SNS Klystron Developments

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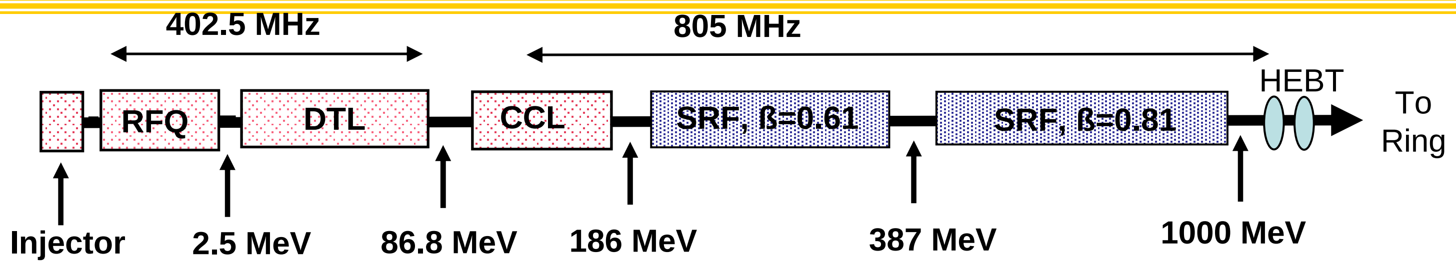
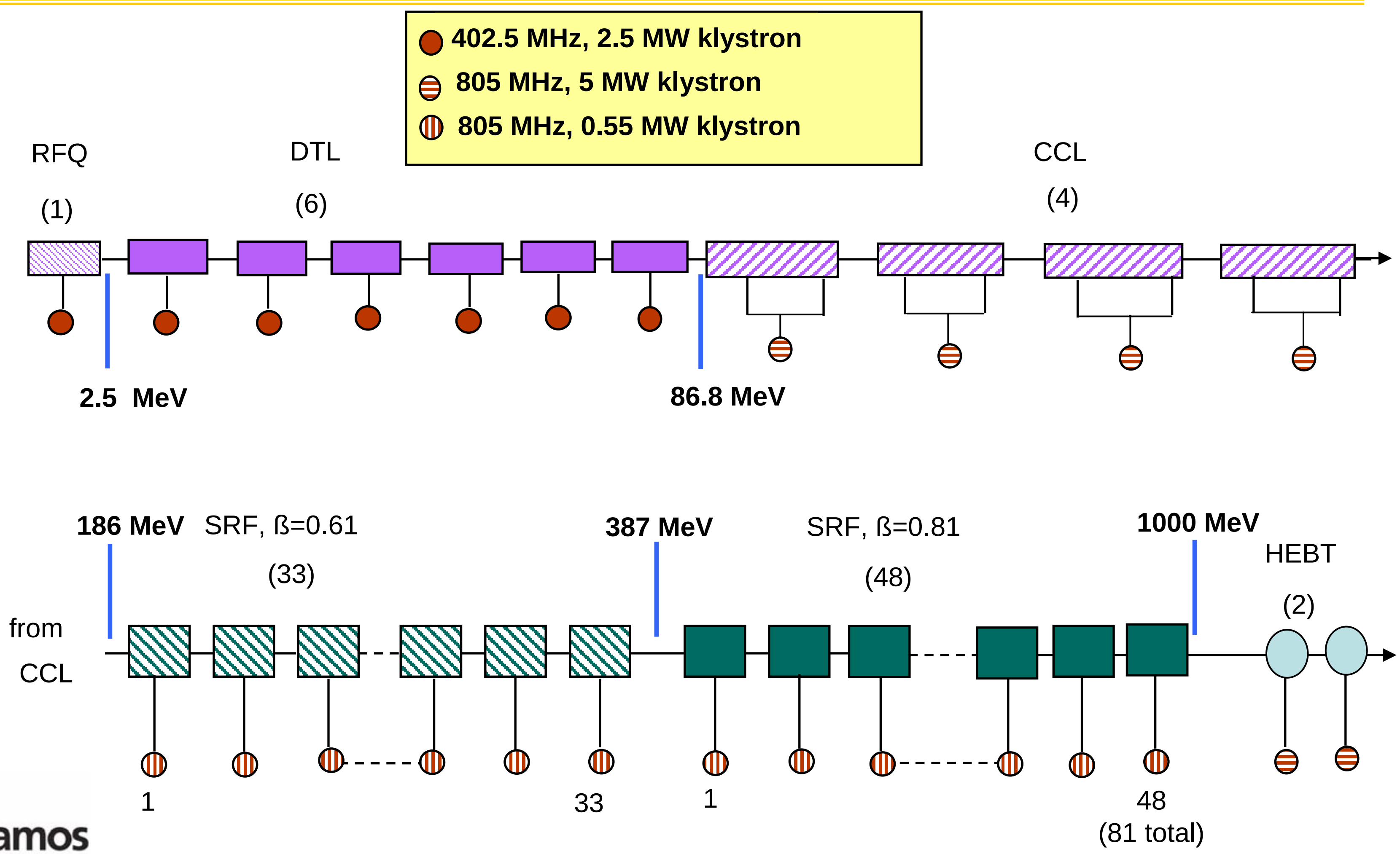
Linac for SNS

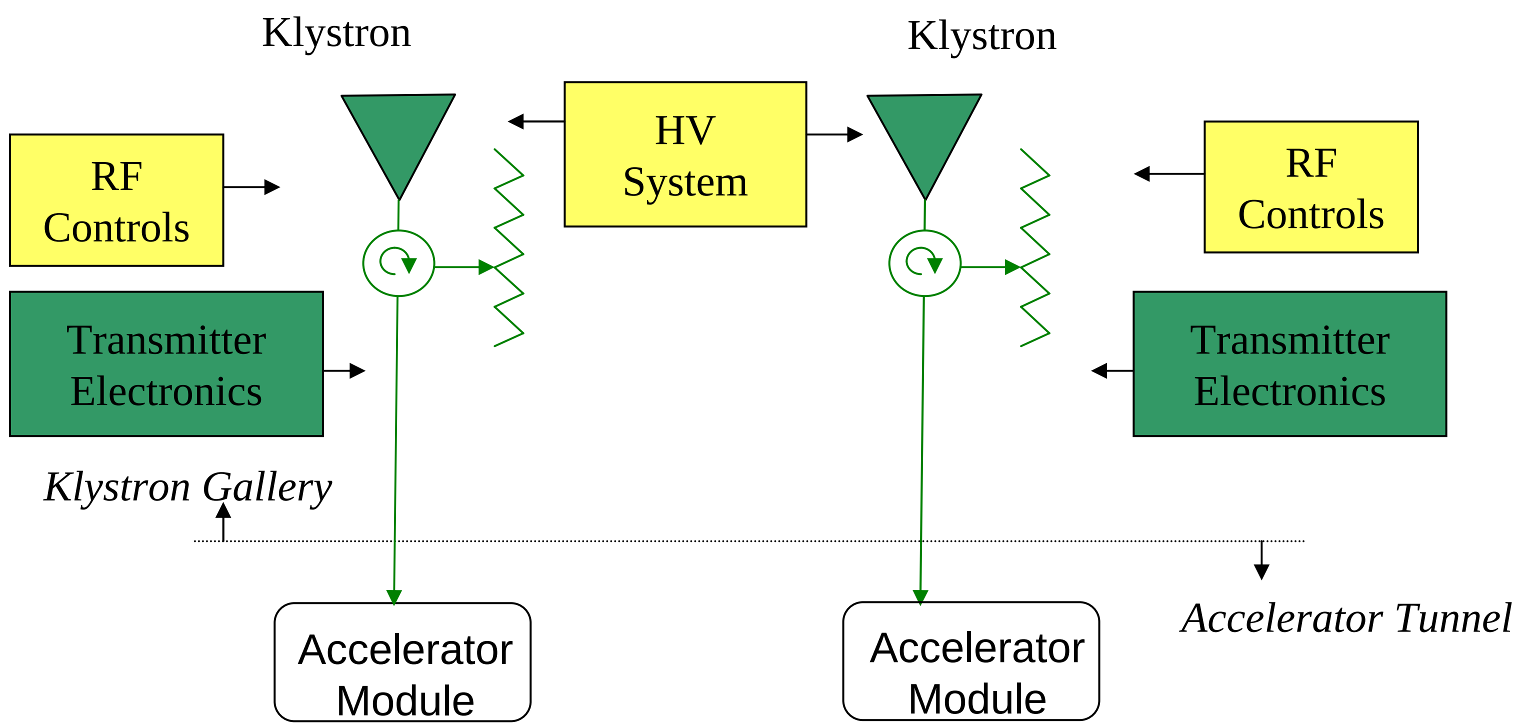


H- energy	**1000 MeV**
Beam power	**1.55 MW, avg.**
Average Current during pulse	**26 mA**
Pulse Width	**1 ms**
Rep Rate	**60 Hz**
Klystrons	
402.5 MHz, 2.5 MW pk	**7**
(includes 1 for RFQ, 6 for DTL)	
805 MHz, 5 MW pk	**6**
(includes 4 for CCL, 2 for HEBT)	
805 MHz, 0.55 MW pk, SRF	**81**
HV Systems	**1 for each 5 MW klystron or pair of 2.5 MW klystrons** *except 1 for RFQ and first 2 DTL tanks and 1 for 2 HEBT cavities*
	1 for 11 or 12 each 0.55 MW klystrons (15 total, plus 3 for test stands)
Total AC power for RF	**Less than 20 MW**

Layout of Linac RF with NC and SRF Modules

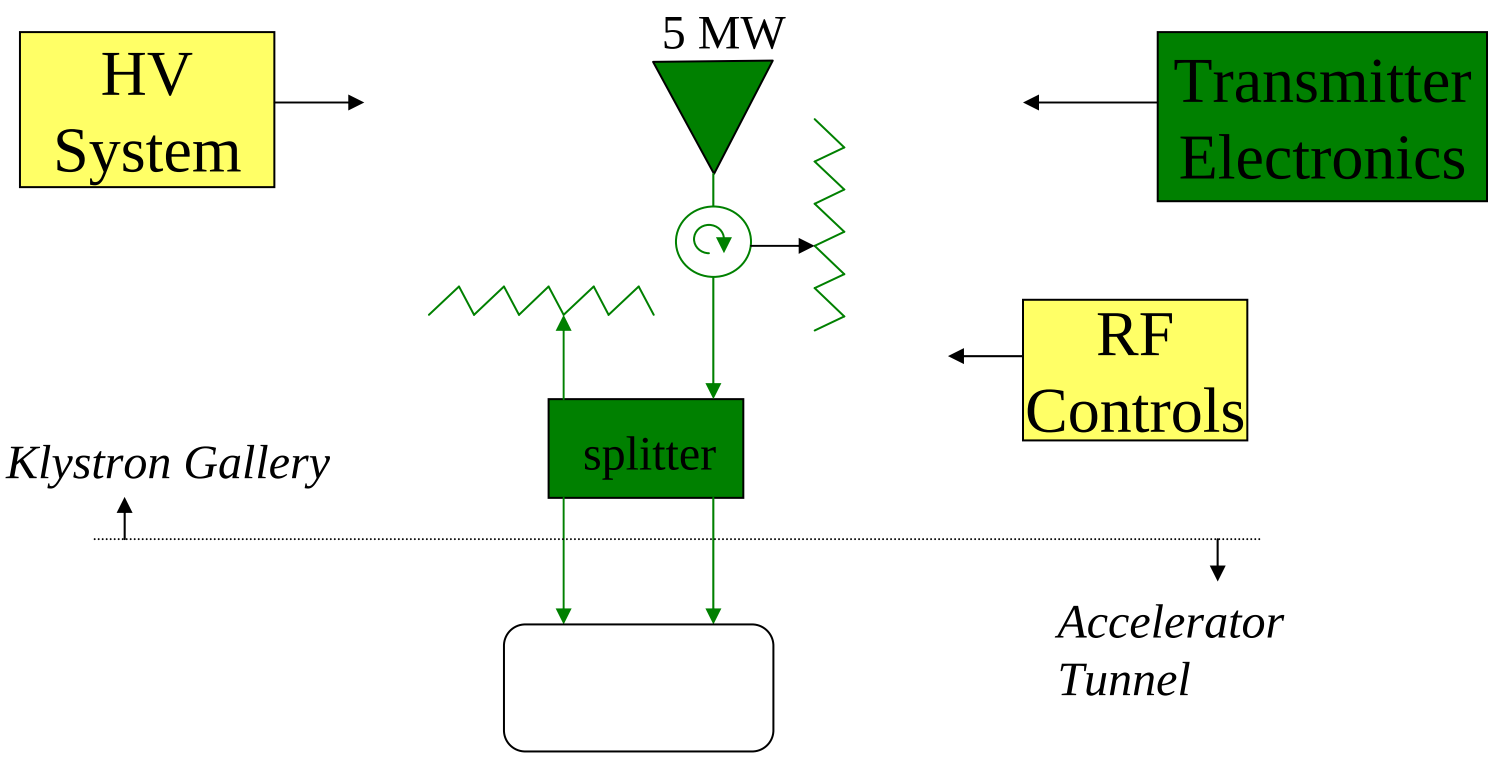


RF System Block Diagram, 402.5 MHz, 2.5 MW klystrons



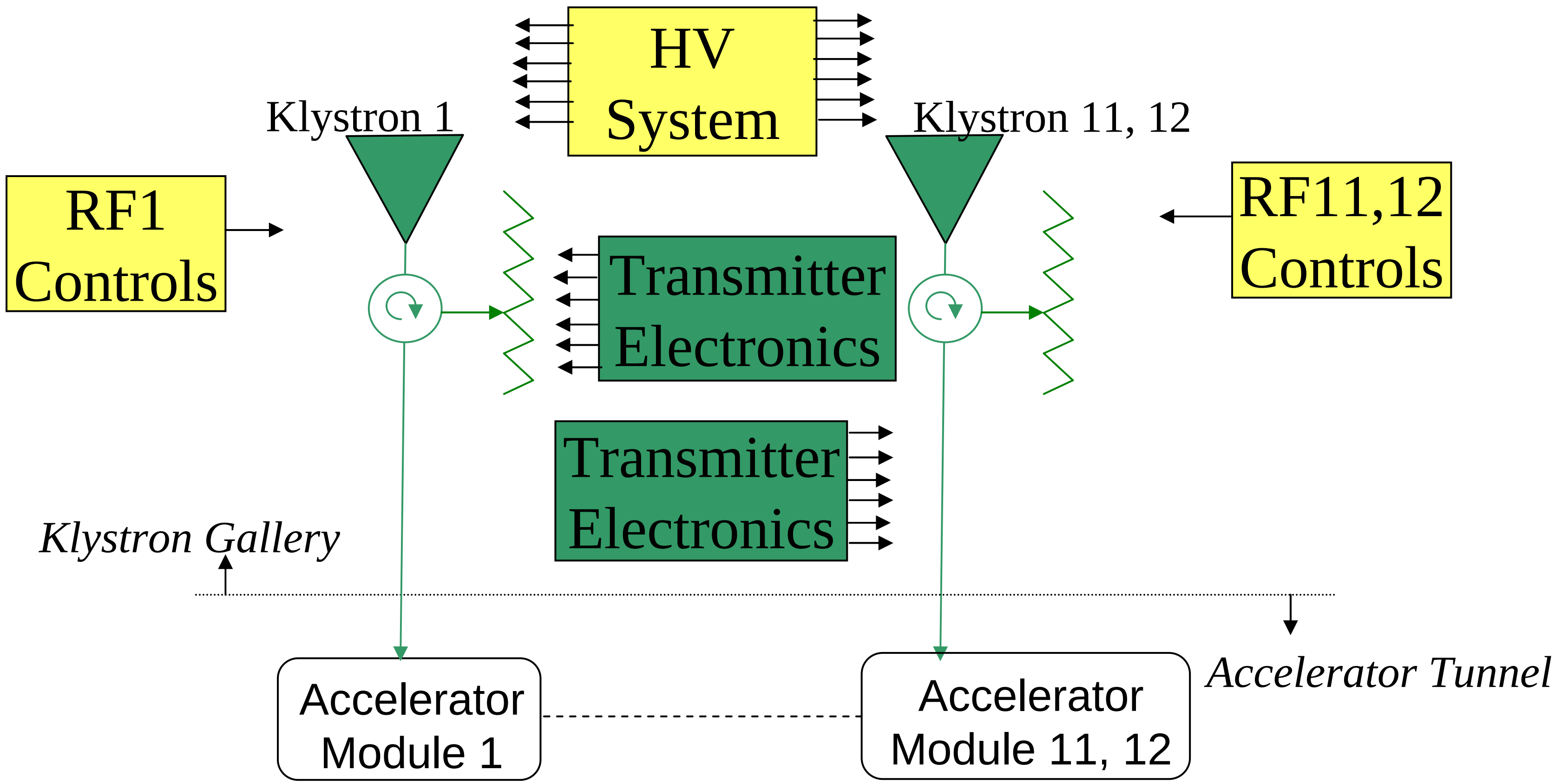
** First 3 klystrons driven by 1st PS, remainder - 2 klystron per PS

CCL RF Systems, 5 MW klystrons, 805 MHz



Single Accelerating Module

RF System Block Diagram, 805 MHz, 0.55 MW klystrons



Klystron Specifications

Peak Power	2500 kW	5000 kW	550 kW
Test Power	2750 kW	5500 kW	605 kW
Frequency	402.5 MHz	805 MHz	805 MHz
Duty Factor	8%	8%	9%
Efficiency	58%	55%	65%
Beam Voltage Maximum	125 kV	140 kV	75 kV
Bandwidth (1 dB)	1.0 MHz	2.6 MHz	2.6 MHz
Height	13 feet	13.4 feet	9 feet
Approximate Cost	$450 k ea for 11	$220 k ea for 9	$120 k ea for 81
Vendor	EEV/Marconi/ E2V	Thomson / Thales	CPI
Number Ordered / Required	11 / 7	9 / 6	96 / 81

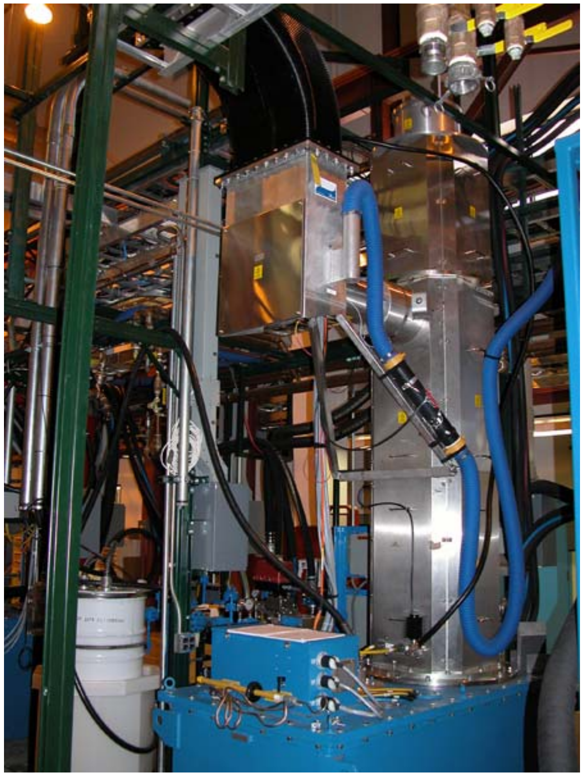
Klystron Development Summary

- **402.5 MHz, 2.5 MW EEV/Marconi/E2V**
  - **Years late.**
  - **First 2 tubes didn't meet spec. Third and subsequent tube met spec.**
  - **Became and "communications/internet" company during the tube development.**
  - **Experienced team quit the superpower klystron group.**
  - **Exited the high power klystron business during the development.**
- **805 MHz, 5 MW Thales**
  - **Years late.**
  - **Tube never met all performance specs.**
  - **Received "consideration" from Thales.**
- **805 MHz, 550 kW – Two Vendors**
  - **CPI: Met spec., production was on a schedule.**
  - **Thales: Never met spec, years late, order was reduced.**

2.5 MW, 402.5 MHz Klystron

Coming off exhaust

Awaiting Factory Test



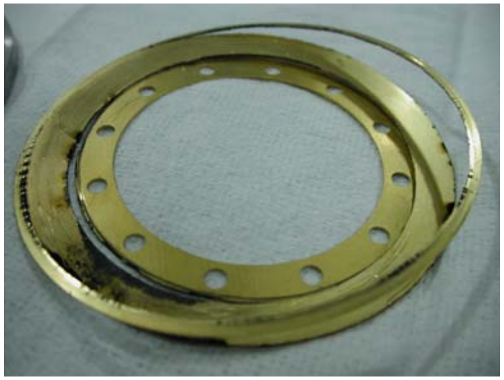
In the test stand at Los Alamos

402.5 MHz, 2.5 MW Klystron Statistics

- **Development of a pulsed DC power supply for the test stand put EEV a year or more behind schedule at the start**.
- **9 Klystrons passed vendor acceptance tests (when LANL handed contract over to ORNL).**
  - First 2 at reduced peak power spec.
- **9 Klystrons site acceptance tested**
- **8 Klystrons eventually passed 1 of 8 Klystrons passed without any rework**
  - First 2 at reduced peak power spec.
- **7 Klystrons required site adjustment, repairs, and/or tuning.**
- **Our record was 4 things wrong with a single tube.**
- **For 3 klystrons, the problems discovered during the site tests led to changes in all other klystrons.**

Marconi Klystron Issues and Solutions

- **Issue - RF Gasket which connects coaxial output center conductor to waveguide t-bar failed during 96 hour heat run. Same gasket on other tubes showed damage.**
  - -Discovered coaxial center conductor tolerance problem and lack of gasket assembly procedure (inconsistent bolt torques).
  - -Implemented new assembly procedure.
  - -Will use shims to address mechanical tolerance problem on delivered klystrons.
  - -Proposed 2 additional gasket inspections (after 500 hrs and 1 year later)
  - -Corrections to all fielded klystrons required about 5 months



Marconi Klystron Issues and Solutions

- **Issue – Second cavity load undersized starting with serial no. 5 klystron.**
  - **-**SN- 1 & 2 had internally loaded 2cnd cavities.
  - -As part of changes to achieve full performance, implemented water cooled resistors to replace internal loading.
  - -As a result of a measurement mistake, underestimated the load power and changed to air cooled resistors after sn4.
  - -Air cooled resistors failed and caused the vacuum leak in the sn5 tube during site acceptance tests/96 hour run at LANL.
  - -Other tubes currently in test were found to have failed loads.
  - -Air cooled loads are now being replaced with the water loads used successfully on sn3 and 4.
  - -Discovery led to stop operations order from E2V and the repair of all tubes required site retrofit and took about 2 months with ordering loads and machining hardware.
- **Issue – Shorted magnet winding on SN 6.**
  - -Klystron tested in lead garage without all shielding installed. Shield installation can short out coil.
  - -Measure for shorts post shield installation with ohm meter before shipping.
- **Issue – water leak on SN 2.**
  - -Quality control issue.
  - -Implemented additional inspections during pressure test.

Marconi Klystron Issues and Solutions

•Issue – Change in tuning of second harmonic cavity between factory and site test resulting in dramatic change in efficiency. Klystron saturated at 600 kW instead of required 2.5 MW.

-Several possible causes

-Finally settled upon water pressure test deforming second harmonic cavity as most likely cause, however, they still aren't certain.

-They used to do the pressure test post electrical tests.

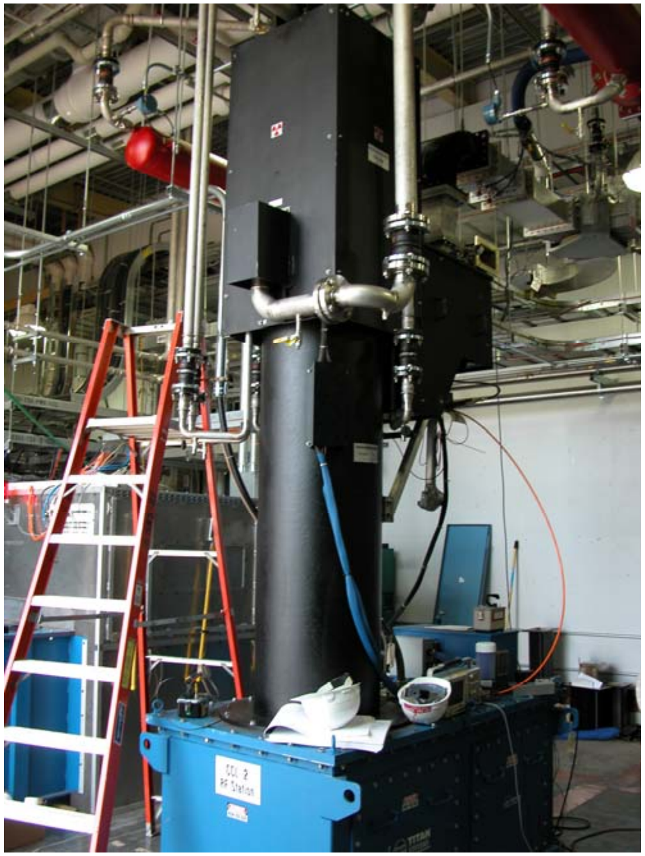
-They changed the test order to where they execute the pressure test first.

-Problem hasn't been observed in last 3 klystrons received and tested.

-Problem took about 4 weeks to correct.

5.0 MW, 805 MHz Klystron – This klystron advanced the state of the art for simultaneous peak and average power.

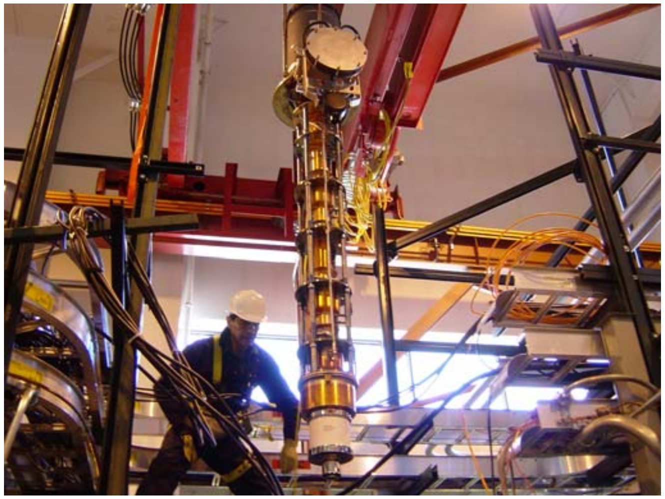
During Installation



Installed at ORNL

Thales 5 MW, 805 MHz Klystron

- The combination of peak and average power made this a challenging klystron.
- Thales could not factory test to the full average power.
- The most challenging technical aspect of the tube couldn't be tested at the factory.

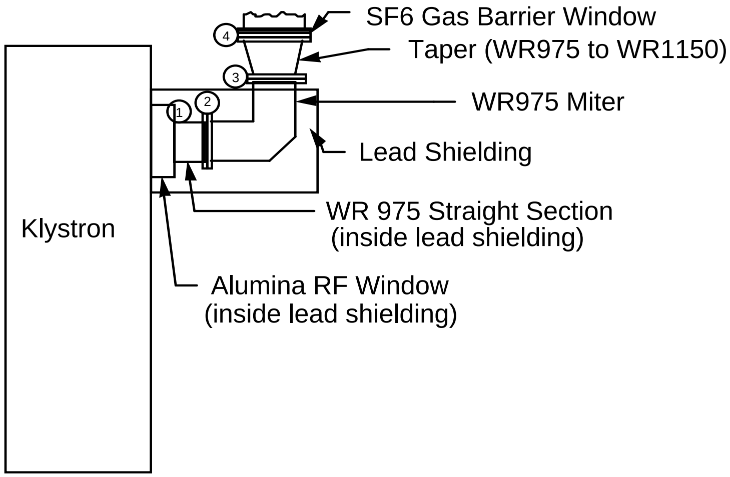


Issues Summary

- **Primary problem was RF arcing in the output elbow.**
  - Thales tests with SF6 in their waveguide
  - Doesn't replicate environment defined in the spec.
  - Hide's RF arcing problems.
- **One klystron had a window break during site test.**
- **One klystron had an unrecoverable vacuum even during site test.**
- **The klystron could not meet the efficiency requirement.**
  - Traded off reduced efficiency requirement for 2 free rebuilds.
- **Some of the klystrons exhibited a high cathode arc rate at full power**
- **Complex installation assembly.**

We had to help Thales redesign the output waveguide on the 5 MW klystron.

SF6 Region in Waveguide Output Circuit



Joint Description:

1. Between Alumina RF window and Straight Setion
2. Between Straight Section and Miter
3. Between Miter and Taper
4. Between Taper and Straight Section

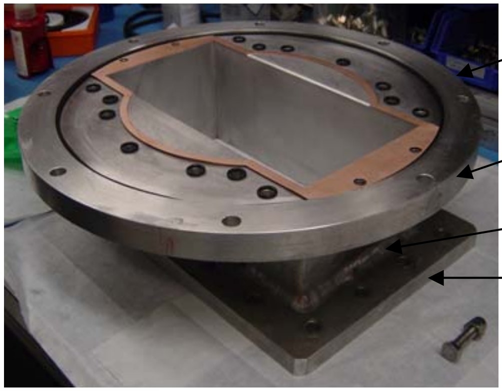
SF6 Requirements:

- **A pressure relief valve set to 15 psia.**
- **A valve to isolate the region filled with SF6.**
- **A pressure gauge to read both pressure and vacuum.**
- **The interface fitting after the valve shall be 1 1/3 inch Conflat flange.**
- **The SF6 region shall be leak tight with a leak rate less than 30 mTorr per hour at a pressure equal or lower than 100 mTorr.**

Thales 5 MW, 805 MHz klystron output waveguide modifications

O-ring Damage near Copper Gasket that caused SF6 leaks (Joint 1):

O-rings (SF6 seal) and Copper Gasket (electrical seal) before assembly (Joint 1):



- **Joint 1:** Arcing due to SF6 leaks and poor RF contact.
  ==> By helium leak checking we found SF6 leaks at this joint. O-rings were later found to be damaged.
  ==> Thales plans to replace all o-rings with a flat rubber gasket.
  ==> Thales plans to machine this piece instead of weld it because the welds limit the torque that can be applied to Joint 1 and Joint 2.

- **Joint 2:** Arcing at the joint between the straight section and miter bend. This joint was sealed with a Parker seal.
  ==> We tightened bolts at this joint but the torque is limited by welds.
  ==> We faced the flanges to make them flat

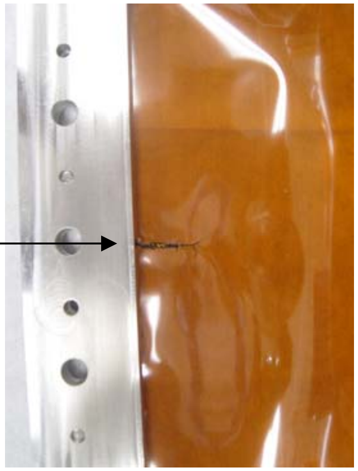
Thales 5 MW, 805 MHz klystron output waveguide modifications

- **Joint 3:** Arcing at the joint between the taper and miter. O-ring from Mega was the wrong size. Thales made an o-ring which failed to provide a good RF contact.
  ==>we machined the flange flat to eliminate the o-ring grove. Will use a Parker seal.

O-ring between taper and miter (Joint 3)

- **Joint 4:** Arcing at the Kapton window.
  ==> We speculate it is arcing due to high order modes in the region of the Kapton window. We plan to move the Kapton window 16 inches farther away from the klystron.

Arc Damage on Kapton Window (Joint 4)



Issues - Thales 5 MW, 805 MHz Klystron

- **Lead shielding insufficient**
  - At full duty factor klystron was producing on the order of 18 mr/hr.
  - Thales improved lead shielding in problem areas based on measurements during site acceptance tests.
  - Partially caused by difference in OSHA regulations between US and Europe making factory measurements difficult.

- **Interference between plumbing connections and shielding.**
  - Shielding and plumbing were never assembled in final form at factory.
  - Shielding and plumbing designs are now modified.
  - Plumbing hookups require that shield assembly be only partially done first, and overhead crane is required for final shield assembly after plumbing is done.
  - Crane not available at installed position at ORNL.

Issues - Thales 5 MW, 805 MHz Klystron

- **Test stand calibration was off in Thales' favor.**
  - Proven at site test
  - A well done calibration plan was key to realizing vendor acceptance of their problem.
  - Klystron design couldn't achieve 55% efficiency on a calibrated test stand.
  - Spec. reduced to 51%. Received consideration.

- **Klystron installation and shielding assembly took 3-4 day. Thales-supplied procedure was inadequate.**
  - LANL provided candid feedback and is withheld payment until Thales provided new procedure and dry runs procedure at factory.
  - Thales did prepare a new procedure.
  - Thales assembles the collector shielding with the tube in a pit and the personnel on scaffolding. We had to assembly the shielding on ladders, 13 feet off the ground.
  - Next time I will more rigidly specify the amount of site assembly that is allowed.

CPI 550 kW Klystron Summary

- The only klystron development that went well, but still had some problems.
- First klystron late, then failed due to being bent.
- Second klystron a little low in efficiency (63% vs 65%) and a design change was made (drift tube length on tube 2)
- Third and subsequent klystrons exceeded the efficiency spec. (67% achieved)
- CPI caught up the initial schedule delay during production.
- Robust tube. Early tube tested to 770 kW at full pulse width. We took a tube up to 990 kW at rated duty factor.

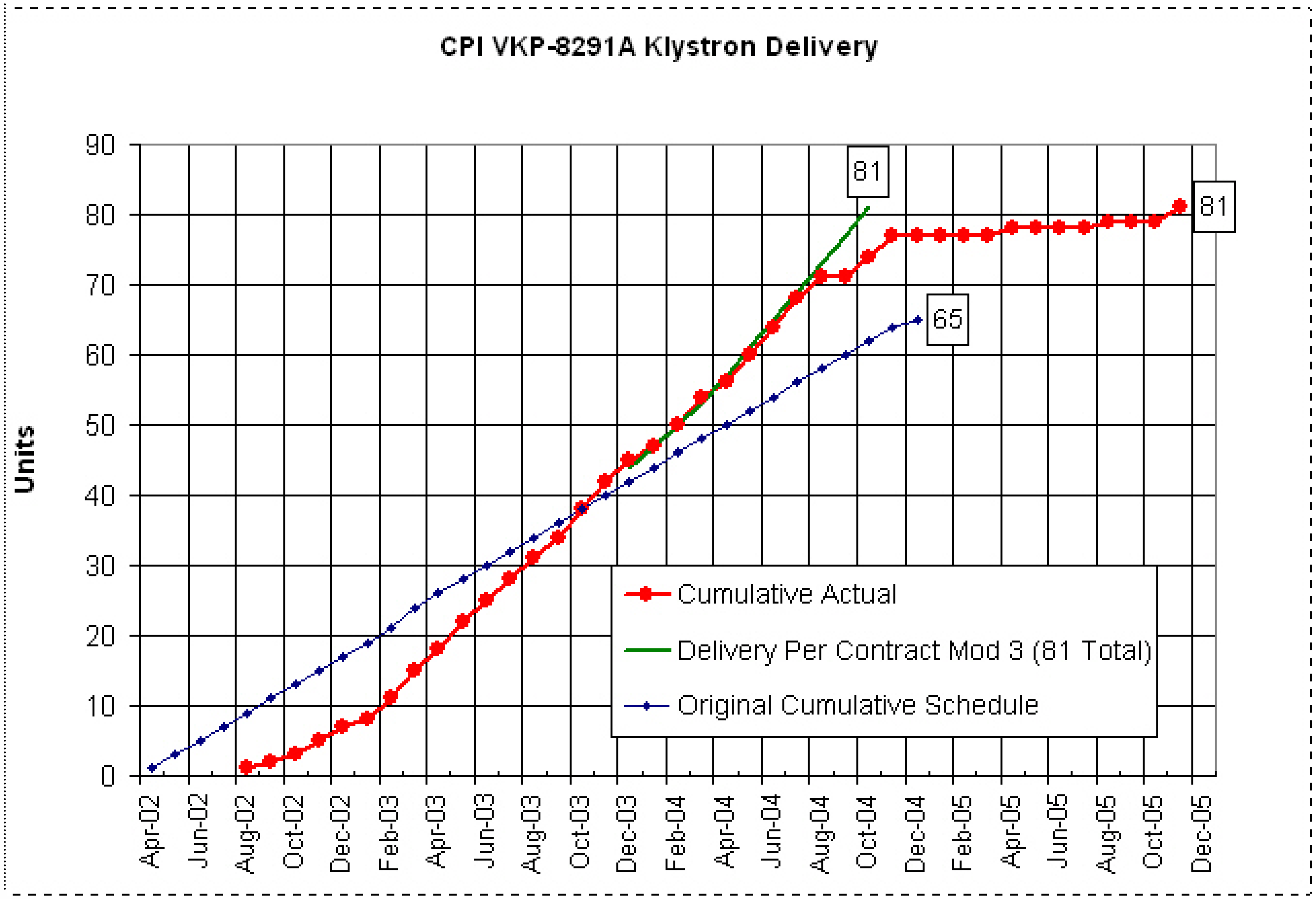
CPI 550 kW, 805 MHz Klystron

Tube pre bakeout with cavities visible.

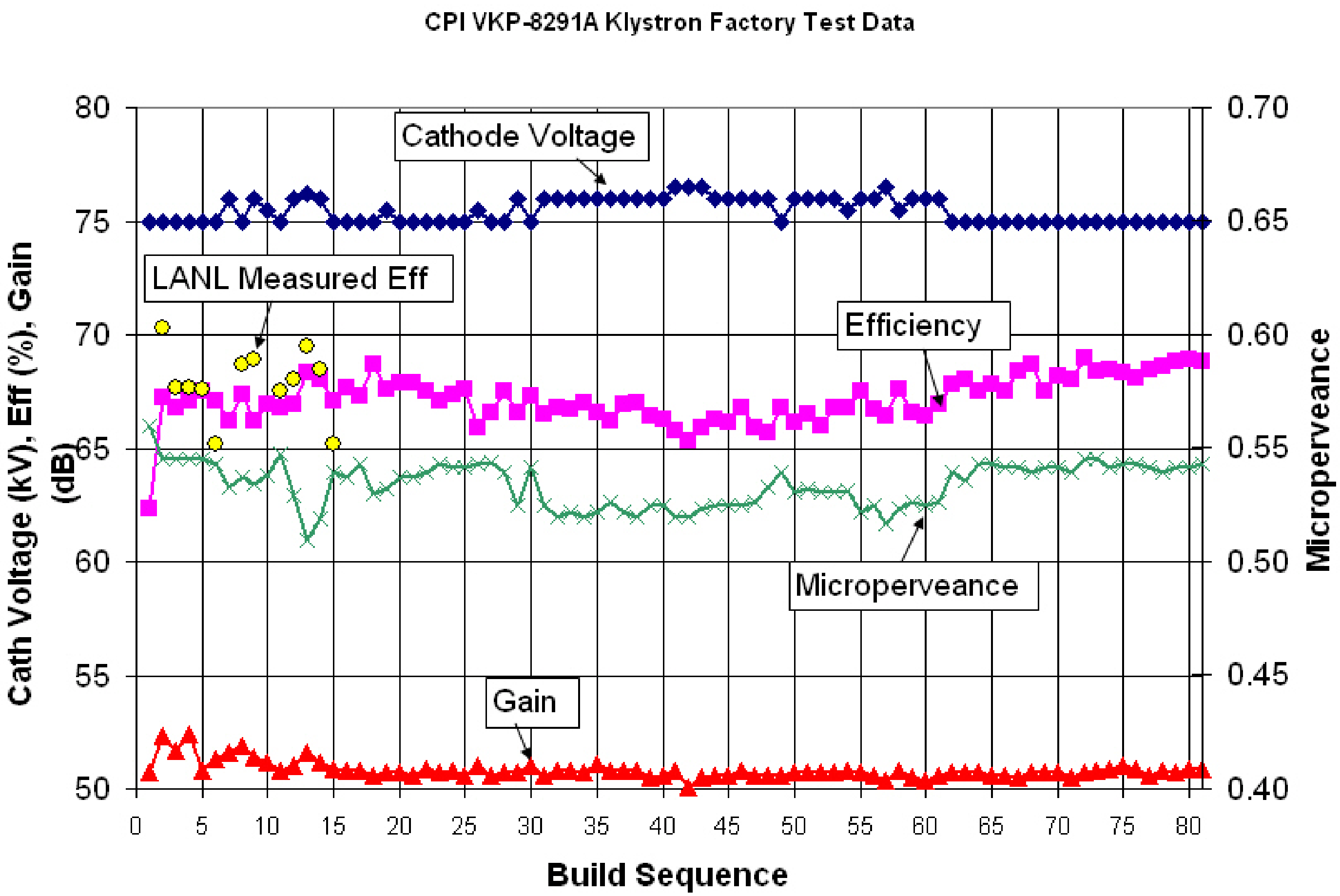
Tube sealed in shroud. Shroud facilitates fit down the bore of the magnet.

Tube installed in transmitter at Los Alamos

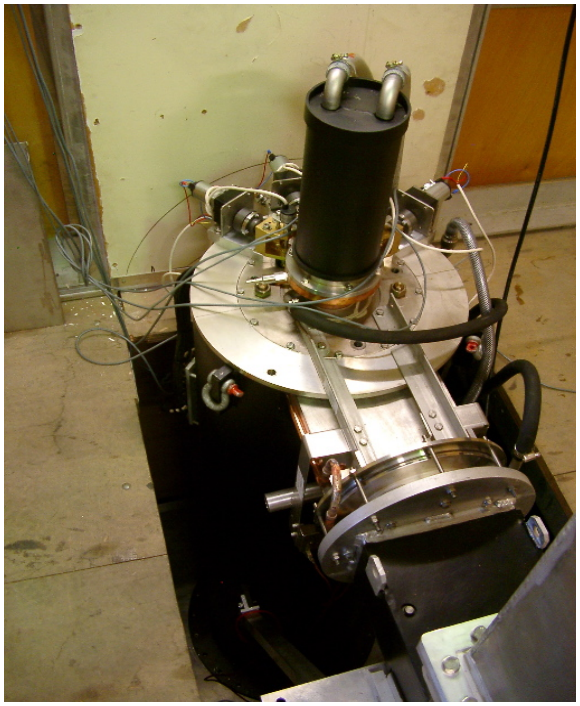
550 kW Klystron CPI Delivery Performance



CPI 550 kW Klystron Performance Data

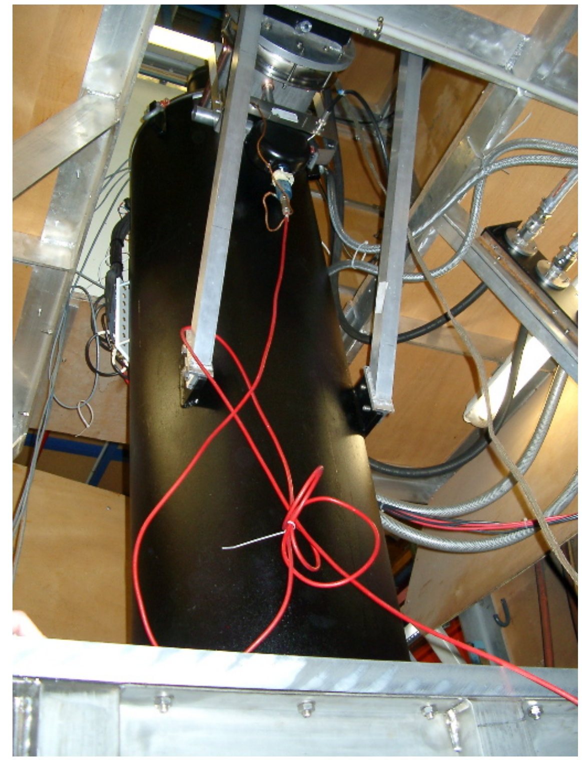


Thales 550 kW, 805 MHz Klystron



Top of klystron showing the collector and output window (in testing 'pit' at Thales)

- First klystron passed all factory acceptance tests Feb. 28, 2003 (We thought).
- Late, partially because of issues with 5 MW tube partially due to problem with the initial magnet design.
- Calibration error in factory test stand in Thales' favor resulted in 4 tubes being shipped that didn't meet spec.
- We required Thales ship all tubes back for retest.
- Efficiency spec. reduced to 62% and the Thales order was reduced from 23 to 15 tubes.



Body of klystron in the focusing solenoid mounted on modulator

Thales 550 kW, 805 MHz Klystron

Review of problems:

- **The efficiency is marginal:**
  - **The spec was reduced to 62%**
- **The Thales test stand was poorly calibrated and measuring power levels too high by 4 – 6%.**
- **Initial magnet design needed too much solenoid current. Magnet redesigned.**
- **Multiple, long repair, failures of HV system of the Thales test stand delayed testing.**
- **Fourth tube had a water leak that occurred after the bake out.**
- **Fifth tube has a water leak in a sub assembly during the braze process.**
- **In the end we ended up reducing the order by 8 tubes because of both the poor efficiency and schedule delays.**

Conclusions

- All first articles were late.
- Only 1 of 4 tube orders made up the delay from the prototype.
- Test stand issues for 3 of 4 tube orders significantly hurt the schedule – utilization conflicts, test stand failures, calibration, and modifications.
- We had planned for the delays in our procurement schedule and were able to avoid significant program impacts.
- The site testing often found problems that the factory testing missed.
- A well calibrate test stand on site is critical.
- In the end all tubes made it to SNS before they were needed for installation.