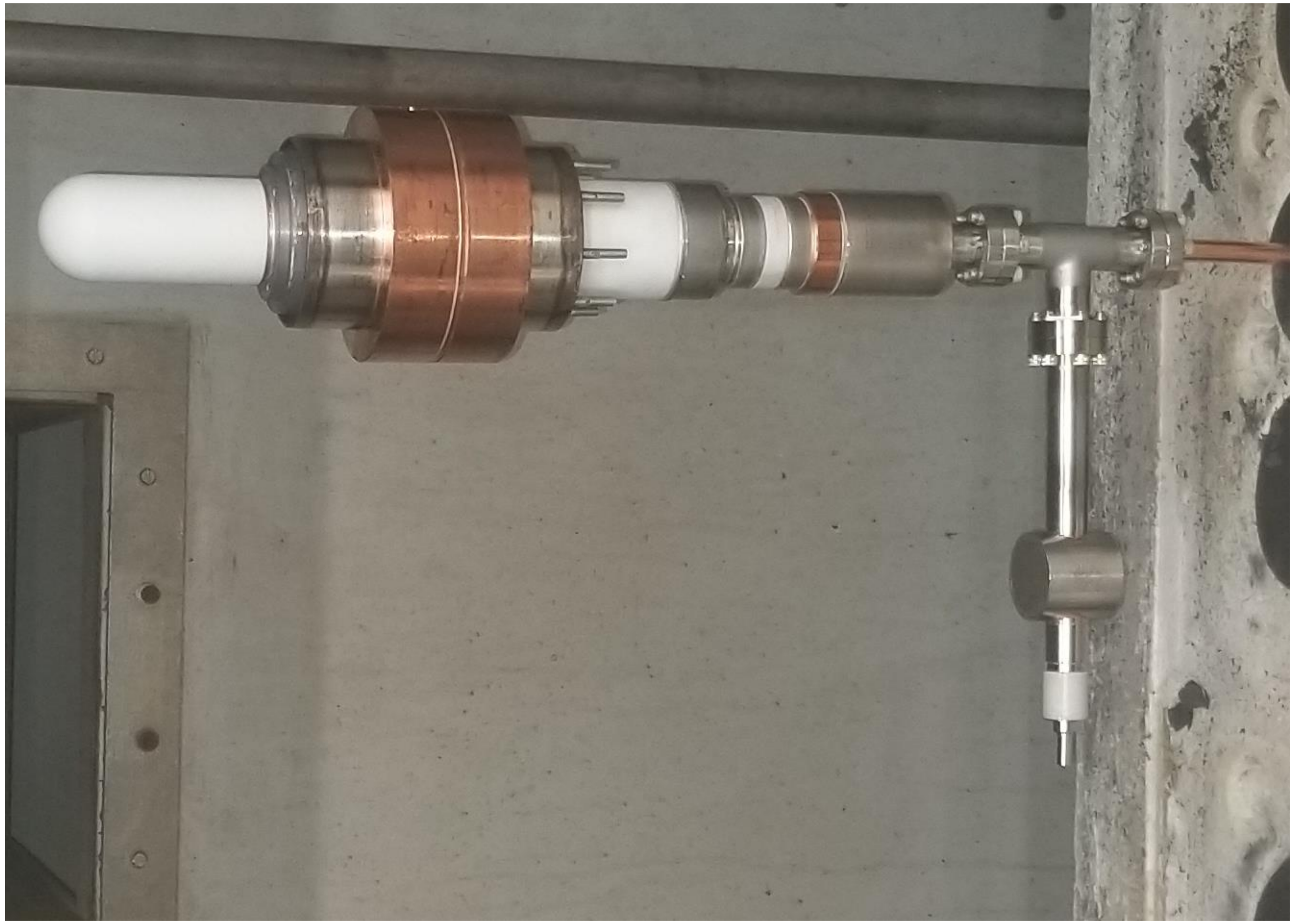
Magnetron Efforts at JLab

Kevin Jordan PE

1497 MHz Vertical Slice Project



First tube prior to baking at Richardson Electronics

Outline

- Vertical Slice Project
- Infrastructure
- Tube design & tuning
- Power Control
- Innosys Inc Power Supply
- Low Level RF & Cavity interlocks
- Budget
- Schedule & milestones
- Summary

Magnetrons as an RF Source for Accelerators

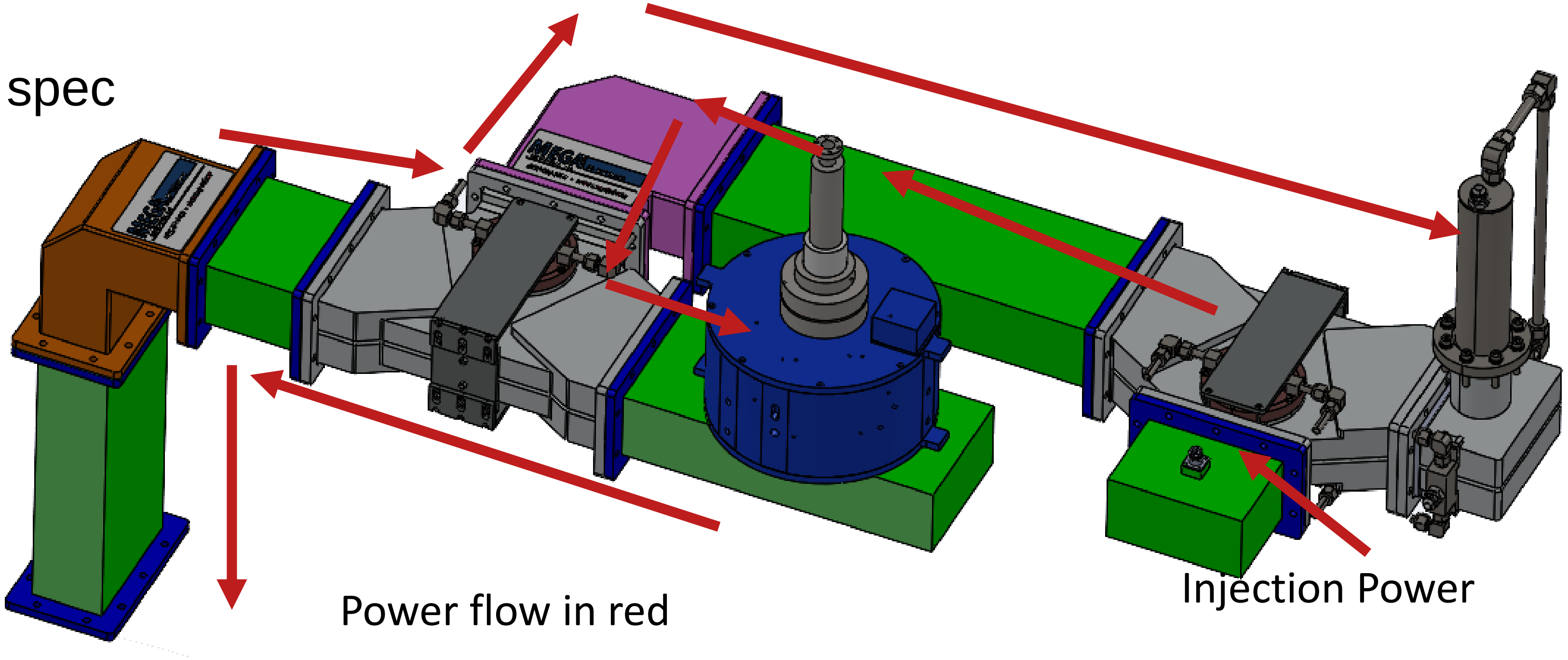
- Higher efficiency >80% and lower cost <1$/W
- Larger industrial and commercial markets
- Cost saving in accelerator operation and infrastructure
- Magnetron works as an oscillator; a klystron is a linear amplifier
- Frequency (phase) lock, amplitude modulation are keys to control the magnetron as a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

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
  - Muon Inc. is supplying 1497 MHz magnetron (SBIR funding)
  - Innosys Inc. will supply high efficiency switcher power supply for filament & high voltage (SBIR funding)
  - JLab RF group will support Low Level RF (LLRF)
- Stretch goal for this effort is to accelerate electrons
- Installation will be in the Low Energy Recirculation Facility (LERF)
  - Facility has 10 cavities at 2K
  - LCLS-II HE CMs are tested in this facility – using Solid State Amplifiers (SSAs)

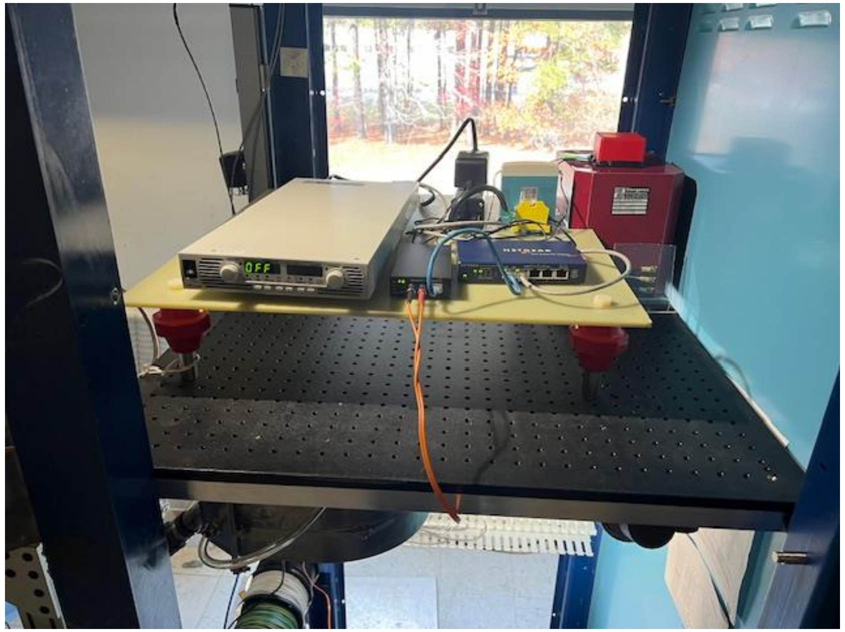
1497 MHz Vertical Slice Magnetron Project

- Initially 2 LCLS-II CMs were tested together; ~1,000’ of waveguide was installed for this project and two of three zones of klystrons were removed. (8 Klystrons per zone)
  - LCLS-II HE only tests one CM at a time so the ‘empty’ zone will be used for the magnetron testing
- JLab has placed an order for 53 new 15kW isolators, 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.
  - The initial design failed, there are iterations needed to meet spec
  - Hope is to have ferrite design complete by January
  - Contract is ~ 9 months late
  - These have to be installed in CEBAF during summer down

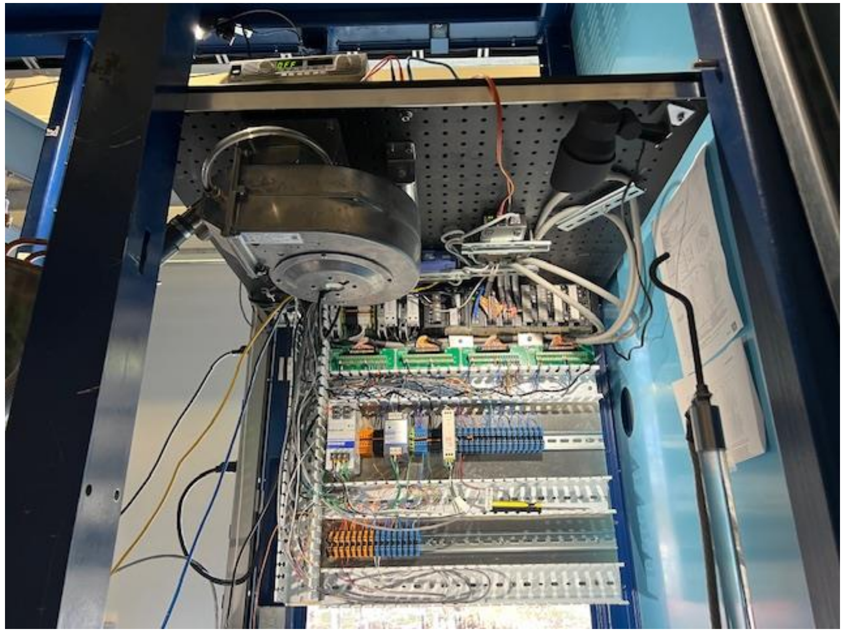


Rack Build-Out & Infrastructure

- The ‘empty’ zone from LCLS-II testing is used to house the 1497 MHz magnetron
- Initial testing with high power loads shown
  - 100 kWatt & 5 kWatt circulators are being used until the 15 kWatt ones are received



High Voltage deck with fiber optical interface



PLC interlock interface

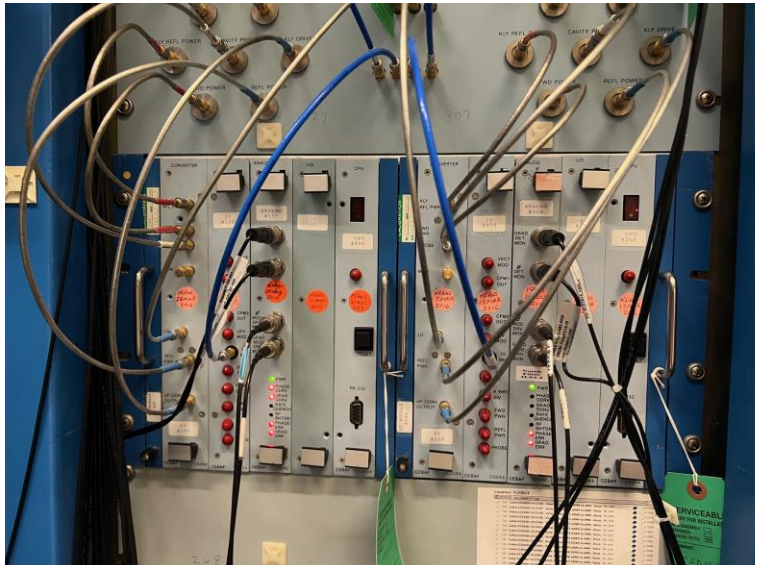
LCW water manifolds from LCLS-II

Waveguide Connections to SRF Cavity

- There was ~1,000 feet of WR650 waveguide installed as a part of the LCLS-II project
- Waveguide will be routed to the second cavity in the cryomodule
- No need to purchase any E or H bends
- May have to trim a waveguide section
- E bend to connect to SRF cavity in vault
- 1st cavity operates at 10 MV/m

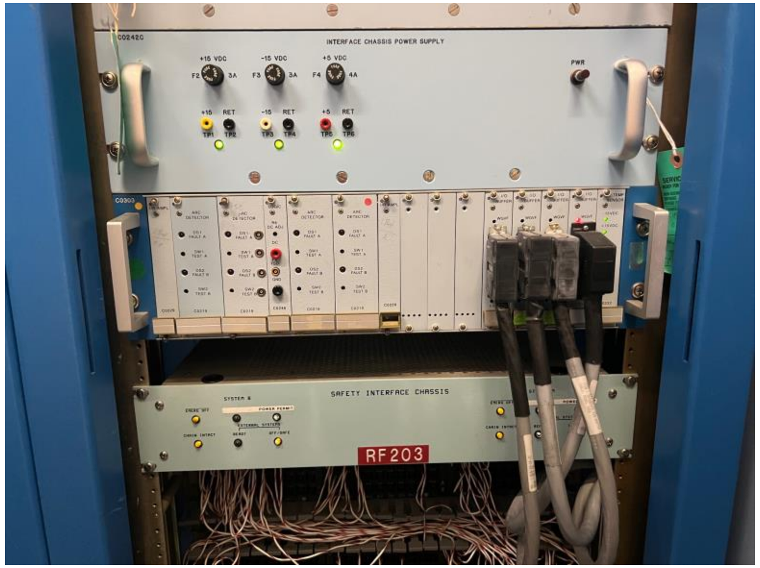
Low Level RF (LLRF) & SRF Cavity Interlocks

- Once the initial tests for injection locking are complete with high power load the magnetron will be connected to a SRF cavity in the LERF vault
- The SRF cavity tuner design is 1497 MHz $\pm$ 200 kHz – It is crucial that the tube be in or near this bandwidth
- We will use the existing LLRF interlocks
  - The cathode HV will be shut down in the event of a waveguide Arc, waveguide or beamline vacuum excursion, or cavity quench
- Phase error signal drives injection lock amplifier, amplitude error drives trim coil power supply



Left; LLFR for phase & amplitude control of SRF cavity

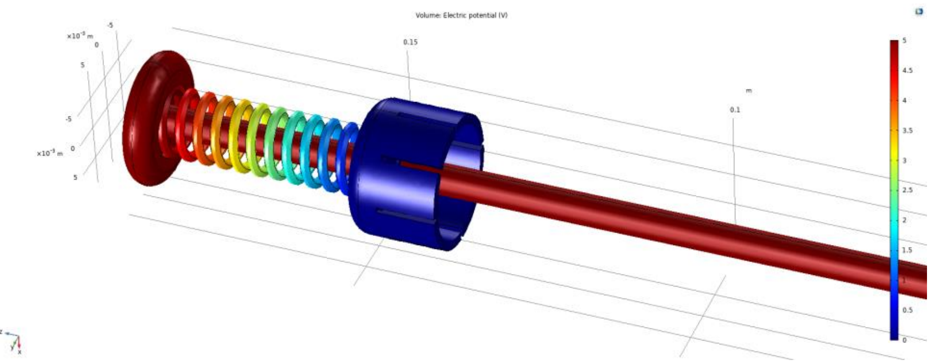
Right; interlock interface for arc detector & vacuum

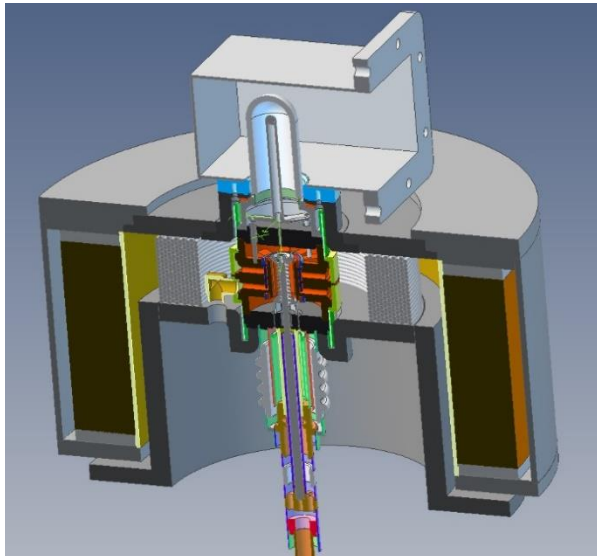


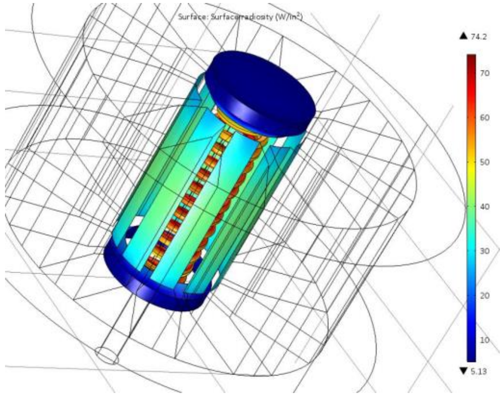
Muons Inc Tube Design

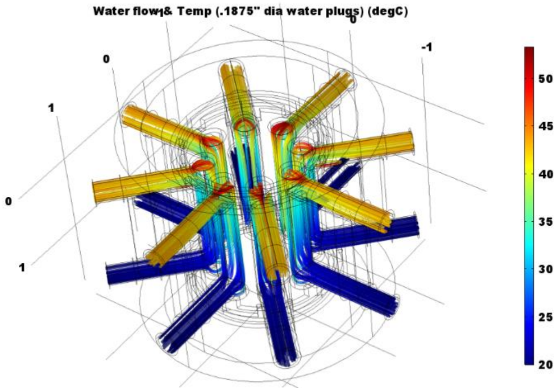
				Pyro
Date,	Voltage	Amps	Power	Temp.
Time	VAC			Filament
7/16/2019				
10:50	1.08	30.9		
11:00	1.190	29.2	34.748	
11:15	2.010	39.7	79.797	
11:55	3.070	46.9	143.983	
12:30	4.040	57.6	232.704	
12:35	3.030	45.1	136.592	1460
1:00	4.100	53.6	162.408	1604
1:04	4.530	55.6	227.755	1657
1:08	5.010	59.9	271.528	1742
1:20	5.510	63.0	315.530	1772
1:30	6.690	66.1	364.211	1834
1:35	6.510	68.9	460.941	1920
1:45	6.990	71.6	466.116	1993
1:49	7.540	74.4	520.056	2033
1:56	8.050	77.3	582.842	2110
1:59	7.990	76.5	615.825	2098
	0.000	0.0		

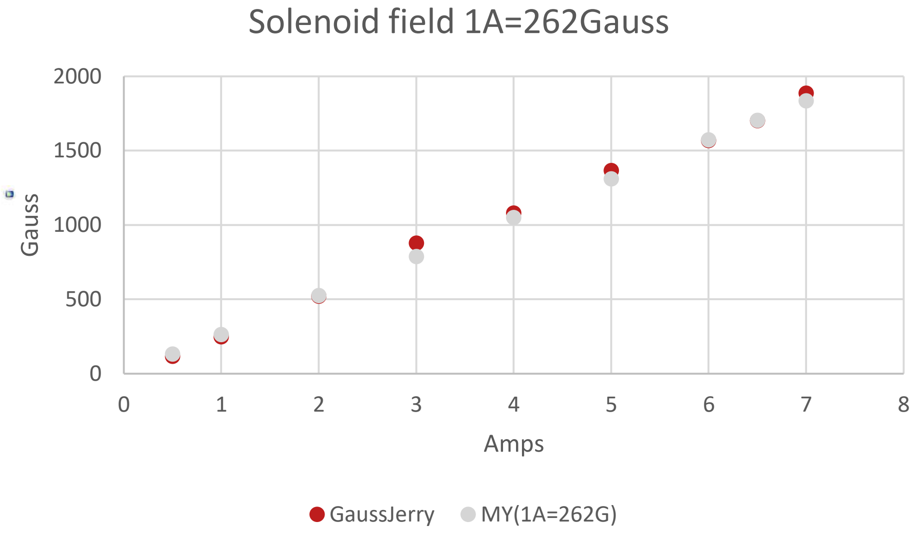
Cathode temperature as measured after assembly in a vacuum bell jar





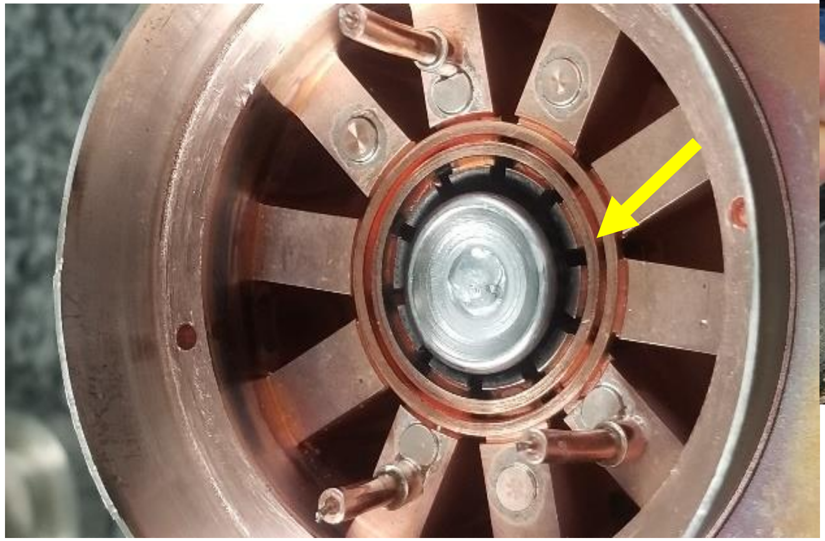


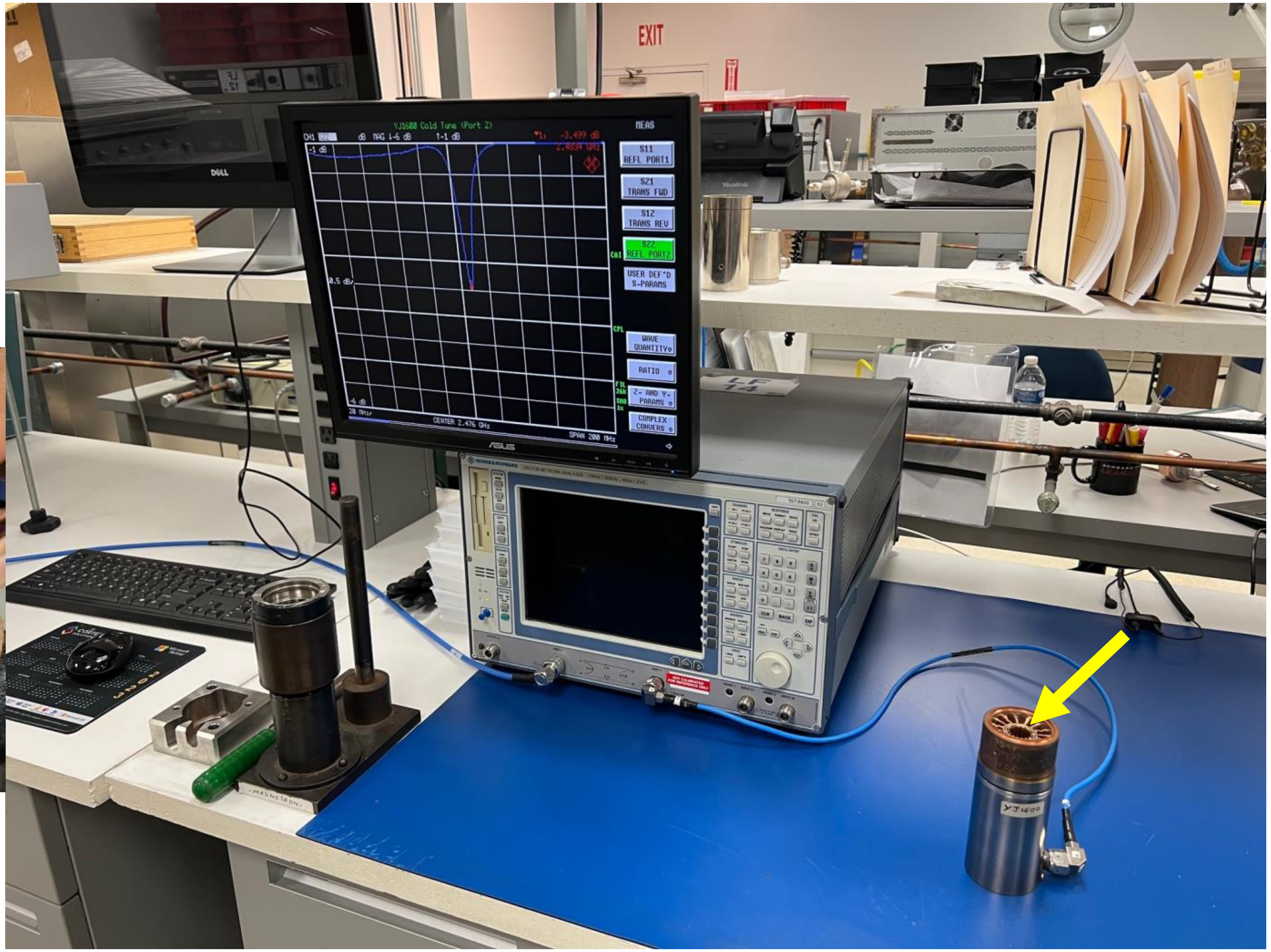




Magnetron Tube Tuning

- The lower right image shows tuning of a 2450 MHz tube at Richardson Electronics
- The yellow arrow points to brazed rings, these are ‘dimpled’ to adjust the frequency
  - The rings should be uniformly deformed on both the top and on the bottom
  - It appears to be a bit of black art…

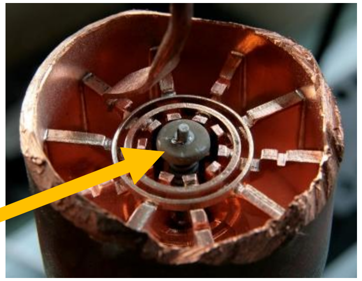


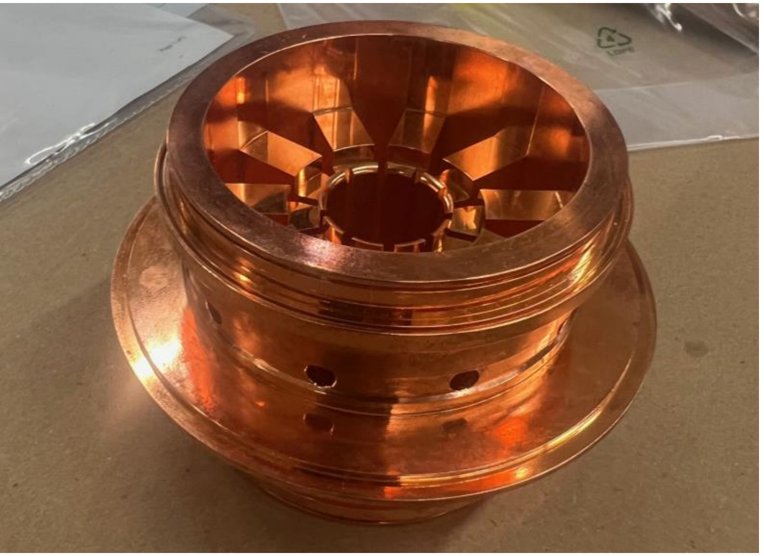


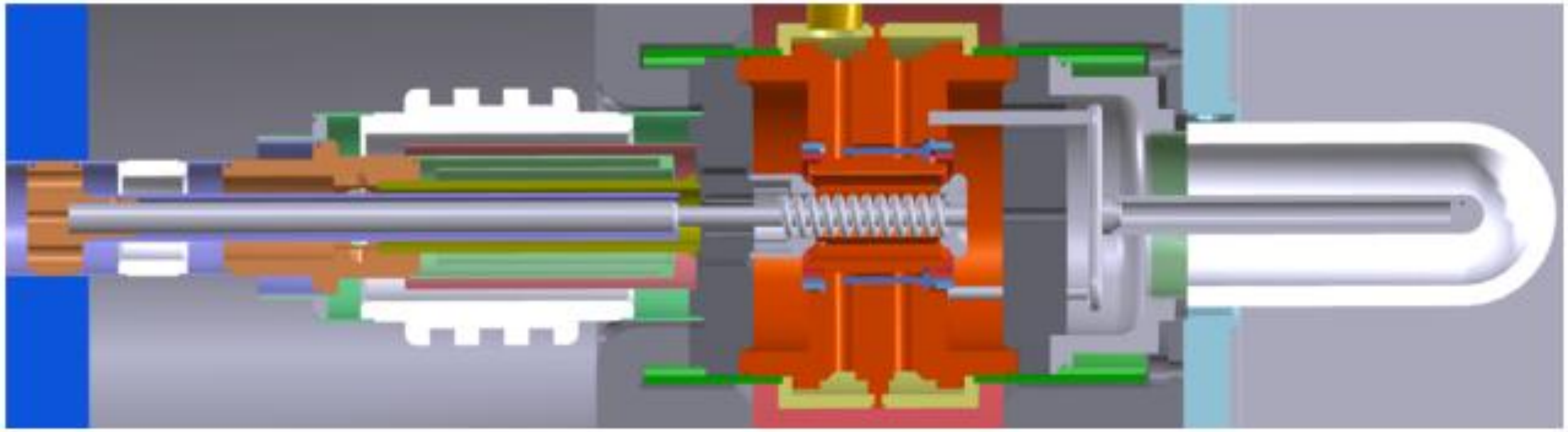
Jefferson Lab

Magnetron Tube Delivery

- The first tube assembled by Richardson Electronics can out at ~1510 MHz, too high to injection lock to an SRF cavity
- First tube tested to 8 kWatts (3/2022), 12kV cathode voltage
- Helical cathode is mounted to center hole
- The second tube is in final assembly; photo from August 28, 2023
- Image showing cathode; https://en.wikipedia.org/wiki/Cavity_magnetron
- As of Dec.6, 2023 there is a vacuum leak on the new tube, Richardson is investigating
  - If repair goes well tube should be ready for testing in 2 weeks







Cutaway of the magnetron showing filament coil & output coupler (Muons Inc)

Power Control of the Magnetron

- Since the magnetron is an oscillator the injection lock signal has little control over output power. I will investigate driving a low inductance trim solenoid* for tube amplitude control.
- The commercial 75kWatt 915 MHz tube (photo) has a very similar design to the 15 kWatt 1497 MHz tube design
    - These tubes vary in output power from 10 to 75 kWatt by lowering the solenoid current from 4.8 Amps to 4.3 Amps
    - This is roughly a change of field strength 75 gauss
    - A 4” long 600 Amp-Turn solenoid can easily reach this field strength with modest current using a 4-quadrant power supply
    - Trim would be driven by LLRF amplitude error signal

KW Setpoint	Voltage	Freq.	Leakage	HV	AMP 1L1	Filament	Solenoid	Anode
0 kW	479 VAC	NA	0	18,605	6.4	113	5.70	0.00
10 kW	478	905	0.5	18,285	20	109	4.83	0.62
20 kW	477	909	1.2	18,120	34	104	4.75	1.28
30 kW	477	912	2.2	17,960	49	100	4.65	1.94
40 kW	476	914	3.0	17,765	64	96	4.60	2.62
50 kW	476	914.5	4.8	17,605	80	92	4.55	3.30
60 kW	475	915	6.4	17,400	96	87	4.45	4.04
70 kW	474	915	7.6	17,195	114	83	4.35	4.81
75 kW	473	915	8.7	17,100	123	80	4.31	5.21

* W C Brown, “The Magnetron - a Low Noise, Long Life Amplifier,” Applied Microwave, summer 1990, pp 117-120.

INNOSYS inc.

SBIR Topic C55-23 c. Particle Beam Sources and Techniques High average current and high voltage reliable and stable power supplies for high current electron beam sources – DOE Award No. DE-SC0023581 (PM: Dr. Michelle Shinn)

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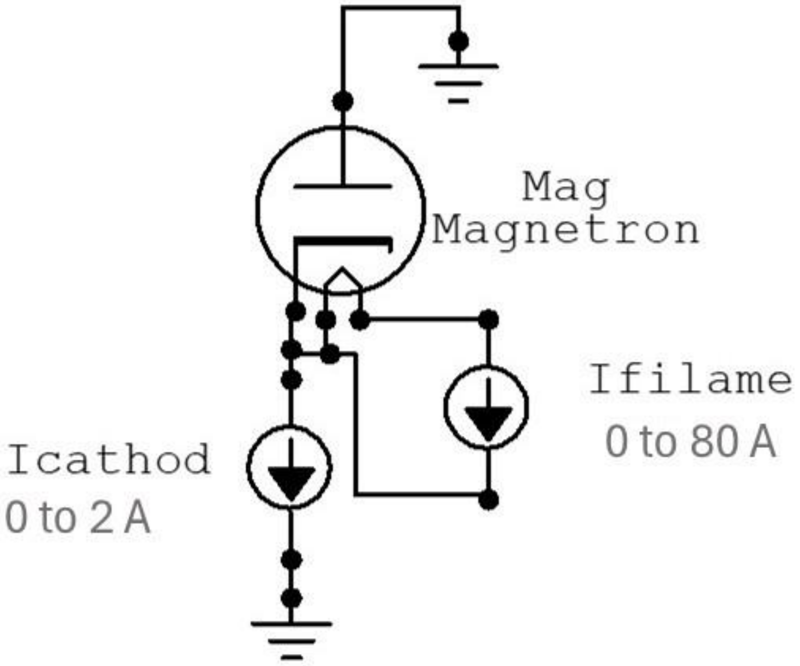
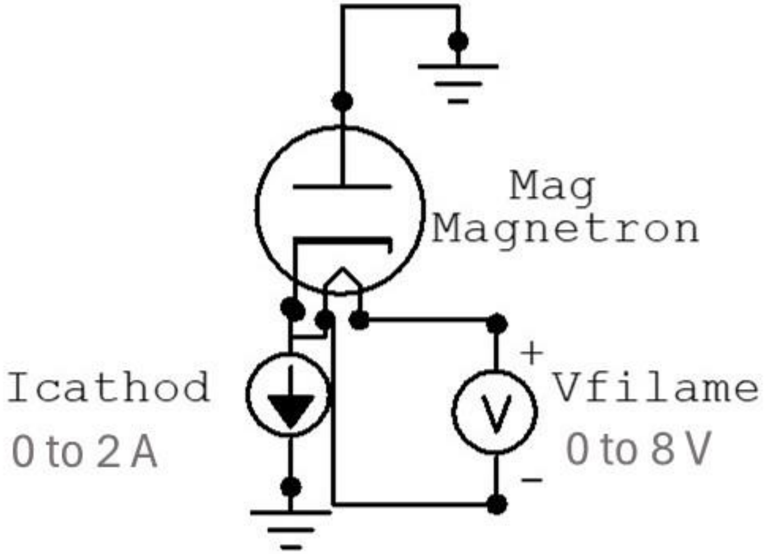
InnoSys DC Magnetron Power Supplies: 1497 MHz 15 kV 2A 30 kW Beam Power

- The general design and development of the inexpensive low noise fast switching DC high voltage power supply suitable for driving a L-band (1 to 2 GHz) CW magnetron with amplitude modulations up to (and well beyond) 1 kHz and is based on previous related InnoSys magnetron and traveling wave tube amplifier high voltage, high stability, high efficiency power supplies.
- These power supplies are constant current output supplies designed to be able to feedback on the negative differential current vs. voltage relation for magnetrons – that is as current goes up, voltage goes down.
- The proposed 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.
- The current spec for the power supply is 0 to 2 Amps Beam Current with a floating heater/filament power supply capable of supplying 80 Amps at ~8 Volts or ~640 Watts of heater/filament power. This will be the main challenge for this Magnetron Power Supply is supplying such a relatively large amount of power floating at the cathode potential of approximately -15 kV (anode grounded configuration).
- Working with moving specs and working on expediting this power supply.

InnoSys DC Magnetron Power Supplies: 1497 MHz 15 kV 2A 30 kW Beam



With Constant Current Control for the Filament



With Constant Voltage Control for the Filament

Note: Constant Current or Constant Voltage Control is Front Panel Switch Selectable or Rear Panel Digitally Selectable and dimmable from 100% to Zero

Budget

- Summary of expenditures by fiscal year (FY):

	FY22 ($k)	FY23 ($k)	Totals ($k)
Funds Allocated	$407,000	$258,000	$665,000
Actual costs to date	$155,145	$0	$155,145

- Due to delays in delivery of Tube, Power supply, and Circulators I will likely need No Cost Extension
- Additional delays from 3+ month safety stand down
- Cost savings from re-using more of the LCLS-II infrastructure than originally planned
  - Also I had two SULI students working on this project Alexander Kerr during the summer and Christian Cagnino for the fall semester, he is also joining us for the spring term

Schedule & Milestones

	FY 24 Q1	FY 24 Q2	FY 24 Q3	FY 24 Q4
Must	Continue working on infrastructure	Complete infrastructure & safety documentation	Initial turn on of 1497 MHz tube and power supply	Connect tube to SRF cavity
Like	Working on safety approvals	Receive tube and power supply	Injection lock studies	Phase & amplitude locked cavity

Summary

- Delivery problems have delayed progress on original schedule
  - Power supply from Innosys (SBIR funded) may be 1 year late
  - 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
  - Additional delays from Jlab site wide safety stand-down
- I have made good progress on infrastructure in spite of these delays
- I have realized cost savings by using more of the left over LCLS-II hardware than I originally planed
- SULI students have also resulted in lower labor costs

Thank you!