RF Amplifier Choice for the ISAC Superconducting Linac

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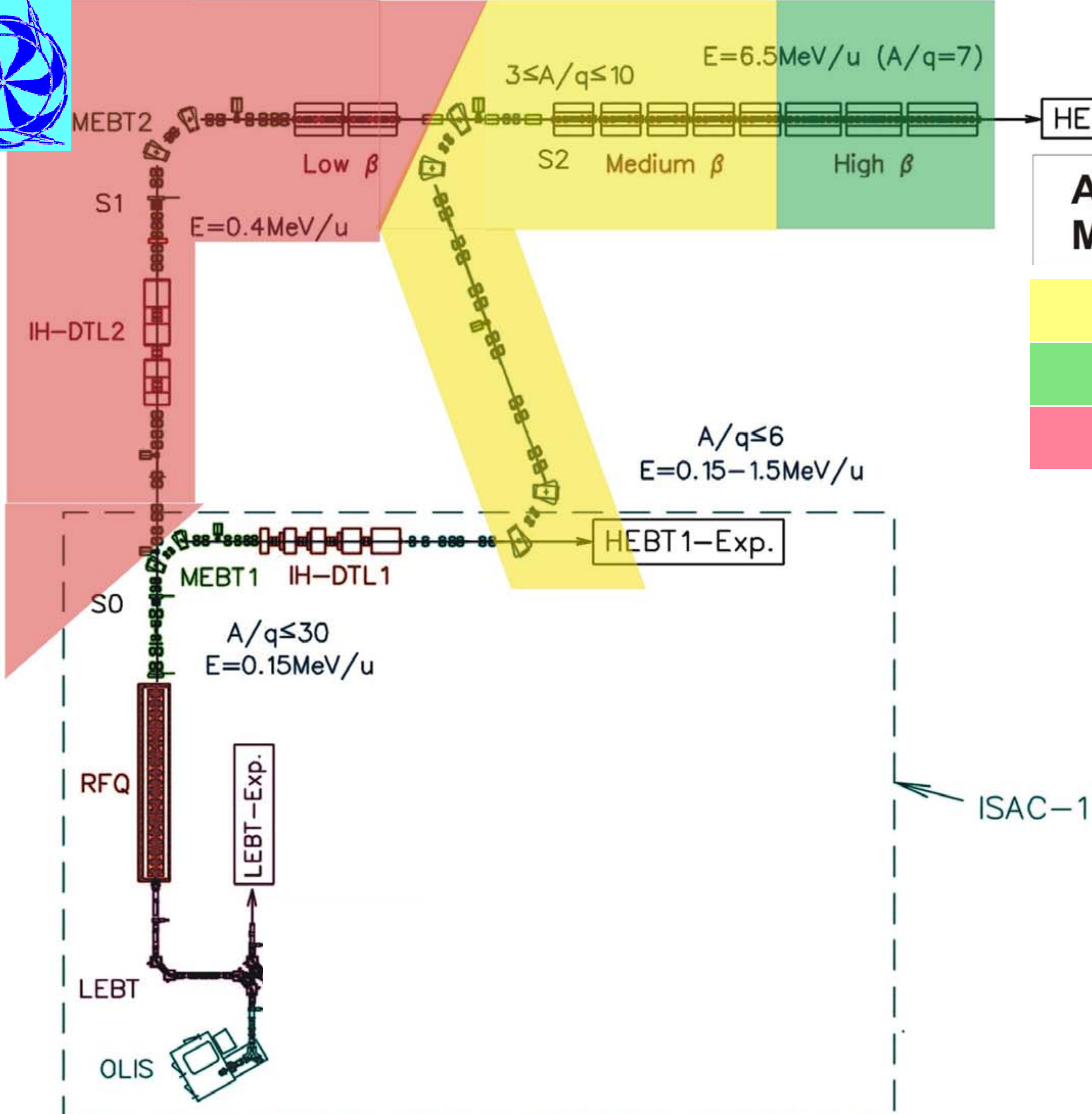
Outline

- Introduction to ISAC-2 accelerator
- Amplifier specifications
- Prototype amplifiers measurements
- Operational experience analysis
- Cost evaluation
- Amplifiers comparison summary
- Conclusion



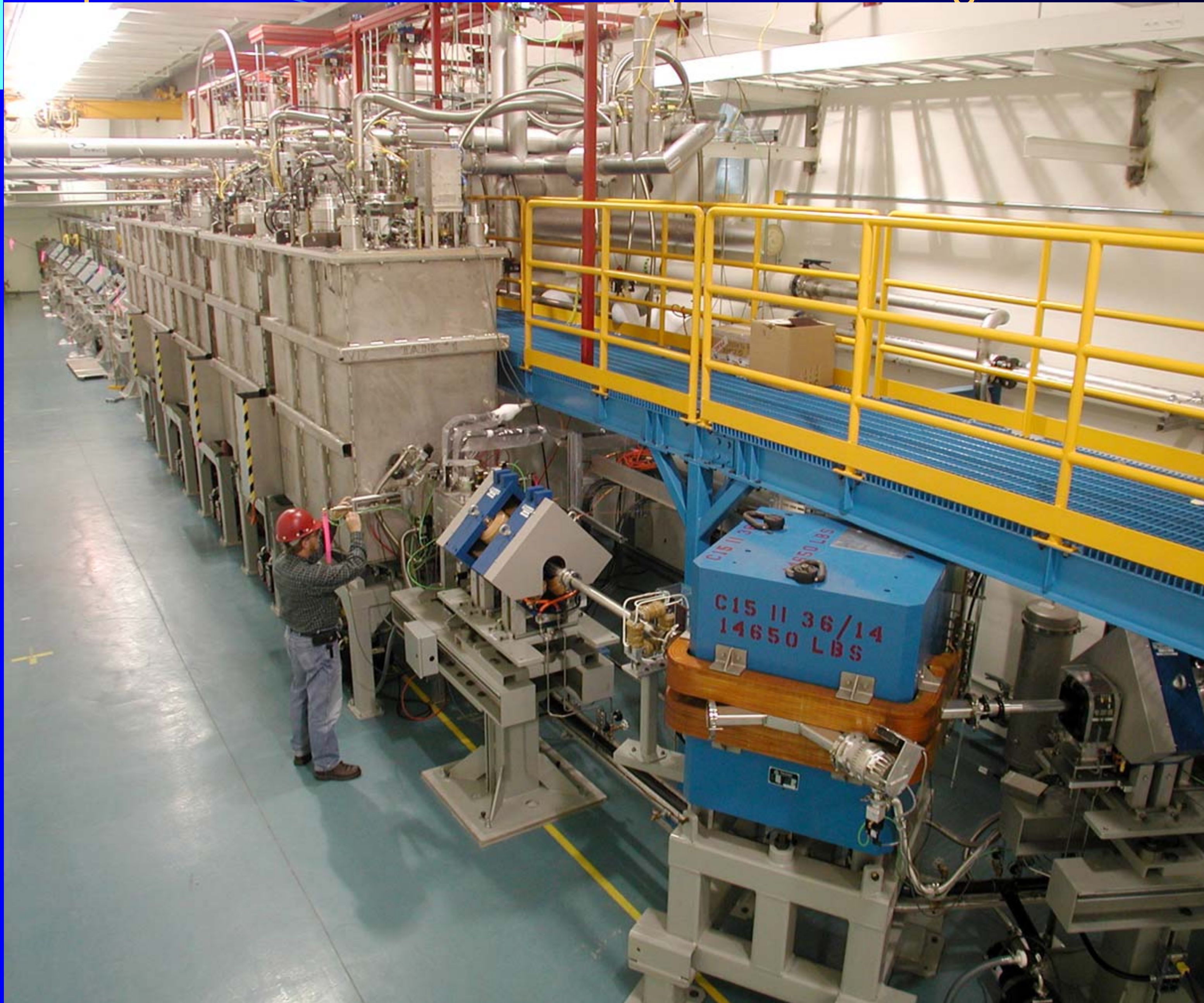
ACCELERATOR MILESTONES

2006

2010

>2010

Operational medium beta superconducting linac

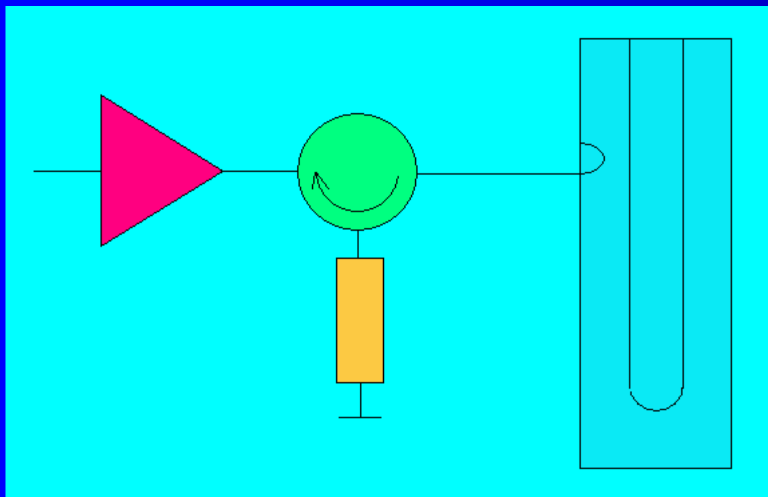


Beam dynamics requirements

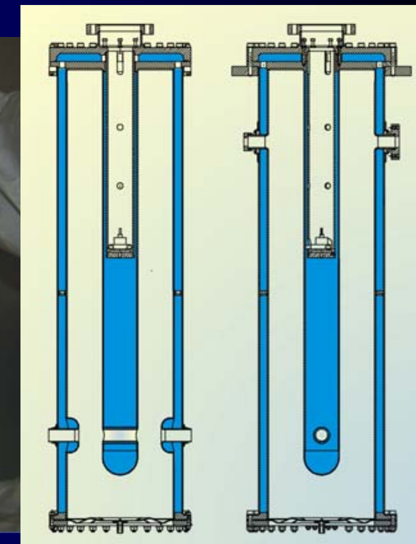
- High beta section of ISAC-2 linac needs 20 superconducting cavities (~1MV each)
- Accelerating field stability per cavity:

Amplitude variations (rms)	<0.2%
Phase fluctuations (rms)	<0.2°

RF System configuration



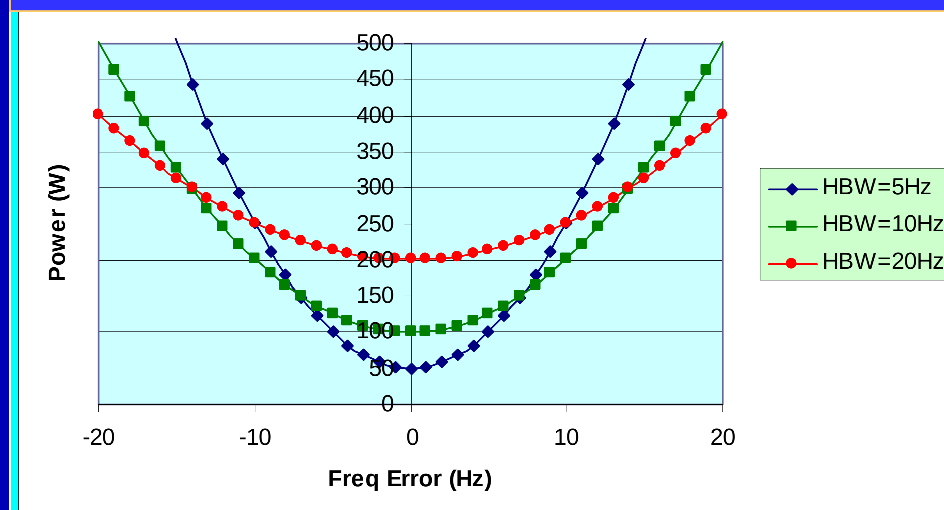
Superconducting quarter wave resonator



RF cavity:

- $Q = 10^9$
- Accelerating field $E_a = 6$ MV/m
- Wall losses 7 W
- Required bandwidth $f_{1/2} = 20$ Hz
- Achieved by overcoupling: $\beta = 200$
- Require $P_f = 200$W at cavity

Forward power required for Ea=6MV/m and given bandwidth



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	141.0–142.0MHz
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

Mode of operation	CW operation	Pulse conditioning
Power range	1 - 250 Watt	250 - 600 Watt
Gain linearity	$< \pm 0.5$ dB	$< \pm 2.0$ dB
Phase drift, degree	$< \pm 5^{o}$	$< \pm 20^{o}$
Phase noise*, rms	0.3^{o}	-
Amplitude noise*	0.6%	-

* 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

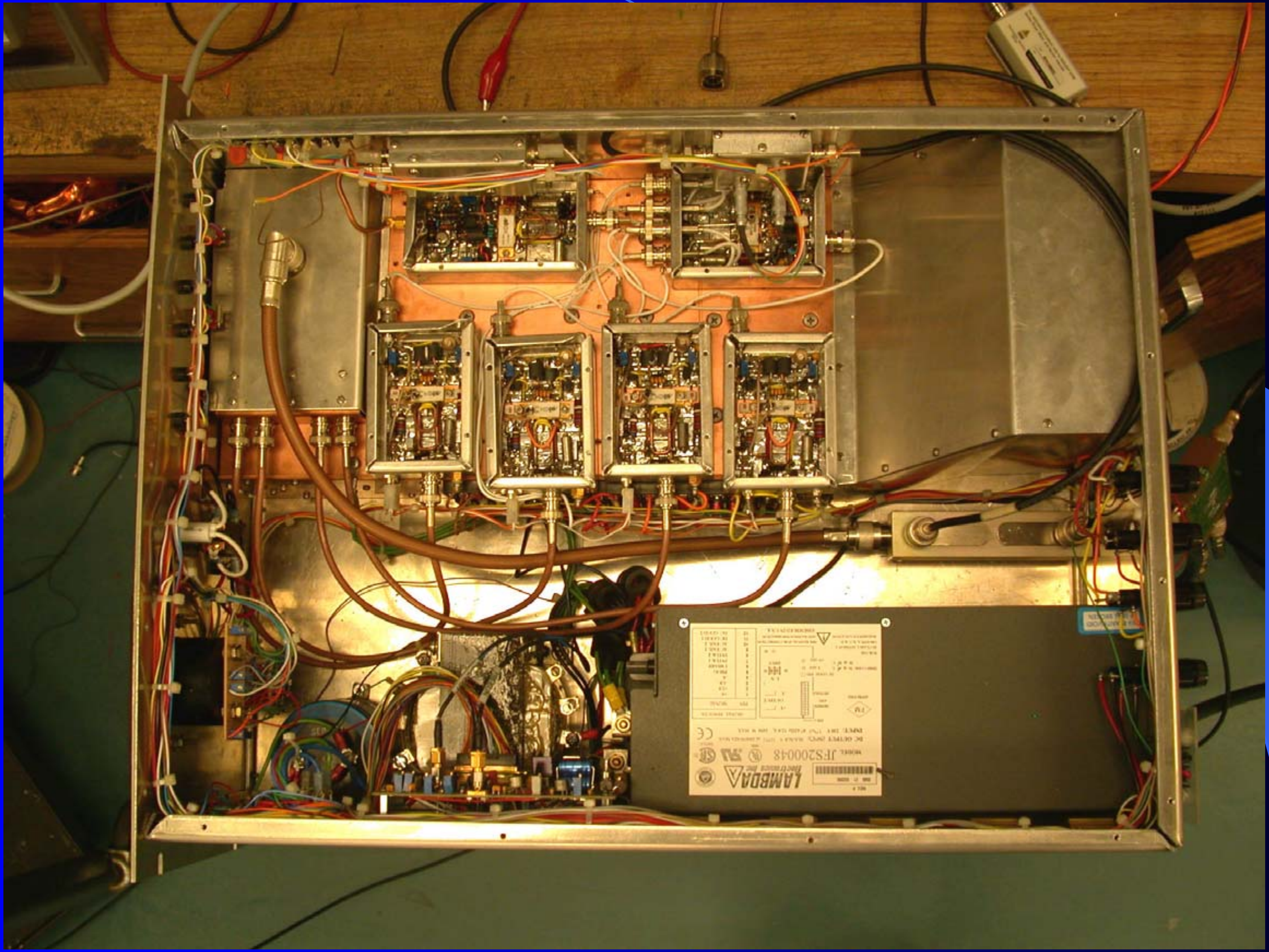
- Performance
  - Power capability
  - Gain linearity
  - Phase stability
- Reliability
- Serviceability
- Efficiency
- Cost

Amplifier prototypes tests

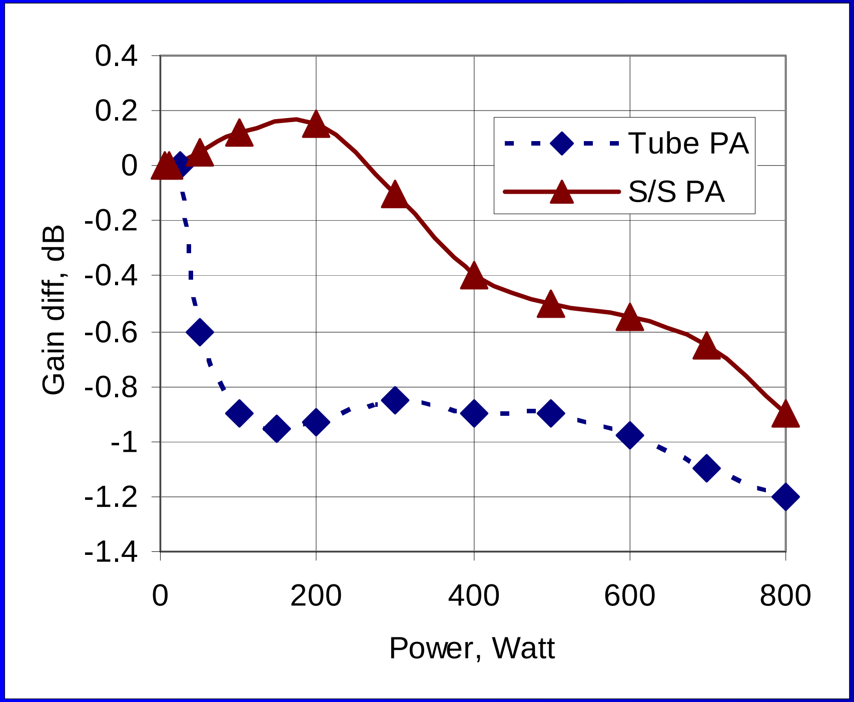
Evaluated amplifiers :

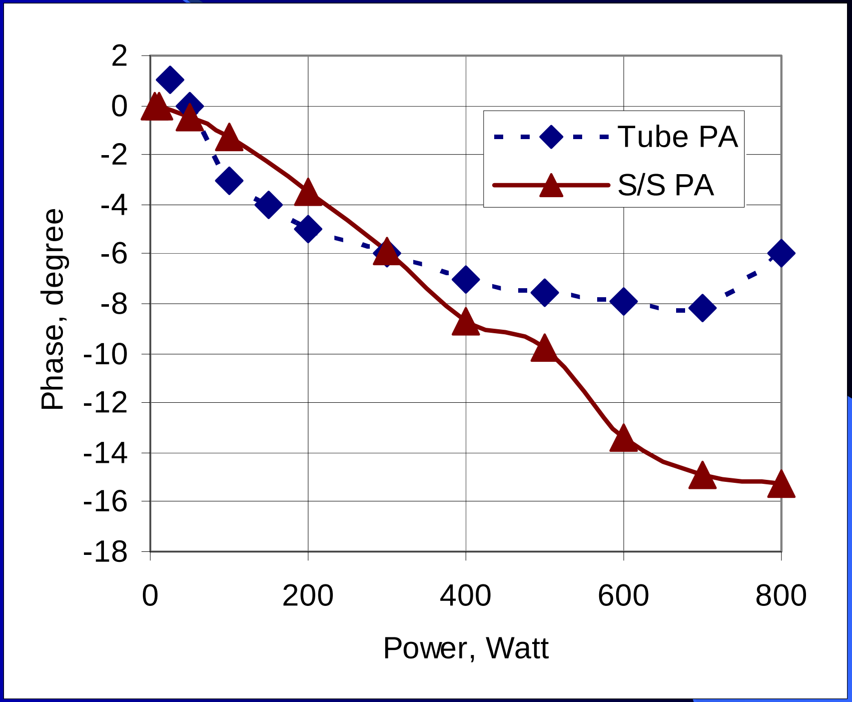
1. Tube amplifier (Eimac 3CX1200Z7)
2. Four Solid State amplifiers:
   - 3 commercial units
   - 1 amplifier of TRIUMF design

S/S amplifier prototype view

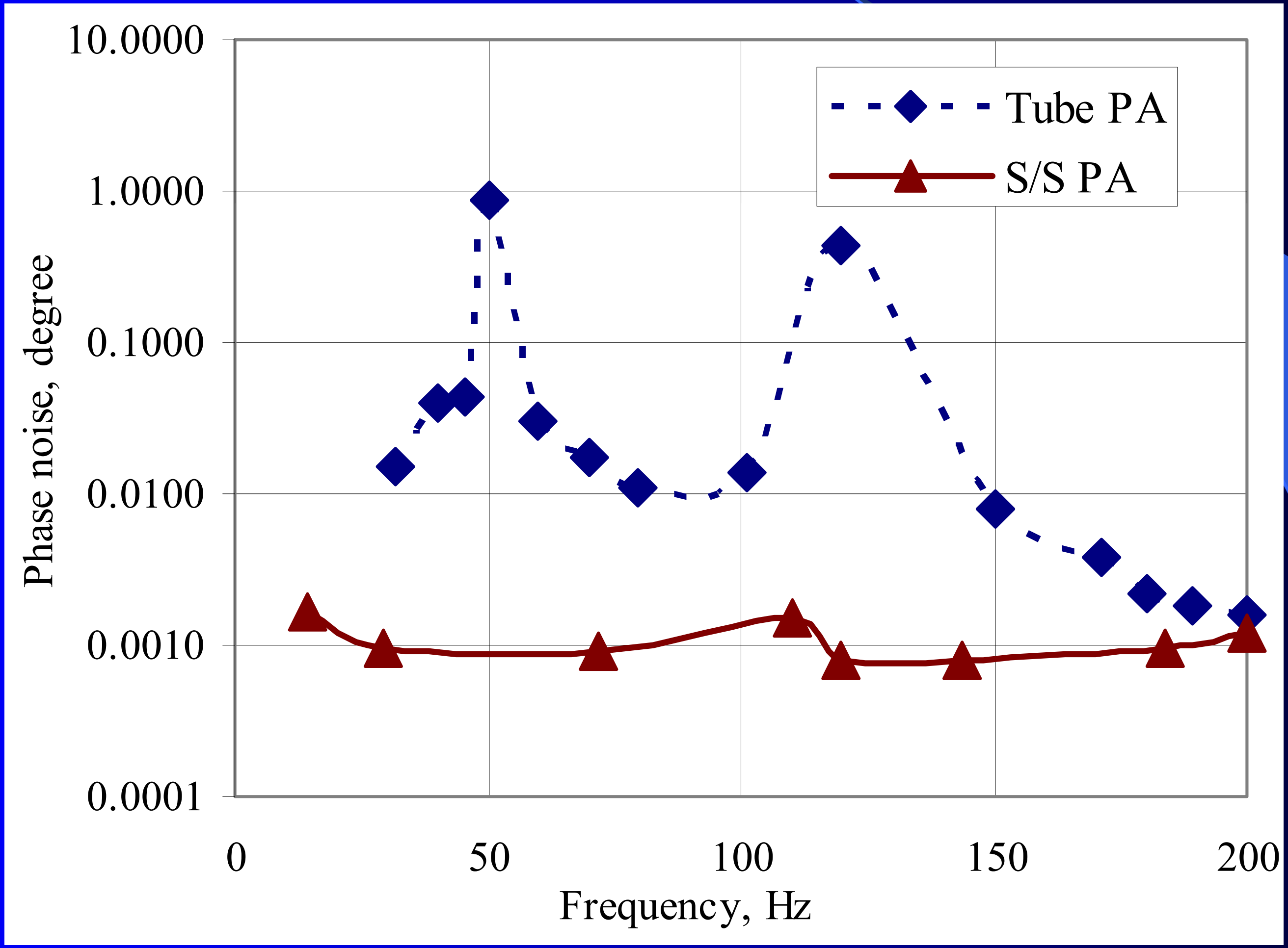


Amplifier gain and phase variations





Phase noise measurement



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)

Parameter	New tube	Retired tube
Tube input VSWR	1.2	2.5
Tube stage gain	14 dB	2 dB
Maximum power	900 W	90 W
Frequency	106.1 MHz	109.5 MHz
Phase shift	0	>100°

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

Description	Tube PA	S/S PA
Budgetary price	15 k$	25 k$
Electricity cost	3 k$	2 k$
Tube / transistor replacement	10 k$	0.1 k$
Fan & other components replacement	1 k$	1 k$
Total cost over 10 years	29 k$	28.1 k$

Tube and Solid State Amplifiers Comparison

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

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.