Klystrons
(and other vacuum electronics
power amplification devices)

Gap-Coupling, Beam-Loading
Admittance

Eric Colby,
SLAC

USPAS, January 21st
Outline

- How a linac’s properties interact with the power source
- General principles of microwave tubes
  - Beam loading admittance
  - Radial gap-coupling coefficient
  - Bunching
- Specific examples
- General scaling laws
- Other examples
Linac / Power Source Parameter Couplings

Linac Gradient

\[ G' = \sqrt{P' Z'_s T} \]

- \( G' \) = gradient per unit length
- \( P' \) = rf peak power per unit length
- \( Z'_s \) = shunt impedance per unit length
- \( T \) = transit time factor

Linac fill time

\[ \tau = \frac{Q_L}{2\omega} \ll \tau_{rf} = \text{rf pulse length} \]

\( Q_L \) = Accelerating loaded cavity Q

\[ Q_L = \frac{Q_o}{1+\beta} \]

Average Beam Power

\[ P_b = \eta P_{rf} \]

- \( P_b \) = (average beam current) x (beam voltage gain)
- \( \eta \) = net efficiency of coupling rf to beam
- \( P_{rf} \) = rf average power (\( = f \tau_{rf} P_{peak} \))

Linac coupling factor

\[ \beta = \text{VSWR (oc) @ tube} \]

Phase stability of linac \( \Leftrightarrow \) phase stability of source

frequency stability of source
Basic Klystron

Energy modulation

modulate

Energy

modulation

V_{z,0}, I_0

E_z

V_{c}

Velocity bunching

Beamtube must not propagate the rf backward wave or the tube can oscillate!

RF power input

“RF Drive”

RF power output

V_{z,0}, I_1
Beam Loading Admittance

So far, we’ve taken $\beta \rightarrow 1$ in treating beam/cavity interaction, which allows for the approximation of the beam as an ideal current source (i.e. the beam current is not modified by the gap voltage in the cavity).

For vacuum power tubes, however, $\beta \sim (0.2-0.8) \leftrightarrow (V=10\text{kV}-500\text{kV})$, and the beam current changes significantly while in the gap.

$$\tilde{J}_1 = \tilde{\rho}_1 V_{z,0} + \rho_0 \tilde{V}_{z,1}$$

$$I_b = \int_S \tilde{J}_1 dS$$

Diagram:

- Source
- Coupler
- Cavity
- Beam
Beam Loading Admittance

Proceeding from the Continuity equation and Lorentz force law, the action of the rf fields on the beam velocity and density can be described, yielding:

\[
\tilde{I}_{rf} = -I_{dc} \frac{e}{m\gamma^3 V^2_{z,0}} \frac{1}{j\theta} \left[ 1 + e^{-j\theta} + \frac{2j}{\theta} (1 - e^{-j\theta}) \right] \tilde{V}_c = \tilde{Y}_c \tilde{V}_c
\]

writing

\[
\tilde{Y}_c = G_c + jB_c
\]

\[
\theta = \frac{\omega L}{V_{z,0}} \quad \text{Gap transit angle}
\]
Beam Loading Admittance

\[
\theta = \frac{\omega L}{\beta c}
\]

Gap Coupling

The beams used in vacuum tubes generally occupy a significant fraction of the beam pipe (often $r_b = 2/3 R_{\text{pipe}}$), so the variation of the gap fields with $r$ must be accounted for. This is done with the radial gap coupling coefficient.

The solution to wave equation in cylindrical coordinates yields the form of the gap voltage with $r$:

$$\tilde{V}_c (r, \omega) = \tilde{V}_c (R, \omega) \frac{I_0(\Gamma r)}{I_0(\Gamma R)}$$

$$\Gamma = \frac{\omega}{\gamma V_z}$$

Averaging over the beam’s cross section yields the gap coupling coefficient:

$$M = \frac{2I_1(\Gamma r_b)}{\Gamma r_b I_0(\Gamma R)}$$

$[R/Q] \rightarrow [R/Q]*M^2$
Ballistic Bunching

• Ballistic (no space charge) Theory

\[ I_1 = 2I_{DC} J_1(B) \exp(j(\varphi_0 - \theta_0 + \pi / 2)) \]

with

\[ B = \frac{\theta_0}{\gamma_0^3(V_{z,0} / c)^2} \frac{e|V_c|}{mc^2} \]

Bunching parameter

\[ \theta_T = \omega D / V_{z,0} \]

Transit angle of drift D

• Matlab demonstration (space charge free)
Klystron Efficiency vs. Perveance

\[ k_\mu = \frac{I}{V^{3/2}} \]

Fig. 1 The empirical relation of efficiency to the perveance.

Real Klystron Schematic

FIGURE 1. The 150-MW klystron assembly shown with magnets and lead.

- **f = 2996 MHz**
- **Gain = 55 dB**
- **Efficiency: >40%**
- **P = 150 MW**
- **B~2100 Gauss**
- **PRF: 60Hz**
- **K = 1.8 µP**
- **Group Delay 150 nsec**
- **Pulse length: 3 µs**
- **V_b = 535 kV**
- **J_{cath} = 6 A/cm^2**
- **I_b = 700 Amps**

B-Factory Tube (CW)

f = 476 MHz
P = 1.2 MW CW
K = 0.83-1.3
V_{b} = 83 kV

Gain > 43 dB
Efficiency: >50%

BW = +/- 3.0 MHz at -1dB points
VSWR tolerance: 1.2

Group Delay 150 nsec

J_{cath} = 0.63 A/cm^2

I_{b} = 24 Amps CW

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Figure 1. Predicted Small-Signal Gain versus Frequency Response at 90 KV

Figure 2: output power versus drive power.
Klystron Amplifier Scalings

Cathode current density: $f^0$

Focusing field strength: $B \sim \lambda_q^{-1}$

Output Cavity Gap Fields $\sim f^0$

Circuit losses: $f^{1/2}$

Beam area convergence: $f^0$

Tube length: $\lambda_q \sim V^{3/2}$

Beam Power & Output Power: $f^{-2}$
RF PULSED HEATING OF CAVITY WALLS

[O.A. Nezhevenko, PAC’97, Vancouver, 1997, p. 3013.]

Structure lifetime is limited by fatigue from pulsed heating in a thermal-diffusion layer. Assume OFE copper NLC-like cavities, “safe” temperature excursions of 110 °C, and collider operation at 120 Hz, 6000 hrs/yr. [For 20 year life, \( n = 5 \times 10^{10} \) pulses.]

[Experiments (Pritzkau, 2000) achieved \( \Delta T = 120 \) °C for \( 5.5 \times 10^7 \) pulses, observed surface damage.]

CALCULATED EFFECTS OF RF PULSE HEATING OF IDEAL CAVITY WALLS.

<table>
<thead>
<tr>
<th>freq (GHz)</th>
<th>( G_0 \sim \omega^{5/6} ) (MV/m)</th>
<th>( \tau_p \sim \omega^{-1.5} ) (ns)</th>
<th>( \Delta T \sim \omega^{1.42} ) (°C)</th>
<th>( T_o = 27 ) °C</th>
<th>( T_o = 77 ) °C</th>
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<tbody>
<tr>
<td>11.424</td>
<td>100</td>
<td>250</td>
<td>23</td>
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<td>22.848</td>
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<td>90</td>
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<td>34.272</td>
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<td>45.696</td>
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<td>30</td>
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<td>2.5×10^{9}</td>
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<tr>
<td>57.120</td>
<td>380</td>
<td>22</td>
<td>225</td>
<td>1.5×10^{9}</td>
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<tr>
<td>68.544</td>
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<td>17</td>
<td>290</td>
<td>1×10^{8}</td>
<td>1.8×10^{7}</td>
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<tr>
<td>79.968</td>
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<td>370</td>
<td>9.8×10^{6}</td>
<td>2.6×10^{6}</td>
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<tr>
<td>91.392</td>
<td>560</td>
<td>11</td>
<td>440</td>
<td>1.4×10^{6}</td>
<td>4.7×10^{5}</td>
</tr>
<tr>
<td>102.816</td>
<td>620</td>
<td>9</td>
<td>520</td>
<td>2.6×10^{5}</td>
<td>1×10^{5}</td>
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<tr>
<td>114.240</td>
<td>680</td>
<td>8</td>
<td>600</td>
<td>6×10^{4}</td>
<td>3×10^{4}</td>
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</table>

For collider applications, RF technology development >40 GHz appears unjustified.
Typical operational problems with a klystron

- Input drive power is too low and klystron is not saturated (although this is required if the tube is included in a feedback loop) → reduced output power, efficiency, and increased output power amplitude jitter
- Wrong cathode filament current → wrong perveance → poor efficiency (minor) or beam interception (major)
- Modulator voltage jitter causes jitter in
  - The tube output power $P \sim V^{5/2} \rightarrow \delta P / P \sim (5/2)(\delta V / V)$
  - The tube transit time, which in turn causes phase jitter on the output $\partial \phi / \partial V = (L_f / \beta^3 \gamma^3 c)$
- Mismatched load causes significant output instability
Typical Klystron Failure Modes

- Burnt-out or shorted cathode filament
- Beam interception erodes output cavity
- Rf breakdown erodes the output cavity
- Multipacting on or near the output window sputters metal onto the ceramic window, resulting in breakdowns
- Slow vacuum leak contaminates ("poisons") the cathode
- Focusing magnetic field changes, resulting in a current density change that either:
  - If minor: changes the gap-coupling and space charge forces
  - If major: results in beam interception
- Input cavity erodes (rare)
- Output cavity oscillates (not necessarily at an integer multiple of the rf frequency)
- Gun supports an rf resonance
Examples of other beam-based power amplifiers
17.136 GHz Klystron (Haimson Research, NRL)

FIGURE 2. Prototype 17 GHz TWRK and solenoid assembly showing the electron gun vacuum isolation valve and the precision alignment supporting mechanism.

17.136 GHz Klystron

(Haimson Research, NRL)

Measured Properties:

• Output Power: 26 MW @ 150 ns
• Efficiency: 49%
• Saturated Gain: 67 dB
• 560 kV/95 A beam

FIGURE 1. Model X7100 17 GHz TWRK showing the WR62 rectangular waveguide and body water-cooling connections, and the high vacuum port for the independently pumped, electrically isolated beam collector.

1 MW, 91.4 GHz Sheet Beam Klystron (SLAC/MRC)

**SBK Details:**
- $I_o = 15$ A
- $V_o = 140$ kV
- $P_{rav} / \Box = 14.4$ nP/\Box
- $L \times W = 8\text{ mm} \times 0.4\text{ mm}$
- $P_{in} = 400$ W (at ports)
- $f_{rf} = 91.41$ GHz

**PIC Details:**
- $\delta t = 0.135$ ps = $t_{rf} / 84$
- $\delta z = 200 \mu \text{m} = \lambda / 16$
- $N = 198,000$, $n = 17$/cell
- $dt_{sim} / dt_{real} = 3.1$ ns/day

October 6, 1998
SBK Simulation

Configuration Space Images of Bunching

Vertical Plane

Horizontal Plane

October 6, 1998
L. Song, *et al.*, in PAC03 proc.
The Gyroklystron

Synchronism condition: \( \omega - k \parallel z \parallel = n \Omega_c \)

FIGURE 1. Schematic diagram of the Ka-Band gyrokylystron experiment.

Helix TWT (Preamplifier)

- Generally used for driving klystrons.
- Gain (typ) ~ 20-30 dB
- Output ~ 1 kW or less

Figure 5 - Electron beam bouncing and a detail foto of a helix (Measure detail for 20 windings)
34 GHz Magnicon
(Omega-P)

FIGURE 1. Schematic diagram of 34.272 GHz magnicon amplifier tube. Inserts at upper left show rf field patterns for drive and all deflection cavities (TM$_{110}$ mode at 11.424 GHz), and for the output cavity (TM$_{310}$ mode at 34.272 GHz).

FIGURE 10. Computed steady-state evolution with $z$ of radial orbit displacements (bottom) and particle energies (top). Also shown are the cavity outlines.

Transverse Deflection

Energy

Ubitron or Free Electron Laser

LLNL 140 GHz FEL Amplifier

Measured Properties:

- Power: 1-2 GW (!) @ 20 ns
- Efficiency: 14%
- Beam: 6 MV/2500A

Compact Linear Collider (International collaboration centered at CERN)

FIGURE 3. The 3 TeV RF Power Source.

CLIC Test Facility II

CTF-II Demonstrated:

• Generation and acceleration of 48x13.4 nC drive beam

• 120 MW of 30 GHz power generation in 16 ns pulses from the Power Extraction and Transfer Structures

• 59 MV/m acceleration of the probe beam
High Power Fiber Lasers

Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power

Jay W. Dawson, Michael J. Messerly, Raymond J. Beach, Micolas V. Shverdin, Eddy A. Stappas et al.

Abstract: We analyze the scalability of diffraction-limited fiber lasers considering thermal, non-linear, damage and pump coupling limits as well as fiber mode field diameter (MFD) restrictions. We derive some new relationships based on practical considerations. Our analysis shows that if the fiber’s MFD could be increased arbitrarily, 36 kW of power could be obtained with diffraction-limited quality from a single fiber or amplifier. This power limit is determined by thermal and non-linear limits that combine to prevent further power scaling, irrespective of increases in mode size. However, limits to the scaling of the MFD may restrict fiber lasers to lower output powers.

Typical Specifications

Optical Parameters

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<thead>
<tr>
<th>Unit</th>
<th>YLR-1000</th>
<th>YLR-3000</th>
<th>YLR-5000</th>
<th>YLR-10000</th>
<th>YLR-20000</th>
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<tr>
<td>Nominal Output Power</td>
<td>W</td>
<td>1000</td>
<td>3000</td>
<td>5000</td>
<td>10000</td>
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<tr>
<td>SPF after Feeding Fiber</td>
<td>mm/um</td>
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<tr>
<td>RPF after Concentrating Fiber</td>
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<td>Feeding Fiber Core Diameter</td>
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Electrical Parameters

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<th>YLR-5000</th>
<th>YLR-10000</th>
<th>YLR-20000</th>
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</thead>
<tbody>
<tr>
<td>Typical Power Consumption</td>
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<td>3.5</td>
<td>10</td>
<td>17.3</td>
<td>35.4</td>
</tr>
</tbody>
</table>

General Parameters

<table>
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<th>Unit</th>
<th>YLR-1000</th>
<th>YLR-3000</th>
<th>YLR-5000</th>
<th>YLR-10000</th>
<th>YLR-20000</th>
</tr>
</thead>
</table>

Carrier Phase-Locked Lasers

Fig. 2. White-light fringes resulting from the interference of the two continua generated by the two phase-locked IR laser pulses when the relative delay is properly adjusted to zero.

Fig. 3. Spectrally dispersed white-light fringes. Clear and well-defined fringes indicate that a stable phase relationship is conserved across all the generated visible spectrum.

Sources by Power Density and Wavelength

Source Frequency [GHz]

Source Power Density [TW/cm²]

SLAC MKB
SLAC 5045
Mitsubishi C-band
SLAC X-band PPM
Halmson 17 GHz K
CLIC 30 GHz TBA
UMD/CCL/CP 194 GHz G-K
LLNL 140 GHz Ubitron
HEPL-SCA FEL
Vanderbilt FEL
1 TW CO2 Laser
1 TW Ti:Sapphire Laser
10 GW Er Fiber Laser
LANL RAFEL

Source Wavelength

30 cm
3 cm
3 mm
300 μm
30 μm
3 μm
300 nm