RF Power Generation With Klystrons

amongst other things

Dr. C Lingwood

Includes slides by Professor R.G. Carter and A Dexter

Engineering Department, Lancaster University, U.K.

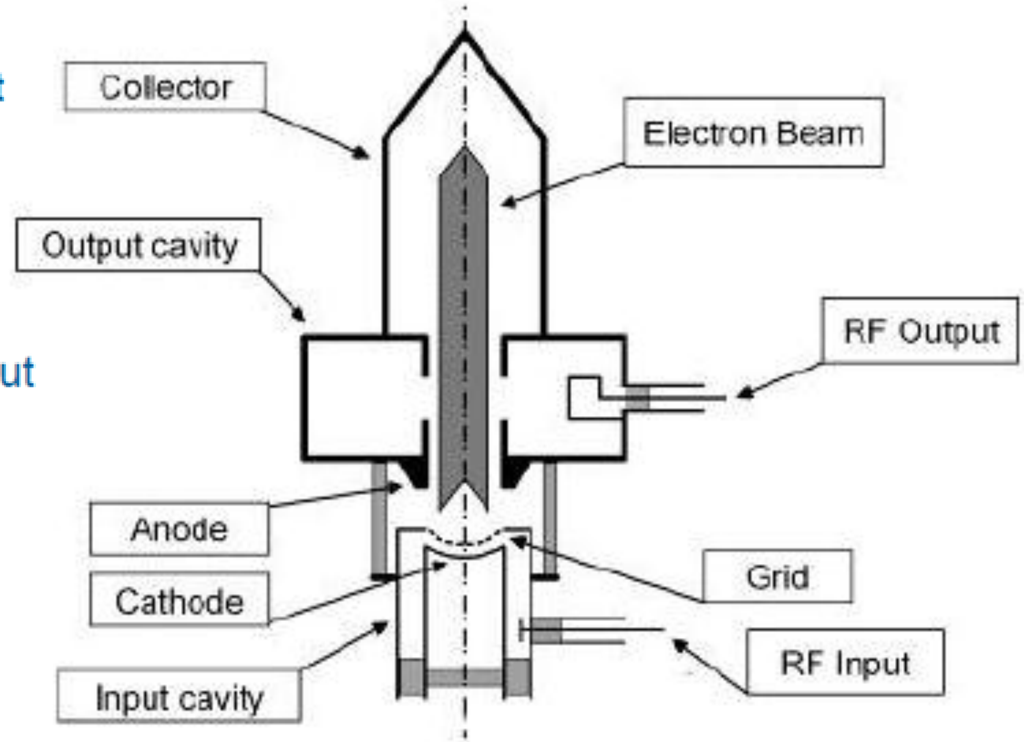
and

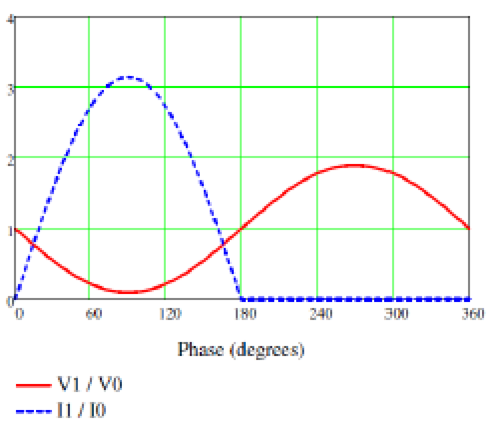
The Cockcroft Institute of Accelerator Science and Technology

- Basic Klystron Principals
- Existing technology
- Underrating
- Modulation anodes
- Other options
  - IOTS
  - Magnetrons

IOT

- Electron flow axial
  - Requires axial magnetic field to prevent beam spreading
- Anode voltage is constant
  - Electron velocity is high
- Bunched beam induces current in output cavity
- Separate electron collector
  - Large collection area
- Increased isolation between input and output

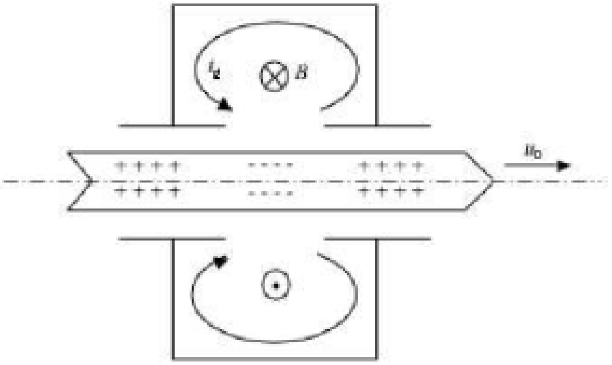


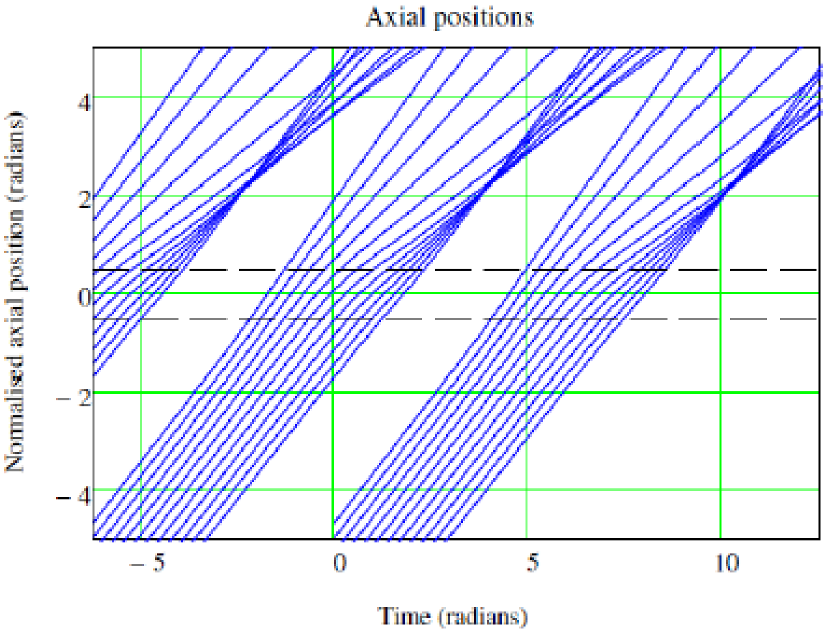


IOT Output gap

- Beam current class AB or B like a tetrode
- At resonance electric field in the gap is maximum retarding when bunch is in the centre of the gap
- Effective gap voltage reduced by transit time effects
- Effective gap voltage less than ~$0.9V_0$ to allow electrons to pass to the collector
- Theoretical efficiency ~ 70%

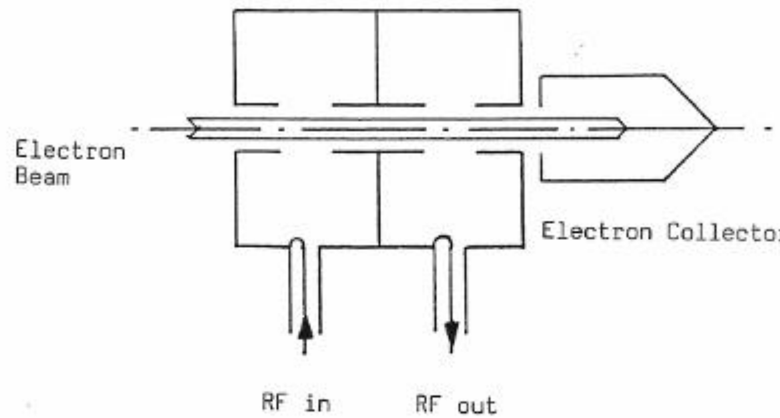
$$P_2 = \frac{1}{2} I_2 V_{g,eff} \approx \frac{\pi}{4} 0.9 I_0 V_0$$

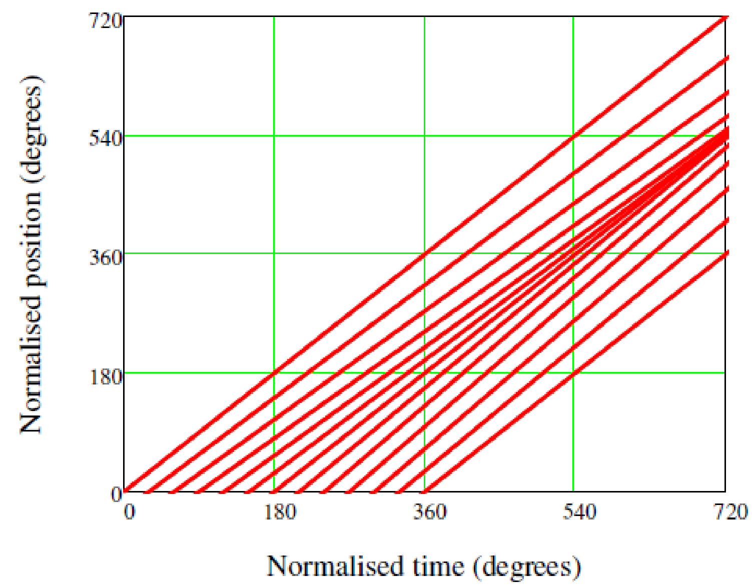




Velocity modulation

- An un-modulated electron beam passes through a cavity resonator with RF input
- Electrons accelerated or retarded according to the phase of the gap voltage: Beam is velocity modulated:
- As the beam drifts downstream bunches of electrons are formed as shown in the Applegate diagram
- An output cavity placed downstream extracts RF power just as in an IOT
- This is a simple 2-cavity klystron
- Conduction angle = 180° (Class B)



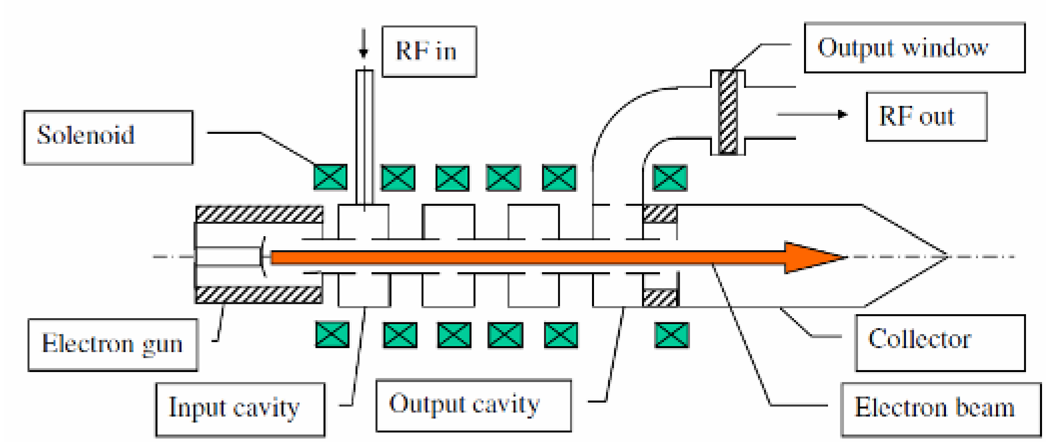


Multi-cavity klystron

- Additional cavities are used to increase gain, efficiency and bandwith
- Bunches are formed by the first (N-1) cavities
- Power is extracted by the N^{th} cavity
- Electron gun is a space-charge limited diode with perveance given by

$$K = \frac{I_0}{V_0^{\frac{3}{2}}}$$

- $K \times 10^6$ is typically 0.5 - 2.0
- Beam is confined by an axial magnetic field



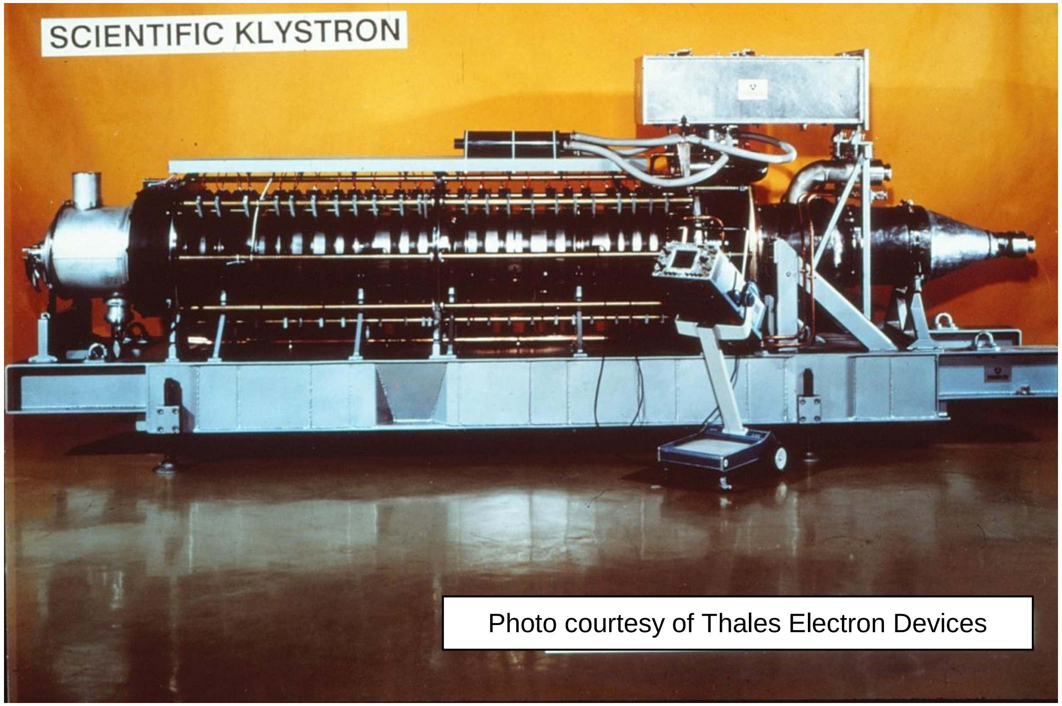


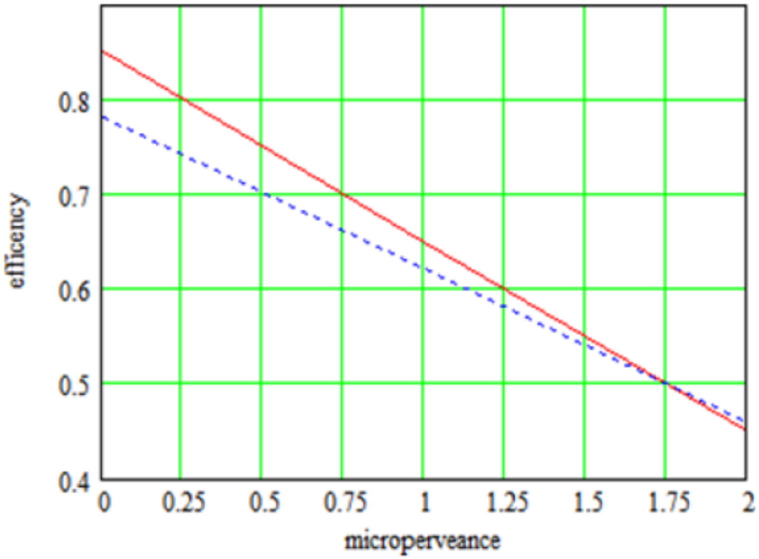
Photo courtesy of Thales Electron Devices

Efficiency and Perveance

- Second harmonic cavity used to increase bunching
- Maximum possible efficiency with second harmonic cavity is approximately

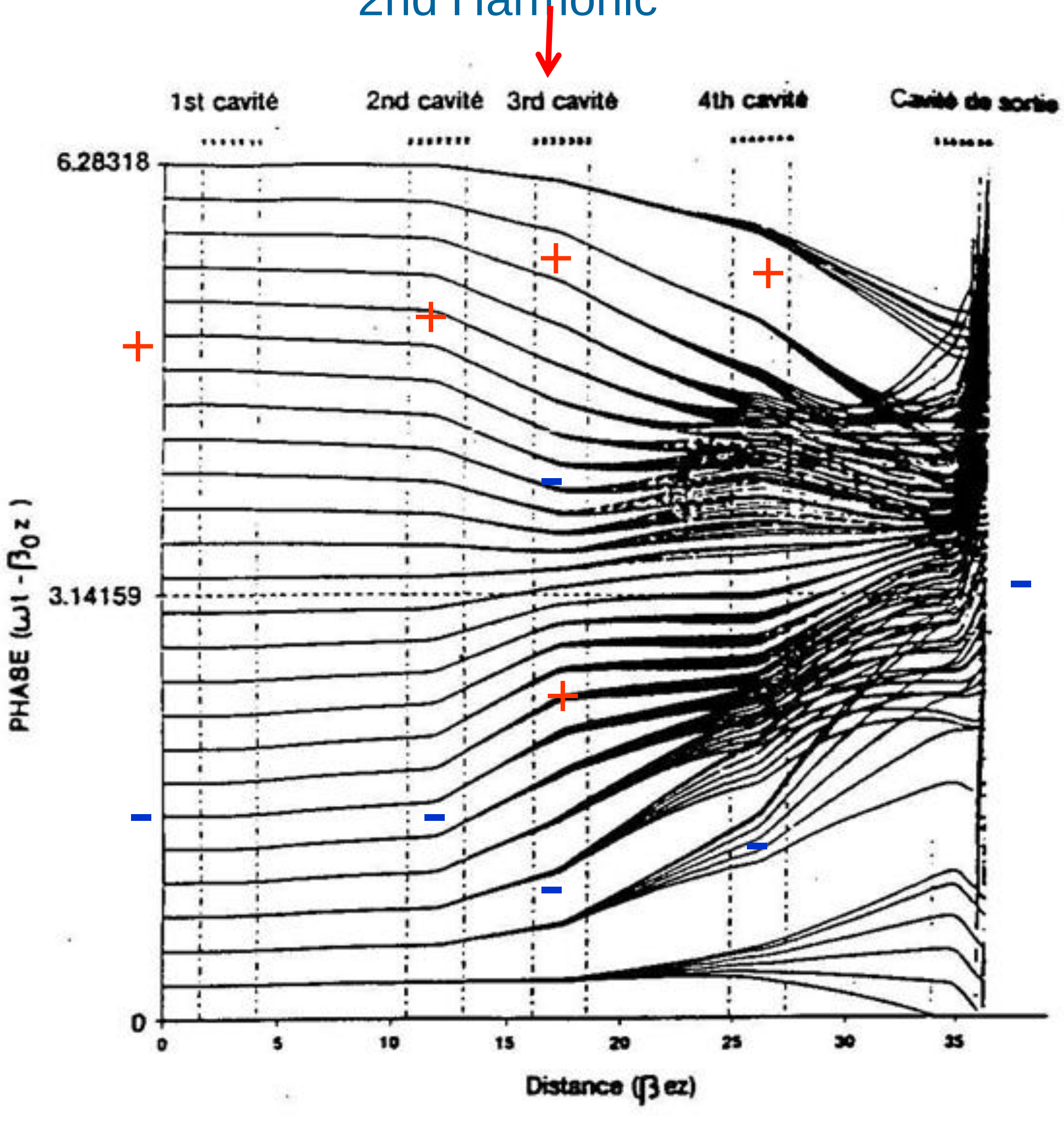
$$\eta_e = 0.85 - 0.2 \times 10^{-6} K$$

$$\eta = 0.78 - 0.16 \mu K$$



Typical Applegate diagram

2nd Harmonic



- Distance and time axes exchanged
- Average beam velocity subtracted
- Intermediate cavities detuned to maximise bunching
- Cavity 3 is a second harmonic cavity
- Space-charge repulsion in last drift section limits bunching
- Electrons enter output gap with energy ~ V_0

Image courtesy of Thales Electron Devices

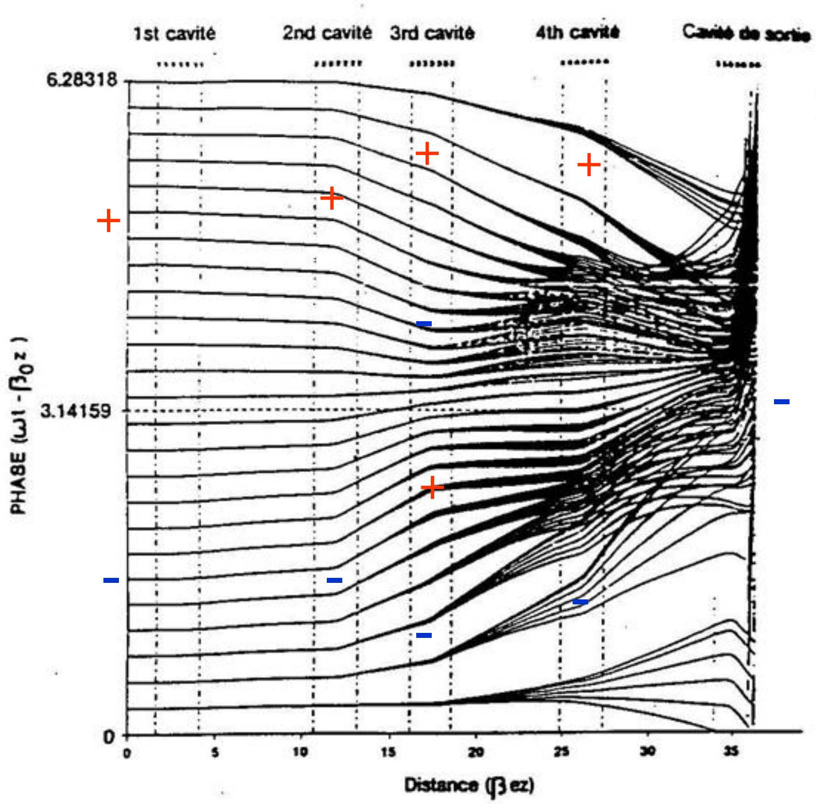
2^{nd} Harmonic Cavity

- 70s Klystron (805MHz 1.25MW) with a detunable second harmonic cavity
  - With 2^{nd} Harmonic **57.4%**
  - Without 2^{nd} Harmonic **52.9%**

HIGH PERFORMANCE KLYSTRONS FOR ACCELERATOR APPLICATIONS, By Paul J. Tallerico

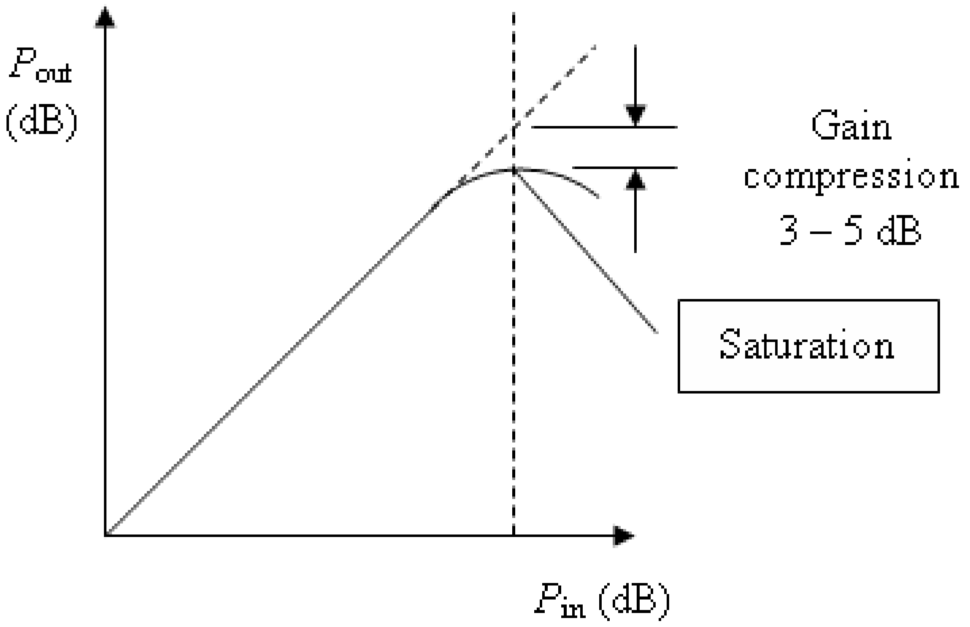
Why not 100% Efficient

- The simple answer is
  - Imperfect bunching
  - Can't remove all energy from beam. Electrons must have residual energy > $0.1V_0$ to drift clear of the output gap and avoid reflection

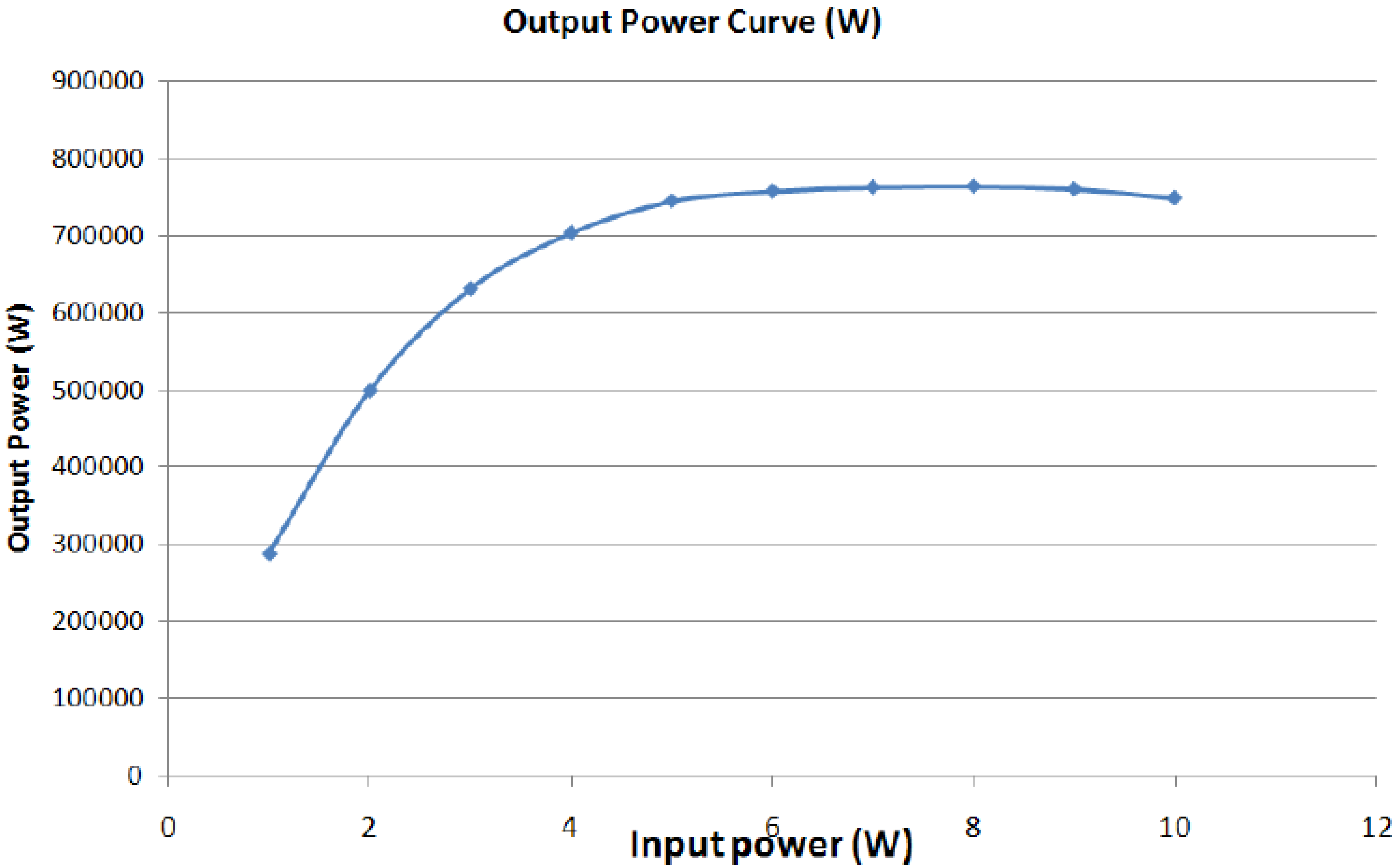


Saturation

- Non-linear effects limit the power at high drive levels and the output power <u>saturates</u>
- Point of highest efficiency



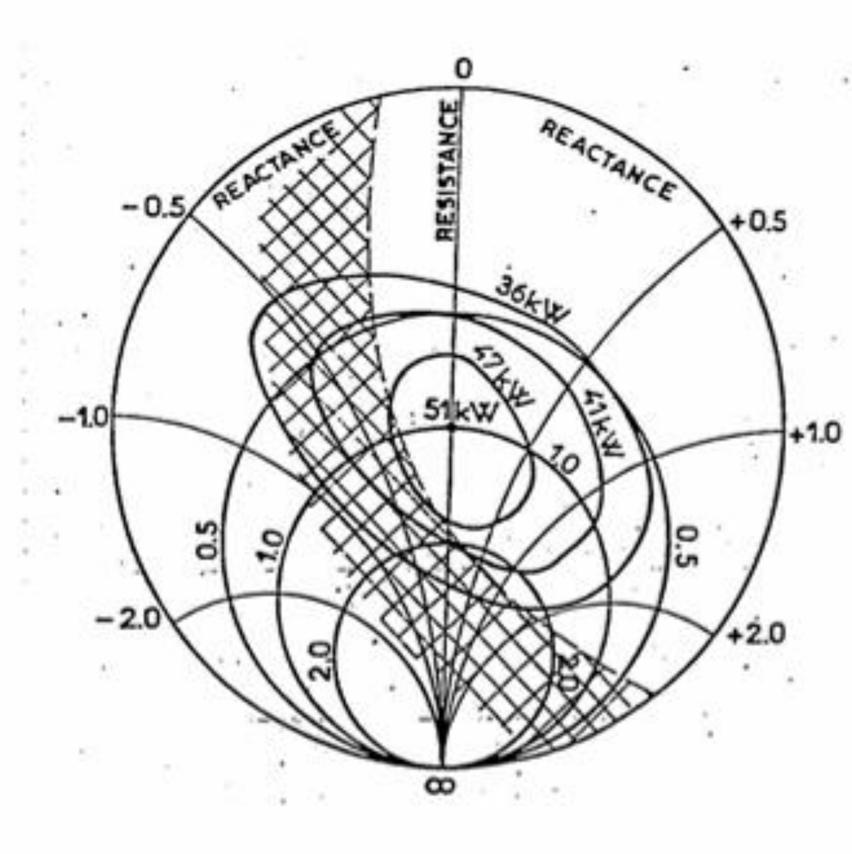
Transfer Curve



Linear region can be far from saturation

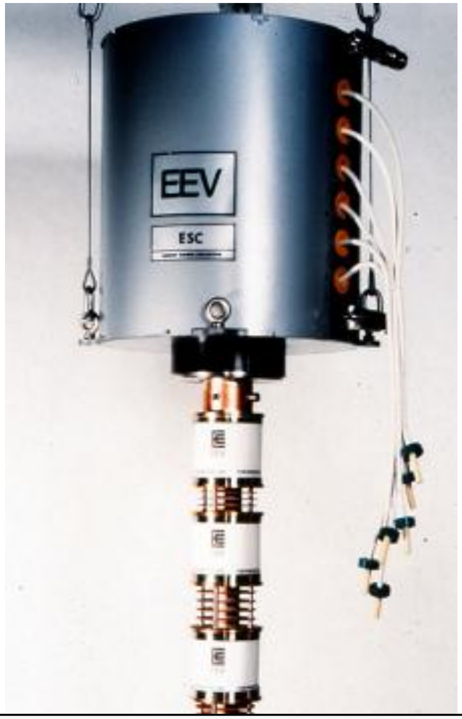
Effect of output match

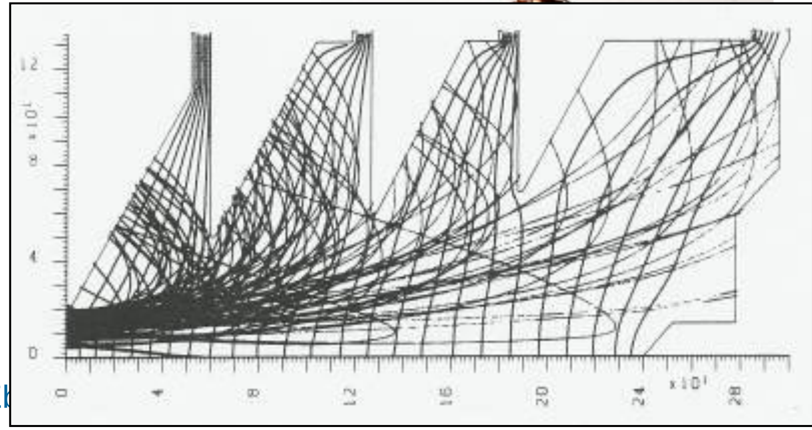
- Reflected power changes the amplitude and/or phase of the output gap voltage
- Rieke diagram shows output power as a function of match at the output flange
- Shaded region forbidden because of voltage breakdown and/or electron reflection
- Output mismatch can also cause:
  - Output window failure
  - Output waveguide arcs
- A Circulator is needed to protect against reflected power



Clever things

- Depressed collector
  - Decelerate electrons to regain energy
  - Complex
  - More HV (hold sections at different voltages)
  - Better optimised klystron, wider velocity spread
- MBK
  - Multiple beam klystron
  - Complex
  - Many eggs in one basket
  - No advantage at ESS power level
    - Need around 10MW





ESS Specification

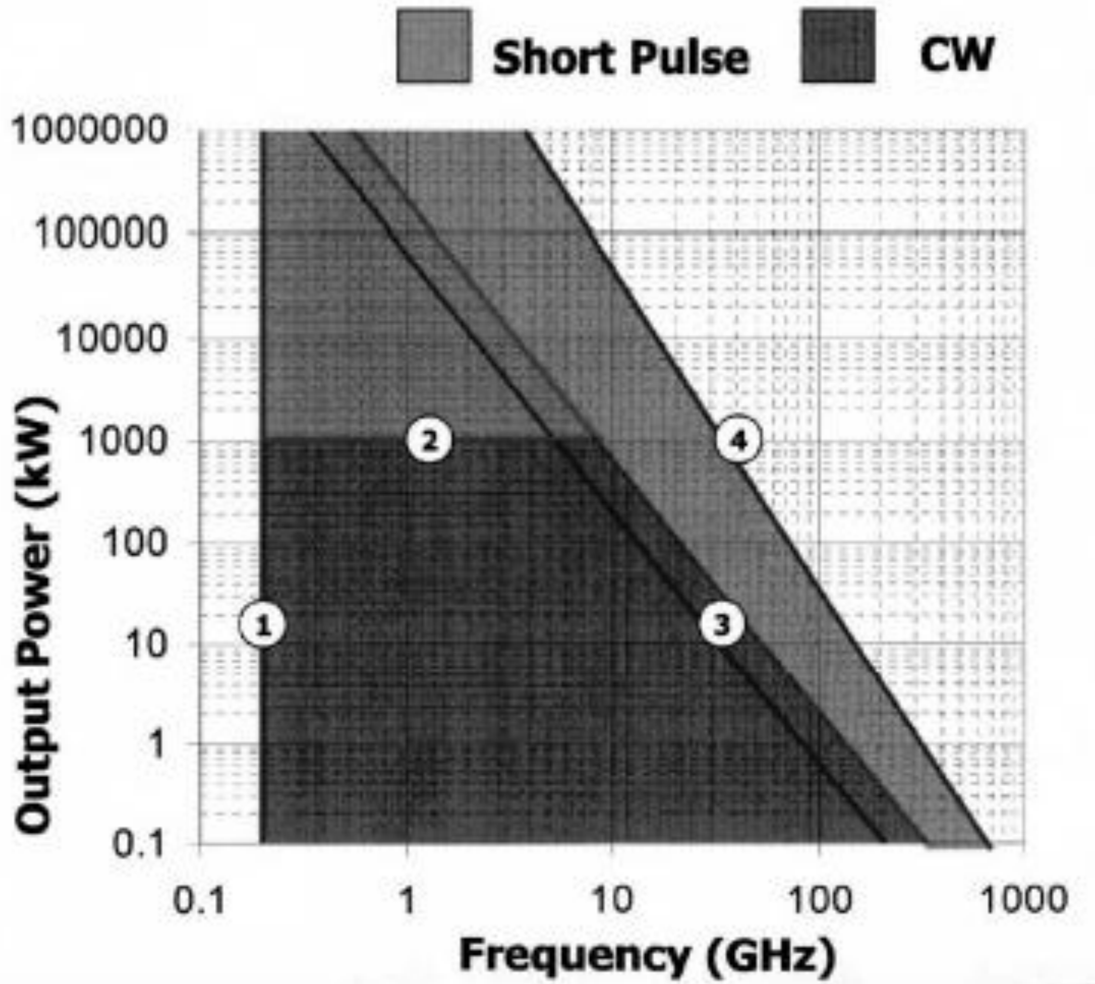
Frequency	704.4MHz
Peak Output Power	1.3MW
Beam Voltage	106kV
Beam Current	18.9A
Micro-Perveance	0.548
Gain	48dB
Duty Factor	4.9%
RF Pulse Width	3.5ms
Repetition Rate	14Hz
Efficiency	65%
Bandwidth (-1dB)	4Mhz

Klystron Technology Limitations

- Plot showing the PF spectrum for klystrons, both short pulse and CW

- Approximate limitations

(1) Size (CW & Pulsed)
(2) Window (CW)
(3) O/P Cavity Power Density / Cyclical Fatigue (CW)
(4) RF Breakdown (Pulsed)



Klystrons: State of the art

CW Klystrons

Frequency	352	700	3700	MHz
Beam voltage	100	92	60	kV
Beam current	19	17	20	A
RF output power	1.3	1.0	0.5	MW
Efficiency	67	65	43	%

Pulsed Klystrons

Frequency	2.87	3.0	11.4	GHz
Beam voltage	475	590	506	kV
Beam current	620	610	296	A
RF output power	150	150	75	MW
Efficiency	51	42	50	%

Note: Breakdown voltage is higher for short pulses than for DC

Existing Klystrons LEDA (e2v K3510L)

	Design	Measured
Frequency	700MHz	
Cavities	6	
2nd Harmonic	Yes	
Pulse Length	CW	CW
Duty	CW	CW
Output Power	1MW	1.01MW
Voltage	95kV	95kV
Current	16.5A	16.3A
Efficiency	65%	65.20%
Gain	40dB	40.8dB

DESIGN OF A HIGH EFFICIENCY 1 MW CW KLYSTRON AT 700 MHz FOR LOW ENERGY DEMONSTRATOR ACCELERATOR, D. Bowler, LANL

Existing Klystrons SACLAY (CPI VPK 7952B)

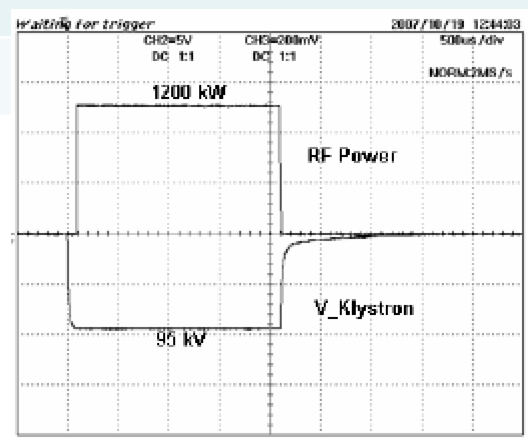
	Design	Measured
Frequency	704MHz	
Cavities	6	
2nd Harmonic	Yes	
Pulse Length	CW	CW
Duty	CW	
Output Power	1MW	1.03MW
Voltage	95kV	92kV
Current	17A	17.1
Perveance	0.55	0.6
Efficiency	65%	66.2
Gain	40dB	48.4dB

NEW 1MW 704MHZ RF TEST STAND AT CEA-SACLAY

, S. Chel,

Existing Klystrons SACLAY (CPI VPK 7952C)

	Design	Measured
Frequency	704MHz	
Cavities	6	
2^{nd} Harmonic	Yes	
Pulse Length	2.2ms	2.2ms
Duty	11%	
Output Power	1MW	
Voltage	95kV	95kV
Current	17A	19A
Efficiency	65%	
Gain	50dB	



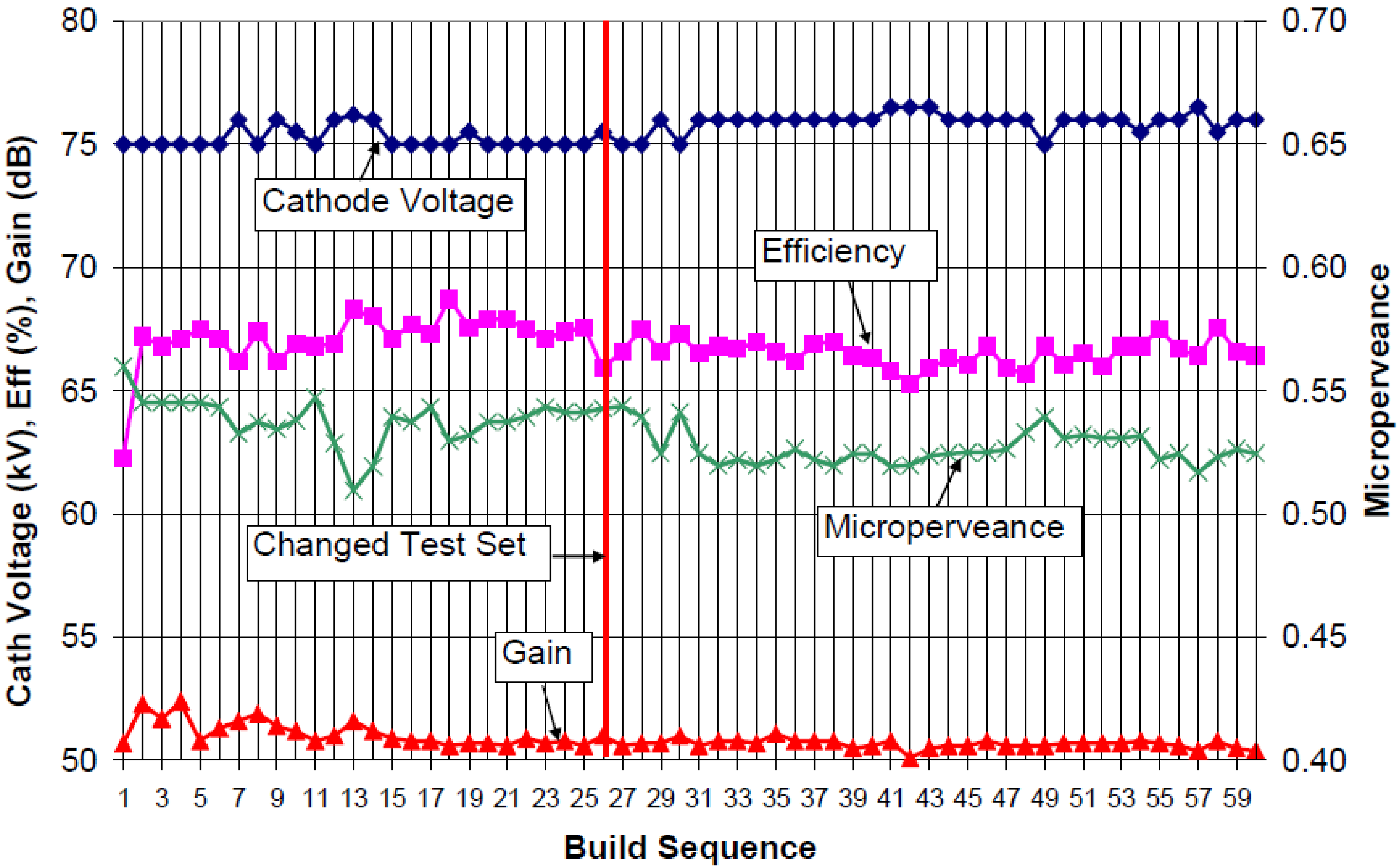
NEW 1MW 704MHZ RF TEST STAND AT CEA-SACLAY
, S. Chel,

Existing Klystrons SNS (VKP-8291A)

	Design	Measured (~60 units)
Frequency	805MHz	
Cavities	6	
2nd Harmonic	Yes	
Pulse Length	1.5ms	
Duty	9%	
Output Power	550kW	
Voltage	75kV	75-77kV
Current	11.2A	
Perveance	0.54	0.51-0.56
Efficiency	67%	63%-68%
Gain	51dB	50-53dB

Status of the 805-MHz Pulsed Klystrons or the Spallation Neutron Source, S. Lenci

Yields



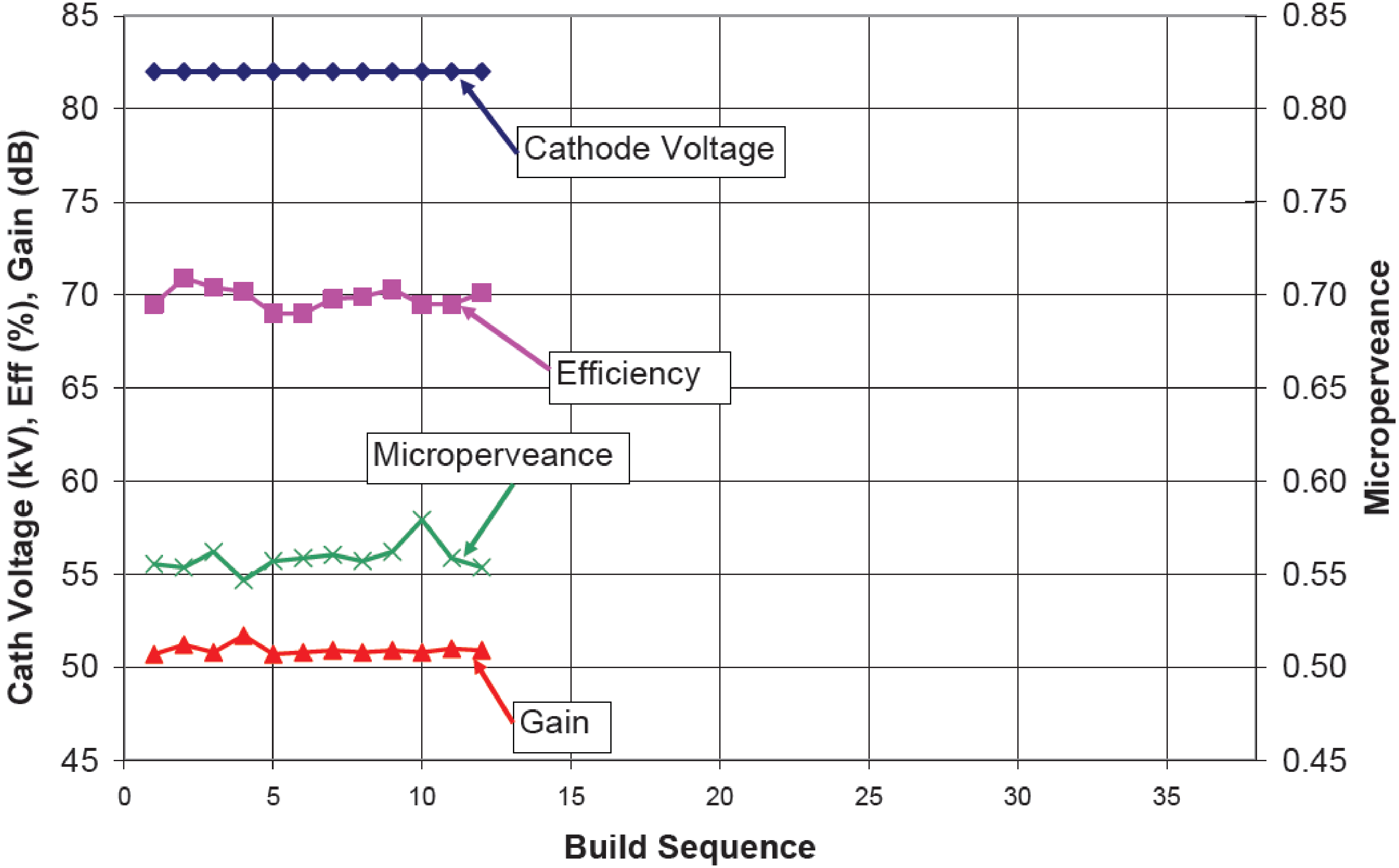
Status of the 805-MHz Pulsed Klystrons for the Spallation Neutron Source, S. Lenci

Existing Klystrons SNS (VKP-8291B)

	Design	Measured (~13 units)
Frequency	805MHz	
Cavities	6	
2^{nd} Harmonic	Yes	
Pulse Length	1.5ms	
Duty	9%	
Output Power	**700kW**	
Voltage	85kV	82kV
Current	13.7A	
Perveance	0.55	0.55-0.57
Efficiency	65%	68-72%
Gain	50dB	51-52dB

- **Status of the 805-MHz Pulsed Klystrons**
- **for the Spallation Neutron Source, S. Lenci**

Incremental spec change



Incremental design changes allow the manufacturers to “get their eye in”

Status of the 805-MHz Pulsed Klystrons or the Spallation Neutron Source, S. Lenci

Pulse length

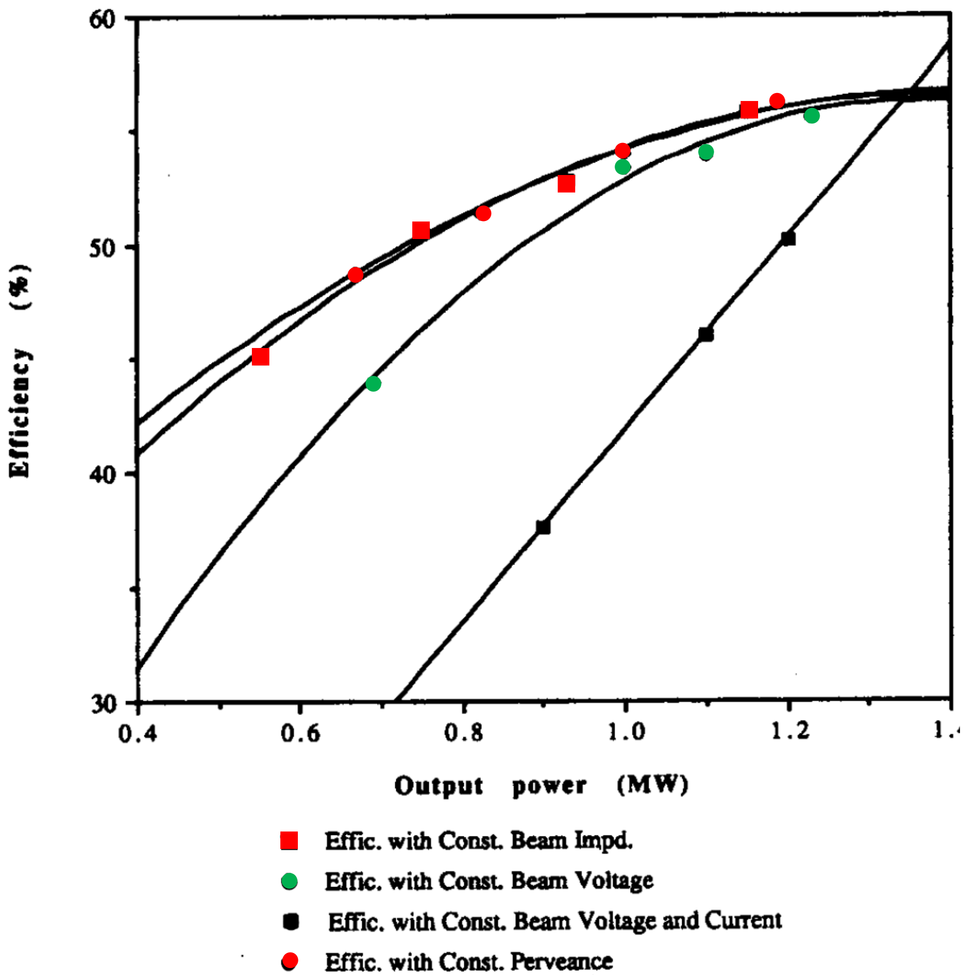
- Very long pulse
  - In the literature 1.5ms is often described as long pulse.
- The klystron is probably OK
  - Effectively CW (from the point of view of breakdown)
- The modulator is challenging (although...)
  - This needs to be thought of (to some extent) as a separate unit.
  - Klystron manufactures assume they will get a suitably long pulse with a sufficiently flat top.
  - What if you get an insufficiently flat top (or too short a pulse)
    - Change in electron velocity (not relativistic enough to ignore)
    - Change in output power

Efficiency

- 65% efficiency *at saturation* does not look overly optimistic
- Sadly you can’t operate here.
- For 950kW to cavity you need 1.2MW at klystron output
  - with 20% head room for LLRF and 95% klystron to cavity
- Lets say you operate at 1.2MW saturated power and 950kW nominal klystron output power
  - Attainable klystron efficiency 51.5%
- Total RF efficiency ~23%

- Not only that but you don’t want ~900kW for all cavities...

Underrate the tube



- Turn down the input signal amplitude.
  - Beam power remains constant
- The best way to reduce power is
  - Constant perveance (lower beam voltage) ●
  - Constant impedance (lower beam voltage and current) ■
  - Different gun voltage for each tube (adjustable modulators?)
- Lower beam current ●

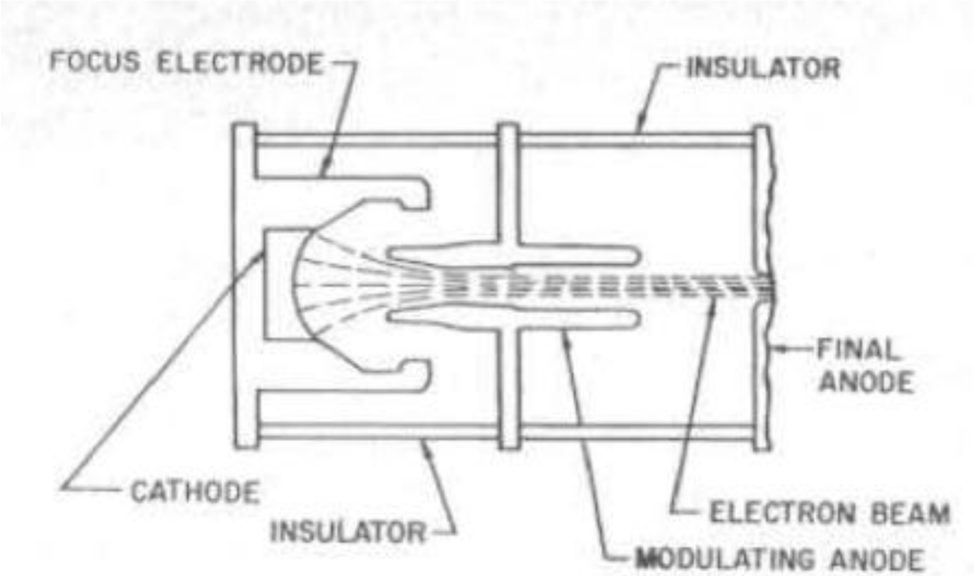
TABLE I
TH 2138 OPERATING CHARACTERISTICS

Frequency	850 MHz
Peak output power, min.	1.25 MW
Average output power, min.	75 kW
Cathode voltage	85 kV
Cathode current	28 A
Gain, min.	48 dB
Efficiency, min.	52 %
Pulse duration	2.0 msec
Duty factor	6.0 %
-1 dB instantaneous bandwidth	4 MHz

Modulating Anode

- A secondary anode between the cathode and primary anode.
- Higher risk of gun arcing
- More complex gun design
- More ceramic joints

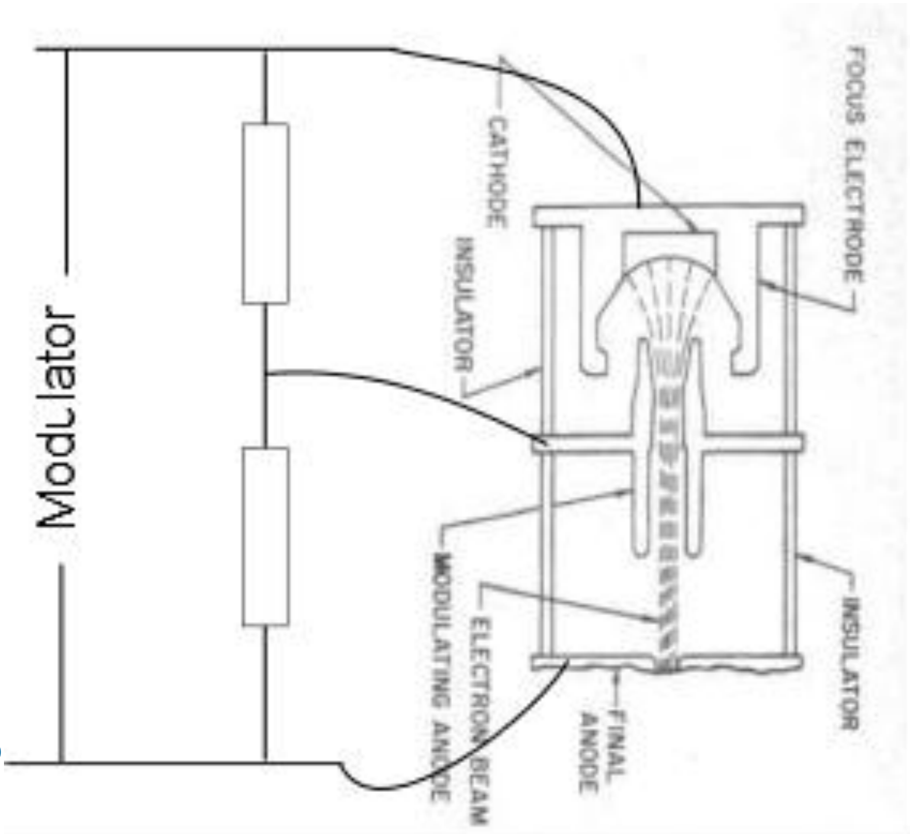
- 3 interesting functions
  - Some may be better performed by a grid/focus electrode but...



High power linear-beam tubes, Staprans

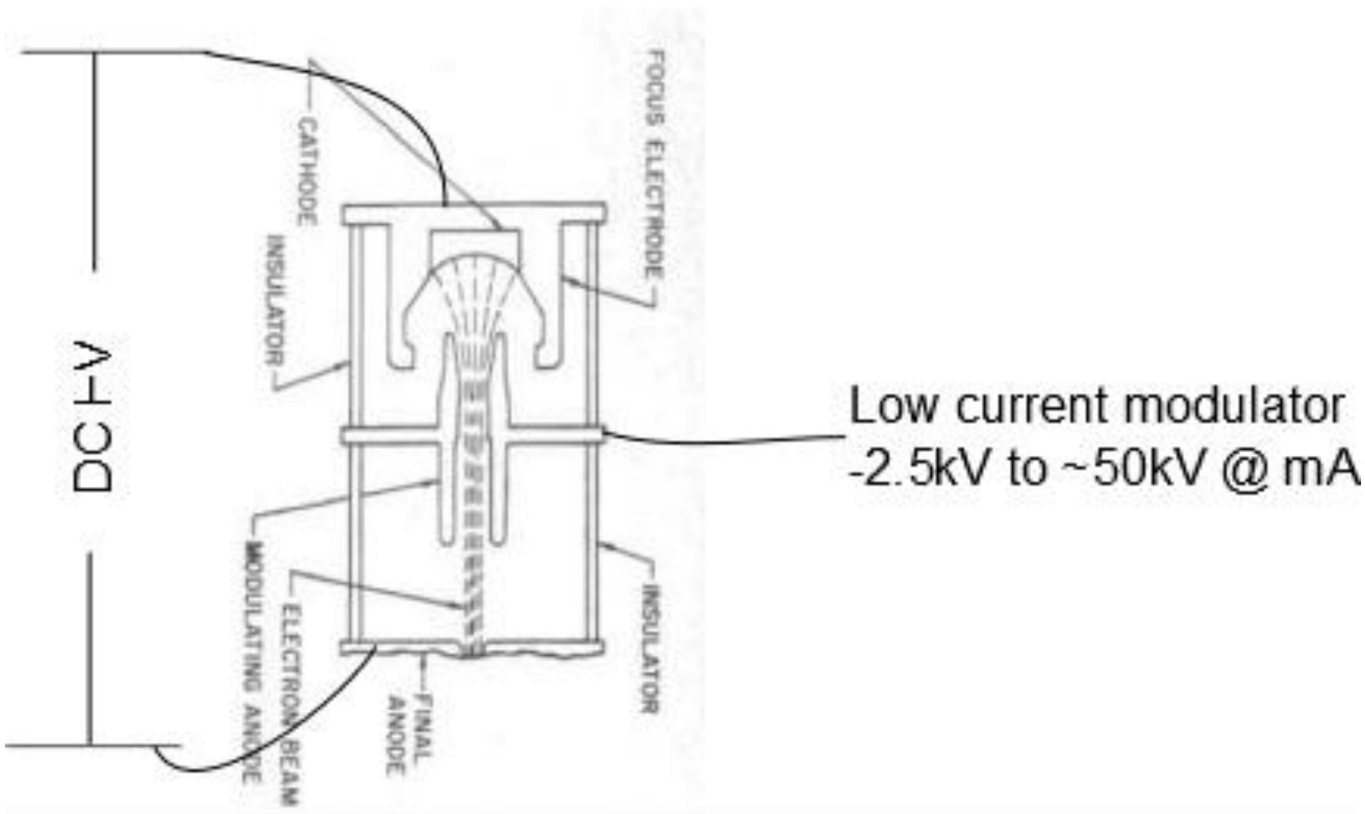
1. Reduce current

- Allows you to run at a lower output power
- Little power dissipated in voltage divider
- Needs mechanical intervention to alter the working point (during conditioning for instance)
- Tried & tested
- Better to just lower beam voltage



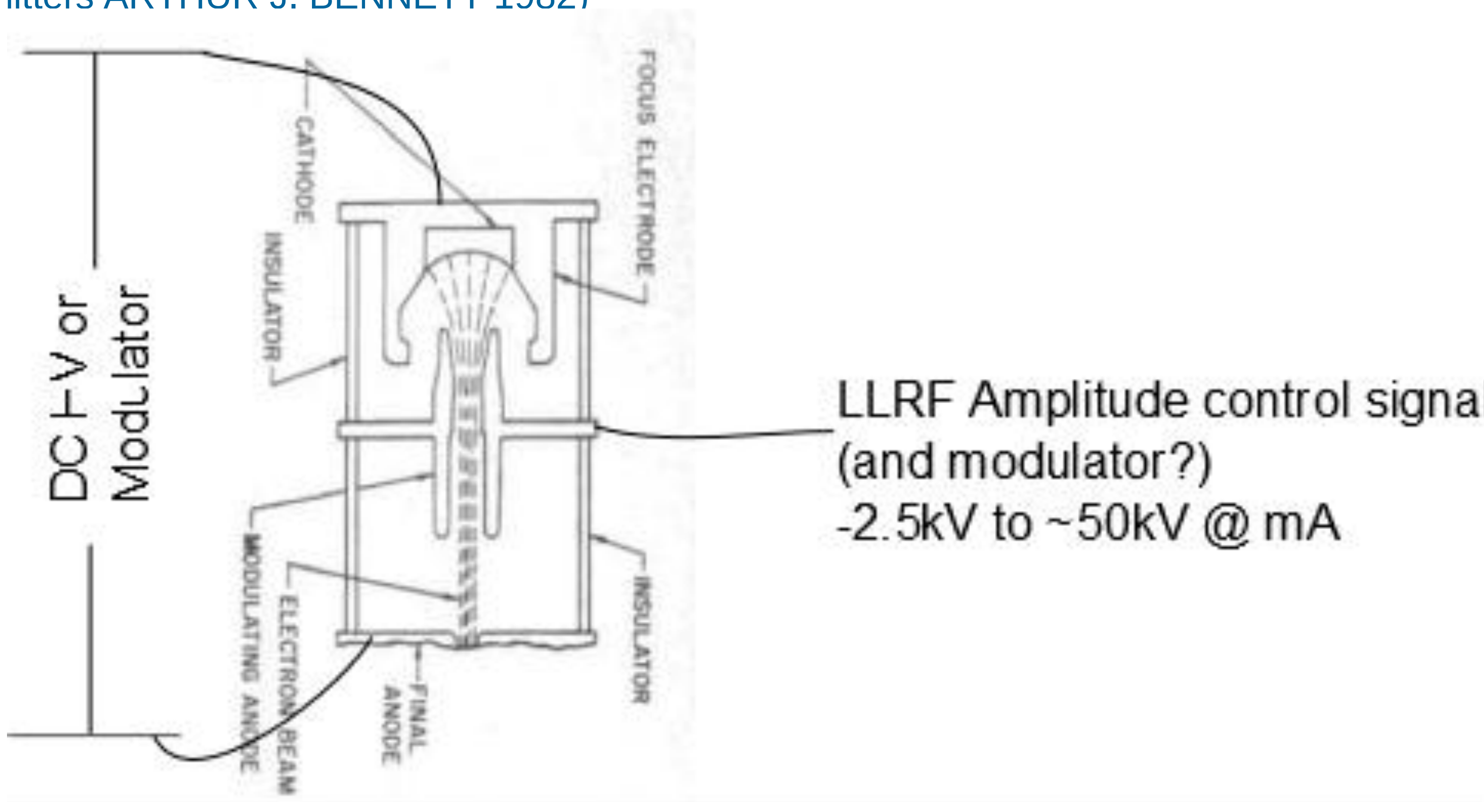
2. Pulse gun

- Avoid high current modulator
- Perhaps use same DC HV for multiple klystrons (easier/harder?)
- Potential for active control depending on your low current modulator.
- Not too brave



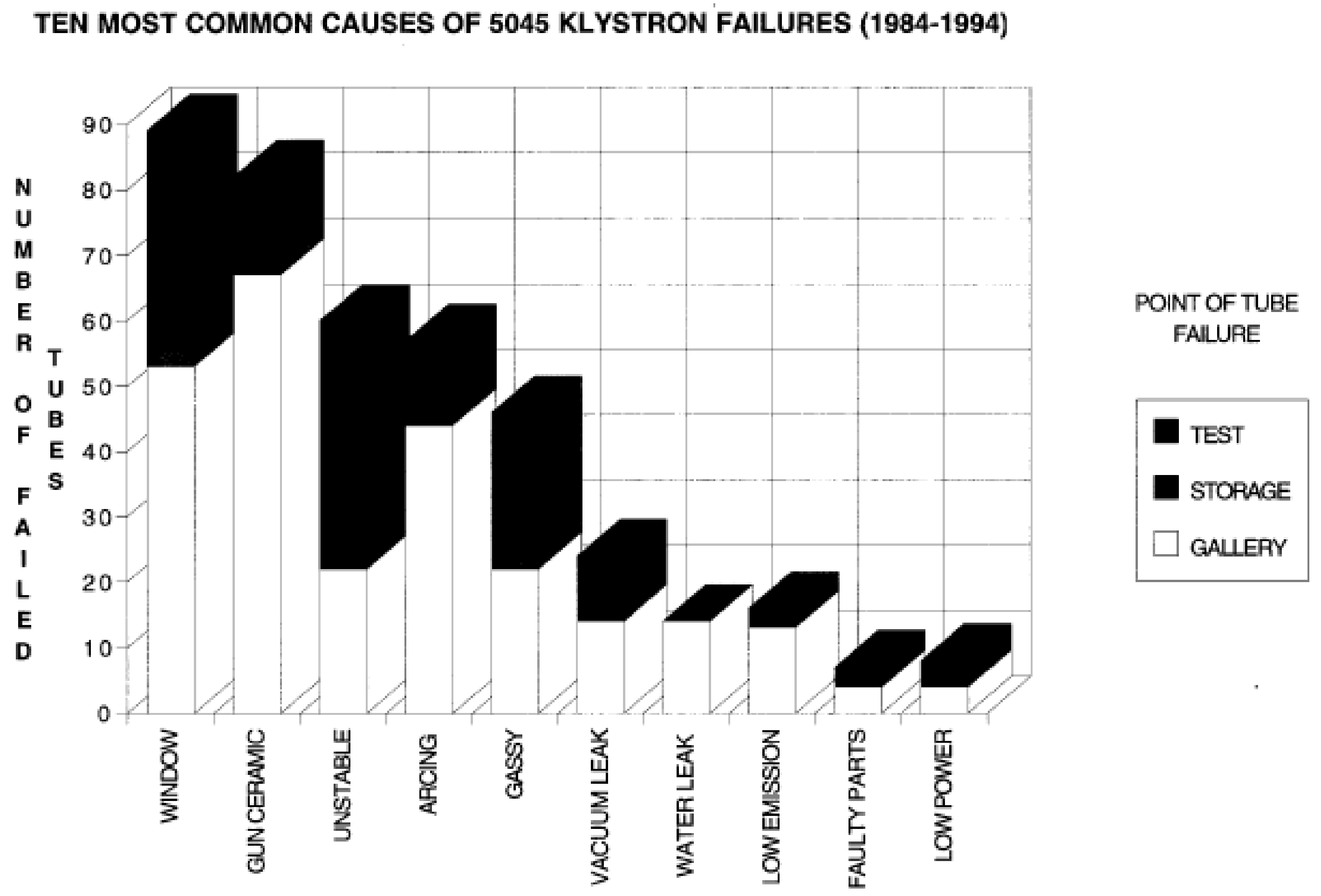
3. Modulate tube gain

- Reduce beam power to reduce output power
- Always run the tube at or near saturation (highest efficiency)
- Complex LLRF problem
- Not used in accelerators (New Modulation Techniques for Increased Efficiency in UHF-TV Transmitters ARTHUR J. BENNETT 1982)



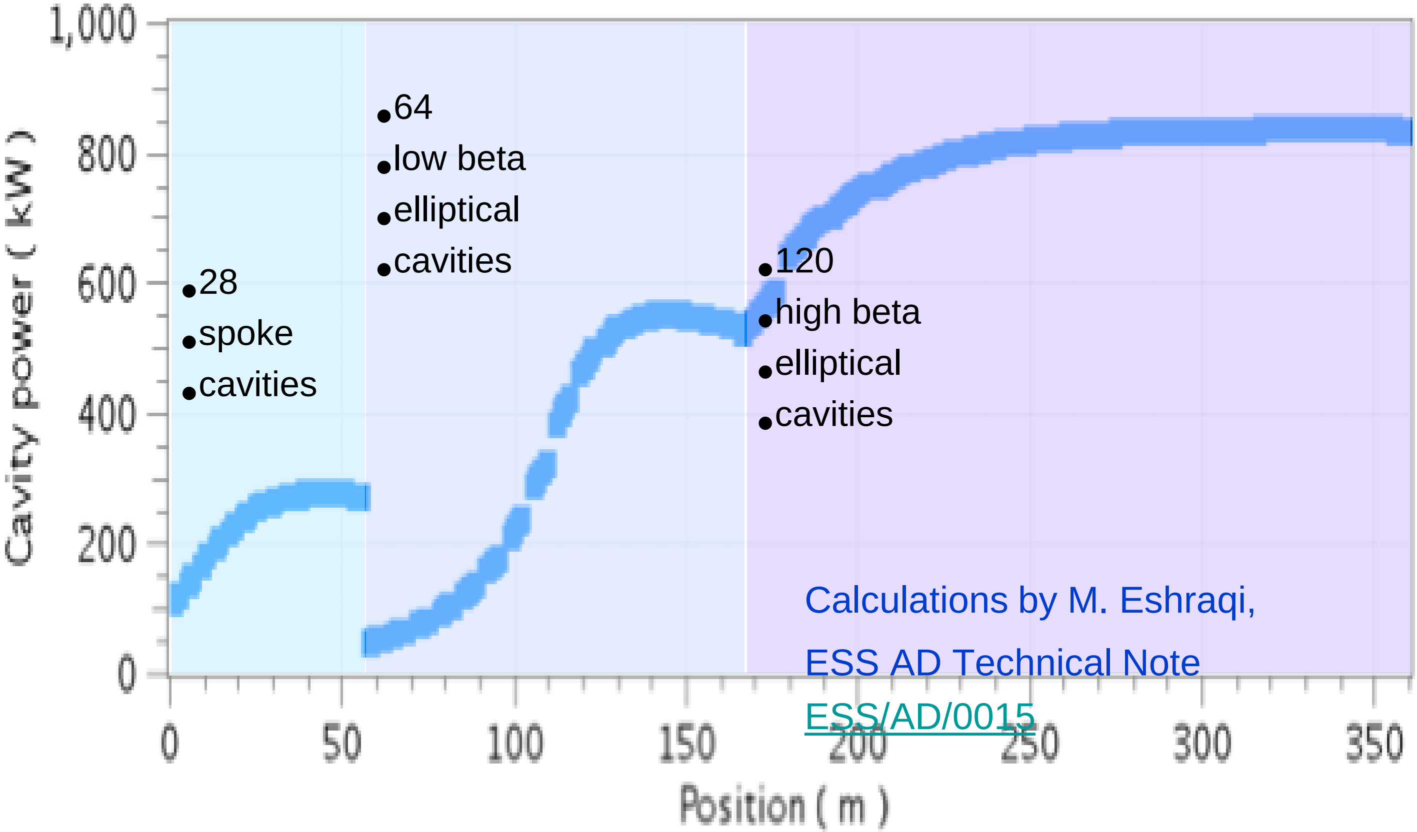
Failures (on an adventurous klystron)

SLAC Klystron Reliability G. Caryotakis



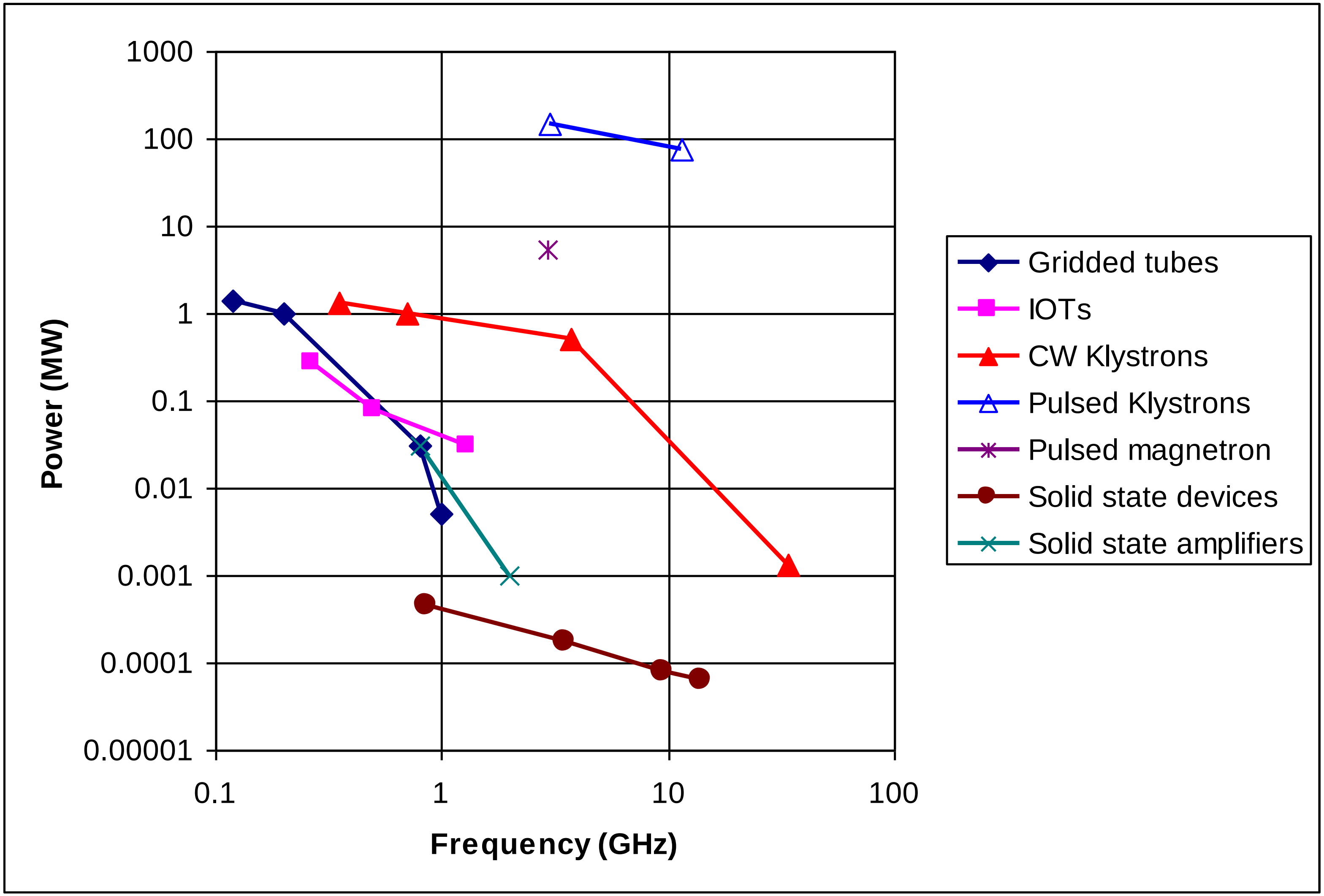
Any other options?

- Klystrons are big, expensive and over specified for many of the cavities



Calculations by M. Eshraqi, ESS AD Technical Note ESS/AD/0015

State of the art



Don’t forget the IOT!

- Low gain ~20-30dB
- High efficiency ~70-80%
- Low power (compared to a klystron) low 100s of kWs
- Cheaper (only the one cavity)
- Easier to replace (1 hour vs 1 day)

- To increase the power the outputs can combined.
  - Diamond use 3dB hybrids and magic Ts to tolerate a failure for 400kW per cavity
  - Perhaps good for spokes and low power low beta

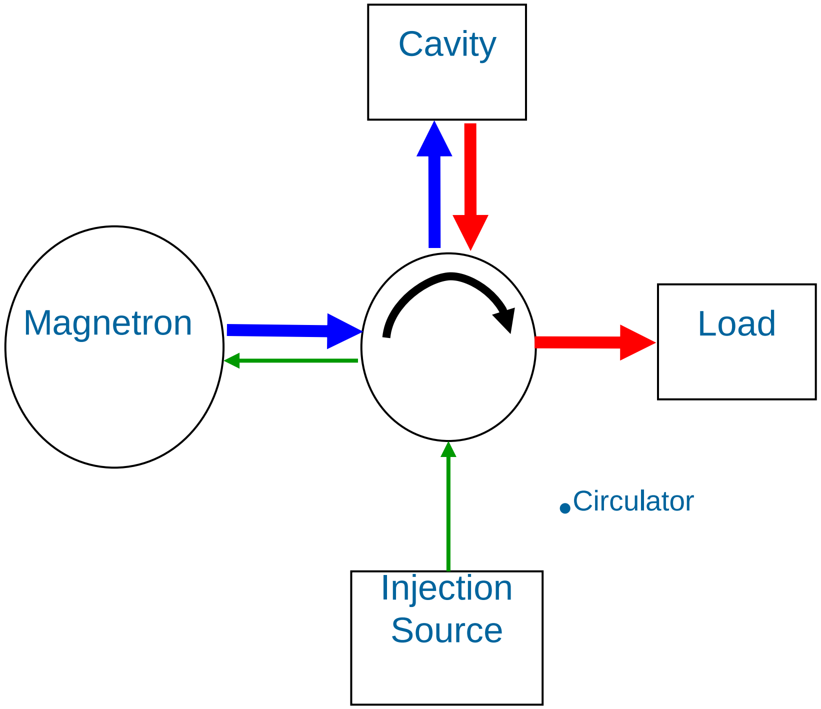
Accelerator klystrons

Frequency	508 MHz
Beam	90 kV; 18.2A
Power	1 MW c.w.
Efficiency	61%
Gain	41 dB

- Quite huge

Photos courtesy of Phillips

Magnetrons



- **Compared to Klystrons, in general Magnetrons**
  - **are smaller**
  - **more efficient**
  - **can use permanent magnets (at 704 MHz)**
  - **utilise lower d.c. voltage but higher current**
  - **are easier to manufacture**
- **Consequently they are much cheaper to purchase and operate**
- **BUT are oscillators**

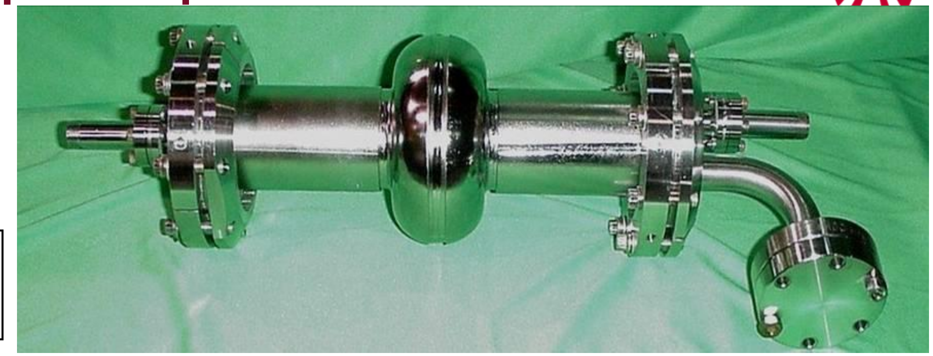
- **Linacs require accurate phase control**
- **Phase control requires an amplifier**
- **Magnetrons can be operated as reflection amplifiers**

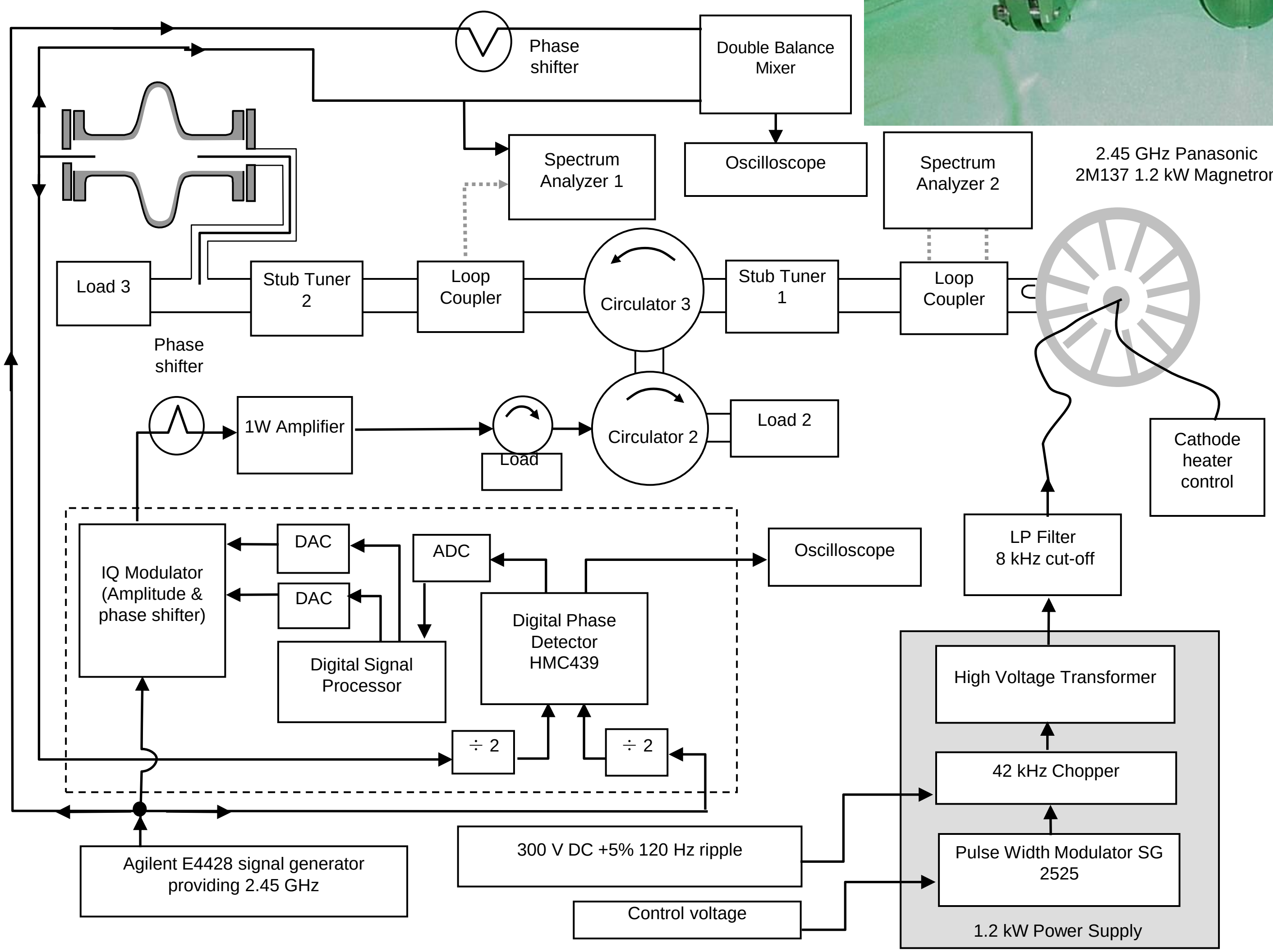
J. Kline "The magnetron as a negative-resistance amplifier," *IRE Transactions on Electron Devices*, vol. ED-8, Nov 1961

H.L. Thal and R.G. Lock, "Locking of magnetrons by an injected r.f. signal", *IEEE Trans. MTT*, vol. 13, 1965

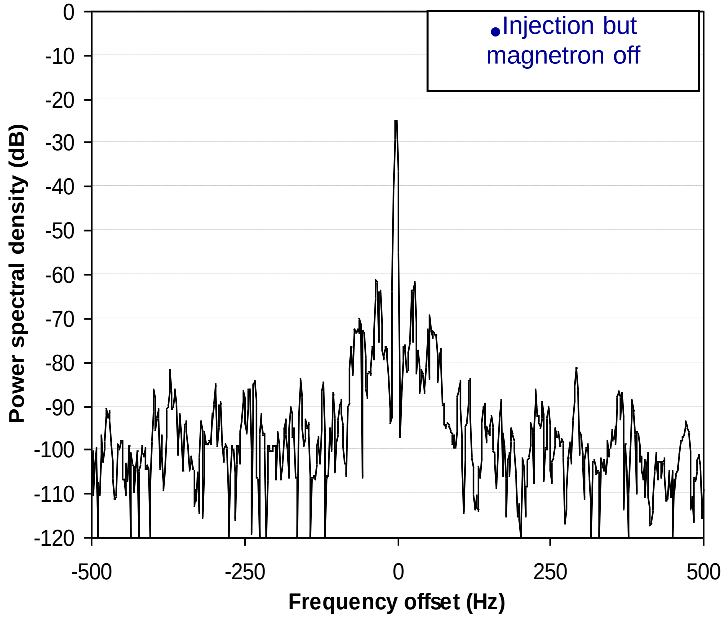
Proof of principle

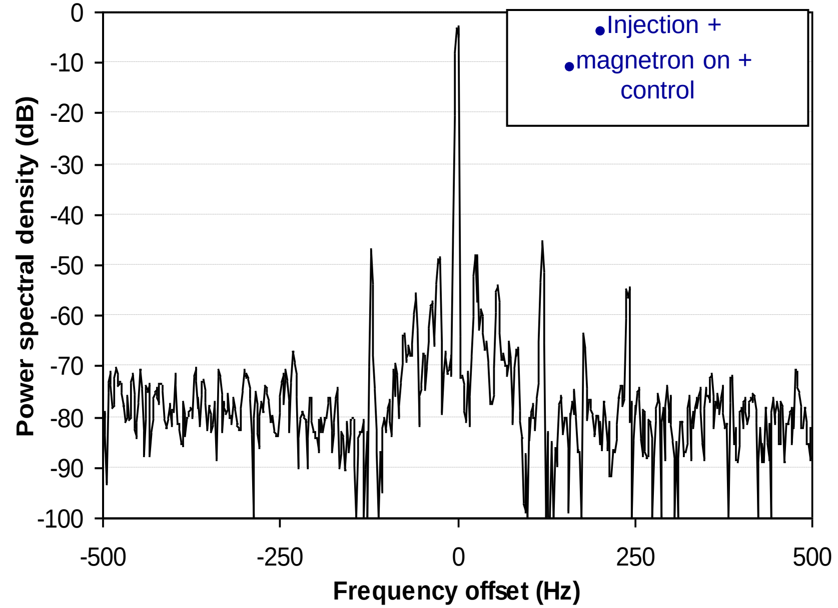
- Demonstration of CW 2.45 GHz magnetron driving a specially manufactured superconducting cavity in a VTF at JLab and the control of phase in the presence of microphonics was successful.

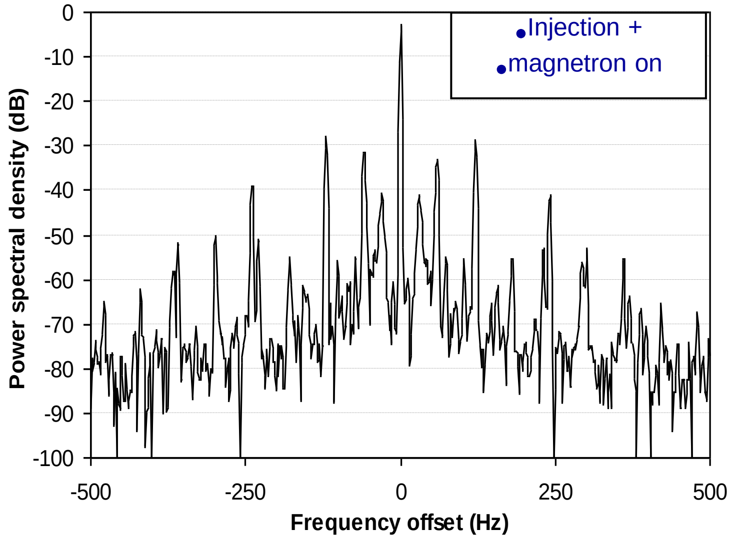


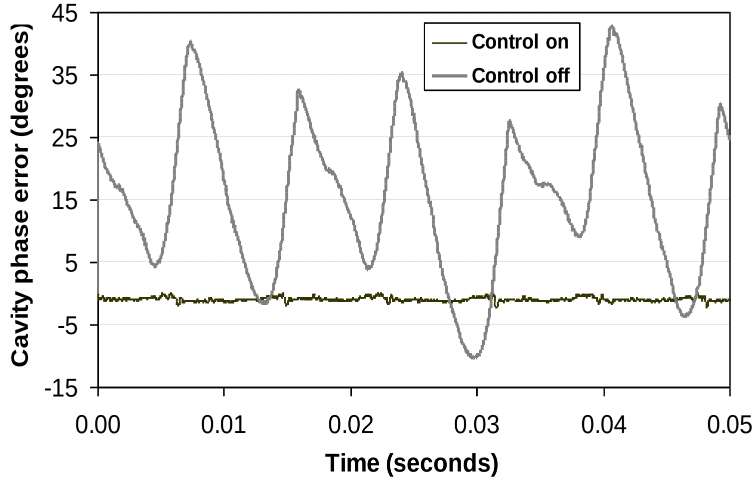


SCRF cavity powered with magnetron









The Cockcroft Institute of Accelerator Science and Technology

Layout using two magnetrons per cavity

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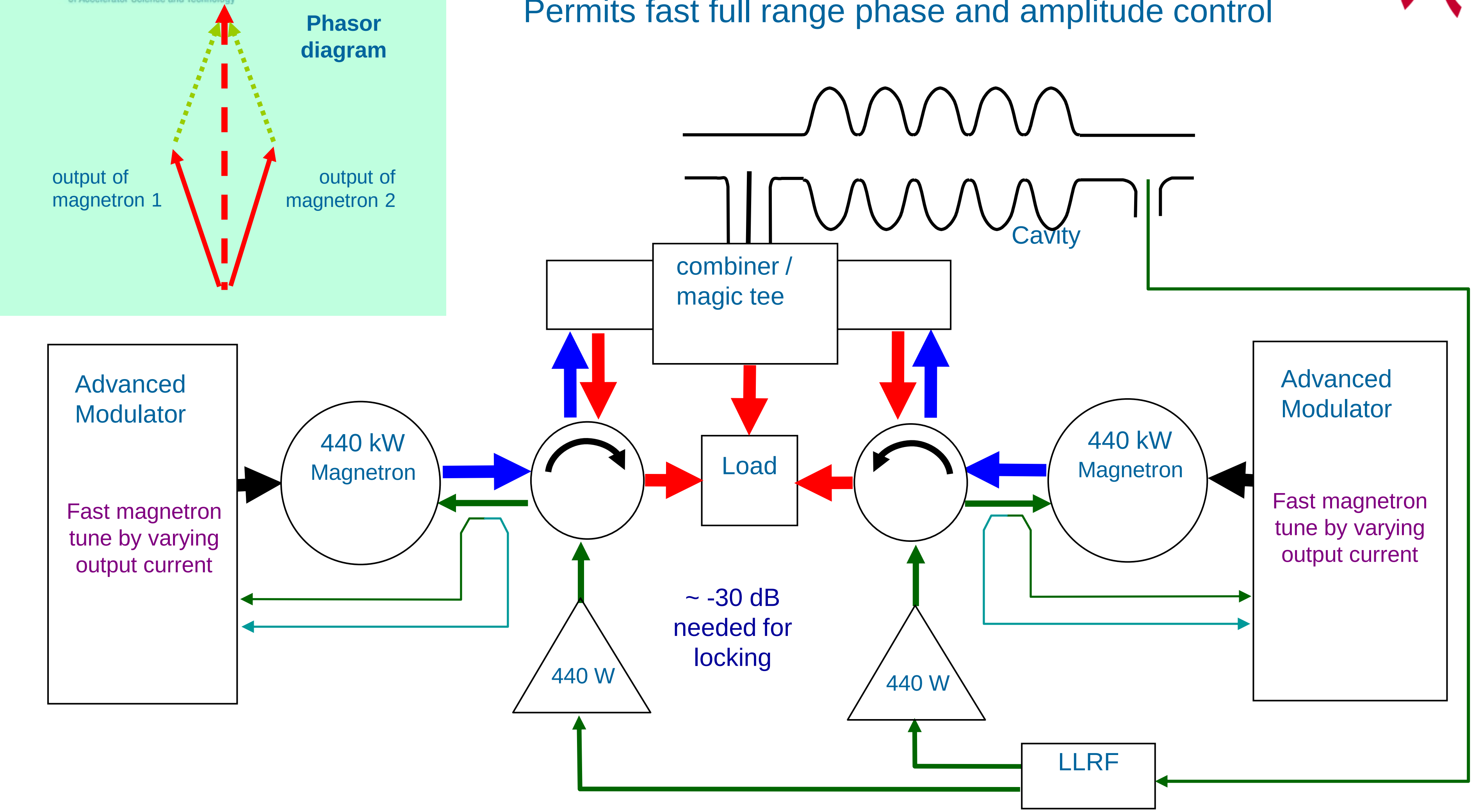
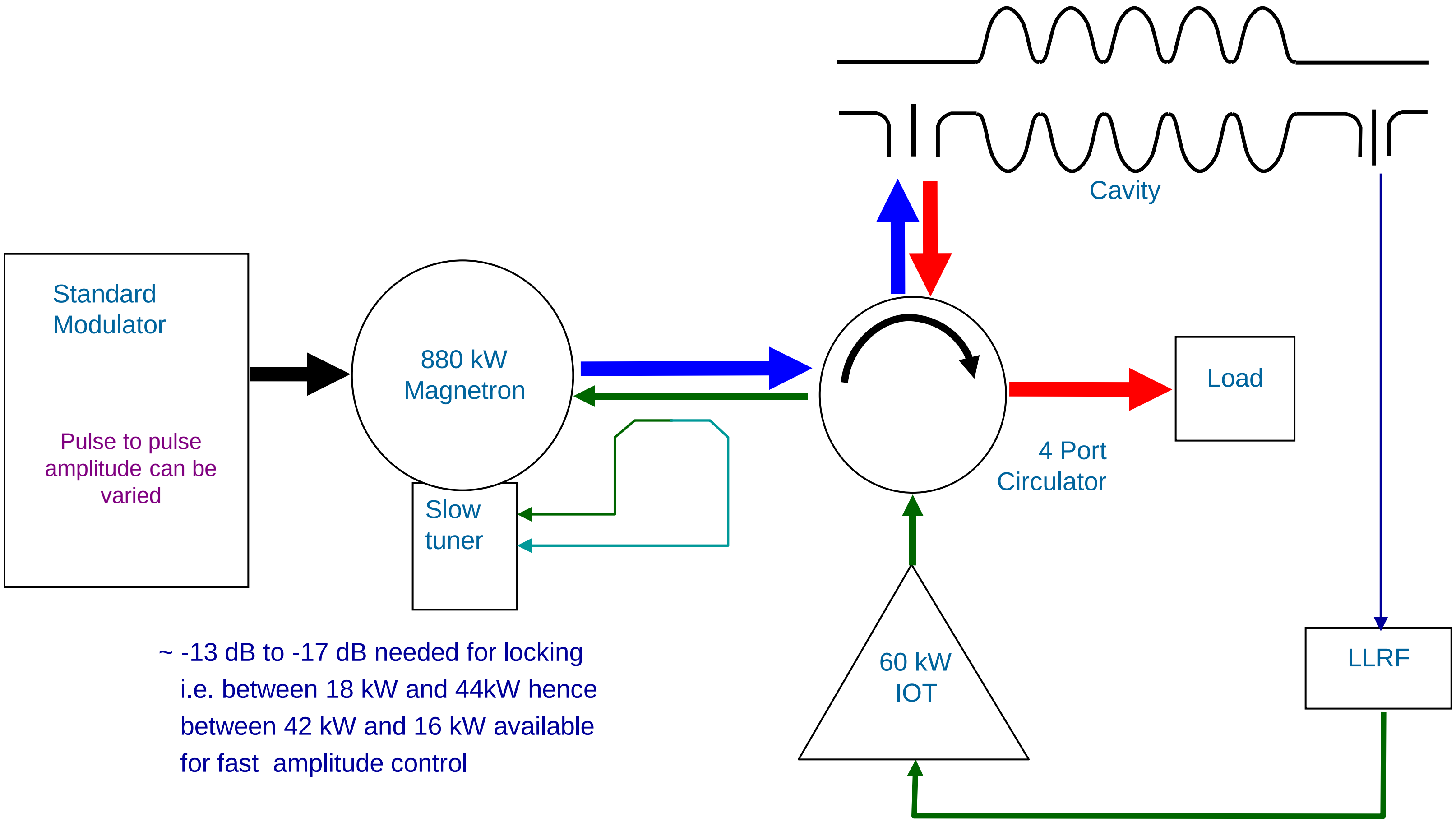
Permits fast full range phase and amplitude control



Layout using one magnetron per cavity

- Permits fast phase control but only slow, full range amplitude control



~ -13 dB to -17 dB needed for locking
i.e. between 18 kW and 44kW hence
between 42 kW and 16 kW available
for fast amplitude control

Could fill cavity with IOT then pulse magnetron when beam arrives

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Next Steps

- **Development of a 704MHz Magnetron (440kW – 880kW)**
  - **Collaboration with CEERI, Pilani, India**
- **Establish test station with Television IOT as the drive amplifier**
  - **Could be used for conditioning ESS components**
- **Understand locking characteristics of new magnetron**
- **Commission advanced modulator with in-pulse current control**
- **Establish minimum locking power**
- **Establish two magnetron test stand**
- **Develop LLRF for simultaneous phase and amplitude control**
  - Frequency: 704 MHz
  - Power: 200 kW to 1 MW
  - Pulse length: 5μs to 5 ms (for max power)
  - Max average power: 100 kW
  - Efficiency: > 90% above 500 kW
  - Magnet: NyFeB (< 0.5 T)
  - External Q: ~ 50 (for ease of locking)
  - Mechanical Tunability: ~ 5 MHz
  - Cathode heating: indirect and controllable

Conclusions

- Klystrons needed are at or near the state of the art for CW
- Efficiency is achievable
- Pulse length is achievable
- MBK/depressed collectors are too complicated/no advantage
- Regulating power with beam voltage is best

but

- Modulation anodes look interesting from a number of directions
- Magnetrons could be interesting for the future/ the test stand.

- Thank you for your attention