Calabazas Creek Research, Inc.

A 100 kW, 1.3 GHz, Magnetron System with Amplitude and Phase Control

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Phase Locked Magnetrons

- Application is for driving superconducting accelerators
- Magnetrons are very inexpensive
  - ~ $0.50/W for magnetrons to 100 kW CW at 915 MHz
  - ~$2.5/W for accelerator relevant magnetron system versus ~$5/W for klystron
- Phase locking allows control of phase and combining of multiple magnetrons – previously demonstrated
- Many systems require amplitude control based on accelerator loading
- Fermilab recently demonstrated method for amplitude as well as phase control[1]

[1]B. Chase, R. Pasquinelli, E. Cullerton and P. Varghese, "Precision Vector Control of a Superconducting RF Cavity driven by an Injection Locked Magnetron," Journal of Instrumentation, Volume 10 March 2015.

Fermilab Approach

- Applicable for high Q (superconducting) accelerator cavities
- Uses external phase locking of magnetron
- Amplitude control achieved by phase modulating the locking signal → transfers power to side bands
  - Side bands are rejected by high Q accelerator cavity
  - Power into the cavity = magnetron power less the side band power

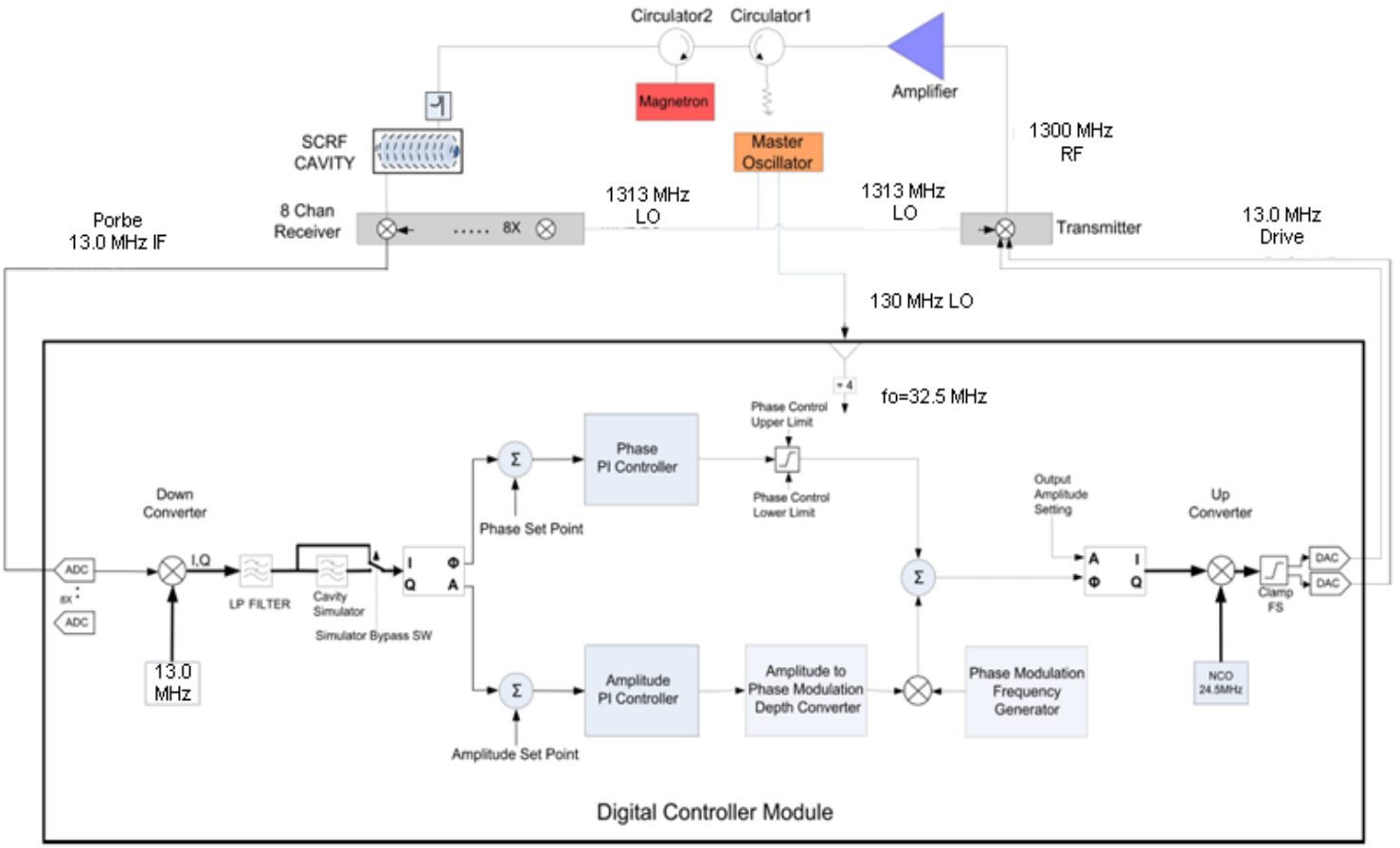
Program Goals

Demonstrate a phase locked, 100 kW 1300 MHz magnetron with phase and fast amplitude control

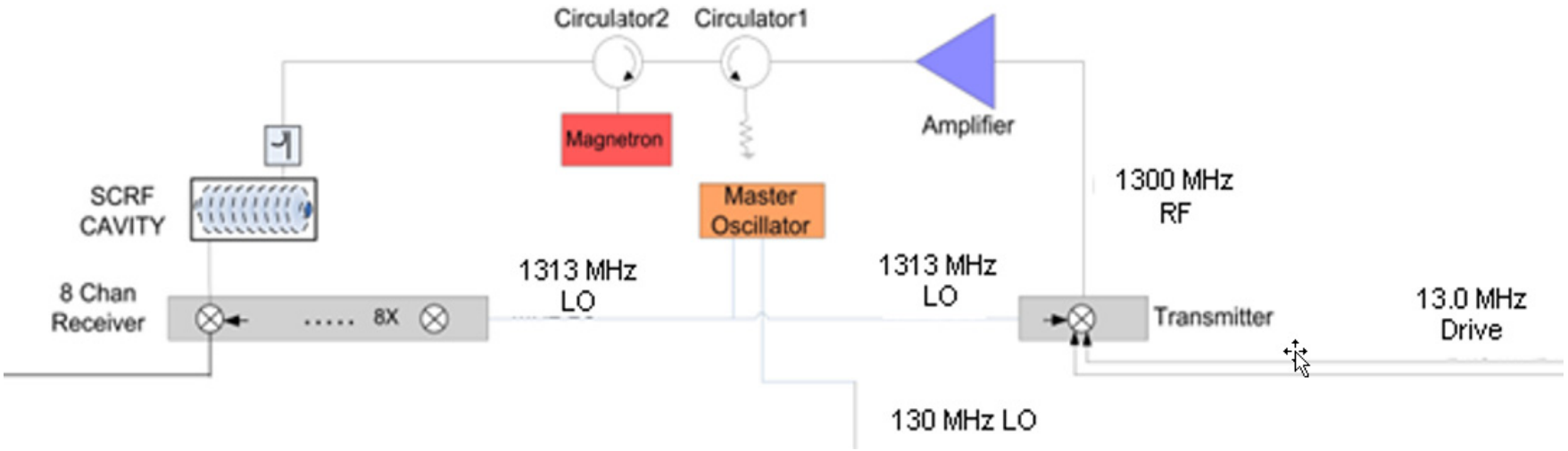
Principal Tasks:

- Development of 100 kW 1300 MHz at 10% duty
- Build integral system with magnetron and support systems (system controls, diagnostics, cooling, interlocks, locking power source, etc.)
- Demonstrate phase locking
- Demonstrate fast amplitude control

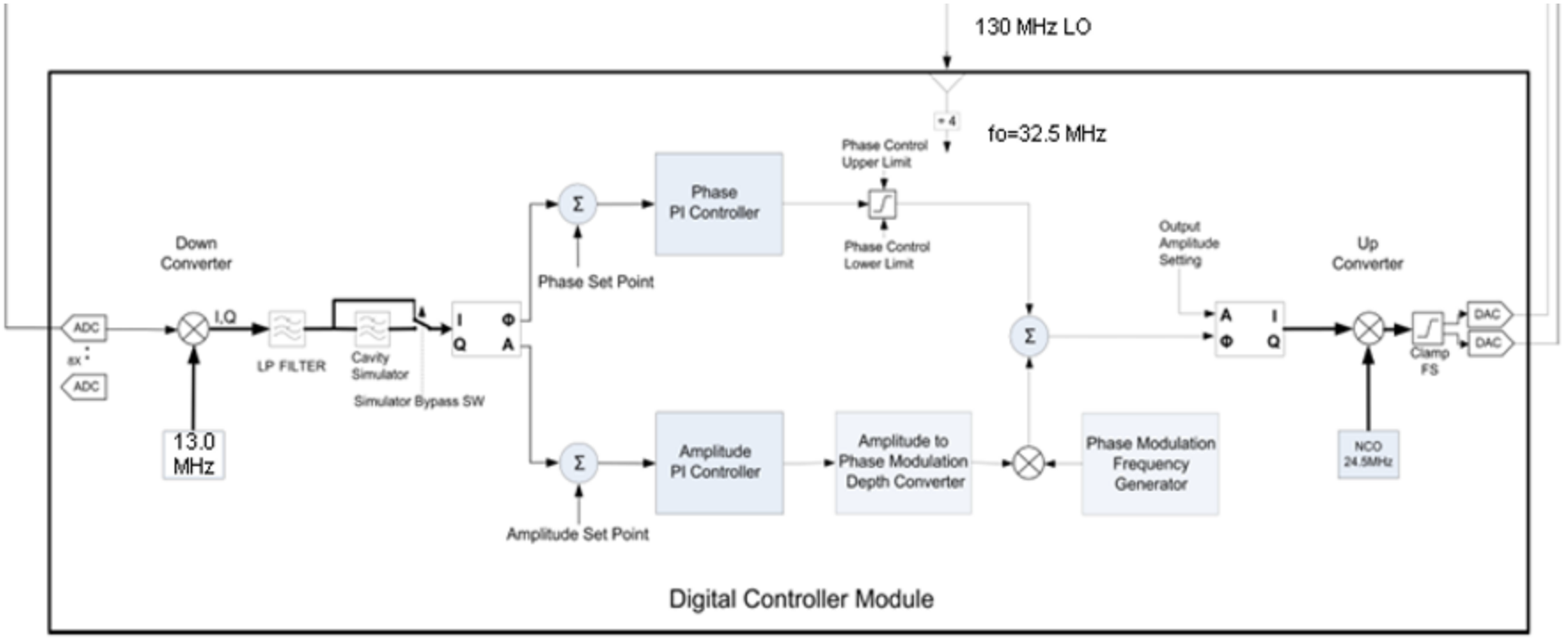
Fermilab System Layout



Fermilab System Layout

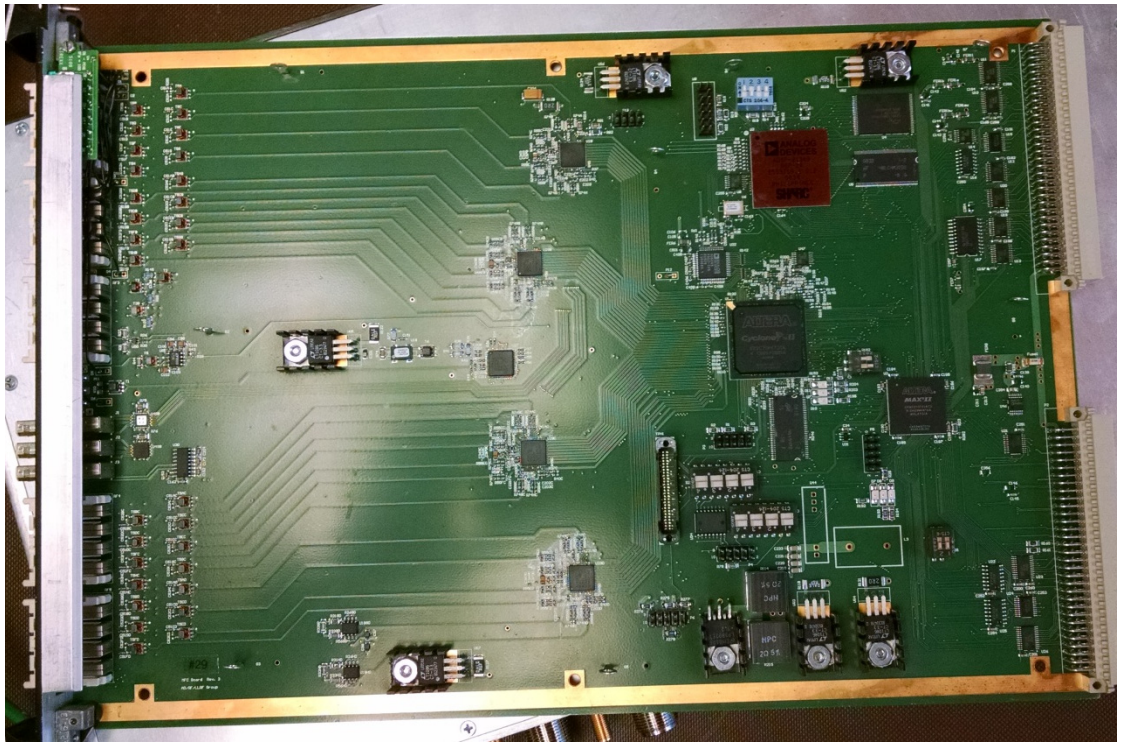


Fermilab System Layout

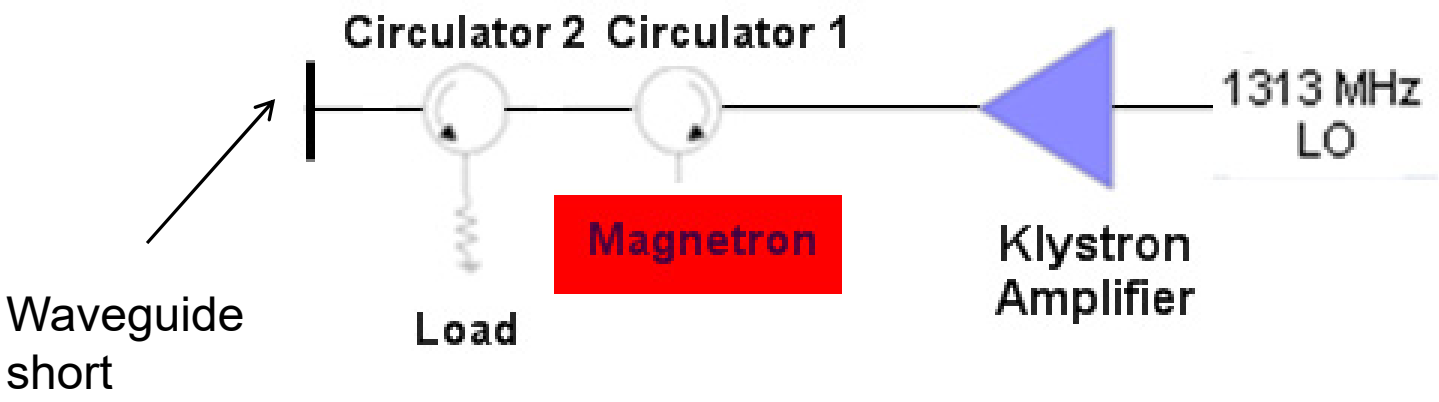


Electronics Development

- Electronics including the Field Programmable Gate Array (FPGA) will be next generation of board developed at Fermilab
- Current 10 layer board has 8 channels

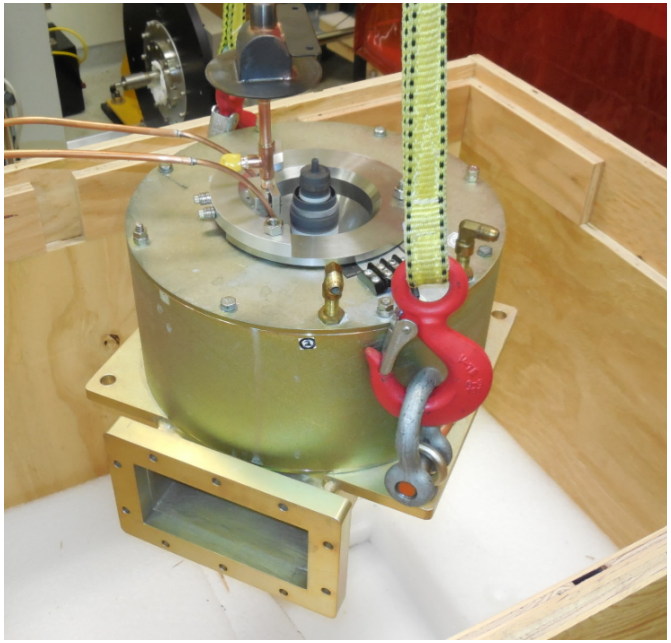


CCR System

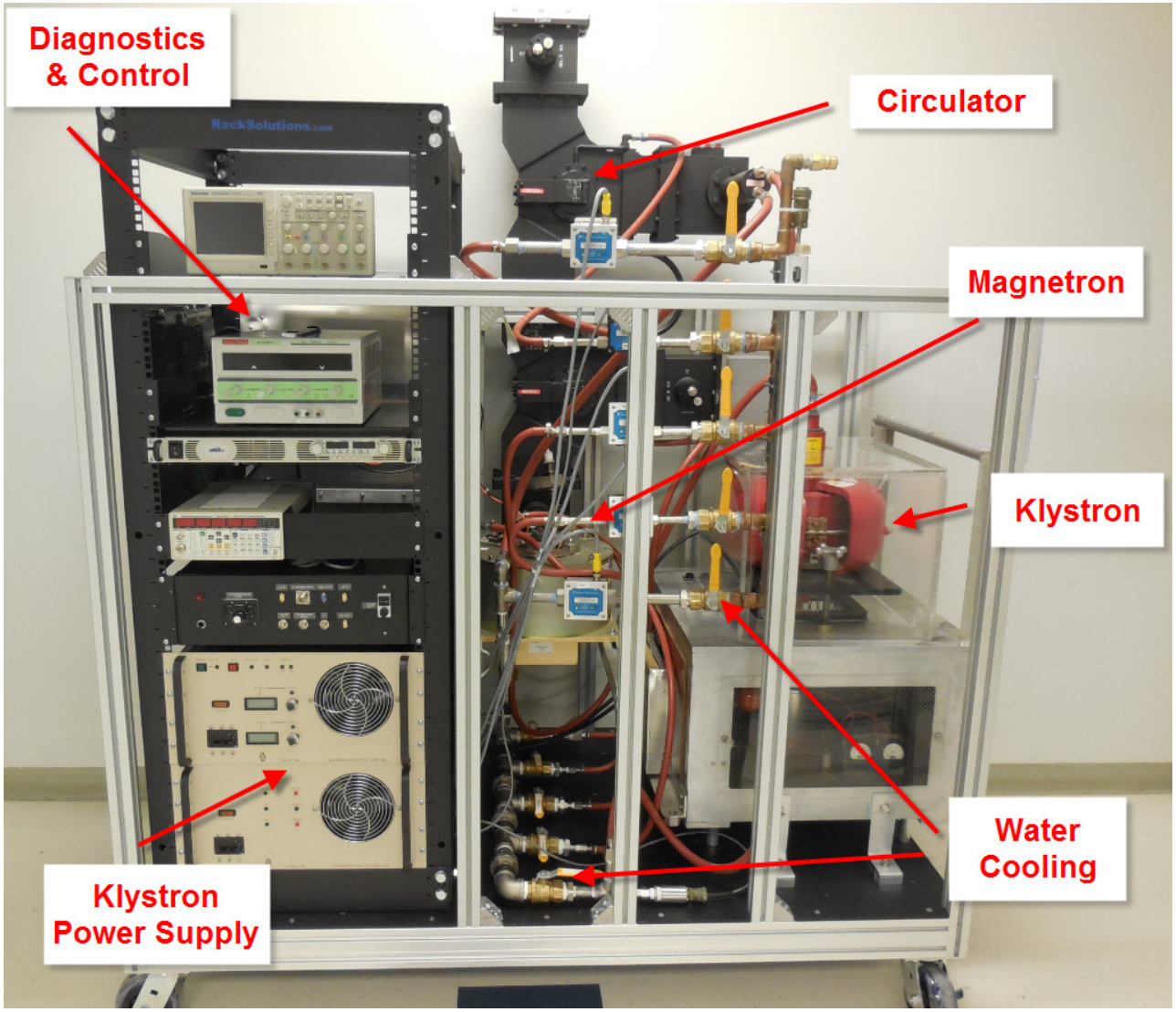

Circulator 2
Circulator 1
1313 MHz
LO
Magnetron
Klystron
Amplifier
Waveguide
short
Load

Magnetron

- 1300 MHz
- 100 kW peak
- 10 kW average
- 1.5 msec pulse width
- 17.5 – 23.5 kV
- 2 – 5 A beam current

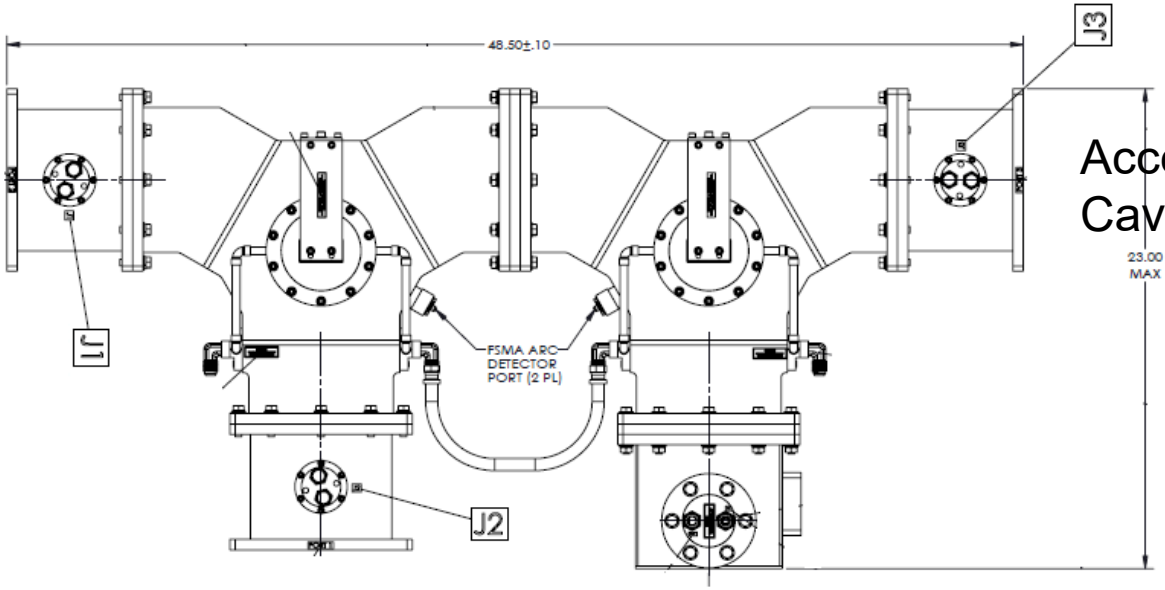


Packaged Magnetron System



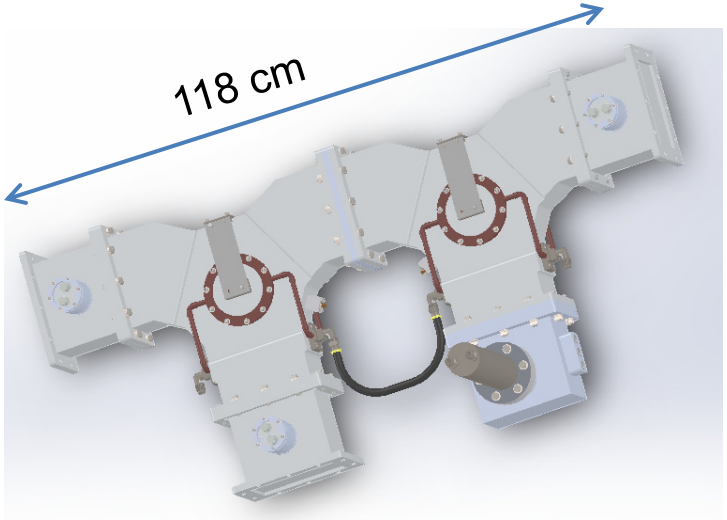
Circulator

Magnetron



Accelerator Cavity

Driver

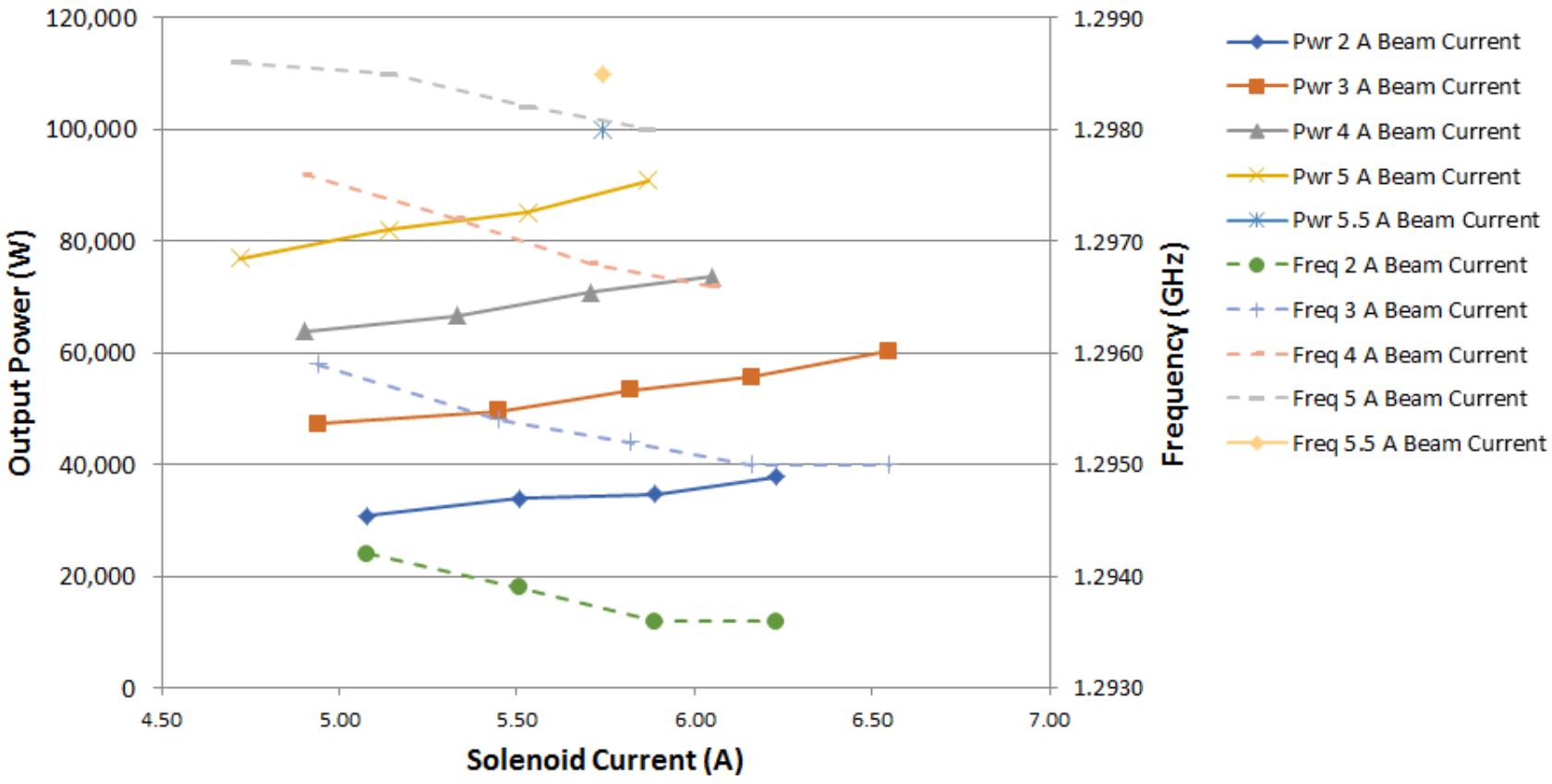


Manufacturer:
Ferrite Inc.

Test Results

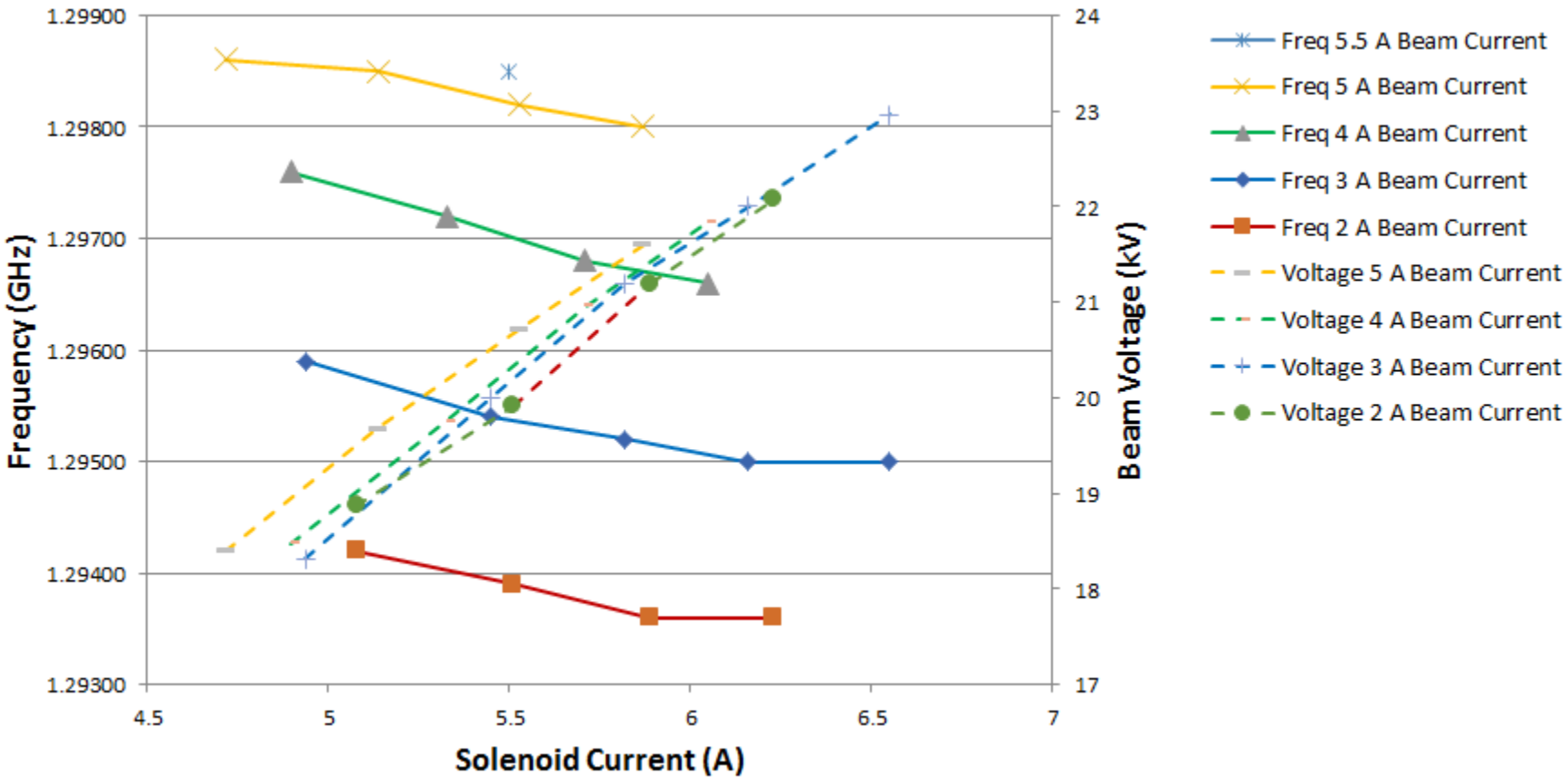
- Magnetron operated to full 1.5 ms pulse width and 100 kW peak power
- Average power of 300 W limited by test time
  - Design is based on 100 kW 915 MHz tube
  - Scaling by $f^{-2.5}$ gives a power capability of 42 kW at 1300 MHz
- Locking demonstrated at
  - 2.6 MHz with -15 dB drive
  - 0.9 MHz with -25 dB drive
- Phase modulation demonstrated

Magnetron Operating Range



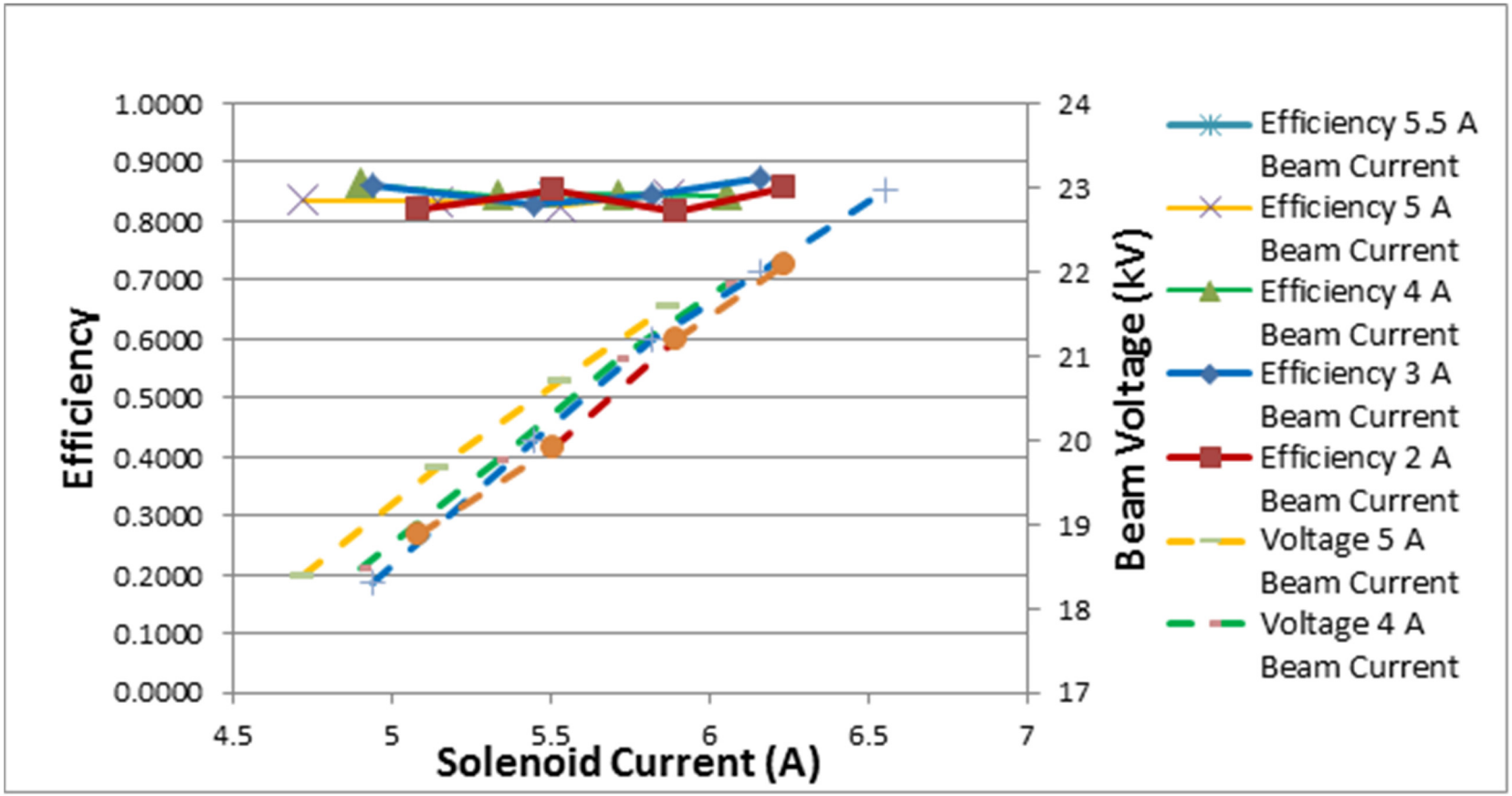
Magnetron Operating Range

Frequency / Beam Voltage – Solenoid Current



Efficiency

Efficiency varied between 81% and 87%, depending on parameters



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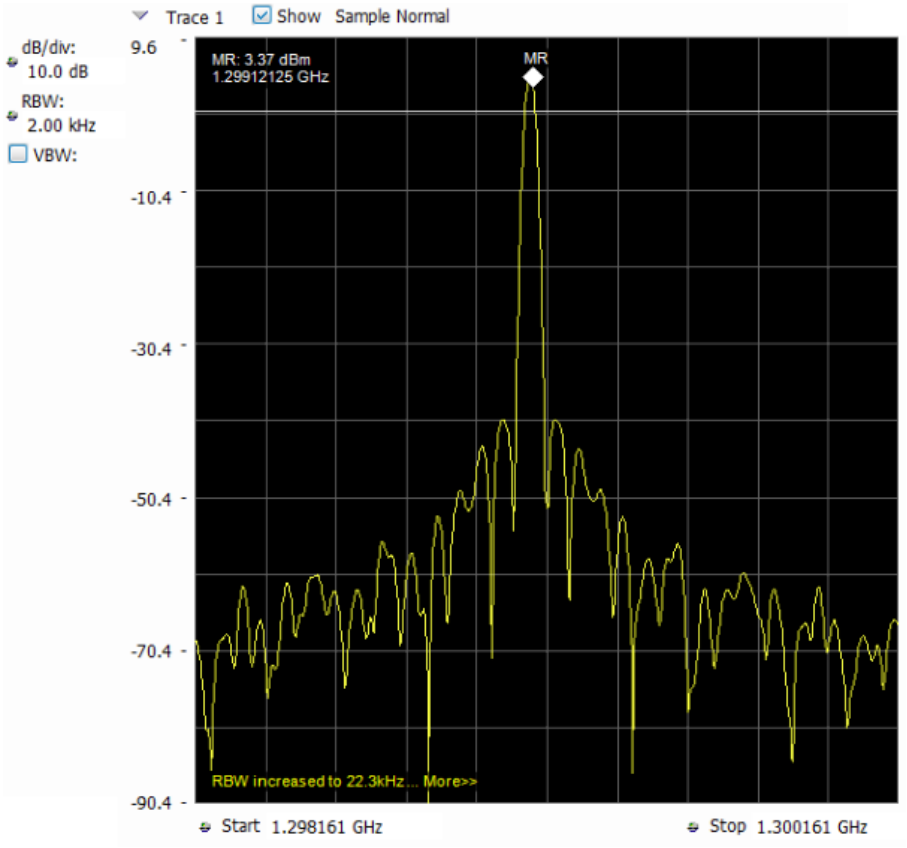
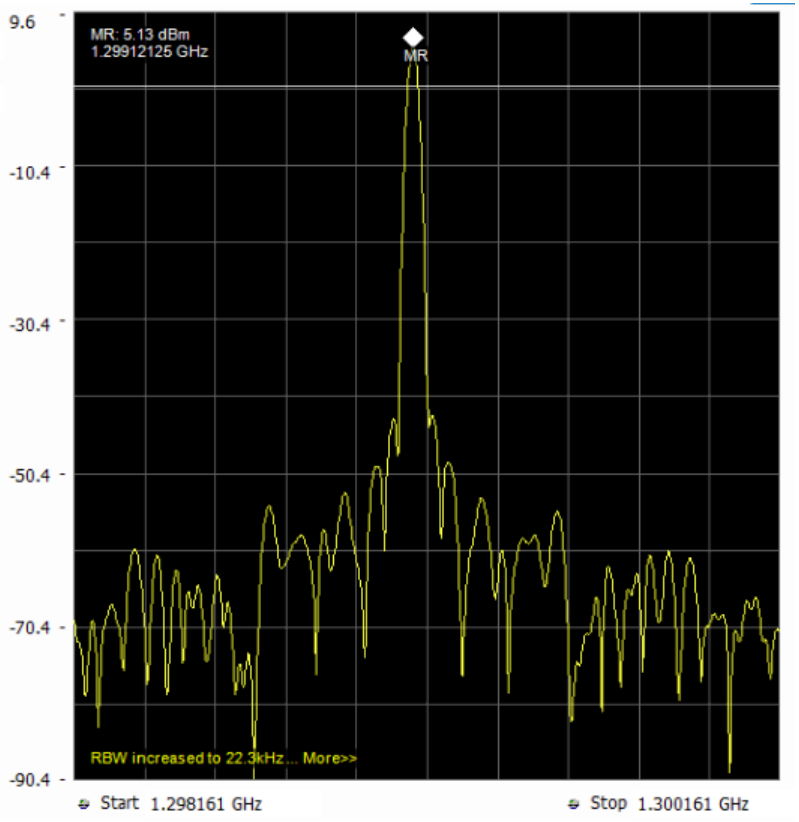
Magnetron Spectra

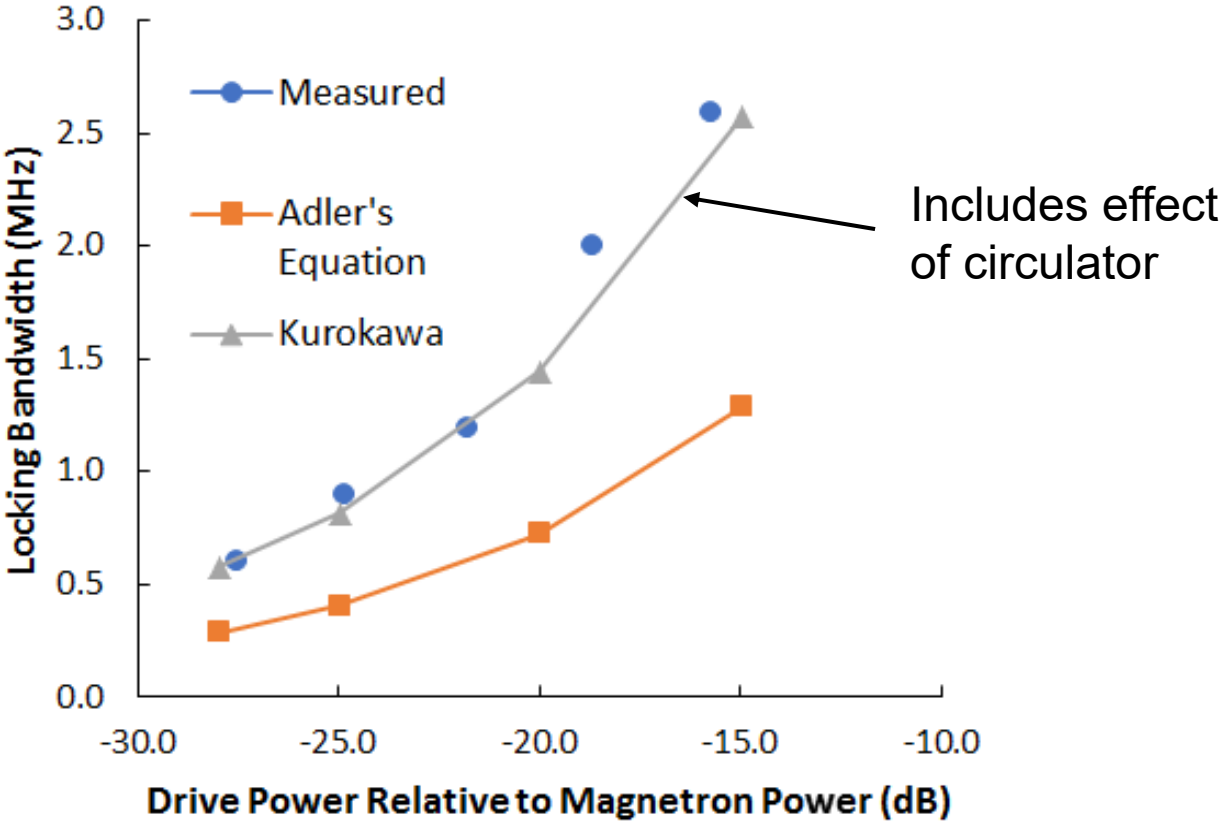


Free Running Magnetron



Driven magnetron with drive power -15 dB at the natural frequency of the magnetron.

Locking Bandwidth



R. Adler. "A study of locking phenomena in oscillators," Proceedings of the I.R.E. and Waves and Electrons, 34:351–357, June 1946.

K. Kurokawa, "Injection Locking of Microwave Solid-State Oscillators," Proc. IEEE, Vol 61, No. 10, (1973).

Phase Locking

- For 83 kW of magnetron power, 269 W was required to lock over a bandwidth of 0.9 MHz.
- Implies 302 W required for 0.9 MHz bandwidth at 100 kW.
- Solid-state power supplies available for phase locking
- Locking power requirement in good agreement with theory that includes circulator

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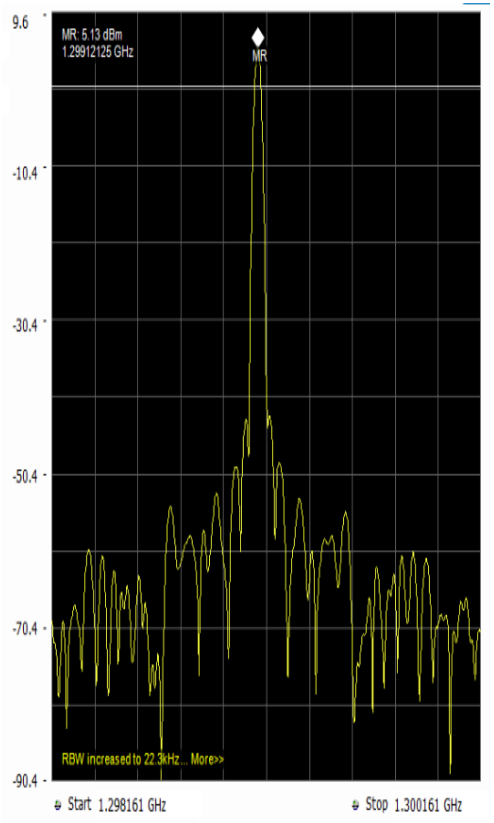
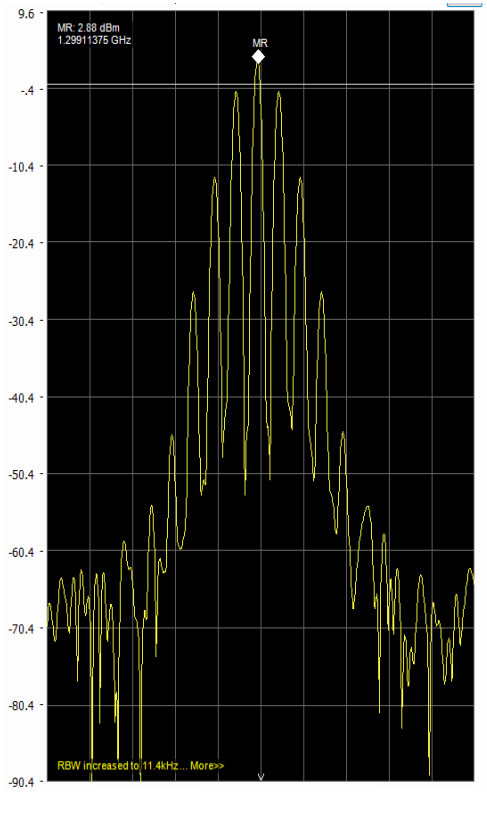
Phase Modulation

50 MHz Phase Modulation



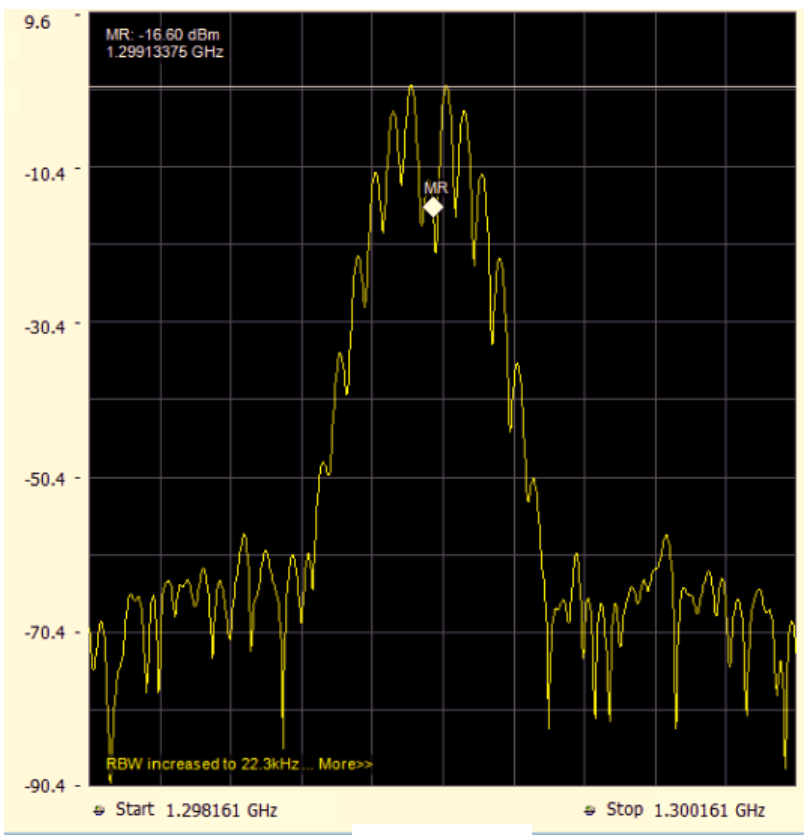
2 MHz

No Modulation



1 MHz

60° Modulation



2 MHz

122° Modulation

System Status

- Major testing completed
- System currently stored at Fermilab
- Available for further testing
  - would like to test into SC cavity

System Cost

Estimated for one system (exclusive of high voltage supply)

Magnetron	$72,000
500 W SS amplifier for locking	$17,000
Circulator w waveguide	$20,000
Controls	$10,000
Packaging	$10,000
TOTAL	$129,000

Magnetron pricing (July 2018)

Part Number	Product Description	Min Qty	Max Qty	Unit Price
VML3133	MAGNETRON	1	1	$72,283
VML3133	MAGNETRON	5	5	$39,831
VML3133	MAGNETRON	20	20	$26,748
VML3133	MAGNETRON	100	100	$19,835

Summary

- Peak Power goal of 100 kW achieved
- Average power limited due to test time
  - design value is 10 kW
- Magnetron efficiency was 81% - 87%
- Required locking power less than 400 W
  - available from solid state supplies
- Fast amplitude control demonstrated
- System cost approximately ¼ of klystron cost