MAGNETRON R&D PROGRESS FOR HIGH EFFICIENCY CW RF SOURCES OF INDUSTRIAL ACCELERATORS

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NAPAC 2022

North American Particle Accelerator Conference

Albuquerque, New Mexico

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SRF/NC-RF Compact Accelerator Designs for Wastewater Treatment

An Electron Beam Irradiation Beamline at Jefferson Lab for PFAS Remediation in Wastewater

Xi Li, TUXD2 talk
Also WEPA28 Poster

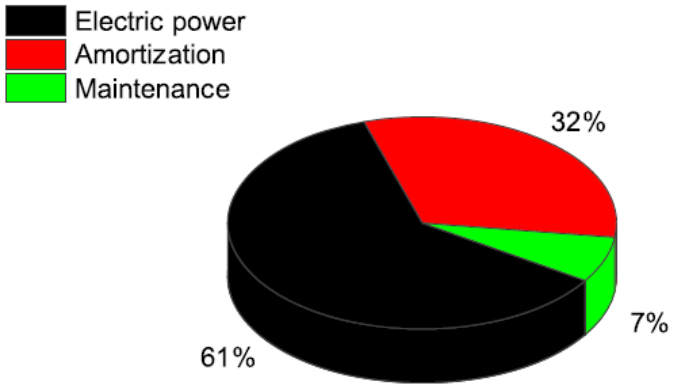
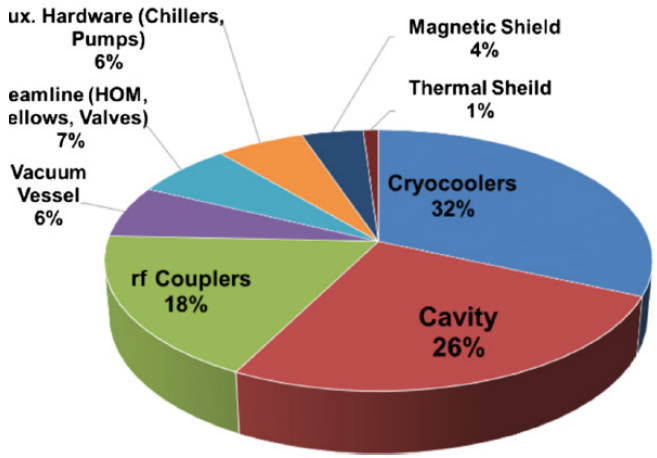


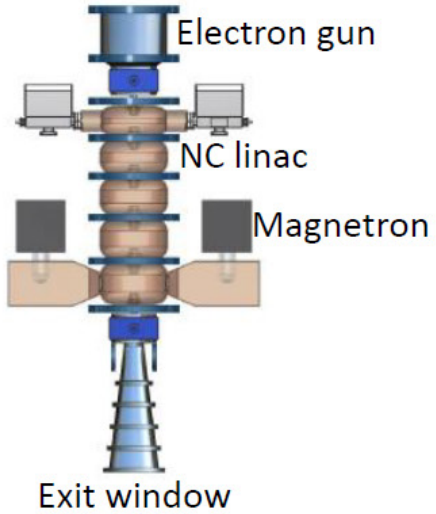
FIG. 28. Breakdown of the processing cost.



Cryo-cooled SRF technology development

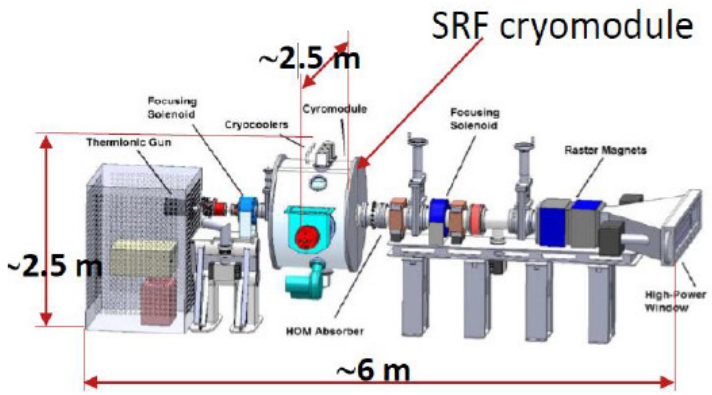
- **G. Ciovati, et al. Multi-metallic conduction cooled superconducting radio-frequency cavity with high thermal stability Supercond. Sci. Technol. 33 (2020) 07LT01 (7pp) https://doi.org/10.1088/1361-6668/ab8d9**
- **R C Dhuley, et al. First demonstration of a cryocooler conduction cooled superconducting radiofrequency cavity operating at practical cw accelerating gradients Supercond. Sci. Technol. 33 (2020) 06LT01 (6pp) https://doi.org/10.1088/1361-6668/ab82f0**

1 MeV, **10 – 500 kW, 915 MHz**



Slot-Coupled CW Standing Wave Accelerating Cavity
Patent #US9655227, May 16, 2017
https://patentimages.storage.googleapis.com/fc/86/69/c1d812a13dc43f/US9655227.pdf

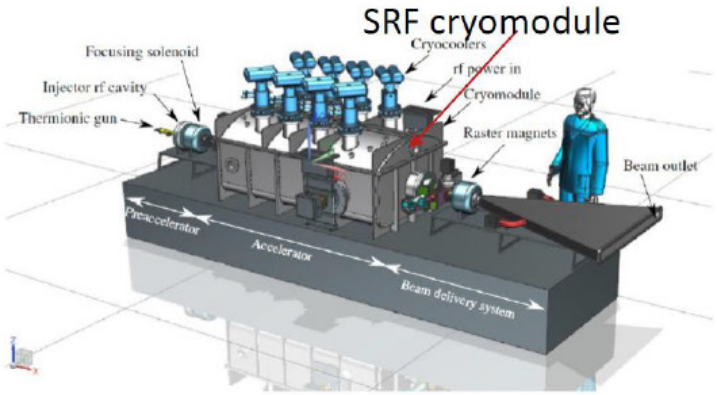
1 MeV, **1 MW, 750 MHz**



G. Ciovati *et al.*, *Phys. Rev. Accel. Beams* **21**, 091601 (2018)

Jefferson Lab design

10 MeV, **1 MW, 650 MHz**



R.C. Dhuley, *et al.*, *Phys Rev. Accel. Beams* **25**, 041601 (2022)

Fermi Lab design

Jefferson Lab

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.**

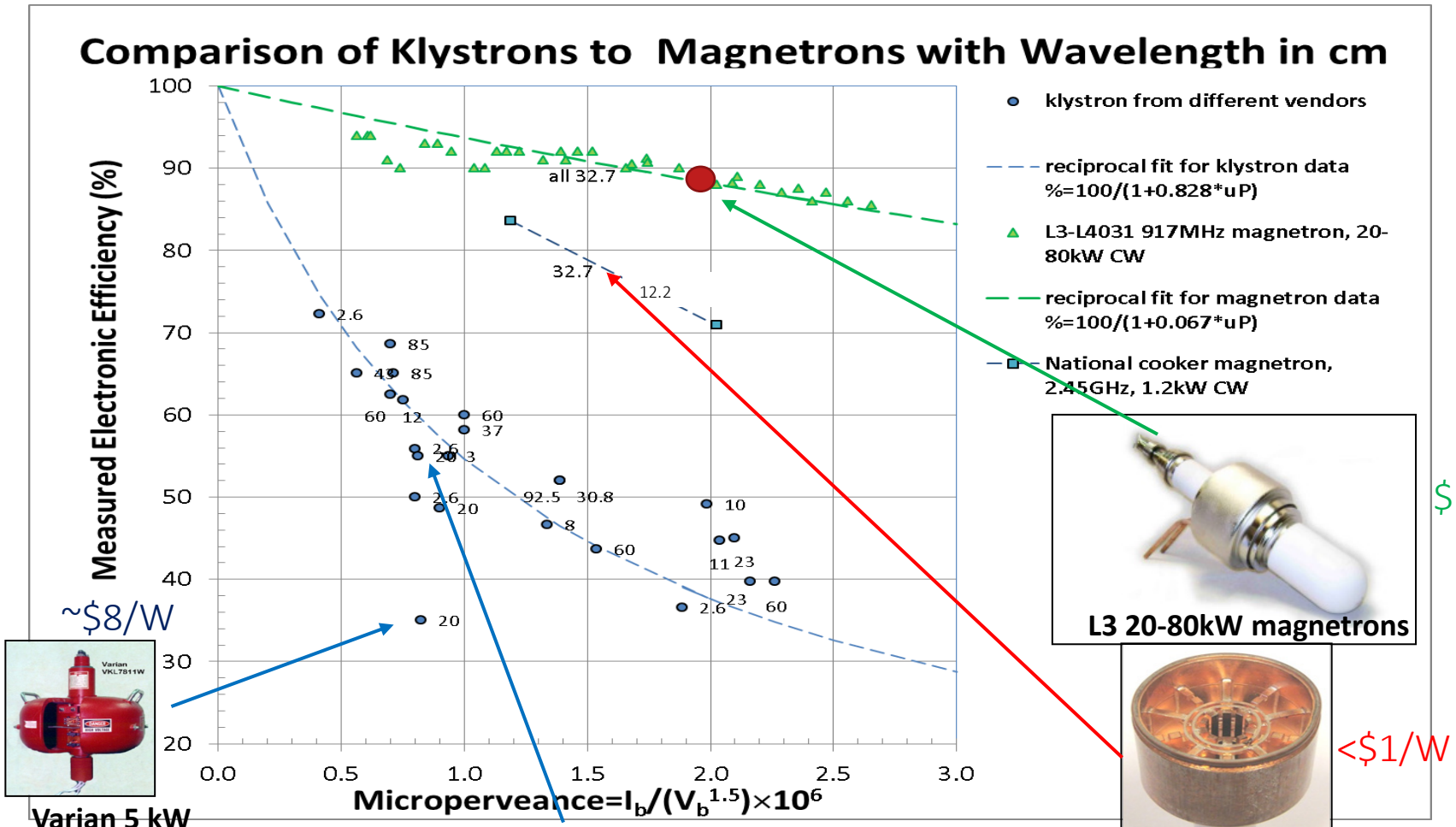
Klystrons:

- **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



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Motivations, Technical Challenges and R&D Programs

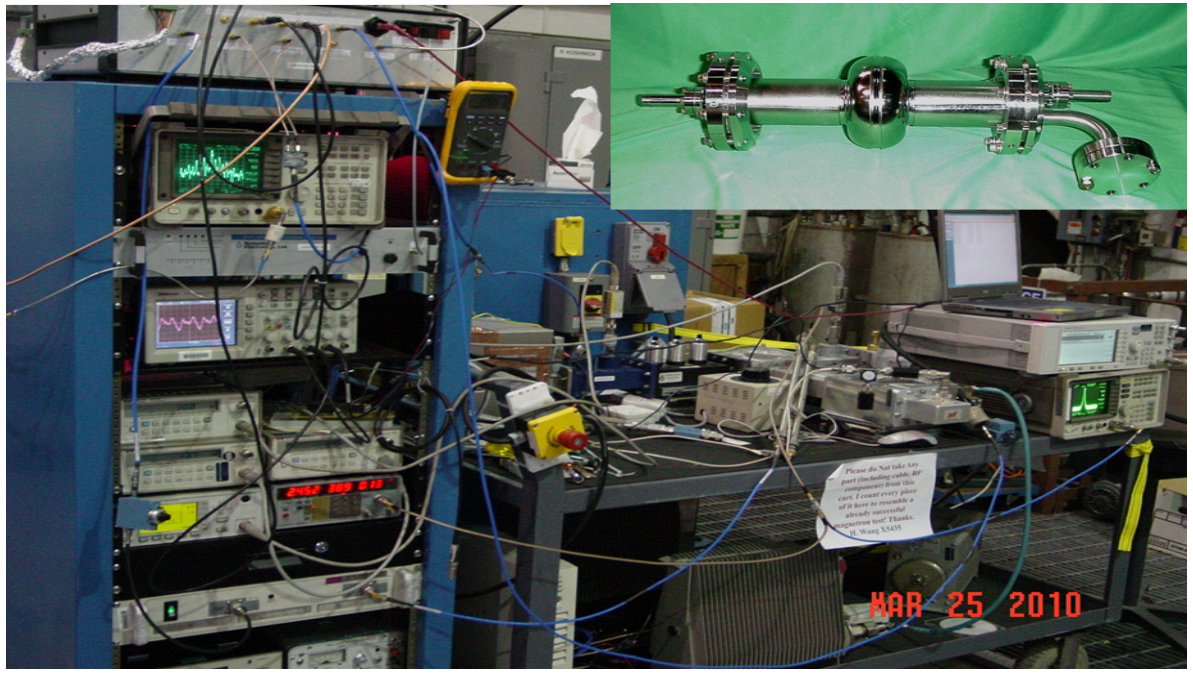
- Higher efficiency >80% and lower cost <1$/W
- Larger industrial and commercial markets
- Cost saving in accelerators operation on large electrical bills, particularly for the DOE's large science facilities
- Such technology, if feasible, should transfer to industry and facility users for larger field 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 key R&D 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, understanding of proof-of-principle and REU student education.

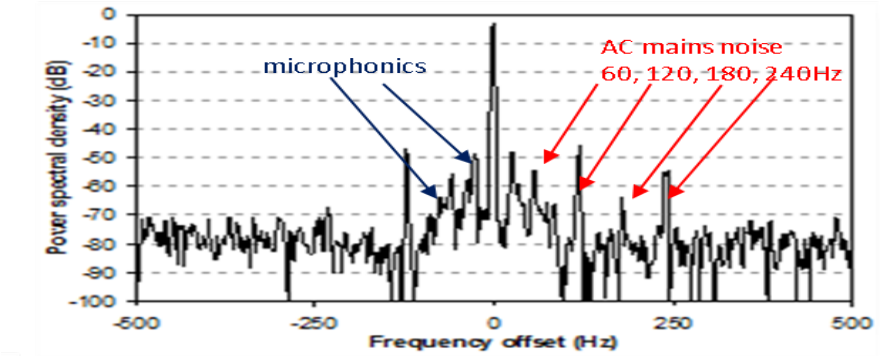
Magnetron RF source, the potential impact for SRF Accelerators

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

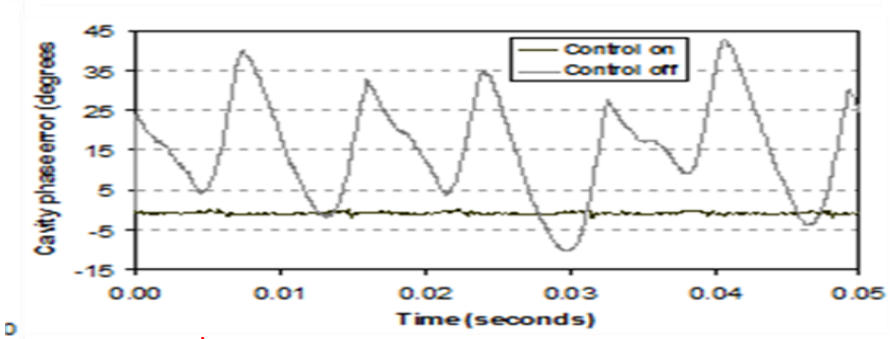
- Low cost of magnetron device
- DC-to-RF efficiency from klystron to magnetron improves from ~35% to 80-90%

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





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..

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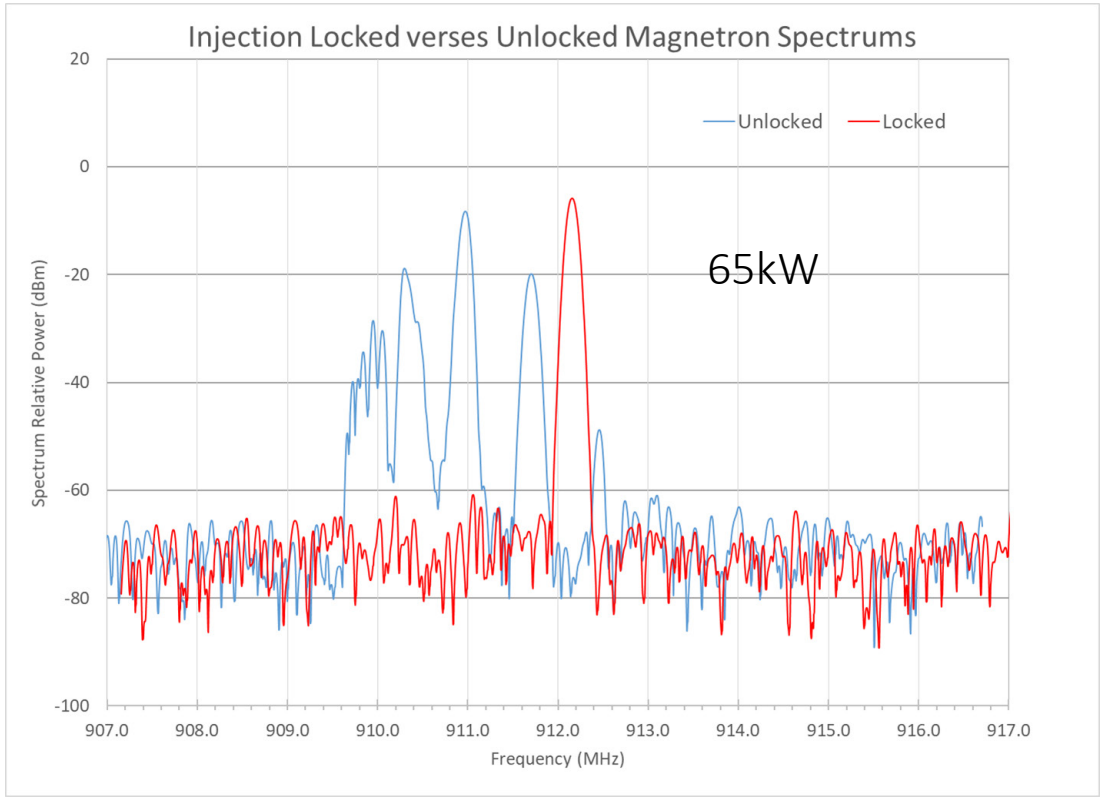
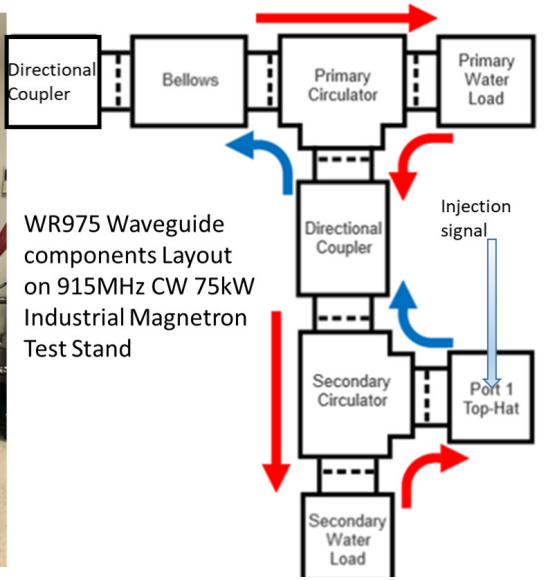
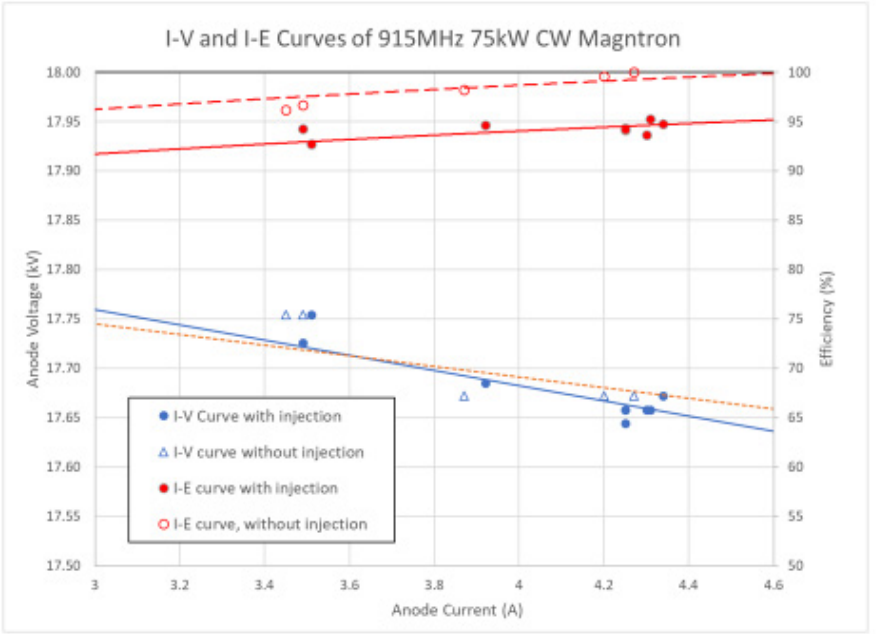
First Demonstration of Injection Phase Lock to 75kW CW AMTek Magnetron





WR975 Waveguide components Layout on 915MHz CW 75kW Industrial Magnetron Test Stand



- Injection phase-lock at 75kW, -26.6dB (164W) injection
- More than 90% of DC to RF efficiency
- 480Vac 3-Phase transformer SCR only DC power supply
- Double isolation with AMTek circulators and water loads
- Iron shunt plates magnetic field trimming
- Performance and cost suitable for Industrial Accelerators

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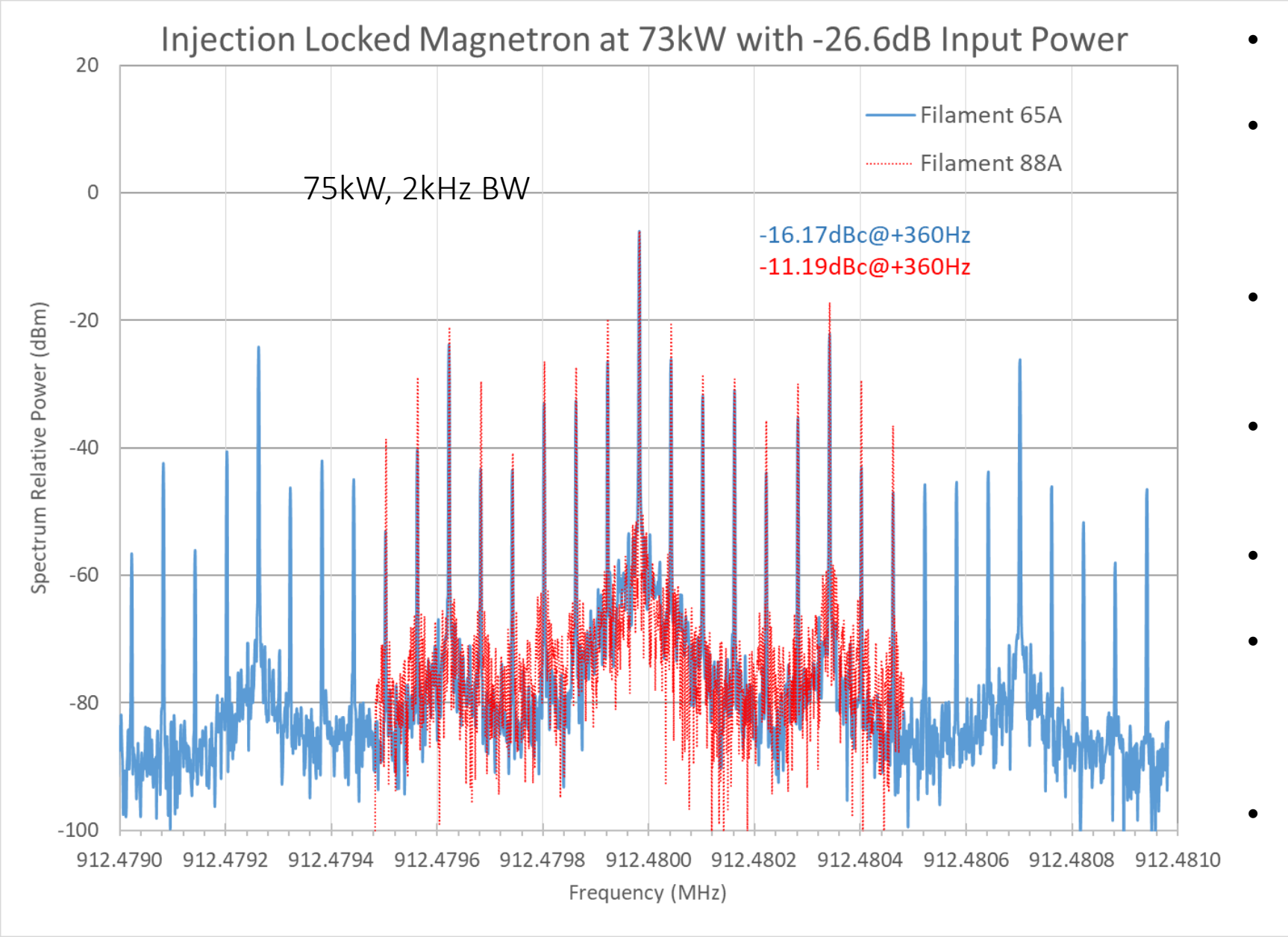
Phase locked power spectra with sideband suppressions



- **Sub-Hz** frequency stability with power deliver to water loads
- -5dB noise reduction at 360Hz sideband down to -16.17dBc by reducing filament current from 88A to 65A
- Good enough for SRF accelerator applications with loaded Q of 1e6, (1kHz BW, 0.13° in RF phase error)
- Energy spread requirement from linac is from 10^{-2}(NCRF) to 10^{-4} (SRF) for energy gain
- Higher noise at 360Hz with 60 Hz intervals as expected
- For SRF Accelerator cavity of 1kHz bandwidth, the noise reduction could be improved by adaptive feedback
- Prefer to use switching power supply (SBIR-II with Innosys, Incs)

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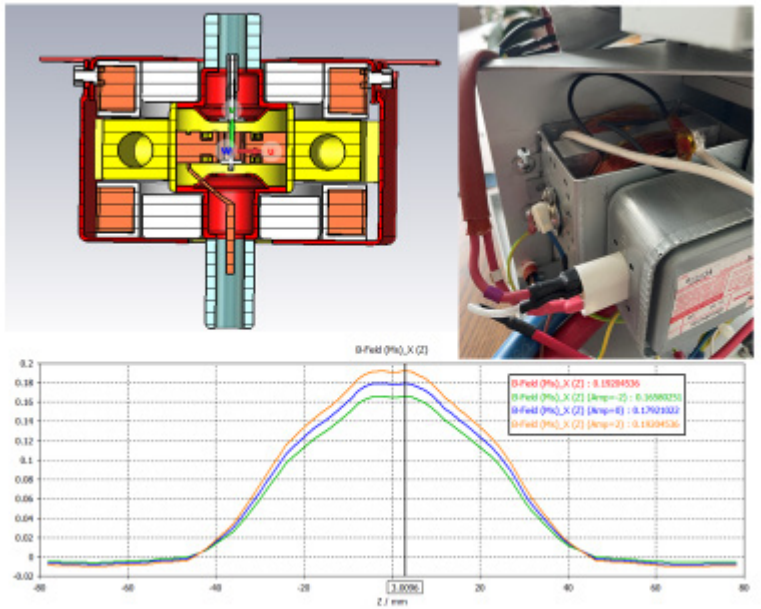
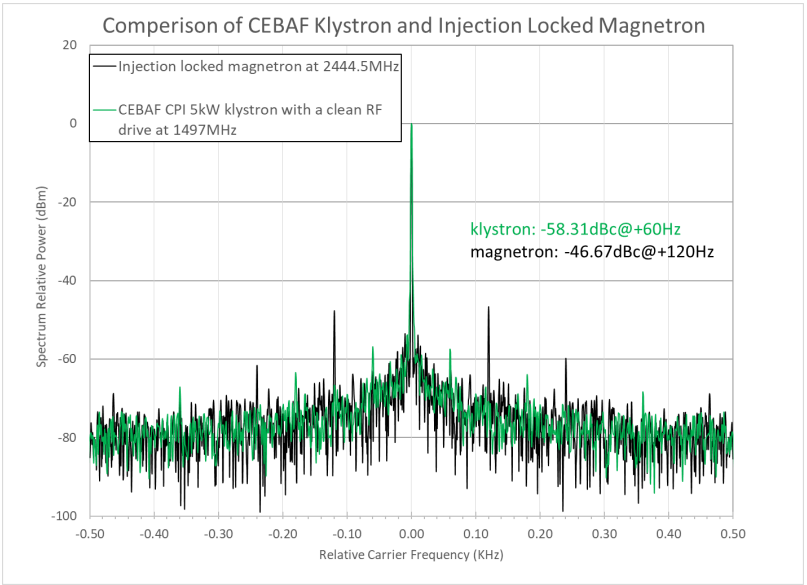
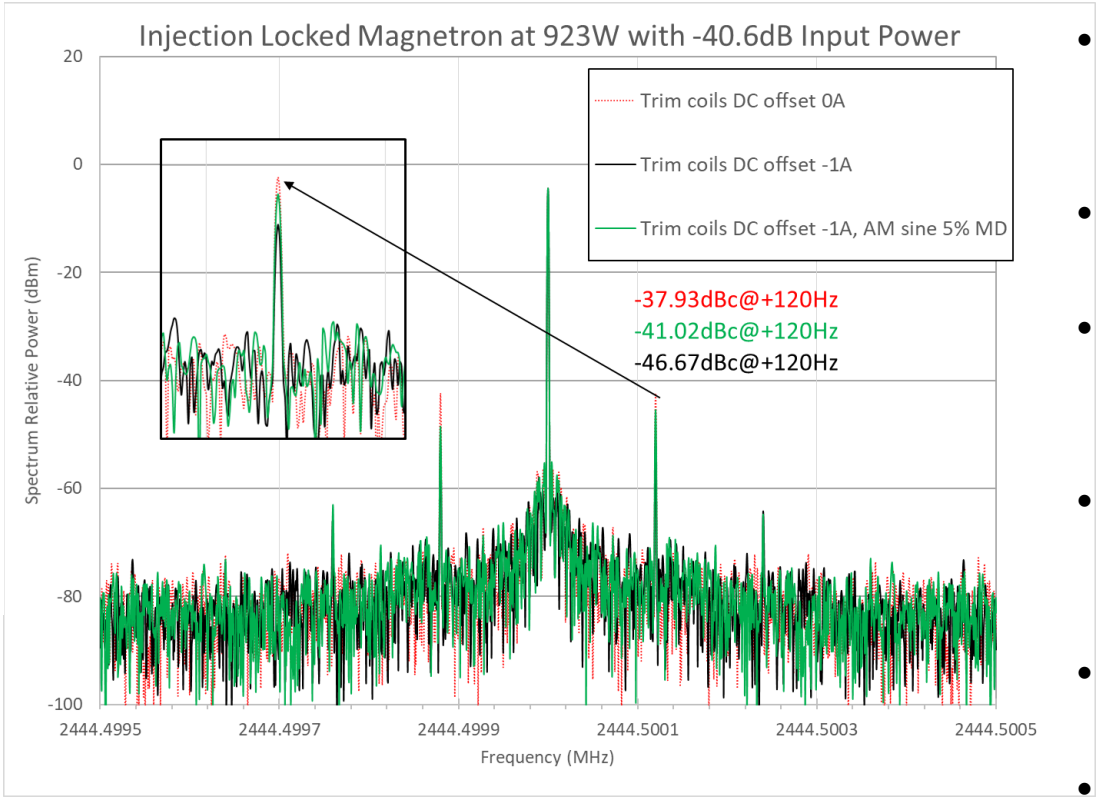
Amplitude Modulation Techniques for Injection Phase Locked Magnetrons at 2.45GHz







- A pairs of trim coils added on a water-cooled magnetron head
- ⍰7.5% static field trimming with ⍰2A DC bias current
- Up to 1kHz of AM has no reduction due to magnetic hysteresis
- DC bias can suppress 8-12dB noise down from injection alone to -46.7dBc
- Other AMs can reduce noise further by 3-4dB.
- Need fast LLRF PLC and smarter power supplies with digital adaptive feedback controllers

Three AM methods for Proof of principle experiment:

1. Anode current power supply
2. RF injection signal
3. **Trim-coils current**

Nominal 5% modulation depth at fixed 120Hz

No adaptive feedback and a fast controller yet

- Trimming magnetic field with DC bias is most effective

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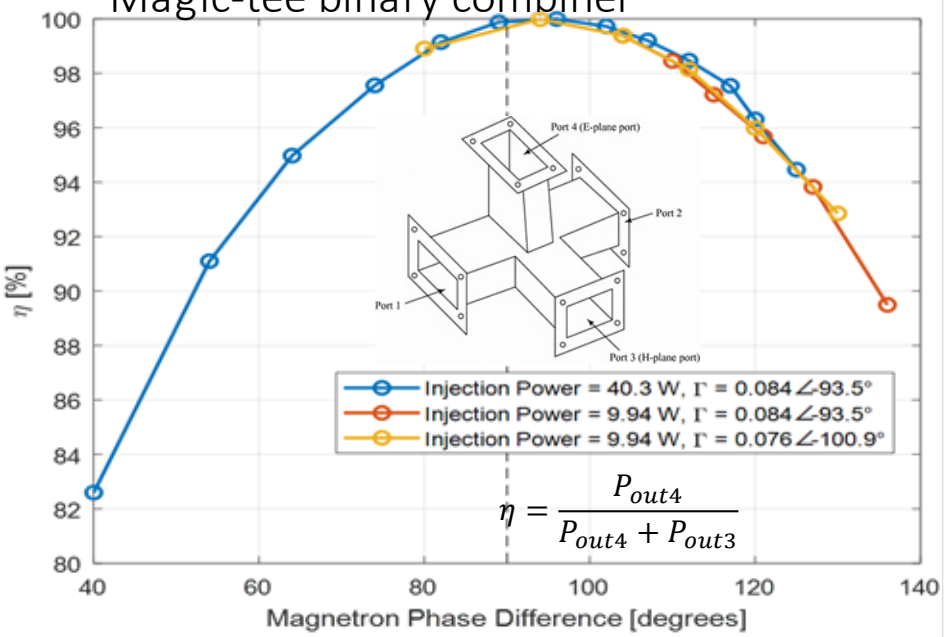
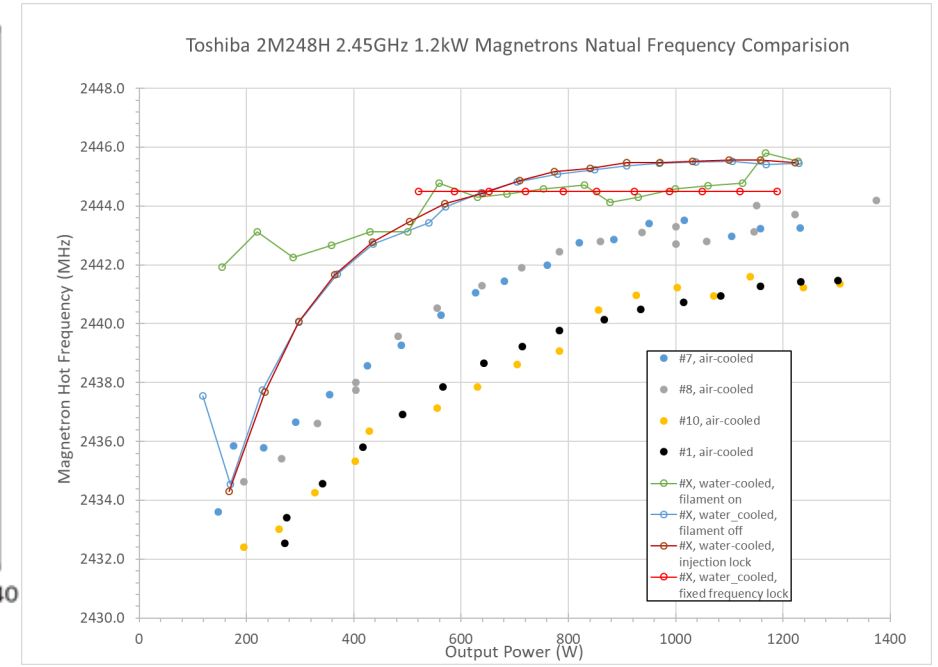
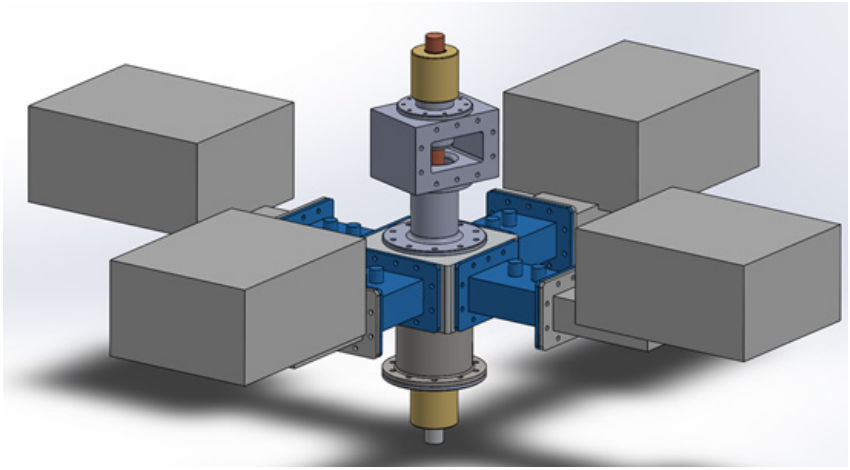
Waveguide Magic-Tee and Cavity Type Power Combiners Study at GA

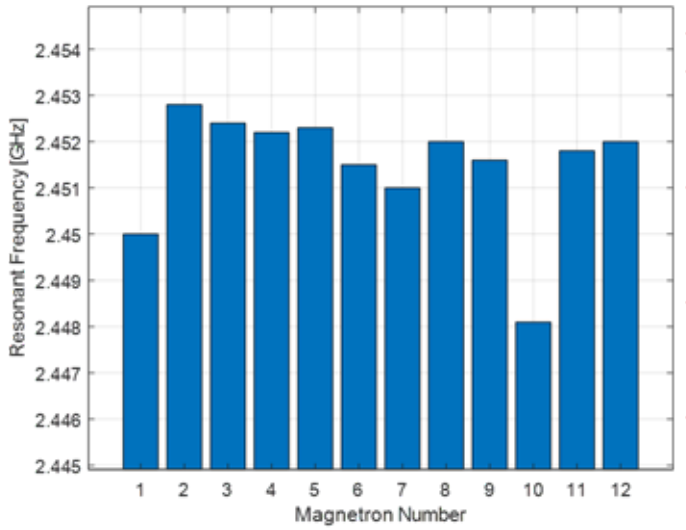
Magic-tee binary combiner





4 to 1 cavity type combiner





- **S-parameters**
- **Adler-Chen's injection instability**
- **trim-coil frequency pushing**
- **Sideband noise reduction**
- **Peer-to-peer phase locking**

- Nearly 100% power combing efficiency (CE) from magnic-tee type
- Nearly ~80% CE from TM010 cavity type
- Need phase shifter at combiner output port to compensate reactive load
- Characterize natural frequency pushing and I-V curve for each magnetron head
- Understand peer-to-peer phase locking and beat wave damping and tuning mechanism for smart controller
- Developed a Matlab code to choose optimum control parameters

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Conclusions and near-term plans

- First injection phase lock performance demonstration at 75kW 915MHz magnetron has proved that industrial grade power supply can be used and upgraded for the power combining and driving for the industrial particle accelerators for wastewater treatment application
- More than 90% of DC-RF efficiency, low capital cost <1$/W and -26.6dB injection power only for the < 1Hz locking stability make the magnetron transmitters being an ideal candidate for the high power, low energy electron accelerators' RF sources, for both NC and SC RF cavity modules.
- Amplitude modulation and power combing experiments at 2.45GHz have confirmed possibilities of using magnetic trim coil or solenoid current to push magnetron frequency and sideband noise reduction
- We need to further FPGA embedded smart and fast power supplies and their controllers' development for controlling nonlinear characteristics of magnetrons for further power combing and linac with beam loading experiments
- High power magic-tee combining experiment of 2X75kW is the next milestone of the experimental demonstration in the Accelerator Stewardship program

Picture place holder for second AMTek transmitter crane lifting operation to LERF Building at 7:00-8:00am on August 10, 2022.

Next Proposed scheme for 4x75kW binary power combing