Magnetron R&Ds for High Efficiency CW RF Sources of Particle Accelerators

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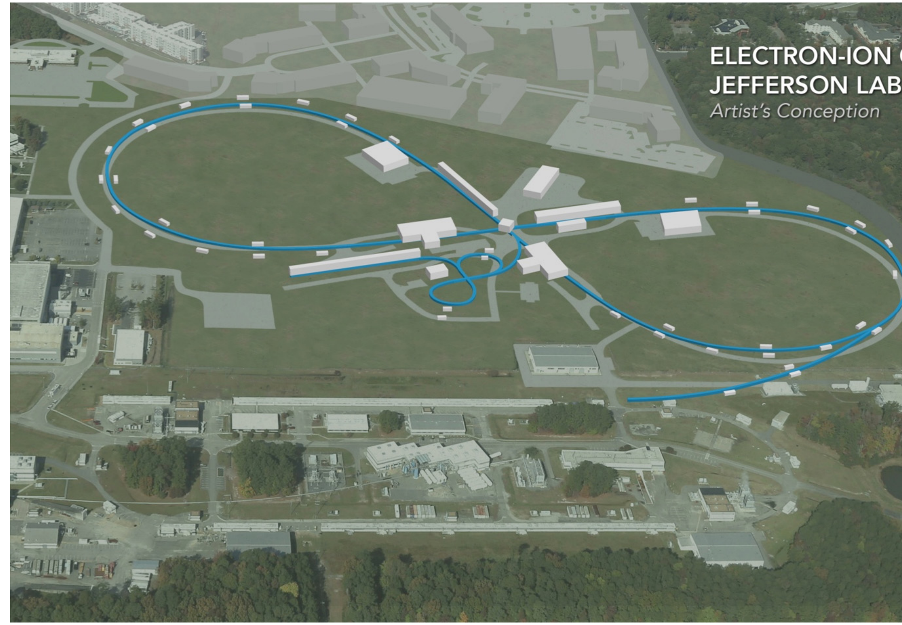


IPAC19

Muons, Inc.
Innovation in Research

GENERAL ATOMICS

10th International Particle Accelerator Conference

Melbourne Convention & Exhibition Center, Australia

May 19-24, 2019

Jefferson Lab

Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177, DOE OS/NP STTR Grant DE-SC0013203 and DOE OS/HEP Accelerator Stewardship award 2019-2021

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Motivations, Technical Challenges and R&D Programs

- Higher efficiency and lower cost
- Larger industrial and commercial markets
- Cost saving in accelerators operation on large electrical bills, particularly for the DOE's large science user facilities
- Such technology, if feasible, should transfer to industry and accelerator users for larger field of applications
- Magnetron works as an oscillator than klystron as a linear amplifier
- Frequency (phase) lock, amplitude modulation are keys to control the magnetron as a reflection amplifier
- Noise reduction from cathode, power supplies and thermal stability are R&D key area
- Understanding and controlling the nonlinear responses of the magnetron characteristics
- Develop state-of-art digital controllers and user friendly control interfaces
- Three R&D test stands at 915, 1497 and 2450MHz have been developed by different funds. The 2450MHz test stand is the most productive on the measurement data for the guidance of new designs and for understanding of proof-of-principle

Motivation of using magnetrons as RF sources of particles accelerators

Magnetrons:

- Forms bunches in spoke-on-hub process in circular motion. Beam-to-RF cavity interaction in multiple circular passes. Much less wasted energy.

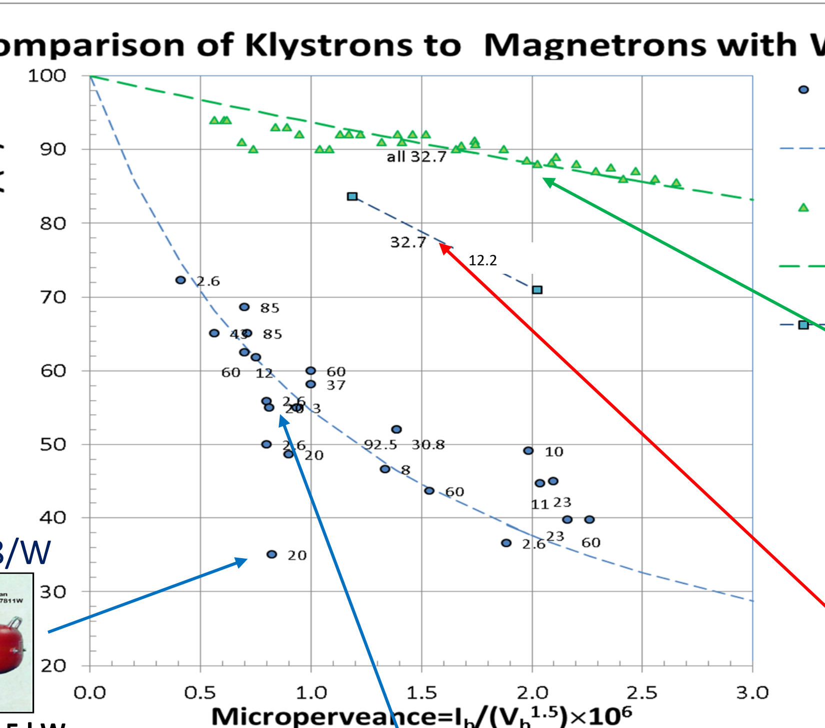
Klystrons:

- Space-charge effect in electron bunch forming process in linear motion dominates the efficiency. Spent energy deposits in the collector.

References:

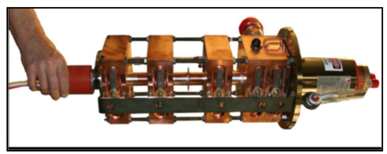
- High efficiency klystrons (>80%) ? Lower perveance:
- Multi-beam (cluster)
- Long cavity interaction to do adiabatically bunching
- High efficiency SSAs?

Low frequency, <1.5GHz, <45%, $11-15/W, need more R&D for higher efficiency and lower cost



~$8/W

Varian 5 kW klystron



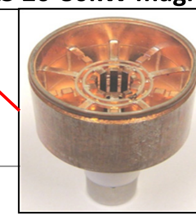
~$5/W

L3 13 kW klystron

$1-2/W

L3 20-80kW magnetrons

<1/W



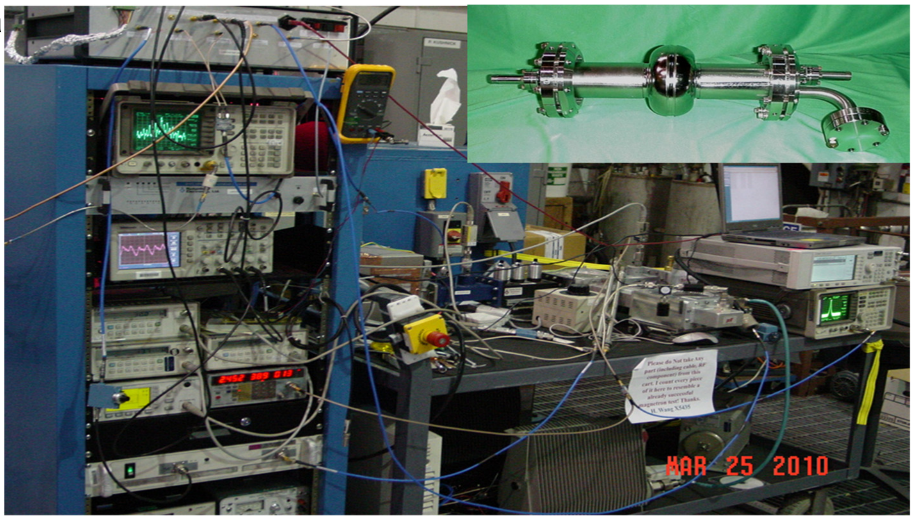
National 1.2kW oven magnetrons

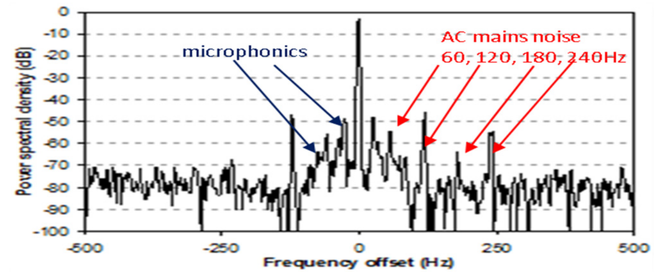
Magnetron RF source, the potential impact for SRF Accelerators

Capital and operation cost saving for CEBAF SRF cavities, 418 klystron units in 1497MHz, CW operation

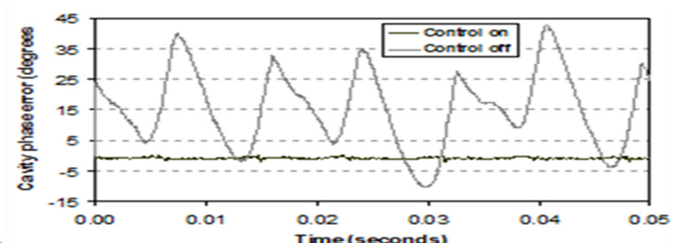
- Low cost of magnetron device
- DC-to-RF efficiency from klystron to magnetron improves from ~35% to ~90%
- 2.22MW of DC power saving
- $2.8 million saving in power bill, if 41 weeks/year of CEBAF in 6-12GeV operation

Technology demonstration for all SC/NC RF accelerators in the DOE complex for science and the industrial a





with injection signal -27dB at Pout=500W



with amplitude modulation feedback

First Demonstration of Injection Phase Lock to a Superconducting Cavity with Lancaster University, UK in 2010

References:

[1] A. C. Dexter, G. Burt, R. G. Carter, I. Tahir, H. Wang, K. Davis and R. Rimmer, PRST-AB, 14, 032001 (2011).

[2] H. Wang, et al., "Use of an Injection Locked Magnetron to Drive a Superconducting RF Cavity", in Proc. 1st Int. Particle Accelerator Conf. (IPAC'10), Kyoto, Japan, May 23-28, 2010, pp. 4026-4028..

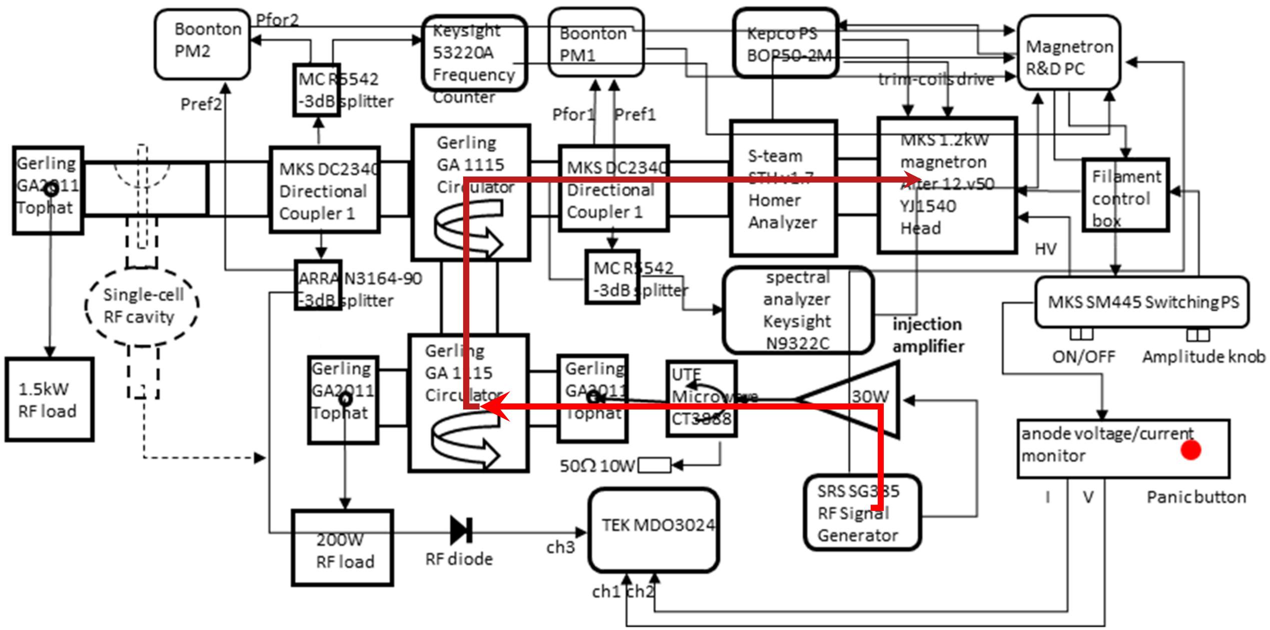
JLEIC-Future EIC: High Efficiency, High RF Power Needs

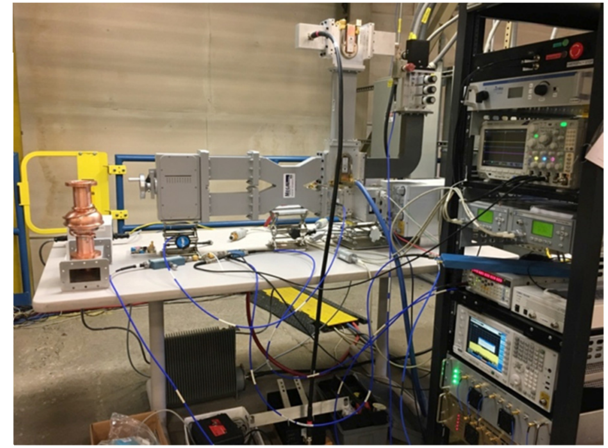
	CEBAF 12GeV	E-Ring PEP-II 10GeV	Ion-linac up to Pb 60MeV/u	Booster	Ion-Ring Proton up to Pb 200GeV/u		CC-ERL Cooler 110MeV	Crab (40)X2MV
Frequency (MHz)	1497	476.3	100 /200	0.6-1.3	1.2-1.3	952.6	476.3 /952.6	952.6
Duty Cycle (%)	cw	cw	0.5	ramp	ramp	cw	cw	cw
Cavity	sc 2K	nc	nc	nc	nc	sc 2K	nc/sc 2K	sc 2K
Max Peak Power(MW)	2.76	12.9	1.7		0.36	~4	2.2	0.0041
Average Power (MW)	2.76	12.9	1.7	0.084	0.36	~4	2.2	0.0041
Klystron DC-RF Efficiency (%)	35-51	67	50-60	na	na	50-60	50-60	50-60
Magnetron DC-RF Efficiency (%)	80-90	80-90	80-90	na	na	80-90	80-90	80-90
DC Power Save (MW)	3.4-3.8	3.1-4.9	0.51	na	na	1.2	0.66	0.0012

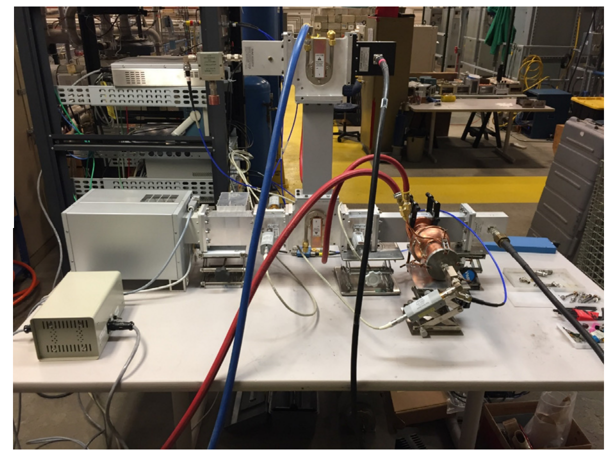
cost reduction driver for magnetron R&Ds

Magnetrons can save JLEIC DC power of 11.1MW, or $5.1M annual (35weeks) power bill cost.

JLab's 2.45GHz Oven Type Magnetron R&D Test Stand

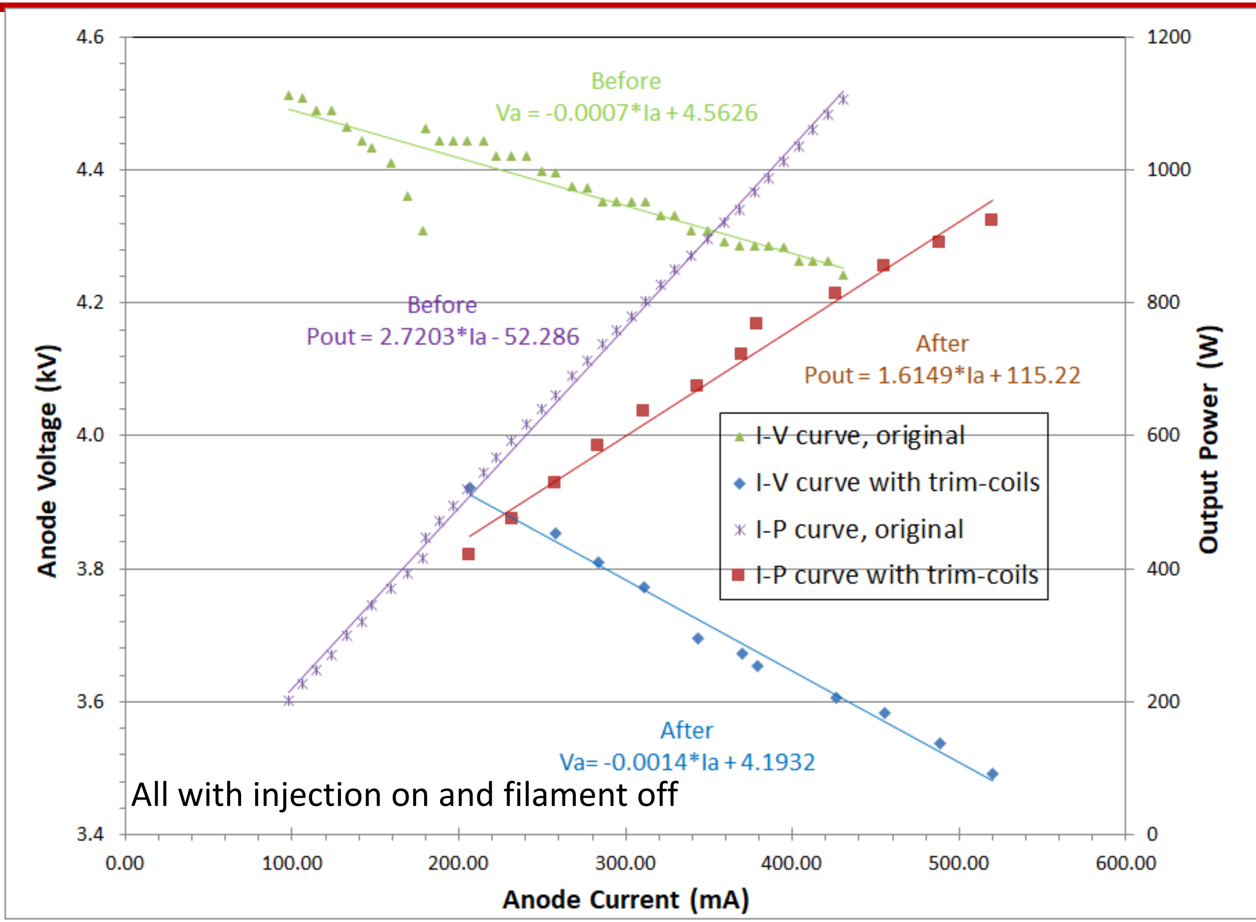




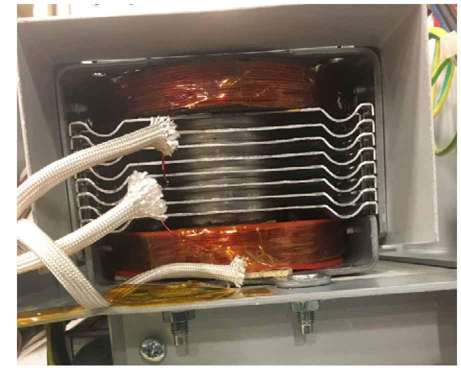


Simplified Schematic Layout of 2.45GHz, 1.2kW CW Magnetron R&D Test Stand for Matched and RF cavity Loads with back injection path marked up.

Magnetron I-V and I-P curves depends on the magnetron model and structure

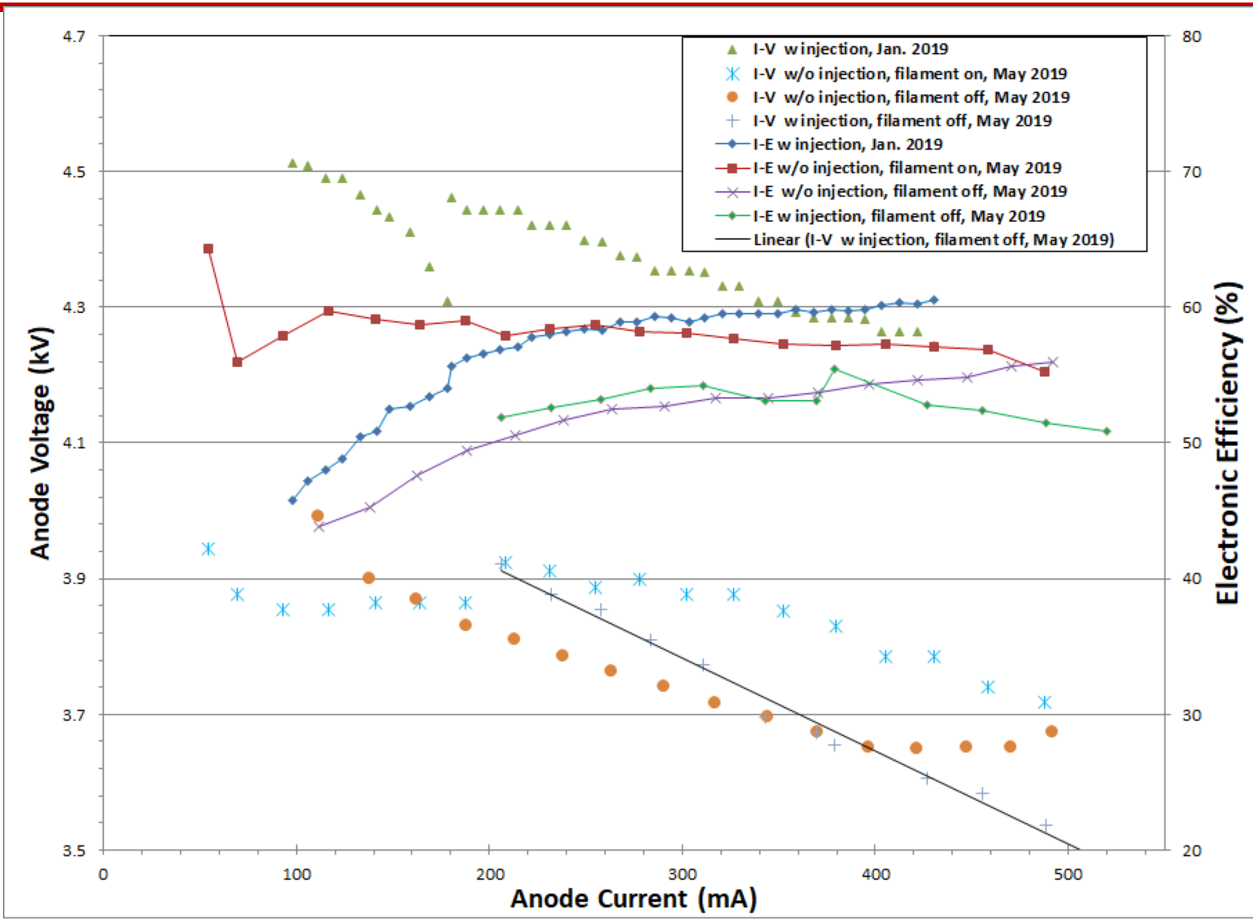


Original YJ1540 (2M137)
Magnetron, data taken as Jan. 2019

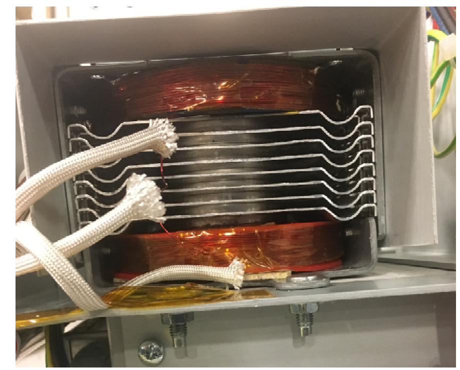


Modified YJ1540 (2M137)
with 2X360 turns of trim-coil pancakes,
data taken as May, 2019

Magnetron I-V and I-E curves depends on the operation conditions

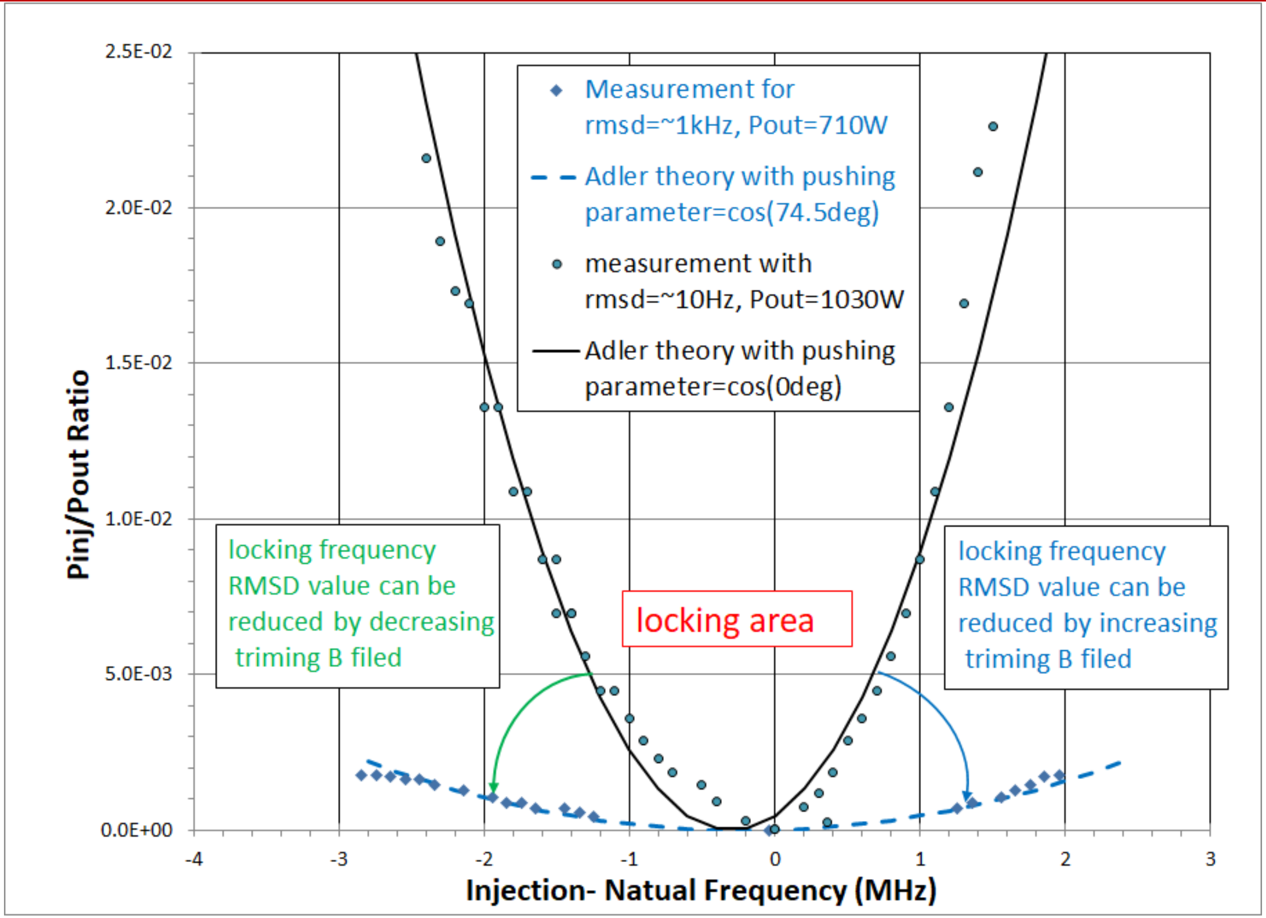


Original YJ1540(2M137) Magnetron, data taken as Jan. 2019



Modified YJ1540 (2M137) with 2X360 turns of trim-coil pancakes, data taken as May, 2019

Injection phase locking performance with trimming magnetic field optimization

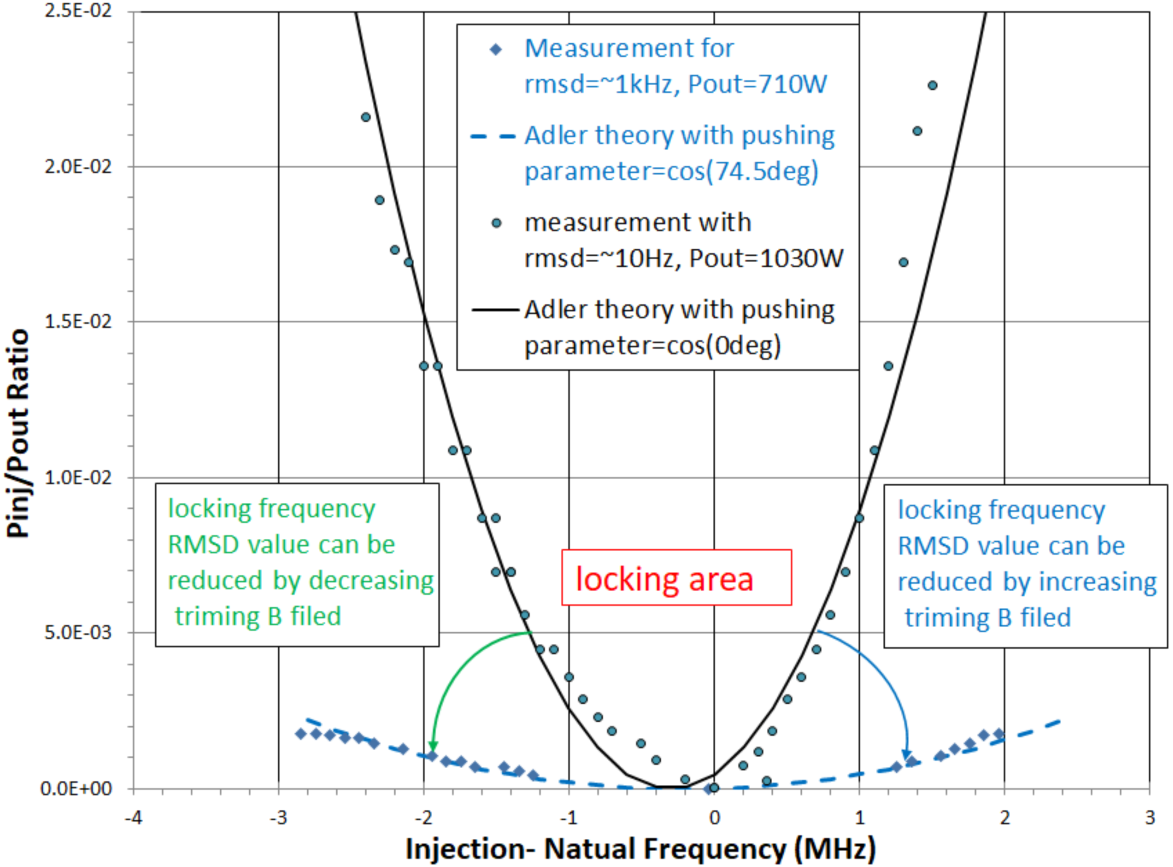


Adler equation [7] stated the injection locking phase ϕ which was later modified by Chen [8], with a pushing angle α is:

$$\sin\emptyset = 2Q_L \cos\alpha \sqrt{\frac{P_{out}}{P_{inj}}} \frac{\omega_0 - \omega_i}{\omega_0}$$

- P_{inj} is locking power
- P_{out} is output power
- Q_L is the loaded Q of magnetron
- ω_i is the frequency of injection signal
- ω_0 is instantaneous natural frequency of magnetron
- α is phase lag between electron rotating spoke and resonant RF peak called frequency pushing parameter

Injection phase locking performance with trimming magnetic field optimization



IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 18, NO. 3, JUNE 1990

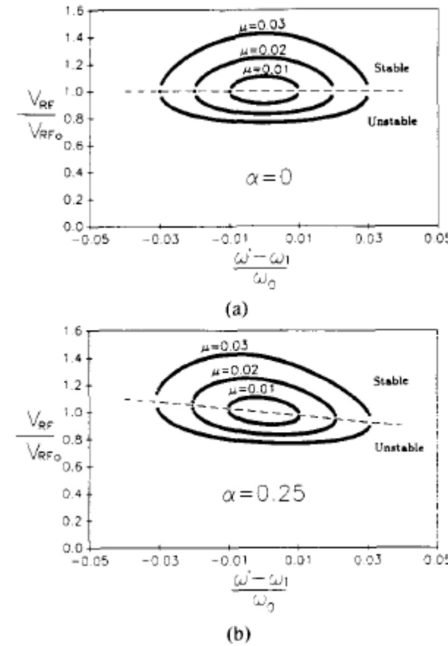
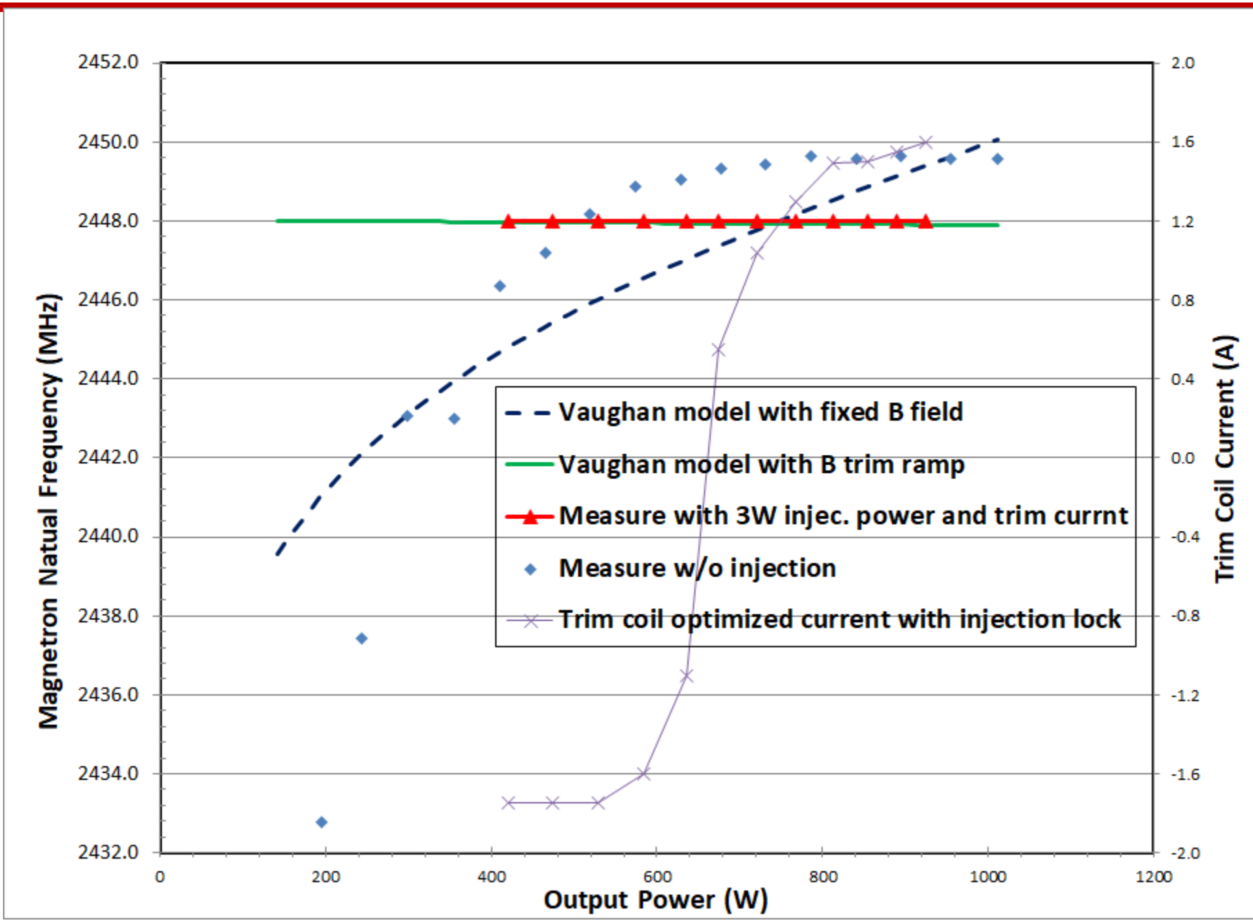


Fig. 4. Amplitude (V_{RF}/V_{RF0}) versus normalized frequency difference σ in the phase-locked states for three injection amplitudes, μ = 0.01, 0.02, and 0.03. (a) No frequency pushing, each ellipse corresponds to an injection parameter μ. (b) The effect of frequency pushing (α = 0.25) rotates the ellipses and results in a wider locking bandwidth and a shifted amplitude resonance frequency.

Static modulation of magnetic field to enhance the phase locking performance



- Combination of back injection and trimming the magnetic field can overcome the frequency pushing from 45% to 100% of magnetron output power with a locked frequency error $\leq$ 2.1Hz RMSD value by ramping the trim-coils from-1.75 to +1.6A.
- Once a strong phase locking is optimized, the frequency counter reading on the forward power is only vary at Hz range.

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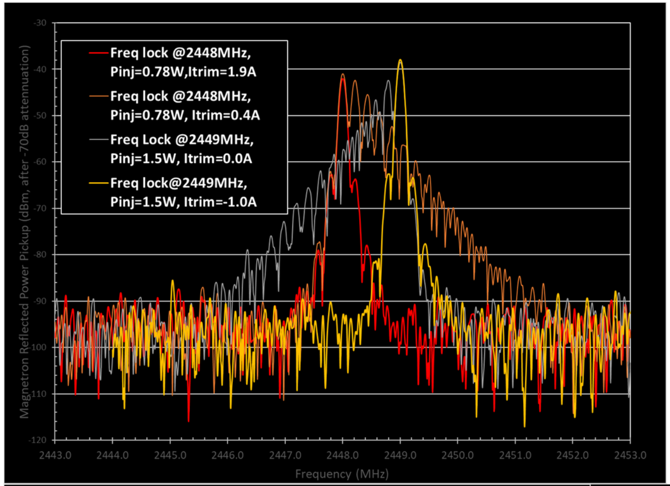
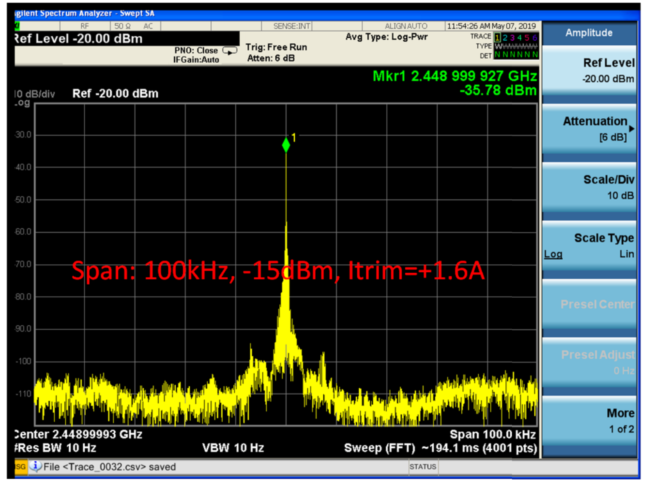
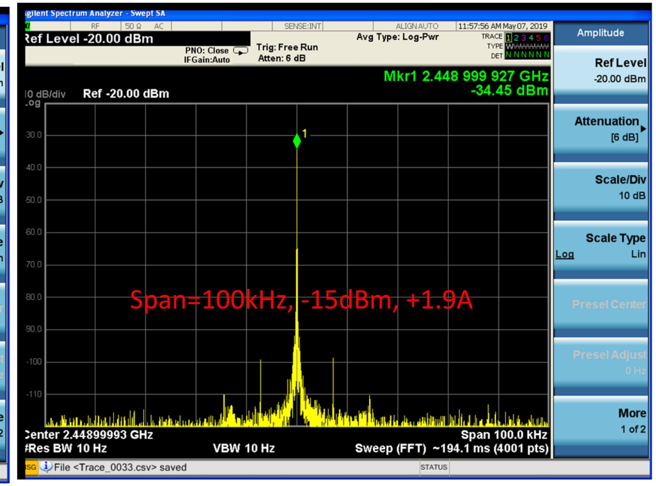
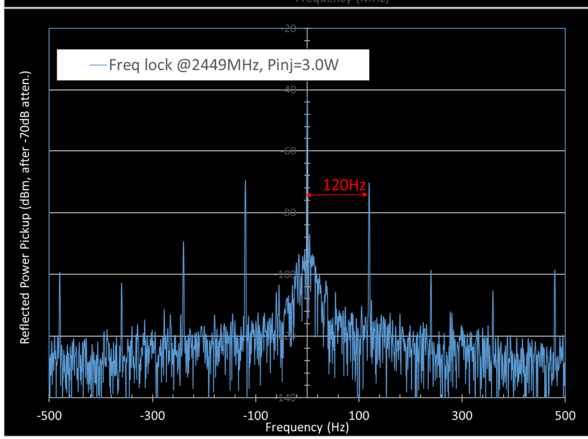
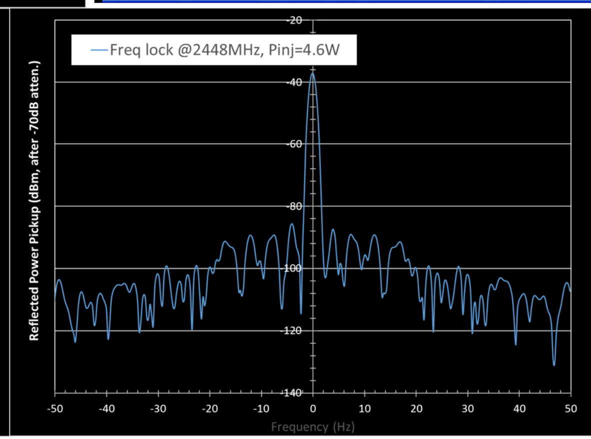
Phase locked power spectra with sideband suppressions





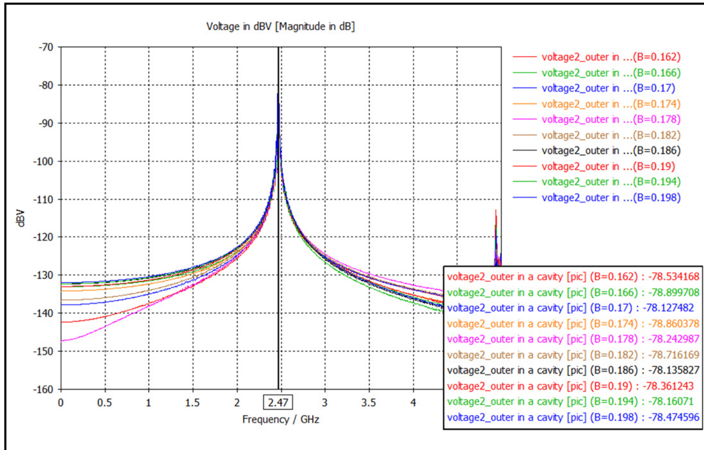




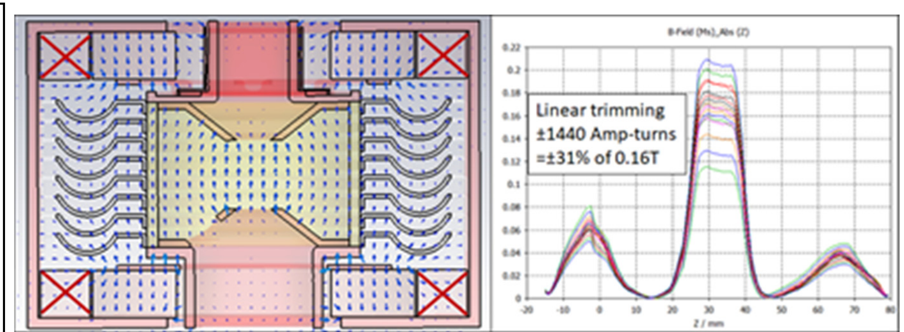


- Trimming magnetic field can suppress the sideband excitations when it is at the locking boundaries
- There are no sideband excitations within 100Hz bandwidth with optimization.
- -27.6dB peaks at ±120Hz of noise from the mains.
- -26.4dB peaks at ±84.5kHz of noise from the switching IGBTs.

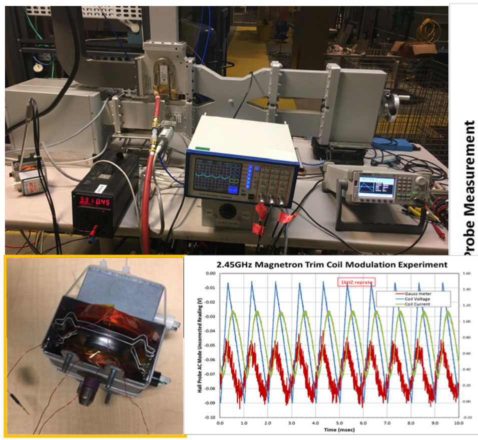
Trim-Coil Modulation Simulations and Experiments

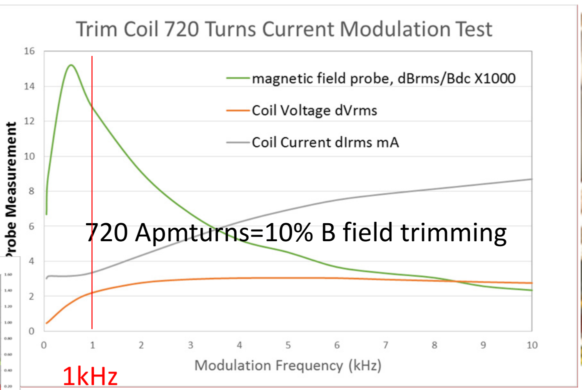


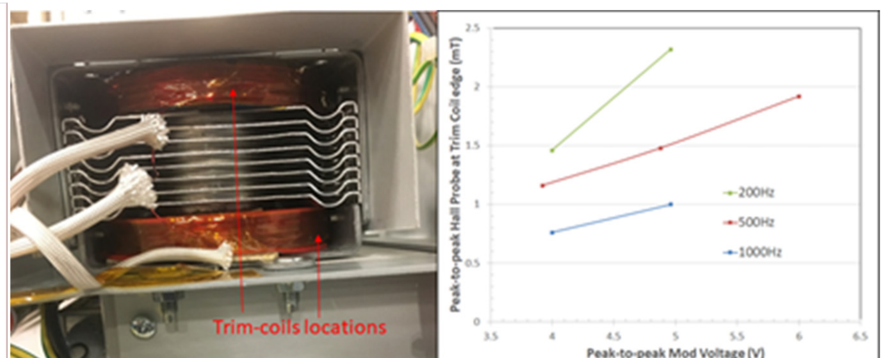
CST (particle-in-cell) simulation of 2.457 GHz magnetron with the magnetic field trimmed from 0.162T to 0.198T and anode voltage amplitude increased proportionally from -3.87kV to -4.73kV



The electrical current can be trimmed ±2A resulting in ±31% AC variation of the 0.16T of DC ferromagnetic field







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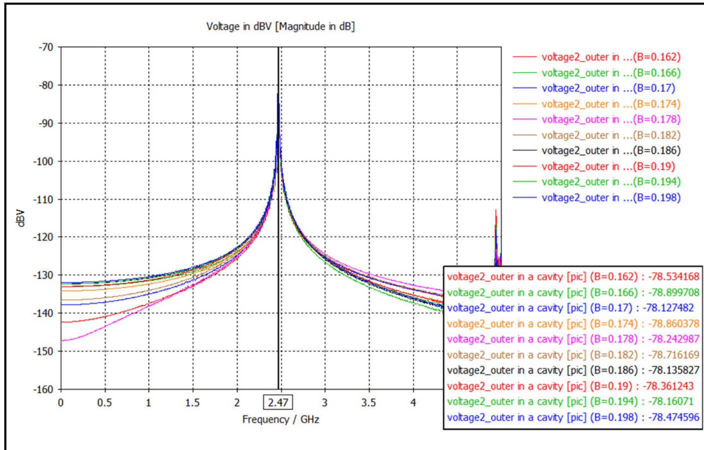

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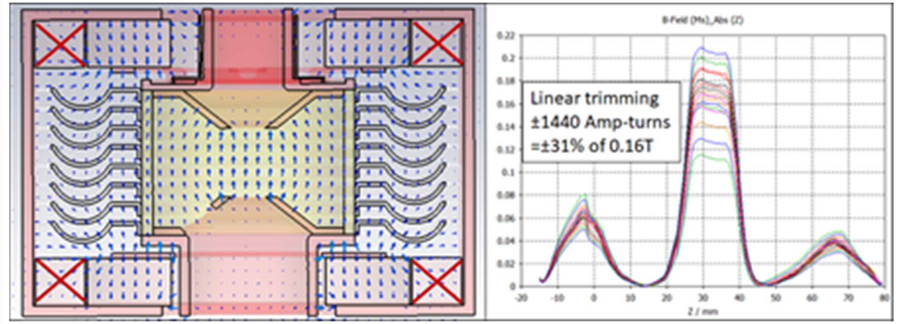

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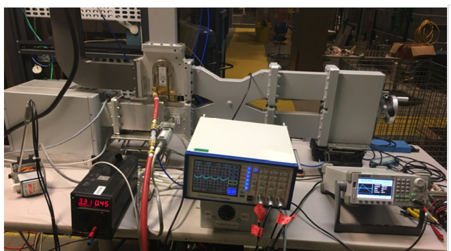

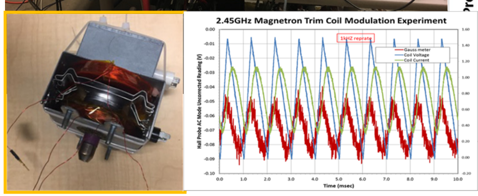

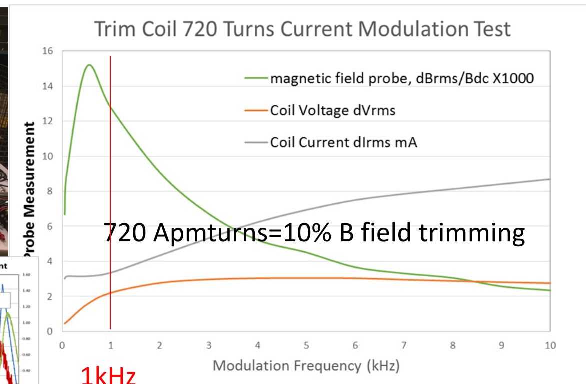

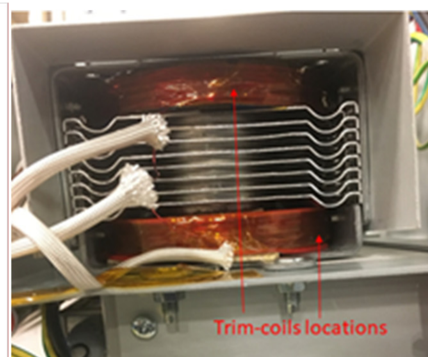

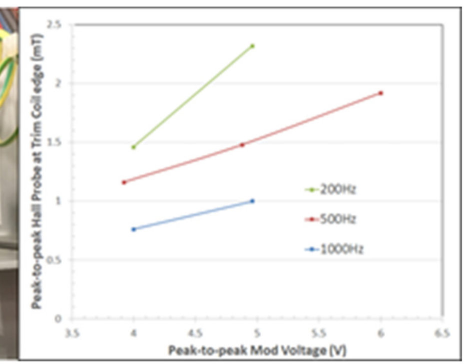

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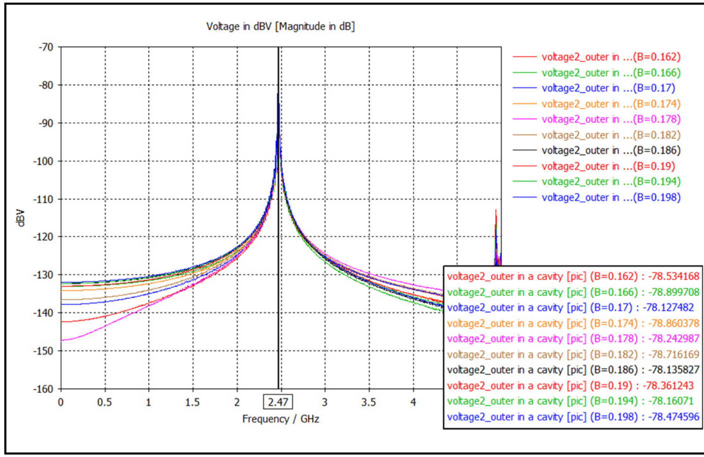

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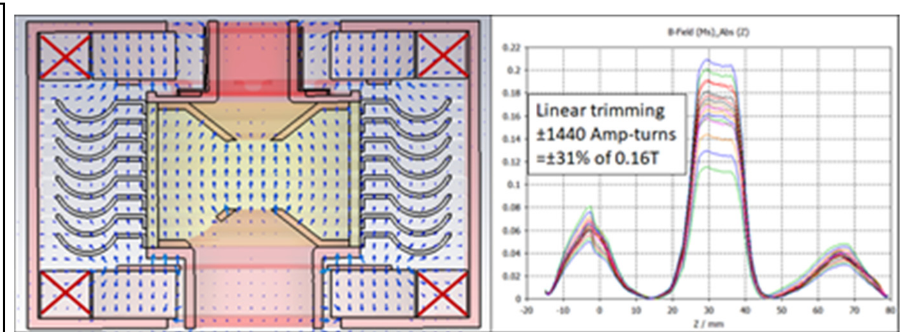

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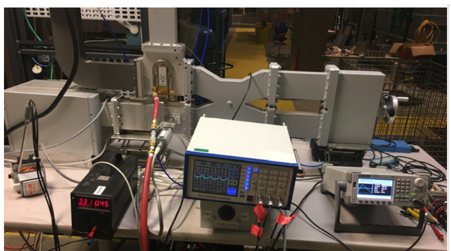
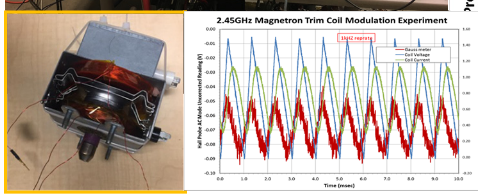
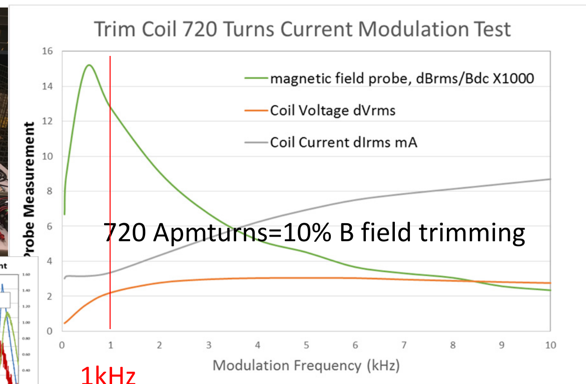
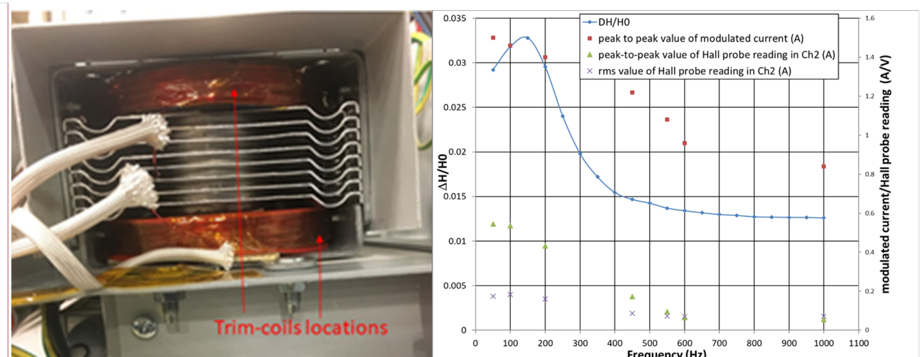
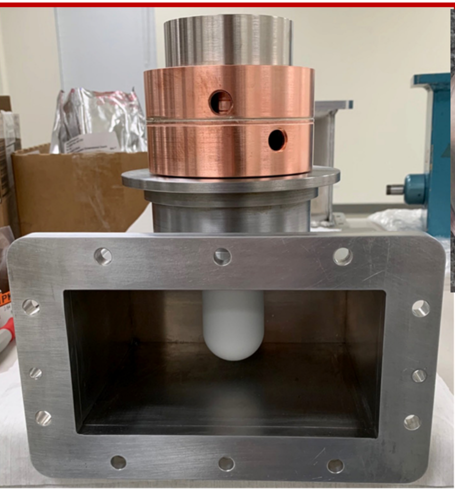


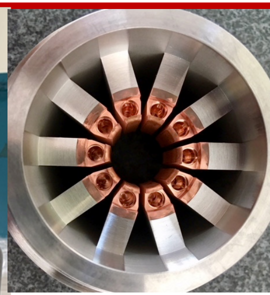


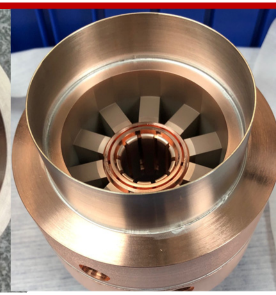




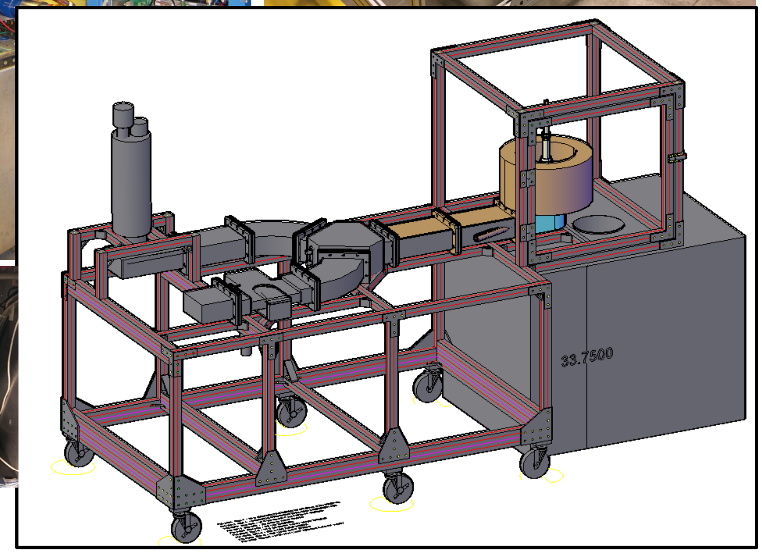
New 1497MHz test stand development for Muons Inc's magnetron high power tests



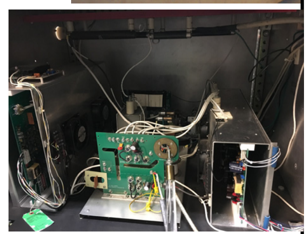




Muons Inc designed
Stainless steel/copper
hybrid anode structure
Poster presentation
on THPTS090



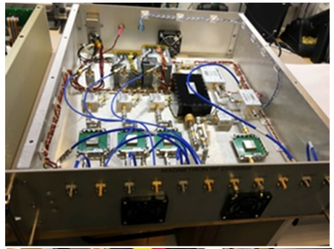
- Muons Inc designed and prototyped 1497MHz, 13kW CW magnetrons with Altair Technologies, Heatwave Labs and High Energy Metals.
- JLab has constructed a portable test stand to be fully compatible with existing 13kW klystron test stand
- To demonstrate injection phase lock and amplitude control for CEBAF machine
- Share power supplies (anode, solenoid) with klystron
- Reuse klystron circulators and water loads
- Build new isolation transformer with DC cathode PS
- Support ion pump monitoring at HV terminal

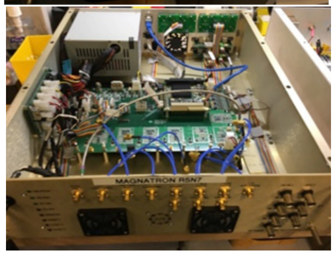


Inside of HV cabinet

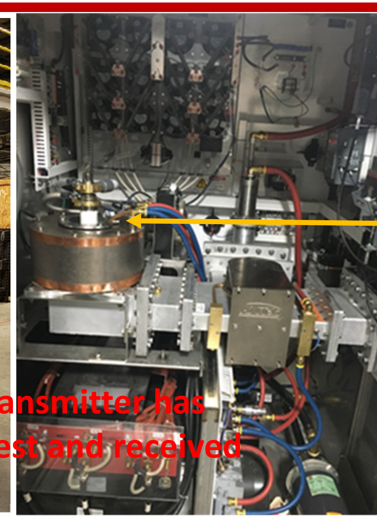
915MHz industrial oven type magnetron to be used for accelerator applications

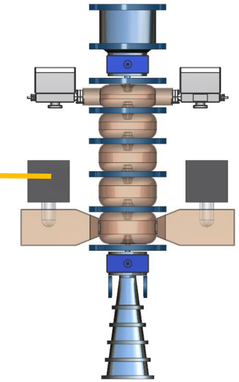
- Support by DOE/OS/HEP Accelerator Stewardship Program for 3 years
- 1st year, Using AMTek, 75kW, CW magnetron oven product (for food processing industry) for the R&D demo tests
- High power combiners design with GA
- Scalable to1MW for 1MeV graded beta electron Linac structure
- Compare SCRs, Switching, and klystron type anode power supplies for the ripple noise reduction
- Injection phase locking with electromagnet control by LLRF/AC/DC digital controllers developed by JLab
- Noise reduction from cathode heater, the mains (SCRs) and high frequency switching
- Technology transfer to industrial partners and develop user friendly controller interfaces

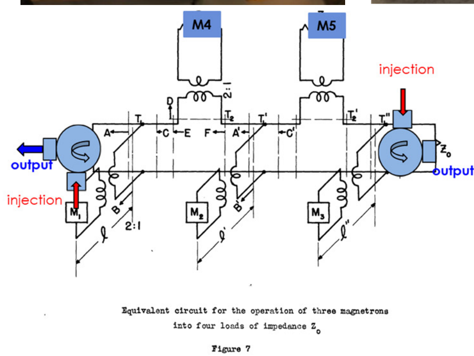




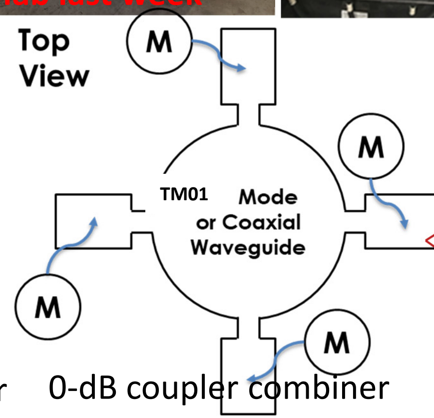
Amtek magnetron transmitter has passed high power test and received at Jlab last week



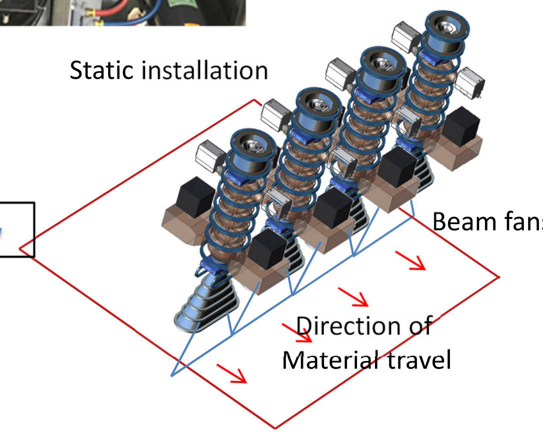




Waveguide iris coupled combiner



0-dB coupler combiner



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Conclusions

- The experiments using the commercial 2.45 GHz magnetron have clearly demonstrated that such a device with a simple modification for trimming magnetic field can be used as an RF source for accelerator cavities with a few watts of injection power equivalent to effective gain of >25dB. The frequency locking error is in 2.1Hz rmsd value
- Further active feedback control for the amplitude stability with a digital controller is next R&D goal for all test stands
- The development of low eddy current, high efficiency magnetrons at 1497 MHz, 13kW, CW operation offers an alternative RF source to the existing klystrons used in CEBAF. Also such demo machine can be also expanded to all accelerator user facilities including further EIC in US.
- Using high power 915 MHz magnetrons with optimized injection locking, power supply ramping and field trimming with digital LLRF control offers a pathway to a cost effective MW class source. The end goal is to transfer this technology into industrial applications with user-friendly interfaces