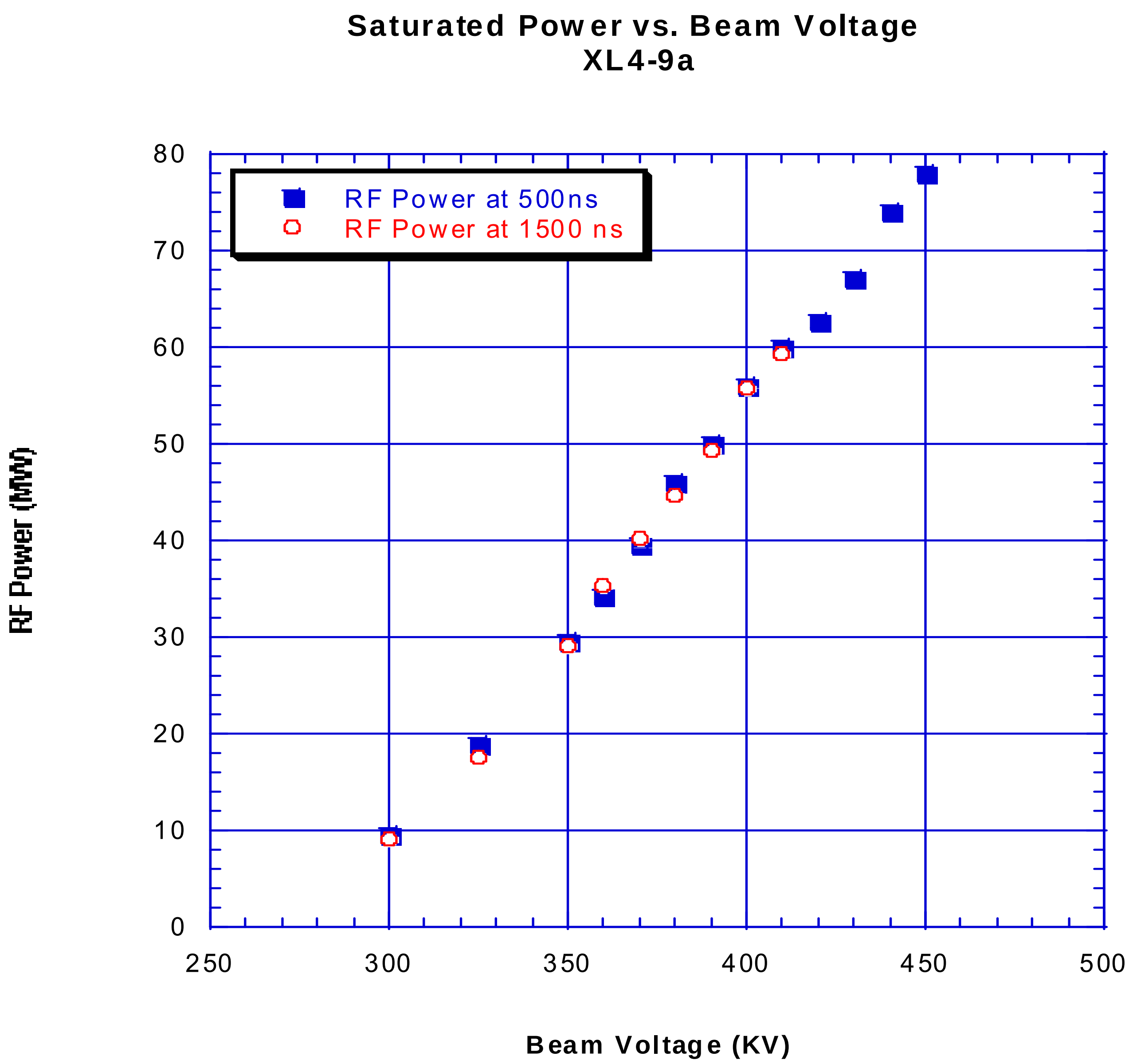
XL3 and XL4 were designed with a 4 cell traveling wave output structure operating in the $\pi/2$ mode.

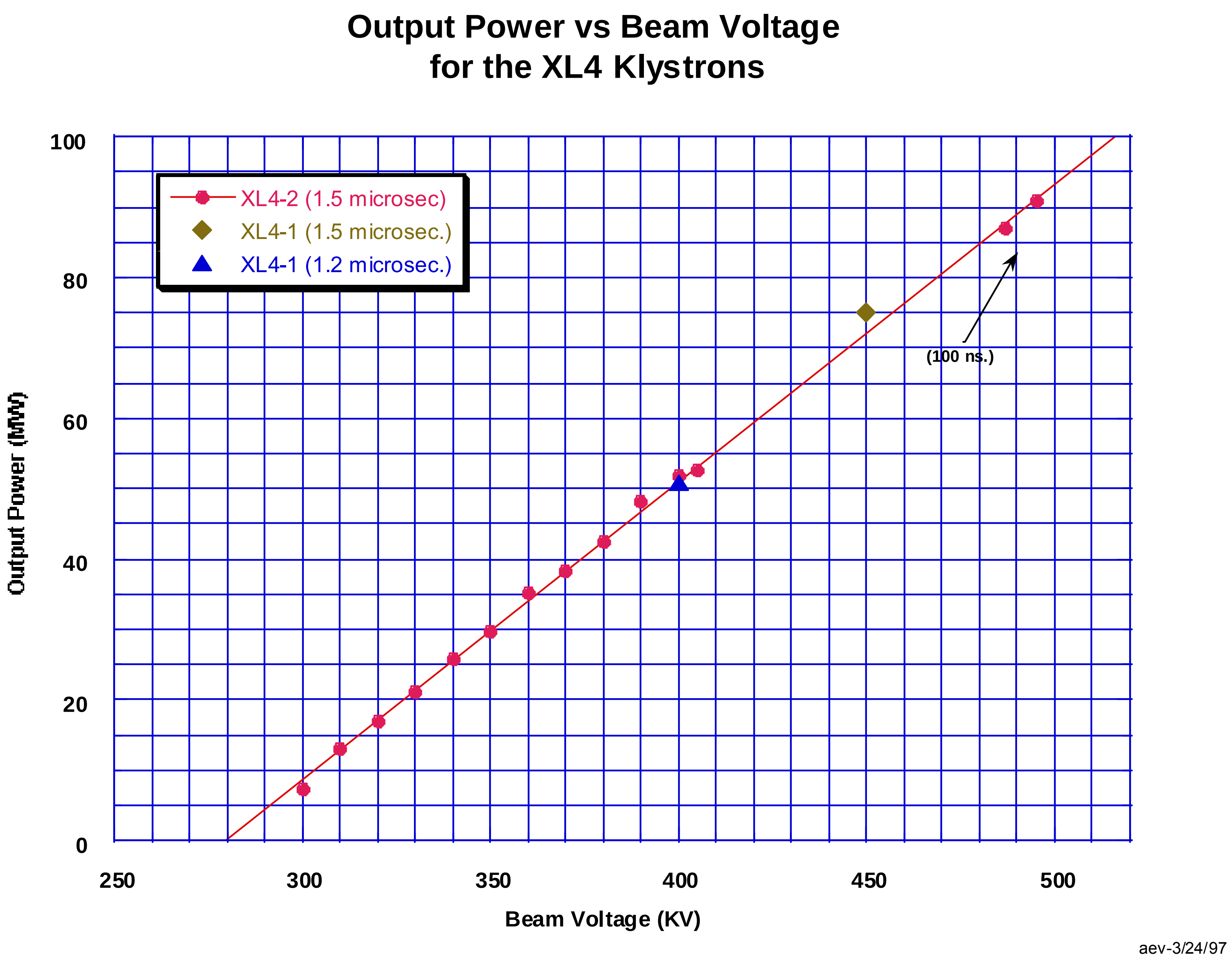
Although the XL1 and XL2 worked well, the standing wave structure did not take into account that the beam was slowing down as it passed through the cells. It also didn't take into consideration the generation of rf current as it passed through the cells. In the TW output structure, both **velocity tapering and Impedance tapering could permit a higher efficiency design.**

An additional problem was also addressed in XL3/XL4.

The bandwidth of XL1 was only 30-40 MHz. wide. This prevented the pulse shape from pulse compression schemes from being flat. The new design had bandwidths of approximately 120 MHz. A marked improvement.

In the XL-3, some higher order instabilities were observed. To remove this problem, the last two drift tunnels in XL-4 were made from **Stainless steel rather than copper**. This resulted in a klystron which was unconditionally stable.


Saturated Power vs. Beam Voltage
XL4-9a
RF Power at 500ns
RF Power at 1500 ns
RF Power (MW)
Beam Voltage (KV)
0
10
20
30
40
50
60
70
80
250
300
350
400
450
500



Output Power vs Beam Voltage
for the XL4 Klystrons
XL4-2 (1.5 microsec)
XL4-1 (1.5 microsec.)
XL4-1 (1.2 microsec.)
(100 ns.)
Output Power (MW)
0
20
40
60
80
100
250
300
350
400
450
500
Beam Voltage (KV)
aev-3/24/97

XL-4

The XL-4 has been the workhorse of X-band tests over the last 12 years.

•It has been used in evaluating accelerator performance for the NLC program

•It has been used to test window designs.

•It has been used in SLED-II pulse compression schemes to generate ≈ 500 MW RF power

•It is being used to study breakdown limits on a variety of RF components. Four test stands in the Klystron Test Lab. are performing these tests. Two test stands are being used in the NLCTA.

•Two XL-4's were used in a 5 ½ cell RF gun Photoinjector program for several years.

•LCLS uses one XL-4 to linearize its electron beam profile.

•15 XL4's have been built thus far.

XL Series:

It should be pointed out that during all Klystron tests, there were no window failures although only a single TE01 window was used.

XL-1 eventually suffered a gun ceramic puncture. It was rebuilt with a vac-ion pump mounted directly on the gun pump-out tubulation.

No XL tube has failed due to gun ceramic puncture since.

Towards a Next Linear Collider…

Periodic Permanent Magnet focused Klystrons:

Although the XL series of Klystrons perform well they have two shortcomings for an NLC.

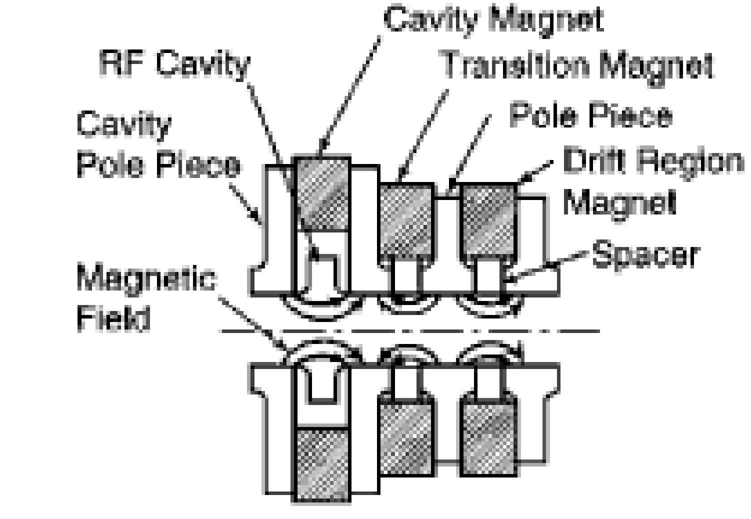
•The efficiency was a bit low

•The Solenoid magnet required about 20 KW of average power

These problems could be improved if the perveance of the Klystron is lowered and if periodic permanent magnets (ppm) are used to confine the beam.

Note: PPM focusing is not a new idea in the microwave industry. It has been used successfully in couple cavity TWT's for years although not for klystrons.

Periodic Permanent Magnets



PPM Series:

The first PPM focused klystron was similar to the XL-4 except the gun was redesigned for a lower perveance-0.6 μP, for efficiency. Also, an extra cell was used in the output section.

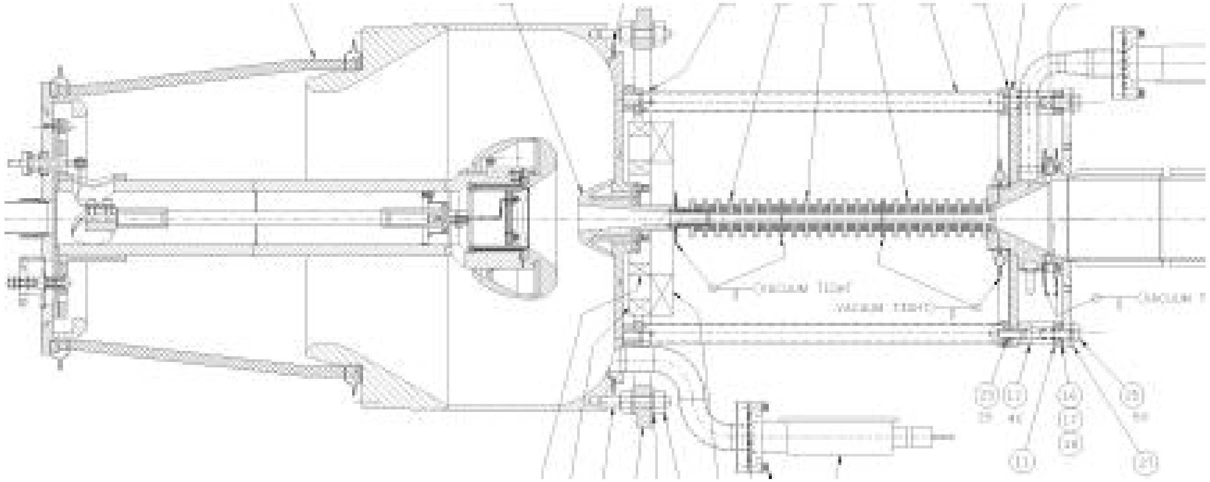
This required the building and testing of a beam diode (Beam Tester) to verify the gun optics and PPM focusing.

The beam diode consisted of the new gun and 20 magnetic periods, which was approximately the number used in the future Klystron. Samarium Cobalt magnets (peak fields of ≈ 3000 Gauss) were used.

It was operated up to 550 KV with a beam transmission of ≈99.9%.

Even at a beam voltage of 100KV the transmission was ≈99%.

XL-PPM-Diode



•Tested at 2.8 μs,120pps for one week.

•99.9% beam transmission

•Beam Voltage-490 KeV

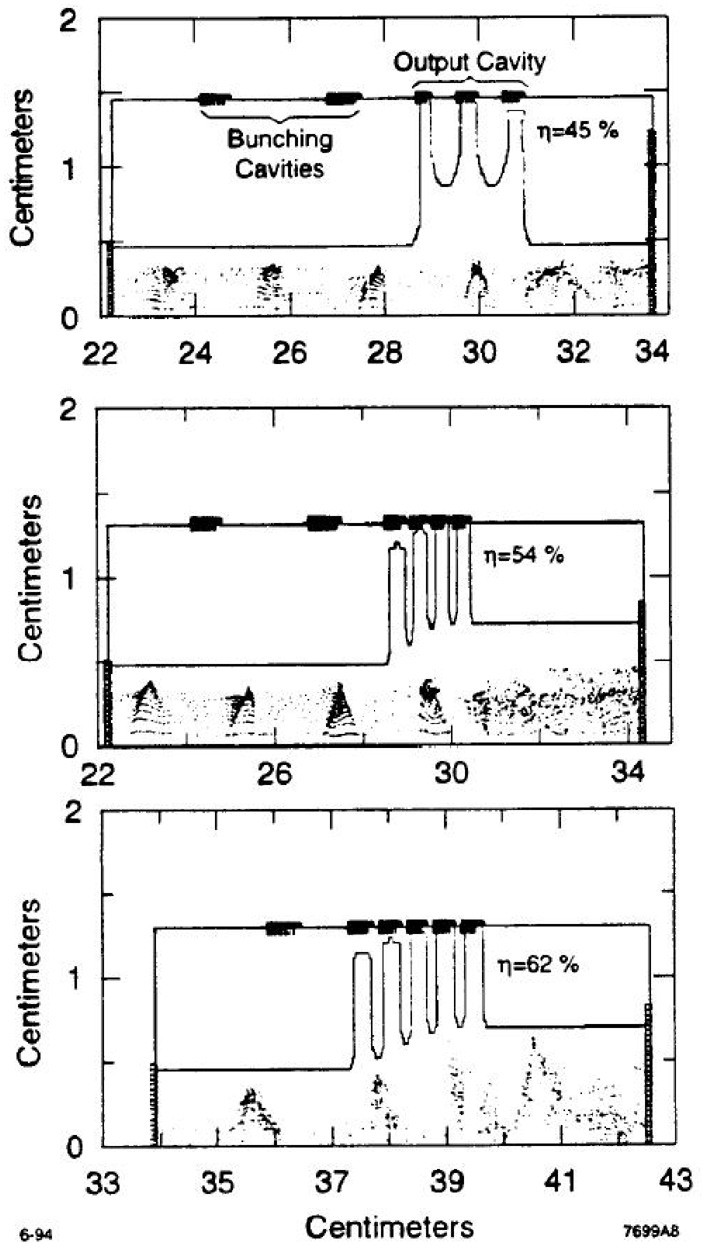
•Measured Perveance-0.66 μP

CONDOR simulations were used in the design process:

XL1

XL4

XL-PPM



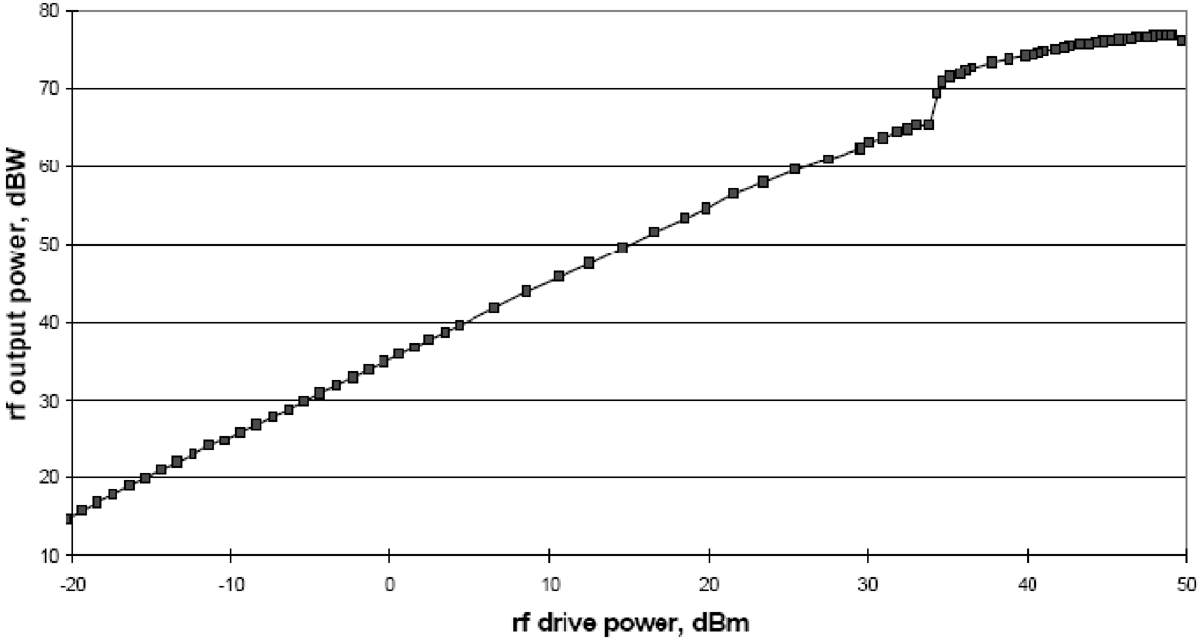
XL-PPM-Design Specifications/properties

- 50 MW @1.5 μs -> 2.4 μs
- Beam Voltage-464 KV
- Beam Current-190 A
- μPerveance 0.60
- Cathode Loading 7.4 A/cm^2
- Integral Pole piece design-drift tube constructed from subassemblies of alternating iron pole pieces and monel spacers brazed together and then subassemblies welded together.
- In gun area, three anode magnet coils and a bucking coil were used to optimized beam minimum for best transmission.
- Output cavity magnetic field is unidirectional

XL-PPM-Results

- **Successfully operated at design specifications**
  - 465 KV,190 A, 60 pps
  - 1.5 μs ->2.4 μs
  - 120 pps operation limited to 2 minute bursts due to insufficient cooling.
- Verified PPM design capability
- No oscillations were observed. Measurements made at input, output ports and at collector using an antenna.
- Several jumps in the gain curve were observed and attributed to multipactor. This was almost completely removed by coating the drift tube with ≈100 A TiN. (1 jump remained)
- Note: The beam diode was tested at 120Hz., 2.8 μs for a week. Beam transmission-> 99.9%

Gain Curve of XP-PPM



75 XP-1

Because of the success with XL-PPM, it was decided to design a higher power Klystron to reduce the costs of the NLC program.

Since 500 KV modulators were available, it was determined that at least 75 MW could be generated if the perveance was raised to 0.75 μP. Simulations with CONDOR, suggested that 80 MW was possible.

Several changes were made to the PPM design.

•Drift tube was enlarged slightly because of higher beam current.

•An all stainless steel drift tube was employed. Iron Pole pieces and spacers were external to vacuum envelope. This required an additional gain cavity because of lossy SS.

•NdFeB magnets were used. NdFeB has a a higher energy product, less brittle, less expensive in large quantities, but has a lower Curie temperature compared with Samarium Cobalt.

•Anode coils were removed from design

75 XP-1

- During initial operation, two oscillations were observed at 1.4 and 20 GHz.
    - It was determined that the oscillation came from the Gun. Analysis with “Superfish” found a trapped mode in the gun at 1.43 GHz
- The klystron was opened and lossy ceramics added around the cathode stem.
- This removed the 1.4 GHz. A new oscillation was found at 19.96 GHz. this came from an oscillation at the output cavity-Collector region. This was removed by lossy ceramics near the collector.
- The tube was retested and successfully reached 79 MW at 2.8 μs.
- The tube was limited to 10 Hz. operation because of inadequate cooling of the tube body.

75XP-3

This was the first tube with design changes to reduce costs of manufacturing.

The major change was the introduction of "Clam-Shell" magnet assemblies. This permitted testing prior to installation on the klystron.

The gun design was simplified by removing alignment fixturing using tighter tolerances.

Other changes included:

- **Reduced drift tube diameter in gain region. (0.375")**
- **Gun Coil Assembly.**
- **Increased the Penultimate-output cell separation.**
- **Tailpipe diameter longer with small diameter.**
- **Direct drift-tube water-cooling in buncher region. (4 places) and output section.**
- **Dual output window assemblies.**

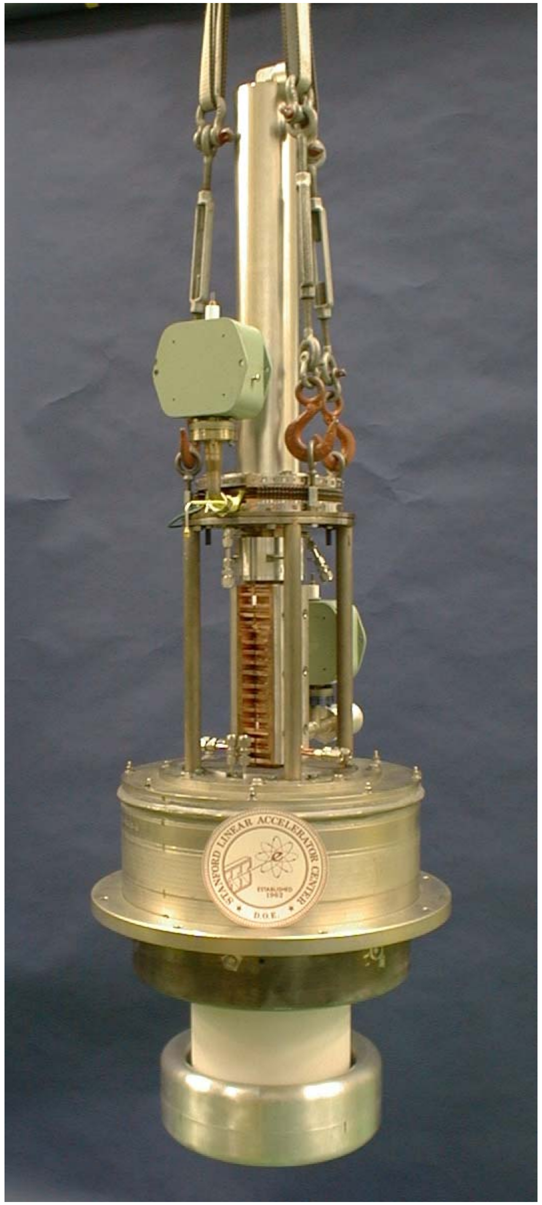
75 XP-Diode

- **PPM Focusing**
  - **Used original "Integral pole Piece" design (same as 75XP-1 and 50 MW PPM Klystrons)**

- **Stepped drift tube to simulate new klystron drift tube**

- **New magnetic field profile , cavity magnetics and output.**

- **Tested new focusing, gun and collector designs.**
  - **Added gun coils.**
  - **Redesigned (reduced size) gun.**



Diode-Tests

- **Initial Tests:**
  - **Processed to 490 KV at 3.0 μs. and 5 Hz.**
  - **Gun oscillation detected at 3.17 GHz.**

- **Redesign and Tests:**
  - **Designed a loss collar around gun stalk.**
  - **Tube ran at 120 Hz.**
    - **99.9% transmission**
    - **490 KV, 257 A (.75 μP)**
    - **Extended run of 1 week at max. Beam Power.**

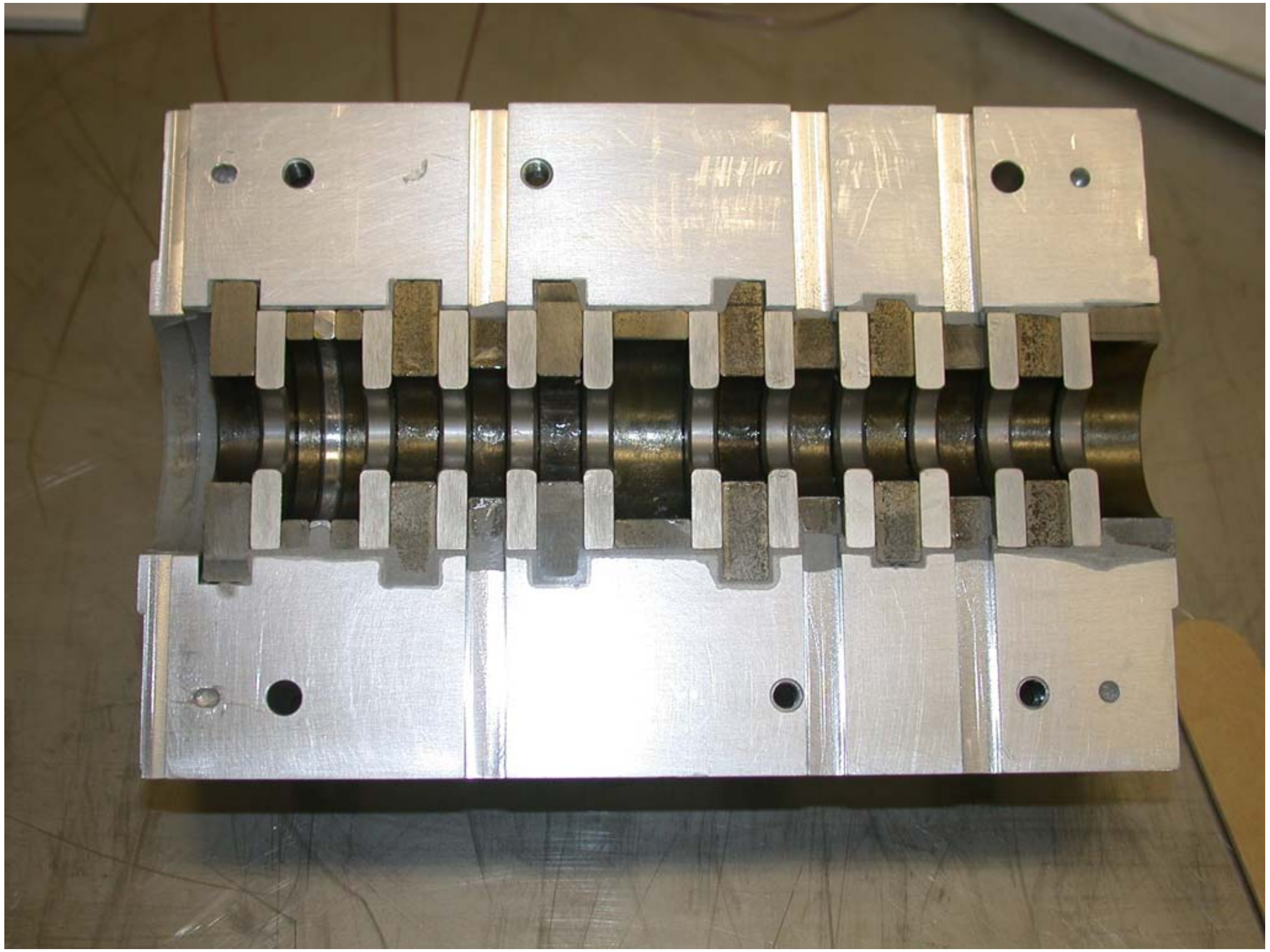
Diode Gun Showing lossy Ceramics

75XP-3 Klystron Specifications

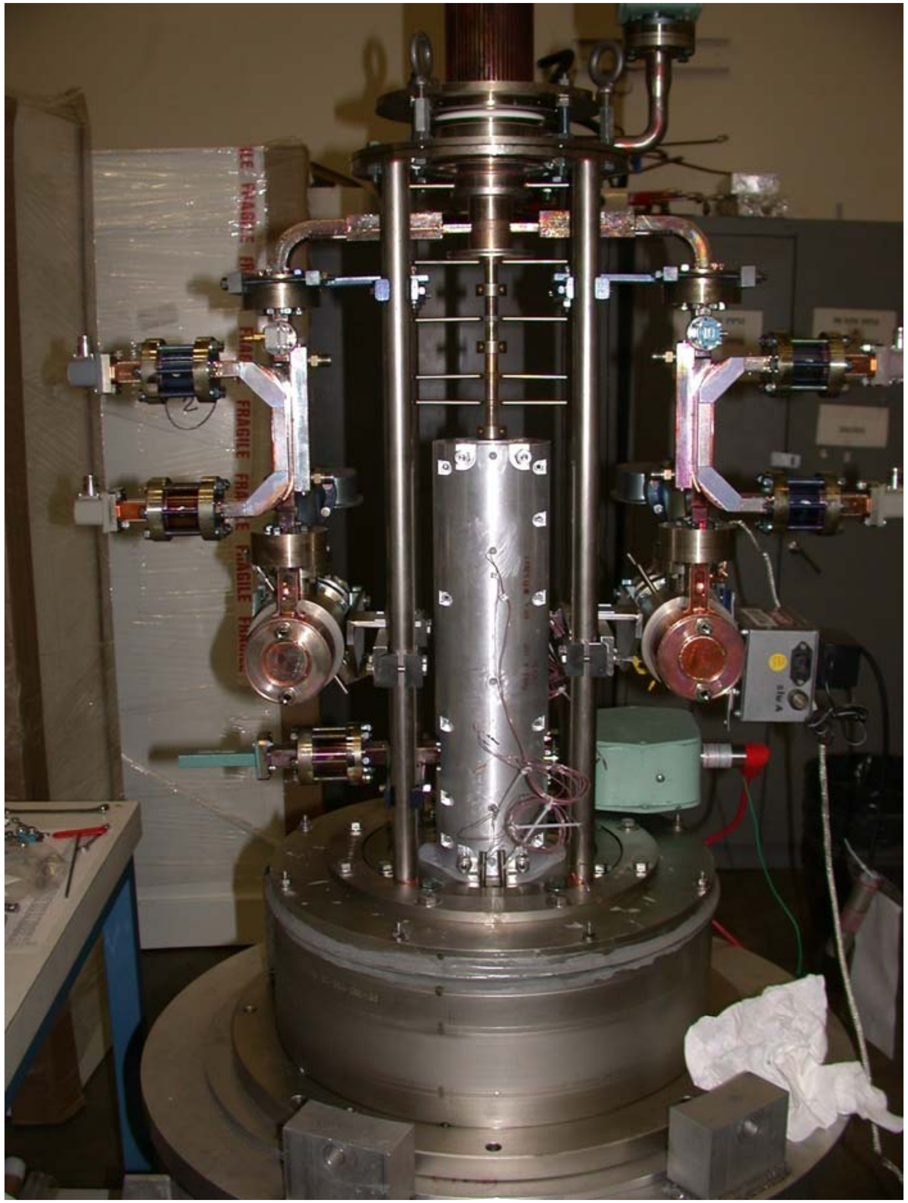
Output Power	75 MW
Beam Voltage	490 KV
Beam Current	257 A
Perveance	0.75
Pulse Length	3.2 μs
PRF	120 Hz.
Average RF Power	27 KW
Gain	55 dB min.
Efficiency	60%
No. Output Windows	2

75XP-3

Section of “Clam-shell” magnet assembly



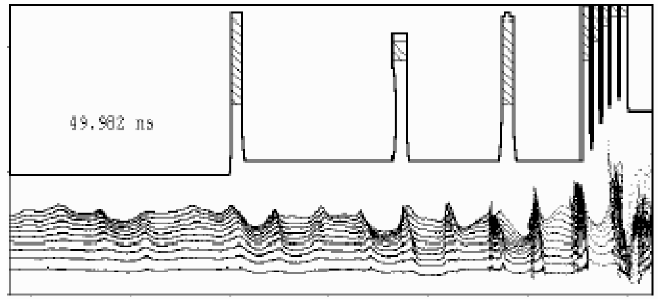
Magnet Assembly partially Installed



75-XP3-3

Simulation of 75-XP3 using "MAGIC"

Simulation predicts 76 MW at 490 KV.



- **Has been run to full power (75 MW) at 1.6 μs and 120 pps.**
  Note reduction in spec pulse width.

- **No evidence of oscillations at gun or output.**

Despite the success of 75-XP3-3, there were still some mechanical issues to improve upon.

Measurements of beam transmission showed excessive interception.

It was not possible to measure magnet heating during operation using “clam-shell” design. One of the magnets overheated.

The drift tubes were too weak and showed some bending.

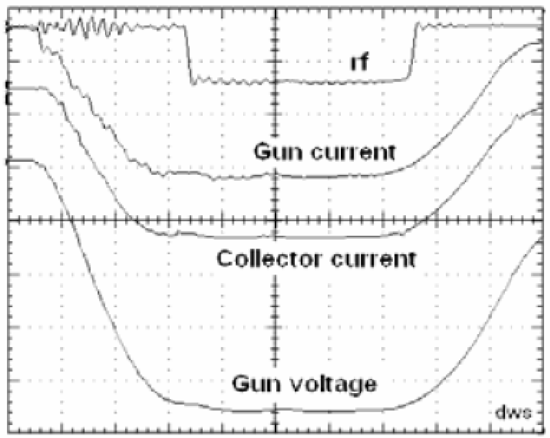
75 XP3-4

- Return to the integral pole piece magnet design.
- The RF design remained essentially the same.
- XP3-4 was operated at 506 KV
- Was air cooled rather than water cooled
    - 75 MW
    - 120 Hz.
    - 1.6 μs
    - 60 dB gain
    - 50 % efficiency

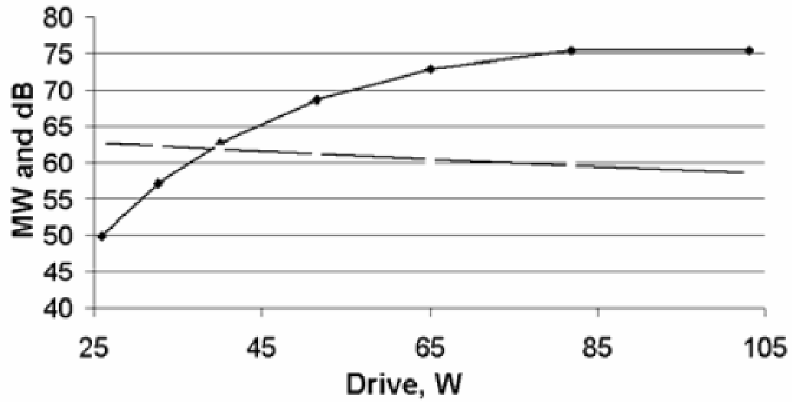
Unfortunately, further improvements to PPM klystron design ended due to termination of NLC program.

Long term reliability and robustness need to be verified.

Results of 75 XP3-4 Tests



Pulse Shapes for 75 MW, 506 KV, 120 Hz.,1.6 μs Operation. Beam loss 1.3%



Output power vs. gain at 510 KV.

Future Work

- A new klystron, XL-5 is currently being designed for use at other Laboratories.
    - It will be very similar to the XL-4 except the operating frequency will be 11.99x GHz rather than 11.424.
- Tests will be made to XL-4 to study its performance under a variety of mismatch conditions. (XL-4’s are often used to test components which can have considerable reflected RF power)

Acknowledgements

It should be obvious that many people played roles in Klystron development at SLAC. Chief among these are:

Ed Wright, Sami Tantawi, Daryl Sprehn, Richard Schumacher, Chris Pearson, Terry Lee, Erik Jongewaard, Andrew Haase, W.R. Fowkes, Ken Eppley, George Caryotakis, Richard Callin

I have also freely taken information from a variety of publications and presentations. These include:

Sprehn et Al. SLAC-Pub. 11733

Sprehn et Al. SLAC-Pub. 8346

Sprehn et Al. SLAC-Pub.11162

Caryotakis SLAC-Pub. 6361

Wright et Al. SLAC-Pub. 95-6676

Vlieks et Al. SLAC-Pub. 5480