The LANL C-Band Engineering Research Facility (CERF-NM) Test Stand Installation, Operation and Initial Conditioning.

Mark E. Middendorf, LANSCE AOT-RFE, on behalf of:

J.T. Bradley III, C.E. Buechler, R.L. Fleming, E.G. Geros, D.V. Gorelov, H.J. Guas III, M.K. Kirshner, F.L. Krawczyk, J.W. Lewellen, L.N. Merrill, R.C. Moore, M.E. Schneider, E.I. Simakov, T. Tajima.

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Acronyms and Abbreviations

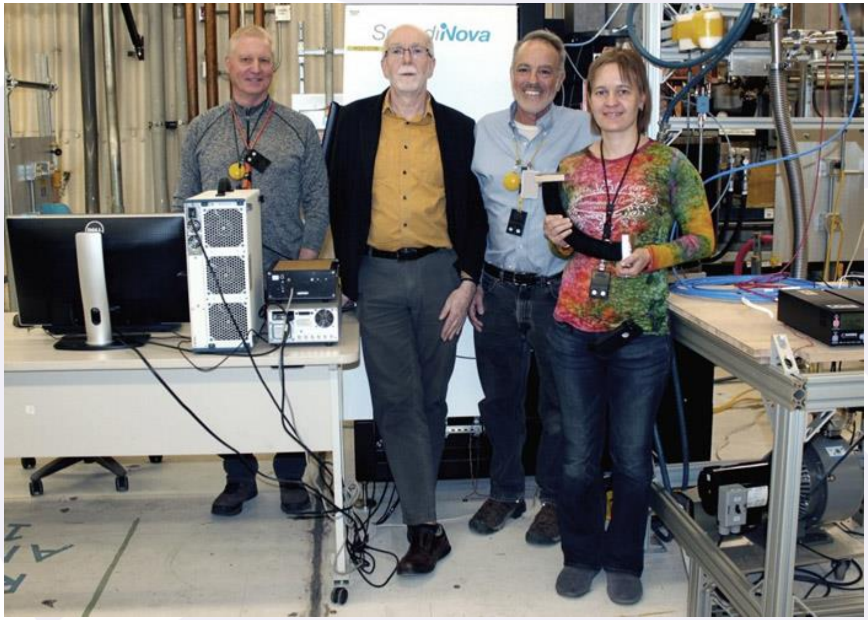
LANSCE:	Los Alamos Neutron Science Center
AE:	Accelerator Engineering
AOT:	Accelerator Operations and Technology
CCPS:	Capacitor Charging Power Supply
FPS:	Filament Power Supply
IPC:	Ion Pump Controller
MCU:	Main Control Unit
MDE:	Mechanical Design Engineering
OSH - DS:	Occupational Safety and Health – Deployed Services
PDU:	Power Distribution Unit
RFE:	Radio Frequency Engineering
RP - FS:	Radiation Protection – Field Service
SU:	Switch Unit
SPS:	Solenoid Power Supply

Agenda

1. Introduction
2. Acknowledgements
3. Timeline
4. Klystron Modulator
5. Waveguide and Waveguide Components
6. LLRF, Data Acquisition and Control
7. Initial Conditioning Efforts
8. Conclusion

Introduction

- The C-Band Engineering Research Facility (CERF-NM) is the first such installation in the US to provide ultra-high peak power (up to ~50MW) radio-frequency (RF) test capability in the C-band (5.712 GHz) frequency range.



- Funded by a 2020 Laboratory Directed Research and Development (LDRD) award, the facility will be used for evaluating novel high-gradient accelerating structures.

- Internal collaborators; Accelerator Operations and Technology (AOT), Engineering Technology and Design (E), and Sigma Divisions.
- External collaborators; University of California, Los Angeles, SLAC National Accelerator Laboratory, and Stanford University.

- This talk focuses on the klystron/modulator installation and integration, and the initial conditioning and commissioning efforts.

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Kevin Andrews, LANL LANSCE RP-FS
Jon Bergemann, LANL LANSCE AOT-RFE
Cindy Buechler, LANL LANSCE AOT-MDE
Ryan Fleming, LANL LANSCE AOT-AE
Ernie Geros, LANL LANSCE AOT-RFE
Paul Martin, LANL LANSCE OSH-DS
Rosliann Miller, LANL LANSCE RP-RS
Robert Moore, LANL LANSCE AOT-MDE
Manuelita Rodriquez, LANL LANSCE AOT-RFE
Keith Stephens, LANL LANSCE AOT-MDE

Timeline

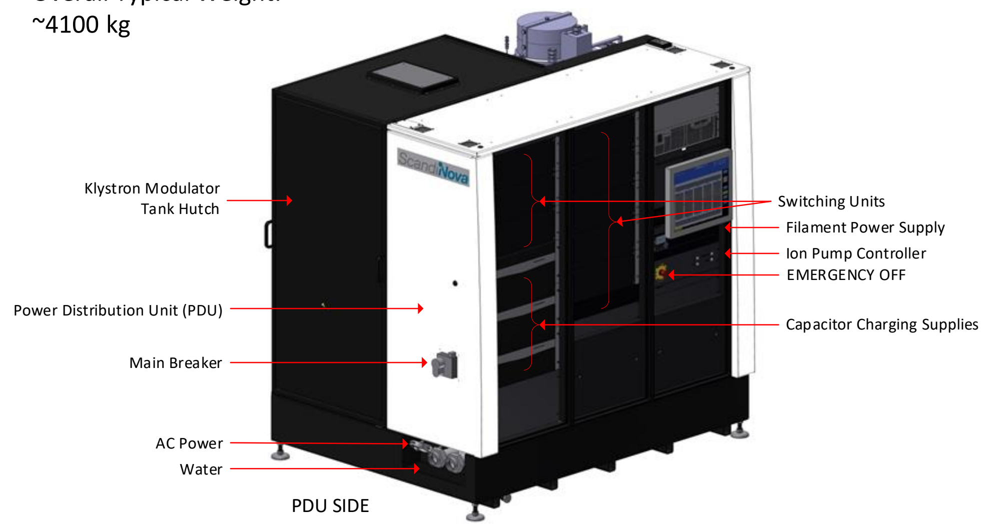
- August 30, 2019; Klystron/Modulator Factory Acceptance Test.
- September 23 to September 27, 2019; Installation at LANL.
- January 30 to February 21, 2020; Conditioning at LANL.
- February 21, 2020; Obtained ~50MW peak power, 1µs pulse width, 100Hz pulse repetition rate (~5kW average power), working into a water-cooled matched waveguide load.
- March 3, 2020; Completed Pout vs Pin gain curve (sight acceptance test).

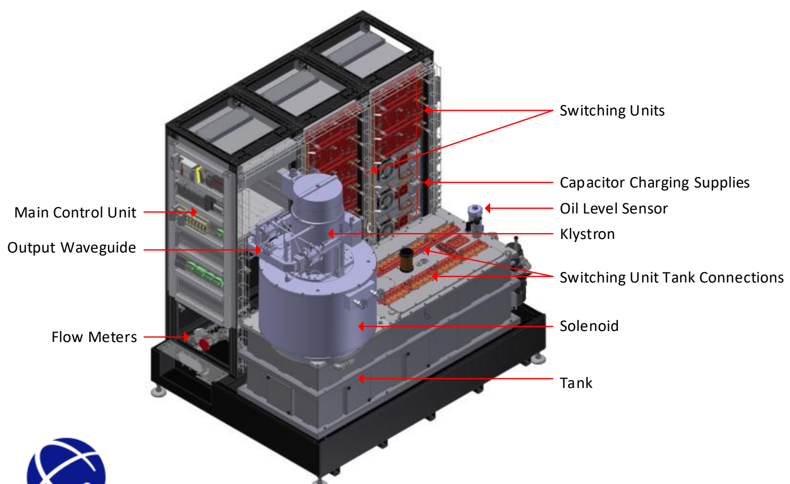
Klystron Modulator

- The K300 is capable of producing a ~370kV, ~325A output pulse, 1µs in pulse length, at a repetition rate of up to 100 Hz.
- The klystron modulator is an integrated stand-alone system, requiring only external power (120VAC control power, 480VAC, 3-phase primary power), and water (~45gpm) for cooling.
- An external source of low-lever RF power is required to drive the solid-state amplifier/klystron.

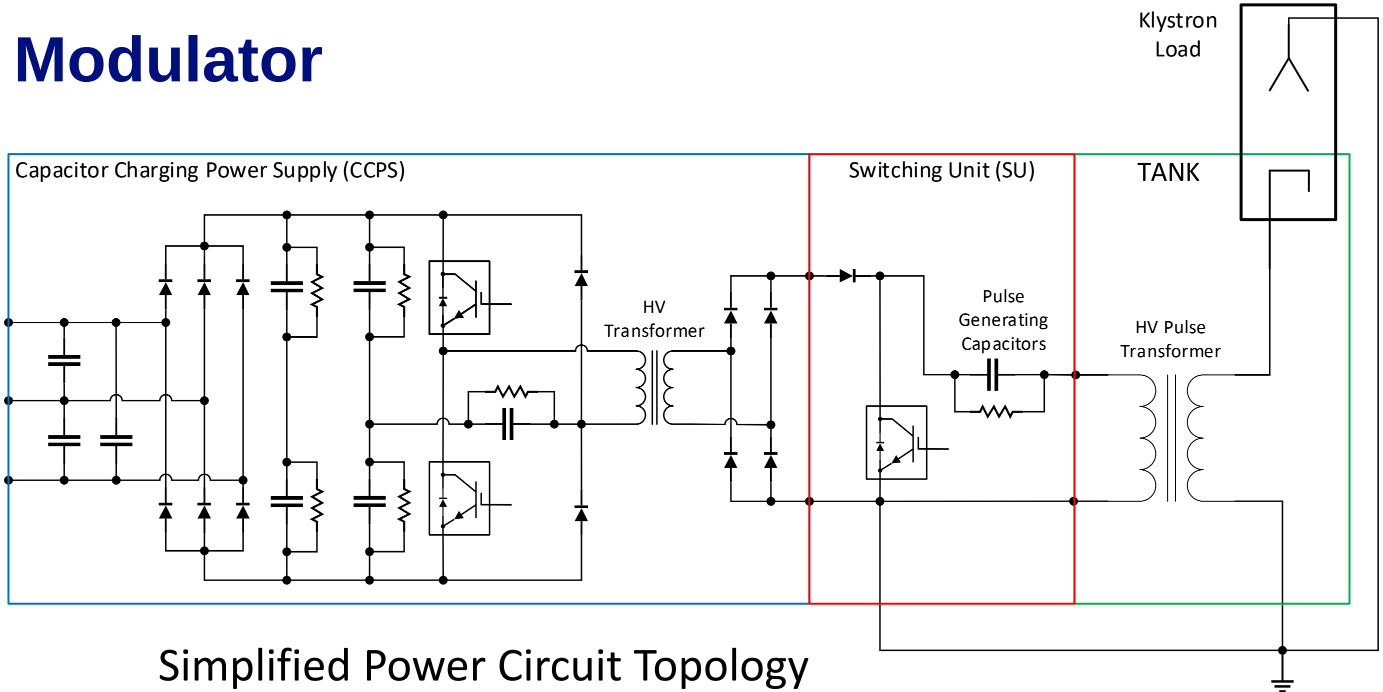
Dimensions (L x W x H):
~1.7 m x ~1.4 m x ~1.5 m

Overall Typical Weight:
~4100 kg





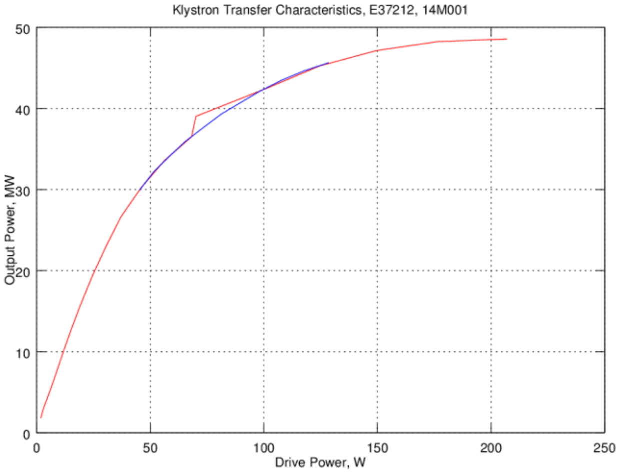
Klystron Modulator



Simplified Power Circuit Topology

- The CCPS rectifies the three phase 480 VAC primary input power.
- IGBT switching is used to chop the rectified DC to drive the HV transformer primary.
- The HV transformer secondary output is rectified, and provides pulsed DC voltage to the SU.
- The SU is a high-power IGBT switching module that switches the energy stored in the pulse-generating capacitors as a current pulse through the primary windings of the HV pulse transformer.
- The HV pulse transformer provides a large step-up in voltage to deliver the required pulse energy to the klystron load.

Klystron Modulator



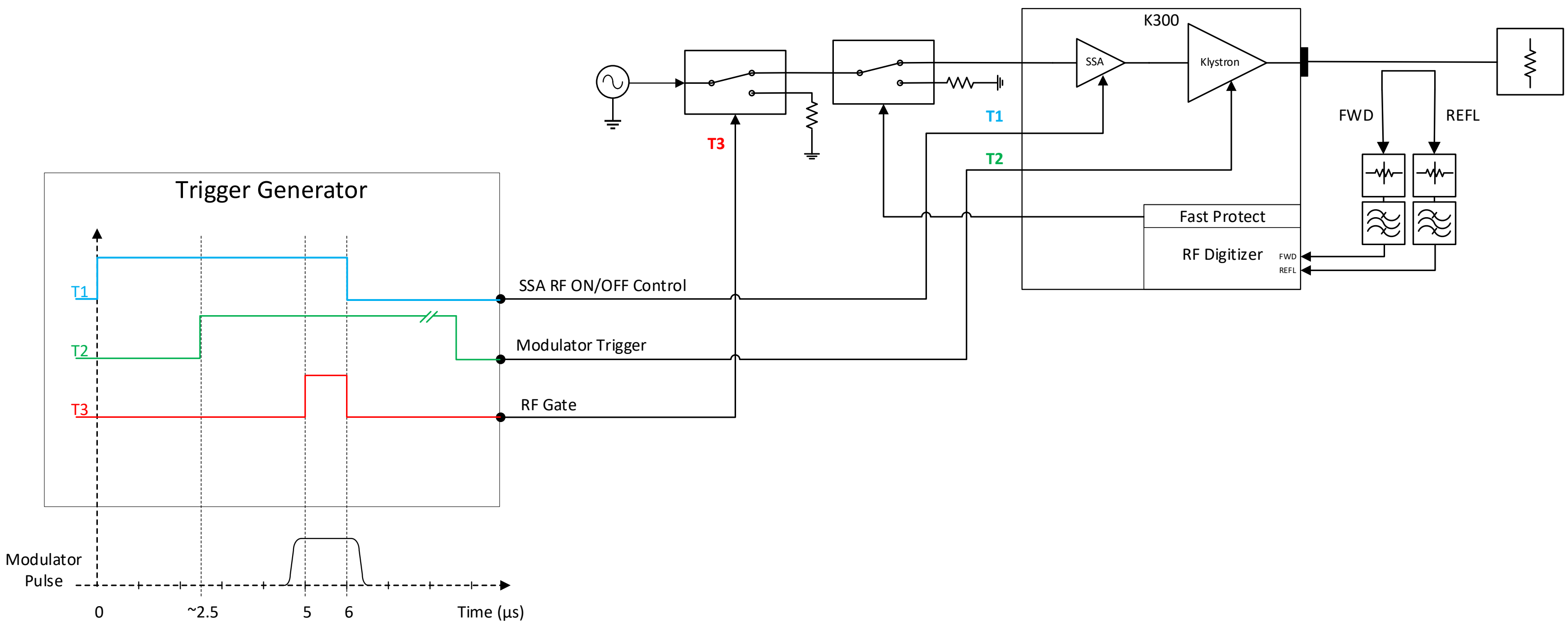
- Modulator: ScandiNova Model K2-2
- Klystron: Toshiba E37212
- Solenoid: Toshiba VT68954

- FAT Performance Test:

Parameter	**Required Value**	**Measured Value**
Output Pulse Voltage (kV)	366 kV	368 kV
Output Pulse Current (A)	325 A	325 A
Klystron Perveance (µP)	1.45 ≤ µP ≤ 1.50	1.46
Average Power to klystron (kW)		29.9 kW
Peak Beam Power (MW)		119.6 MW
Pulse Top Flatness (dV) [%] within 1µs	1%	0.47%
Pulse Repetition Rate (Hz)	100 Hz	100 Hz
Pulse Top Length (µs)	1 µs	1 µs
Pulse to Pulse Amplitude Stability (%)	100 ppm	48 ppm
Voltage Pulse Rate of Rise (kV/µs)	> 250 kV/µs	461 kV/µs
Voltage Pulse Rate of Fall (kV/µs)	> 250 kV/µs	393 kV/µs
Klystron Filament DC Voltage (V)	16.2 V	17.5 V
Klystron Filament DC Current (A)	19.2 A	19.2 A

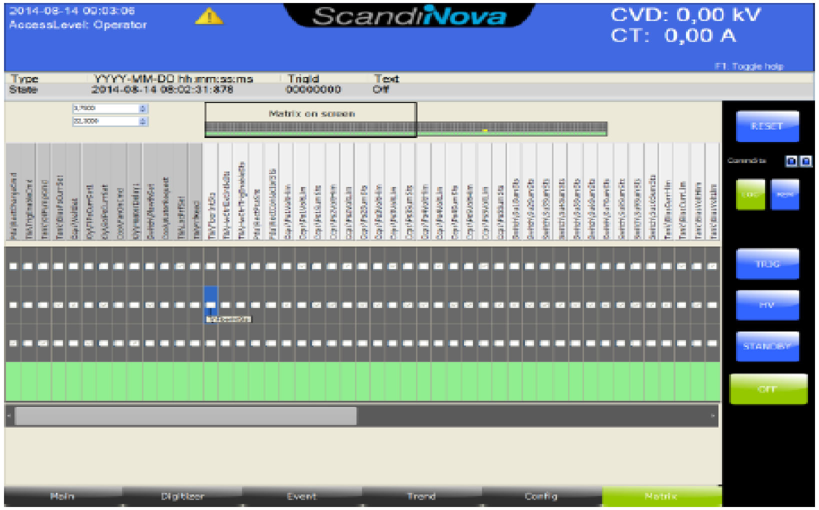
Klystron Modulator

- External Triggering



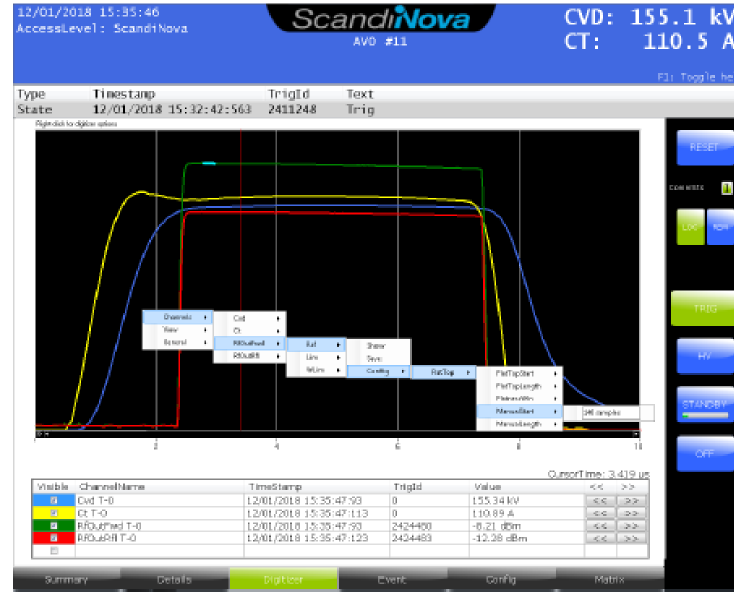
Klystron Modulator

- Control system
  - is a PC/PLC hybrid
    - HMI runs on Windows
    - Typical PLC functionality, providing +24VDC control voltage and state control.
  - Implements a state machine that controls the transition between operational states:
    - Off
    - Standby
    - HV
    - Trigger
- Main Screen
  - Provides local operation and summary status.
- Matrix Screen
  - Displays the parameters and state hierarchy.

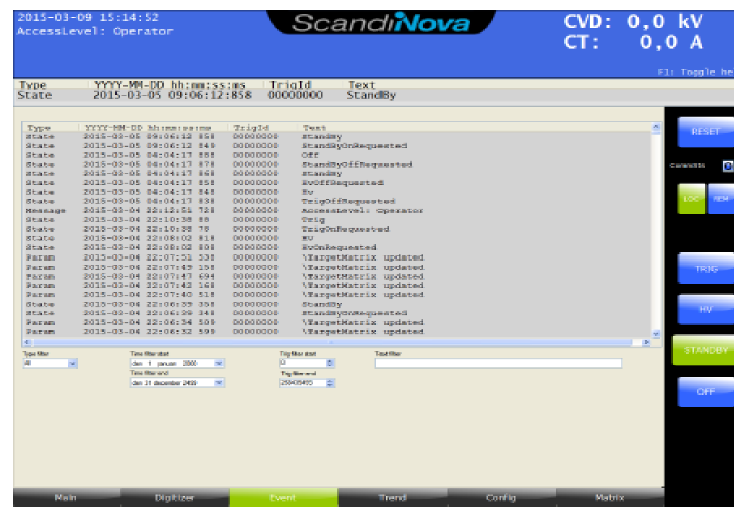


Klystron Modulator

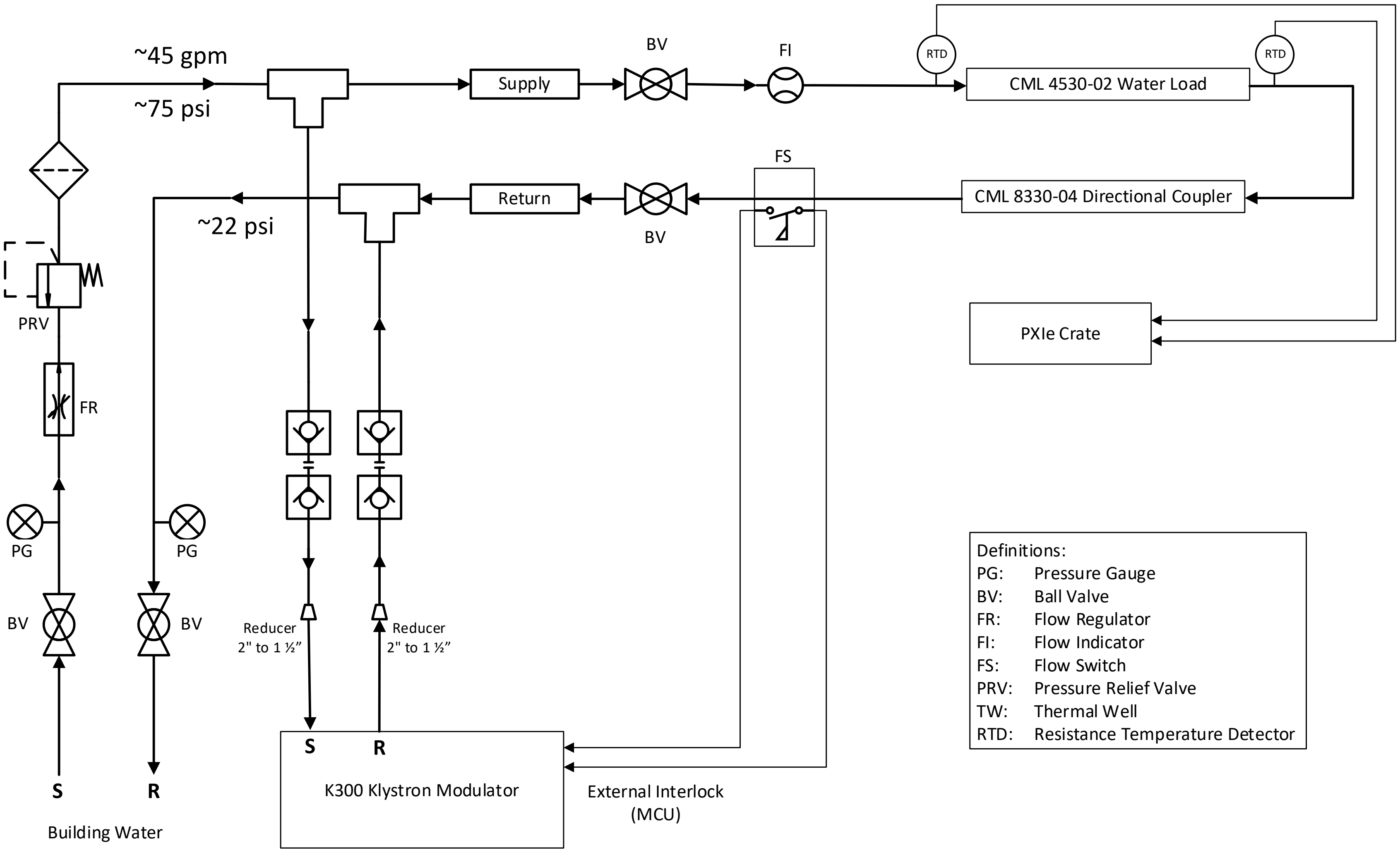
- Digitizer Screen
  - Displays;
    - Modulator voltage and current pulse samples.
    - Forward and reflected power.
    - VSWR
    - RF pulse length
  - Digitizer implements fast protect interlock (~0.1µs) for high reflected power (using external RF switch on the LLRF source output having ~35ns switching time).



- Event Screen
  - Running log that displays errors, warnings, interlocks and state change messages, etc..



Klystron Modulator/Waveguide P&ID

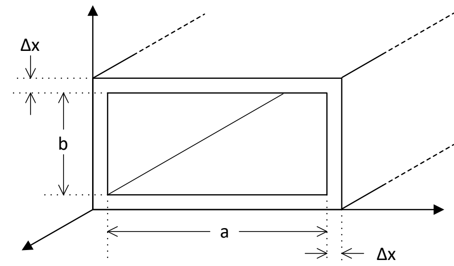


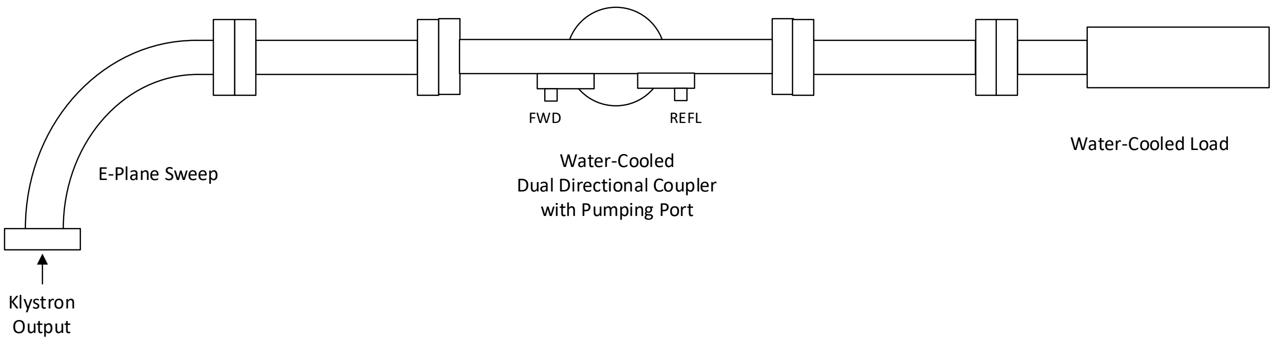
Definitions:
PG: Pressure Gauge
BV: Ball Valve
FR: Flow Regulator
FI: Flow Indicator
FS: Flow Switch
PRV: Pressure Relief Valve
TW: Thermal Well
RTD: Resistance Temperature Detector

Waveguide and Waveguide Components

Waveguide: WR187

- Dimensions:
  - a = 1.872 in. (0.048 m)
  - b = 0.872 in. (0.022 m)
  - Δx = 0.1265 in. (3.213×10^{-3} m)
- Material:
  - Copper
- Waveguide Flanges:
  - Riken-Desy type
  - Flange material; AISI-316L
- Dielectric:
  - Vacuum

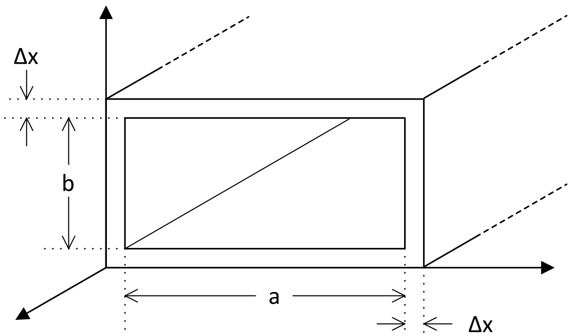




- Dual Directional Coupler, Water-Cooled
  - Coupling, FWD; 60 dB
  - Coupling, REFL; 25 dB
  - Cooling; water (25 °C to 35 °C inlet temp.)
  - Coolant Flow Rate; 1 gpm minimum at full power (~4.5 gpm in practice)
  - Coolant Pressure; 150 psig maximum
- Waterload
  - Power Dissipation; 7.5 kW maximum average power
  - VSWR; 1.10:1 maximum
  - Cooling; water (25 °C to 35 °C inlet temp.)
  - Cooling Flow Rate: 2 gpm minimum at full power (~4.5 gpm in practice)
  - Coolant Pressure; 150 psig maximum

Waveguide and Waveguide Components

- Attenuation due to imperfectly conducting walls
  - Assumptions:
    - Resistivity of copper at 20˚C (Wikipedia);
      - ρ_{res} = 1.678 x 10^{-8} Ω m
    - Dominant propagating mode:
      - TE_{10}
  - Skin Depth at 5.712GHz;
    - δ = 8.626 x 10^{-7} m
  - Attenuation per unit length, α;



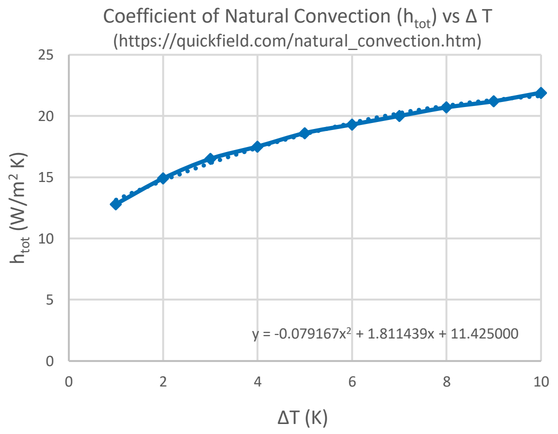
$$\alpha = \frac{2\pi^2 R_s \left(\frac{a}{2} + b + \frac{\beta^2 a^3}{2\pi^2}\right)}{\omega\mu a^3 b\beta} \quad ; \qquad \alpha = 0.031 \text{ dB/m}$$

  - Power loss as a function of length;
    - 50MW peak RF power
    - 1µs pulse width @ 100Hz PRR
    - 1 meter length of waveguide section

$$P(z) = P_0 e^{-2\alpha z}$$

- P_{ave_loss} = P_{loss} * Duty Cycle = 35.76 W

Waveguide and Waveguide Components



- Heat Transfer Considerations
  - Assumptions:
    - Density of copper, near r.t. (Wikipedia);
      - $\rho_{density} = 8.96 \times 10^3$ kg m^{-3}
    - Specific heat capacity of copper at atmospheric pressure and near r.t. (Wikipedia);
      - $cp_{copper} = 385$ J kg^{-1} K^{-1}
    - No power dissipated into dielectric.
    - Power dissipation per unit area in waveguide walls is uniform.
    - Consider only heat loss due to natural convection.
    - Coefficient of natural convection calculated using online calculator (Quickfield).
    - Convective area of waveguide; Awg = L x 2 x (a_o + b_o); (Awg = 0.165 m^2)
    - Initial temperature of the waveguide is equal to the ambient (air) temperature.
    - Steady state application of Paveloss.
  - Energy transferred to the waveguide is given by:

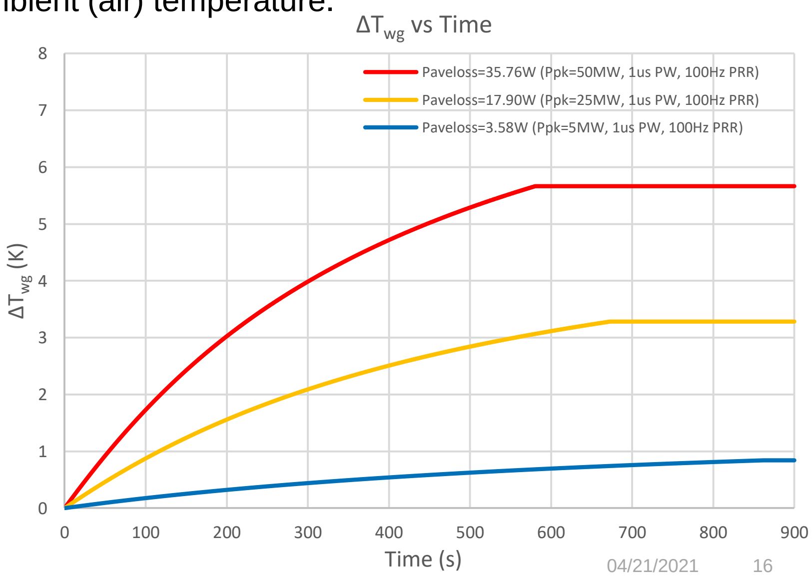
$$Qwg = \int_0^t (Paveloss - Pconv)dt$$

$$Qwg = \sum_{i=1}^{n} (Paveloss_i - Pconv_k) \times \Delta t \qquad (k = i - 1)$$

- Where;

$$Paveloss_i \times \Delta t = cp\_copper \times mwg \times (Twg_i - Tinit)$$

$$Pconv_k \times \Delta t = htot_k \times Awg \times (Twg_k - Tamb) \times \Delta t$$



Waveguide and Waveguide Components

- Take away (my simple-minded understanding of the "conditioning" we've been doing):
  - Conditioning is more an application of peak power rather than average power.
    - The temperature of the bulk copper is not increased significantly.
  - With the application of peak power, two possible mechanisms might occur:
    1. Pulsed peak RF power is dissipated into the skin depth, elevating the surface temperature ("flash heating" the surface).
       - Contaminants adsorbed on the waveguide surface are heated and can abruptly outgas, which we observe in the vacuum.
    2. Surface irregularities, such as edges, corners, particulate, can provide localized field enhancement.
       - The application of peak power can cause "burning" at these locations and field degradation, the energy from which may couple into the vacuum. Field breakdown would result in increased reflected power.
    - Between RF pulses, power dissipates from the skin depth into the bulk copper of the waveguide walls, contributing to an incremental increase in the bulk copper temperature, until equilibrated with heat loss mechanisms.

- Suggests an approach to conditioning:
    - Start with reduced pulse width, low power, low rep rate.
    - Increase power until vacuum activity is observed.
    - Continue to "drive" vacuum activity with small increments in power, working to keep vacuum excursions below the vacuum trip threshold.
    - After full power is obtained, gradually increase repetition rate.
    - After full repetition rate is obtained, gradually increase pulse width.

LLRF, Data Acquisition and Control

PXIe-8840; PXI Controller
- Intel Core i5, 2.7 GHz dual-core processor
- 8 GB RAM
- Windows 10, 64-bit
- 2GB/s maximum controller BW
- LabView 2019

PXIe-6341; Multifunction I/O
- 16 SE analog inputs
- 500 kS/s maximum sample rate
- 16-bit resolution
- 4 counter/timers
- 24 bi-directional digital channels
- 2 analog output channels
- 900 kS/s update rate

PXIe-5654; RF Analog Signal Generator
- 250 kHz to 10 GHz
- -7 dBm to +13 dBm output power

PXIe-5110; Oscilloscope
- 2-channel, 100 MHz BW, 1 Gs/s maximum sample rate
- -20V to +20 input voltage range
- 8-bit analog input resolution
- 64MB onboard memory

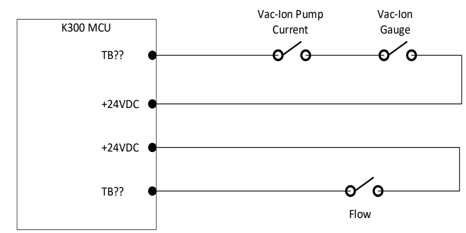
PXIe-5423; Arbitrary Waveform Generator
- 2-channel, 40MHz maximum BW
- 800 MS/s maximum update rate
- 16-bit analog output resolution
- -12V to 12V analog output range

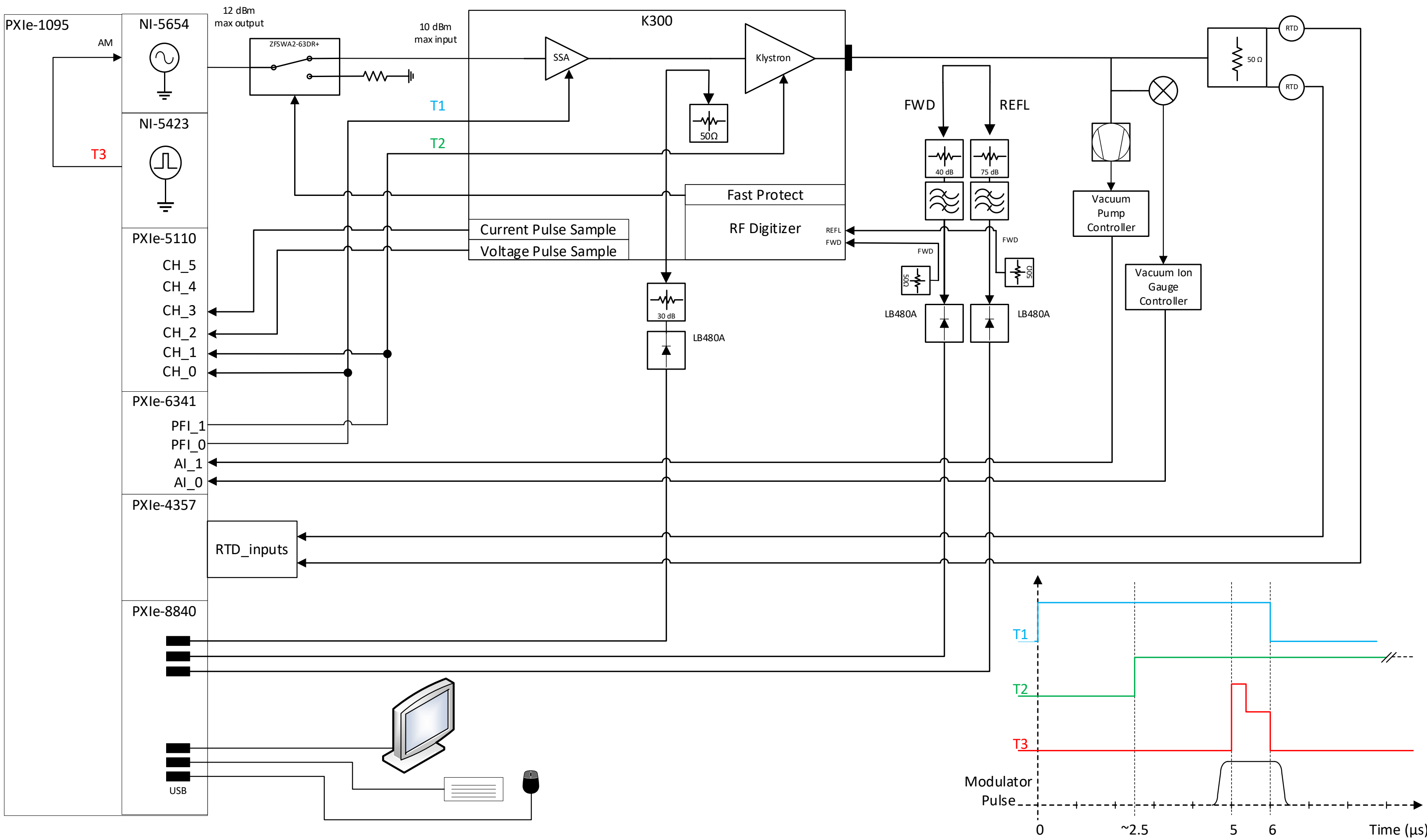
PXIe-4357; Temperature Input Module
- 20 channels, 100 S/s maximum sample rate
- 24-bit resolution
- 2-, 3-, 4-wire PT 100 RTD

PXIe-1095; PXIe Chassis
- 24 GB/s maximum system BW
- 12 PXIe slots
- 5 Hybrid slots

LLRF, Data Acquisition and Control

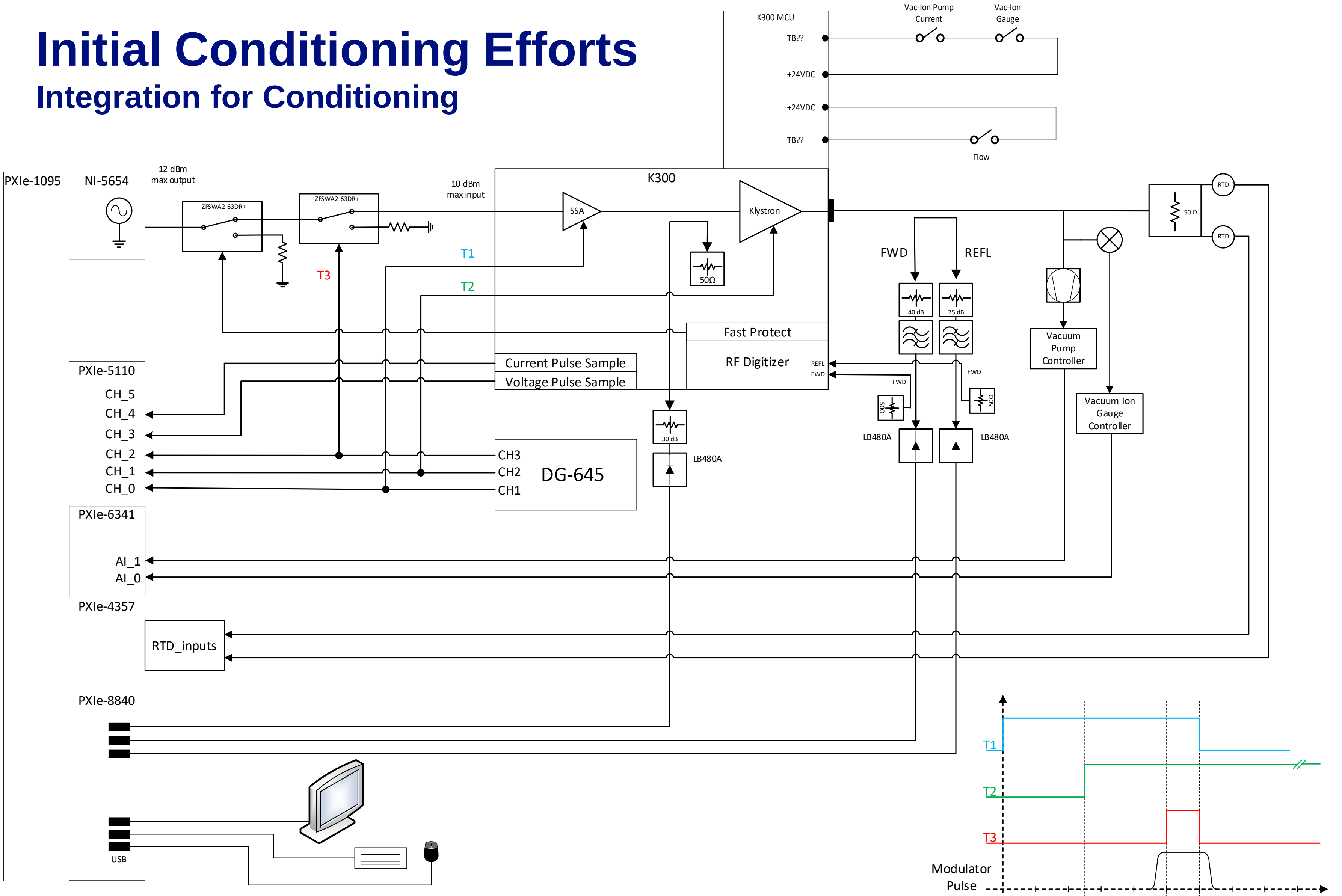
Original Integration Concept





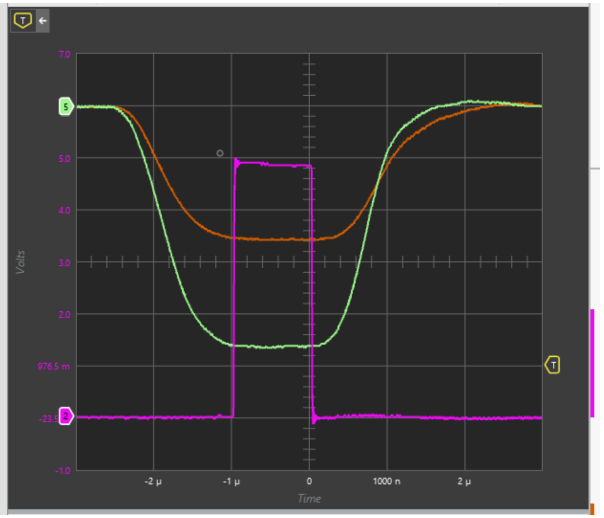
Initial Conditioning Efforts

Integration for Conditioning



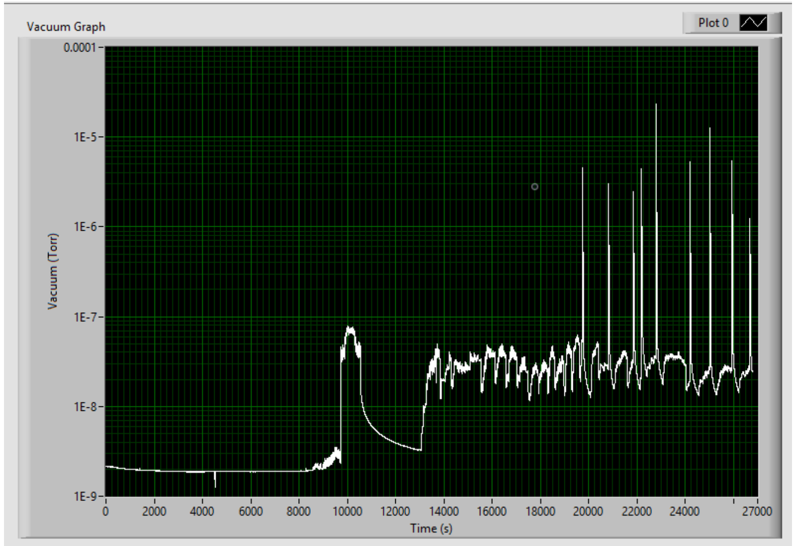
Initial Conditioning Efforts

- Conditioning began on January 30, 2020:
  - 1µs pulse width, 100 Hz PRR.
  - Klystron forward power ~90kW to ~2.6MW.
  - Observed increase in vacuum with increase in forward power.
  - Observed large vacuum excursions from ~2MW to ~2.5MW.



Sensor	Location	Cplng Factor (dB)		CVD (kV):	371.9
				CT (A):	321.5
96	Kly_In	34.1			
29	Kly_Out_Fwd	101.56			
95	Kly_Out_Refl	101.49			

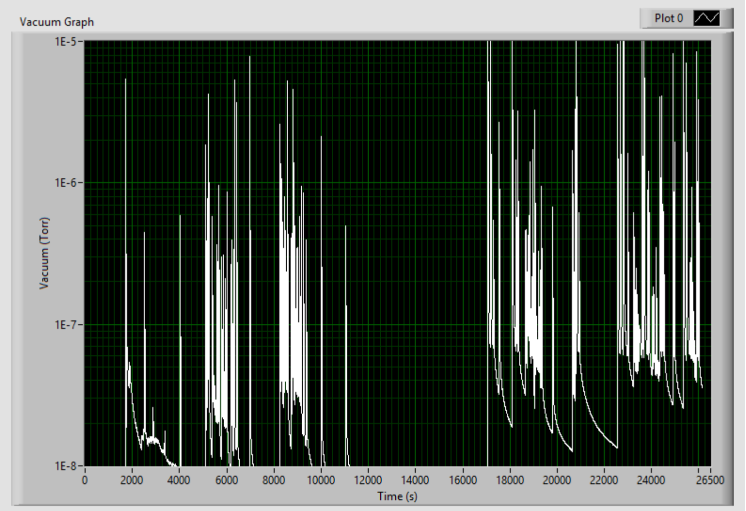
RFGEN (dBm)	LB 96 (dBm)	Klystron Input Drive (dBm)	Klystron Input Drive (W)	LB 29 (dBm)	Klystron Output FWD (dBm)	Klystron Output FWD (kW)	Gain (dB)	Vacuum Gauge	Vacuum Pump Current	PRR (Hz)	ScandiNova Kly_Out_Fwd (kW)	Kly_Out_Refl (dBm)	Kly_Out_Refl (kW)	Notes:
-3.00	-13.70	20.40	0.110	-22.00	79.56	90.4	59.16	1.80E-009		100				
-2.00	-13.24	20.86	0.122	-21.35	80.21	105.0	59.35	1.90E-009		100				
-1.00	-12.61	21.49	0.141	-20.62	80.94	124.2	59.45	1.89E-009		100	120			
0.00	-11.52	22.58	0.181	-19.62	81.94	156.3	59.36	1.89E-009		100	145			
1.00	-10.76	23.34	0.216	-18.72	82.84	192.3	59.50	1.89E-009		100	180			
2.00	-9.79	24.31	0.270	-17.64	83.92	246.6	59.61	1.89E-009	4.20E-009	100	225			
3.00	-8.90	25.20	0.331	-16.80	84.76	299.2	59.56	1.90E-009	4.00E-009	100	285			
4.00	-7.87	26.23	0.420	-15.80	85.76	376.7	59.53	1.93E-009	4.50E-009	50	370			
4.00	-7.33	26.77	0.475	-15.11	86.45	441.6	59.68	2.18E-009	4.00E-009	100	429			
5.00	-6.23	27.87	0.612	-14.23	87.33	540.8	59.46	3.07E-009	3.70E-009	100	560			
5.50	-6.06	28.04	0.637	-14.13	87.43	553.4	59.39	3.80E-008	2.50E-008	10	606			
5.50	-5.82	28.28	0.673	-13.55	88.01	632.4	59.73	6.80E-008	3.50E-008	100	631			
5.50	-5.89	28.21	0.662	-13.60	87.96	625.2	59.75	1.00E-008	8.00E-009	10	650			
5.50	-5.46	28.64	0.731	-13.26	88.30	676.1	59.66	3.91E-008	2.50E-008	100	675			
6.00	-5.17	28.93	0.782	-12.87	88.69	739.6	59.76	3.36E-008	2.30E-008	100	721			
6.50	-4.70	29.40	0.871	-12.59	88.97	788.9	59.57	3.88E-008	2.60E-008	100	820			
7.00	-4.25	29.85	0.966	-12.12	89.44	879.0	59.59	4.26E-008	3.00E-008	100	900			
7.50	-3.75	30.35	1.084	-11.62	89.94	986.3	59.59	3.82E-008	2.70E-008	100	1000			
8.00	-3.48	30.62	1.153	-11.43	90.13	1030.4	59.51	2.52E-008	1.90E-008	100	1100			
8.50	-3.08	31.02	1.265	-11.11	90.45	1109.2	59.43	2.56E-008	1.90E-008	100	1200			
9.00	-2.48	31.62	1.452	-10.69	90.87	1221.8	59.25	2.80E-008	2.20E-008	100	1300			
9.50	-1.85	32.25	1.679	-10.20	91.36	1367.7	59.11	4.29E-008	3.10E-008	100	1400			
10.00	-1.45	32.65	1.841	-9.80	91.76	1499.7	59.11	3.30E-008	2.50E-008	100	1600			
11.00	-0.84	33.26	2.118	-9.25	92.31	1702.2	59.05	4.34E-008	3.40E-008	100	1900			
12.00	0.04	34.14	2.594	-8.35	93.21	2094.1	59.07	5.69E-008	4.30E-008	100	2300			
13.00										20				VACUUM TRIP
12.50												77.30	53.7	VACUUM TRIP
12.40	0.59	34.69	2.944	-7.78	93.78	2387.8	59.09	3.72E-008	3.00E-008	100	2700	77.20	52.5	
12.80														VACUUM TRIP
12.50														VACUUM TRIP
12.40	1.06	35.16	3.281	-7.37	94.19	2624.2	59.03	2.99E-008	2.40E-008	100	2800	77.3	53.7	
12.60											2800			VACUUM TRIP
12.60										60	2800			VACUUM TRIP
12.60	1.02	35.12	3.251	-7.38	94.18	2618.2	59.06	2.57E-008	2.10E-008	70	2900	77.4	55.0	
12.60		34.10	2.570	-7.37	94.19	2624.2	60.09			90				VACUUM TRIP
12.60		34.10	2.570		101.56	14321.9				90				VACUUM TRIP

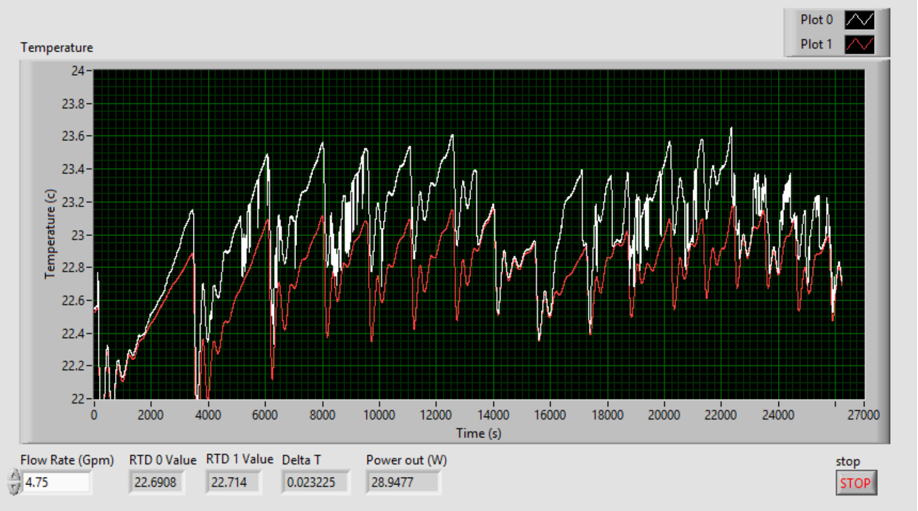


Not much progress!

Initial Conditioning Efforts

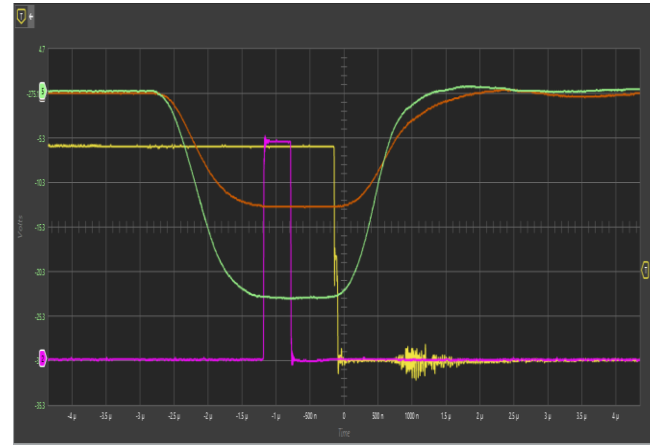
- February 13, 2020:
  - 1µs pulse width.
  - Varied PRR from 10Hz to 150Hz.
  - Klystron forward power ~1MW to ~4.3MW.
  - Working calorimetry.
  - Large number of vacuum trips.

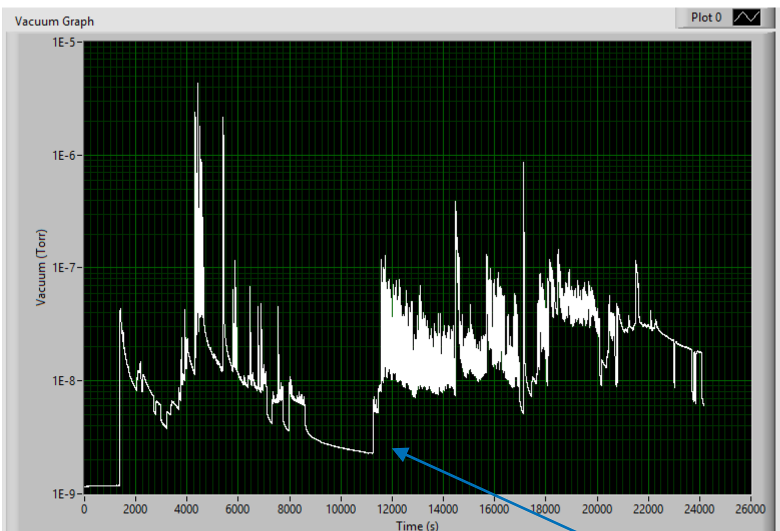


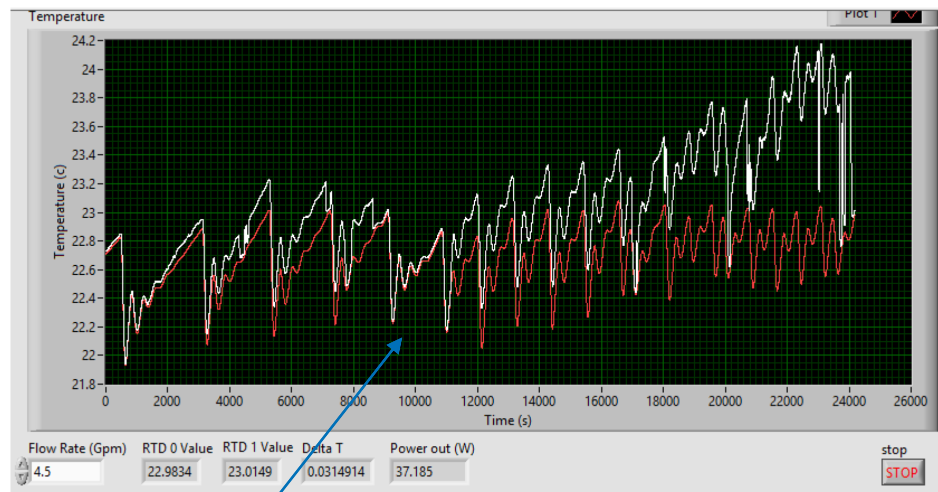


Initial Conditioning Efforts

- February 20, 2020:
  - After lunch decided to reduce pulse width to 0.4µs.
  - 100 Hz PRR.
  - Klystron forward power ~2.8MW to ~14MW.
  - Able to increase drive power while keeping vacuum response below vacuum trip threshold.

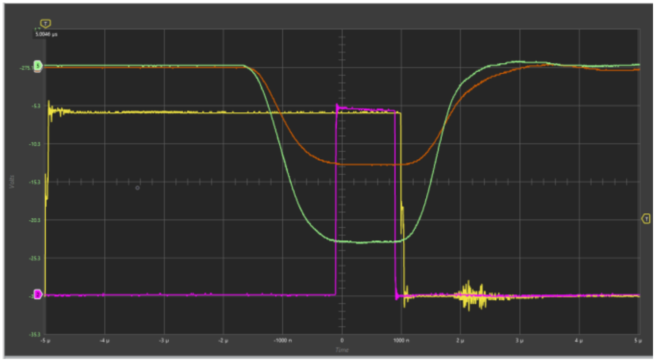




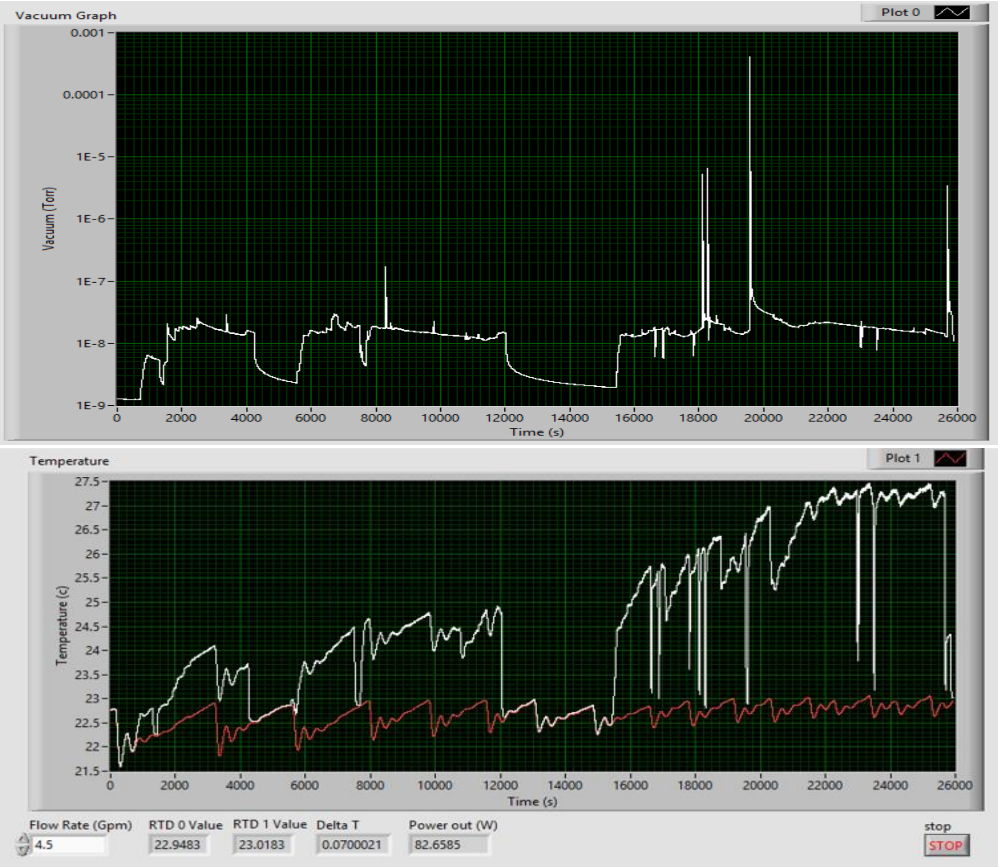


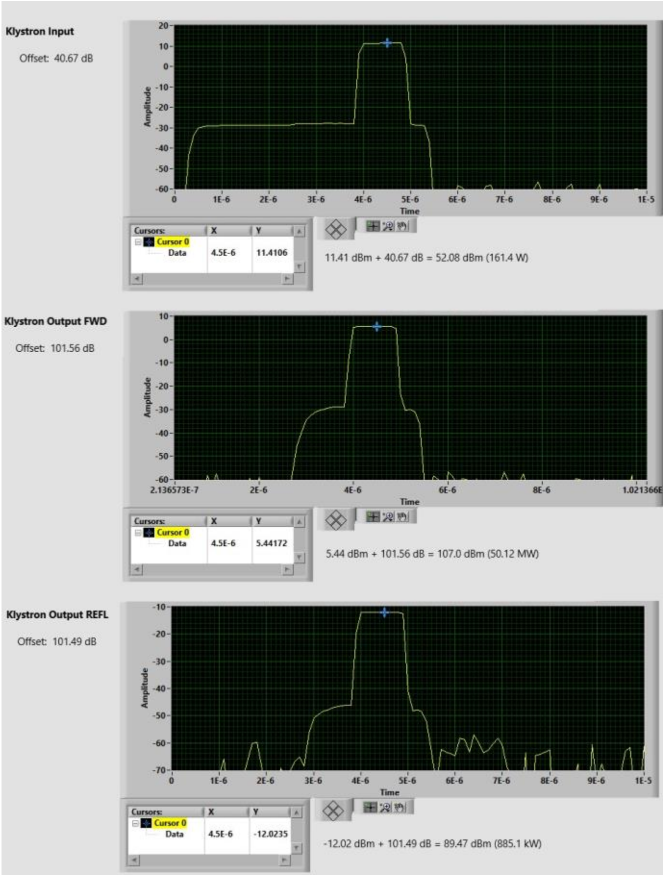
Lunch

Initial Conditioning Efforts



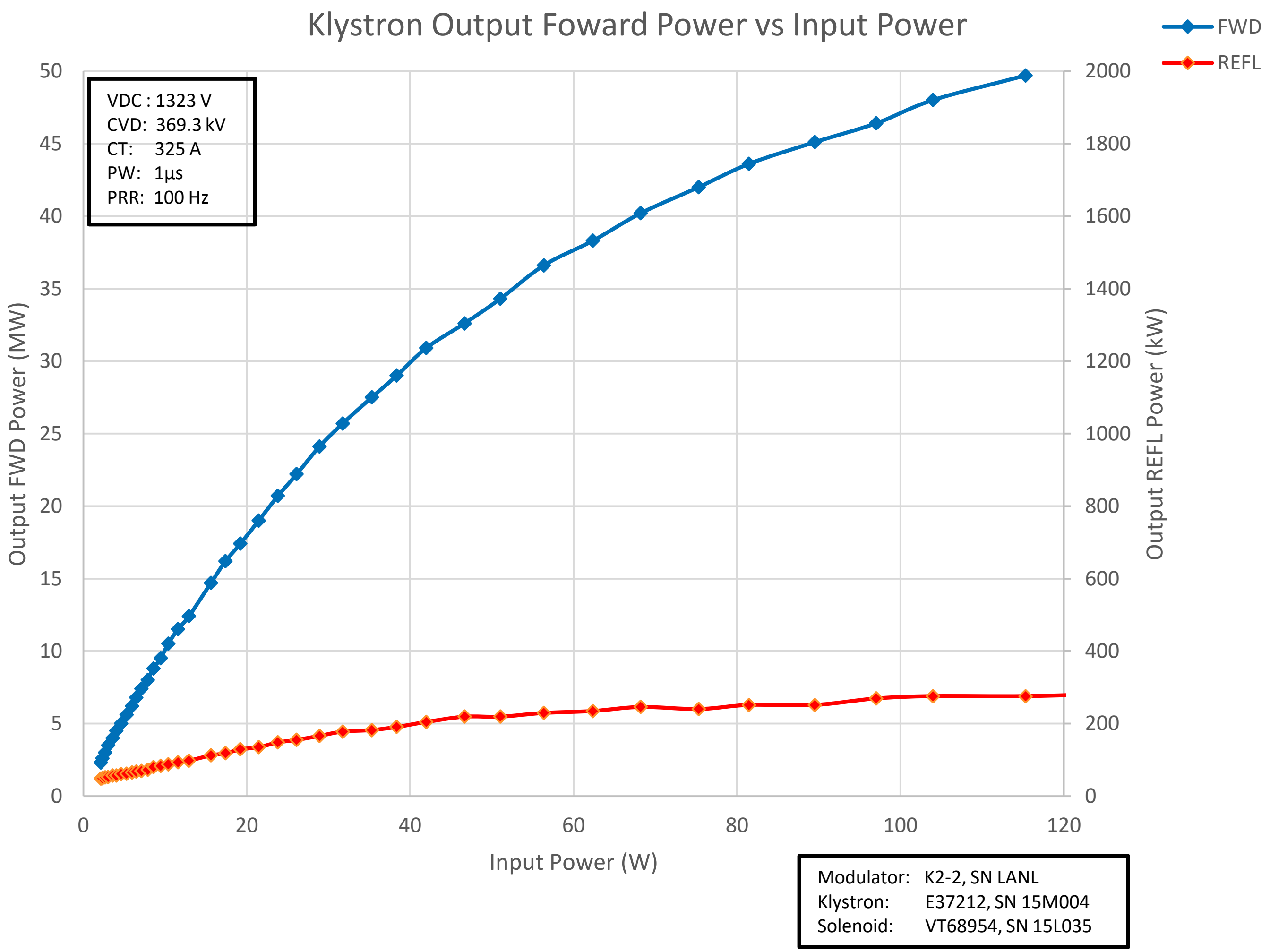
- February 21, 2020:
  - Klystron forward power from ~14MW to ~50 MW, 100Hz PRR, at pw = 0.5µs, 0.7µs, 0.8µs and 1.0µs.





Initial Conditioning Efforts

- Gain Curve:



Conclusions

- Klystron/modulator is a compact, well-integrated system.
- LLRF, data acquisition/control system still a work in progress
- USB-based power sensors proved problematic, recommend using calibrated diode detection for forward and reflected power measurements.
- Gaining valuable conditioning experience as the system continues to expand.

Back Up

Excel spreadsheet calculates ΔTwg by successive substitution.

$$Qwg = \int_0^t (Paveloss - Pconv)dt$$

$$Qwg = \sum_{i=1}^{n} (Paveloss_i - Pconv_k) \times \Delta t \qquad (k = i - 1) \qquad \text{(Approximation)}$$

$$\Delta Qwg_i = \Delta Qrf_i - \Delta Qconv_k$$

$$\Delta Qrf_i = Paveloss \times \Delta t_i$$

$$= cp\_copper \times mwg \times (Twg_i - Tinit)$$

$$\Delta Qconv_k = Pconv_k \times \Delta t$$

$$= htot_k \times Awg \times (Twg_k - Tamb) \times \Delta t \qquad Tinit = Tamb$$

$$(Twg_i - Tamb) = \frac{\Delta Qrf_i - \Delta Qconv_k}{cp\_copper \times mwg}$$

Back Up

- Linear expansion of copper:
  - α = 17µm m^{-1} K^{-1} (Wikipedia)
    - For:
      - length of waveguide, L = 1 m,
      - and ΔTwg = 5 °C;

$$\Delta L = L \times \alpha * \Delta Twg$$

$$= 85\ \mu m$$