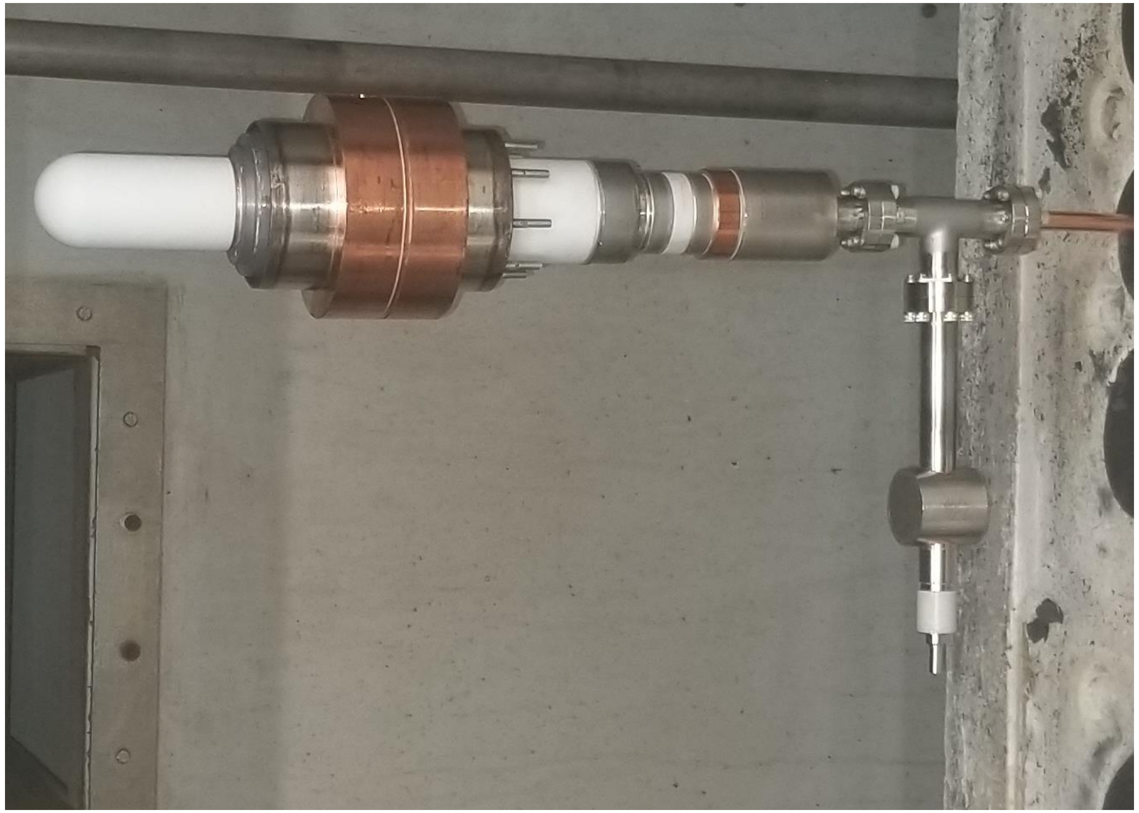
Vertical Slice Magnetron Efforts at JLab

Haipeng Wang

Presenting for Kevin Jordan (PI)



Main Project goal:
Phase and Amplitude lock a magnetron to a JLab 1497 MHz SRF Cavity

DOE R&D PI Exchange Meeting Dec. 2, 2024

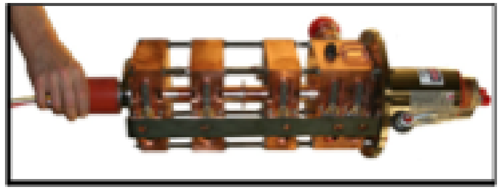
Outline

- Introduction
- Vertical Slice project
- Magnetron design
- Power supply design
- Initial setup
- Test plan
- Budget
- Deliverables
- Summary

Magnetrons as an RF Source for Accelerators

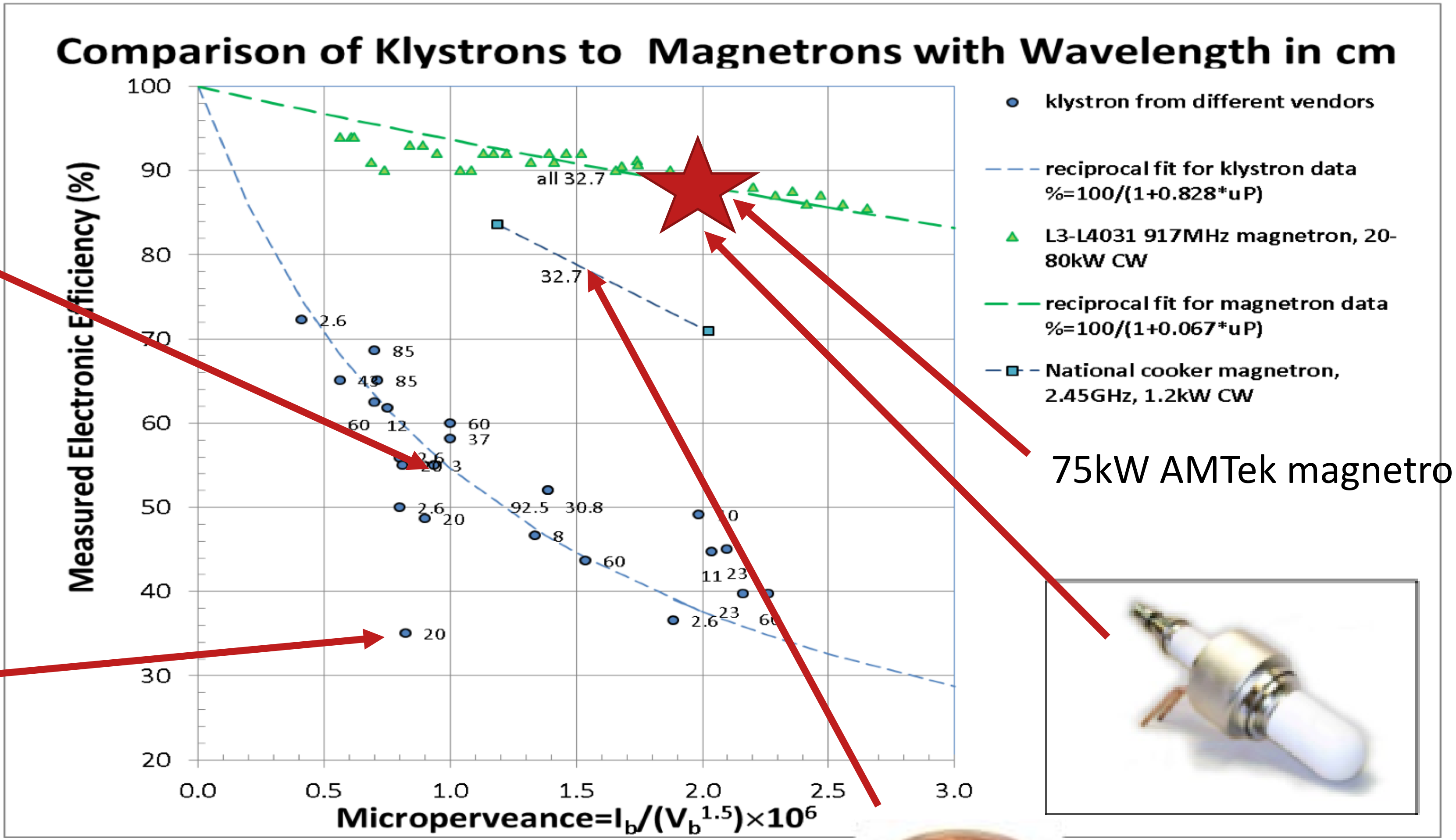
- Higher efficiency >80% and lower cost <1$/W
- Larger industrial and commercial markets
- Cost saving in accelerator operation and infrastructure
- Magnetron works as an oscillator than klystron as a linear amplifier
- Frequency (phase) lock, amplitude modulation are keys to control the magnetron as a reflection amplifier
- Noise reduction from cathode, cathode lifetime, power supplies and thermal stability are key R&D area
- 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 at JLab by different funds.

Motivation of using magnetrons as RF sources of particles accelerators



~$5/watt
L3 13 kw
Klystron

~$8/watt
Varian 5 kw
Klystron



<$1/watt
National 1.2kw
Oven magnetron

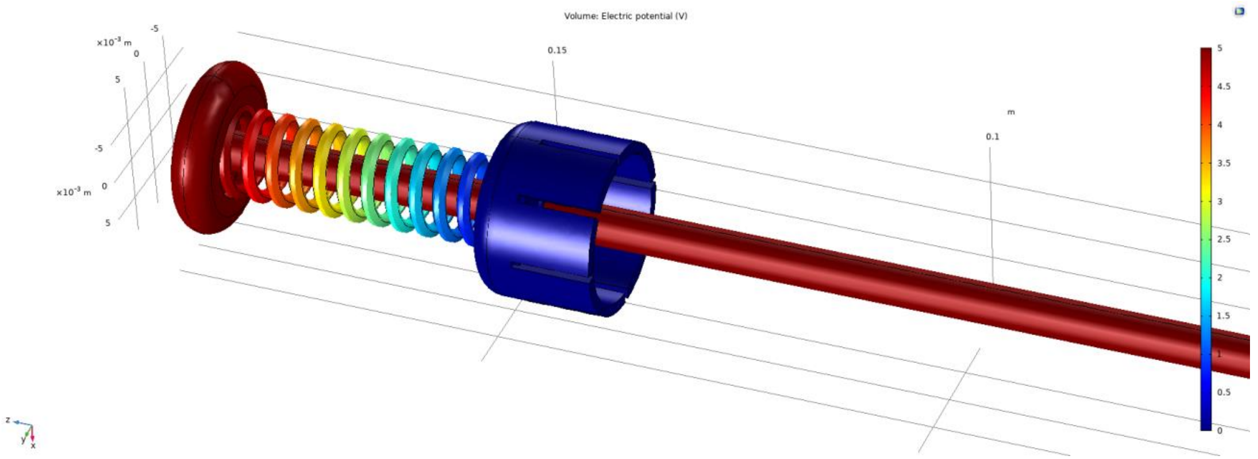
$1-$2/watt
20 – 80kw
Magnetrons

1497 MHz Vertical Slice Magnetron Project

- FOA Funding is to combine SBIR efforts to power up a SRF cavity with phase & amplitude locking – 2 year effort – Now in No Cost Extension
  - Muons Inc. is supplying 1497 MHz magnetron (SBIR funding)
    - First tube frequency was too high (1510MHz) & developed water leak
    - Second tube developed vacuum leak during assembly
    - Third tube is expected to ready for acceptance testing on Dec. 10/11, 2024 at Richardson
  - InnoSys Inc. will supply high efficiency switcher power supply for filament, solenoid and anode high voltage (SBIR funding)
    - This switching power supply has yet to be delivered and is nearly 2 years late. Now we are still on the schedule of delivery in Dec. 2024.
  - JLab RF group will supply Low Level RF (LLRF)
    - Initial injection locking done with existing RF control modules
    - Funding will support JLab FPGA programming with LLRF controller.
- Stretch goal for this effort is to drive the SRF cavity in constant gradient and to accelerate electrons
- Installation will be in the Low Energy Recirculation Facility (LERF)
  - The cryomodule in place has 8 cavities cooled at 2K
  - LCLS-II HE CMs are tested in this facility – using Solid State Amplifiers (SSAs)

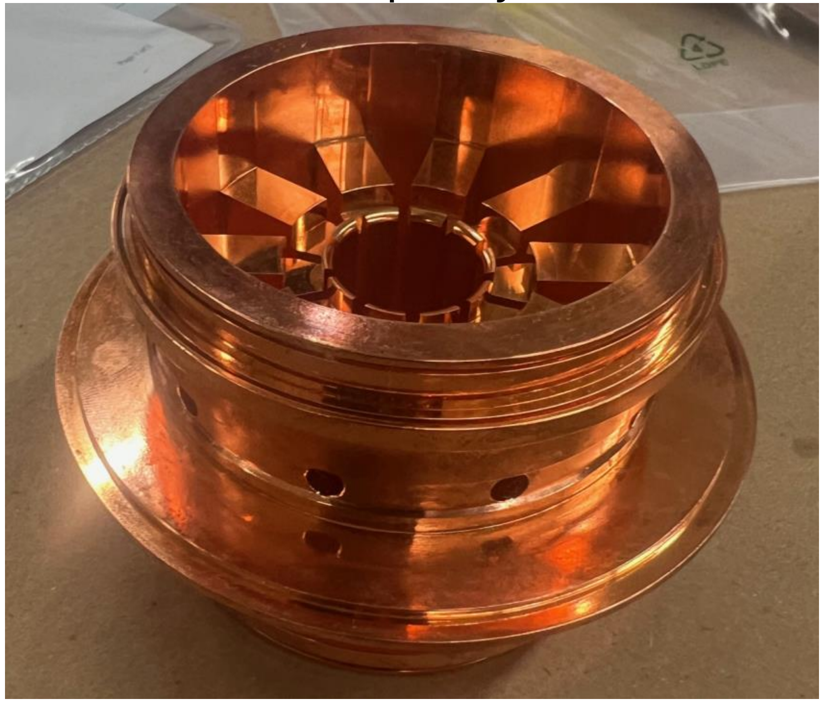
1497 MHz Magnetron Tube Development (DOE NP STTR DE-SC0013203)

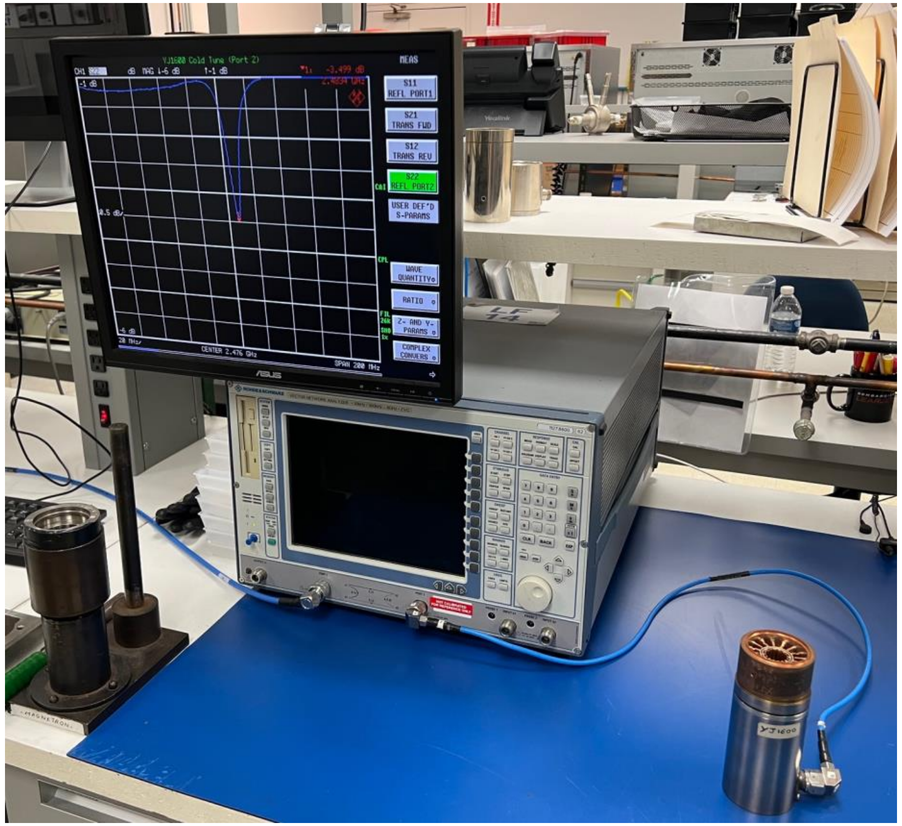
- Muons Inc. is supplying 1497 MHz magnetron (SBIR funding)
  - This tube is similar to 75kW CW, 915 MHz tube design and build by CTL.
  - The tube has 10 strapped vanes, it is water cooled.
  - The power is extracted using a three-legged antenna that is enclosed in ceramic dome.
  - The cathode stalk has a 2 liters/s ion pump and connectors for high voltage and filament power input (Stalk is defined as a plant's main stem).
  - The biggest concern with heat dissipation was related with cathode stalk. After assembling the filament, the temperate of the helix was measured in a Bell jar for different currents. The conclusion was that 75 amps and around 8 volts will create conditions for large electron emission from filament.



1497 MHz Magnetron Tube Development (DOE NP STTR DE-SC0013203)

- Muons Inc. is supplying 1497 MHz magnetron (SBIR funding)
  - Richardson Electronics is manufacturing the third magnetron tube
  - Proper frequency tube is expected to ready for acceptance testing on Dec. 10/11, 2024
  - Long lead ceramics paced this tube – they have ordered 5 parts so additional tubes can be produced
  - ‘Cold’ tuning is the most critical task in assembling a tube
    - The vanes have been fixtured to be uniformly deformed to adjust the frequency



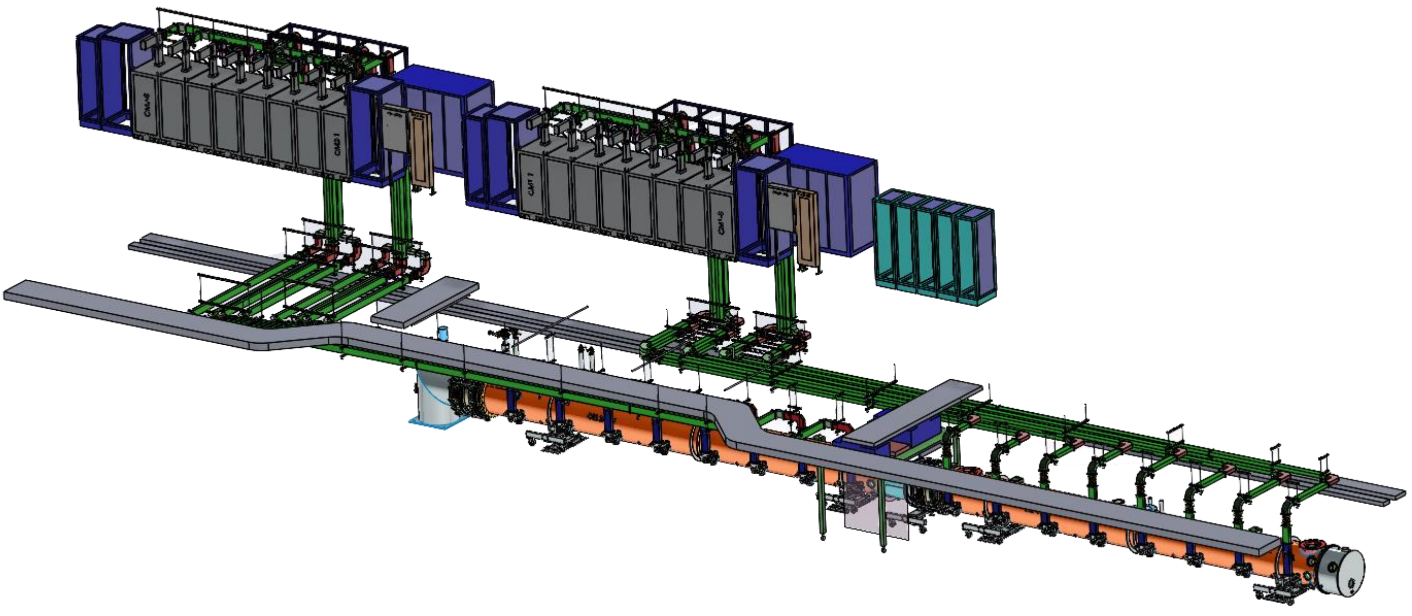


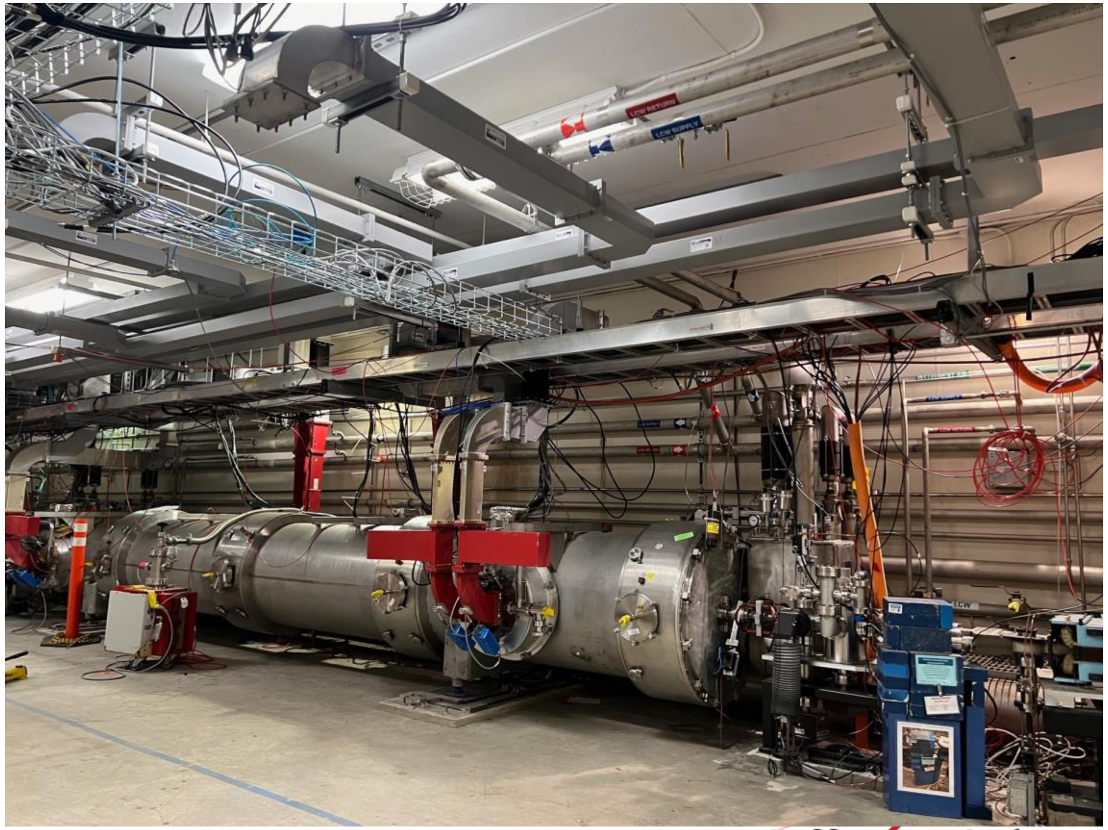
High Efficiency Magnetron Power Supply Development (DE-SC0021455)

- InnoSys Inc. will supply high efficiency (>90%) switcher power supply for filament & high voltage (SBIR funding)
  - This power supply has yet to be delivered & is more than 1 year late
  - The power supply specification consists of a anode high voltage section & a filament power supplies
    - The power supply is rated at 2 amps at -15 kvolts
    - The filament power supply section is not included in the first article
      - I have procured a 8 volt 75 amp DC power supply that will initially be used for the filament
  - Each of these power supplies are independently controlled
    - The control signals are 0 – 10 Volts = 0 – 100 % output
    - The power supply also has a digital interlock signal to disable the high voltage
  - The power supply is fully short circuit, over voltage, over current, over temperature, and arcing protected.
  - In case of a cavity interlock fault the high voltage can be cut off in less than1 millisecond
  - The prime power is 208 VAC, 3 phase, with 100 amp circuit breaker (~80 amps)

1497 MHz Vertical Slice Magnetron Project AT LERF

- Initially 2 LCLS-II CMs were tested together; ~1,000’ of waveguide was installed for this project and two zones of klystrons were removed.
  - LCLS-II HE only tests one CM at a time so the ‘empty’ zone will be used for the magnetron testing
  - Only minor changes to waveguide needed to connect magnetron in the equipment gallery, only cavity # 7 is to be tested in the installed CEBAF cryomodule.

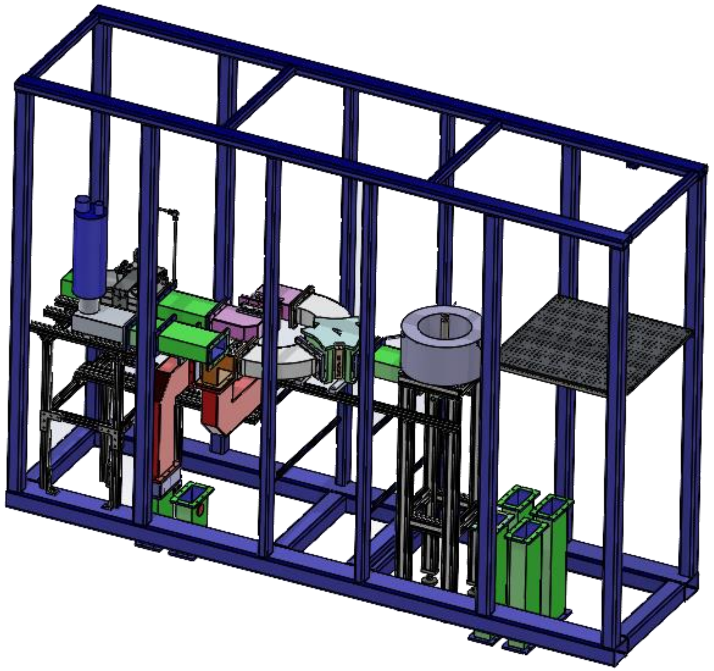


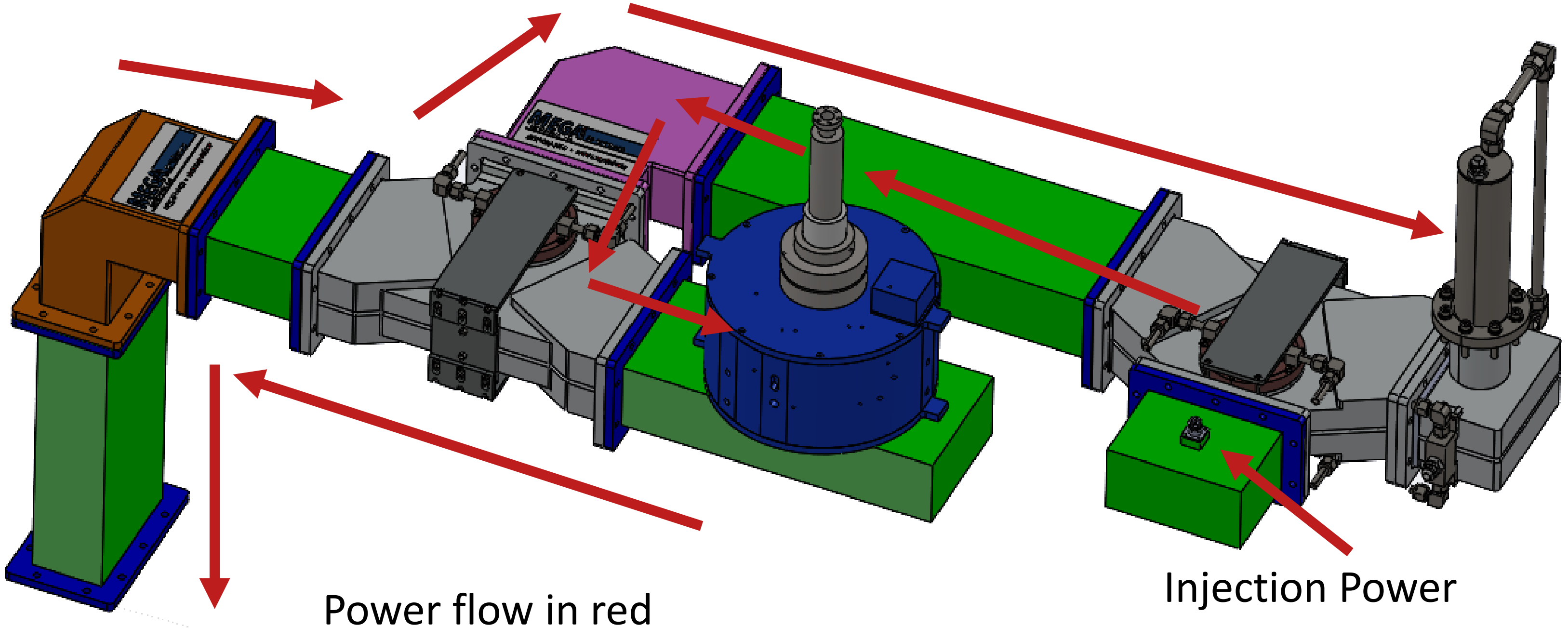


Jefferson Lab

1497 MHz Circulators & Power Flow for Injection Signal to Phase Lock

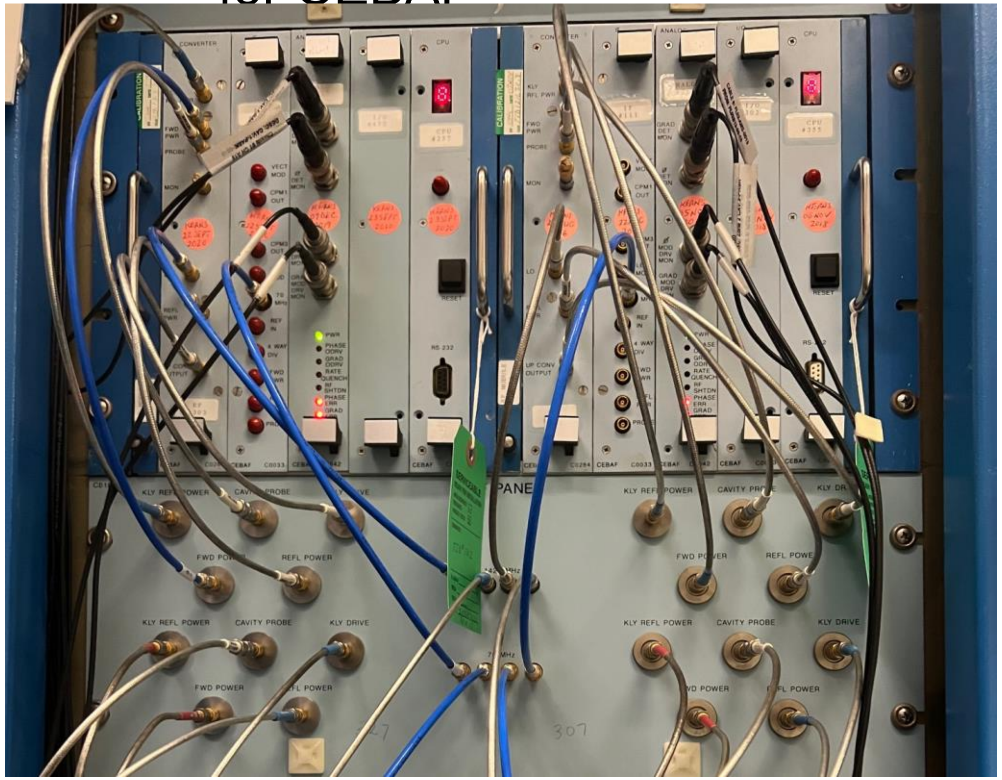
- JLab has placed an order for 53 new circulators, I was able to add on to this order for the two needed to connect to one of the SRF cavities in the vault. Image below illustrates the installation.
  - These circulators are also late; the initial testing failed of the circulators for the CEBAF machine. There was heating and insufficient isolation.
  - I have work-a-round by using old FEL 100 kWatt spare and old 5 kWatt CEBAF style circulators





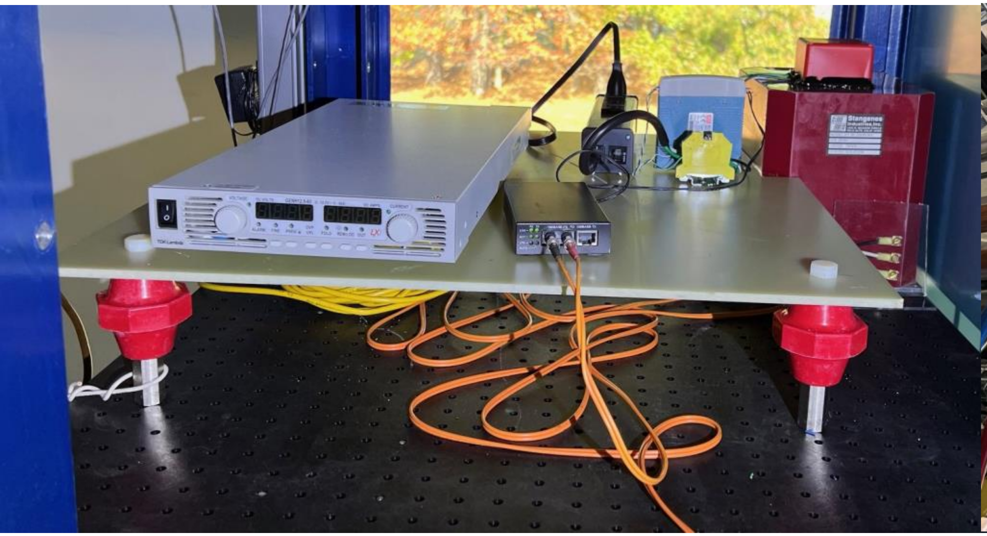
Injection Locking Using Existing Low Level Control Modules

- Installation awaiting 1497 MHz magnetron, power supply, & circulators
- The “Old Style” Low Level RF (LLRF) control modules (RFCM) will be used initially
  - These RFCMs are interfaced to all of the cavity interlocks; cavity field probe, reflected power, arc detector, vacuum, helium liquid level, tuner control…
  - The RF group has been working on a new, more modern controller for LCLS-II and LLRF 3.0 for CEBAF



Initial test set-up

- Once the tube and power supply arrive they will be installed in the rack
- There is a high voltage deck that holds the filament power supply and associated controls.
  - There is a 750 VA isolation transformer (50 kVolt isolation) that provides 120 VAC to the high voltage deck
  - The controls are done via a fiber optic interface to the PLC/HMI
- Water cooling lines are connected & interlocked to the old LCLS-II LCW manifold
- There is also a DC solenoid power supply controlled through the PLC



Test Plan

- Initial testing will be powering the tube connected to a high power water cooled load
- This will determine the natural frequency of the magnetron
- Once the operating parameters have been established into the load, injection locking will be studied
  - These studies will include varying the solenoid current, filament current, and anode current
  - We are considering varying the output coupling on the launcher by varying the end plate gap if the magnetron hot frequency is slightly off from 1497MHz
- After it is very stable phase lock to 1497MHz and also can be amplitude control to a load we will connect to the cold SRF cavity in the LERF vault
  - This will require a careful check of all of the SRF interlocks
  - The tuning range for the C50 cavity mechanical tuner is ± 200 kHz

Budget

- Delivery problems have delayed progress on original schedule
  - The spending profile reflect those delays
  - We had no-cost extension in FY24

PI	ID #	Item/Task
Kevin Jordan	000001.04.05.032.001 (VSLICE)	Accel R&D - Magnetron Vertical Slice

Summary of expenditures by fiscal year (FY):

	FY22 ($k)	FY23 ($k)	Totals ($k)
a) Funds allocated	$407	$258	$665
b) Actual costs to date	$194	$0	$194

Total balance: $471k

Deliverables

Deliverable	Expected Delivery	New Delivery	Vendor
Magnetron Tube	January 2024	December 2024	Muons Inc.
High Efficiency Power Supply	January 2024	December 2024	InnoSys Inc.
High Power Circulators	March 2024	Not show stopper anymore	Symphony Microwave
Control System	January 2024	Operational as far as it can be	JLab

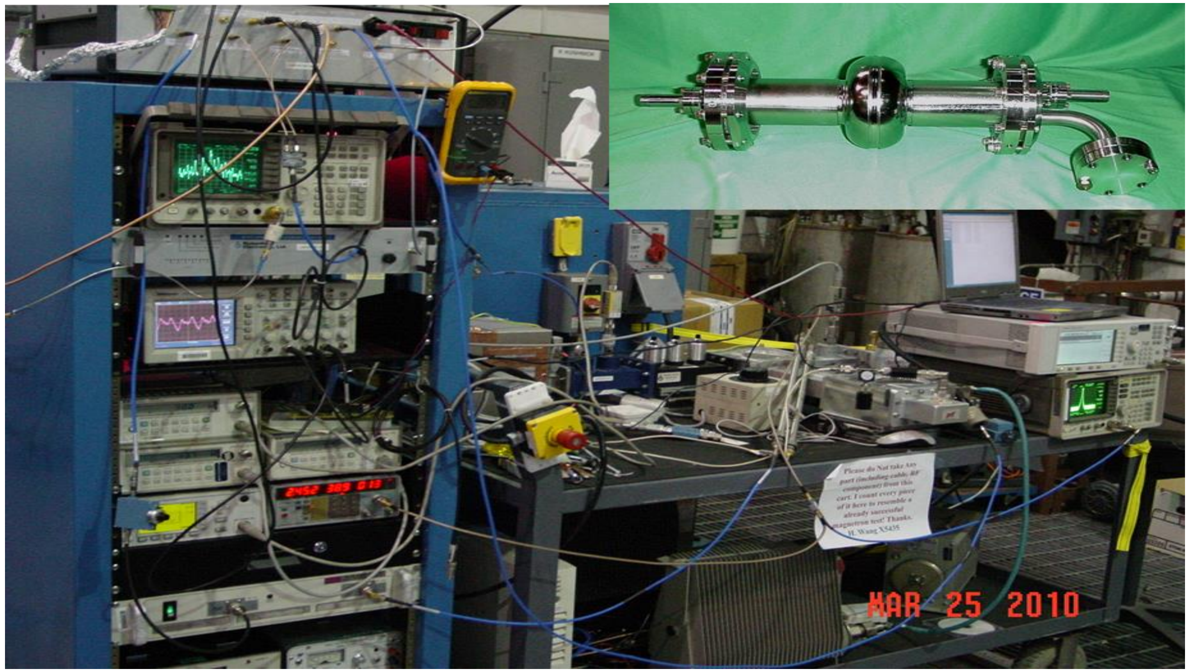
- The power supply & tube are pacing items – I do not have a backup solution
- Circulators are not holding project up – I borrowed FEL spare

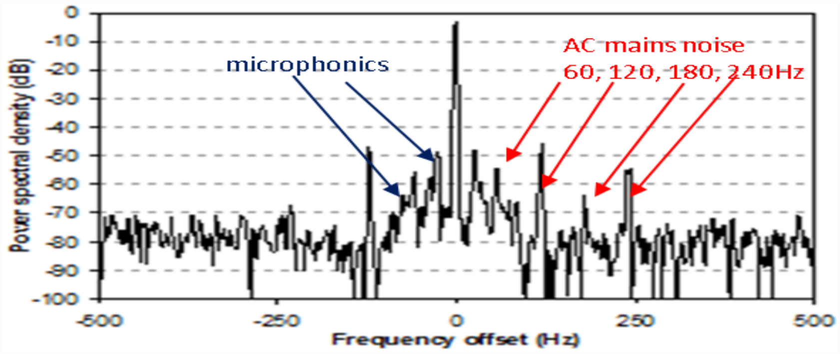
Conclusions

- Delivery problems have delayed progress on original schedule
  - Power supply from InnoSys (SBIR funded) although has a lomng delay, finally making progress
  - Magnetron tube from Muons Inc (SBIR funded) is close to being finished > 6 months late
  - Circulators initial testing failed to meet spec, also could be a year late
    - I have work-a-round by using old FEL 100 kWatt spare and old 5 kWatt CEBAF style
- Good progress has been made on the infrastructure to support testing of the tube
- Injection locking and amplitude modulation studies continue with the 915 MHz and 2450MHz magnetrons, have shown promising results.

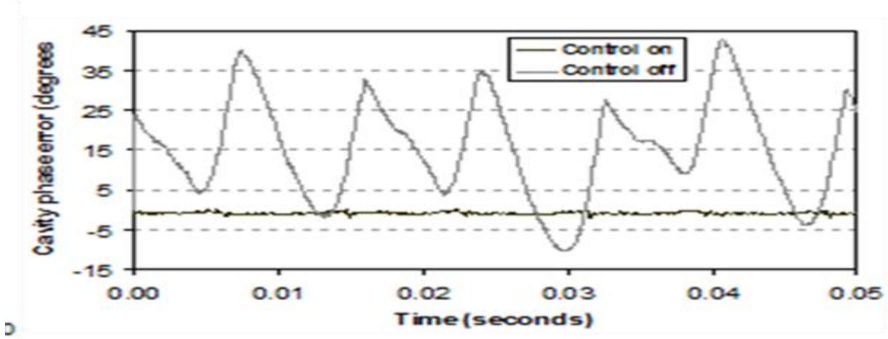
Backup

First Demonstration of Injection Phase Performance to a SRF Cavity





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:

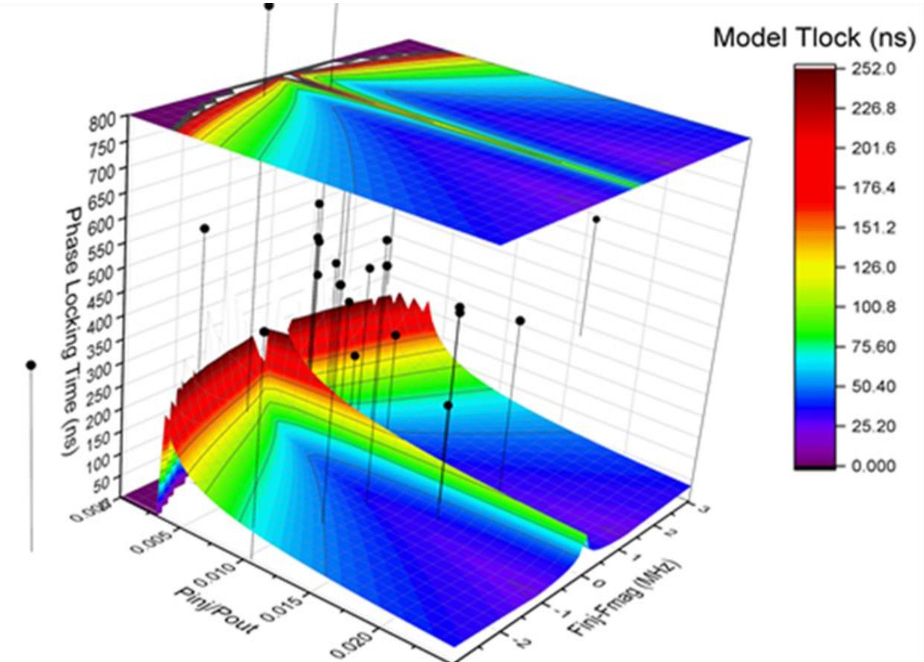
[1] A. C. Dexter, G. Burt, R. G. Carter, I. Tahir, H. Wang, K. Davis and R. Rimmer, PRST-AB, 14, 032001 (2011).
[2] H. Wang, et al., "Use of an Injection Locked Magnetron to Drive a Superconducting RF Cavity", in Proc. 1st Int. Particle Accelerator Conf. (IPAC'10), Kyoto, Japan, May 23-28, 2010, pp. 4026-4028..

Understand the magnetron injection lock control performance is critical R&D

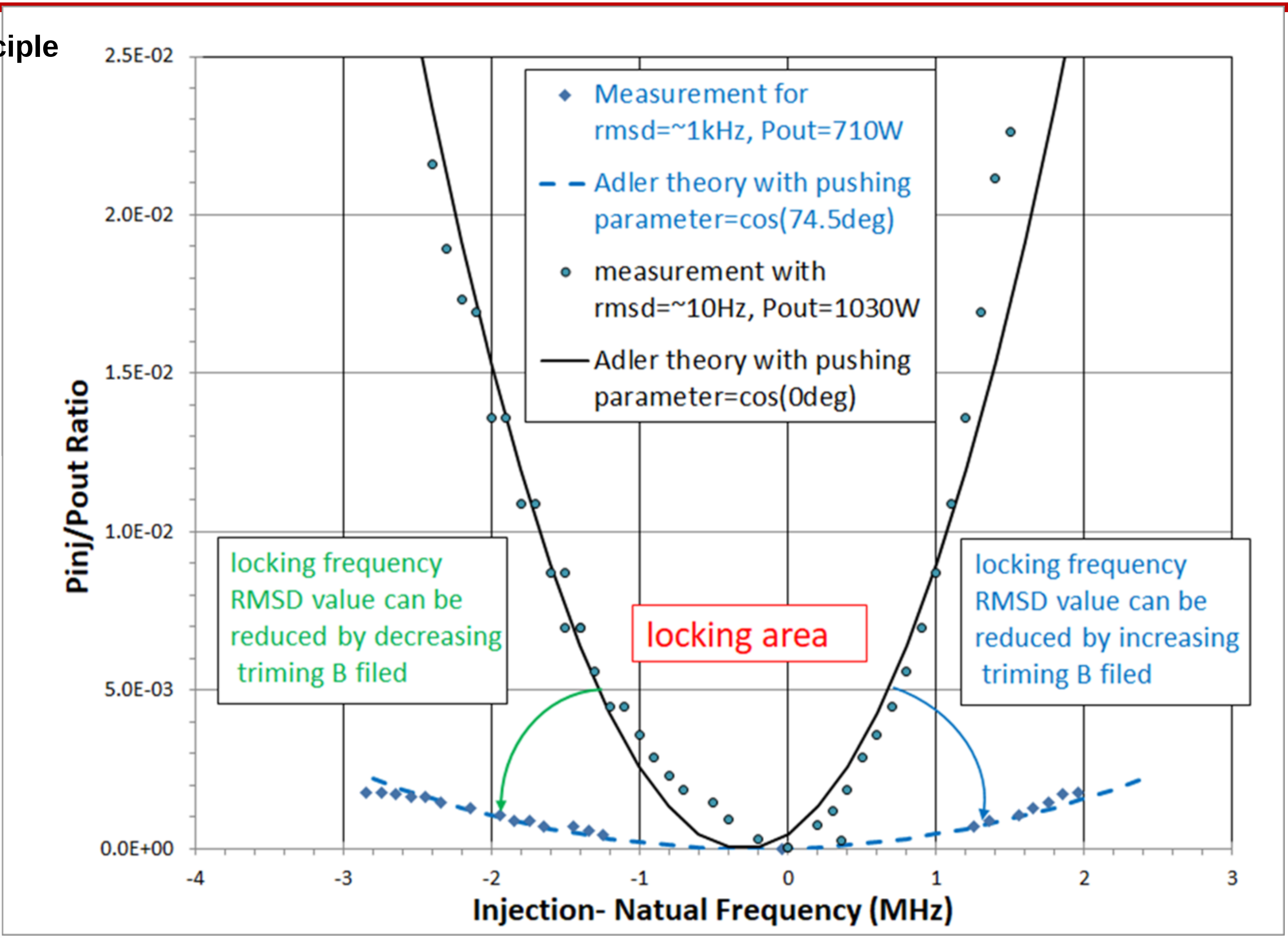
Adler/Chen Injection Phase Lock and Stability Principle

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

- 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. Its stability diagram can be pushed by external magnetic field

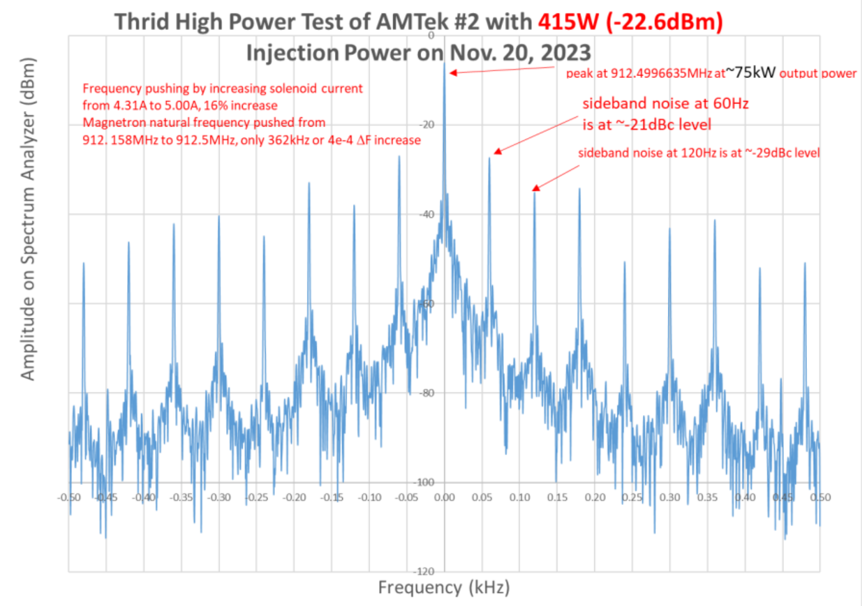


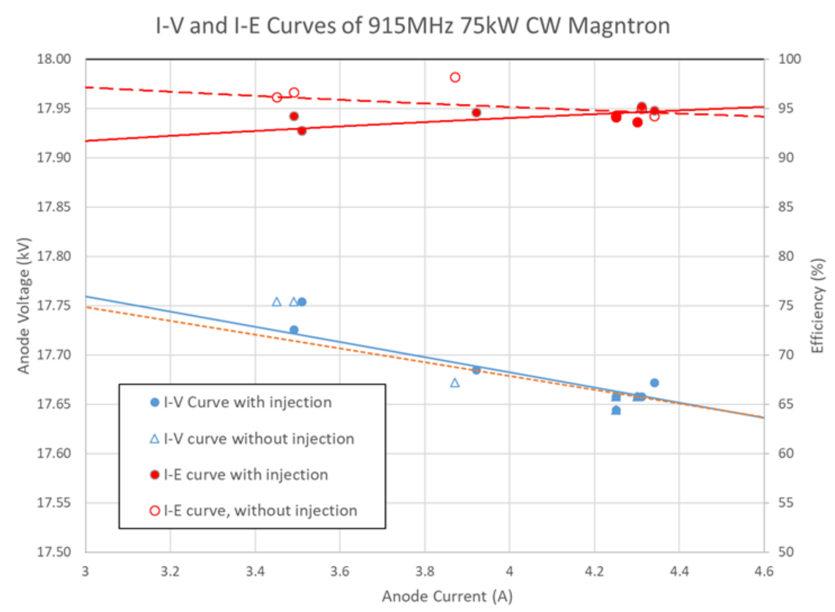
Measured injection lock time vs Chen's model

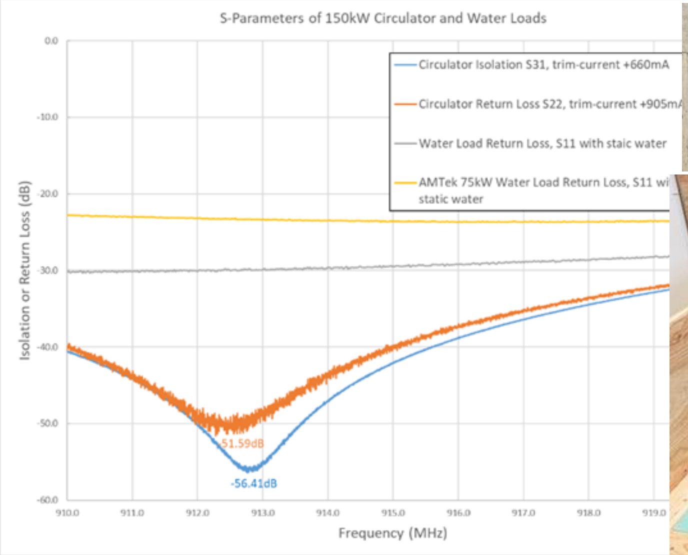


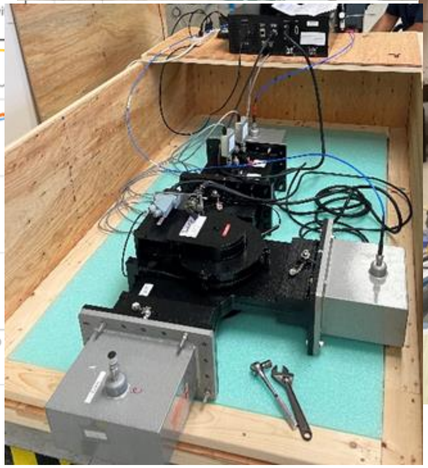
915 MHz Industrial Magnetron R&D Test Stand Result at LERF, JLab

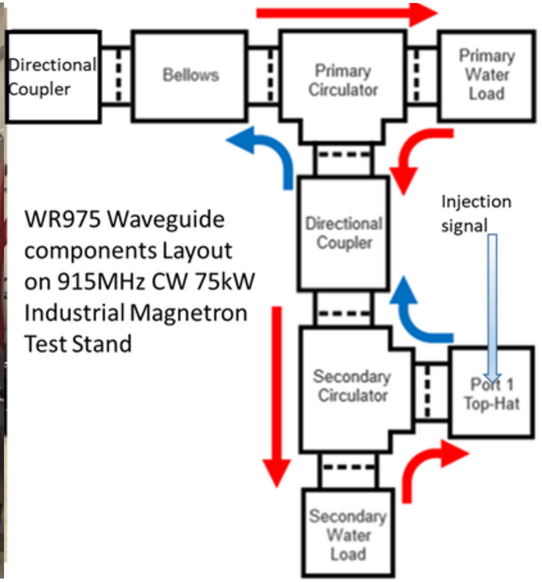
- High (~95%) AC to RF power efficiency demonstrated in 2022-23
- Low ($1-1.5/W) capital cost with transformer/SCR type DC PS
- Demonstrated injection lock performance with reduced filament current
- WR975 waveguide to drive accelerator components
- For industrial type beam quality, transformer/SCR type DC PS could be





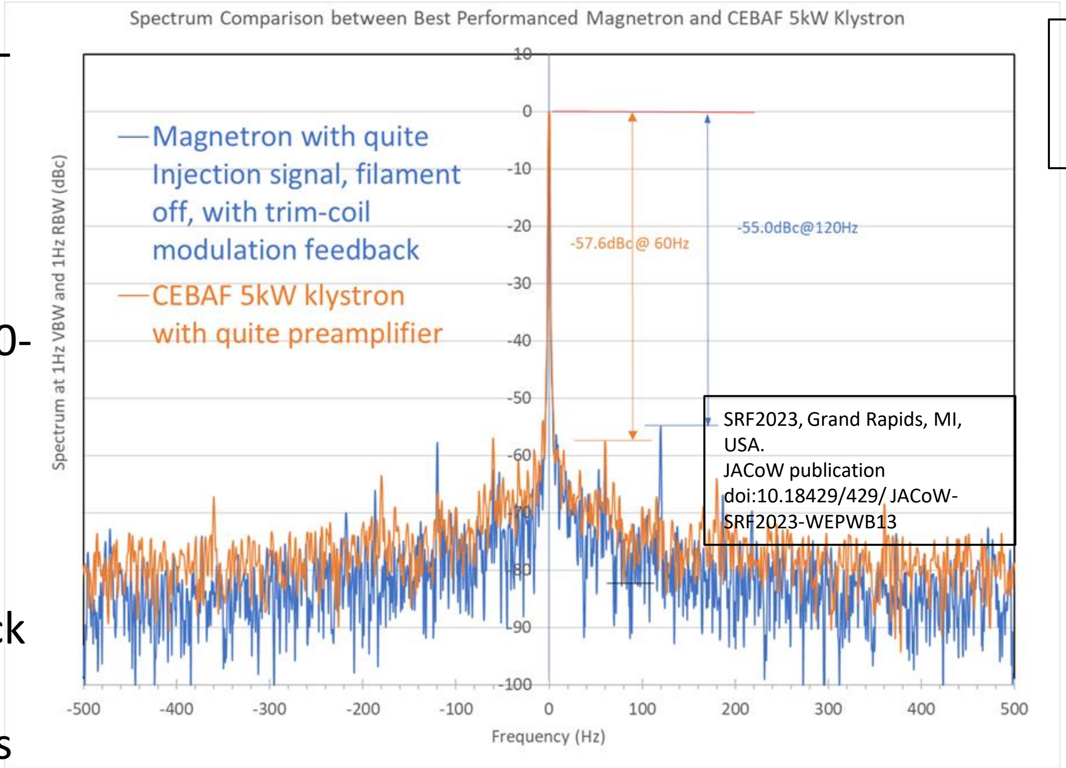


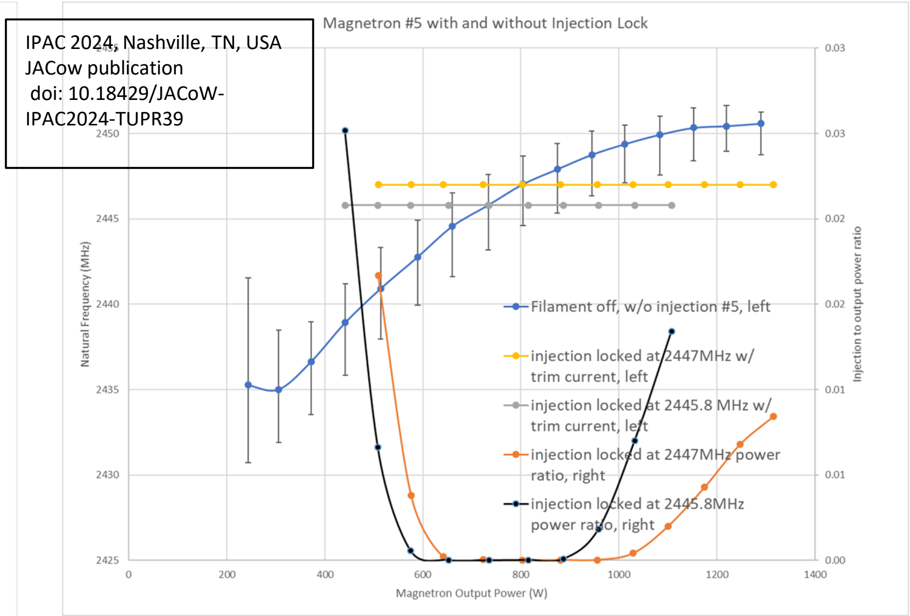




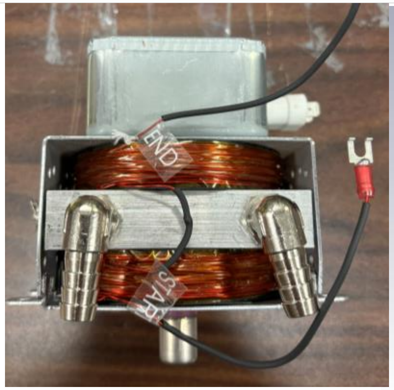
Trim-coil current feedback control to suppress natural frequency pushing

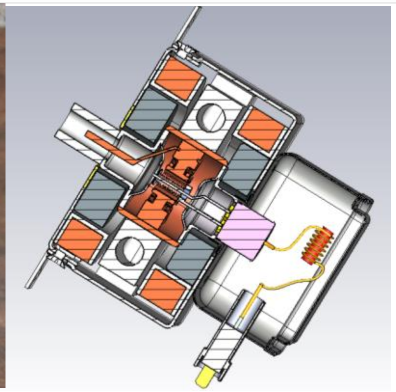
- All magnetron heads (#1-#5) and data have been sent to GA for further power combining experiment.
- Locking range is from 200-1300W, frequency lock accuracy is ~1Hz
- Best noise reduction (at #2, now at #7) by the trim-coil current feedback is at -55dBc
- Switching power supplies is a better choice for SRF accelerator beam quality
- Magnetron technology demonstration has been realized at the 2.45GHz test stand first comparing to the CEBAF klystron performance

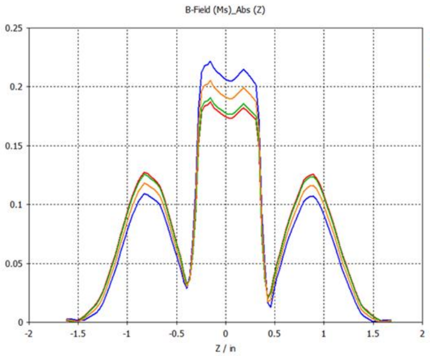




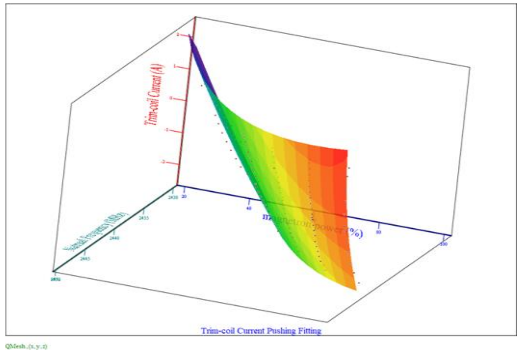
Control algorithm based on 3D data progression fitting model for the automation of a smart controller





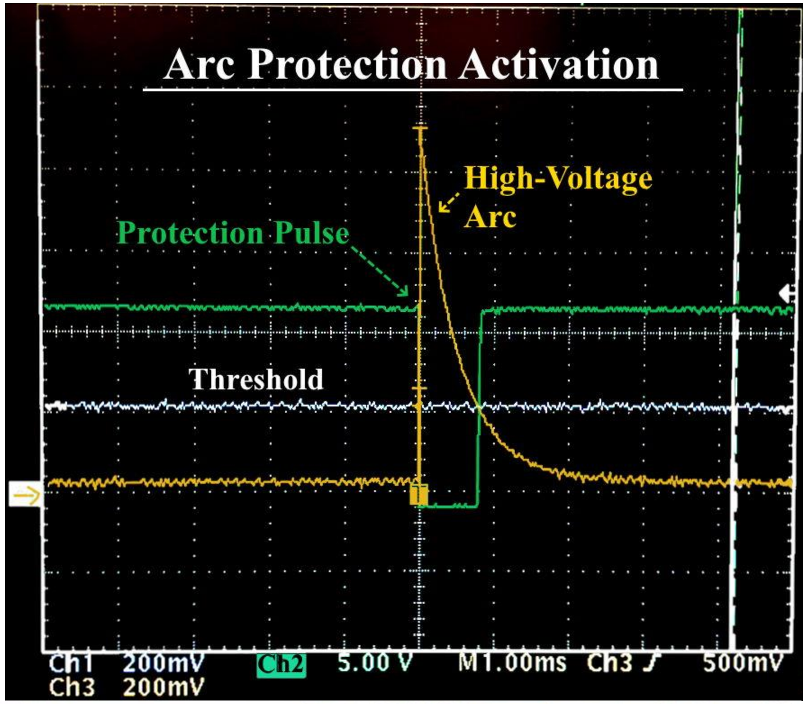


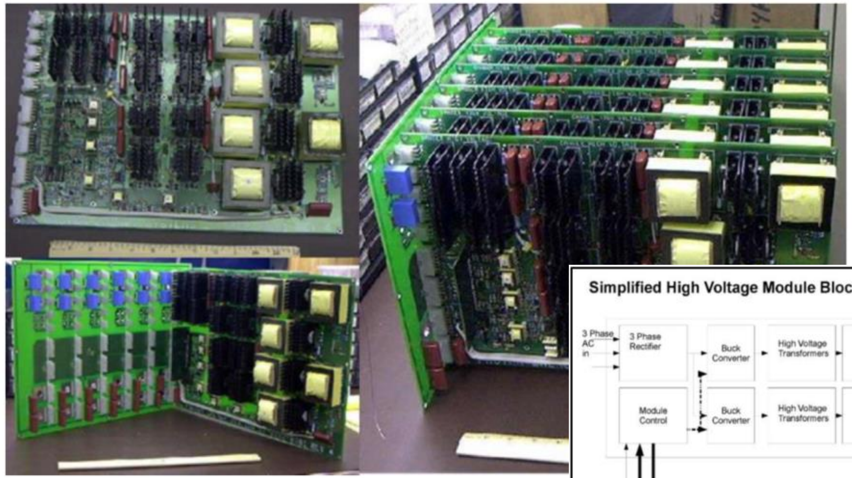
1000 Amp-turns =10% magnetic field trimming

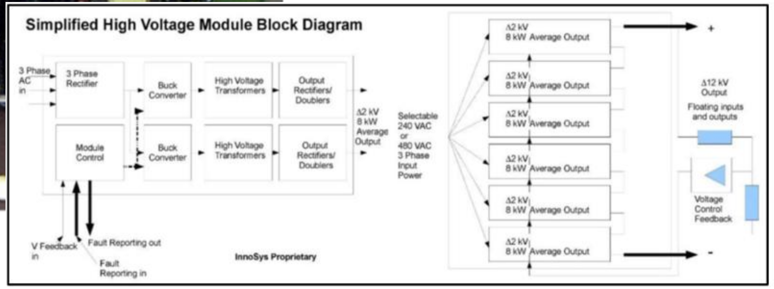


Jefferson Lab

DC Switching Power Supply Development at InnoSys, Inc







- Modular design using 15kV, 0.33 Amp, 5kW modules that can be stacked in parallel or series or both to achieve the desired current, compliance voltage and output power with DC filament current/voltage.
- Anticipated size of the 75 kW output Magnetron DC switching power supply is approximately 2 ft x 2 ft x 2 ft = ~8 ft^3.
- Designed with numerous safety features and interlocks with redundancy built-in.

➢The general design and development of the inexpensive low noise fast switching DC high voltage power supply suitable for driving high power is based on previous related InnoSys magnetron and traveling wave tube amplifier high voltage, high stability, high efficiency power supplies.

➢These power supplies have DC filament power supplies that float at cathode potential.

➢These power supplies are constant current output supplies designed to be able to feedback on the negative impedance for magnetrons – that is as current goes up, voltage goes down.

➢These magnetron power supplies are modular in design allowing the power supply boards, if needed, to be stacked in both series and parallel to achieve the desired high voltage and current required for a given application.

➢ These power supplies are designed in the USA and will be completely manufactured in the USA.

➢Technical progress on track including design, fabrication, implementation and experimental setup and testing.

INNOSYS inc.

Education for undergraduate students with SULI and REU programs at JLab

- Summer 2024: SULI, : Jai Paris, UoT Dallas, Lourdes Leung, UVA
- Fall 2023, Spring 2024: SULI, Christian Cagnino, UCSD
- Summer 2023: SULI, Alex Kerr, UVA, REU: Jai Paris, UoT Dallas
- Summer 2022: REU, Josh Vega, W&M, Josh Blum, VCU
- Summer 2021: REU, Gabija Ziemyte, UoK
- Summer 2020: REU, Jonah Britton, UoM
- Summer 2019: SULI, Catherine Sylvester, UoT
- Summer and Fall 2018: SULI, Clayton Williams, Utah Valley Univ.
- Summer and Fall 2017: REU, Sarah Overstreet, ODU, Guilford College, NC.
- …..

Students' contribution are also in our publications. Most of them have been or are applying for the graduate schools in US for their PhD candidates.