High Power Klystron Design

Jianxun Wang

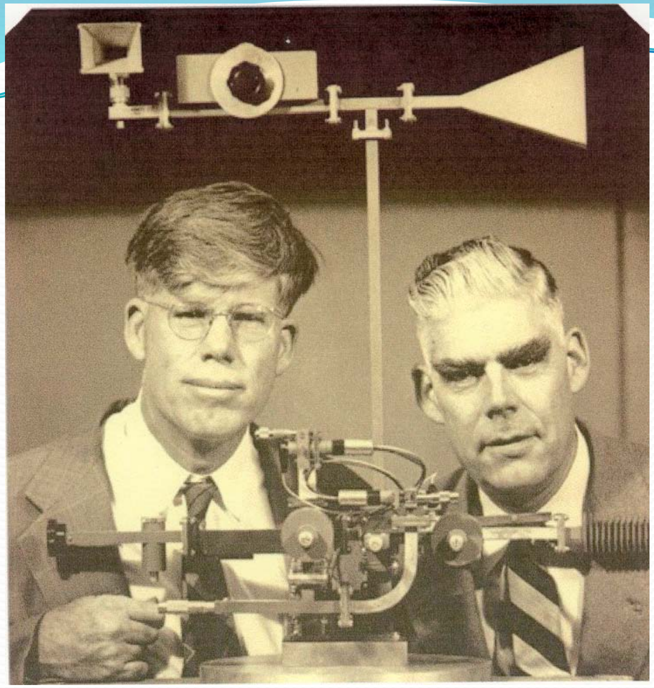
Microwave/Millimeter Wave Technology Enginer Center

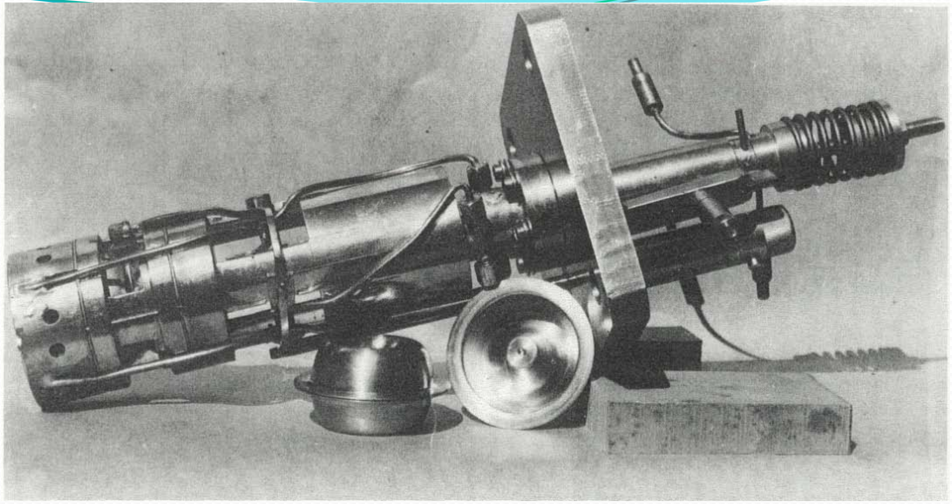
Dept of Physical Electronics

University of Electronic Science and Technology, Cheng Du, China

Outline

- History and applications of Klystron
- Cavities
- Electron gun, beam and collector design
- Klystron Gain-Bandwidth Calculations and Simulations
- Klystron manufacture, processing and testing
- Klystron Power Supplies, Modulators





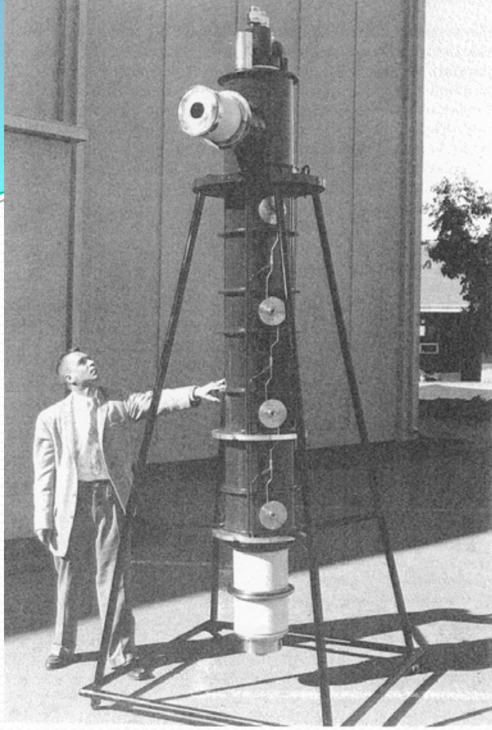
The first klystron oscillator to work at Stanford in 1937.

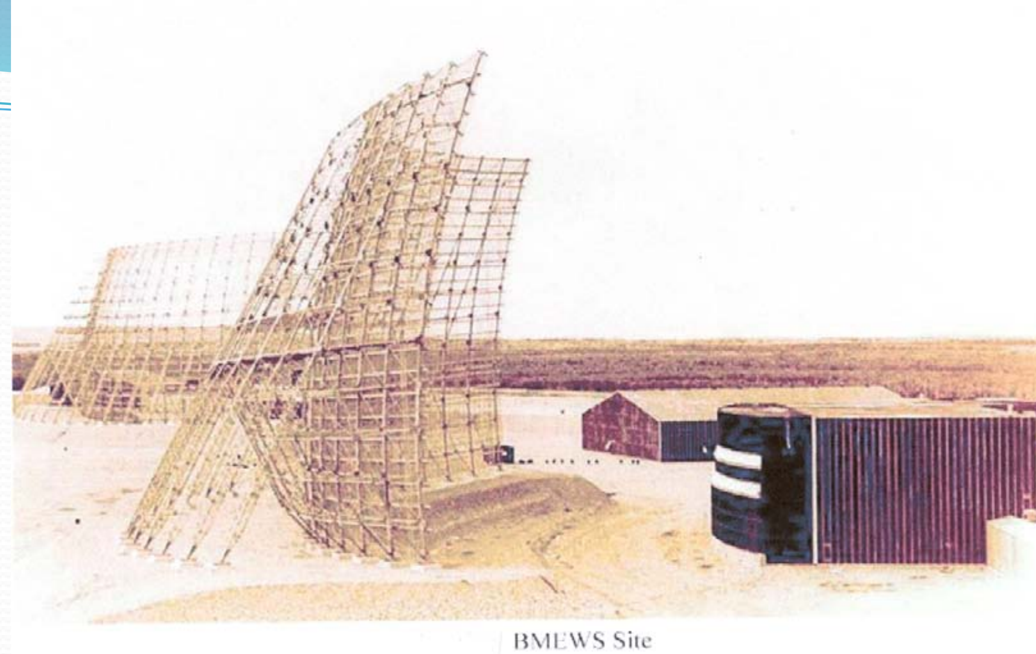
Russell and Sigurd Varian

•In 1937, Russell and Sigurd Varian built a 2-cavity oscillator which was named as “klystron”
•Varian Associates, the company they founded, sold its tube business to an investment concern in 1996. It was renamed “Communications and Power Industries”, or CPI which is very famous now in the world. They do a great job in the development of variety of vacuum devices.

The EMI CV-150 (original UHF resonant cavity)

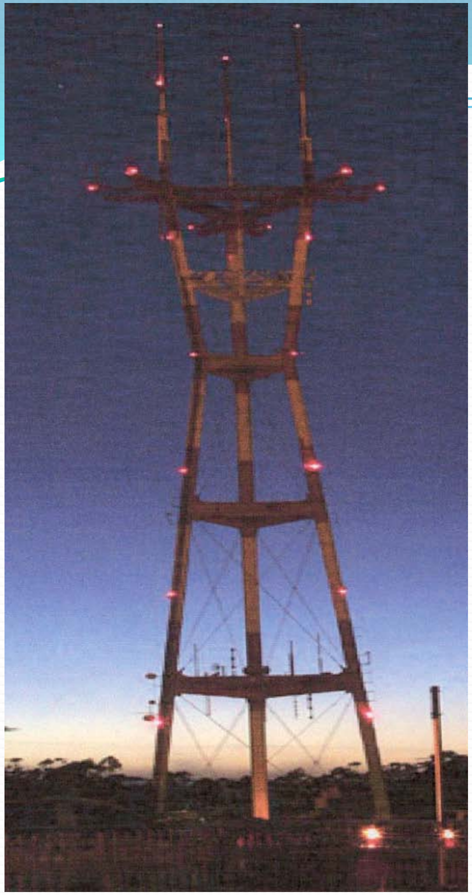
•W. W. Hansen, Associate Professor of Physics in SLAC, invented the microwave cavity. He also derived the first analytical expressions for the eigenvalues in cavities of various shapes. The invention of the high power klystron would not have been possible without Hansen's microwave cavitys.
•The low beam transmission which was below 50% limited the development of klystron. One could not expect average power above a few watts, and that made klystrons unsuitable for transmitter use.
•The improvements in electron beam optics, made possible by J. R. Pierce's work at Bell Labs, gave the possibility of high power klystron. Other components also had to be designed for the first time, such as high-voltage modulators and insulators, and high-power microwave windows.

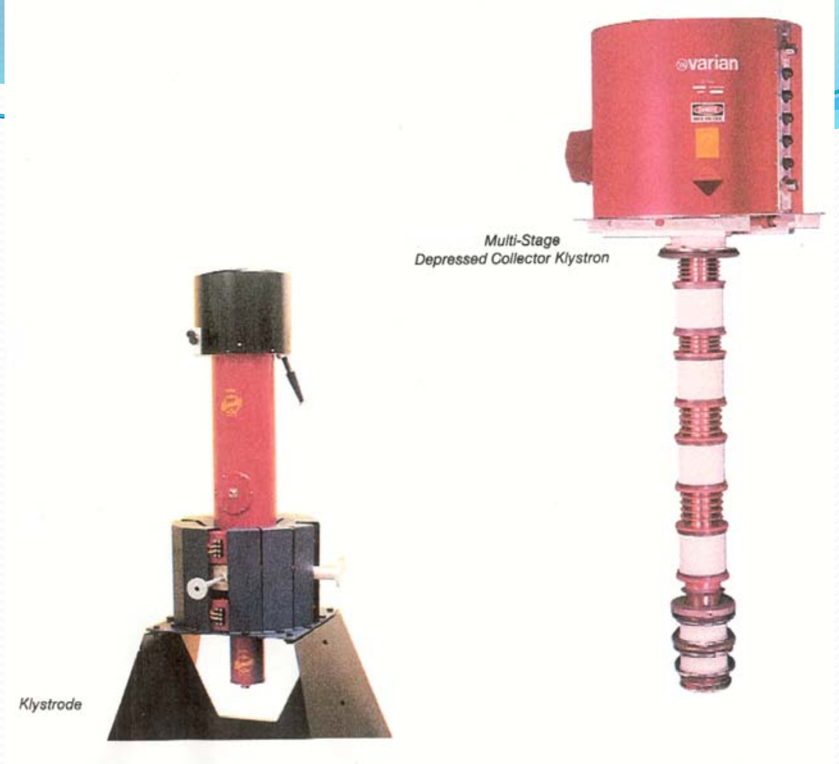




The VA-812 and the BMEWS system

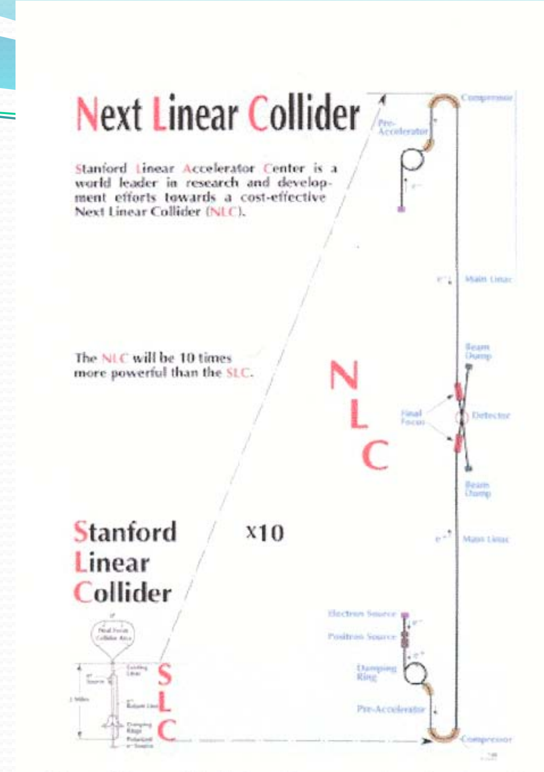
•The BMEWS klystrons operated at 150 kV and produced 1.25 MW peak and 75 KW average power at approximately 450 MHz. At that average power, these klystrons were the most powerful ever produced at that time.





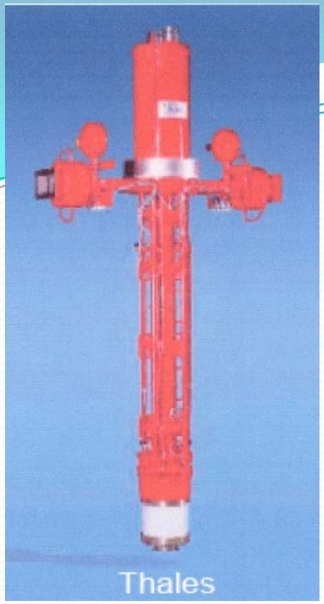
UHF television klystrons

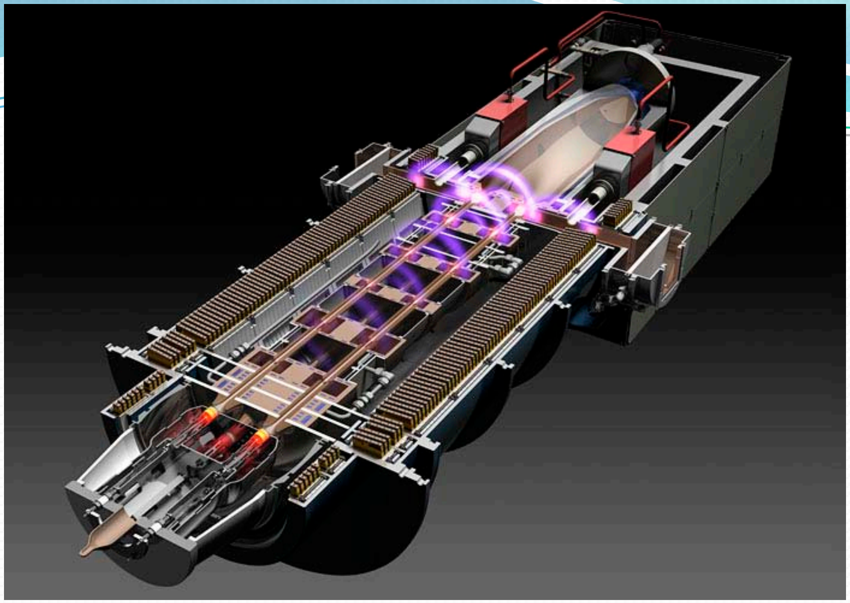
•UHF television was one of the early klystron applications.
•On the left is a “Klystrode”, invented at Eimac in which a gridded gun is part of the input cavity circuit and the beam current is a function of the rf drive. On the right is shown an external cavity klystron equipped with a multi-stage depressed collector (MSDC). The MSDC klystron has an output power of 60 kW, 46 dB gain, and a 70% peak efficiency.



The SLAC 75-MW X-band PPM klystron

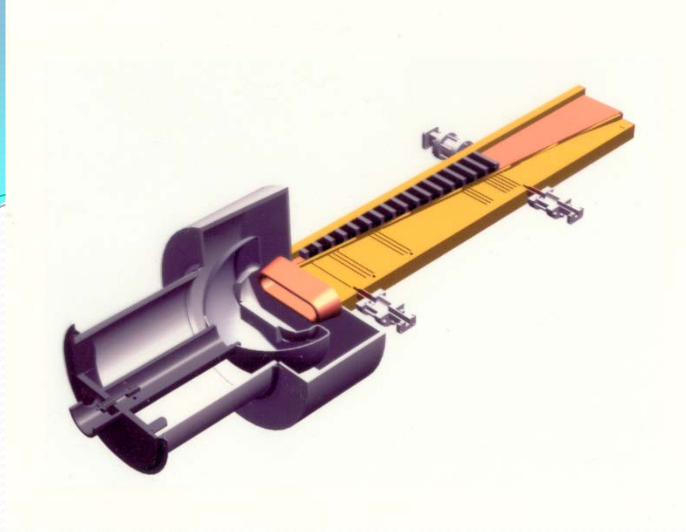
•<u>**Linear Accelerators.**</u> **Particle accelerators continue to set the pace for the development of very high power klystrons. The "Next Linear Collider" (NLC) is being designed, initially, as a 500 GeV collider. Its full length will be approximately 30 kilometers (18 miles). Current design for the 500-GeV version calls for as many as 5000 X-band klystrons, each delivering 75 MW, with 1.6 microsecond pulses and an average power of 14.4 kW.**

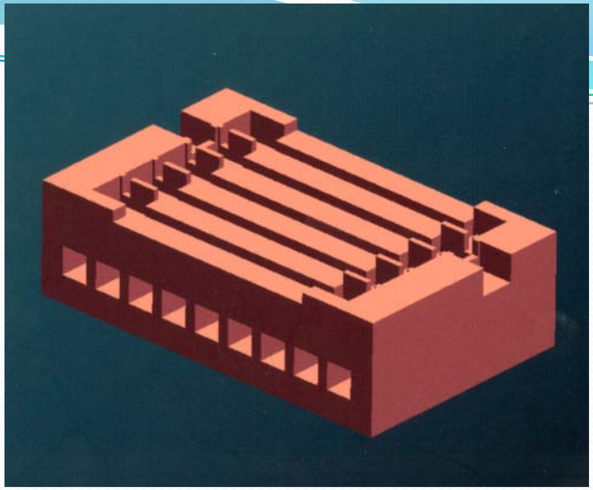


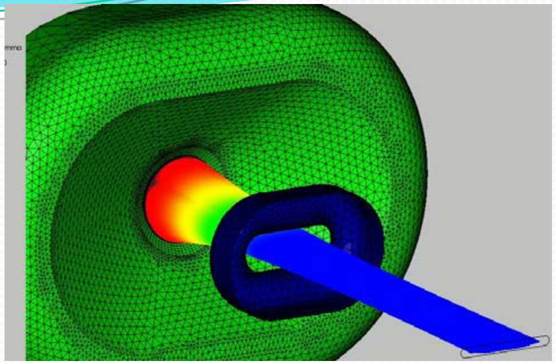


The TESLA Multi-beam MBKs

•TESLA Linear Collider multibeam klystrons: Seven beams, each of micropervance 0.5 are launched into independent drift tubes but common cavities.
•The MBK design was adopted because of the extraordinary power and efficiency requirements of the TESLA superconducting Linear Collider. The tube frequency is 1300 MHz, the peak power output 10 MW, the average power 150 kW and the efficiency “goal” 70 per cent.







The NLC 75-MW sheet-beam klystron design

The Cutaway Model of Five Gap Output Cavity

•Sheet beam klystrons have beams of much lower current density, employ over moded cavities and can be easily PPM-focused.

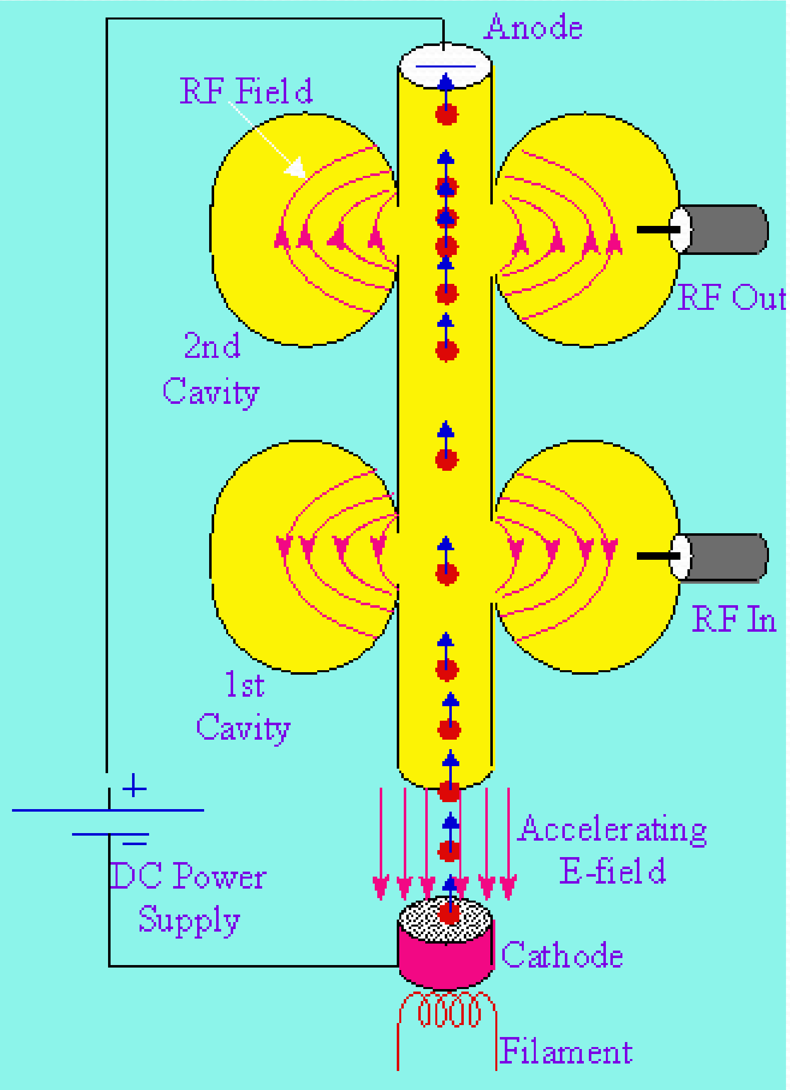
•Their fabrication is much simpler than conventional klystrons and requires considerably fewer parts.

• Since their cathode loading is much lighter, they can be expected to have a much longer life as well.

•Much more effective cooling than is available in the pencil-beam tube. This suggests that the SBK design can make possible a higher duty, or longer pulse NLC klystron.

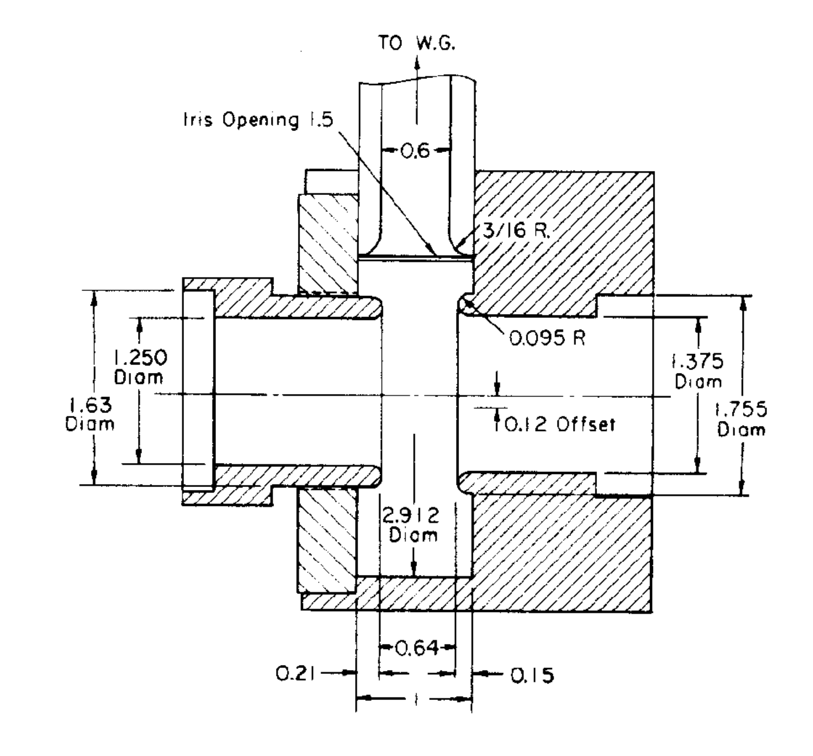
Klystrons

- The filament boils electrons off the cathode
- The velocity (or energy) of the electrons is modulated by the input RF in the first cavity
- The electrons drift to the anode
- Because of the velocity modulation, some electrons are slowed down, some are sped up.
- If the output cavity is placed at the right place, the electrons will bunch up at the output cavity which will create a high intensity RF field in the output cavity
- Klystrons need a minimum of two cavities but can have more for larger gain.
- A klystron size is determined by the size of the bunching cavities.



Cavity Number	Cavity Frequency (GHz)	Q	Gap Transit Angle (Radians)	Drift Length (cm)
1	2.860	200	0.543	5.54
2	2.870	2000	0.574	5.54
3	2.890	2000	0.662	5.54
4	2.910	2000	0.900	28.45
5	2.970	2000	0.955	10.41
6	2.853	21	1.267	

Cavity and Drift Region Parameters of the SLAC 5045 Klystron

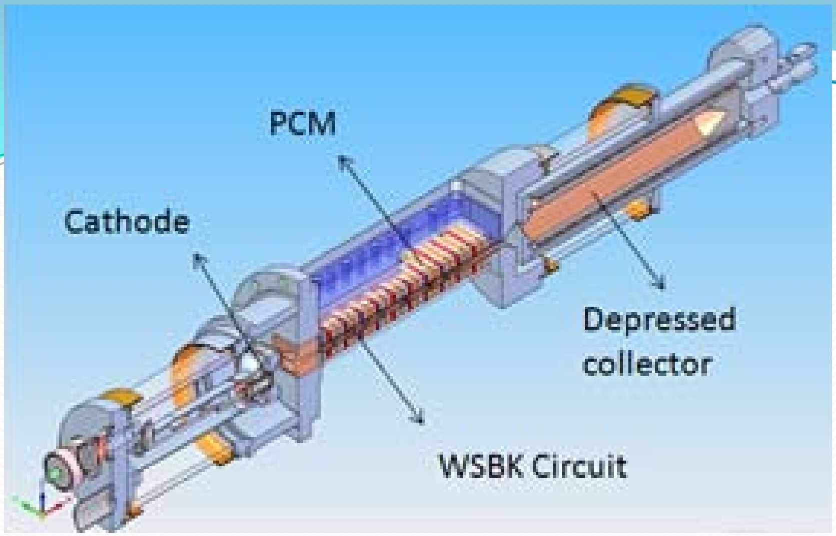


5045 Output cavity geometry.

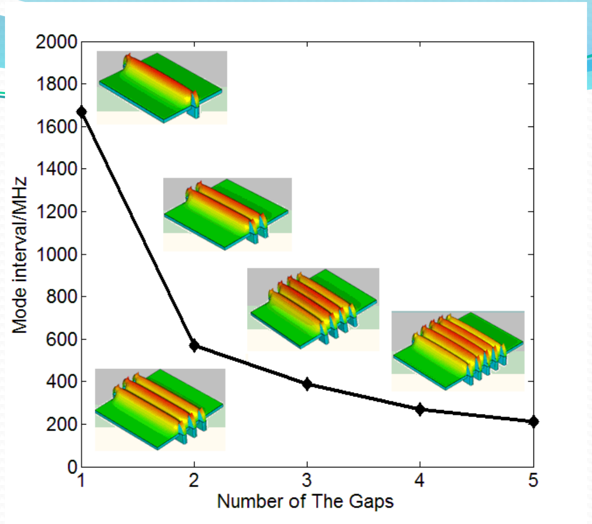
The design of the output gap is extremely important. In the case of the 5045, the designers compromised between the smallest dc transit angle for efficiency optimization. while avoiding rf breakdown across the gap. The calculated gap voltage at saturation is 418 kV which corresponds to 1.32 times the dc beam voltage. The compromises required are reducing the gap electric field while maintaining good coupling to the electron beam. While increasing the radius of the drift tube nose and lengthening the gap would reduce the field, the beam coupling would be reduced to an unacceptably small level.

It shows a photograph of a partially cutaway klystron tube in SLAC. It can produce 65 MW output at a beam voltage of 350 kV and a beam current of 414A. An efficiency of 46% is achieved with a gain of 53 dB.

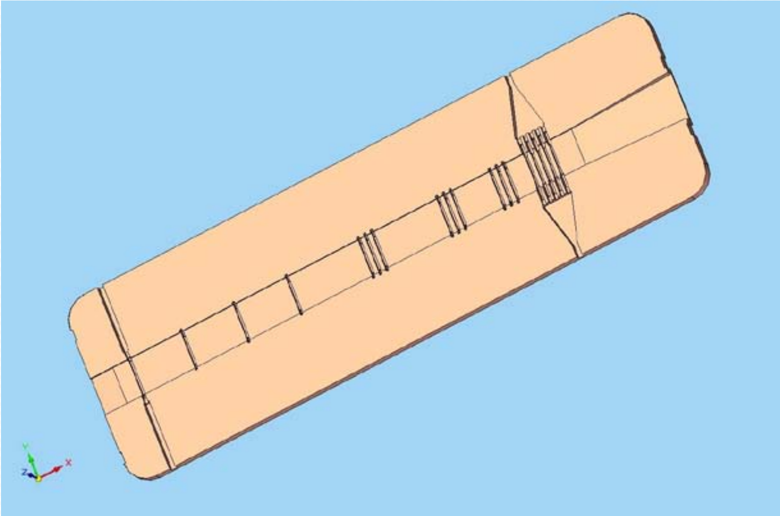
A close-up view of the cavities is displayed



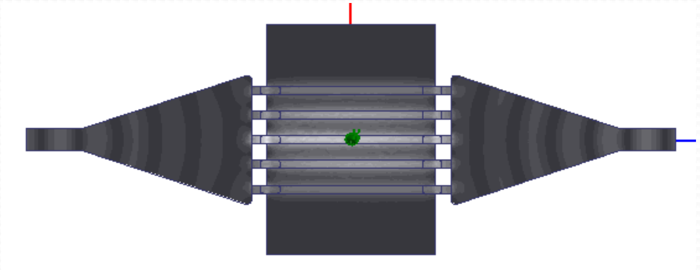
CW WSBK



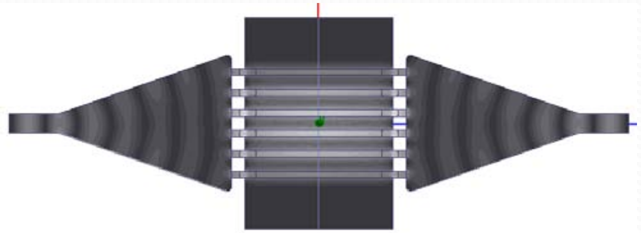
Mode separation with different gaps



Circuit of WSBK



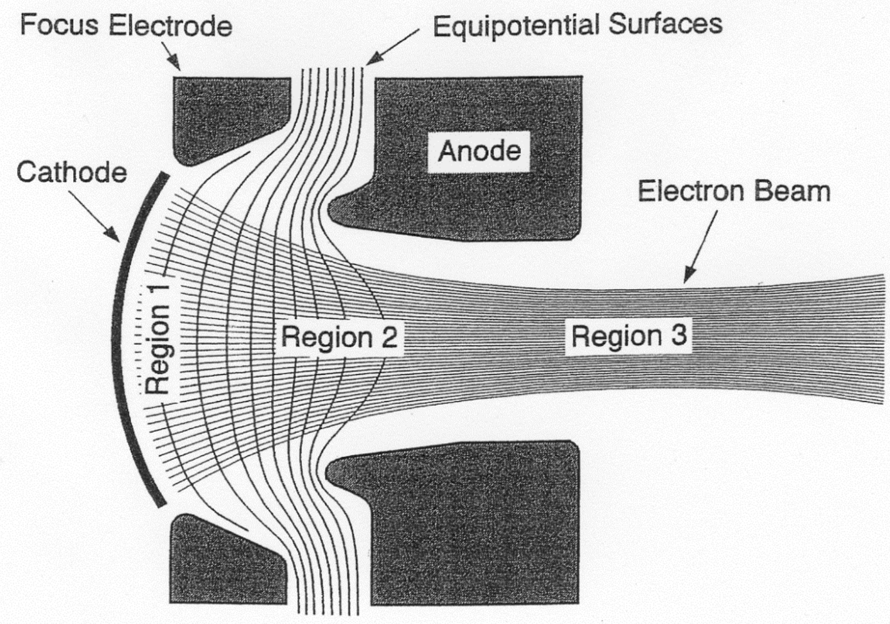
Electric field distribution with 5 gaps



Electric field distribution with 6 gaps

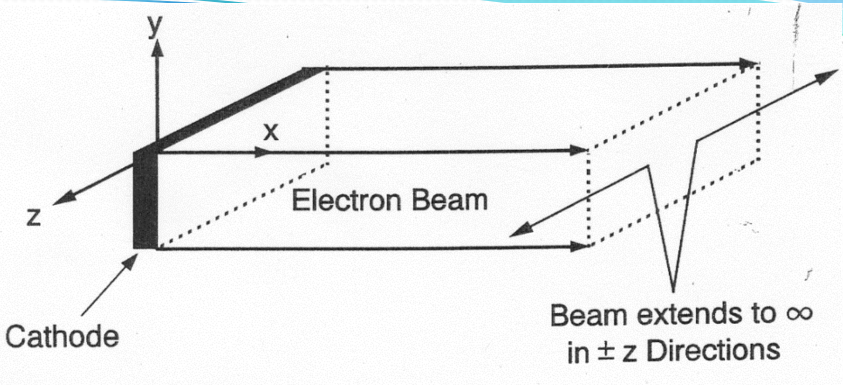
Electron gun, beam and collector design

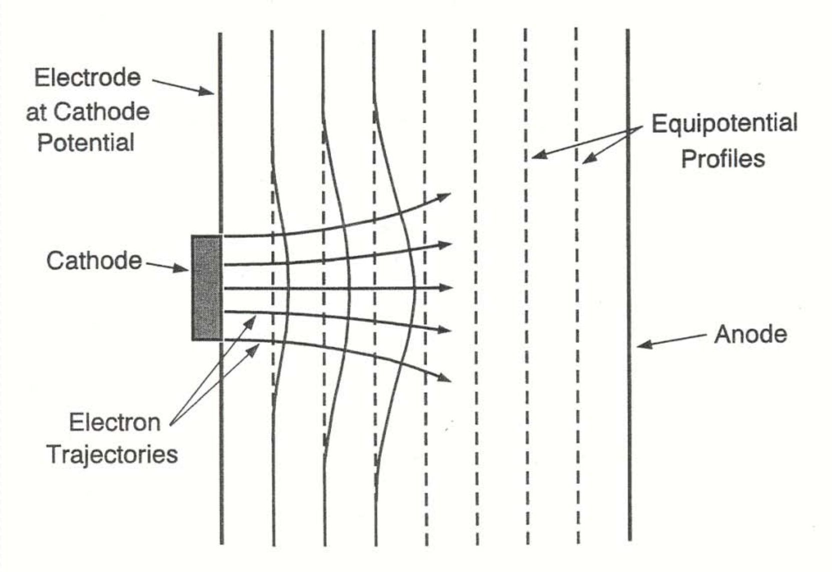
•In region 1 the electron flow is that between two spheres.
•In Region 2, the beam is deflected outward by the diverging lens caused by the hole in the anode.
•In Region 3, there is no remaining accelerating field and the flow is that of the universal beam spread of an electron beam.



Overview of Pierce gun(from *Principles of Traveling Wave Tubes*, A. S. Gilmour, Jr.)

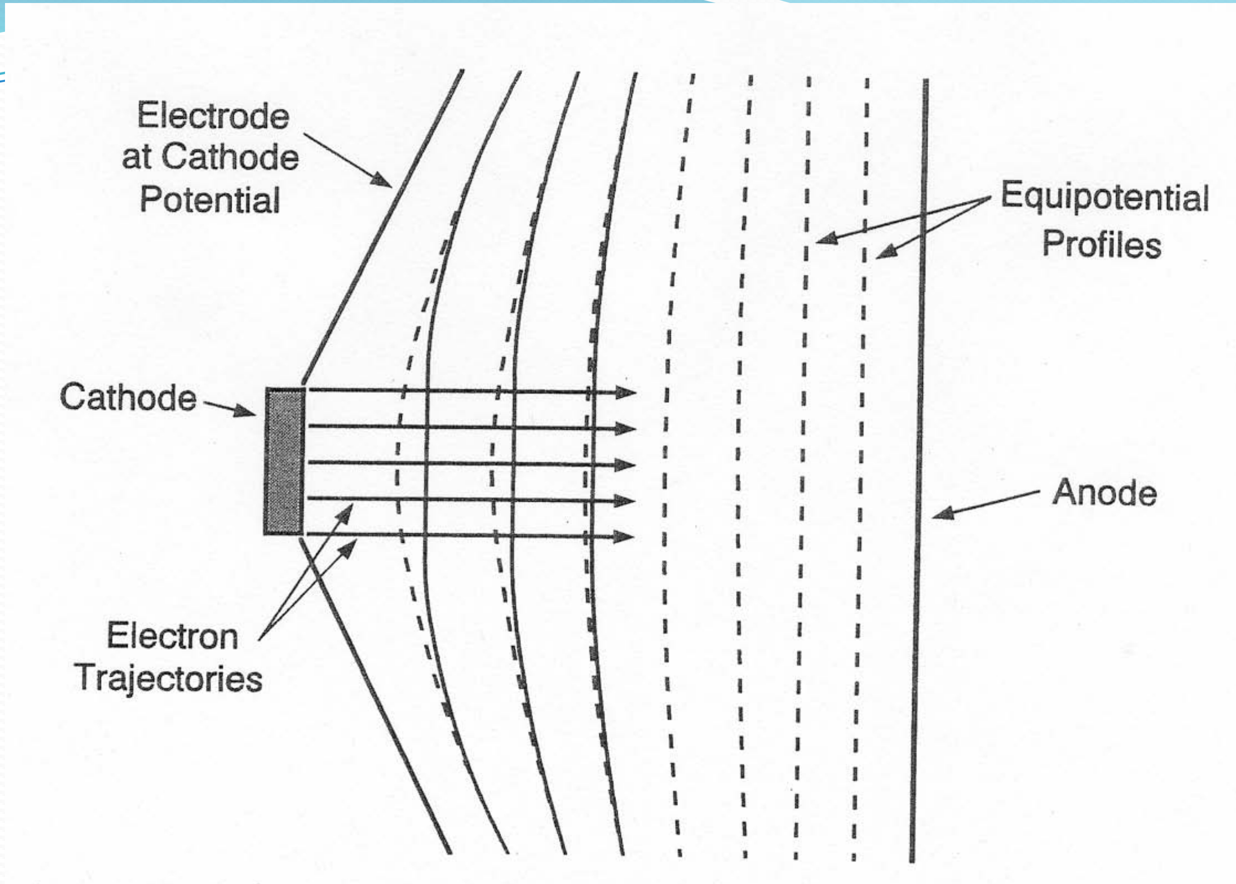
•1. High power klystrons typically require beams having current densities of 100's of amps per square centimeter whereas, the best long-life cathodes will support less than 10 amps per square centimeter.
•2. The larger the area convergence, the greater the focus electrode- anode separation, hence the lower the voltage gradient and the higher the breakdown voltage.
•3. The diverging lens effect of the hole in the anode would cause the parallel beam to begin spreading before a focusing field could be applied. It is optimum to have a beam that is still compressing after passing through the diverging lens.





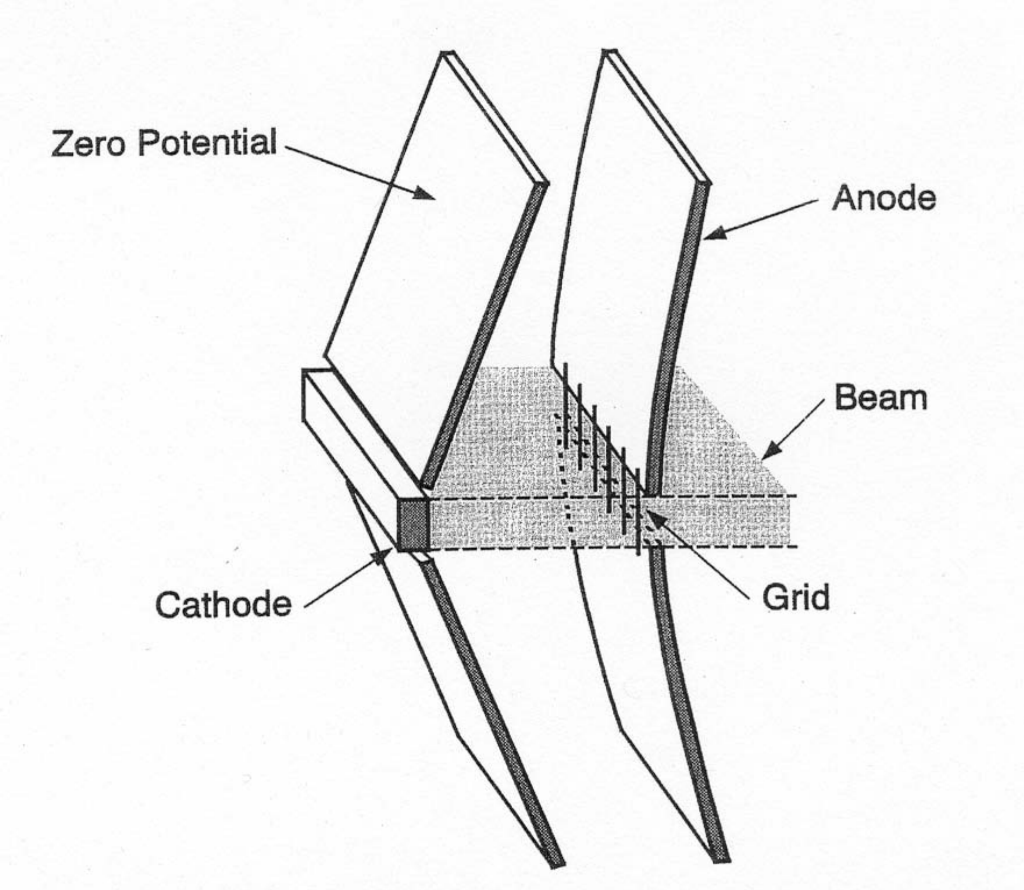
Parallel electron flow – Equipotential profiles

•Given two parallel planes, emission over a limited region results in space charge which bows the equipotentials causing the strip beam to spread.



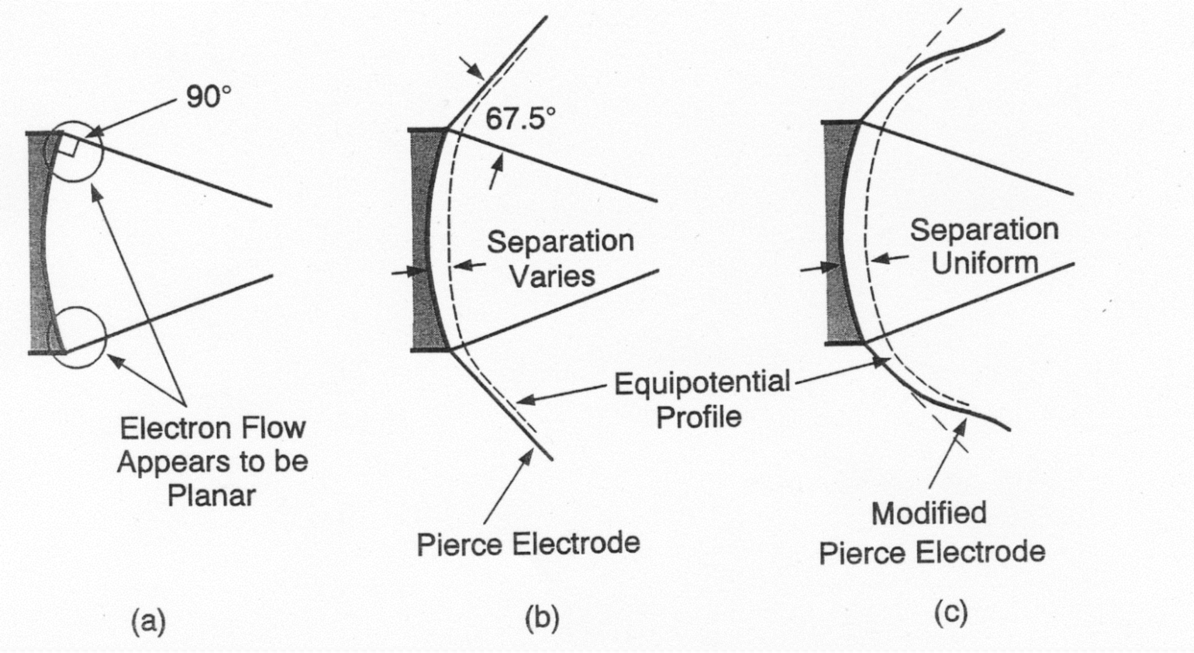
Straightening of equipotential profiles in electron beam

•Tilting the cathode potential electrodes provides an initial curvature to the equipotentials. When the angle between the perpendicular to the cathode and the electrode is made the Pierce angle (67.5 degrees) the equipotentials become parallel with the cathode when space charge is allowed to flow and the beam is focused as a strip beam.



Electron gun for producing rectilinear electron flow

•This is the classic strip beam drawing from Pierce's book on the design of electron guns. The grid shown between the two anode plates supports the field to prevent a diverging lens effect.

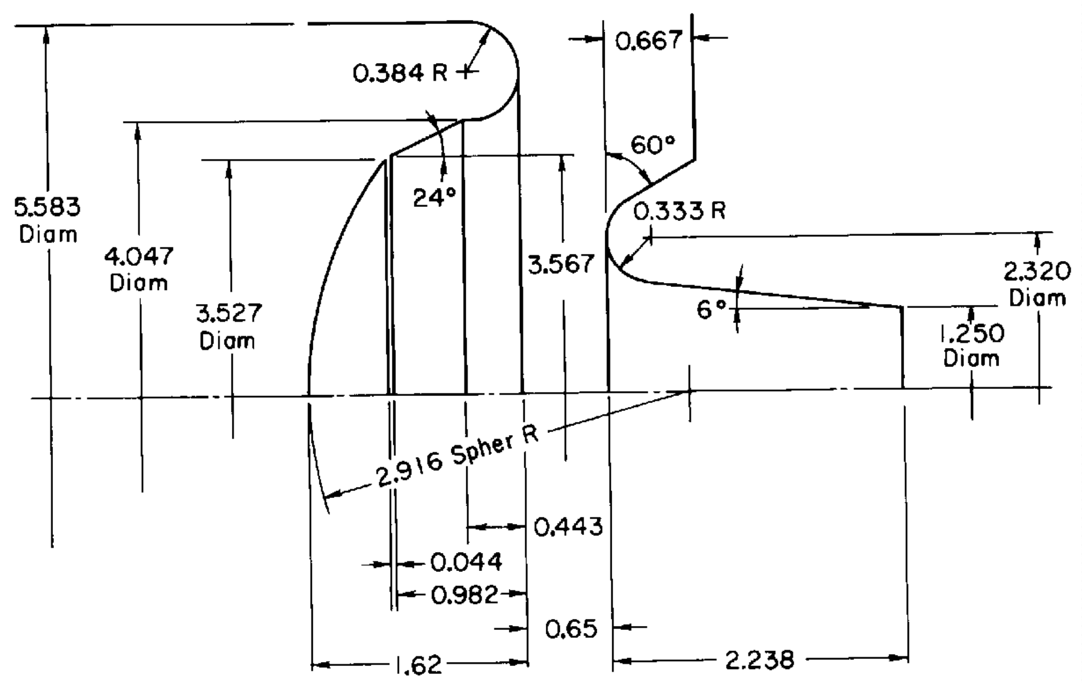


Modification of Pierce electrodes to produce spherical equipotential profiles

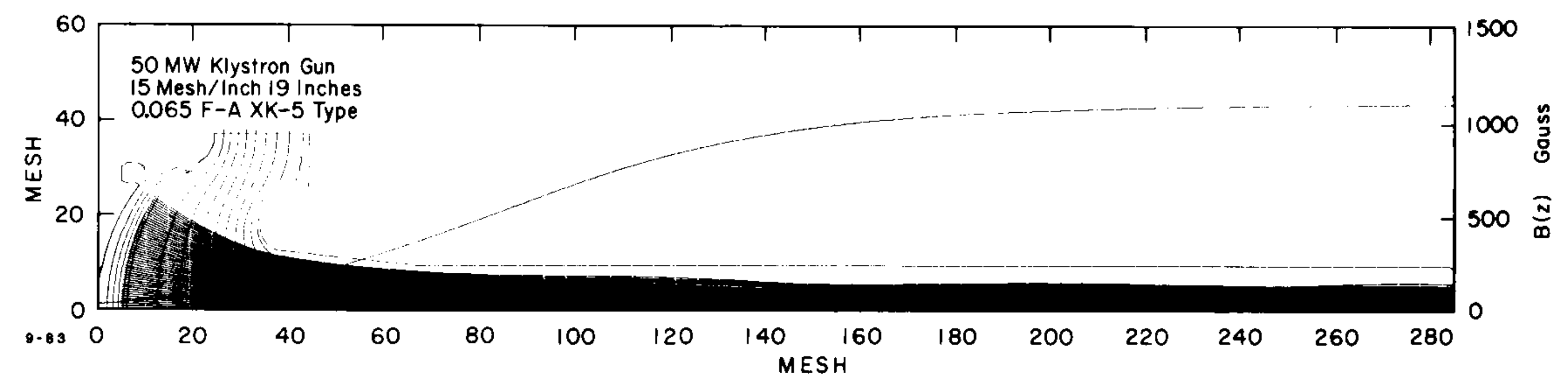
•Because one wants the outer most ray of the electron beam to match that of the defining spherical gun, the angle between cathode and ray are 90 degrees, which is supported by the Pierce angle, once again 67.5 degrees. If one is dealing with a large area convergence, the equipotential will not be a sphere concentric with the cathode, but will bulge slightly as shown due to the space charge well removed from the focus electrode and hence not influenced by it.

•In C, the focus electrode has been modified to force the equipotential away from the cathode near the cathode edge to match the spacing at the center to provide a near uniform spacing separation. Also an equivalent, or better, results can be achieved more simply and without the unfavorable effect on voltage gradient by simply reducing the 67.5 degrees to a more shallow angle.

Electron gun geometry.



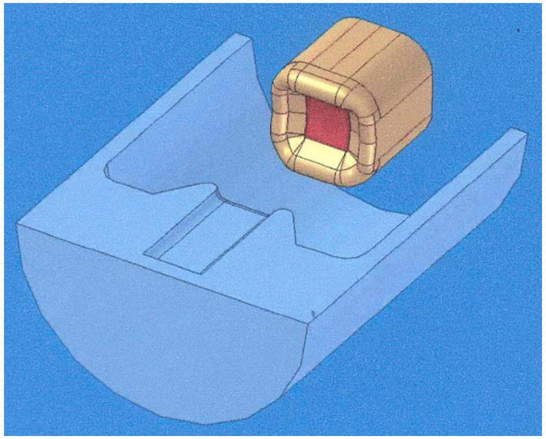
The electron gun is a critical portion of the design due to the high operating voltage (315 kV). Figure schematically illustrates the Pierce electron gun design. The high peak voltage gradient (174 kV/cm) and long voltage pulse duration (6 μs) increase the possibility of voltage breakdown. However, it is reported that following careful selection of electrode materials, extensive polishing and proper conditioning that fewer than two high voltage breakdowns in an eight hour shift occur.



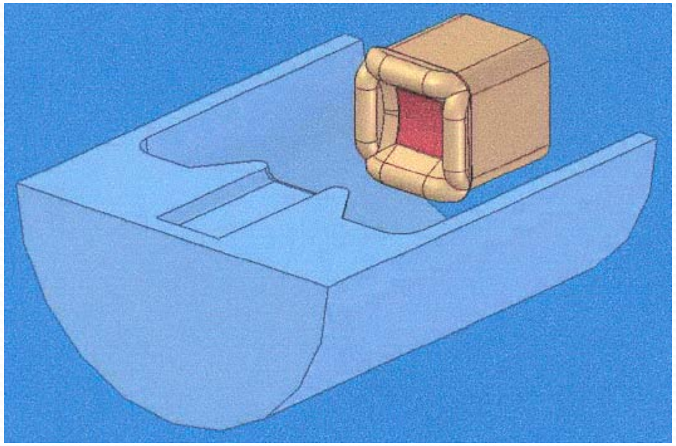
Calculated electron trajectories with magnetic field.

Parameters of the Stanford 5045 Klystron Amplifier

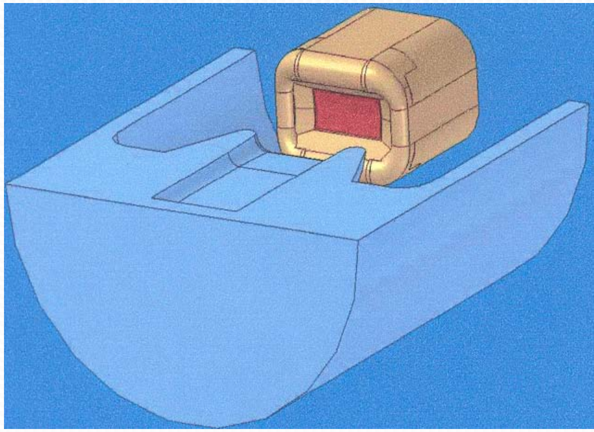
Operating Voltage (kV)	315
Perveance (μp)	2.0
Peak Beam Current (A)	354
Maximum Voltage Gradient (kV/cm)	174
Frequency (GHz)	2.856
Power Output (MW)	50
Repetition Frequency (Hz)	180
Efficiency (%)	45
Gain (dB)	50
RF Pulse Duration (μs)	5.0
Beam Pulse Width (μs)	6.0
Cathode Type	Dispenser
Cathode Diameter(cm)	7.96
Average Cathode Loading (A/cm^2)	5.6
Cathode Loading Uniformity	1.7:1
Beam Diameter (cm)	2.0
Focusing	Electromagnet



Sheet beam gun with
square cathode

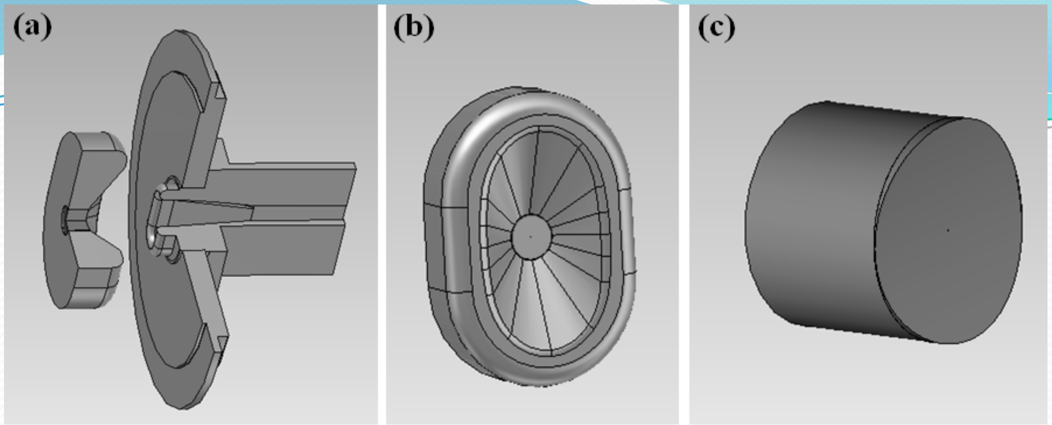


Square cathode gun with another
version of focus electrode

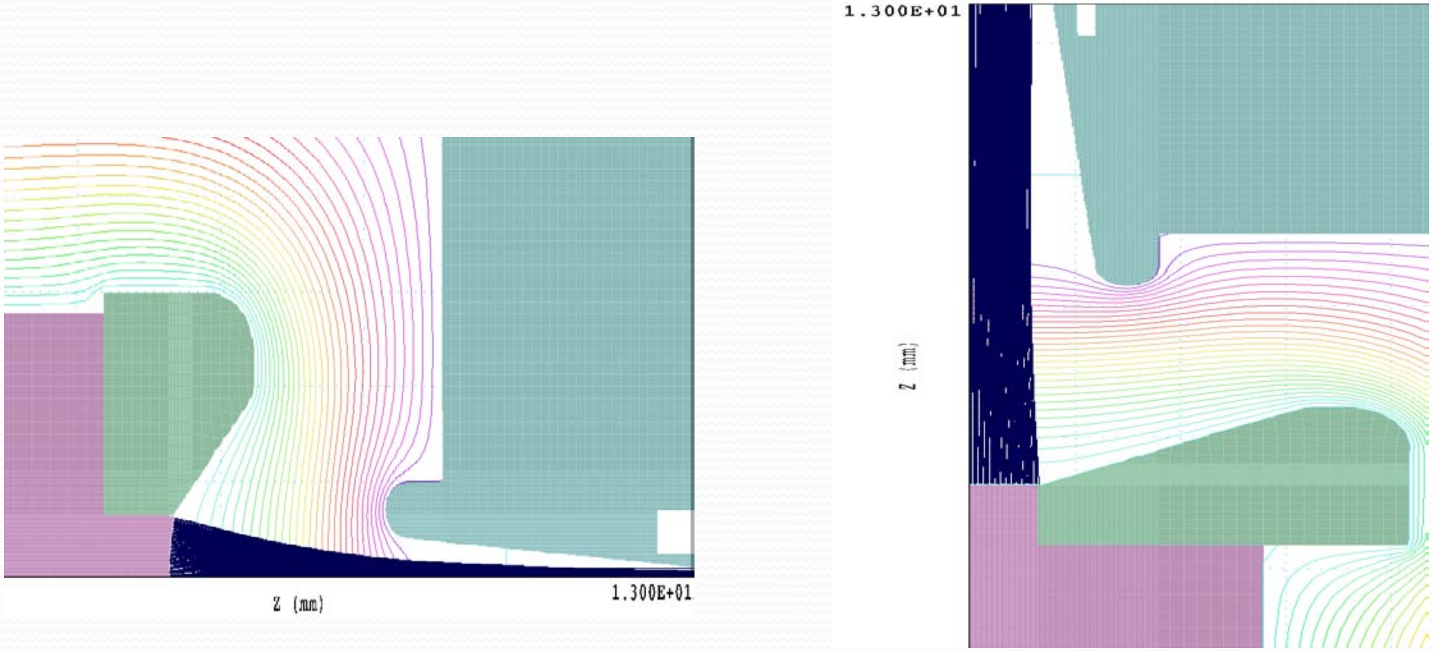


Sheet beam gun with 2:1
cathode aspect ratio

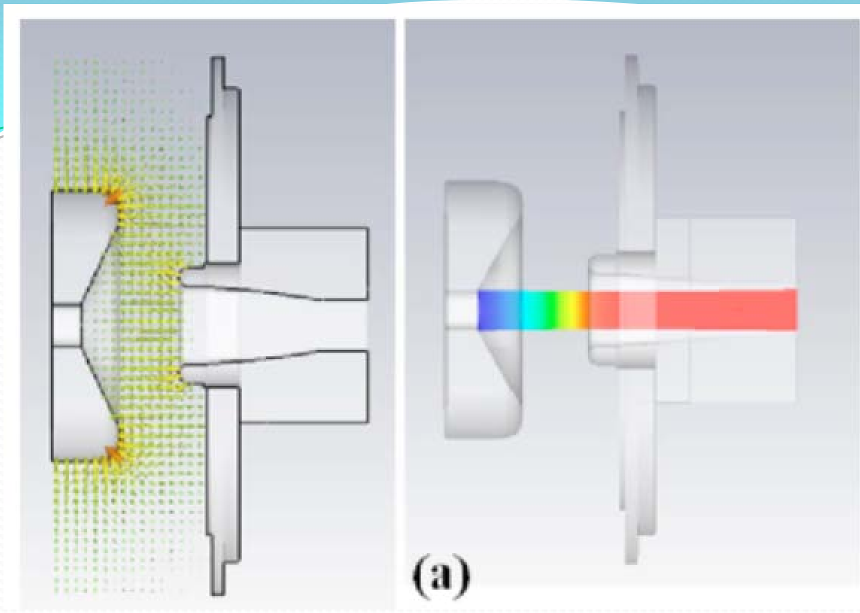
- A much more difficult gun to design is the sheet beam gun for the sheet beam klystron. Here the beam from a typically square cathode is made to converge in one dimension while not in the other dimension.
- The ash tray type corner depressions prevent over-pinching of the corner electrons to avoid creating an elliptical beam cross section.



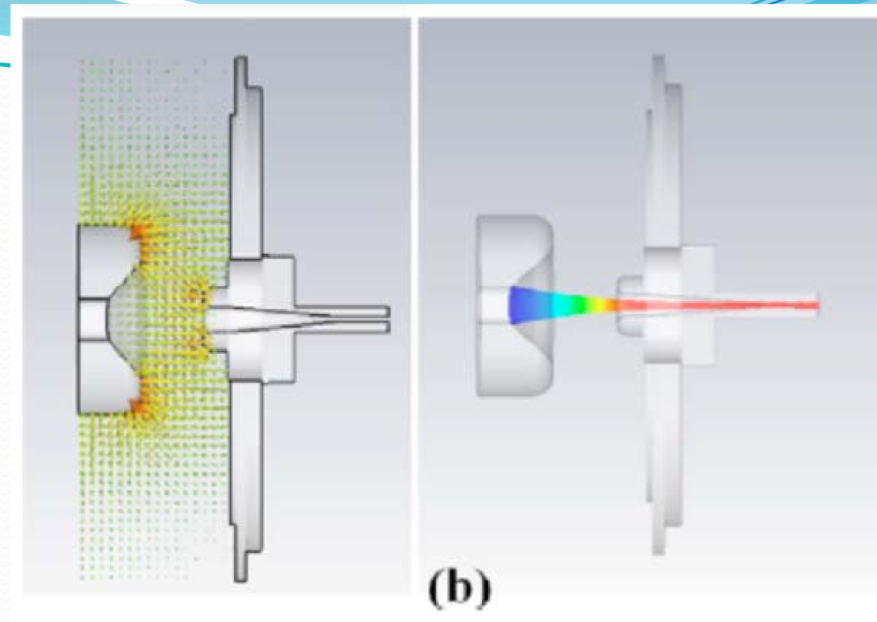
Cathode， Anode and Focus electrode of a WSBK in UCDavis



Omnitrak simulations of the beam focus

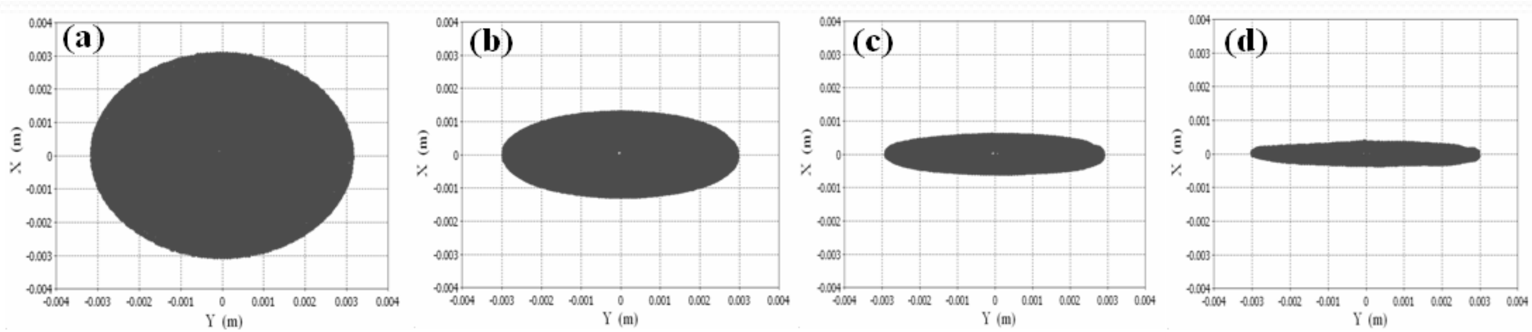


Top View

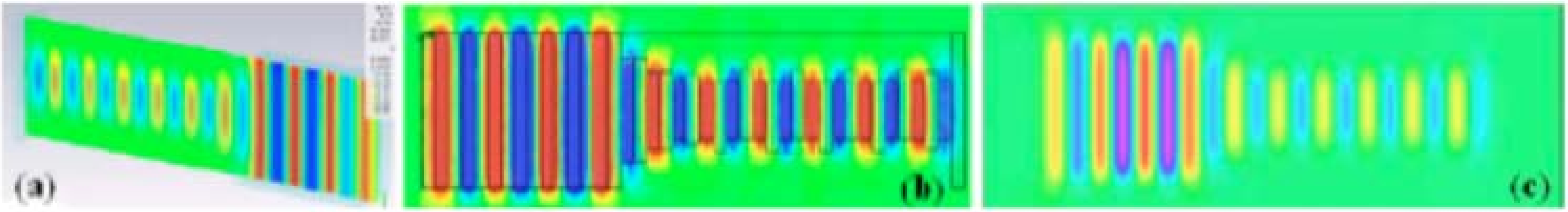


Side View

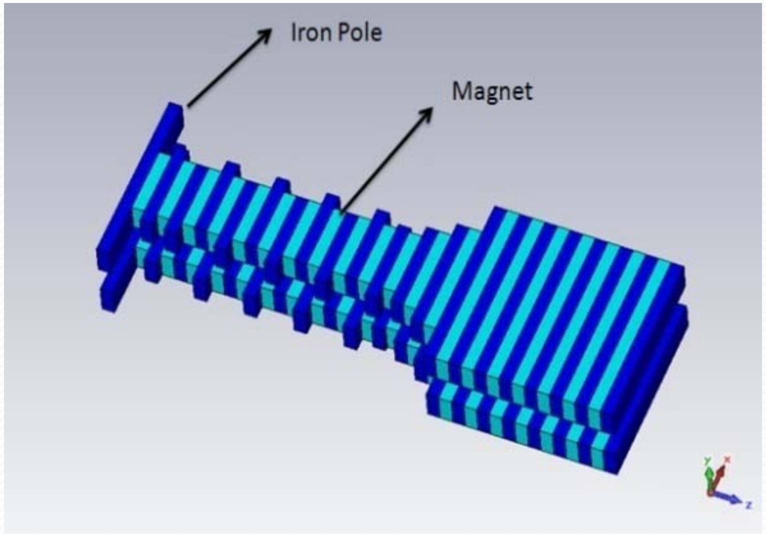
Electrostatic field vector plot and spatial particle distribution of the sheet beam gun in CST-PS. The beam voltage is 54kV and beam current is 2A.



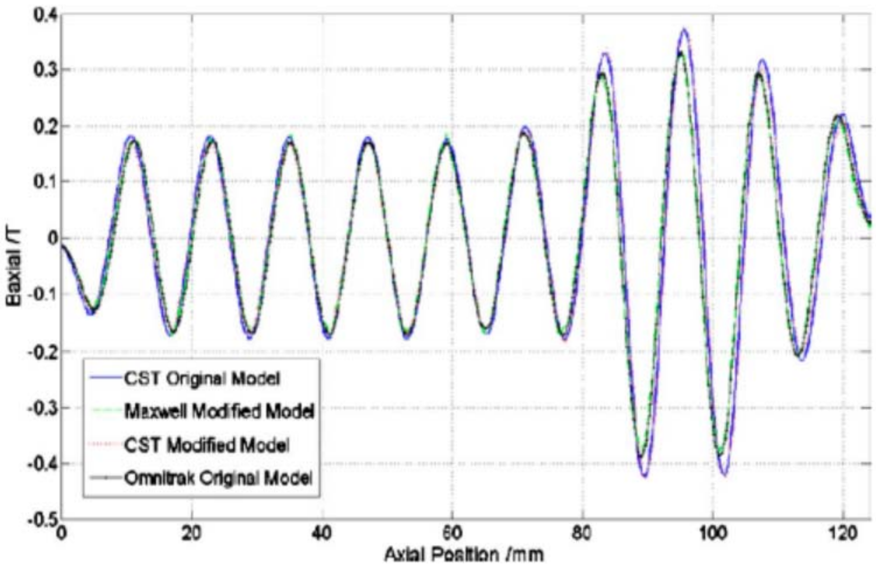
Beam cross section at different axial position



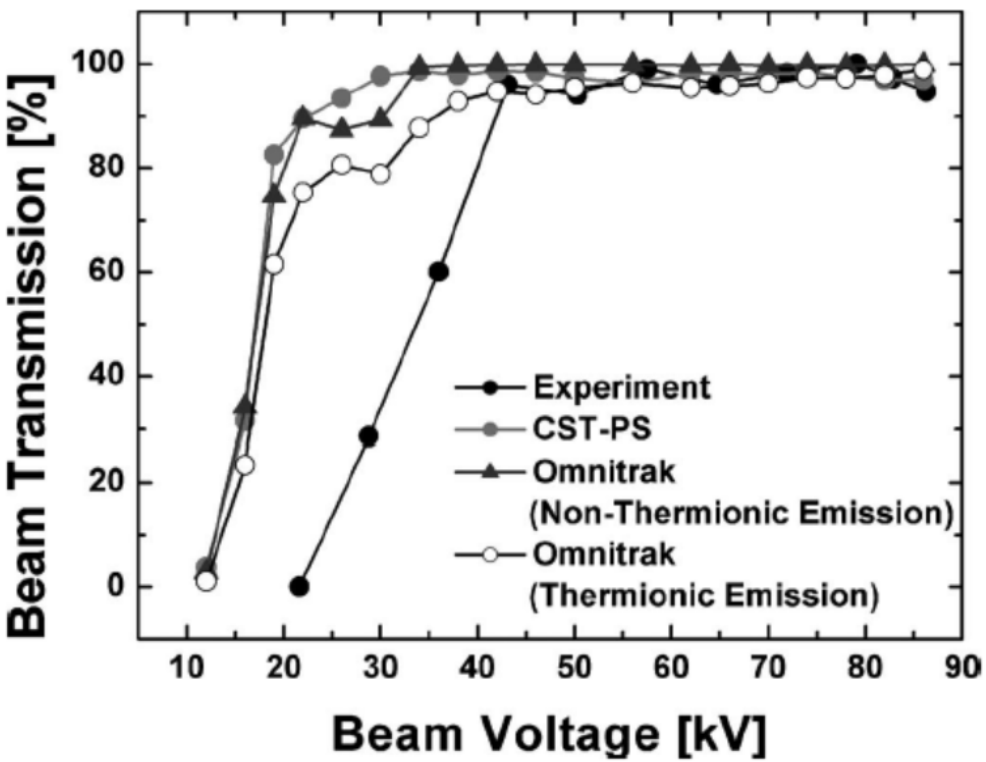
Axial magnetic field distribution from (a) CST-PS, (b) Maxwell and (c) Omnitrak



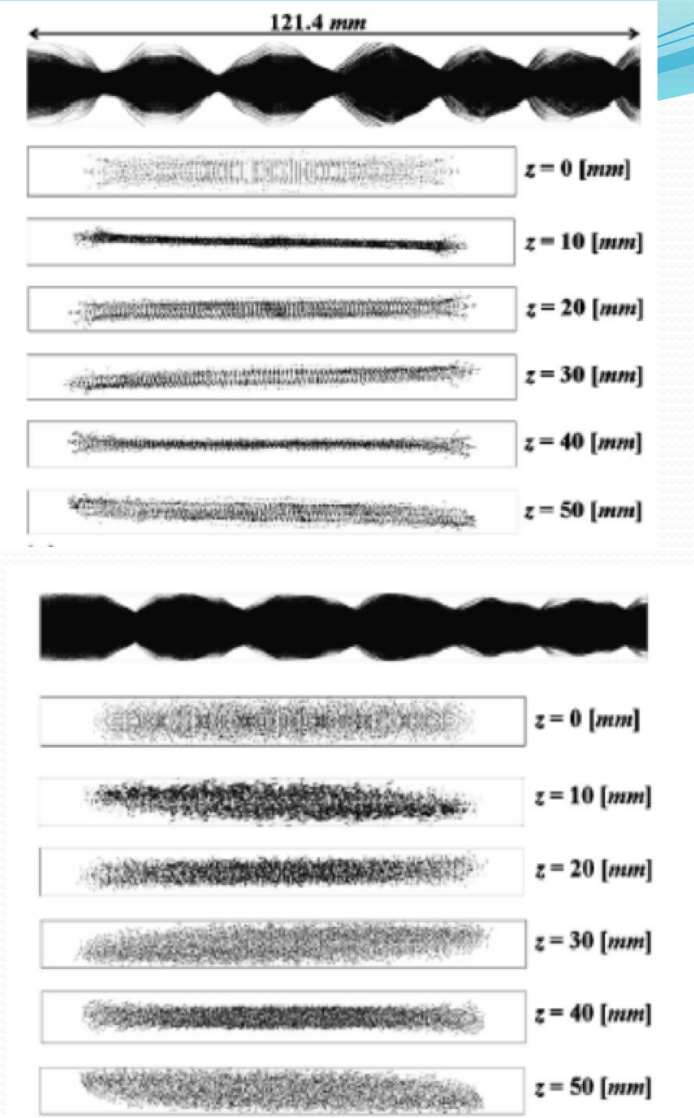
Permanent Cusp Magnet (PCM)



1D distance vs axial magnetic field graph along the beam tunnel axis obtained from CST-PS, Maxwell3D and Omnitrak

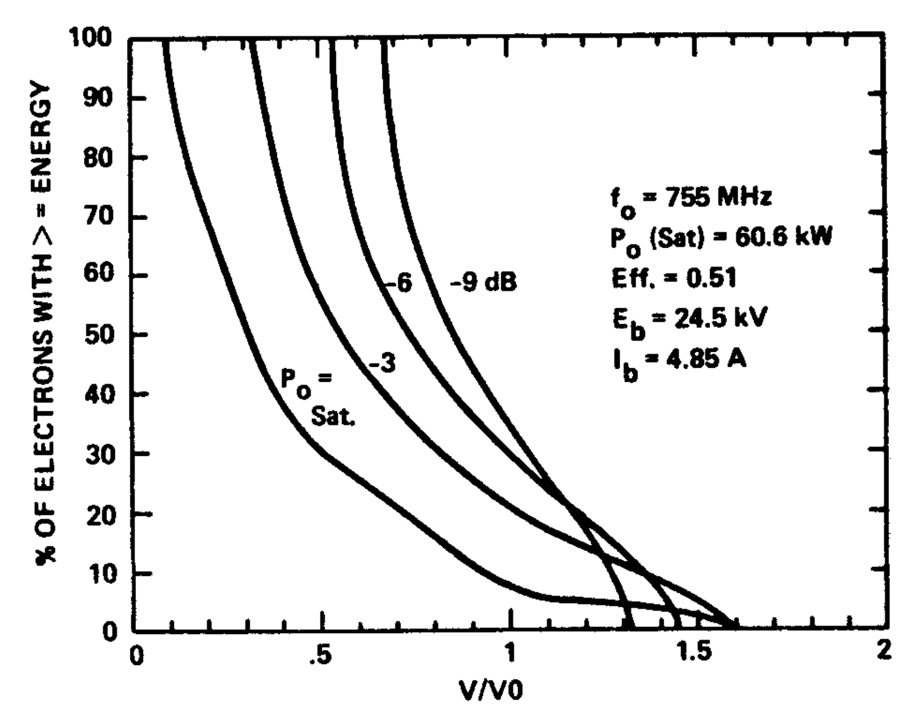


Beam voltage vs transmission graps obtained from experiment and simulation (CST-PS and Omnitrak)

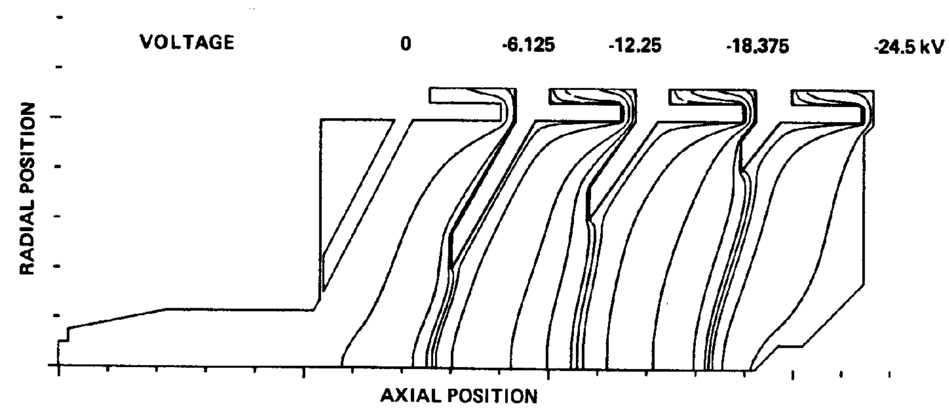


Electron beam distribution in wide and thin direction at several positions with o and 0.16 eV transverse temperature

Depressed Collector Operation



Calculated energy distribution of the spent beam for the VKP-7555 Klystron.

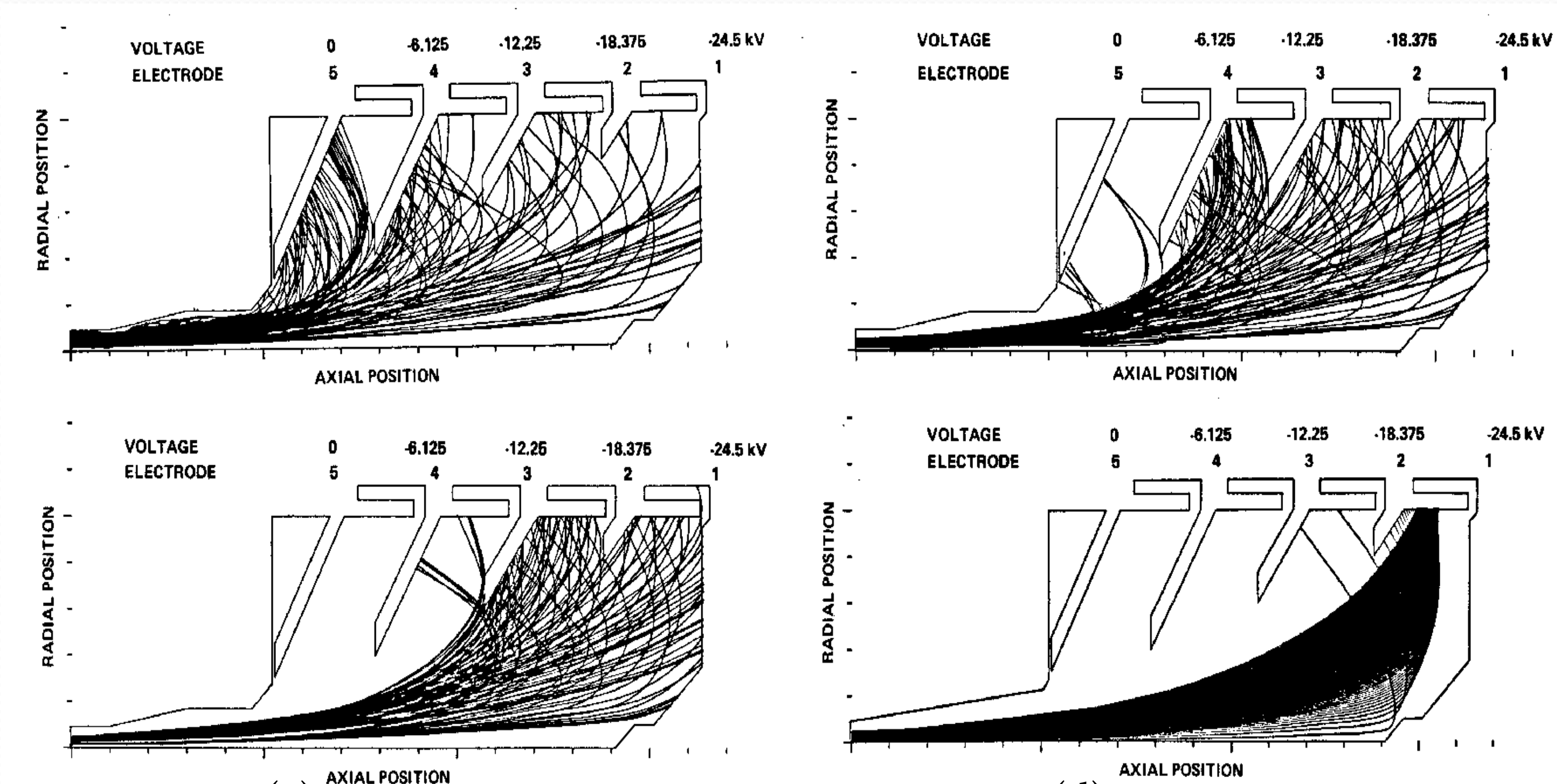


Collector electric field equipotentials.

Figure displays the calculated energy distribution of the spent beam for various signal levels computed using a 2-D particle in cell code. The output of the 2-D code was utilized as the input for a trajectory code employed for the collector design. Right figure shows the final collector design together with equipotential contour lines. In addition, a transition intermediate magnetic field region is employed between the rf interaction circuit and collector for beam reconditioning.

(a) Electron trajectories for 90% saturation. (b) Electron trajectories for 50% saturation. (c) Electron trajectories for 25% saturation. (d) Electron trajectories for no rf signal.

(a) (b)



(c) (d)

Computed electron trajectories for various drive levels

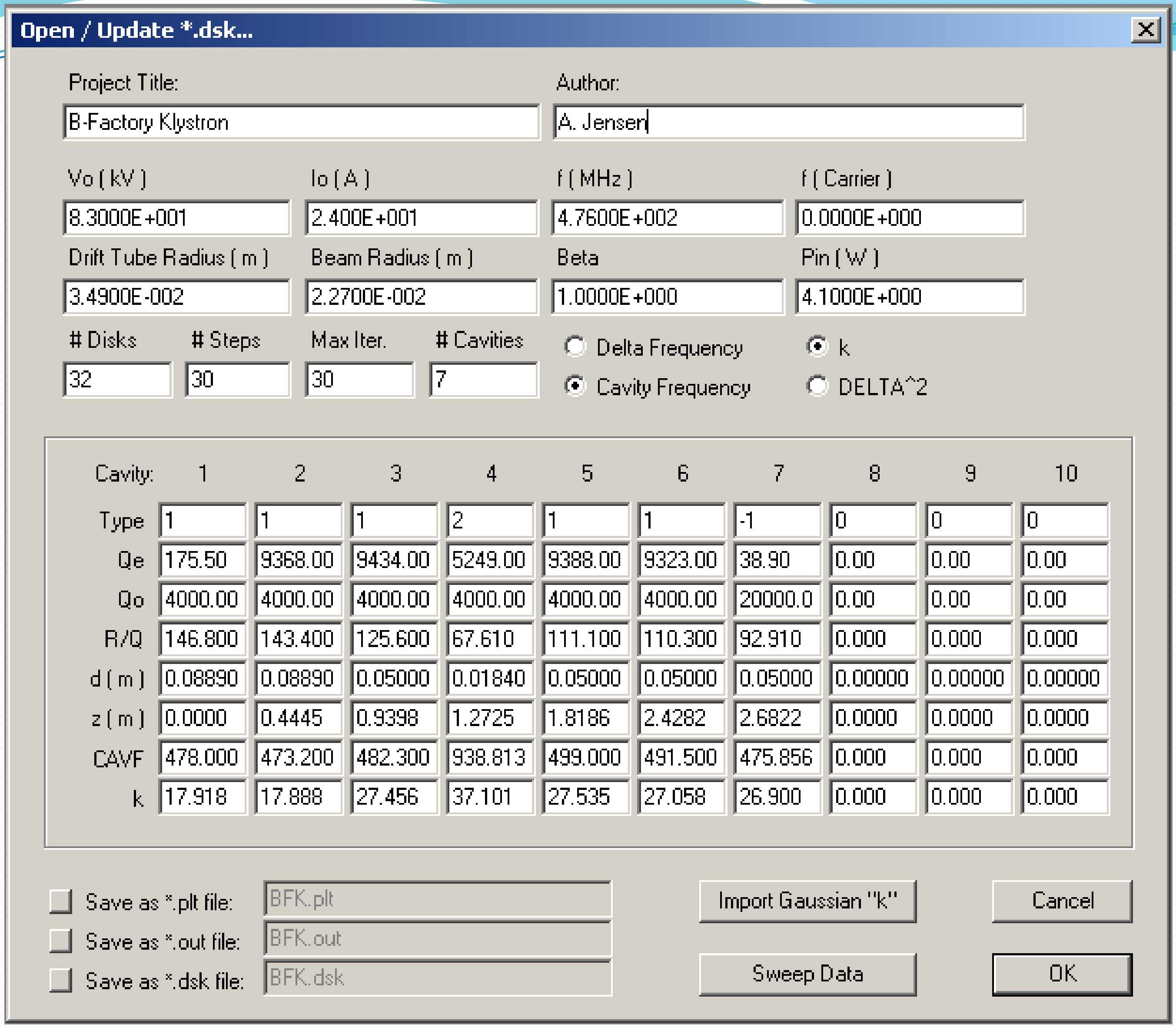
Collector Current and Power Distribution
INCLUDING EFFECT OF SECONDARY ELECTRONS

Beam Voltage = 24.5 kV
Beam Current = 4.85 A

RF Output	Electrode		Current	Power		Collector
Power	5	4	3	2	1	Efficiency
0 kW	0	0	0.08	4.77	0	74.6%
	0	0	0.95	29.23	0	
15.8	0	0.47	2.44	1.38	0.56	69.8%
	0	3.62	10.78	8.35	8.34	
31.9	0.27	2.13	0.97	1.03	0.45	63.0%
	1.56	11.75	4.82	5.46	8.53	
57.8	2.08	1.32	0.64	0.50	0.31	53.7%
	10.05	5.03	3.14	2.78	7.26	

Klystron Gain-Bandwidth Calculations and Simulations

The A-J* disk is a considerably improved 1-dimensional klystron code developed in SLAC. The code employs the "disk model", in which electrons are represented by disks of charge inside a cylindrical drift tube. The disks are accelerated by the beam voltage, their individual charges are made consistent with the current in the beam, and the field arising from these charges is described by a "Green's function", which depends on the disk (beam) and drift tube diameters, the current, the voltage, and the axial component z. The disks can penetrate and overtake each other. The klystron cavities are characterized partly as lumped circuits (functions of the various Qs, R/Q and resonant frequencies), and also by the field developed across their gridless gaps. The gap field is represented as a Gaussian function of the beam and drift tube diameters and the gap length. Output power and efficiency are calculated by integrating disk velocity at the exit of the output cavity, and by forming the product of the induced current and voltage at the output cavity.



Open / Update *.dsk...

Project Title: B-Factory Klystron

Author: A. Jensen

Vo (kV)	Io (A)	f (MHz)	f (Carrier)
8.3000E+001	2.400E+001	4.7600E+002	0.0000E+000

Drift Tube Radius (m)	Beam Radius (m)	Beta	Pin (W)
3.4900E-002	2.2700E-002	1.0000E+000	4.1000E+000

# Disks	# Steps	Max Iter.	# Cavities
32	30	30	7

Delta Frequency

Cavity Frequency

k

DELTA^2

Cavity:	1	2	3	4	5	6	7	8	9	10
Type	1	1	1	2	1	1	-1	0	0	0
Qe	175.50	9368.00	9434.00	5249.00	9388.00	9323.00	38.90	0.00	0.00	0.00
Qo	4000.00	4000.00	4000.00	4000.00	4000.00	4000.00	20000.0	0.00	0.00	0.00
R/Q	146.800	143.400	125.600	67.610	111.100	110.300	92.910	0.000	0.000	0.000
d (m)	0.08890	0.08890	0.05000	0.01840	0.05000	0.05000	0.05000	0.00000	0.00000	0.00000
z (m)	0.0000	0.4445	0.9398	1.2725	1.8186	2.4282	2.6822	0.0000	0.0000	0.0000
CAVF	478.000	473.200	482.300	938.813	499.000	491.500	475.856	0.000	0.000	0.000
k	17.918	17.888	27.456	37.101	27.535	27.058	26.900	0.000	0.000	0.000

Save as *.plt file: BFK.plt

Save as *.out file: BFK.out

Save as *.dsk file: BFK.dsk

Import Gaussian "k"

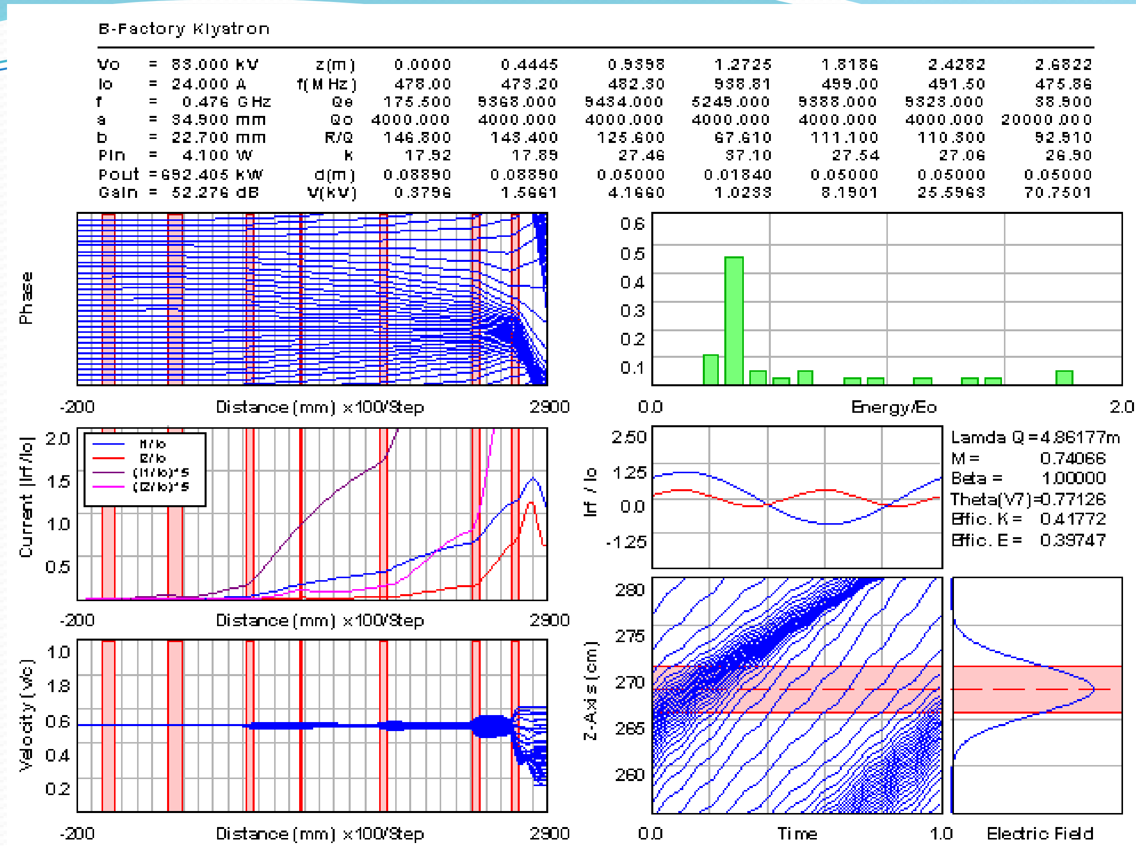
Sweep Data

Cancel

OK

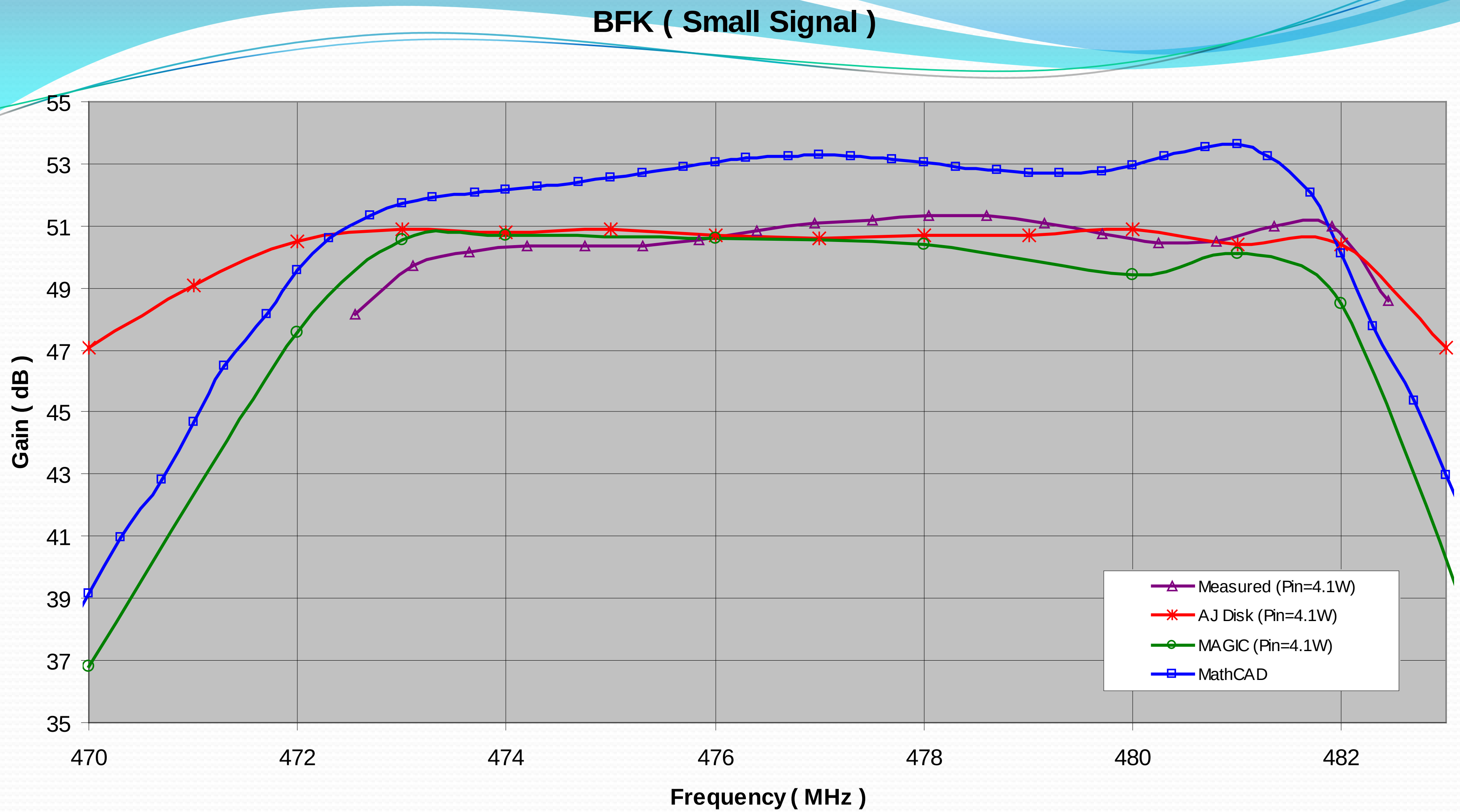
A-J Disk's input deck

$$f(z) = \frac{k}{\sqrt{\pi}} e^{-k^2 (z - z_{center})^2}$$



Simulation results

Phase Diagram: Shows the disks in one period and how their phase changes as a function of axial distance.
Current Diagram: Shows the fundamental and second harmonic components of the beam current as a function of axial distance.
Velocity Diagram: Shows the velocity spread as a function of axial distance.
Energy Distribution: The energy distribution of the spent beam.
Irf/Io Diagram: The fundamental and second harmonic of the induced current at the output cavity as a function of time.
Electric Field Diagram: The approximated Gaussian distribution of the electric field at the output gap.



Calculations and simulations compared to actual performance

Klystron manufacture, processing and testing

- Vacuum
  - A discussion of the vacuum requirements of microwave tubes
- Materials
  - Common materials used in microwave tubes and the reasons for their selection
- Processing
  - Vacuum processing of the completed microwave tube
- Testing and Protection

Why a Vacuum?

- The interior space of a microwave tube must have a low enough density of gas molecules to allow free passage of electrons
- Reliable cathode emission requires low partial pressures of cathode "poisons". To avoid poisoning, dispenser cathodes operating at 1100 ° C shouldn't be exposed to partial pressures more than: 10^{-7} for O_2, 3x 10^{-7} for H_2O, and 10^{-6} for CO_2
- Higher gradients (DC and RF) are supported at lower pressures
- Residual gas in the tube can become ionized by the beam. These ions can lead to a host of problems raging from ion focusing, to ion etching of the cathode, to ion oscillations. CW tube are most susceptible to these problems.

How is a high vacuum achieved and maintained?

- Proper selection of materials
  - Use low vapor pressure materials
  - Use clean materials
- Use clean forming and joining techniques
- Chemical cleaning
  - Removes surface contamination (cutting fluids, surface oxides, etc.)
- High temperature processing, vacuum bake out
  - Drives off adsorbed contaminants and gasses
- Appendage pumping
  - Maintains low pressure during periods of tube outgassing

Materials

- Microwave tube materials must be vacuum compatible
  - Low vapor pressure at operating and bakeout temperatures
  - Few inclusions or stringers that can lead to real or virtual vacuum leaks
- Materials must meet tube operational requirements
  - Electrical, thermal conductivity
  - Expansion match adjacent materials
  - Strength

Metallic Materials

(A representative, not exhaustive list)

- OFE Cu, 99.99% pure, oxygen-free copper
  - High thermal and electrical conductivity
  - Brazes easily
  - Very low strength when annealed
  - Used extensively for RF and high heat flux surfaces
- CuNi, 70% Cu, 30% Ni alloy
  - Brazes and welds easily with proper chemistry
  - Moderate strength
  - Used primarily for weld flanges and compliant members brazed to ceramics

- Monel 404, ~45% Cu, ~55% Ni alloy
  - Acceptable brazability
  - Moderate strength
  - Thermal expansion between copper and iron
  - Used for spacers and cavities in PPM structures

- Austenitic Stainless Steel (primarily 304L), 8-12% Ni, 18-20% Cr, balance Fe alloy
  - Brazes and welds easily
  - High strength
  - Poor thermal and electrical conductivity
  - Used extensively for tube structural components
- Core Iron, pure Fe
  - Brazes and welds well
  - Magnetically soft
  - Non-monotonic thermal expansion
  - Used for magnetic field shaping components

- Ferritic Stainless Steel (430), 16-18% Cr, balance Fe alloy
  - High strength
  - Low thermal and electrical conductivity
  - High microwave loss
  - Used for loss cavities and loads
- Molybdenum
  - Refractory high strength material
  - Acceptable brazing
  - Used for cathode heaters, support structures and components subject to pulsed heating loads
- Tungsten
  - Refractory high strength material
  - Primarily used for dispenser cathode matrix

Braze Materials

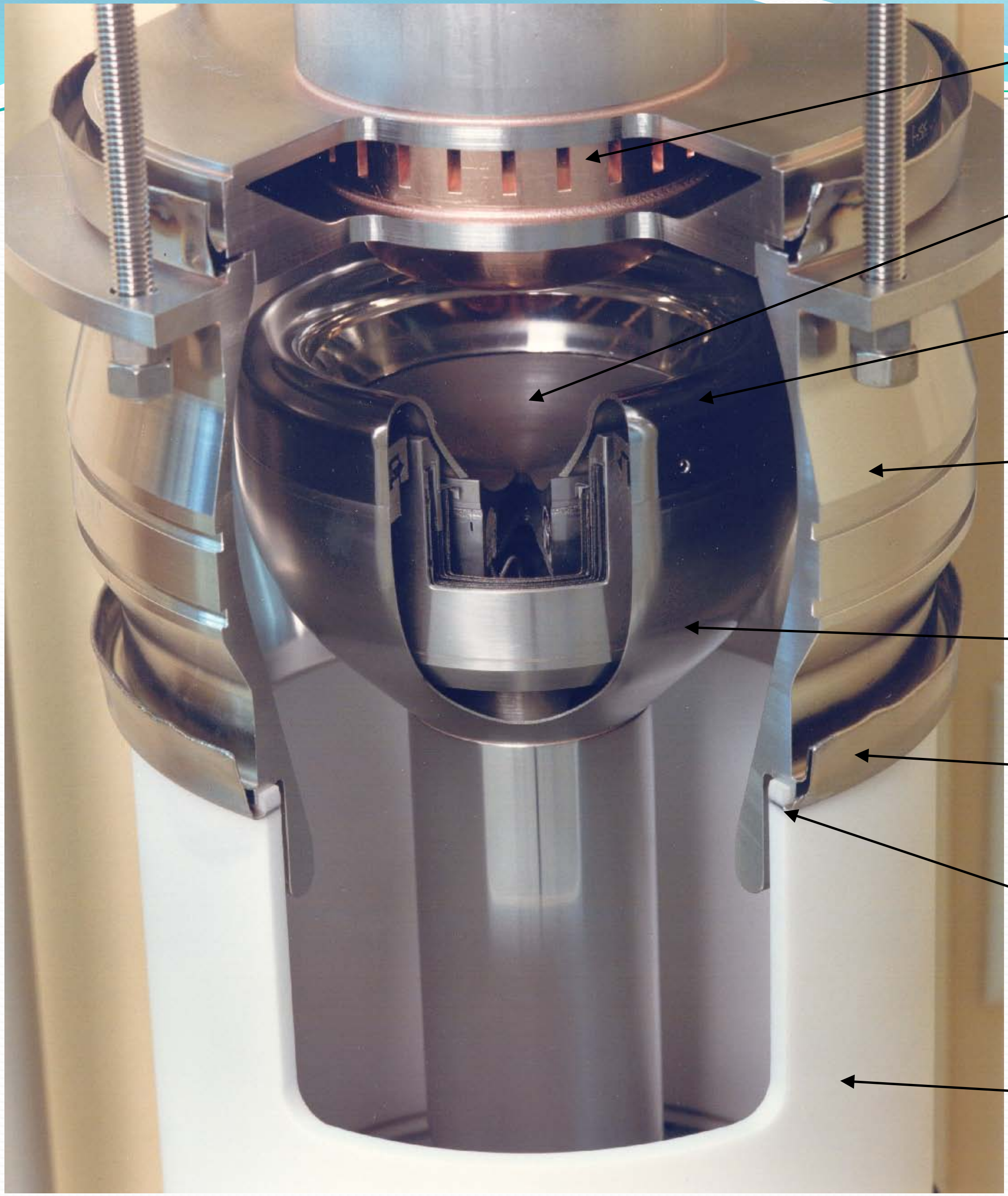
- Copper
  - Least costly
  - Excellent wetting of stainless steels
  - Low vapor pressure
- Gold-copper alloys
  - Costly, dependent upon gold fraction
  - Alloyed with other materials to tailor properties
  - Wide range of melting temperatures allows step brazing
  - Low vapor pressure
- Copper-silver alloys
  - Less costly than gold-copper alloys
  - Lower melting temperature ranges than gold-copper alloys
  - high vapor pressure, can be a problem for high temperature bakeout at low pressures
  - Not used in the klystron department

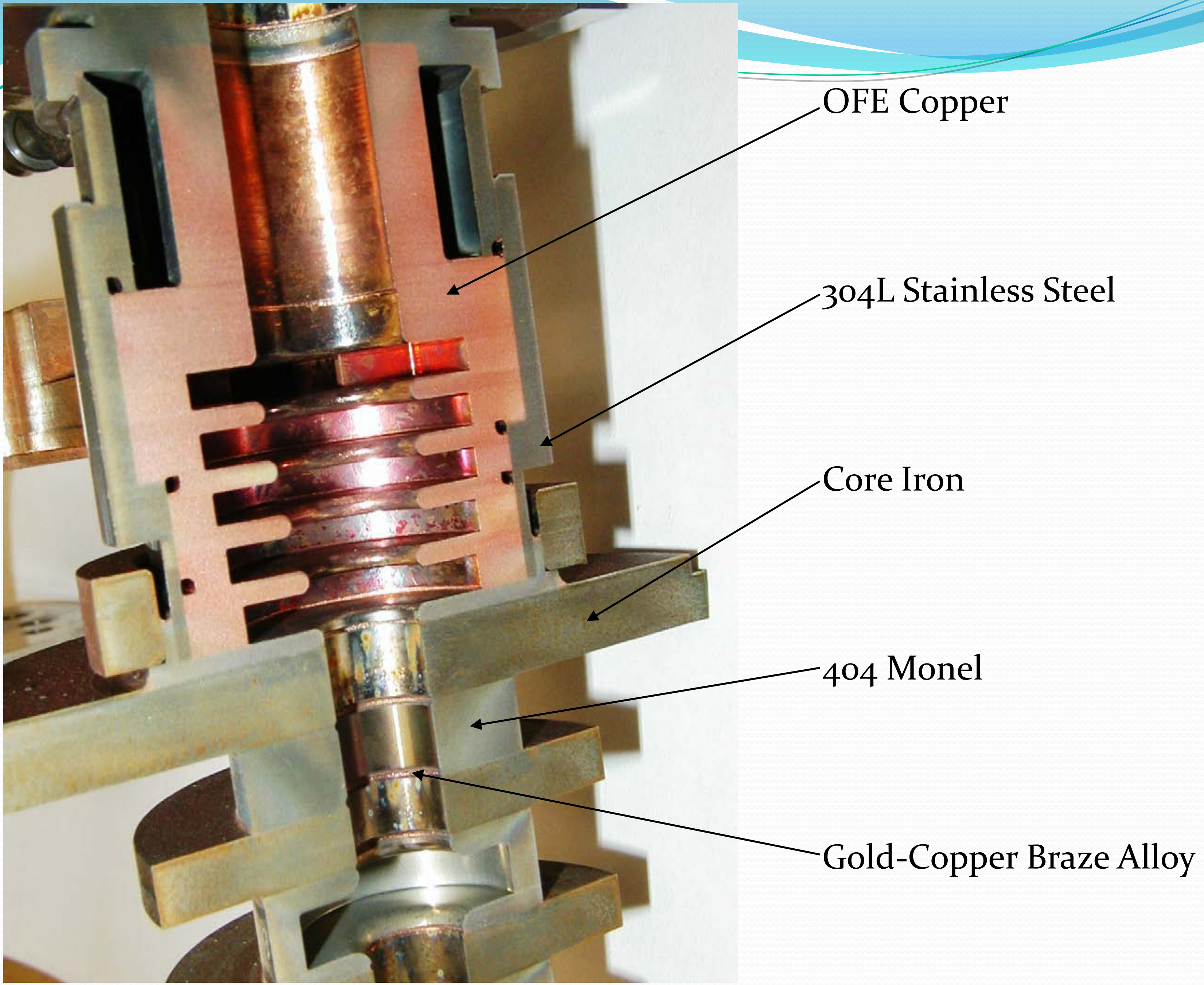
Non-Metallic Materials

- Aluminum Oxide, Al_2O_3
  - Hard, strong dielectric
  - Transparent (mostly) to microwaves (BeO, sapphire, or diamond)
  - Used for HV seals, insulators, and RF windows
- Titanium Nitride, TiN
  - Low secondary electron yield
  - Deposited by reactive sputtering or evaporation
  - Mutipactor and avalanche breakdown suppressor
  - Coat 10-15 Angstrom thick TiN for multipactor suppression on RF windows.

Material Selection

- Usually the desired function makes the material selection obvious
- Sometimes the tradeoffs are more subtle and an optimal selection of material must be arrived at through the use of a "figure of merit"


OFE Copper
Porous Tungsten
317L Stainless Steel
304L VAR Stainless Steel
304L Stainless Steel
Cupronickel
Moly-Manganese
Ceramic Metalization
Aluminum Oxide



OFE Copper
304L Stainless Steel
Core Iron
404 Monel
Gold-Copper Braze Alloy

Part Process Sequence

1. Raw material testing and certification
   - Materials are tested for standards conformance.
2. Part fabrication
   - Manufacture part using appropriate forming technique
3. Inspection
   - 100% inspection of critical components
4. Cleaning/plating
   - Parts chemically cleaned and etched to remove surface contamination and oxides

Part Process Sequence

5. Pre-braze assembly
   - Parts are assembled with appropriate braze alloy using gloves in a clean environment to prevent contamination
6. Braze
   - Assemblies are brazed in dry or wet H_2 atmosphere according to materials used
7. He leak check
   - Verify hermeticity of assembly before proceeding with further assembly
8. Post-braze machining as required

Simplified Cleaning Procedure

1. Degrease
   - Removes surface oils leftover from fabrication
2. Alkaline rise
   - Heavy duty detergent, removes more surface grime
3. Acid etch (one or more steps)
   - Removes surface oxide film and varying amounts of base metal
4. Rinses (several steps of water, solvent rinses)
   - Removes traces of etching solution and leaves surface chemically clean

Joining

- Furnace Brazing
  - Clean, vacuum compatible
  - Choice of atmosphere (wet H_2, dry H_2, vacuum) dependent upon materials to be brazed
  - Used for most tube subassemblies
- Diffusion bonding
  - Used where dimensional control is critical such as x-band accelerator structure assembly. Usually cells are stacked and bonded with 40 psi pressure at 1020 °C
- Welding
  - GTAW (Gas tungsten arc welding)
    - Used to join subassemblies (CuNi weld flange)
    - Used to tack weld parts for braze
  - RSW (Resistance spot welding)
    - Used to used for attaching contact tabs and other non-critical joints

Gun Processing

- Since the gun is both the hottest part of an operating klystron and the most sensitive to pressure it requires special processing:
  - Vacuum fire all gun components, typically at 800 ° C
  - Assemble gun stem and cathode and place in bell jar
  - Raise temperature of cathode and outgass gun components

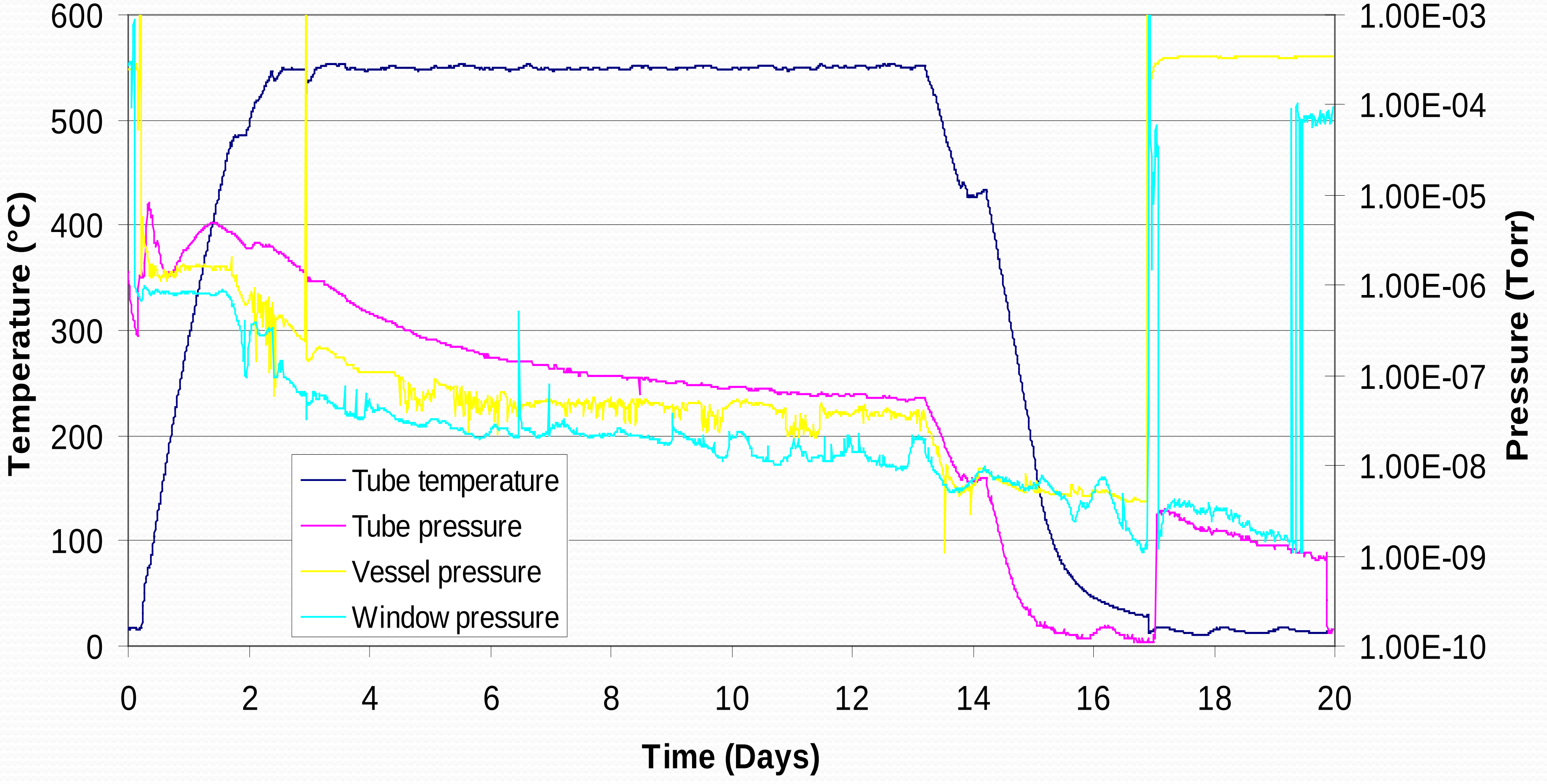
Tube Bakeout Schedule

1. Attach and start pumping tube
2. Close and pump down vessel, ramp filament 2 A/hr to 12 A after tube pressure < $5x10^{-6}$
3. Once tube pressure < $3x10^{-6}$ and vessel pressure < $5x10^{-5}$ start oven
4. Ramp oven 15° C/hr to 550° C as long as tube pressure < $3x10^{-5}$ and vessel pressure < $5x10^{-5}$
5. Ramp filament 1 A/hr to 17 A as long as tube pressure < $3x10^{-5}$
6. Bake until pressure stabilizes
7. Cool oven 15° C/hr to 430 ° C and wait 6 hours

Tube Bakeout Schedule

8. Raise filament to 18 A providing tube pressure $< 5 \times 10^{-8}$ hold until tube pressure $< 10^{-8}$ or stable
9. Cool at 15° C/hr until oven off, ramp filament down at 1 A/hr
10. RGA leak check
11. Remove vessel
12. Ramp filament 1 A/hr to 19 A hold until pressure drops
13. After 1 hour minimum at 19 A emission check at 1 kV
14. Cool
15. Pinch off

75XP3-4A Bakeout



Klystron Power Supplies, Modulators and Testing

- More Processing
  - Voltage processing
    - Burn off whiskers
    - Electro polish surfaces
  - Beam processing
    - More outgassing, beam interception
    - Cathode surface cleanup
      - Obtain even emission – amps/cm^2
  - RF processing
    - More outgassing, beam interception
    - Burn off whiskers in Cavities
- Test- Verification of performance
  - Power output, peak and average
  - Gain Curves
  - Efficiency
  - Cathode roll-off (Emission curve)
    - Best heater power setting
  - RF Breakup check
  - Bandwidth

Test Philosophy

- Pulsed Klystrons
  - Beam Process only
    - Narrow Pulse width
    - Low Rep Rate
    - Slowly raise beam voltage as function of time and pressure
    - Lower voltage, Raise Rep Rate and repeat
  - Add RF
    - Low Rep Rate, Narrow RF Pulse Width
      - Increase RF drive to saturate Klystron as function of time and gas pressure
      - Lower Drive, Raise Rep Rate and repeat
    - Lower RF Drive and Rep Rate, increase RF pulse width and repeat

Test Philosophy

- Widen Beam Pulse Width
  - Beam process only as before with voltage and Rep Rate
  - Add RF (starting at previous width) as before slowly process width RF Drive, Rep Rate and Pulse width
- Continue until full Beam and RF Pulse width with Highest Rep Rate and Klystron saturated
- Processing is a function of time and gas pressure
- CW Klystrons
  - Hi-Pot electron gun with cold cathode
  - Beam Process only
    - Slowly raise beam voltage as function of time and pressure within collector dissipation limit
  - Add RF
    - Increase RF drive to saturate Klystron as function of time and gas pressure

Klystron Protection

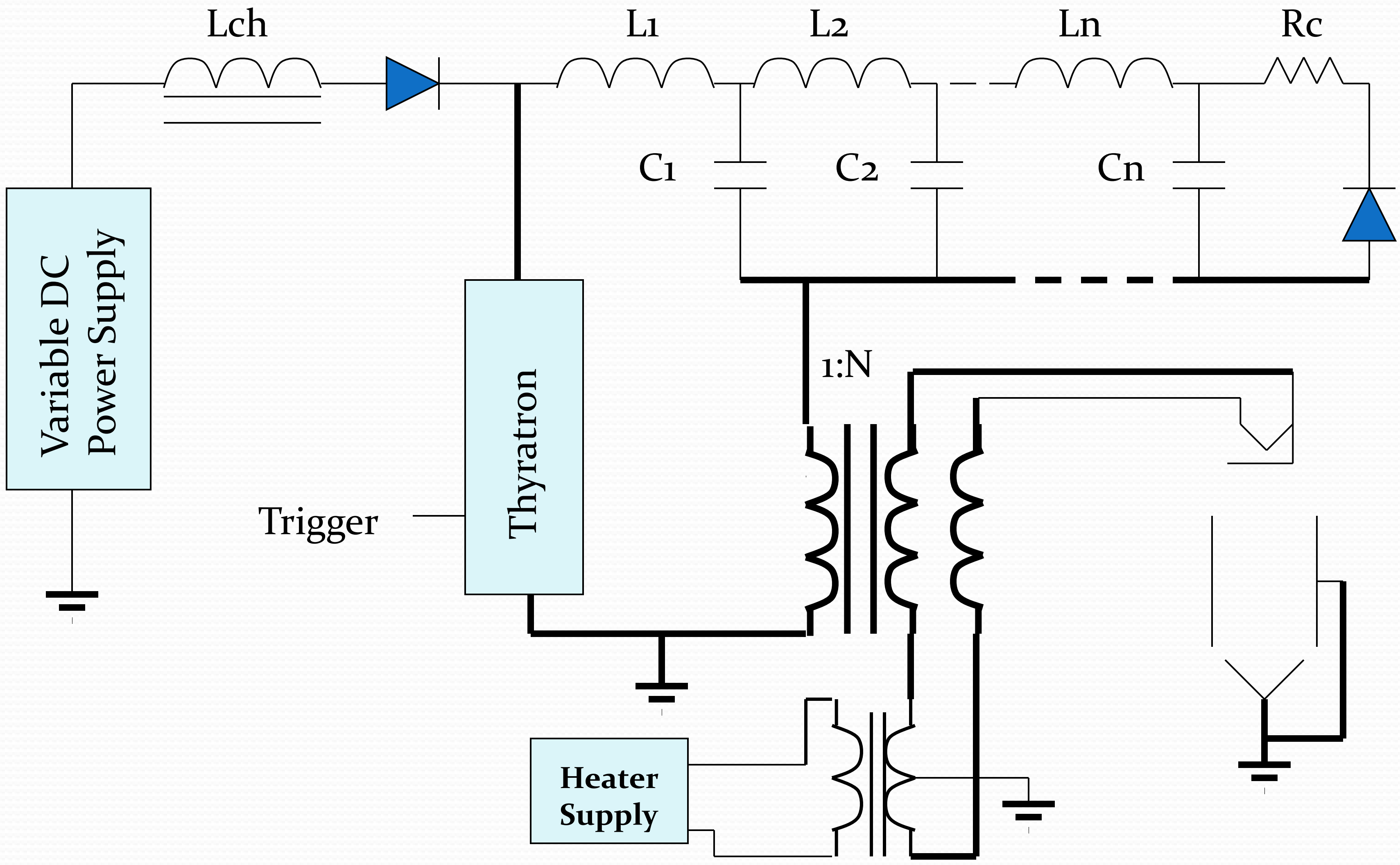
- Gun arcs
  - Limit peak current and peak energy
  - Sense arc and turn off pulse (next pulse)
- Beam interception
  - Sense current and turn off pulse (next pulse)
  - Sense with current, sense with temperature,
  - Sense with delta temperature
- Gas Pressure
  - Gun or collector pressure- turn off beam
  - Output or window pressure- turn off RF
- Pulse klystron can stop pulse for gun arcs, etc.

- Basic Interlocks
  - Klystron Water or air flow
  - Low heater current
  - Modulator fault
  - Low Tank oil
  - Magnet current (over/ under)
  - Magnet Over temp
  - Magnet water
    - Turn off beam, add time delay before magnet off
  - All these interlocks turn off beam

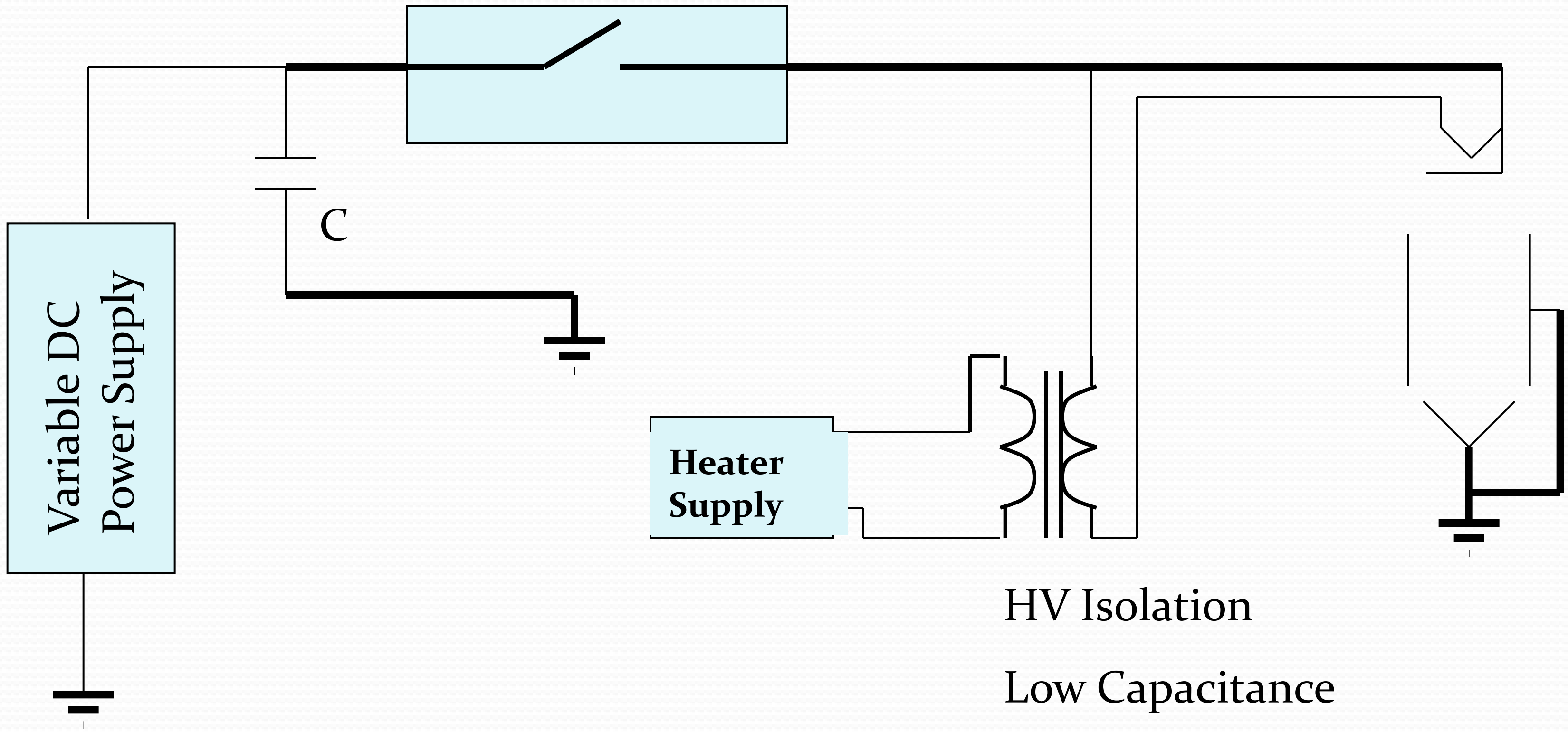
Modulators

- Most high peak power klystrons operate on Line-Type Modulators
  - SLAC has close to 250 Line-Type Modulators on the LINAC
- Advantages
  - Relatively simple electronics
  - Natural Protection with current limiting to 2 times operating
- Disadvantages
  - Fixed Pulse width
  - Matched impedance with klystron
  - Pulse shape load dependent
  - Needs to be tuned for flat pulse
  - Limited Rep Rate

Basic Line Type Modulator



- Direct Switch



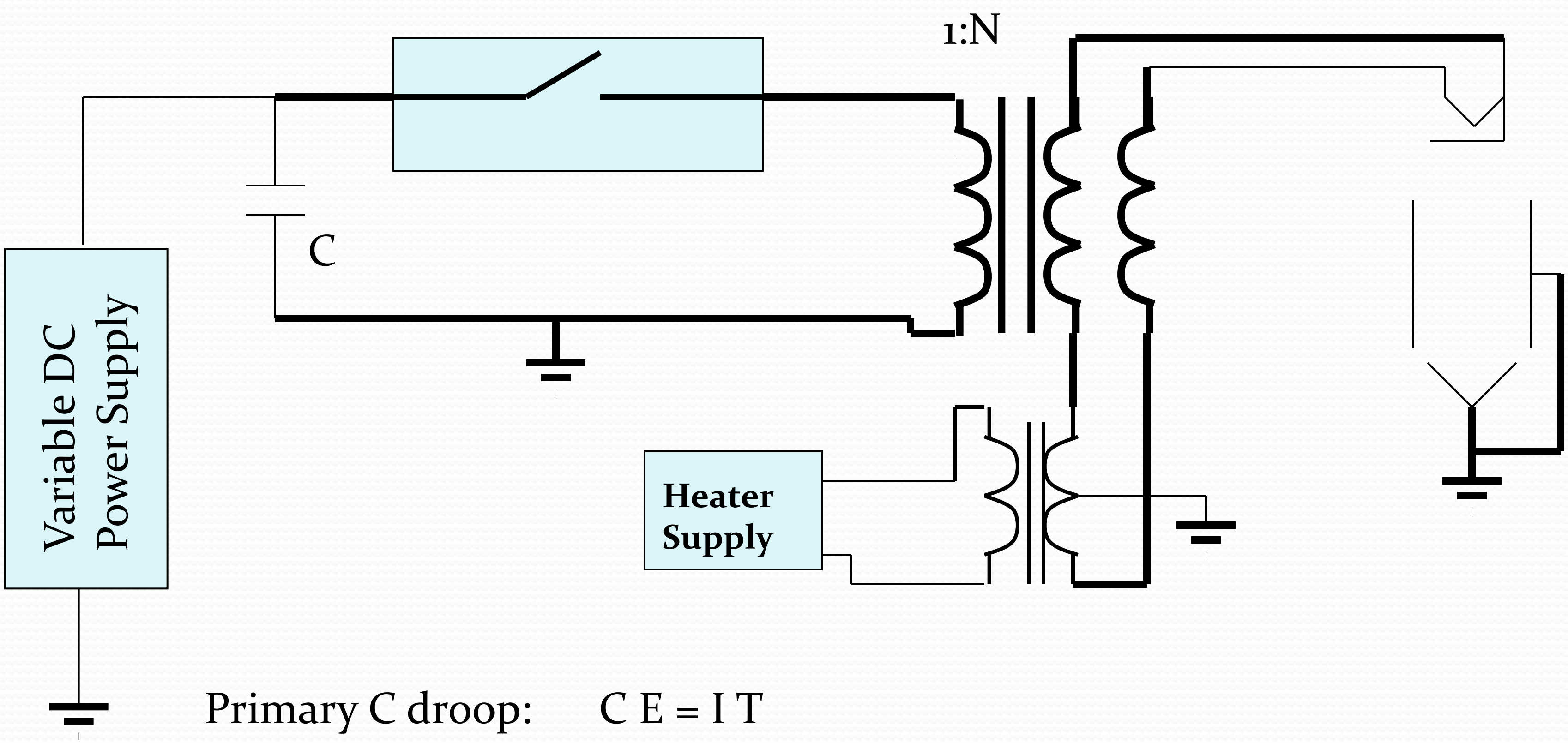
HV Isolation

Low Capacitance

Pulse droop: C E = I T C is filter cap, T is pulse width, I is beam current

Rise Time: C E = I T C is load stray cap, T is rise time, E is beam voltage, I is peak current

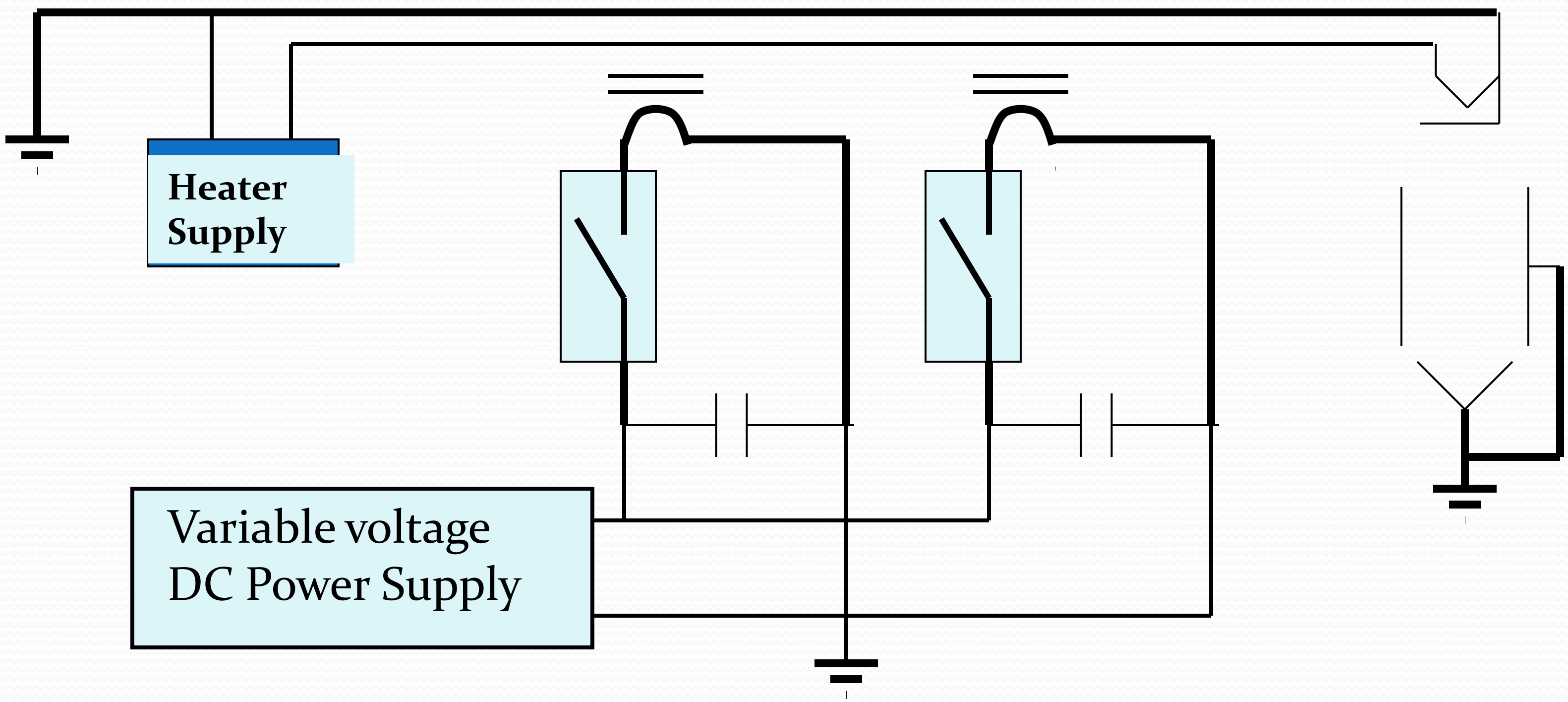
- Hybrid Modulator



Primary C droop: $C\,E = I\,T$

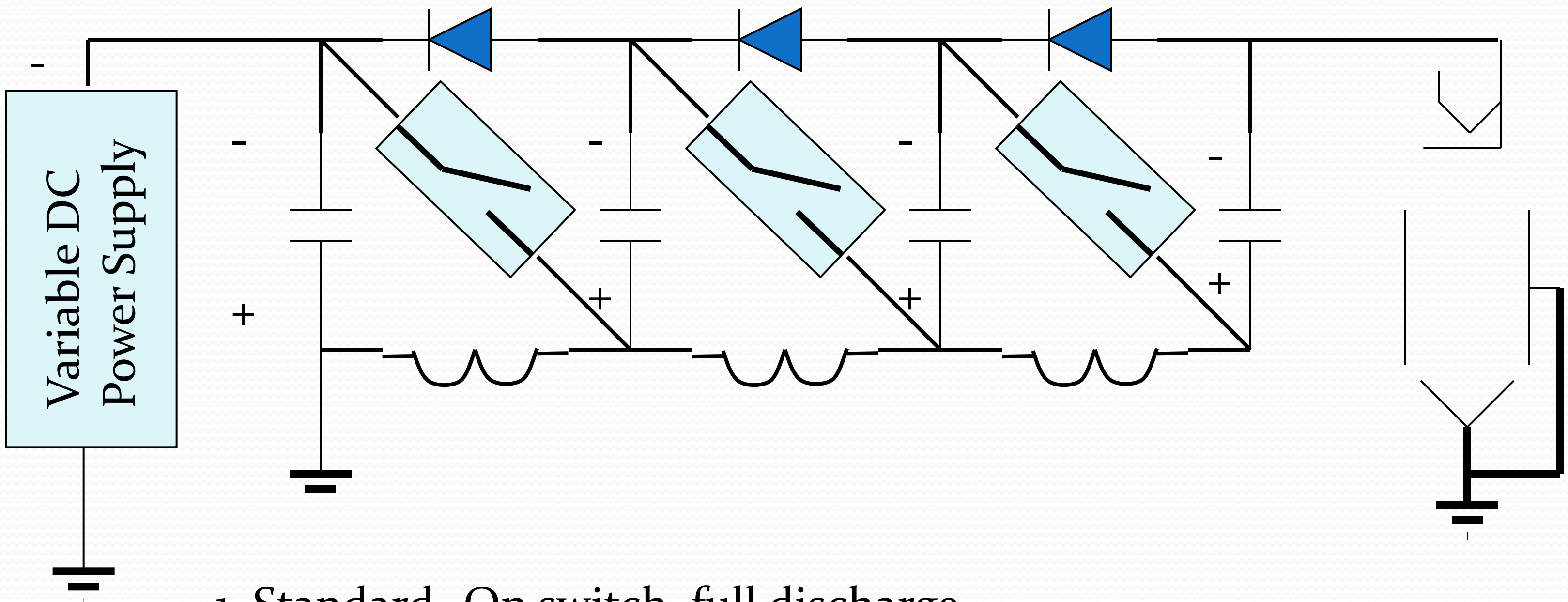
Rise time of pulse is mainly a function of Pulse Transformer

- Induction adder
  - Stacked cores with a common secondary



1. Usually single turn primary and secondary
2. Can use multi-turn secondary

- Marx Modulator
  - Charge in parallel, discharge in series



1. Standard- On switch, full discharge

2. On switch with PFN's in place of capacitor

3. ON/ OFF Switch with Partial discharge of capacitor

Thank You For Your Attention!