RF Amplifier Choice for the ISAC Superconducting Linac

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Outline

• Introduction to ISAC-2 accelerator
• Amplifier specifications
• Prototype amplifiers measurements
• Operational experience analysis
• Cost evaluation
• Amplifiers comparison summary
• Conclusion
Operational medium beta superconducting linac
Beam dynamics requirements

- High beta section of ISAC-2 linac needs 20 superconducting cavities (~1MV each)
- Accelerating field stability per cavity:
  - Amplitude variations (rms) <0.2%
  - Phase fluctuations (rms) <0.2°
RF cavity:
Q = 10^9
Accelerating field \( E_a = 6 \text{ MV/m} \)
Wall losses 7 W
Required bandwidth \( f_{1/2} = 20 \text{ Hz} \)
Achieved by overcoupling: \( \beta = 200 \)
Require \( P_f = 200 \text{ W} \) at cavity
Amplifier operation modes

1. Production mode
   - Continuous wave operation
   - Output RF power – 200 W
   - Amplitude, phase and frequency are regulated

2. Conditioning mode
   - Pulse mode
   - Duty cycle 50%
   - Pulse duration 1 second
   - Output RF power 600 W
   - No RF regulation
Amplifier Basic Requirements

- Operating Frequency Range: 141.0 – 142.0 MHz
- CW Power Output: 600W
- Input/Output Impedance: 50 Ohms
- Maximum RF input power: +5dBm
- Power Gain: 55 ± 2dB
- Operating Load VSWR: 1.01 – 1.5
## Amplifier specific requirements

<table>
<thead>
<tr>
<th>Mode of operation</th>
<th>CW operation</th>
<th>Pulse conditioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power range</td>
<td>1 - 250 Watt</td>
<td>250 - 600 Watt</td>
</tr>
<tr>
<td>Gain linearity</td>
<td>$&lt; \pm 0.5 \text{ dB}$</td>
<td>$&lt; \pm 2.0 \text{ dB}$</td>
</tr>
<tr>
<td>Phase drift, degree</td>
<td>$&lt; \pm 5^\circ$</td>
<td>$&lt; \pm 20^\circ$</td>
</tr>
<tr>
<td>Phase noise*, rms</td>
<td>0.3$^\circ$</td>
<td>-</td>
</tr>
<tr>
<td>Amplitude noise*</td>
<td>0.6%</td>
<td>-</td>
</tr>
</tbody>
</table>

* Amplitude and phase noise is integrated in the range of 0 – 200 Hz.

Phase drift and gain linearity requirements apply to both short term power sweep variation as well as to long term drift.
RF amplifier choice considerations

- Vacuum tube amplifier
- Semiconductor amplifier
RF amplifier choice criteria

- **Performance**
  - Power capability
  - Gain linearity
  - Phase stability

- **Reliability**
- **Serviceability**
- **Efficiency**
- **Cost**
Amplifier prototypes tests

Evaluated amplifiers:

1. Tube amplifier (Eimac 3CX1200Z7)
2. Four Solid State amplifiers:
   • 3 commercial units
   • 1 amplifier of TRIUMF design
S/S amplifier prototype view
Amplifier gain and phase variations

-1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4

Gain diff, dB

0 200 400 600 800

Power, Watt

0 200 400 600 800

Phase, degree

0 200 400 600 800

Power, Watt

Tube PA
S/S PA
Phase noise measurement

Phase noise, degree

Frequency, Hz

Tube PA
S/S PA
Tube PA operational issues

20 tube amplifiers of 106 MHz, 800 W are in operation for the ISAC-2 medium beta cavities

Problems:
1. Phase noise
   - Mechanical vibrations (fan)
   - DC PS rectifier ripple (120Hz)
2. Tube input impedance degradation
3. Tube output circuitry detuning
### Aged tube amplifier degradation (8700 hours)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>New tube</th>
<th>Retired tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube input VSWR</td>
<td>1.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Tube stage gain</td>
<td>14 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Maximum power</td>
<td>900 W</td>
<td>90 W</td>
</tr>
<tr>
<td>Frequency</td>
<td>106.1 MHz</td>
<td>109.5 MHz</td>
</tr>
<tr>
<td>Phase shift</td>
<td>0</td>
<td>&gt;100°</td>
</tr>
</tbody>
</table>
Tube PA design, operation and maintenance recommendations

- Avoid PA mechanical vibrations
- Filter 120 Hz ripple of HVPS (or use switching PS)
- Monitor amplification gain: tube ageing control
- Monitor V plate, I plate, I grid, V filament, I filament
- Filament power management to increase tube life
- Replace tubes at lifetime expectancy (8000 hours)
Solid state PA failures

ISAC-1 linac: 20 semiconductor PA’s in use since 2000
- 10 well protected PA’s – 3 failures
- 10 poorly protected PA’s – 50 failures

Transistor failure reasons:
- High voltage transients
- Input overdrive from RF controls
Solid state PA design recommendations

- Drain voltage and current detection and fast DC cut off
- Input overdrive protection
- Output VSWR protection
- Adequate head room: gain linearity & phase shift
- Good filtering against RF leakage for DC PS
- Monitor DC voltage, current and temperature
- Air cooling
- Separate power supply
## Costs Evaluation

<table>
<thead>
<tr>
<th>Description</th>
<th>Tube PA</th>
<th>S/S PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budgetary price</td>
<td>15 k$</td>
<td>25 k$</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>3 k$</td>
<td>2 k$</td>
</tr>
<tr>
<td>Tube / transistor replacement</td>
<td>10 k$</td>
<td>0.1 k$</td>
</tr>
<tr>
<td>Fan &amp; other components replacement</td>
<td>1 k$</td>
<td>1 k$</td>
</tr>
<tr>
<td>Total cost over 10 years</td>
<td>29 k$</td>
<td>28.1 k$</td>
</tr>
</tbody>
</table>
## Tube and Solid State Amplifiers Comparison

<table>
<thead>
<tr>
<th>Description</th>
<th>Tube PA</th>
<th>S/S PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class of Operation</td>
<td>Class A</td>
<td>Class AB</td>
</tr>
<tr>
<td>Performance</td>
<td>Satisfies most of requirements; marginal with phase drift &amp; noise</td>
<td>Meets all requirements</td>
</tr>
<tr>
<td>Reliability</td>
<td>Tube is rugged, but needs replacement every 12 months</td>
<td>Transistor failure is rare, if protected</td>
</tr>
<tr>
<td>System Downtime</td>
<td>Possible interruptions due to detuning or tube failure</td>
<td>Very little</td>
</tr>
<tr>
<td>Serviceability</td>
<td>Reasonable</td>
<td>Reasonable</td>
</tr>
<tr>
<td>Failure Diagnosis</td>
<td>Easy with incorporated diagnostics</td>
<td>Easy with incorporated diagnostics</td>
</tr>
<tr>
<td>High Voltage</td>
<td>3.5 kV</td>
<td>Below 50 V</td>
</tr>
<tr>
<td>Efficiency at 200 W</td>
<td>25 %</td>
<td>35 %</td>
</tr>
<tr>
<td>Start up cost</td>
<td>15 k$</td>
<td>25 k$</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>1,000 $/year</td>
<td>100 $/year</td>
</tr>
</tbody>
</table>
Conclusion

• Semiconductor PA is better in a few critical parameters compared with the tube PA for SC linac application.

• The only disadvantage of the S/S PA is a higher capital cost, which will be offset by much lower maintenance cost in a long run.

• TRIUMF has chosen a semiconductor amplifier for the high beta section of the ISAC-2 linac.