



# Coupler test results

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FNAL, 12-14 July 2022

In partnership with:

India/DAE

Italy/INFN

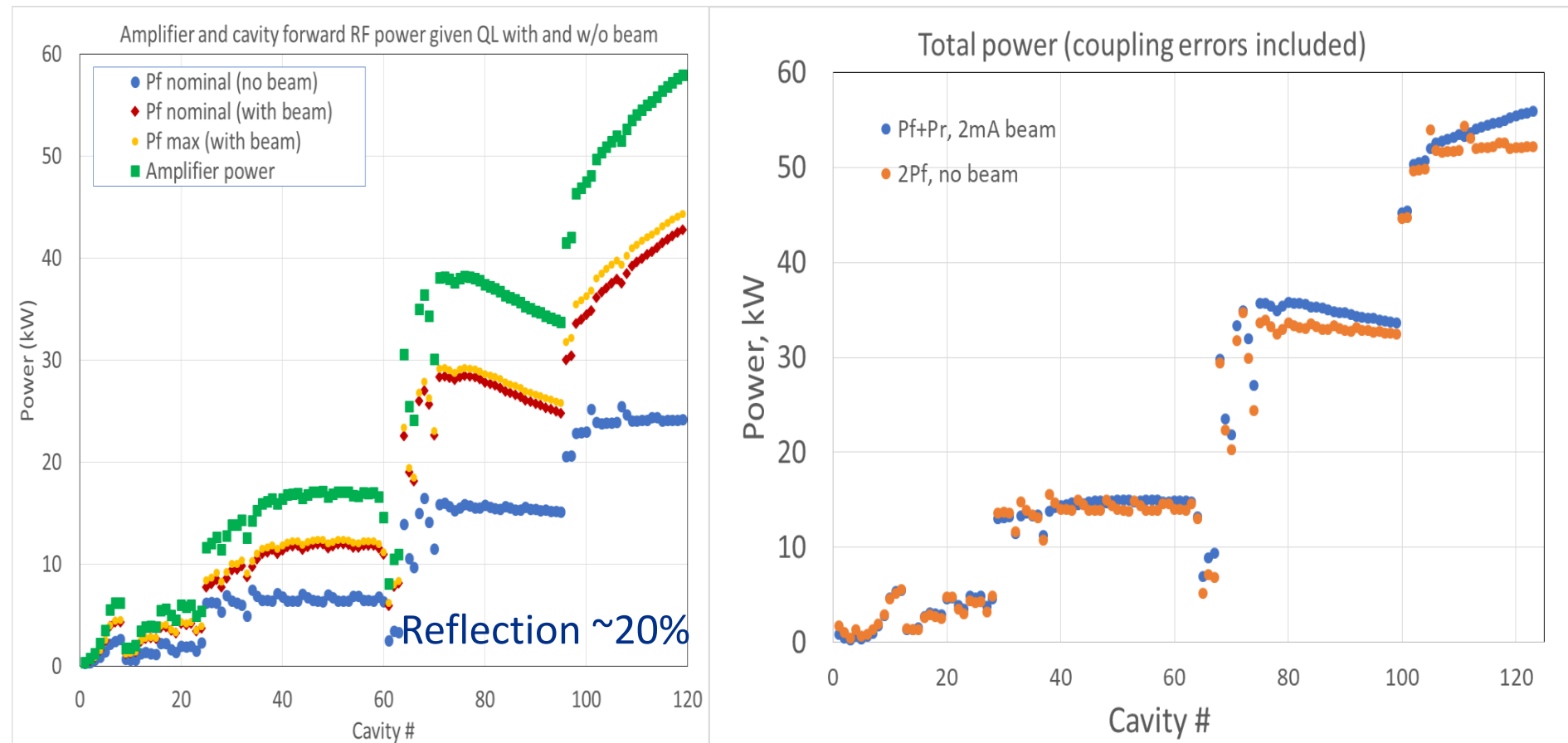
UK/STFC

France/CEA/Irfu, CNRS/IN2P3

Poland, WUST

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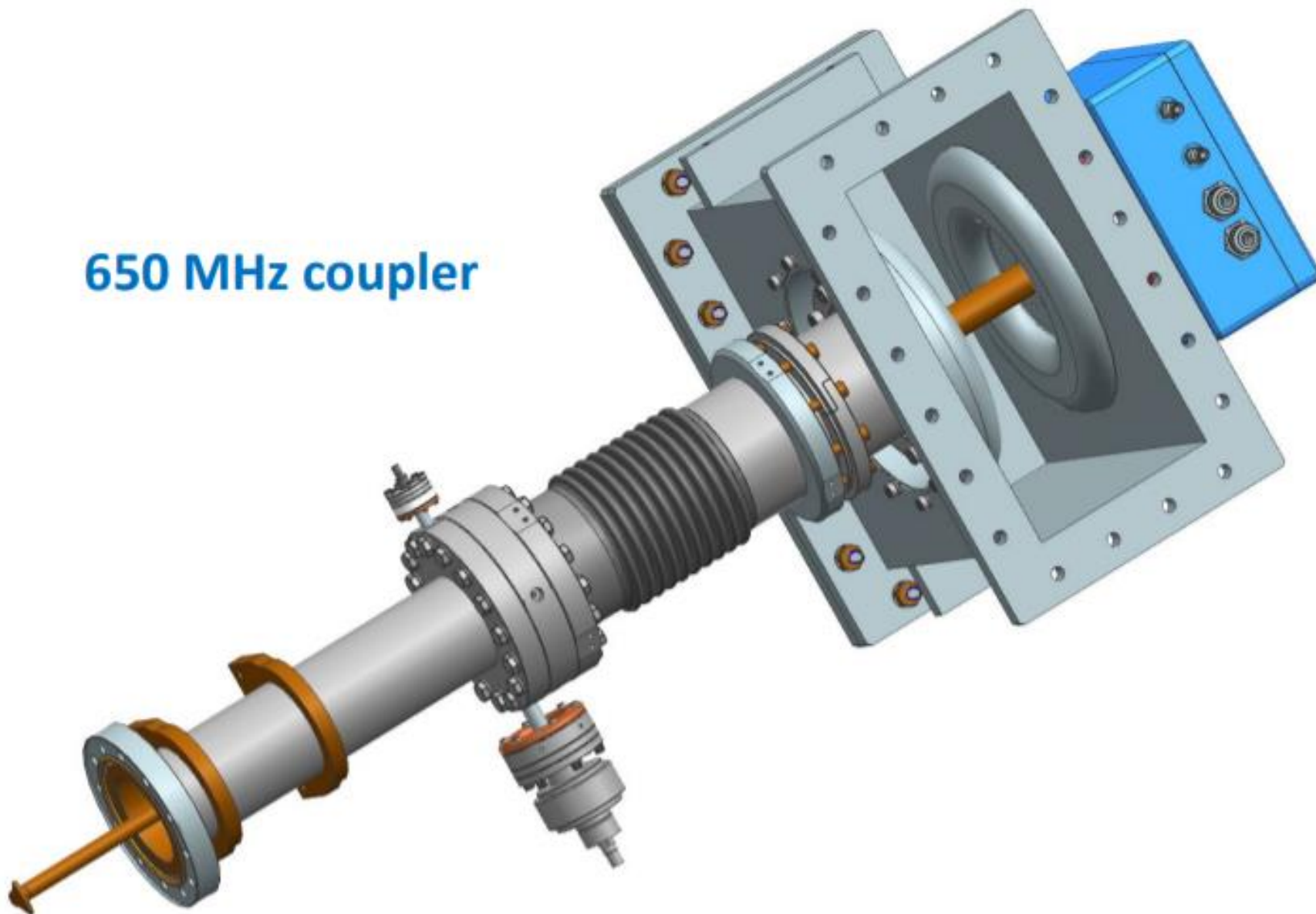
# Total (fwr+refl) power responsible for coupler heating



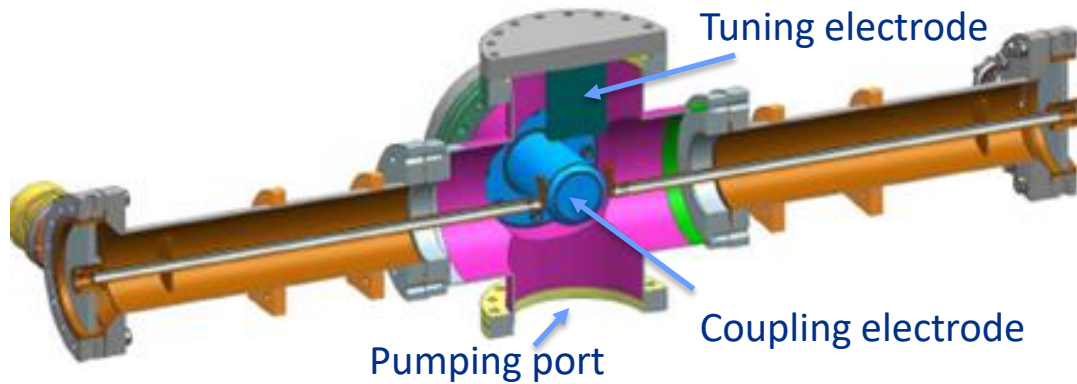
PIP-II beam duty cycle is small.

Coupler test stand: 50kW SW (full reflection with arbitrary phase), which is equivalent to 100kW total power

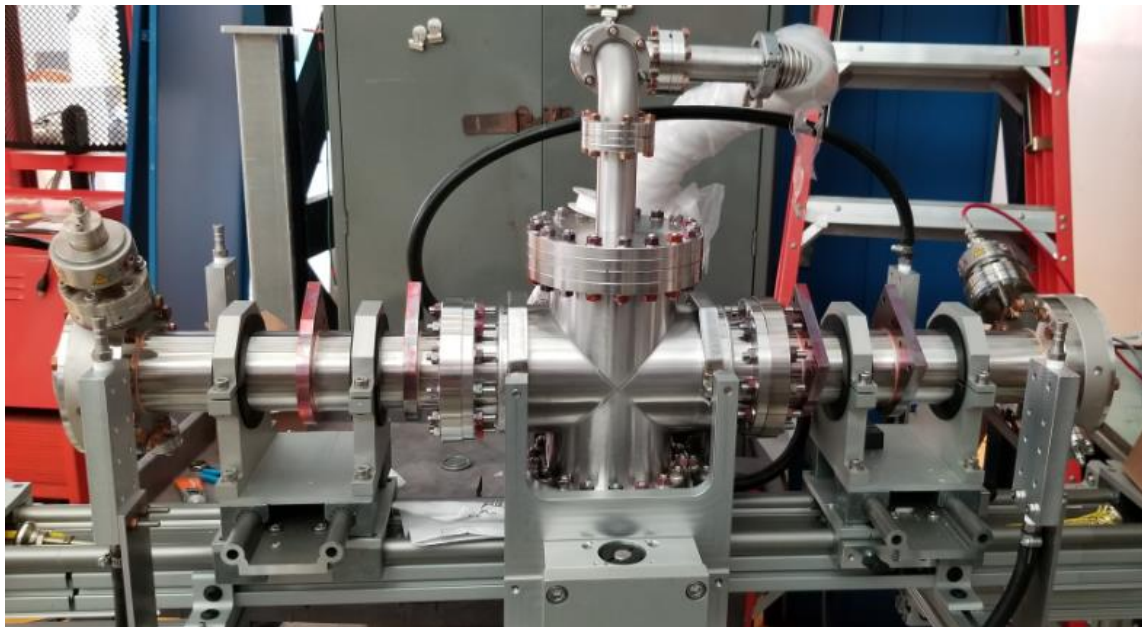
## 650 MHz coupler



# Vacuum parts assembled on coupling chamber

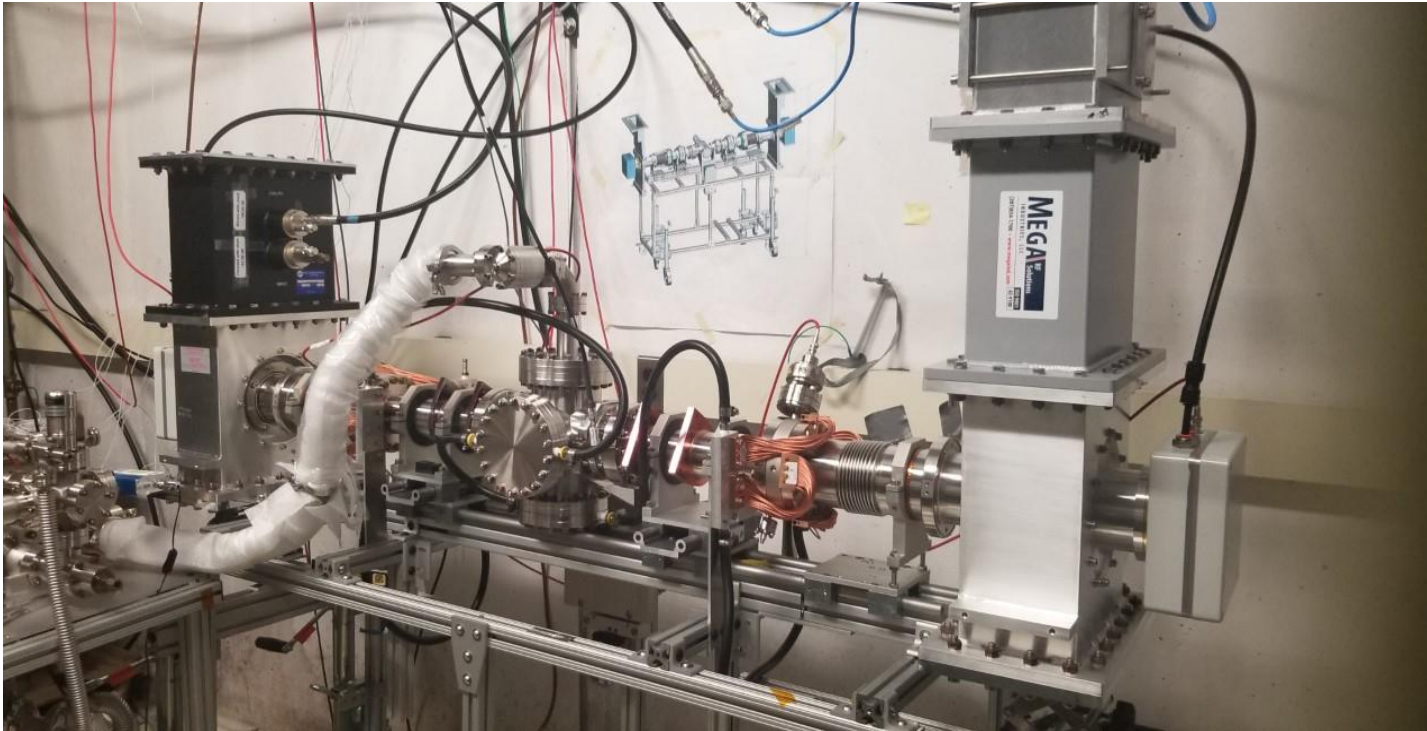


- Assembly in class 10 cleaning room
- Pumped and leak checked
- Baked 120C for 48 Hrs

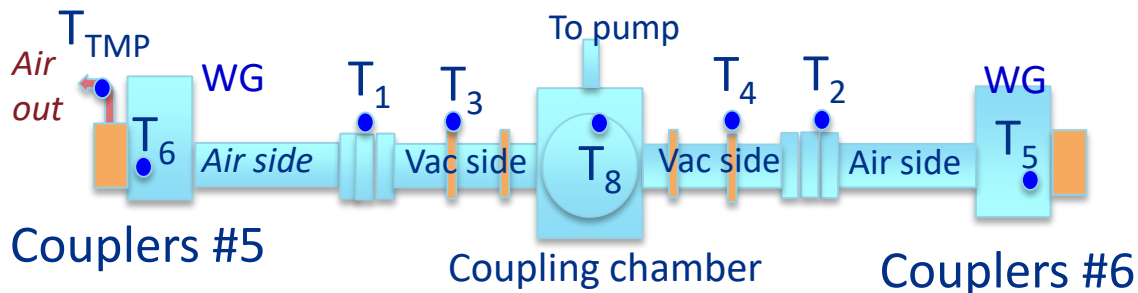


- Then move to MDB for coupler air side assembly, Rf cooling and pumping line connection and Temperature diagnostic

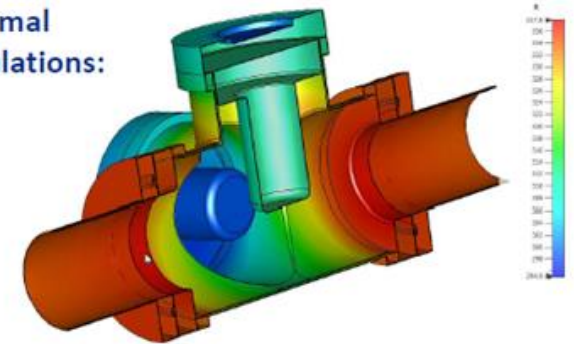
# Couplers at test stand. Phase 0° configuration.



## Temp. diagnostics



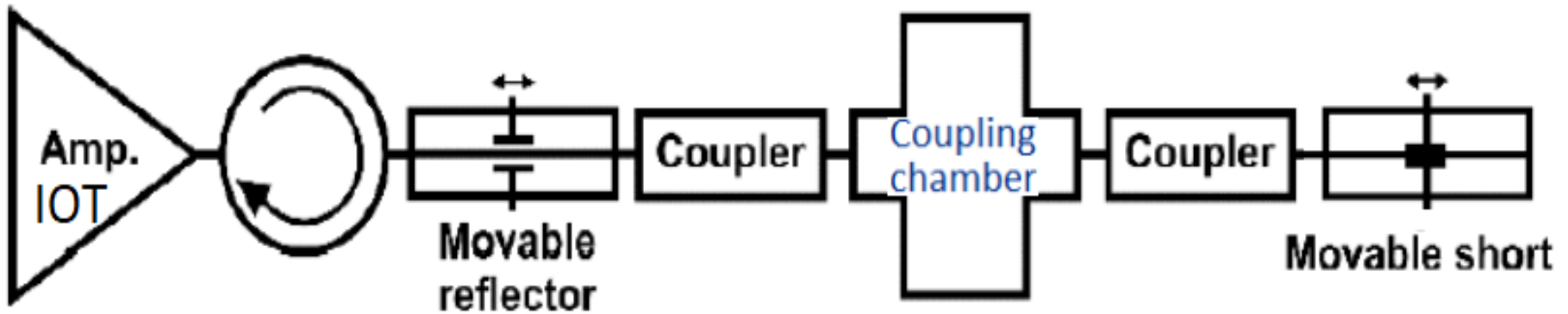
## Thermal simulations:



Max.  $T < 60\text{C}$  for 50 kW, CW, full reflection

# Power configuration

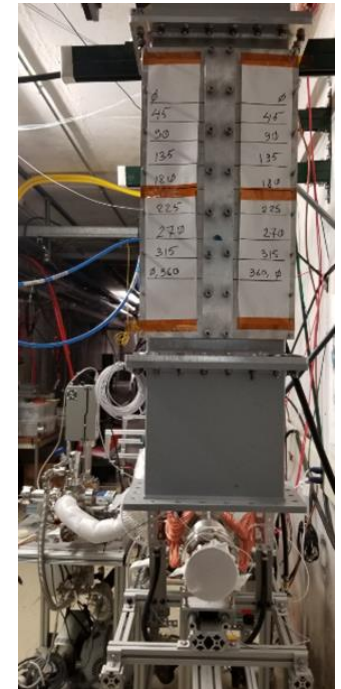
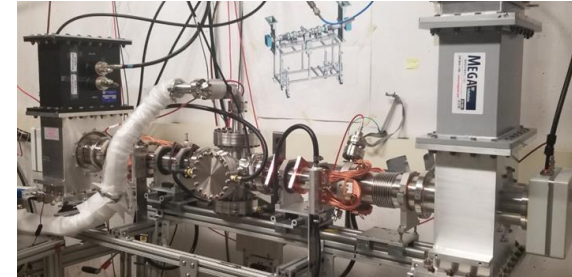
- This schematic allow to achieve x5 amplification in power circulating in coupler



- IOT power is limited 30kW cw. In our setup we can provide 100-120kW power in coupler assembly

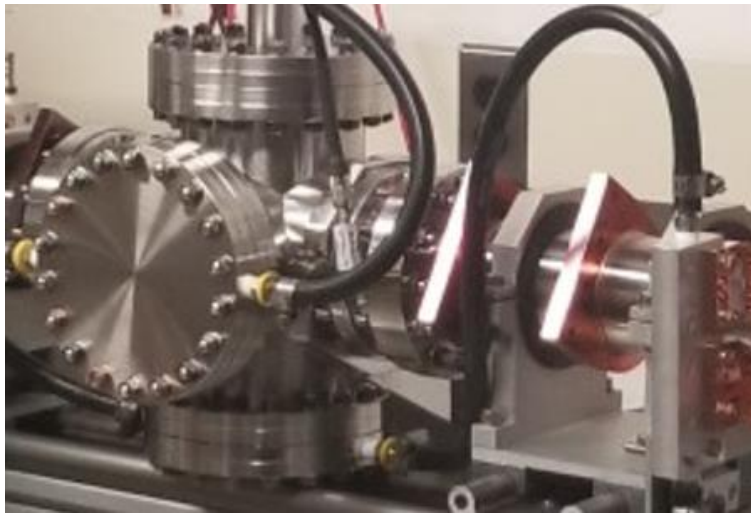
# Low power RF measurements and reflection phase tuning

- Both waveguides are connected to WG-to-Coax transitions. After cable calibration, measure transition/reflection in coupler/chamber assembly.
- After that working configuration is assembled: one end connected to RF power line through movable reflector section, second end have WG insertion (length corresponds phase) and short.
- For each phase configuration the location of movable reflector (diaphragm) is tuned to get resonance in coupler assembly (see marks)



# Cooling and Diagnostics

- Antenna is cooled by dry air with flow rate up to 13 CFPM (7g/s)
- Chamber flanges connected to copper electrode is cooled by water
- Window flange is connected by 4 copper straps to water cooled sink (to provide room temp boundary condition as in real CM)
- Diagnostics: vacuum (3), Temp (8), bias (2), Air flow (2), water flow, e-pick-ups(2)





# Test protocol

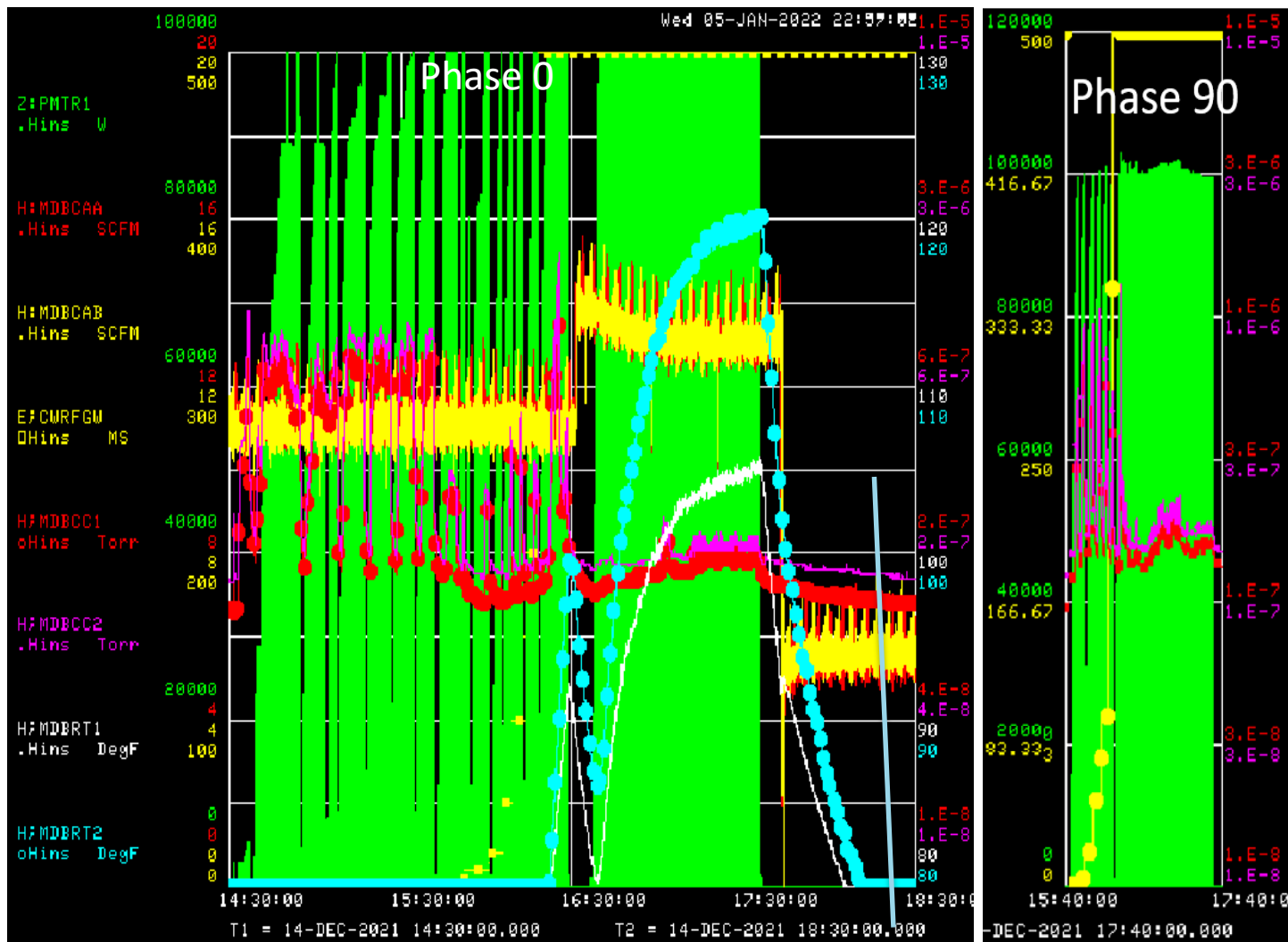
- *Typical Testing Conditions:*
  - DC bias 4.5kV on inner conductor (each coupler) - interlock
  - Air flow rate 13 SCFM (7.4 g/s) – each antenna - interlock
  - Water flow rate - interlock
  - Vacuum gauges (both coupler). - interlock 2.E-6 Torr
  - Temperature interlocks:  $T < 140\text{F}$  (60K) on ceramic window flange
  - Final vacuum after processing  $< 1.e-7$  Torr
- *Short summary of the testing protocol:*
  - *Start with pulse mode: 10, 20, 50, 100, 200, 500 ms: ramping RF power up to 100kW,*
  - *Switch to CW mode, ramping RF power up to 50kW, Stay: 1-2hrs to reach equilibrium temperature.*
  - *In HP tests the power ramping steps were controlled manually to keep vacuum below interlock level (will be automated, script exist and used in earlier tests)*
- Test without HV bias
  - Start with shorter pulses: 10, 20, 50, 100, 200, 500  $\mu\text{s}$ ; 1, 2, 5, 10, 20, ... 200, 500ms and ramping power to 100kW
  - In cw regime power ramping up to 50kW

# Coupler 1&2: Phase 0 and 90 deg

HV=4.5kV,  
Air flow rate ~7 g/s:

- Pulse mode: 0.01; 0.05, 0.1; 0.2...200; 500 ms; (100kW) -- CW mode was not available
- MP processing
- After processing stay at 100kW x 500ms x 1 hour

Green – RF power  
Yellow/red – Air flow  
Magenta/red circle – vacuum  
White-T1; Cyan – T2

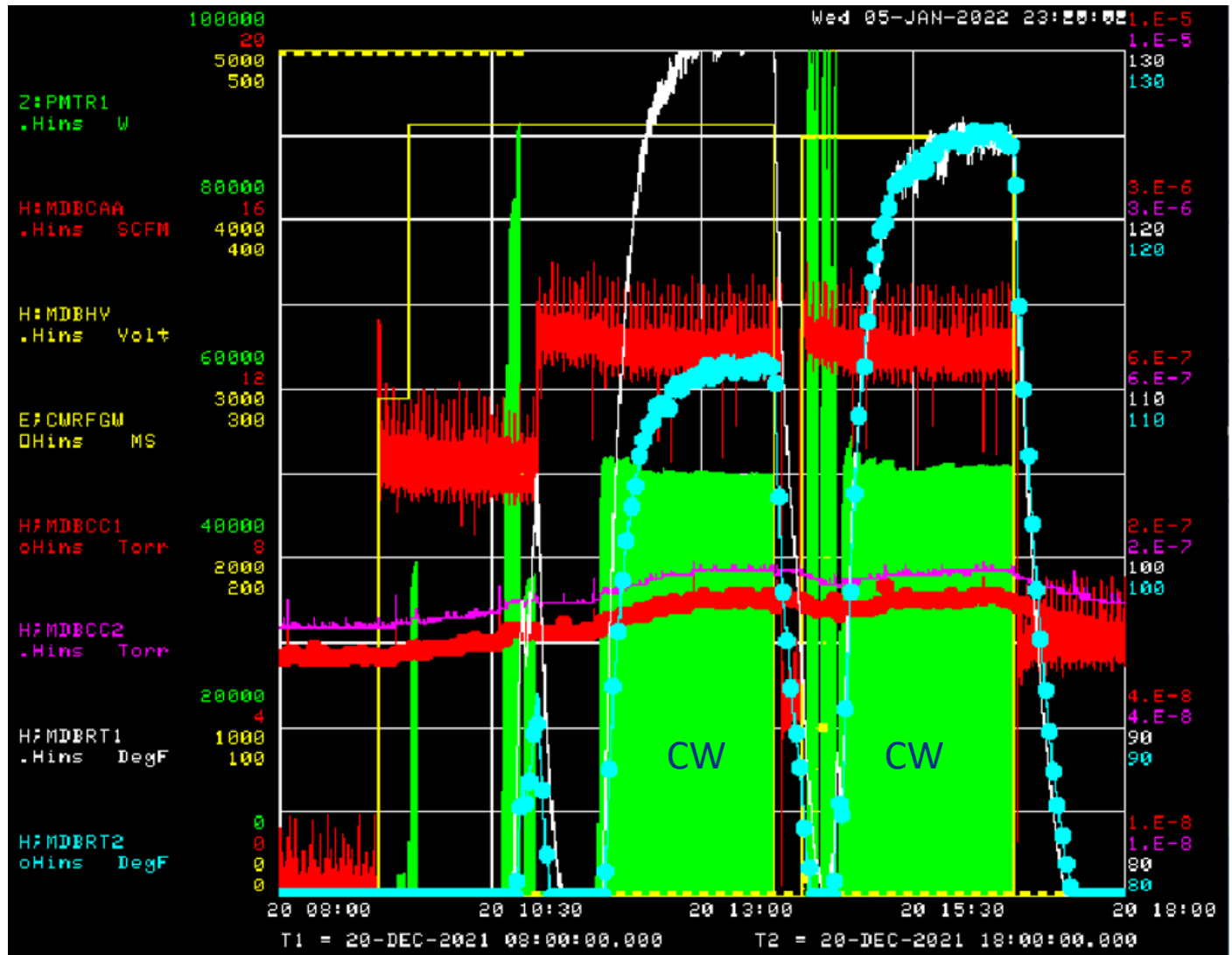


significant MP activity in pulse mode

# Phase 180 and 270 degrees. No MP

Pulse and CW operation.

No MP up to 50kW

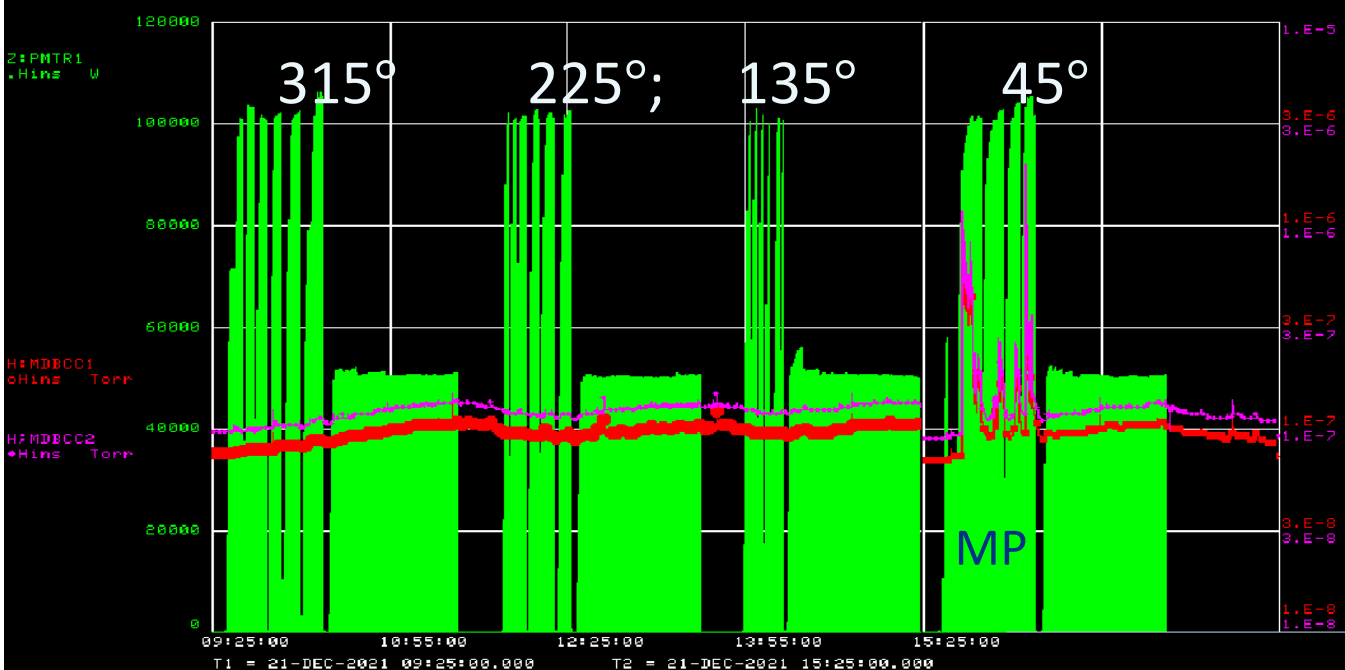


Phase 180 deg, 50kW CW, flow 13 CFM; HV = 4.5kV; T1=132; T2=111;

Phase=270 deg; 50kW CW , flow=13 CFM; HV=4.5kV; T1=125; T2=125K;

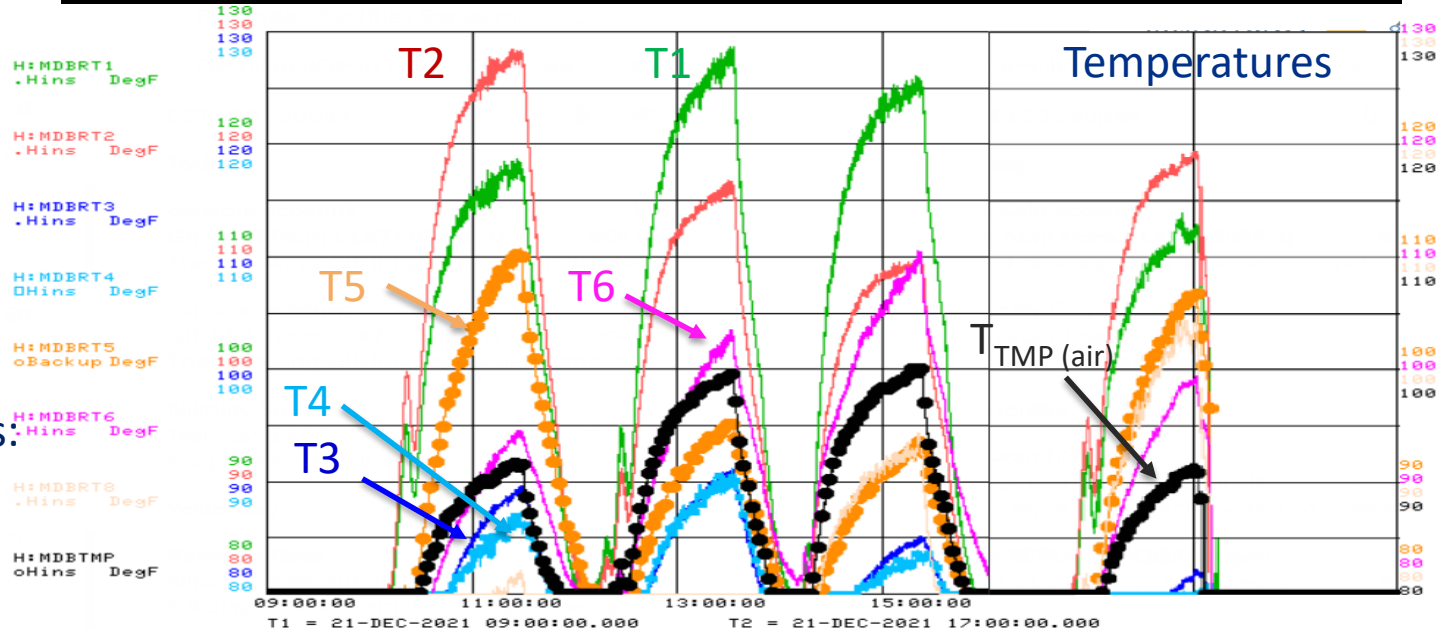
# Coupler #1-#2

- Phase 315; 225; 135 and 45 degrees
- DC bias: 4.5kV;
- Air Flow=13 CFM
- Pulse mode: 10; 20; 50; 100; 200; 500ms; up to 100kW
- CW mode: 50 kW x 1hrs



MP activity at 45deg, starts above 70 kW, vacuum ~1.e-6 Torr

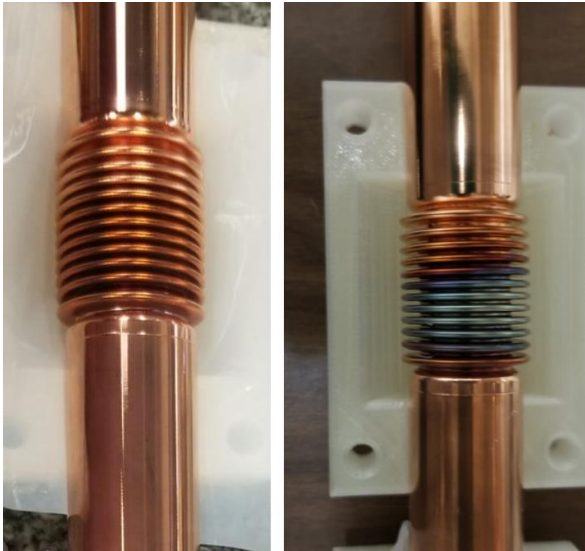
Max temp at windows:  
 $T_1$ - coupler#1,  
 $T_2$ -coupler #2



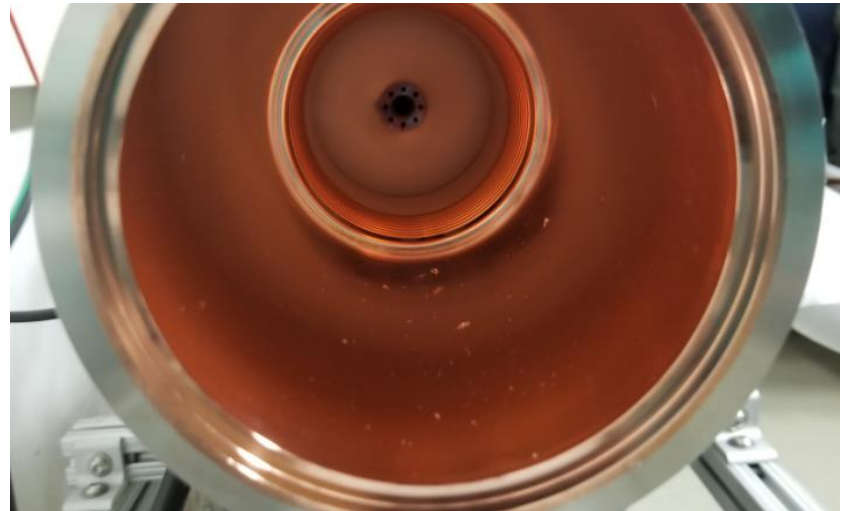
# Inspection after test

## Coupler #1 Air side:

- white flakes (from sharp edges of Teflon support)
- One inner bellow changed colour (oxidation or missing copper)-
  - Oxidation removed successfully

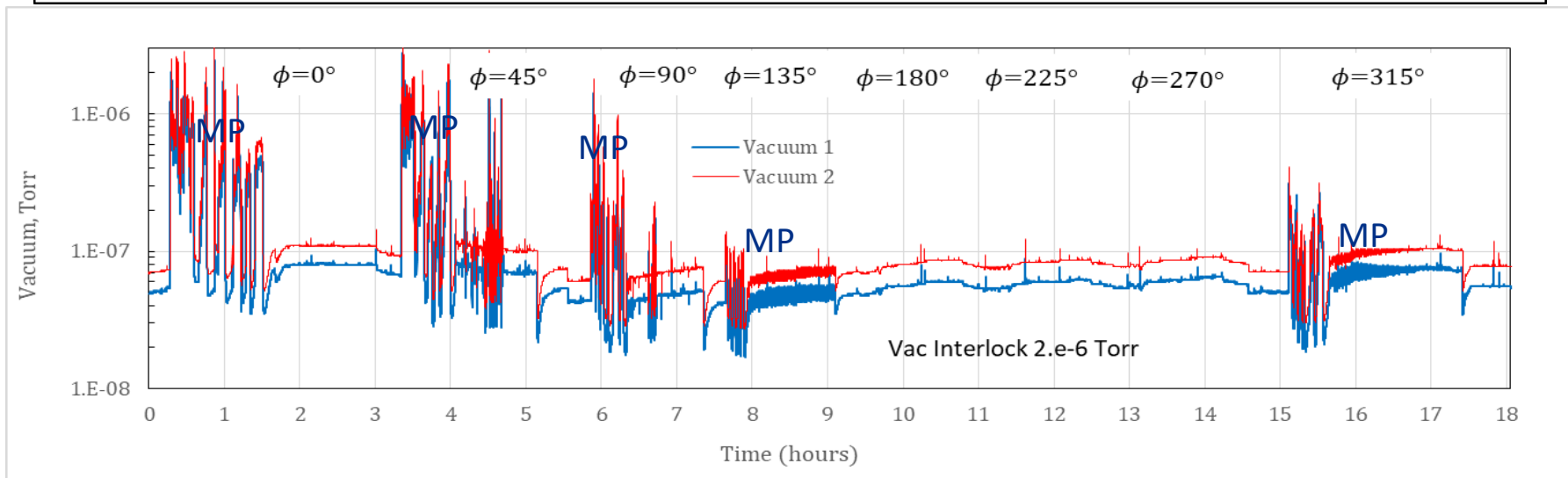
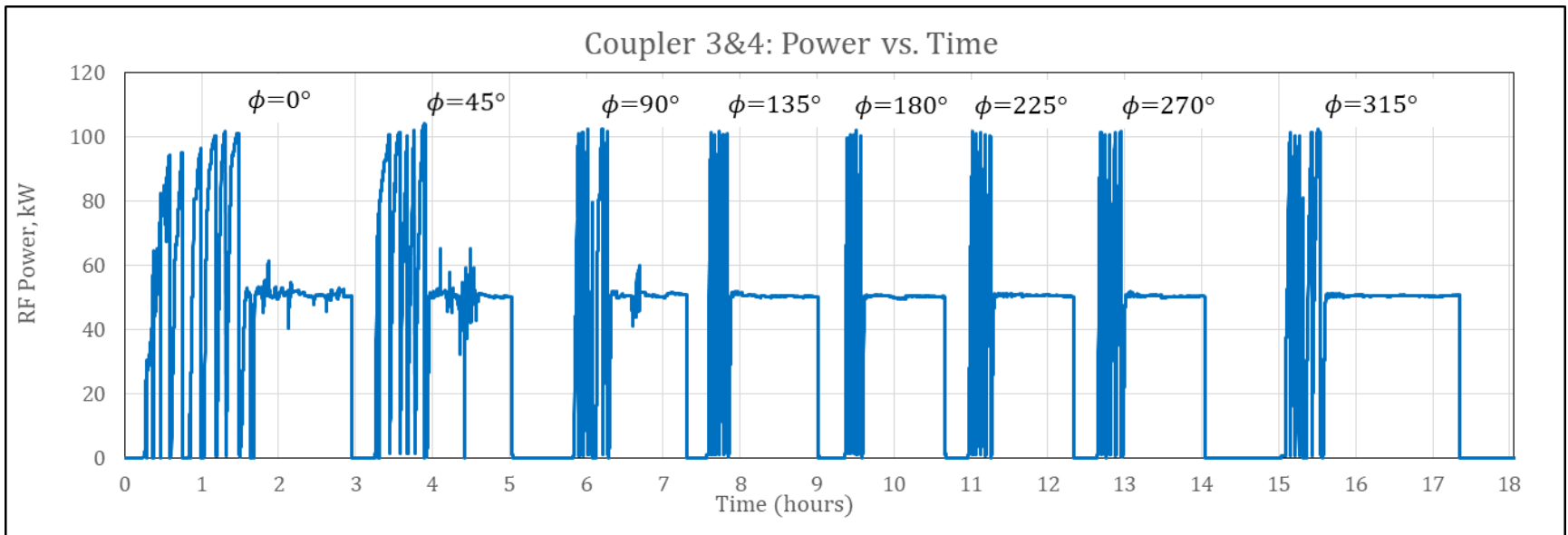


Bellow before and after test



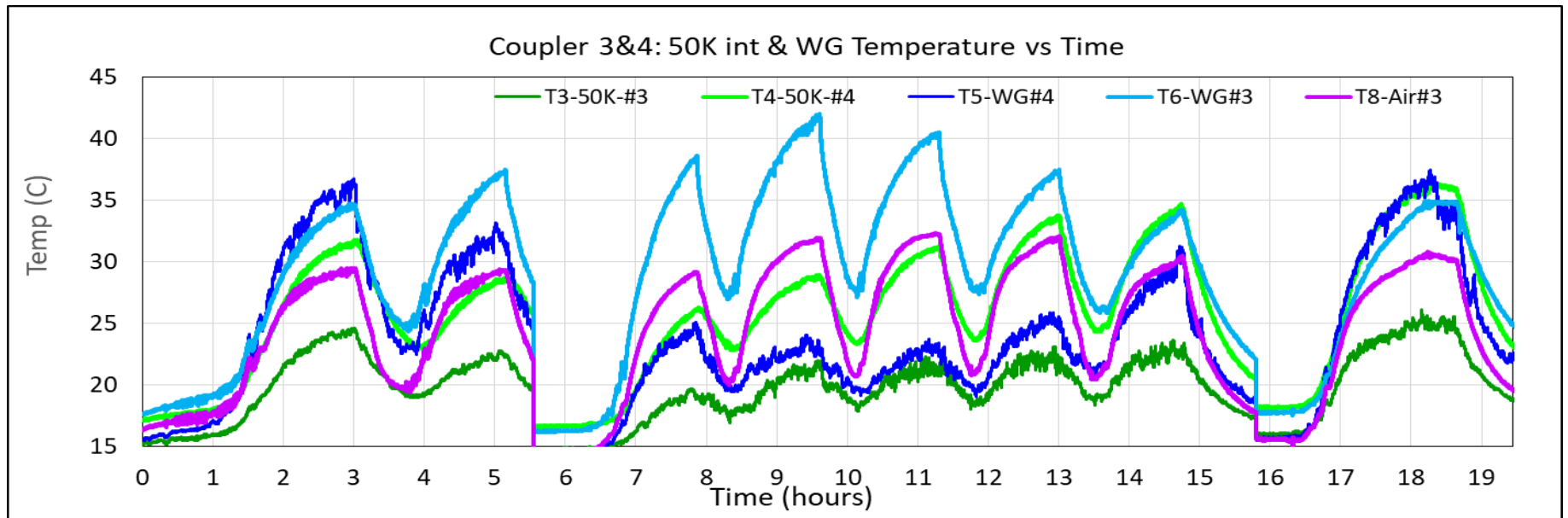
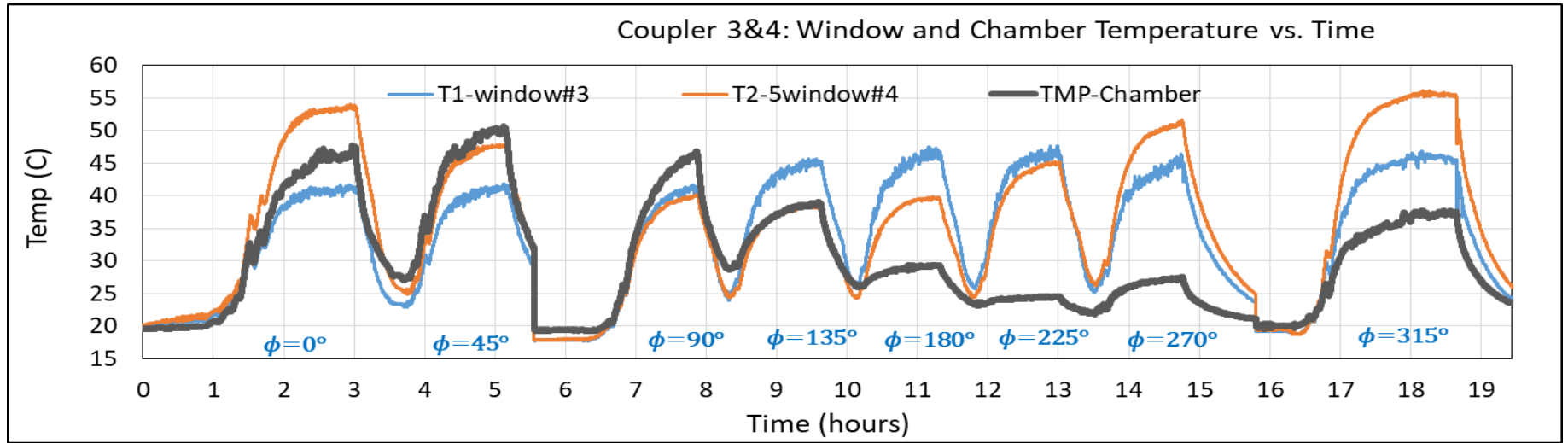
Flakes sent to material lab for investigation

# Coupler 3&4: Power and Vacuum

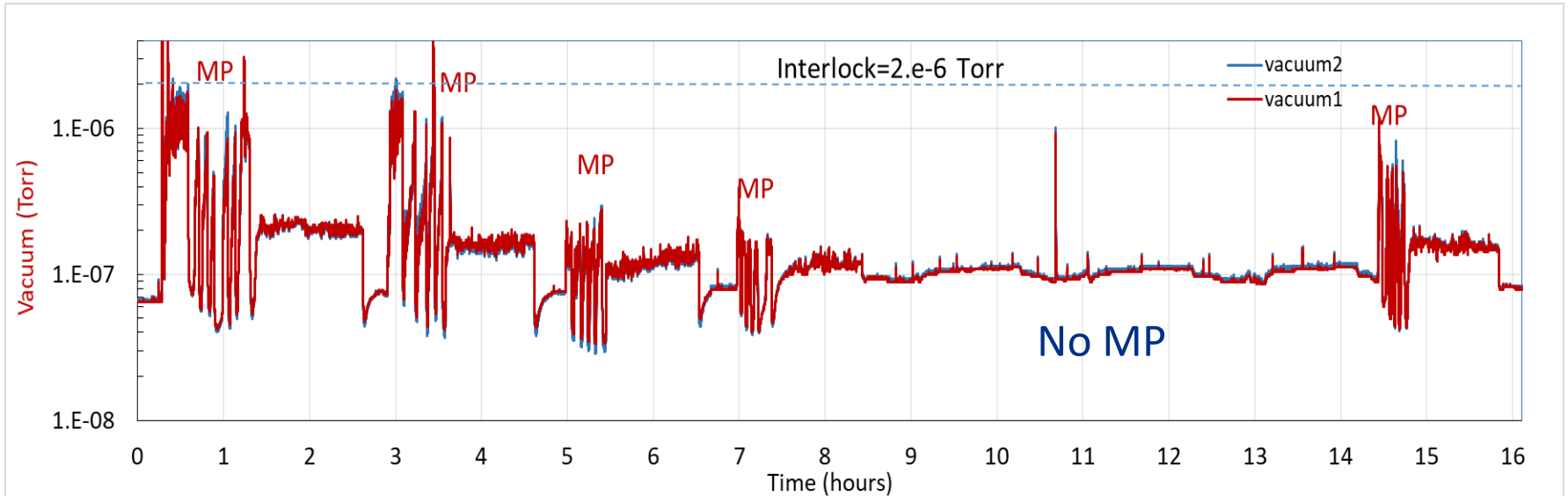
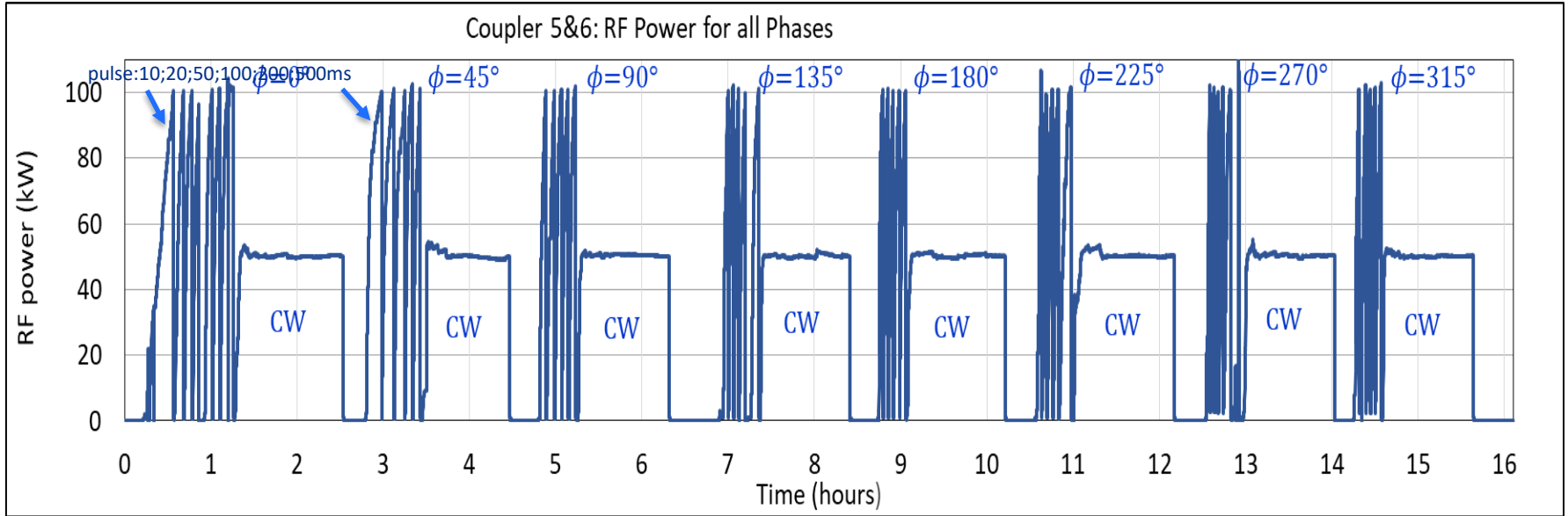


No MP at 180,225,270 phases, vacuum  $<8.e-8$  Torr

# Coupler 3&4: Temperature profile vs RF phase

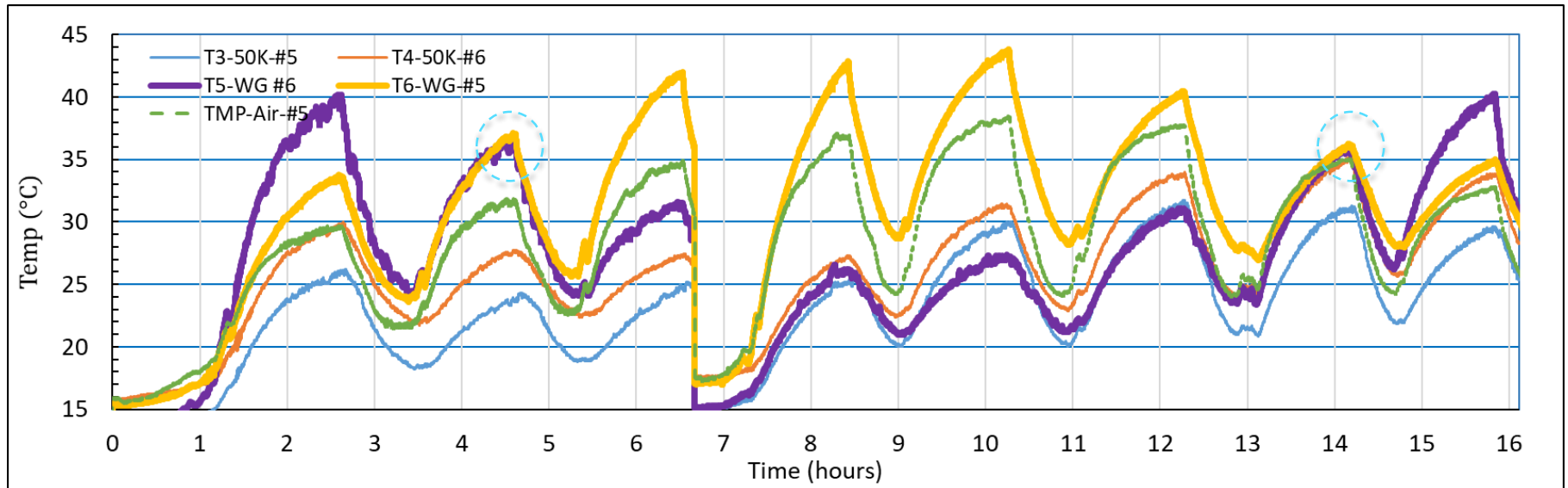
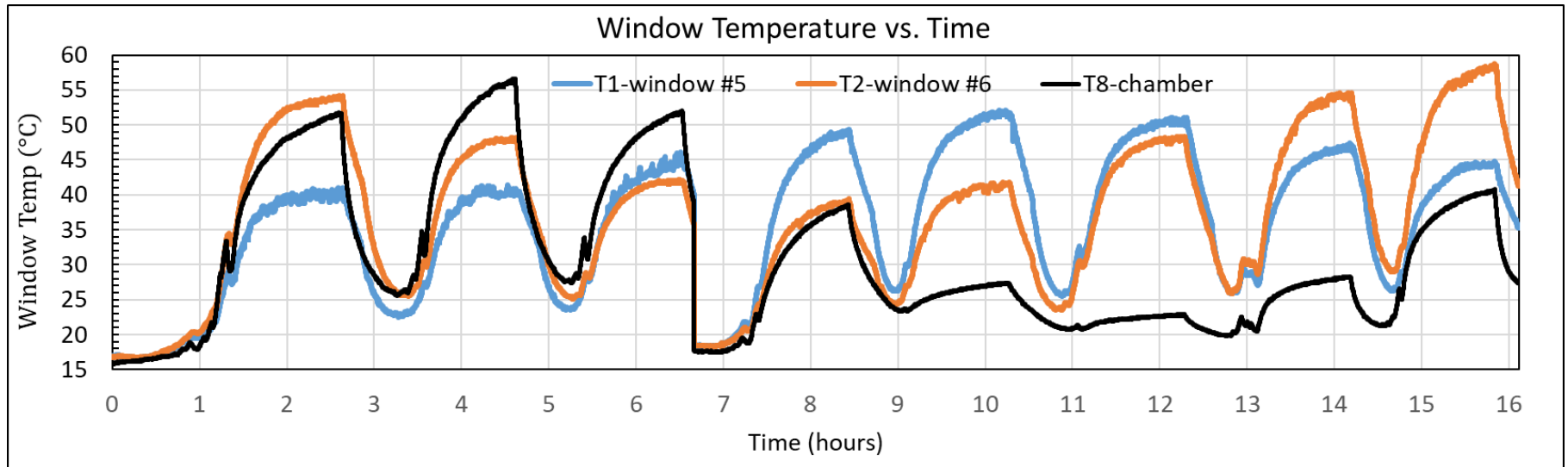


# Coupler 5&6: Power and Vacuum

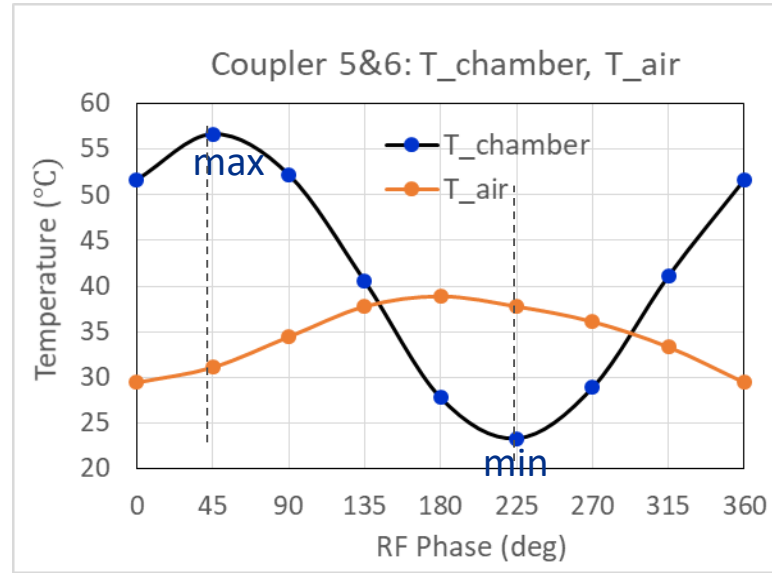
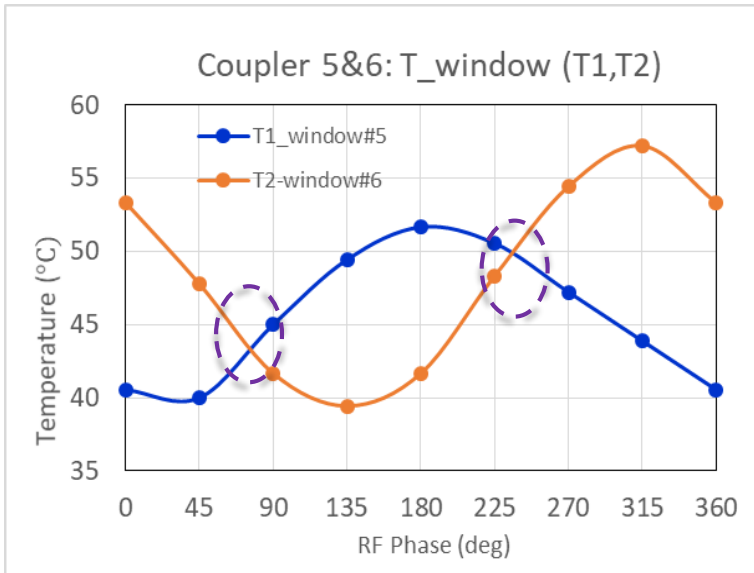




# Coupler 5&6: Temperature profile vs. time



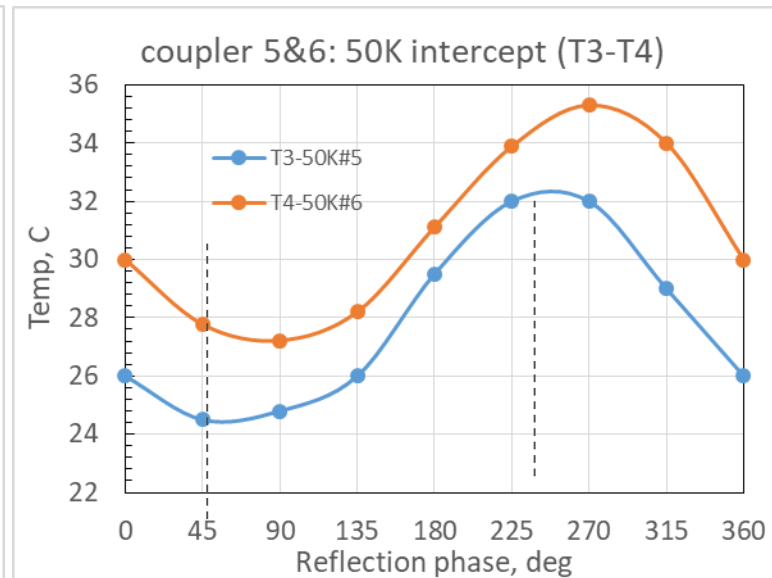
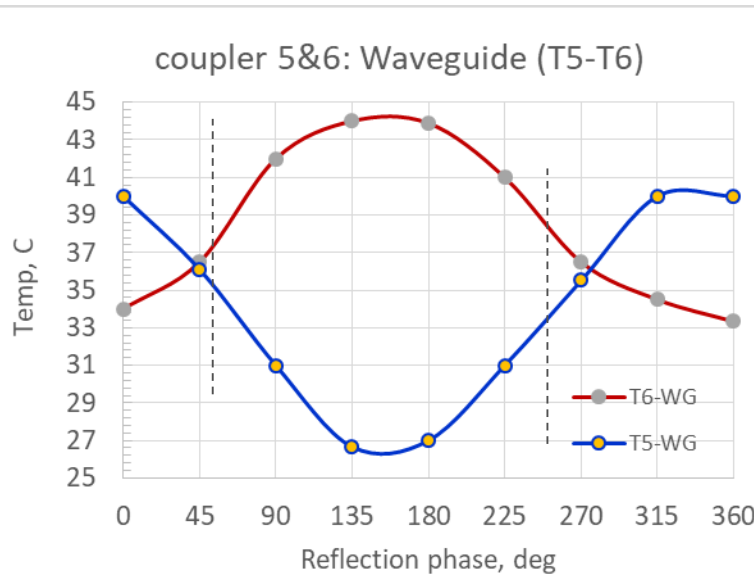
# Coupler 5&6: Equilibrium temperature at 50kW



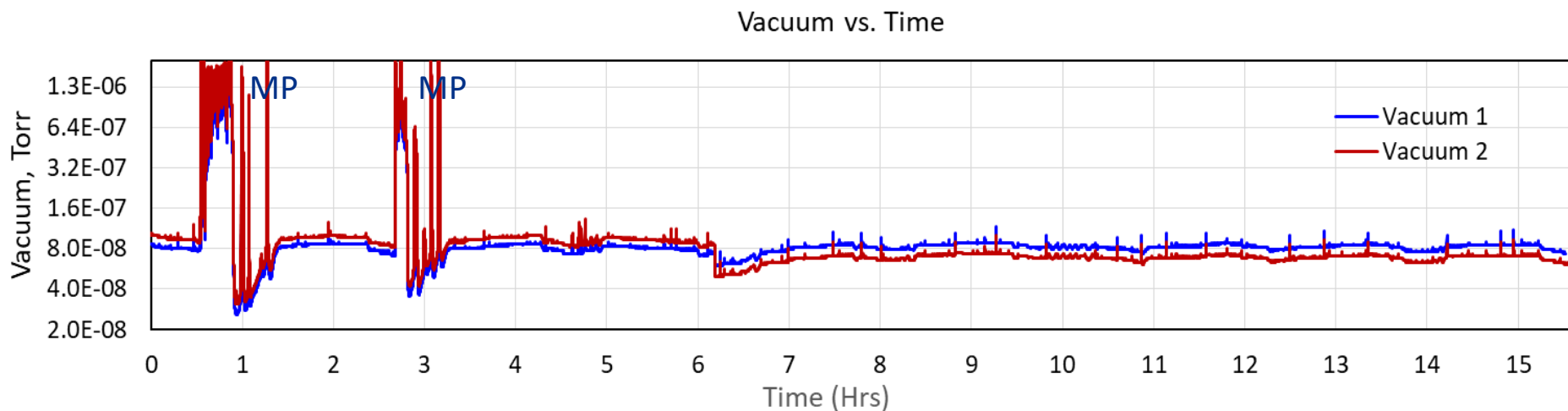
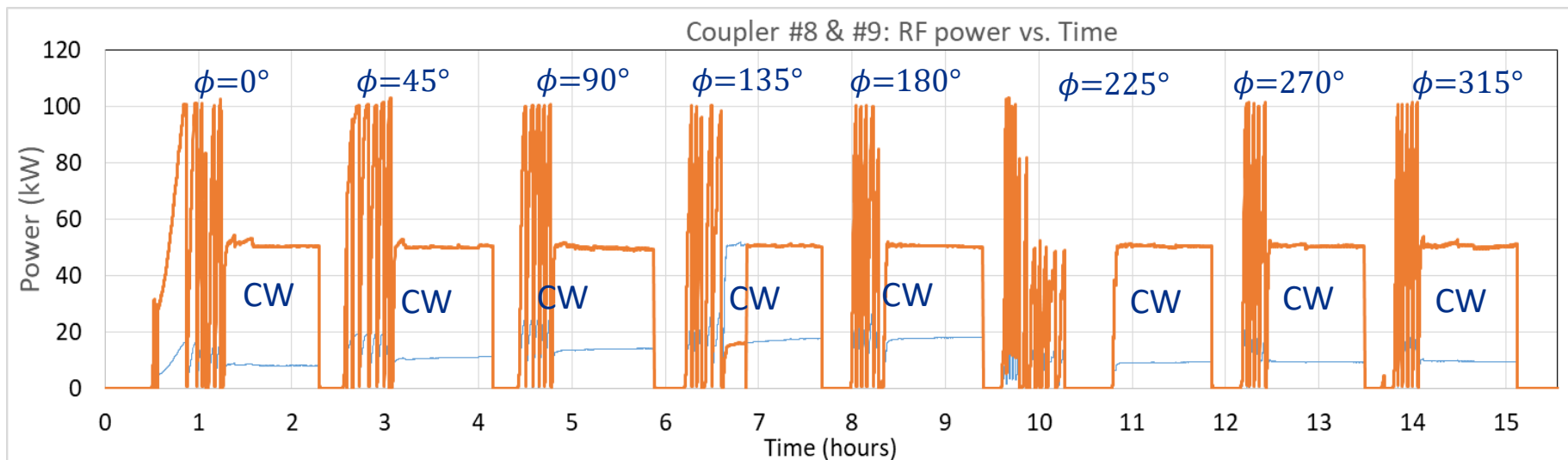
- Min T<sub>chamber</sub> at RF phase ~225

At phase ~ 225° we have ~ symmetry in temperature distr.

- *Window #5 & #6 temp are close*
- *WG #5&#6 temp also similar*

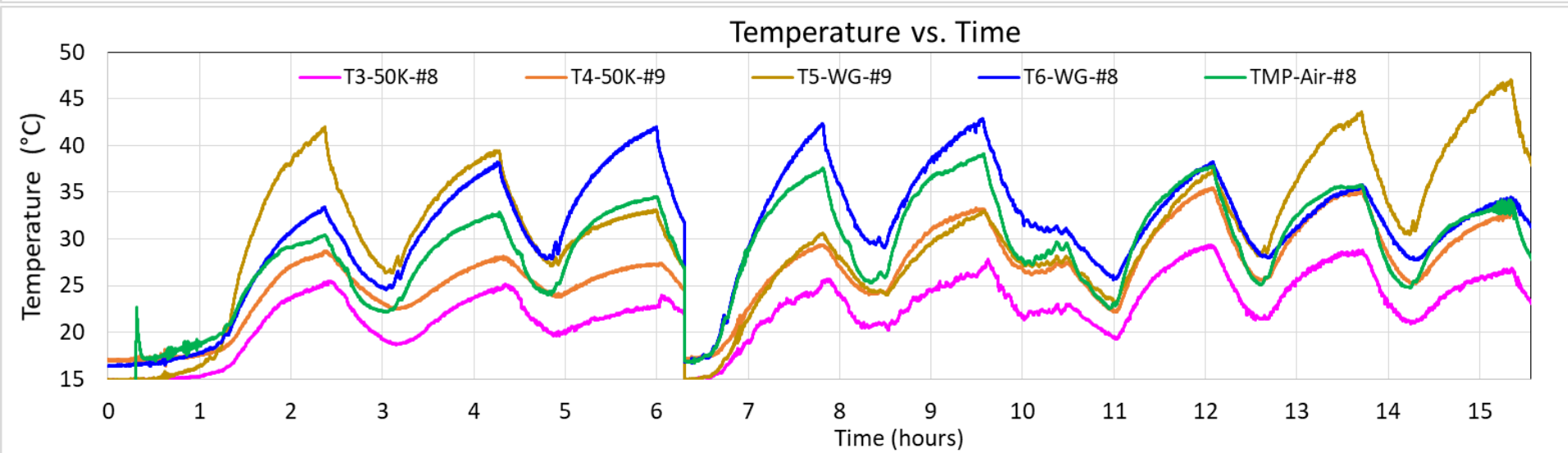
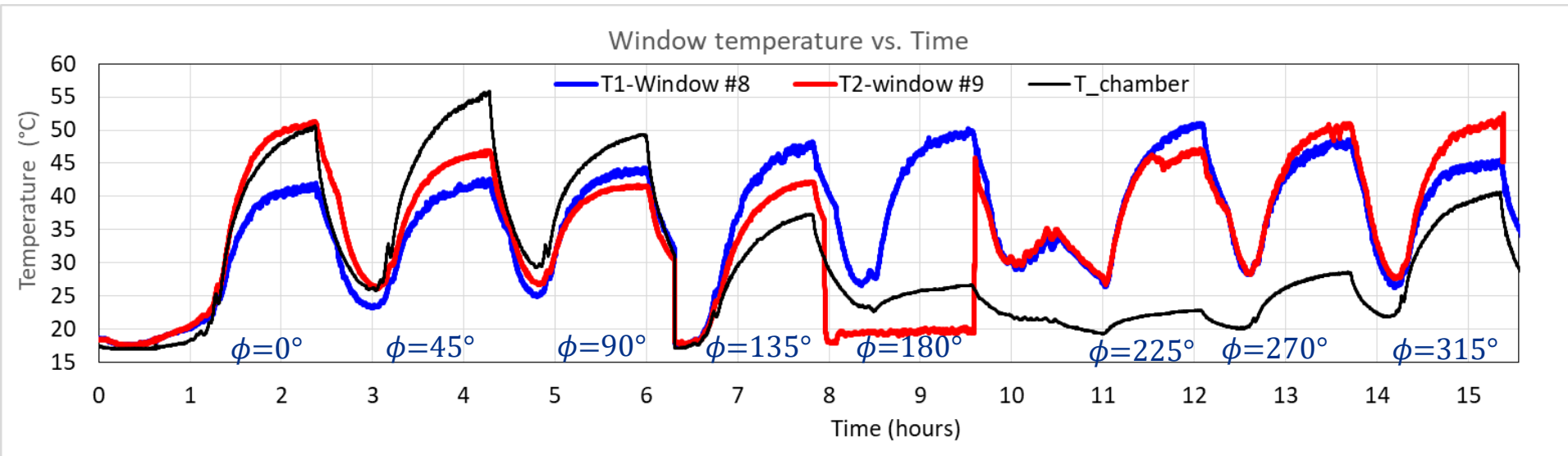


# Coupler 8&9: RF power and vacuum



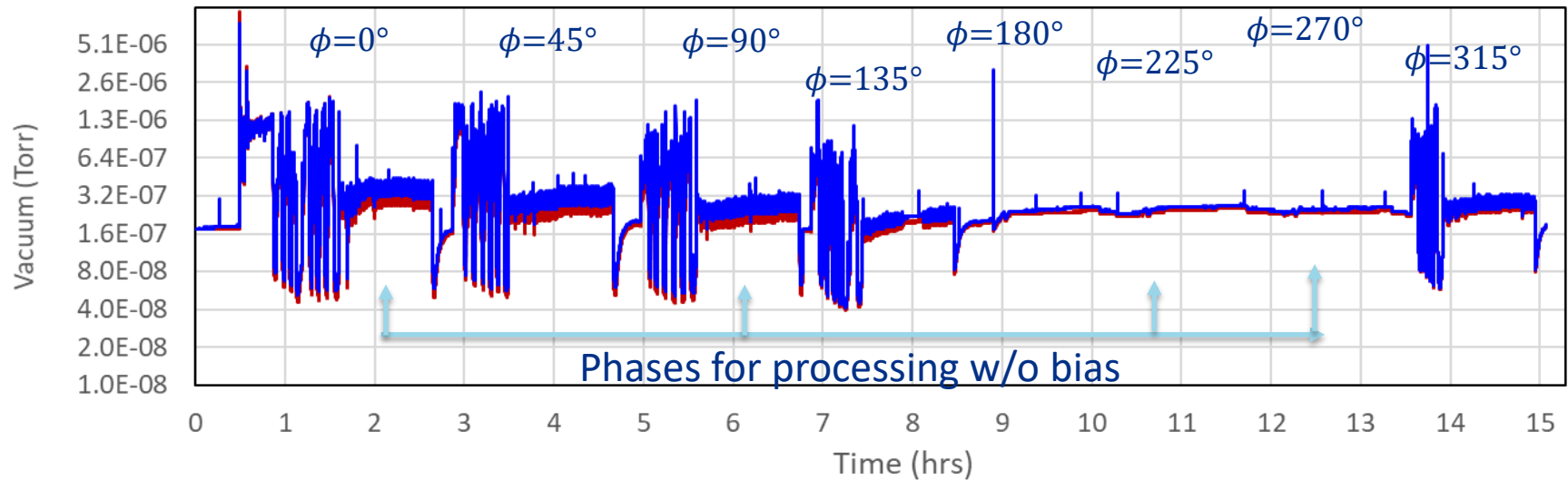
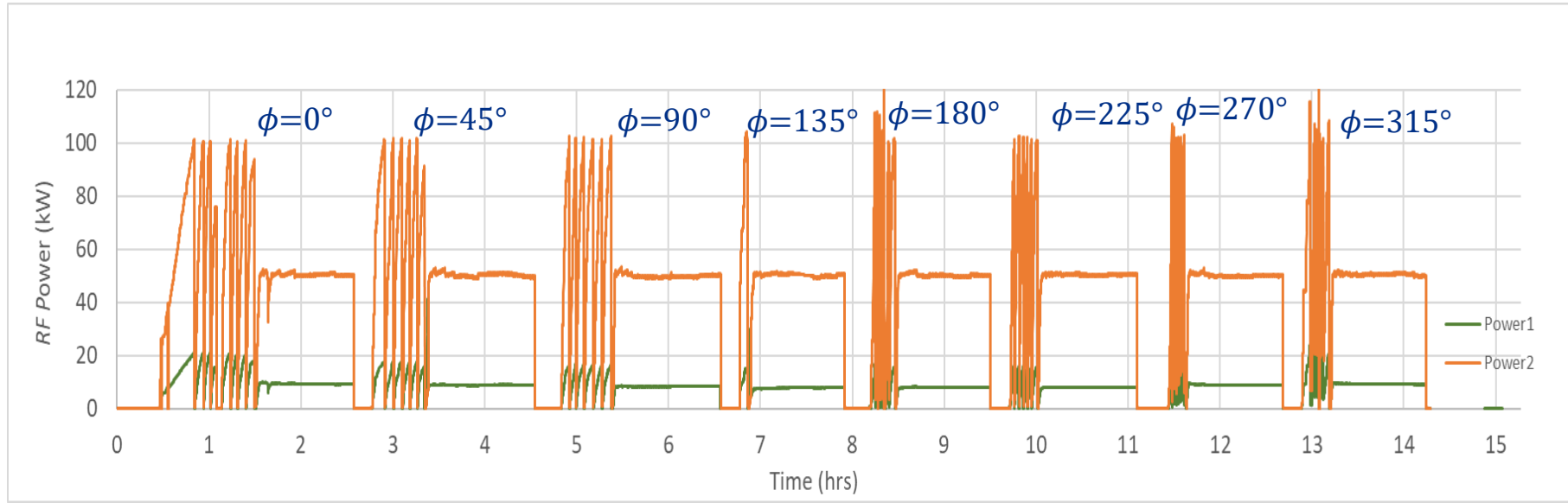
MP at 0 and 45 degrees at power  $\sim 100$  kW, no MP at 50 kW CW. MP mostly in chamber #2, chamber #2 was better processed after first run with coupler 3&4 and extra baking 120C

# Coupler 8&9: Temperatures

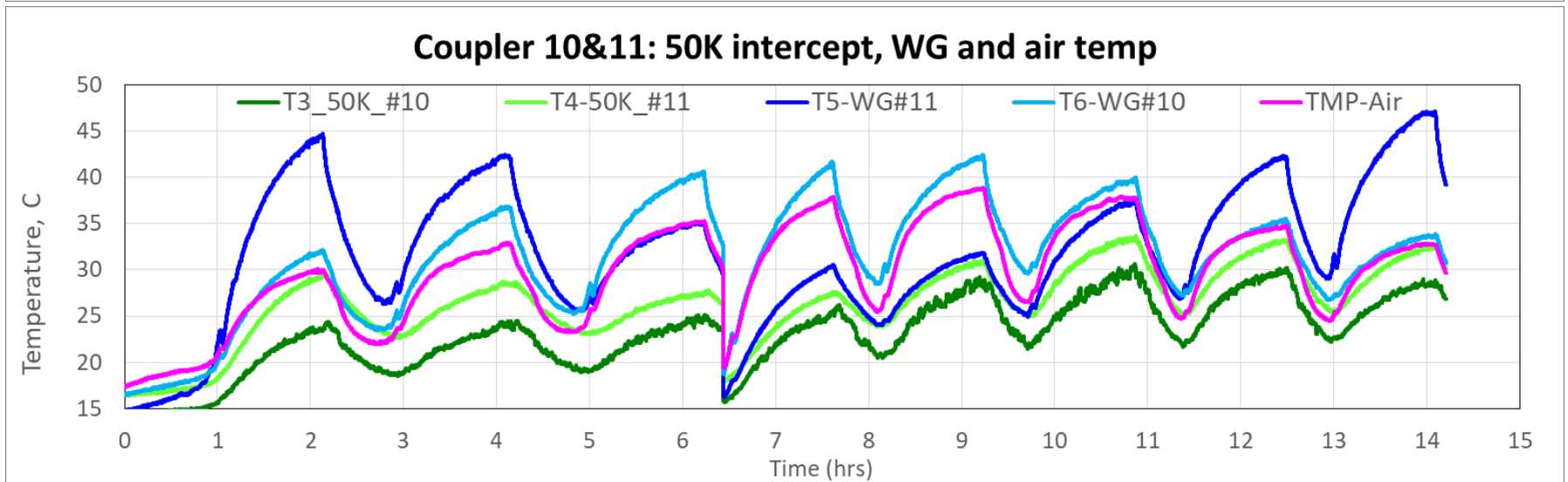
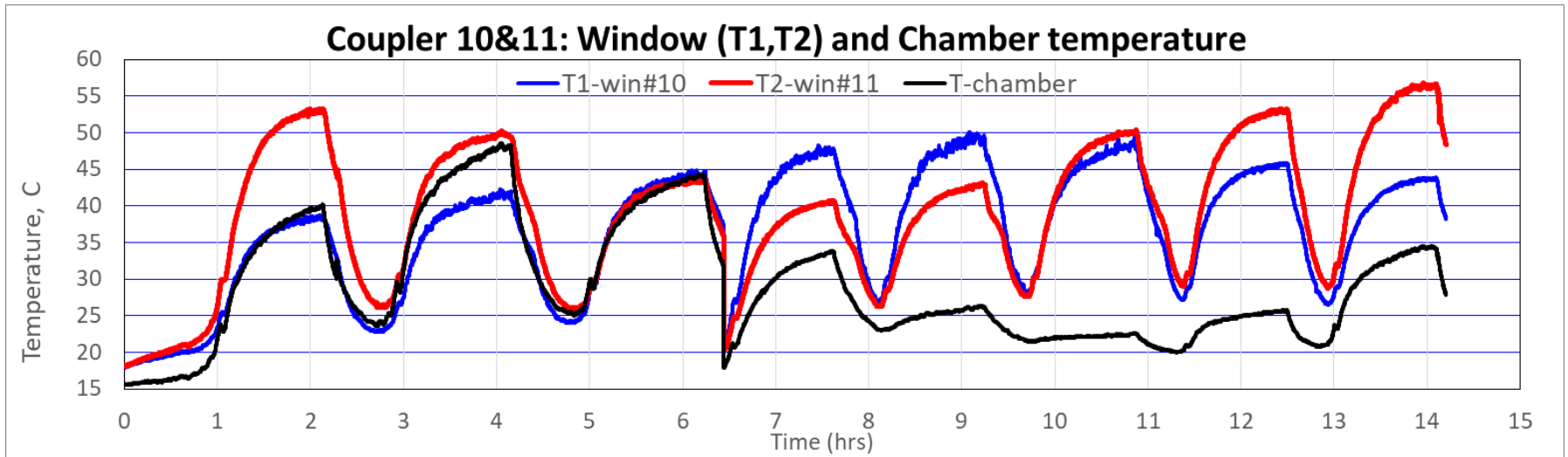


Chamber has min temperature at  $\phi=225^\circ$

# Coupler 10&11: Power and Vacuum



# Temperatures (10 & 11)



# Summary of MP activity with bias on

## MP vs. phase. Test with bias

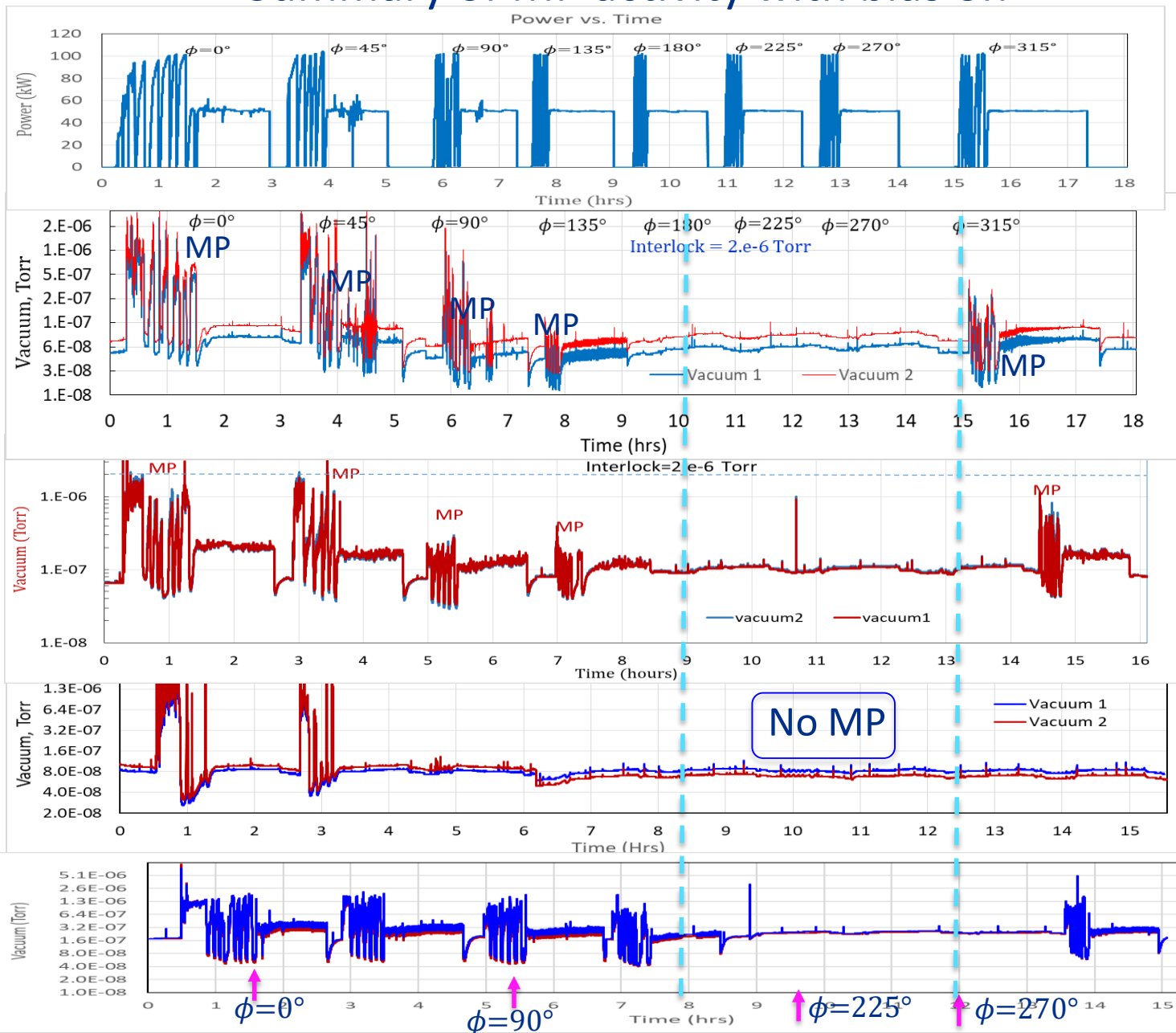
RF power (2&3)

Coupler 3+4  
Chamber#2  
vac=8.e-8 Torr

Coupler 5+6  
Chamber#1  
vac=1.e-7 Torr

Coupler 8+9  
Chamber#2  
vac=8.e-8 Torr

Coupler 10+11  
Chamber#1  
vac=2.e-7 Torr

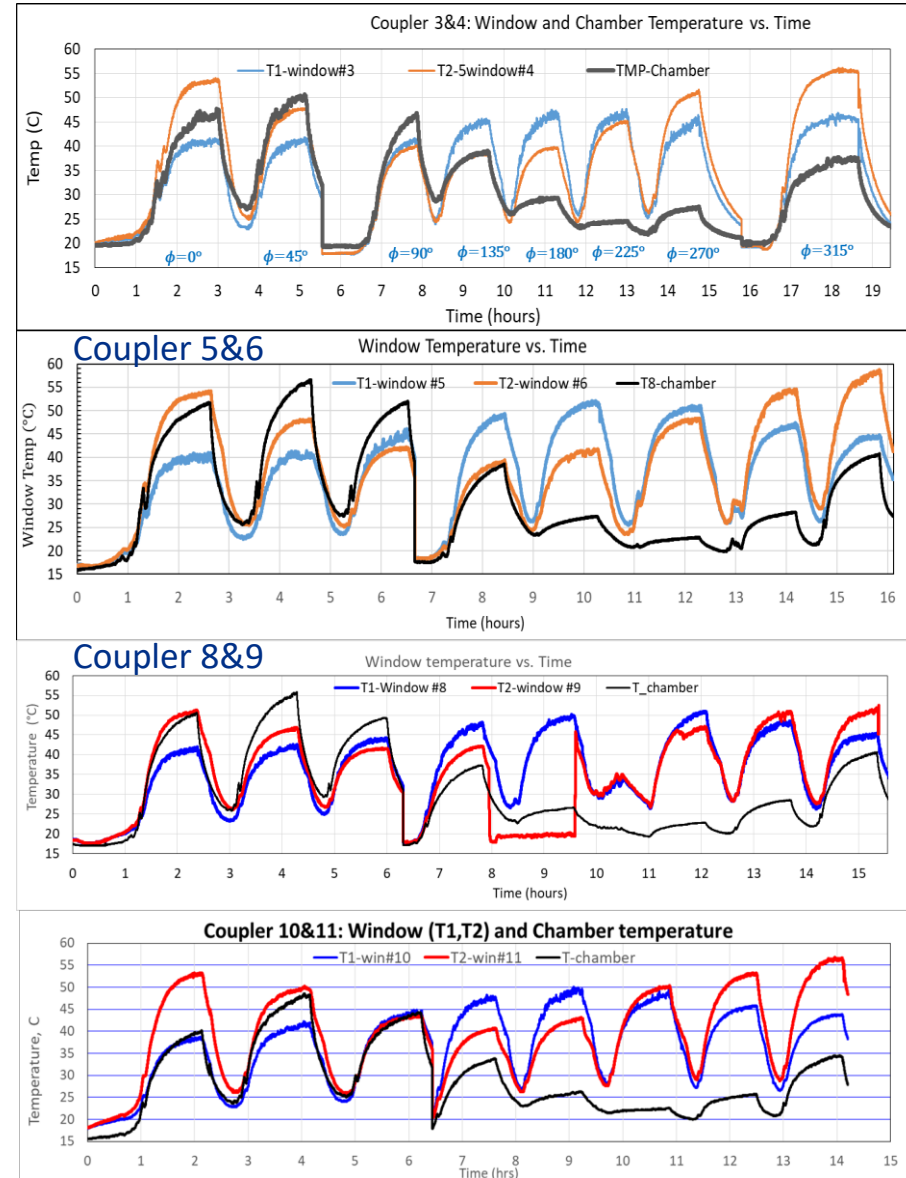


# Window temperature at 50kW cw

Phase~180°    Phase=315°

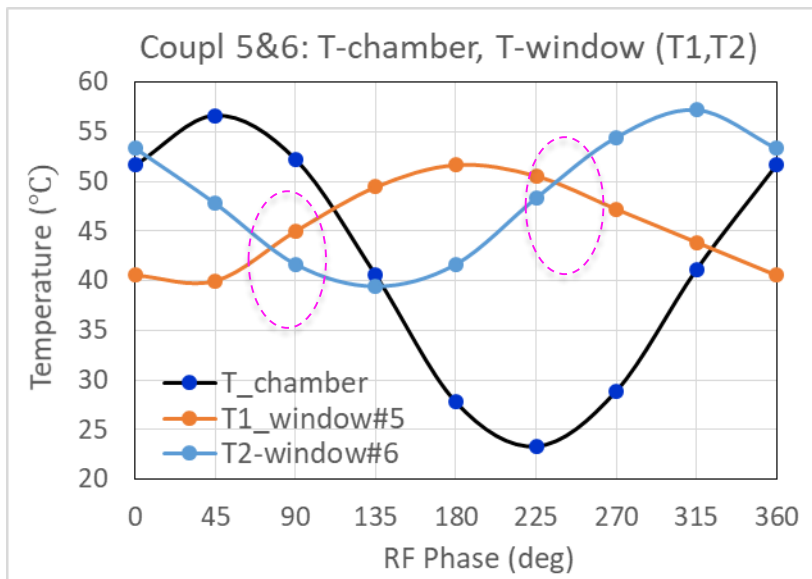
- 1&2, chamber#1: T1=50°C, T2=56°C
- 3&4, chamber#2: T1=47°C, T2=55°C
- 5&6, chamber#1: T1=52°C, T2=58°C
- 8&9, chamber#2: T1=50°C, T2=52°C
- 10&11, chamber#1: T1=50°C, T2=56°C

Similar temperature profiles (vs. Rf phase), deviation ~5 deg can be explained by water and air temp deviations

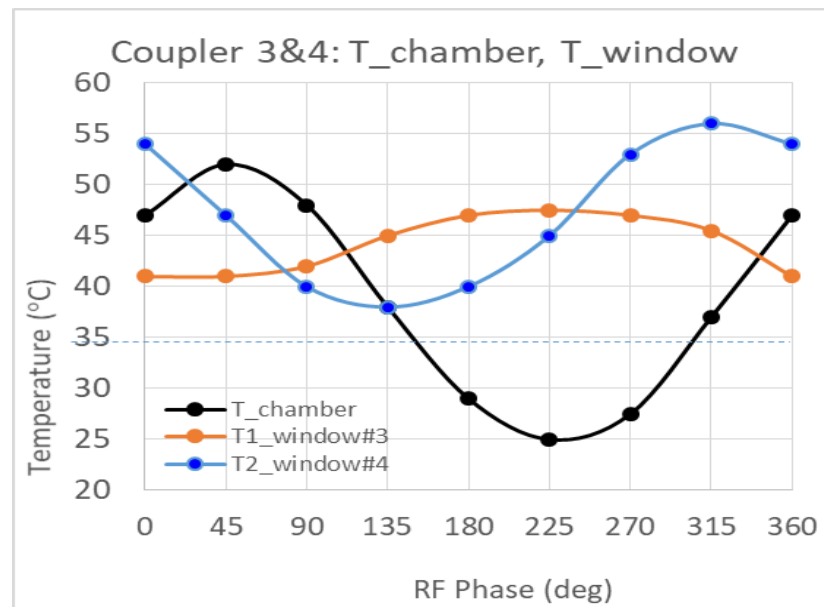
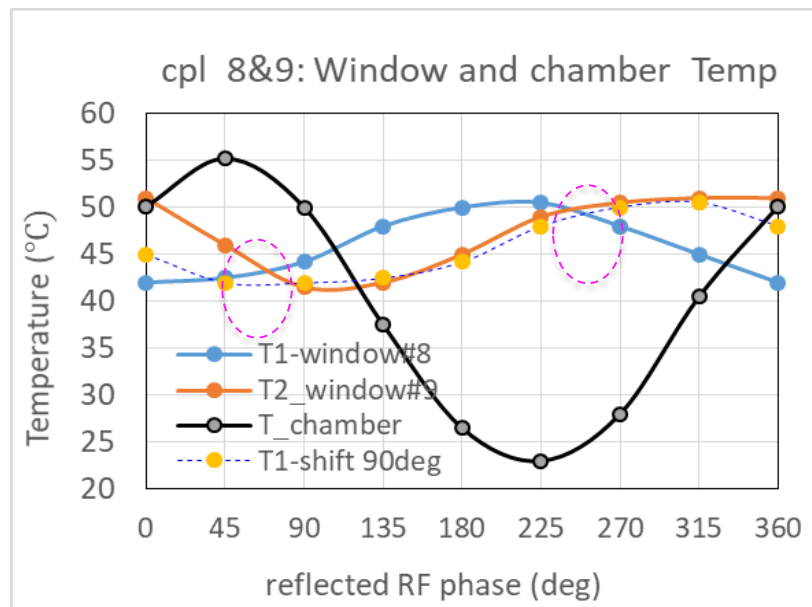




# Coupler: Window /chamber Temp @50kW, cw



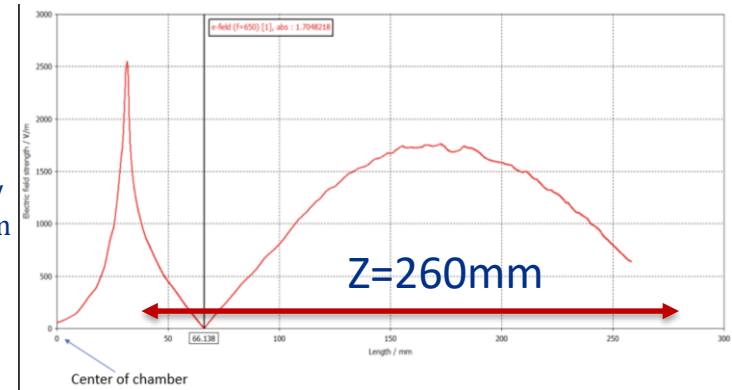
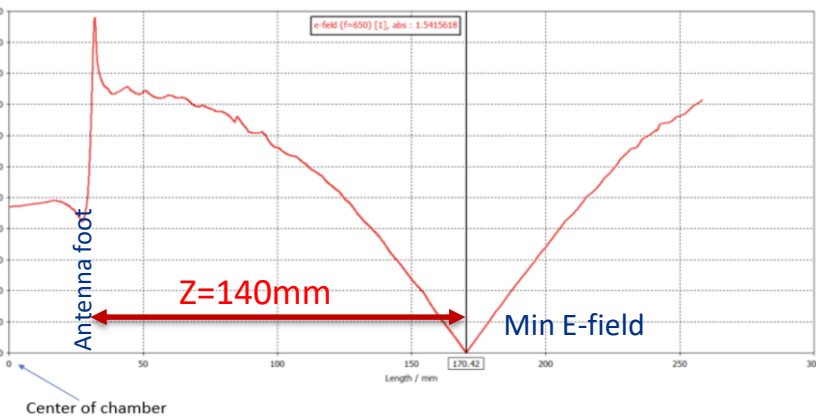
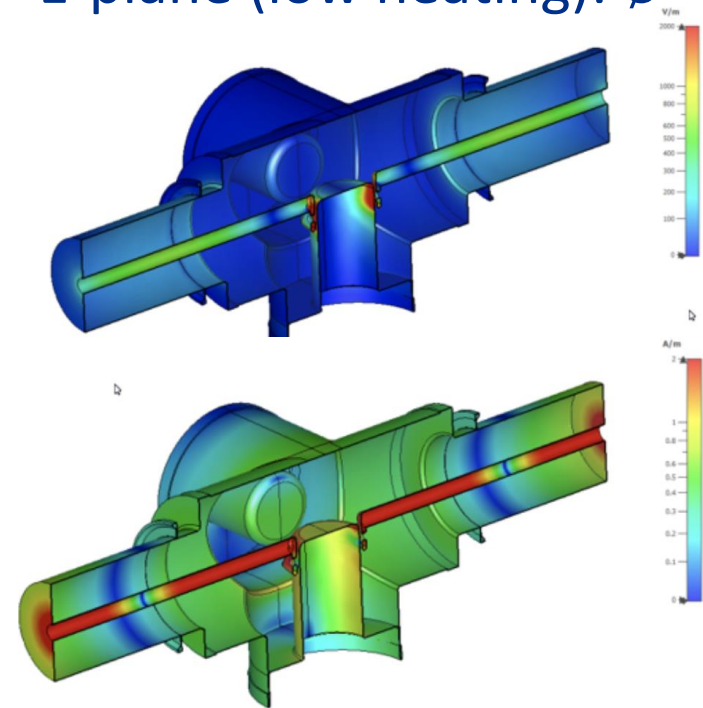
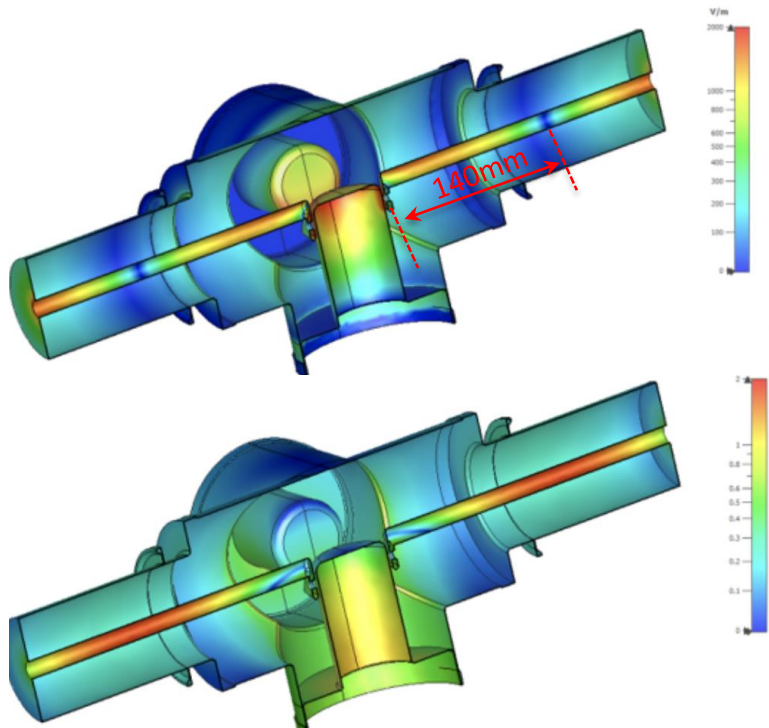
- Temperature variation on windows relatively small ( $\Delta T \sim 10\text{-}20^\circ\text{C}$ ),
- Similar T vs Phase but shifted in RF phase  $\sim 90\text{-}120$  deg.
- Equal temp at phases 60 deg and  $\sim 240$  deg



# Fields in chamber (Simulations)

H-plane (high heating):  $\phi \sim 50^\circ$

E-plane (low heating):  $\phi \sim 230^\circ$

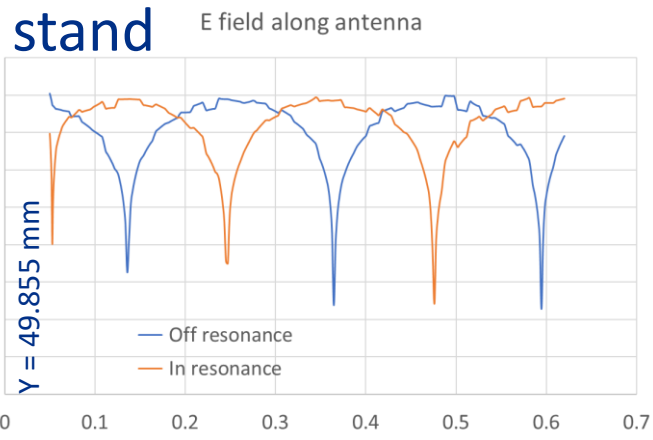
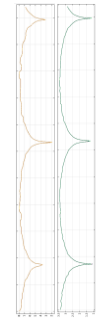


Min shifted by  $\sim \lambda/4 \sim 115\text{mm}$  ( $90^\circ$ )

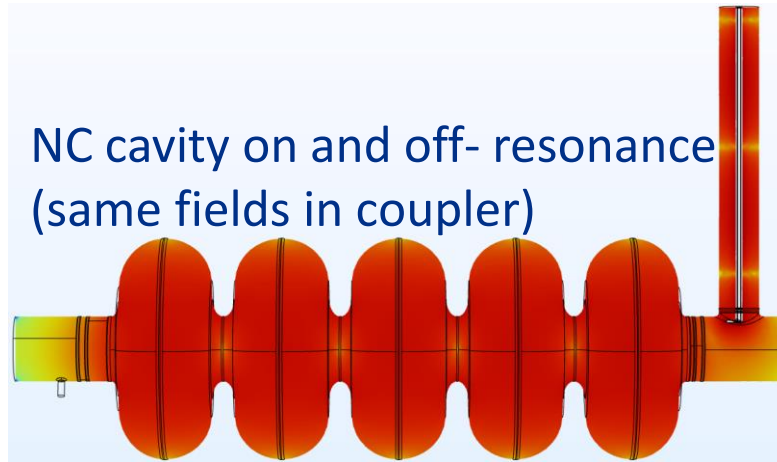
# Reflection phase from SC cavity corresponding phase in coupler test



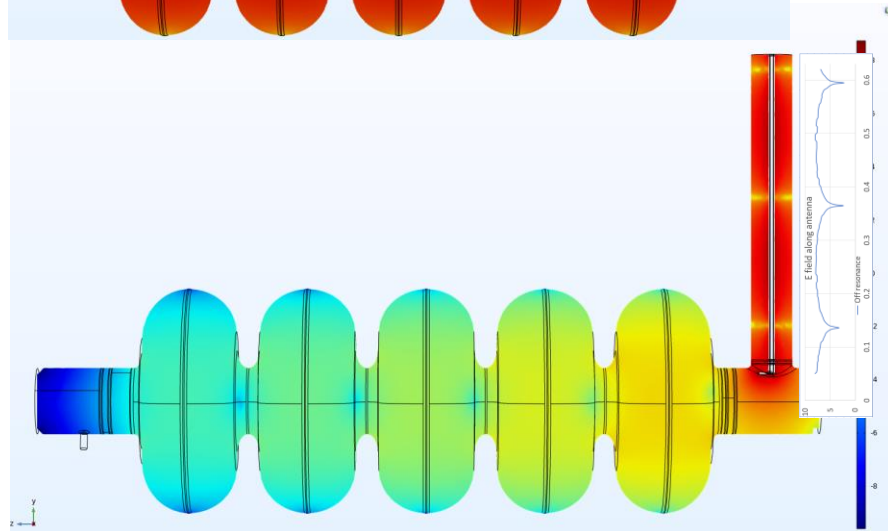
$$\begin{aligned} \phi_{on} &= 325^\circ \\ \phi_{off} &= 145^\circ \end{aligned}$$



NC cavity on and off- resonance  
(same fields in coupler)



	Off-resonance	In resonance
min 1	135.77	247.188
min 2	364.57	475.992
delta	228.8	228.804



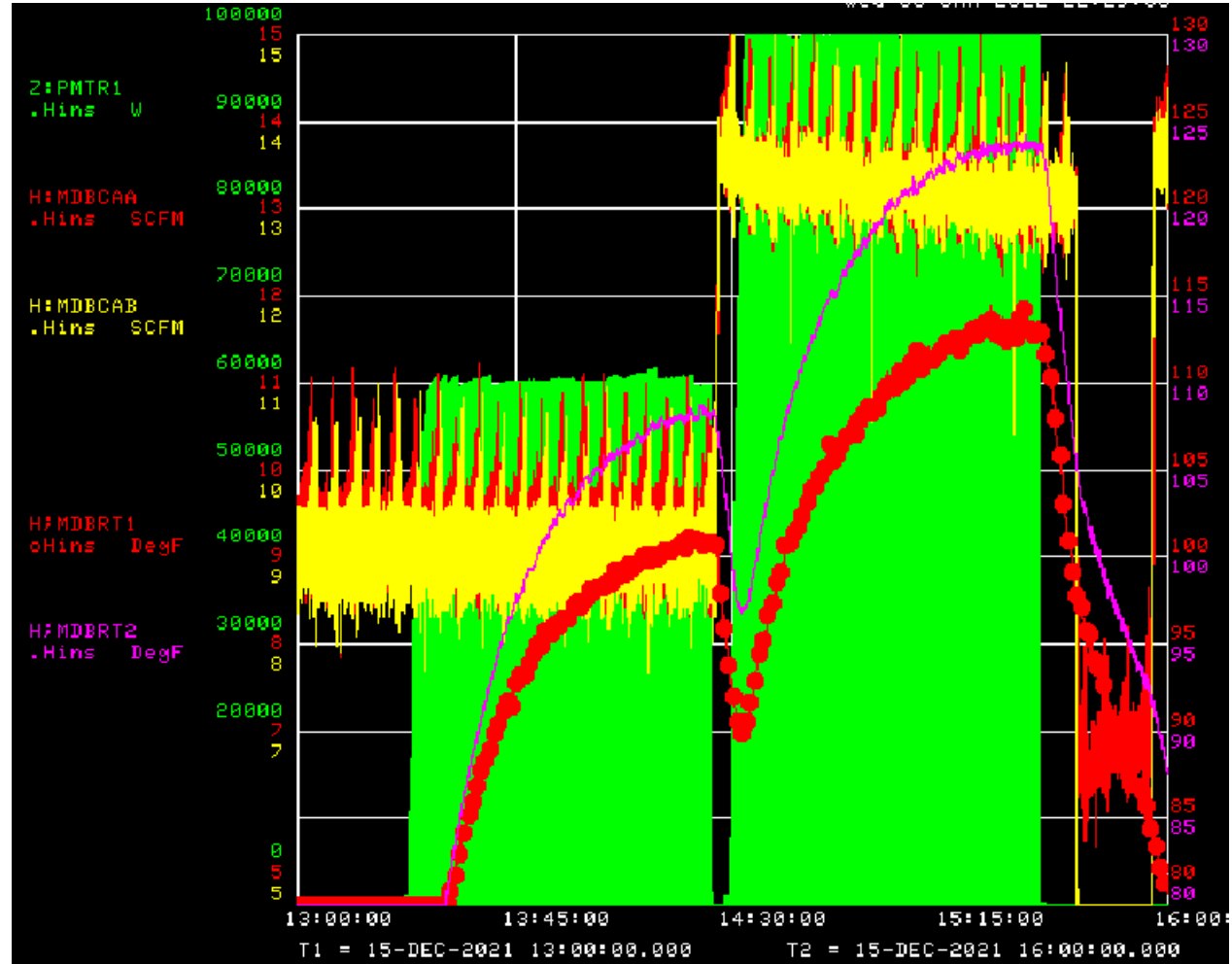
SC cavity in resonance

SC cavity off- resonance

# Window Temp for 50 kW and 30kW in HB650 CM: (Total power 100kW/8.9 SCFM vs. 60kW/13 SCFM)

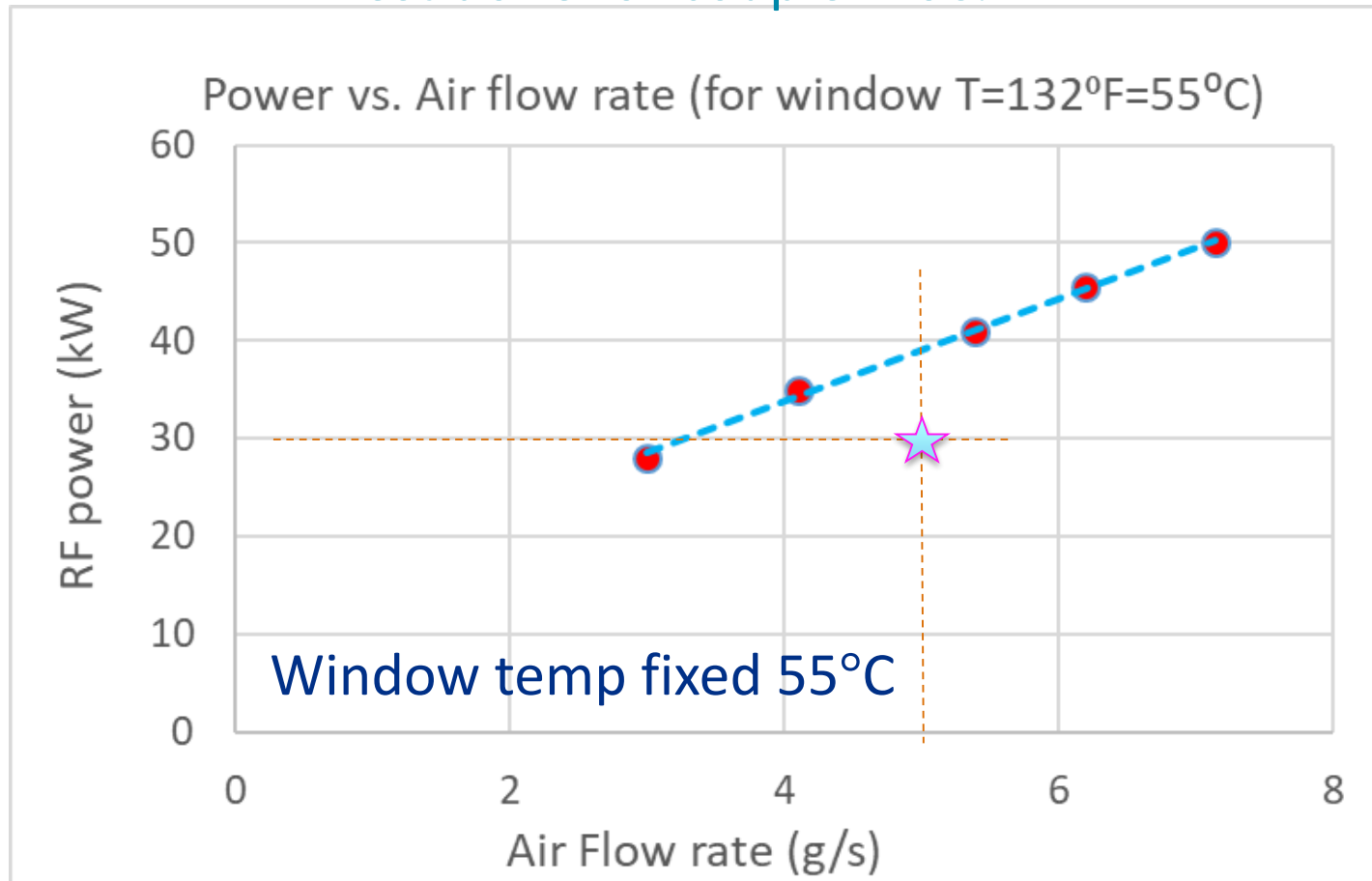
- In test we use max air flow rate  $\sim 13$  SCFM (7.4 g/s)
- TRS: air flow = 8.9 SCFM (5g/s) for  $\sim 50$  kW+20% reflection power (Total 60kW = 30kW at SW)
- For CM temperature will be lower than used in test mode

Green – RF power  
 Yellow/red – Air flow  
 red circle – T1; magenta-T2



# RF power vs. Air rate with T\_window = 55°C

Test done for coupler 10&11



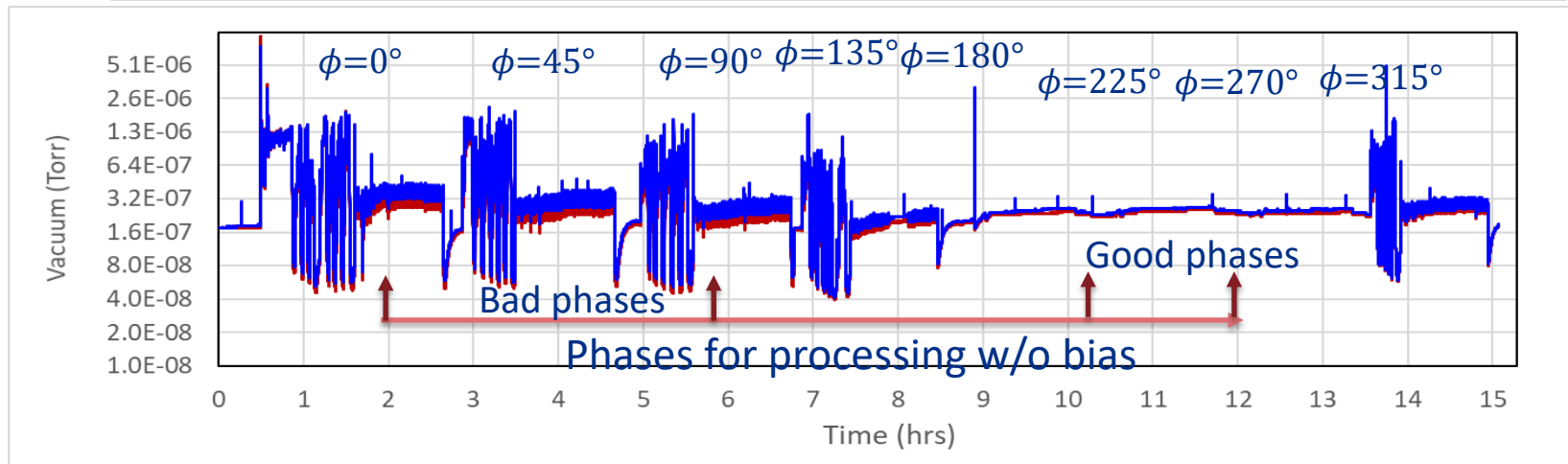
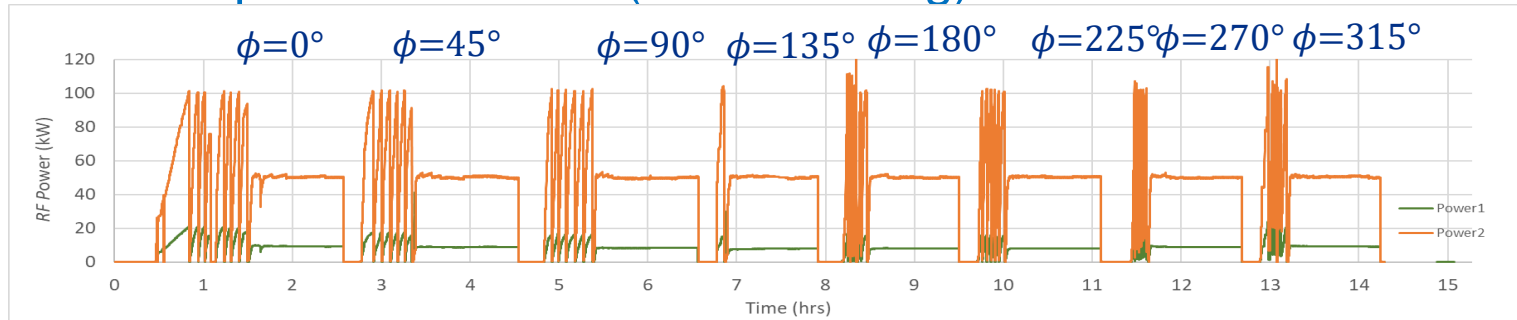
RF Phase = 315 ° (show highest temp on window)

# Power processing of coupler without DC bias

- Recommended by TDR review committee

Done for coupler 10&11 assembly

- Coupler#11 – no bias, other coupler #10 was under bias 4.5kV
- Two good RF phases (225 and 270 deg) and
- Two bad phases with MP (0 and 90 deg)

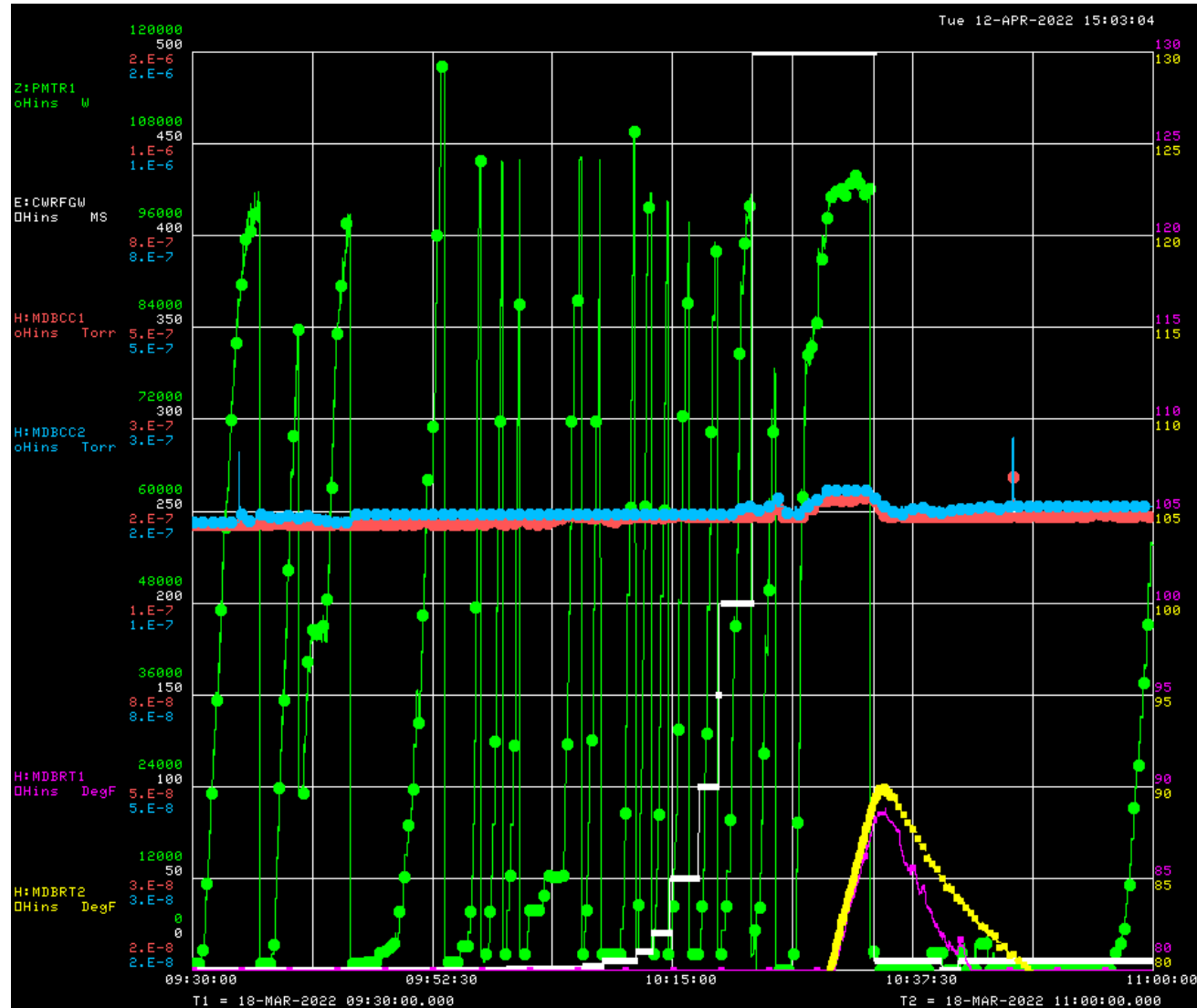


# Good phase=225 deg with no MP (Mar-18-2022)

- Coupler #10 with DC bias 4.5kV
- Coupler #11 with bias tunable from 0 to 4.5kV
- Pulses from 10  $\mu$ s to cw. Power up to 100kW or 50kW at CW

## Results

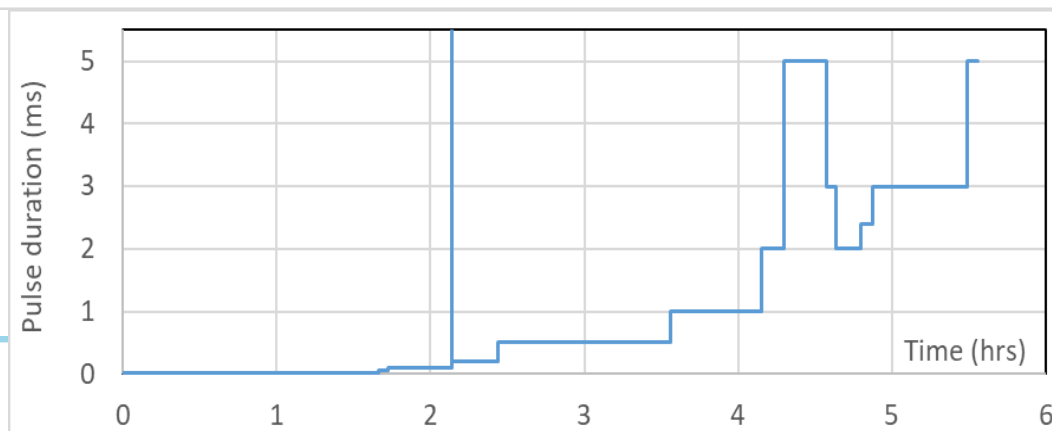
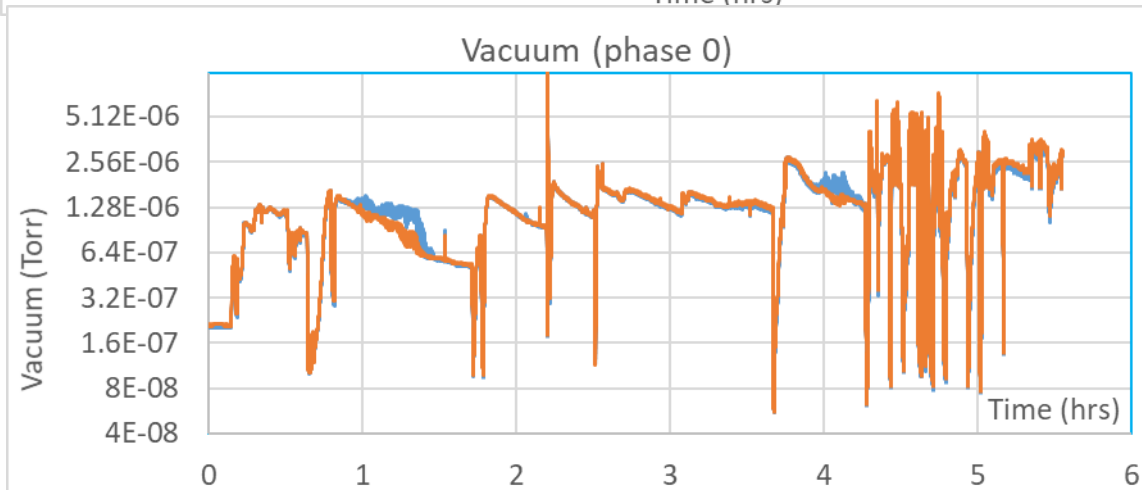
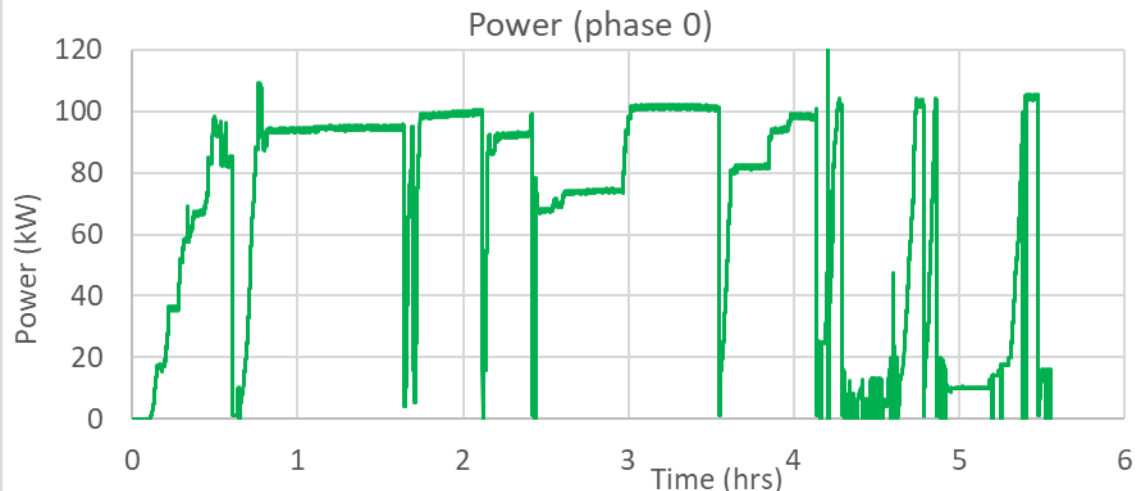
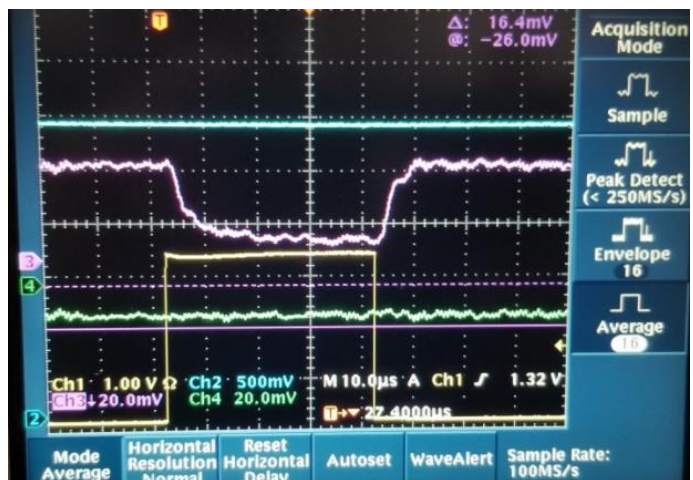
- **No MP** (run ~1 hr)
- Switch bias off on coupler 10. **No MP** in all power range and pulse duration.



Pulses: 10;20;50;100;200;500 $\mu$ s;10;20;50;100;200;500ms.

# Phase=0 (Mar-18-2022)

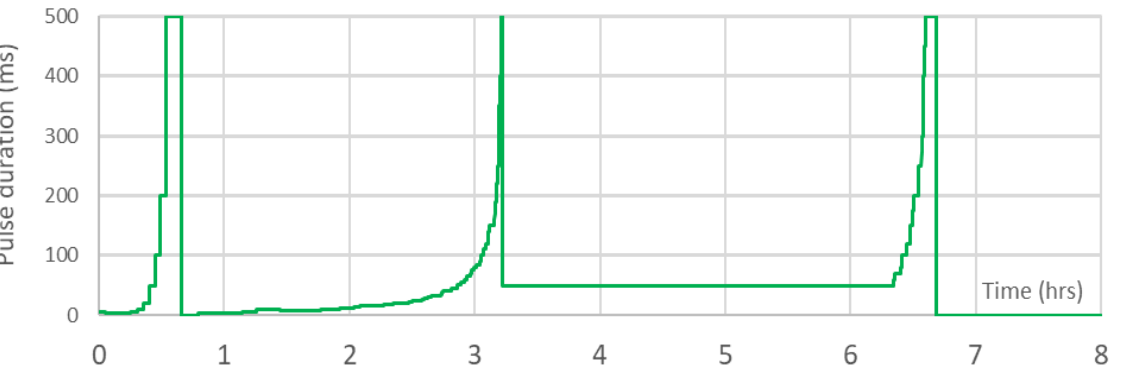
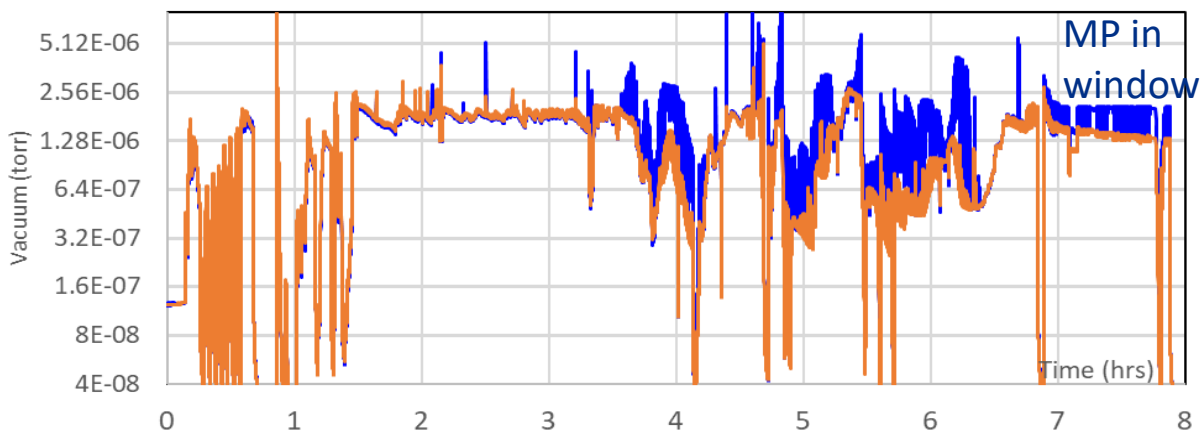
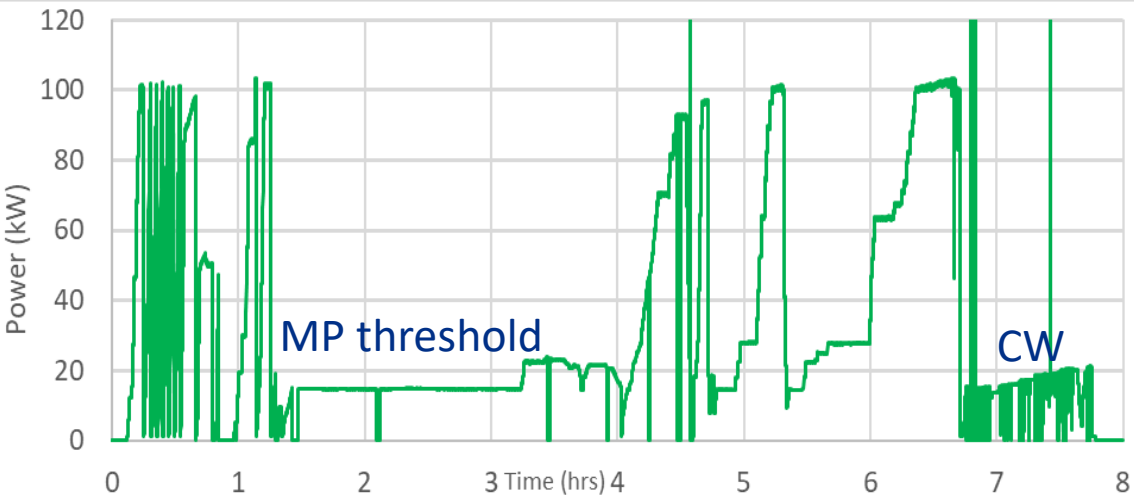
- Coupler #10 bias 4.5kV; coupler #11 - no bias.
- Pulses: 10,20,50,..500us; 1,2,5,...500ms then CW
- MP starts at ~15kW at 10  $\mu$ s.
- Slow progress up to 5ms that day
- Beam loading (80kW w/o bias vs. 100KW with bias)
- E-probe shows MP activity





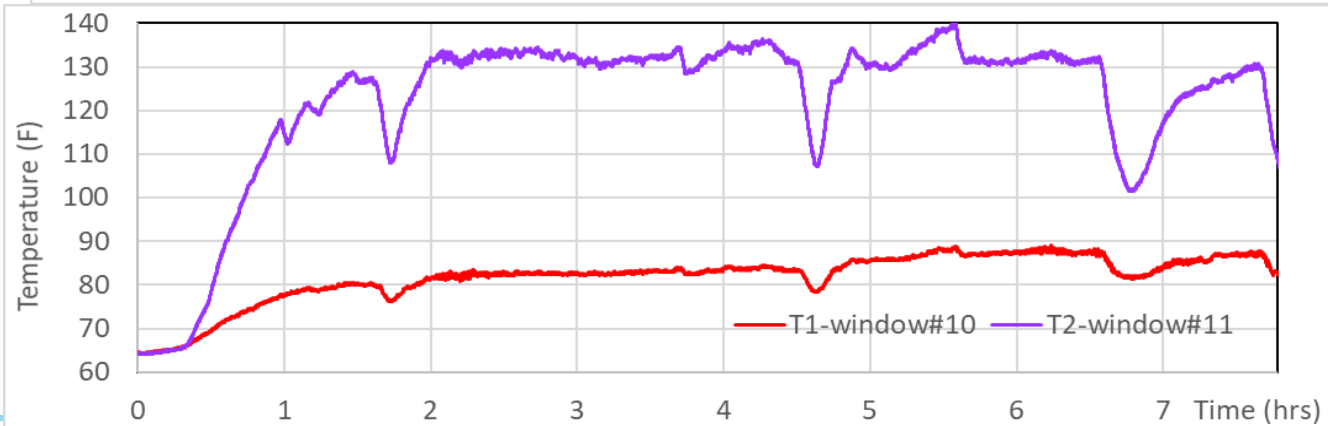
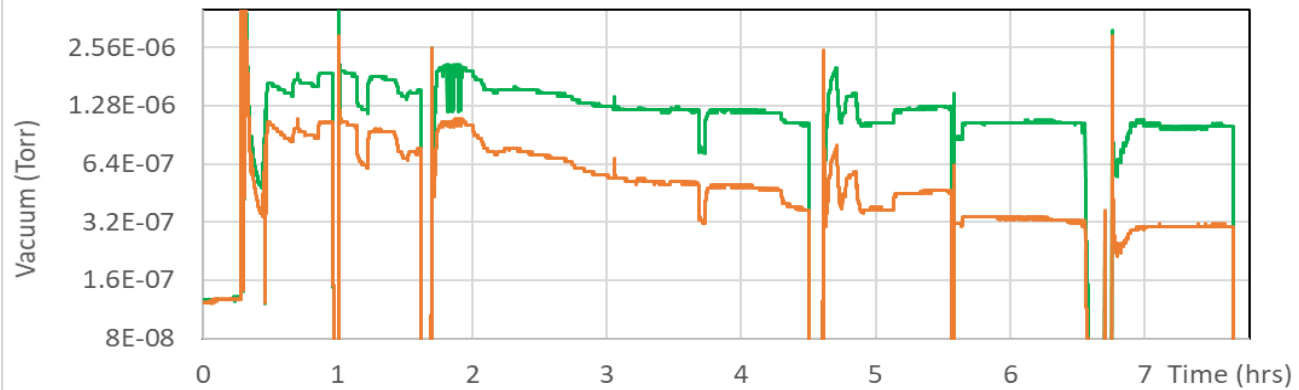
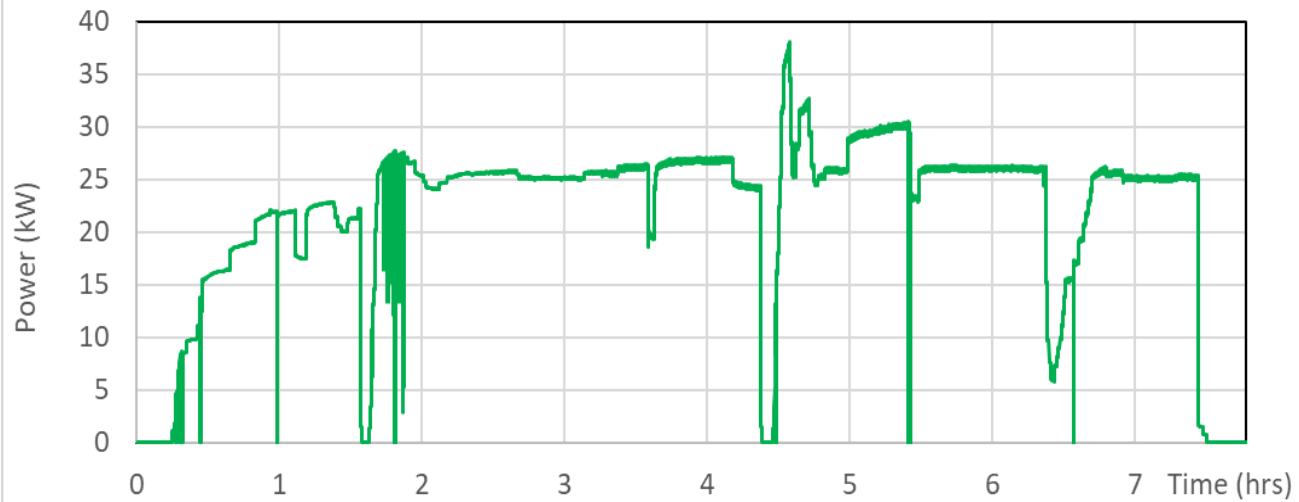
# Phase=0 w/o bias (continue Mar-21-2022, 9am).

- Start with 3kV, ~20min
- Then w/o bias, keep vacuum near interlock threshold 2e-6 Torr.
- MP levels from 15kW to 69kW, no MP above 70kW.
- In CW mode MP all way from 15 to 23kW.
- Vacuum is different in coupler 10 and 11 (signature of MP in coupler)



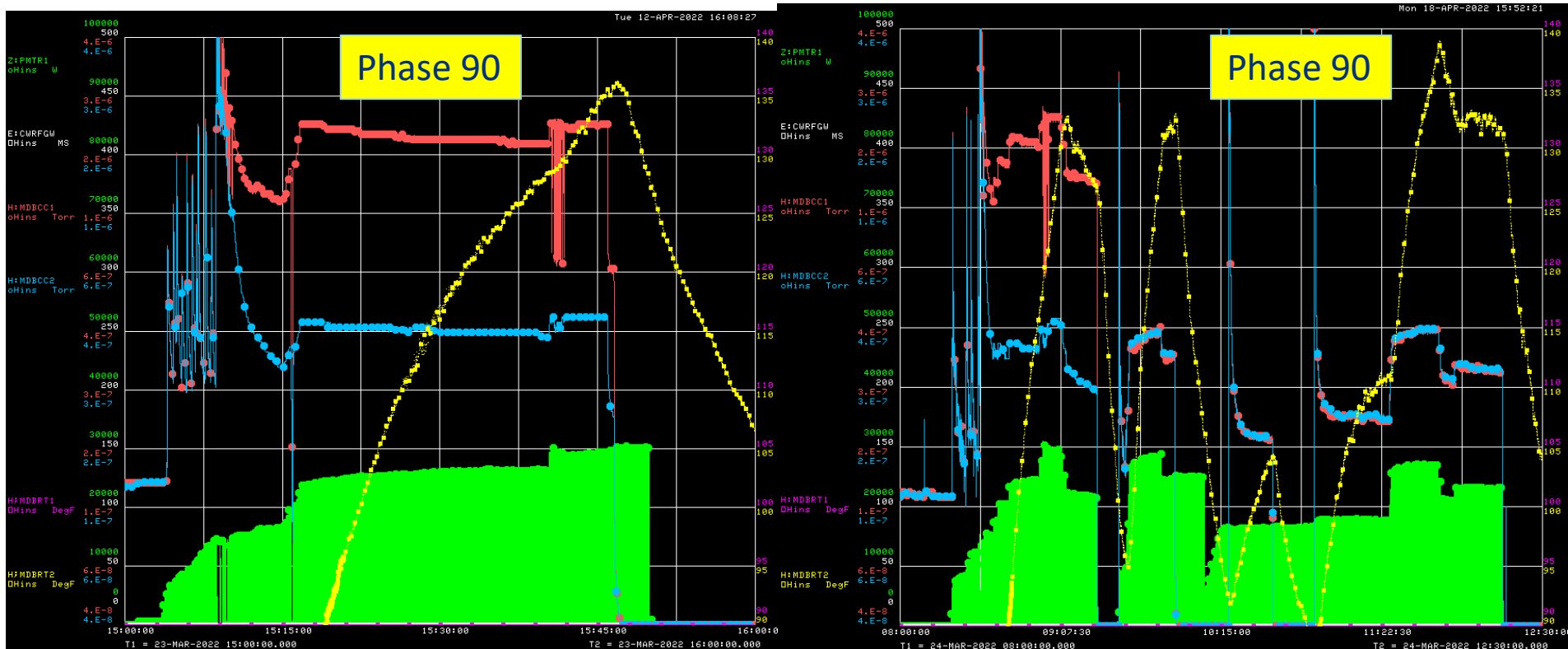
# Phase 0 deg at CW: Slow processing (cont. Mar-22).

- Bias 4.5kV at coupler#10, no bias on coupler#11
- CW only
- Slowly increase power up 25kW, MP threshold=15kW
- Vacuum improved but limitation is **window temperature at #11**. Keep it below 132°F (55°C). Interlock T=150°F
- Vacuum is different in coupler 10 and 11 → **MP in window**



# Phase 90 degrees, CW. Overheating of window due to MP

- Bias 4.5kV at #10, No bias at #11,
- Slow progress in CW mode (no pulse mode). Reached 30kW.
- Strong heating of window#11 (T~135F at 23kW, expected ~112F at 50kW)
- Vacuum #10 and #11 is different.

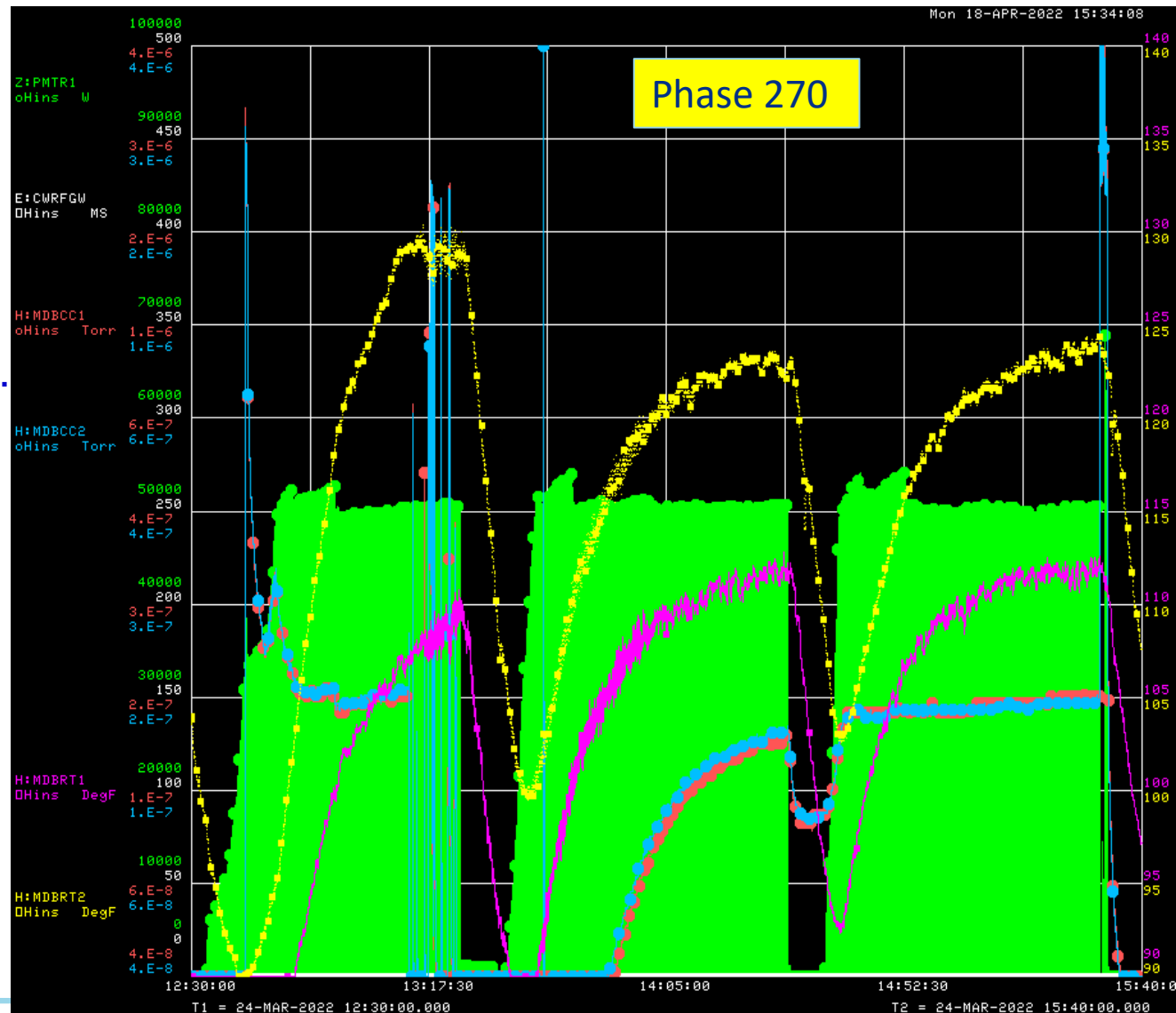


# Phase 270 degrees, CW (March 24). Magnets

- Bias 4.5kV on #10, no bias on #11
- Run1: MP starts at 33kW. Higher temp at #11 window
- Run2: SmCo magnets on. Temp and vacuum is OK.
- Run3:
  - Bias #11 is ON.

Reached 50kW cw with minor MP activity →, Vacuum <2.e-7 Torr, (same as w/o RF power).

MP outgassing improve vacuum



# Studies with magnetic field to suppress MP

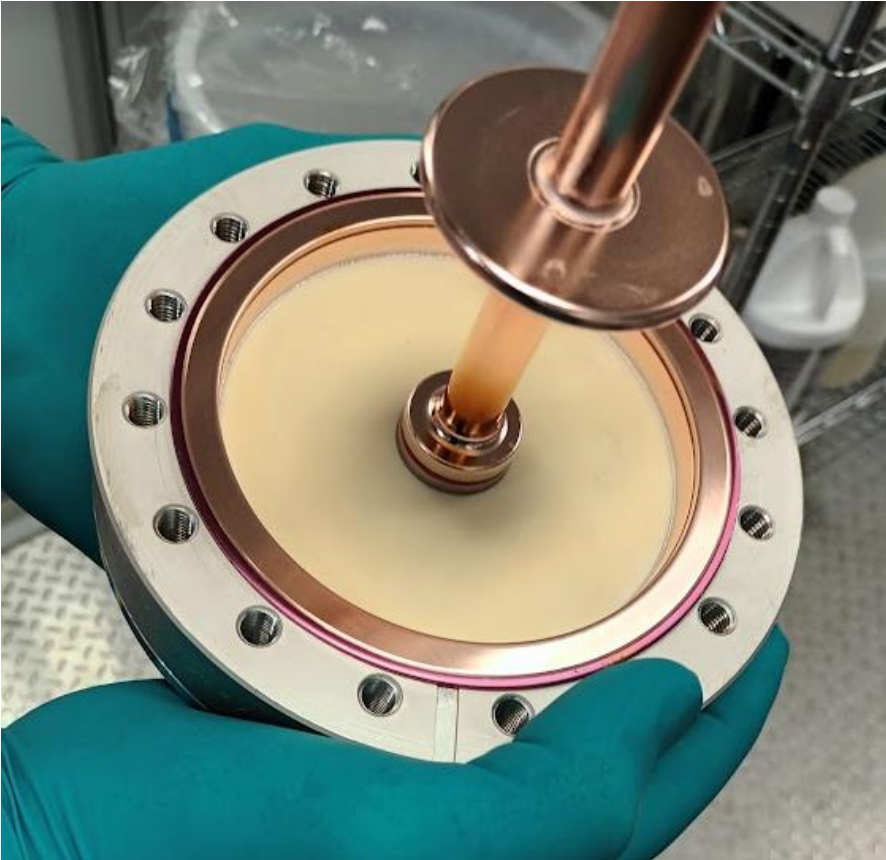
- Configuration  $45^\circ$  , as worst for MP (also  $90^\circ$  and  $270^\circ$ )
- Achieved  $\sim 25\text{-}30\text{kW}$  in CW:
  - MP in window, can be suppressed by SmCo magnets or bias
  - With MP beam loading effect (power drop, when MP)
  - Also vacuum in coupler w/o bias is higher (asymmetry)
  - Bias 3kV completely suppress MP in window, not in chamber
  - Progress is very slow, since ceramic has no TiN coating

## Conclusion from studies:

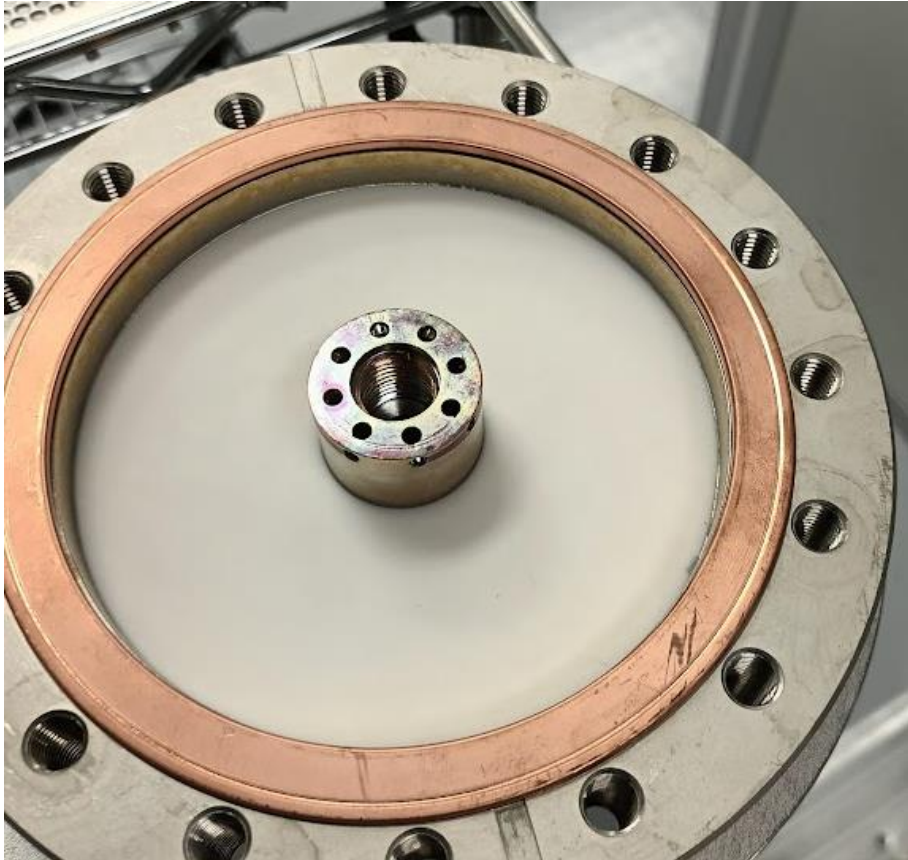
- MP exist in window and in chamber.
- Attempts to suppress MP in chamber by applying magnetic field was failed.  
(Switching magnet ON causes jumping in MP activity in chamber )

Need more MP simulation to explain.

# Coupler #11 window after processing w/o bias

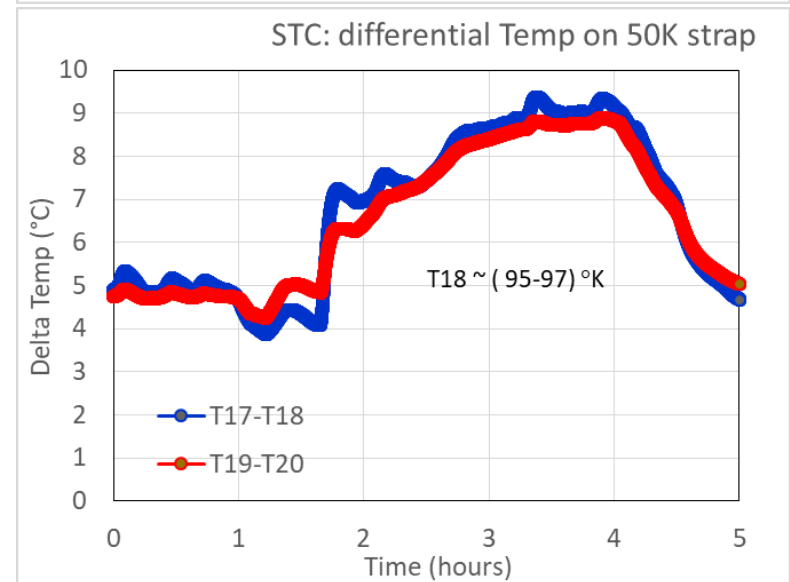
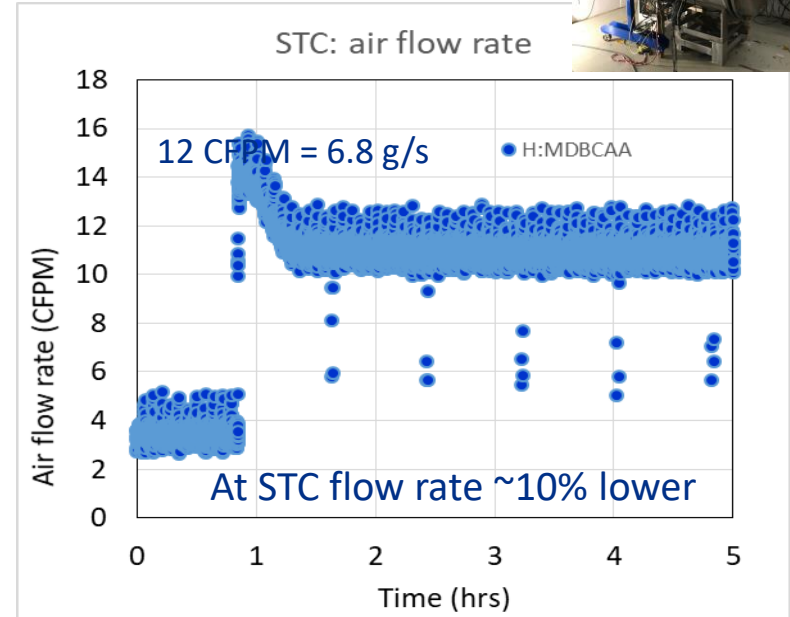
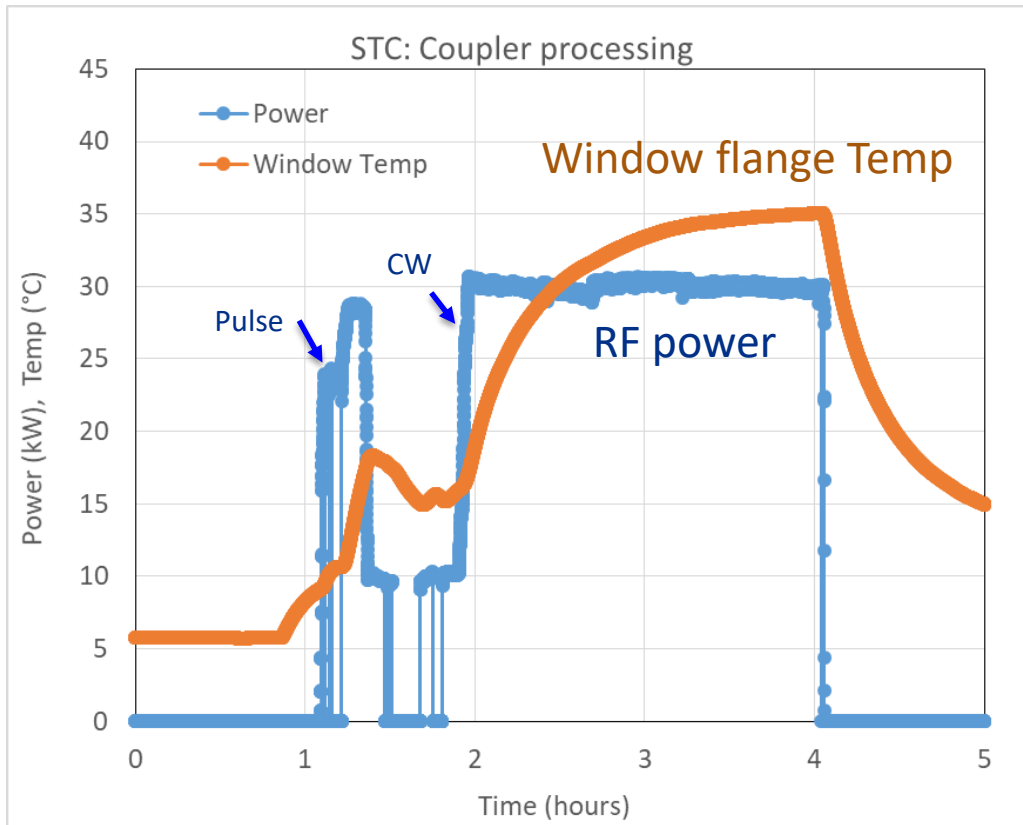


Vacuum side of ceramic after processing w/o bias



Air side of ceramic after processing w/o bias

# STC: Coupler conditioning test



## Conditions:

- HV = 4.5kV
- Air flow
- Flange heater = 6W
- $\Delta T \sim 7^\circ\text{C}$  when air flow rate increases from 4 to 12CFM

# Coupler conditioning summary

- Couplers 1&2; 3&4; 5&6 8&9 and 10&11 were tested successfully at the test stand with the bias, no MP up to 50kW cw after processing. Pulse processing >50kW helps to clean surface. MP configurations: (phase 0, 45, 90, 135, 315)
- Window flange temperature not exceeds 60°C (stress limitation for ~0.1 Mcycles) for 50kW CW. For operation conditions: P<30kW, air flow 5g/s, expected flange temp < 45°C
- HP processing w/o bias is possible and useful for surface cleaning. HP processing procedure need to be develop to protect ceramic from contamination:
  - Reduce power to 30kW, eliminate regimes where MP located in window, better baking of chamber and couplers. TiN coating of ceramic may help.
- First STC test of LB650 cavity with coupler is done. Coupler works well up to 30kW available power. Detail measurements on coupler is planning