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Precision Vector Control of a Superconducting RF Cavity Driven by an Injection Locked Magnetron

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October 10, 2016

NA-PAC 2016 - Chicago

Magnetron Collaboration

- Calabazas Creek Research Inc
  - Michael Read, R. Lawrence Ives, Thuc Bui
- Fermi National Accelerator Laboratory
  - Brian Chase, Ralph Pasquinelli, Ed Cullerton, Philip Varghese Jonathan Edelen, Josh Einstein
- Communications and Power Industries LLC
  - Chris Walker, Jeff Conant
- Previous Collaboration with Muon's Inc.

  Gregory Kazakevitch

Outline

- Multi-megawatt accelerators efficiency goals
- Control schemes
- Experimental results
- Ongoing research

Take-a-ways from the Proton Driver High Efficiency Workshop at PSI

- **Proton Drivers**:
  - GeV-energy range
  - MW-beam power range
- Applications: neutrinos, muons, neutrons, Accelerator Driven Systems(ADS).
- **Types of accelerators for proton drivers:**
  - Cyclotrons and Fixed-Field Alternating Gradient accelerators (FFAG);
  - Rapid Cycle Synchrotrons (RCS);
  - High intensity pulsed linear accelerators;
  - CW Superconducting RF linear accelerators.

Efficiency Goals

ADS Accelerator Efficiency

$$P_{GRID} = P_{beam}\left[\frac{\eta_{el} G_0 k}{1-k} - \frac{1}{\eta_{acc}}\right]$$

For a typical ADS (Rubbia) the first term is of the order of 50

- The electric power to run the accelerator must be small compared to the power produced in the ADS core:

$$\frac{1}{\eta_{acc}} << 50 \Rightarrow \eta_{acc} >> 0.02$$

- Minimum is $\eta_{acc} = 0.2$, but $\eta_{acc} = 0.4$ should achievable and in that case the accelerator takes only 5% of the electric power produced by the ADS, which seems reasonable
- For very high power beams (≥ 10 MW), every MW saved matters, and it is useful to have the highest possible accelerator efficiency, if it does not compromise other properties (cost, reliability, etc.)

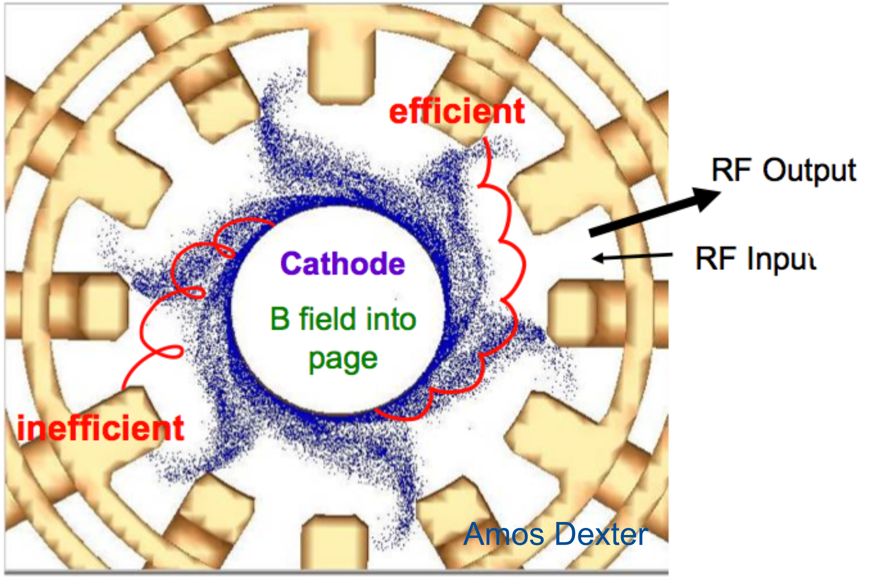
iThEC

Revol/PSI/2016

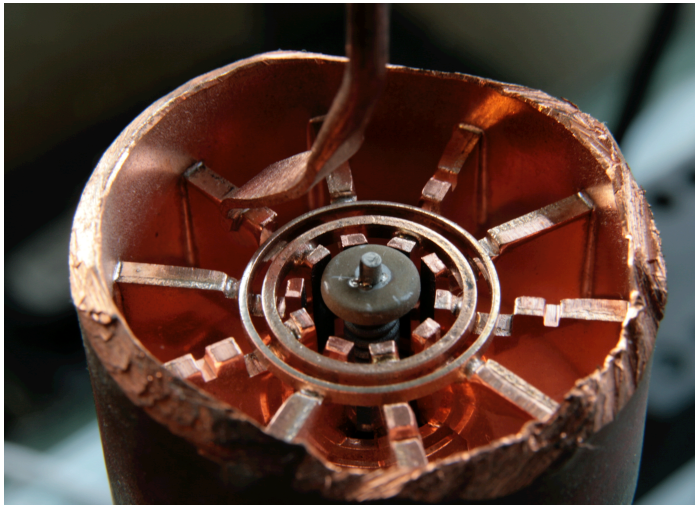
- For high power SRF linacs the RF sources are a key component in overall wall-plug efficiency

The basics of magnetron operation

Cathode at negative potential accelerates electrons outward.
B field causes electrons to spiral
E field across gaps causes bunching into electron cloud spokes. Rotating spokes intern excites cavities. RF power is coupled out and is constant amplitude.



RF maybe driven in on same port and cause the spokes to phase lock up to source.



Cross section of a cooker magnetron showing cathode and cavities

R. Adler, A study of locking phenomena in oscillators, Proc. IRE and Waves and Electrons, vol. 61, no. 10, pp. 351-357, June 1946.

Industrial CW Magnetrons

Table 1. Characteristics of CW Industrial Heating Magnetrons from Domestic Manufacturers

Manufacturer	Type	Frequency (MHz)	Power (kW)	Effic (%)	Voltage (kV)	Current (A)
California Tube Labs	CWM-300L	915	300	90	32	10
California Tube Labs	CWM-100L	896, 915	100	88	19.5	5.8
Burle Technologies	S94608E	896, 915	90	85	21	6.5
CPI Beverly	915MHz-75	915	100	85	20	6.0
California Tube Labs	CWM-15s	2450	15	72	12.6	1.7
California Tube Labs	prototype	2450	30			

- High power CW magnetrons used for industrial heating are catalog items
- > 85% efficiency typical
- 100 kW L-band - 18” length, 5” diameter

Magnetrons excel at many RF source requirements

- Power: >100 kW CW and MW scale pulsed operation
  - average power capability increase with lower frequency
- Efficiency: High power devices > 85% at L-band
- Power supply voltage: < 25kV
- Low cost: $0.50/watt at 100kW and 50 units
- Small size: 100 kW pulsed 1300 MHz tube is 1 foot high and does not require an oil tank
- They are easy to replace and rebuild and can be designed for a reasonably long life and low noise
- However, they are basically a constant power device, not a linear amplifier like a klystron

Groups with recent work on/relevant to cross field devices for accelerators

Phase locked magnetrons

Varian Associates (MA) (1991)	Treado, Hansen, Jenkins	(Short pulse)
Univ. Mitchigan (-2013)	Gilgenbach et al.	(Relativistic Magnetrons)
Univ. Lancaster (2003 – 2010)	Dexter, Tahir, Carter, Burt	(CW Cooker type)
J-Lab (2006 – 2013)	Wang	(CW Cooker type)
Muon Inc. , Fermi-Lab & (2007 – 2013)	Kazakevich, Yakovlev	(Power combining)

Efficient L Band Magnetrons

SLAC, CTL, Raytheon	Tantawi et al. (2004)	(CW Coaxial? 300kW)
Diado Instit. Tech. Japan (1991)	Shibata (1991)	(CW Coaxial 600kW

Gyro Klystrons

IAP Nizhny Novgorad	Lebedev
Univ. Maryland	Lawson
Calabazas Creek	

Gyro TWT

Univ. Strathclyde
MIT
IAP Nizhny Novgorad
Univ. Maryland
NRL Washington
Univ. Mitchigan

Amos Dexter

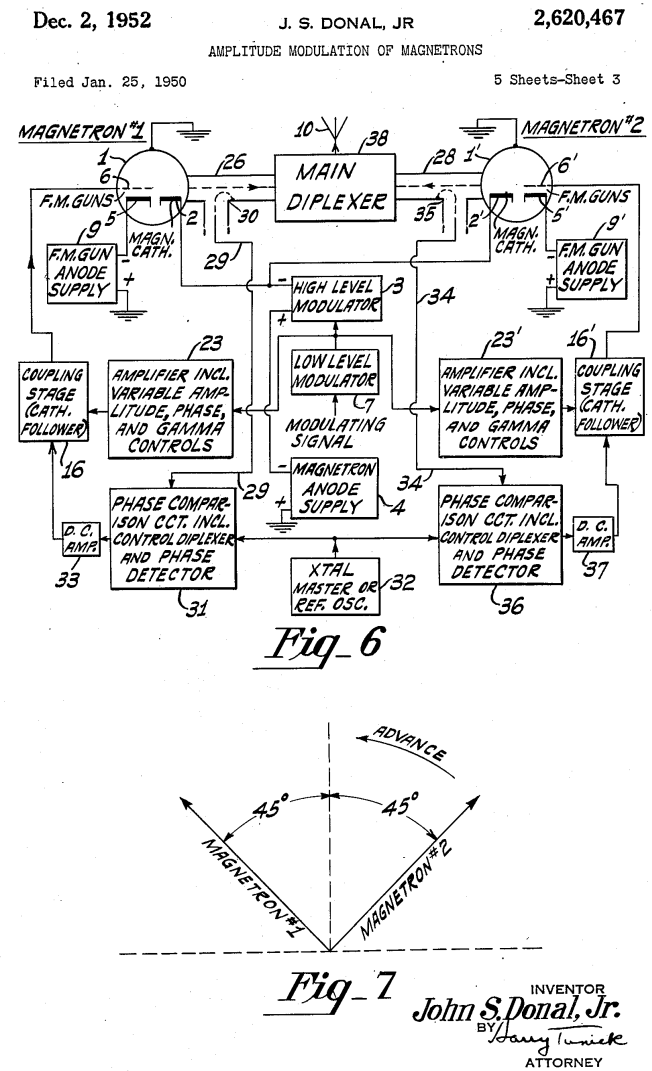
The Royal Academy of Engineering

1950s transmitter using 2 magnetrons and out-phasing

Patent awarded in 1952 for a transmitter design using cathode voltage modulation and out-phasing with two magnetrons

Why was this technology discarded?

Possibly control was touchy with the analog electronics of the time



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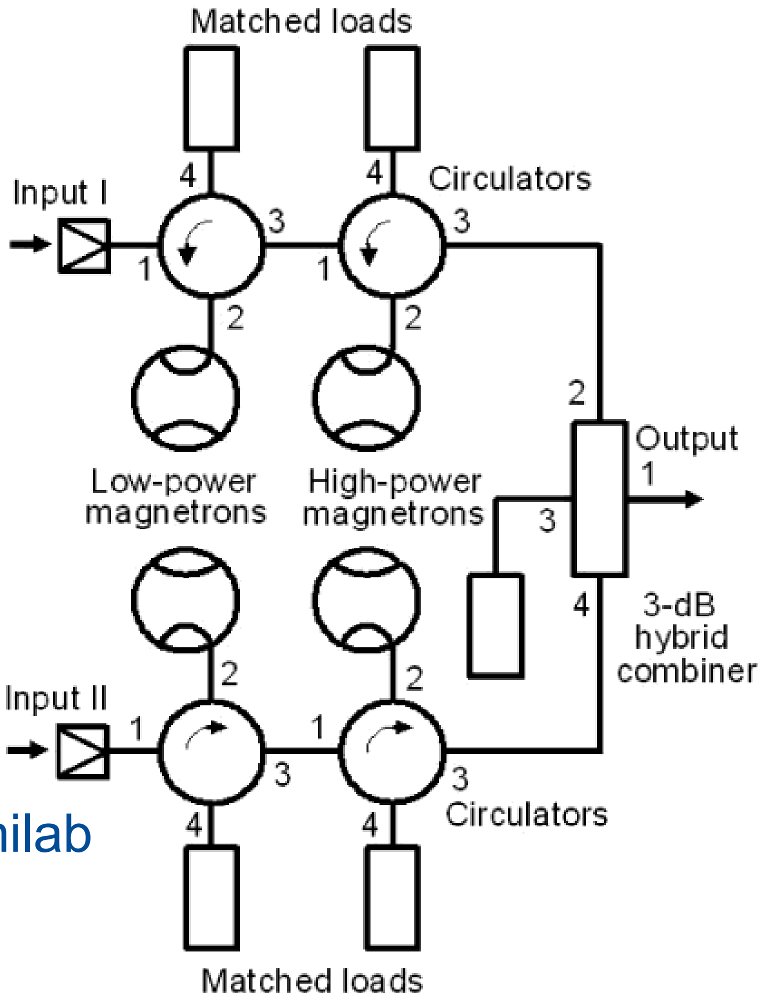
Cascaded magnetrons and out-phasing AM control

Concept: cascade injection locked magnetrons to increase gain, combine two pairs to get amplitude control by outphasing in pulsed mode operation

Outcome: Proof of concept for cascade stage and the realization that we needed CW power supplies to make real progress. Strong belief that this scheme would work but it does have its complexities.

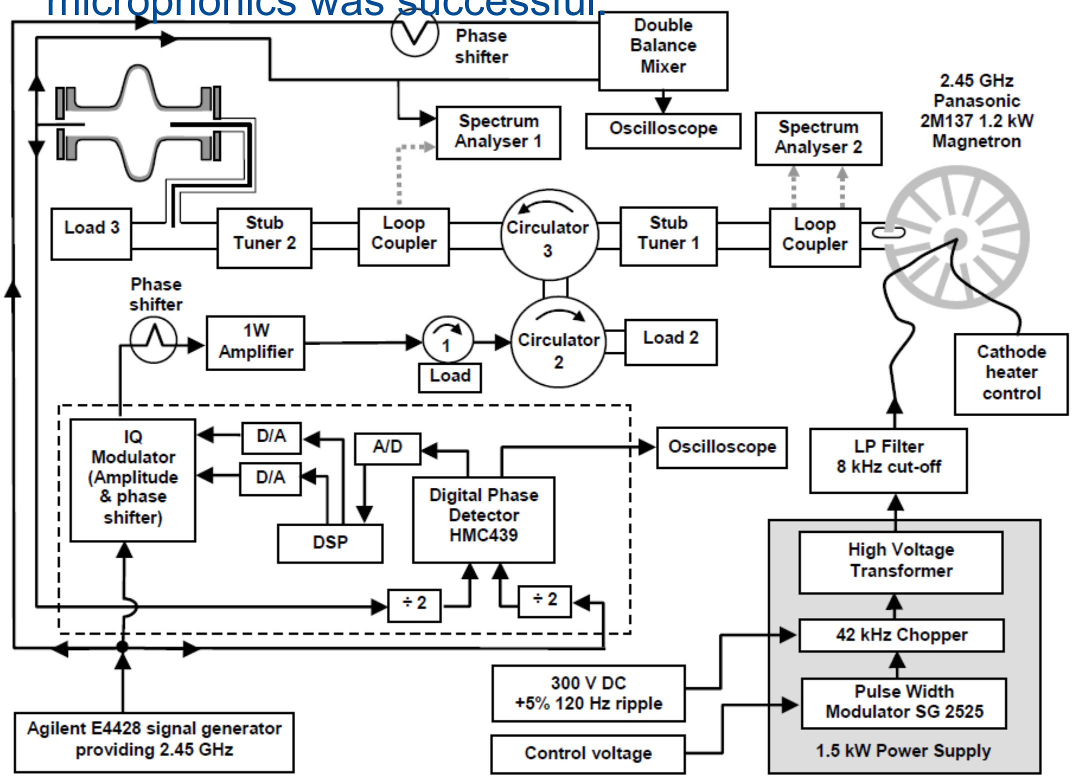
Grigory Kazakevich, et al. Muons Inc.
Yakovlev, Pasquinelli, Chase, et al. Fermilab



Phase control loop around SRF cavity

Lancaster: Amos Dexter, Graeme Burt and Chris Lingwood

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.

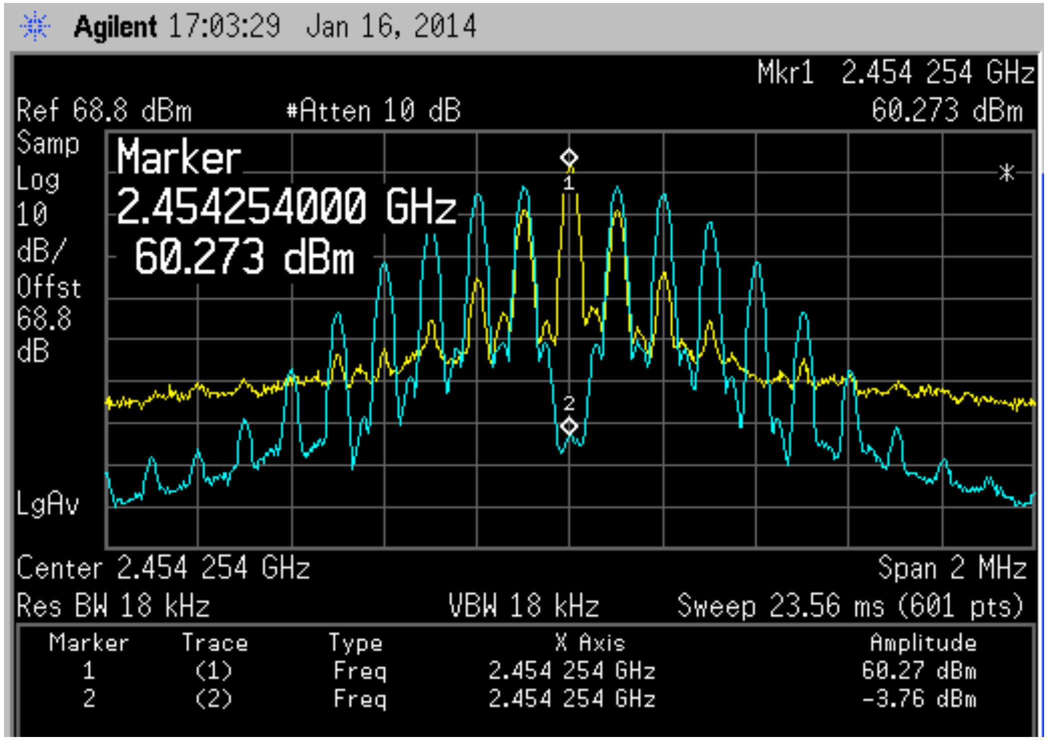


H. Wang *et al.*, "USE OF AN INJECTION LOCKED MAGNETRON TO DRIVE A SUPERCONDUCTING RF CAVITY," in *Proceedings of IPAC'10*, Kyoto, Japan, THPEB067.

Amplitude control by fast phase modulation technique

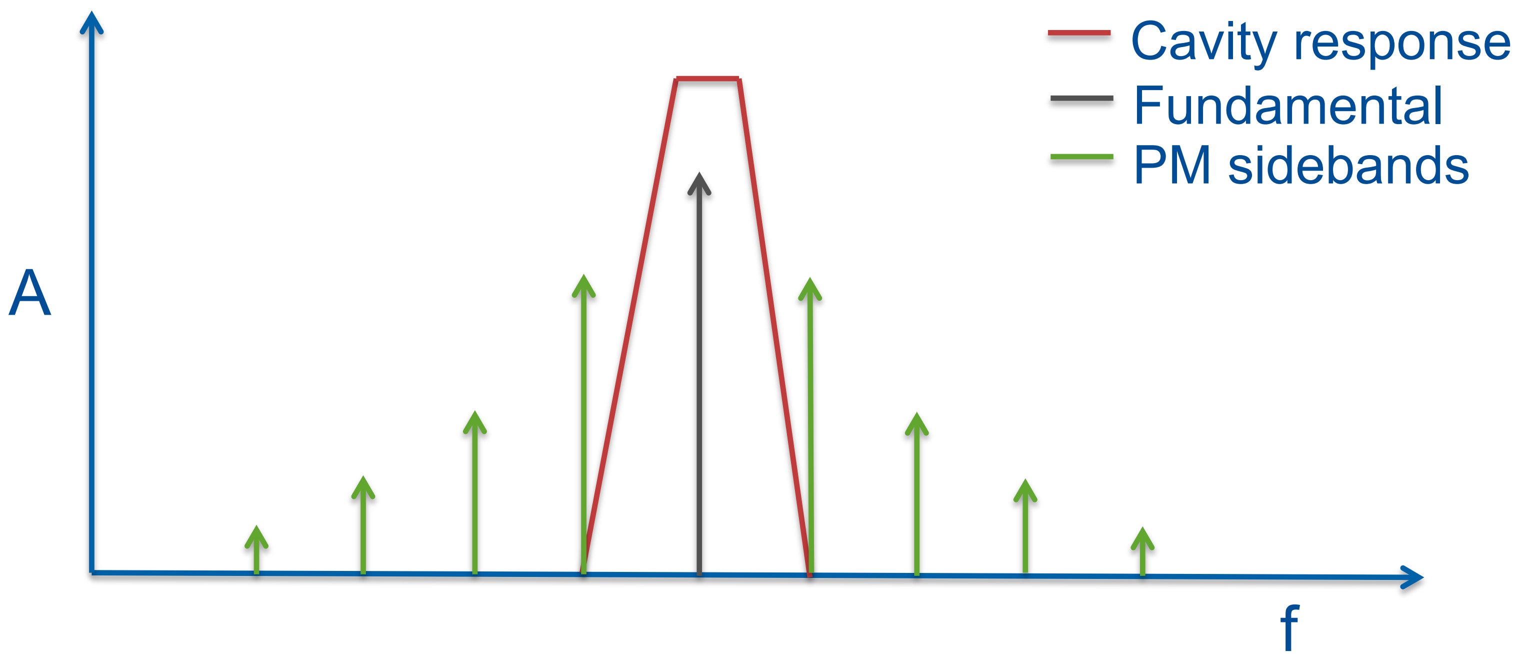
Magnetrons are constant output power devices. However, the power in the carrier destined for the cavity can be reduced by fast phase modulation, moving power from the carrier into discreet Bessel sidebands that are outside the cavity bandwidth. These sidebands will be reflected from the cavity and back to the circulator load

Increasing the modulation depth(137 degrees) suppresses the carrier over a measured 64 dB dynamic range in lab



Rejection of PM sidebands by Narrowband Cavity

While output power is constant, sinusoidal phase modulation creates discrete sidebands at multiples of the modulation frequency while the power shifted from carrier to sidebands is determined by modulation depth



Phase Modulation Equations

$$Acos(\omega_C t + bsin\omega_M t) = AJ_0(\beta)cos\omega_C t +$$

$$\sum_{k=1}^{\infty} J_{2k}(\beta)[sin(\omega_C + 2k\omega_M)t + sin(\omega_C 2k\omega_M)t] +$$

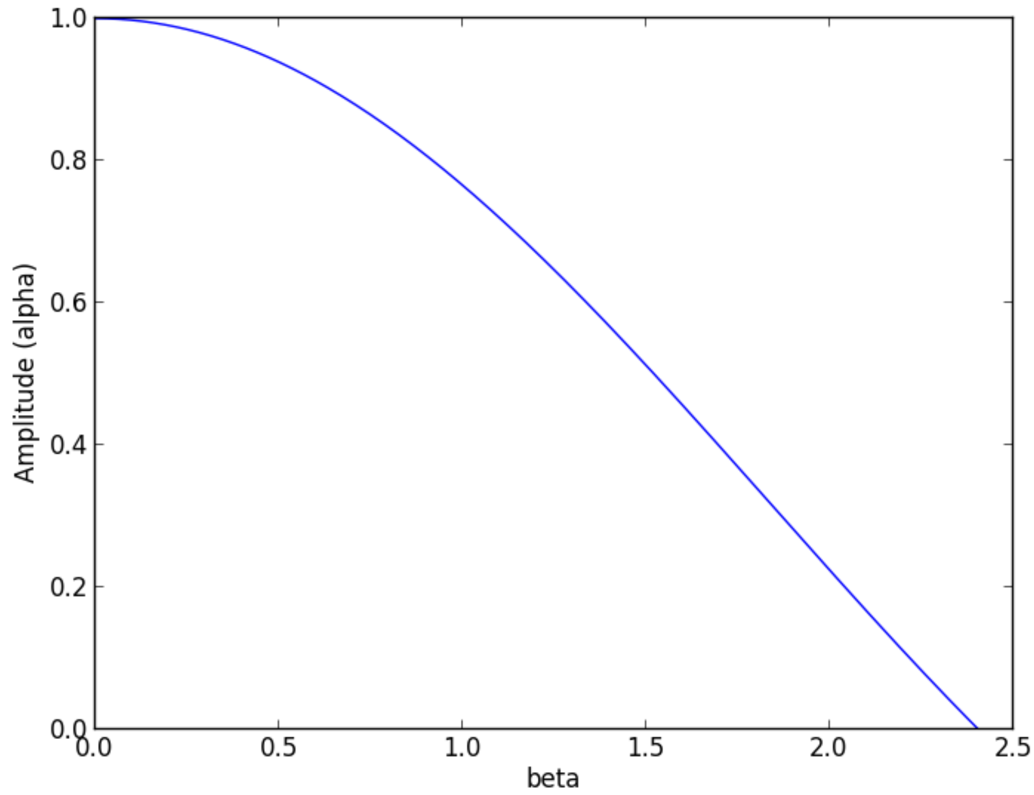
$$\sum_{k=0}^{\infty} J_{2k+1}(\beta)[cos(\omega_C + (2k+1)\omega_M)t - cos(\omega_C - (2k+1)\omega_M)t]$$

$$J_0(\beta) = 1 - \frac{\beta^2}{2^2} + \frac{\beta^4}{2^2.4^2} - \frac{\beta^6}{2^2.4^2.6^2} + \ldots$$

Used for generation of amplitude-to-phase LUT. Generates a lookup table such that the region Before the first null in the Bessel is covered by the controller. Allows for linearization corrections By just adding a scaling table.

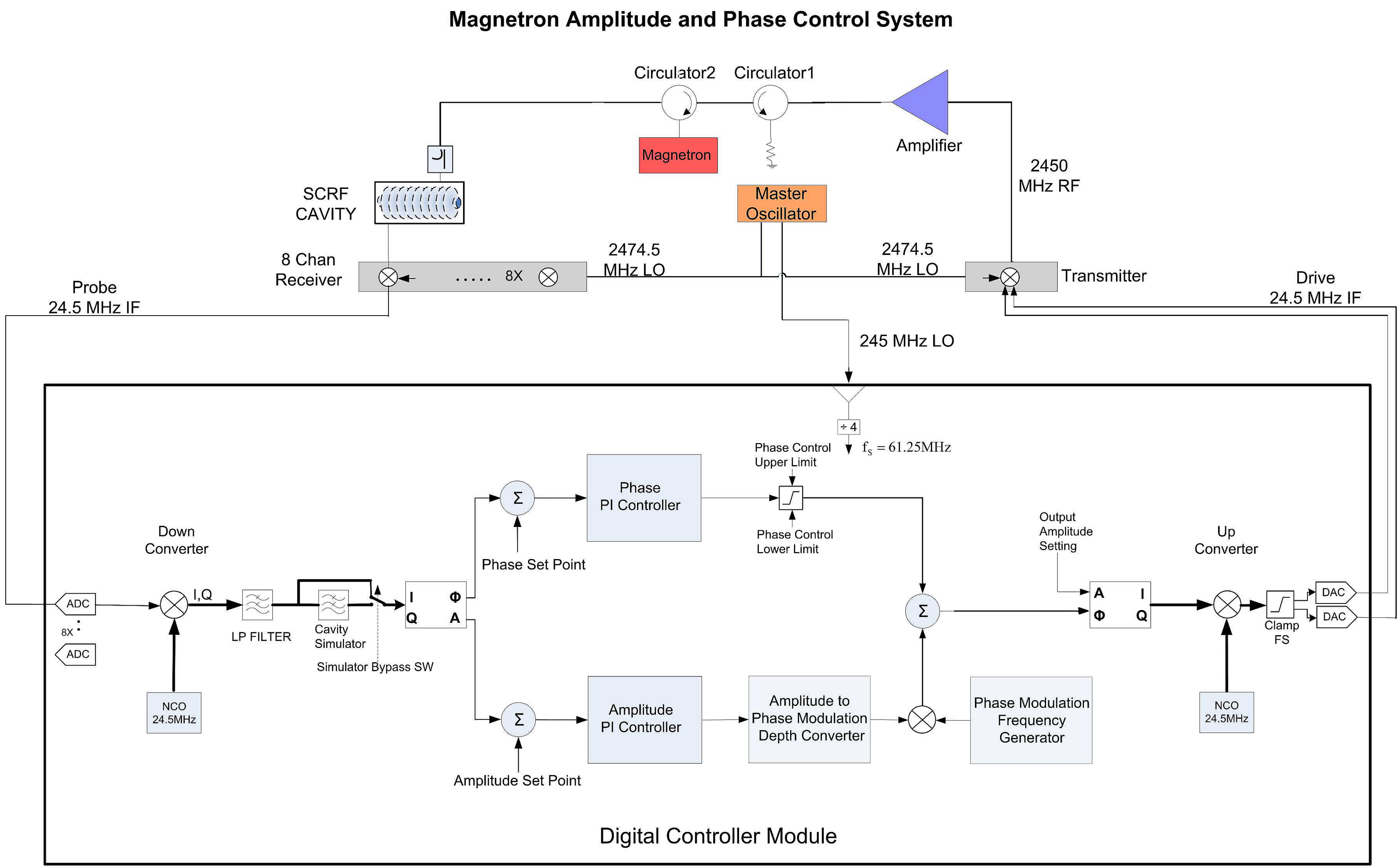
$$J_0(\beta) - \alpha = 0$$

Bessel of the first kind, Region before first null



Inverse function in look up table drives phase modulation depth to linearize cavity drive

LLRF controller for 2.45 GHz SRF cavity driven by 1.2 kW Magnetron using Fast Phase Modulation



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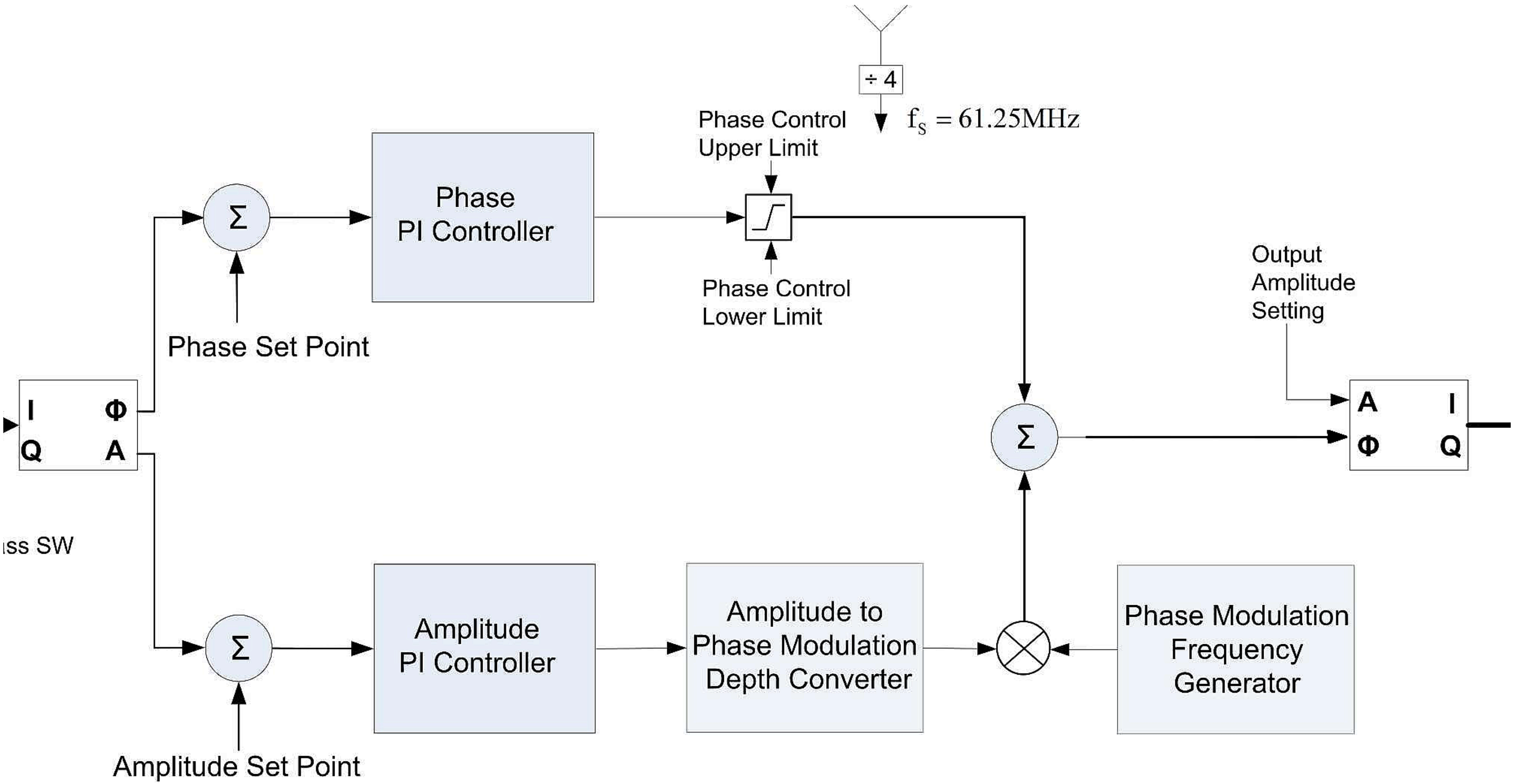
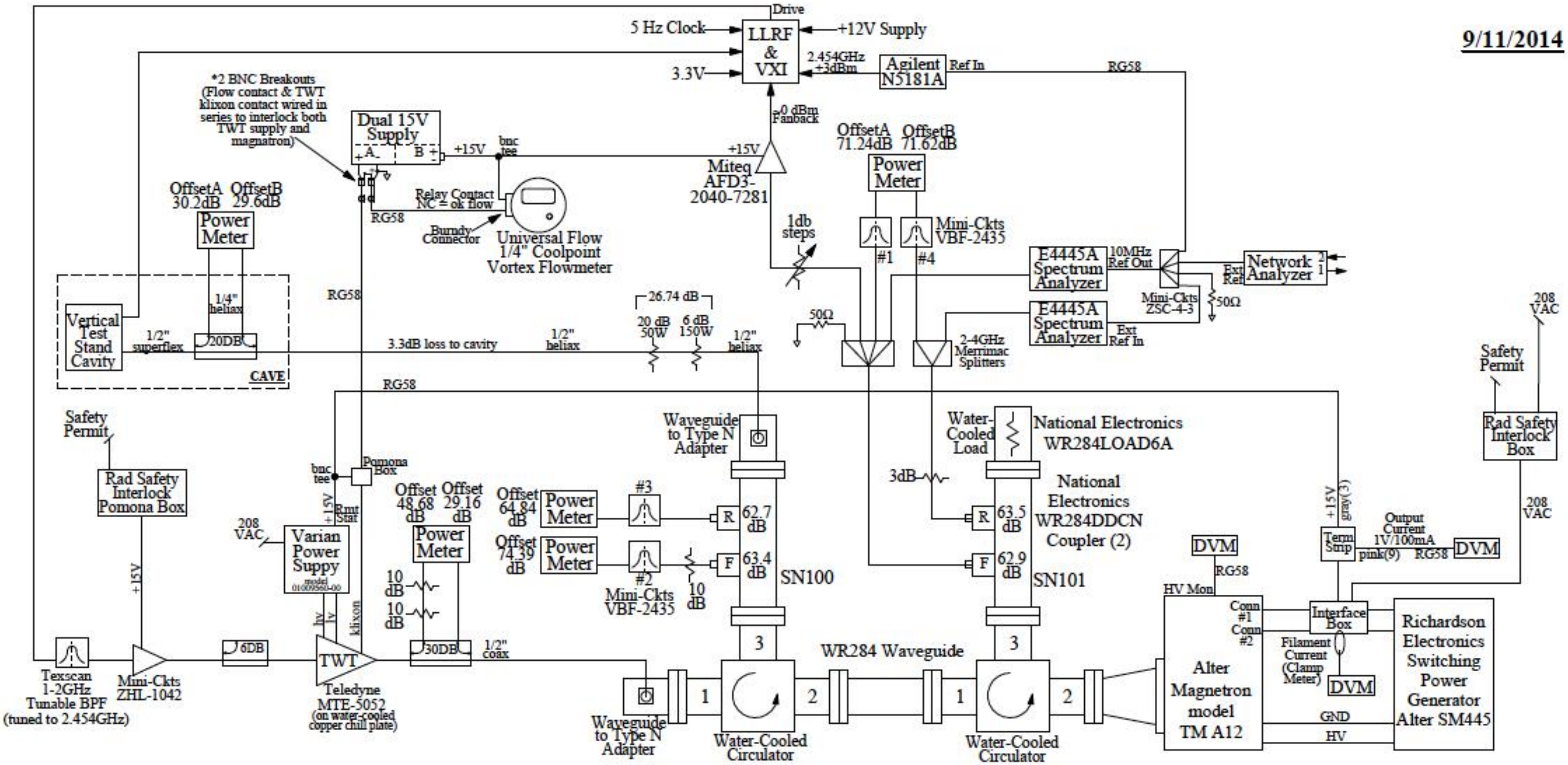
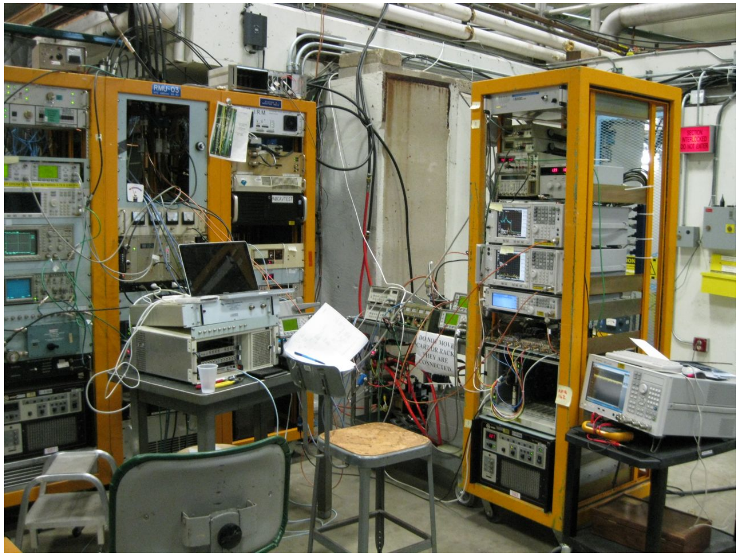
Controller architecture



A0 Vertical test stand, Jlab 2.45 GHz single cell undressed cavity RF block diagram



Injection Locked 2.45 GHz magnetron driving SRF cavity

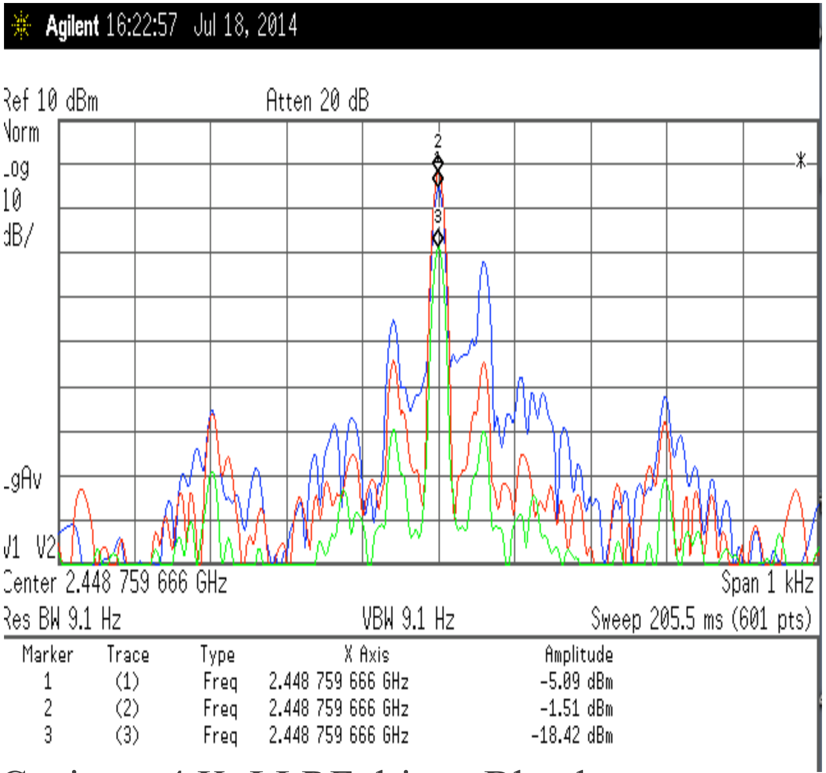


Commercially procured 2.45 GHz 1.2 kW magnetron
Loaned SRF cavity from JLab
Testing took place over one week period in July 2014.
Published in JINST

A0 VTS 2.4 GHz Magnetron - Cavity test results

- Amplitude control shown linear over 30 dB range
- Moderate feedback performance demonstrated
- 0.3% r.m.s, and phase stability of 0.26 degrees r.m.s.

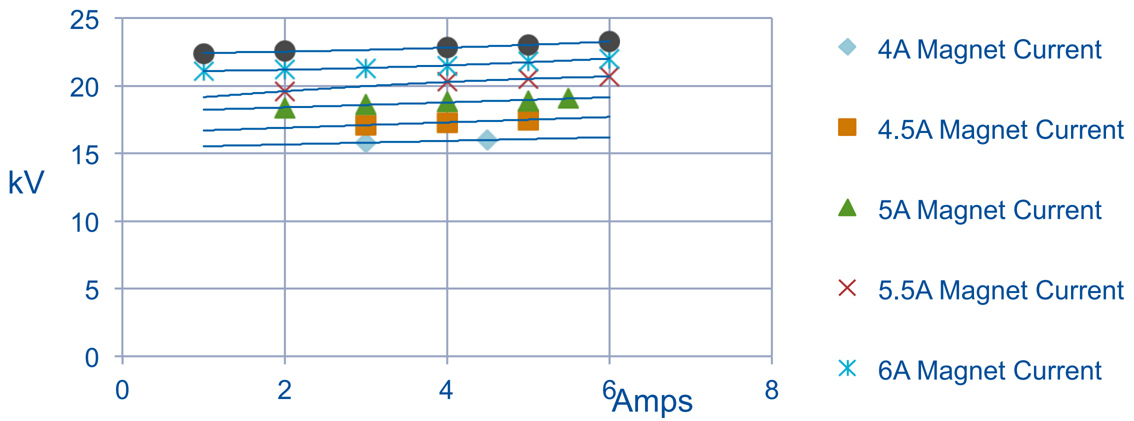
- Tests limited by extreme cavity microphonics and test cave access



Cavity at 4 K, LLRF drive. Blue loops open, Red loops closed and maximum output, Green loops closed and amplitude reduced by 17 dB shows the PM modulation is effective for amplitude control.

CCR / CPI - 100 kW Pulsed, 10 kW Ave. 1.3 GHz Magnetron

Calabazas Creek Research Inc
Phase II SBIR grant to develop a 1.3 GHz, 100 kW peak power, 10 kW average power magnetron station in partnership with Fermilab and Communications and Power Industries LLC, utilizing a full vector control scheme developed by Fermilab.

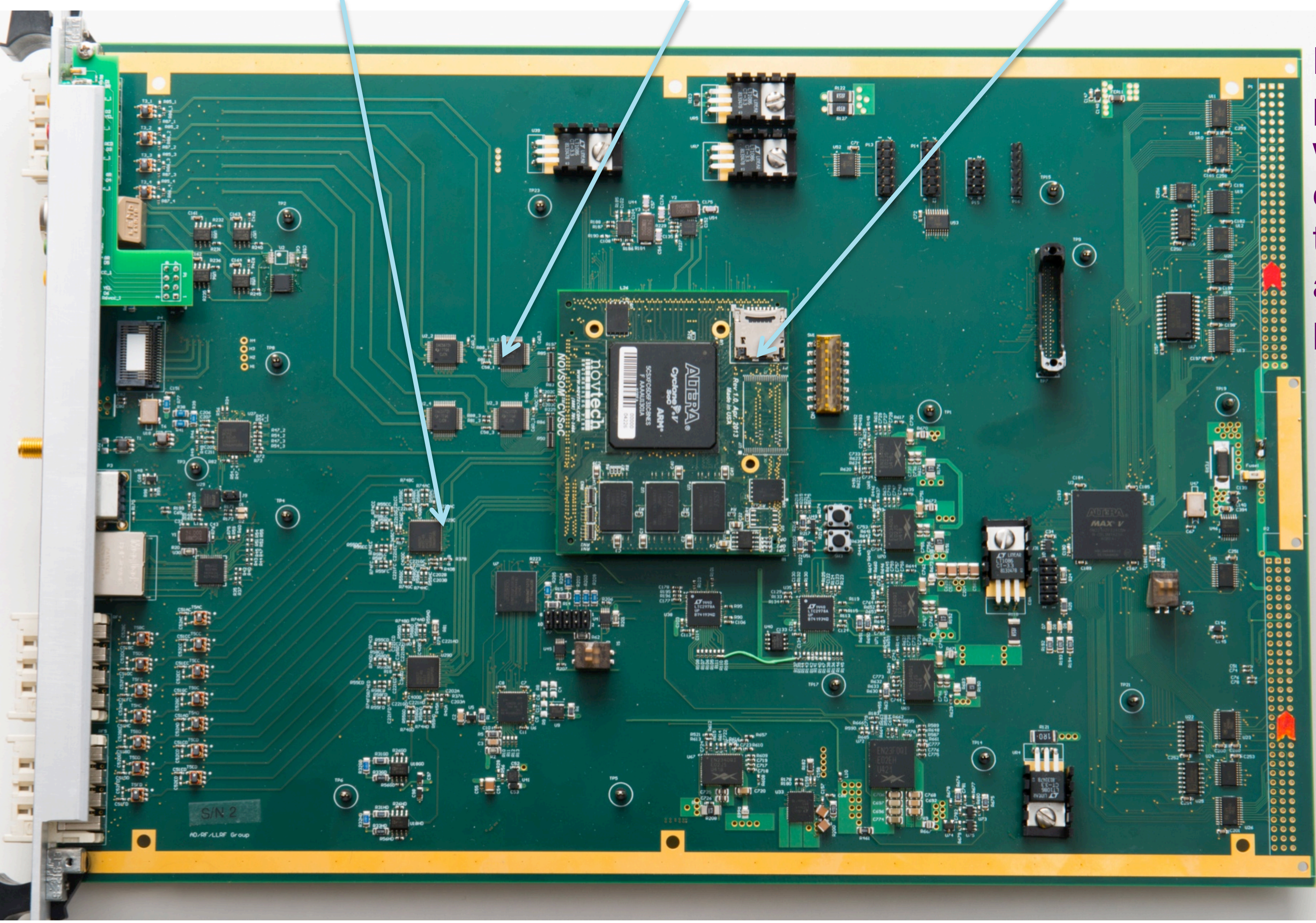


V-I Characteristics of Magnetron at Varying Electromagnet Current Values from initial short pulse tests.

tube~12” tall

Low Level RF Digital Control Card

(16) 14 bit ADCs(8)14 bit DACs System on Module



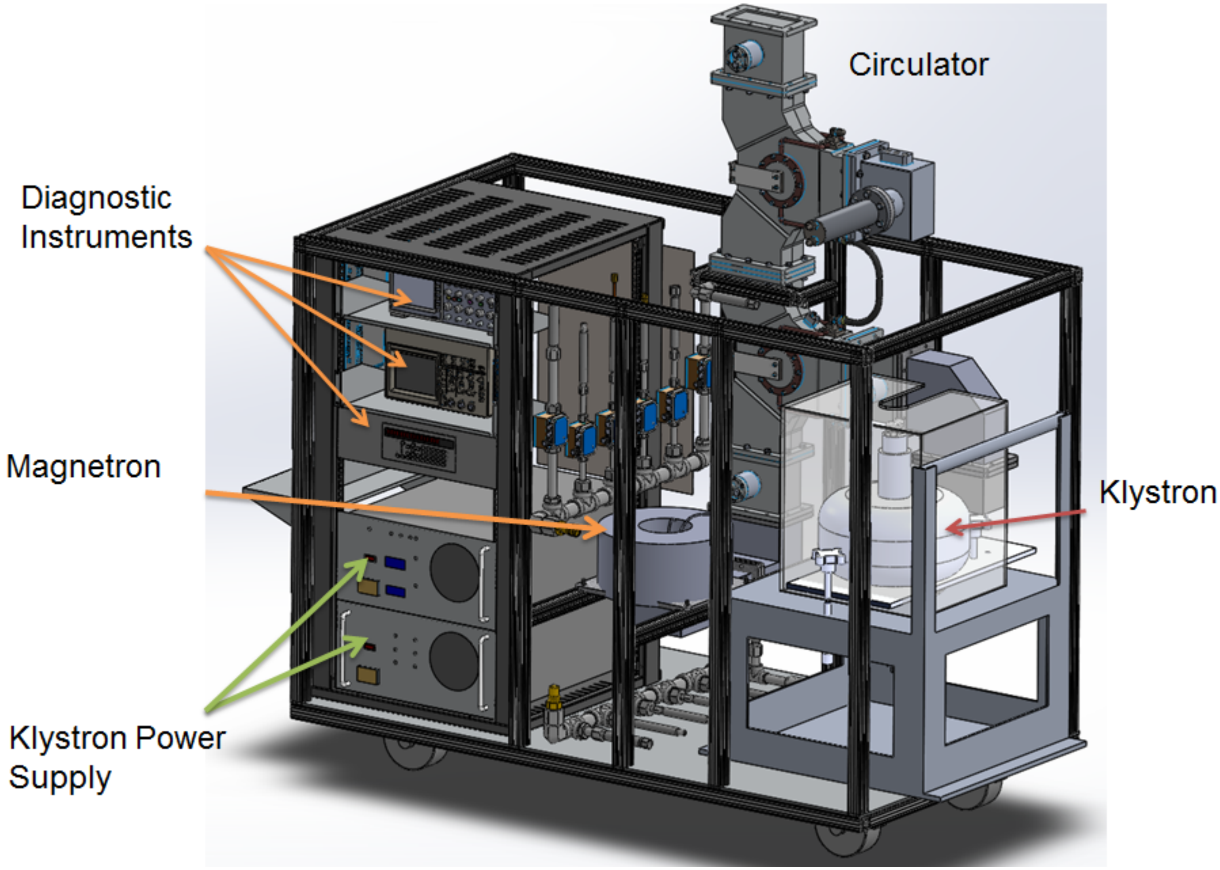
Dual core Arm processor with FPGA eliminates the need for a crate and external processor.

One card drives two RF Stations

Modular Magnetron RF Station under development by CCR

Long pulse tests late 2016

- Injection lock power sweep
- Magnetron heating as a function of modulation depth and frequency
- Power supply sensitivity
- Load impedance sensitivity



Magnetron Control R&D moving forward

- Cathode current control is a logical choice for slow amplitude control to optimize efficiency for operating conditions
  - there is potential for moderate bandwidth with switch-mode PS
  - should be a part of any scheme
- Vector addition of multiple magnetrons has a long history and should work for most designs
  - at the cost of hardware complexity and moderate control complexity
- RF vector control through fast phase modulation is a potential fit for many machine designs
  - single tube design with greatest hardware simplicity
  - at the cost of control complexity and some lower control performance
- All techniques need development time on a stable test platform $$

Summary

- The magnetron has been a remarkable RF source for 75 years that is unparalleled in cost and highly efficient. It is widely used for industrial heating and smaller electron accelerators but has had little impact in hadron accelerators
- There are now several control architectures that can take advantage of the processing capabilities of modern FPGAs
- An SBRI grant is in progress developing a 1.3 GHz 100 kW 10% duty factor magnetron and controller using fast phase modulation. Full power and modulation test are eminent
- Magnetrons may be a strong contender for high power, high efficiency accelerators

Thank you for your attention!

References

- 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*, no. 10 P03007, 2015.
- H. Wang *et al.*, “USE OF AN INJECTION LOCKED MAGNETRON TO DRIVE A SUPERCONDUCTING RF CAVITY,” in *Proceedings of IPAC’10*, Kyoto, Japan, THPEB067.