Circulator Tracking

Software Controlled Circulators for 80.5 MHz Power Amplifier System

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FRIB

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Motivation

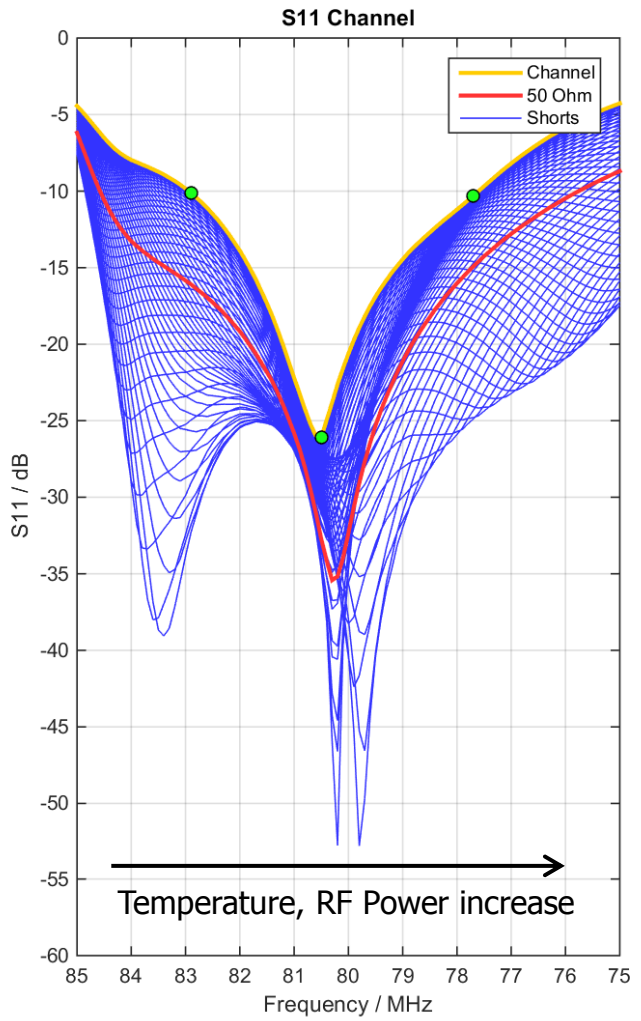
- High power amplifier system for 80.5 MHz linear accelerator was developed in cooperation with Facility for Rare Isotope Beams (FRIB) of Michigan State University in East Lansing, Michigan, USA.

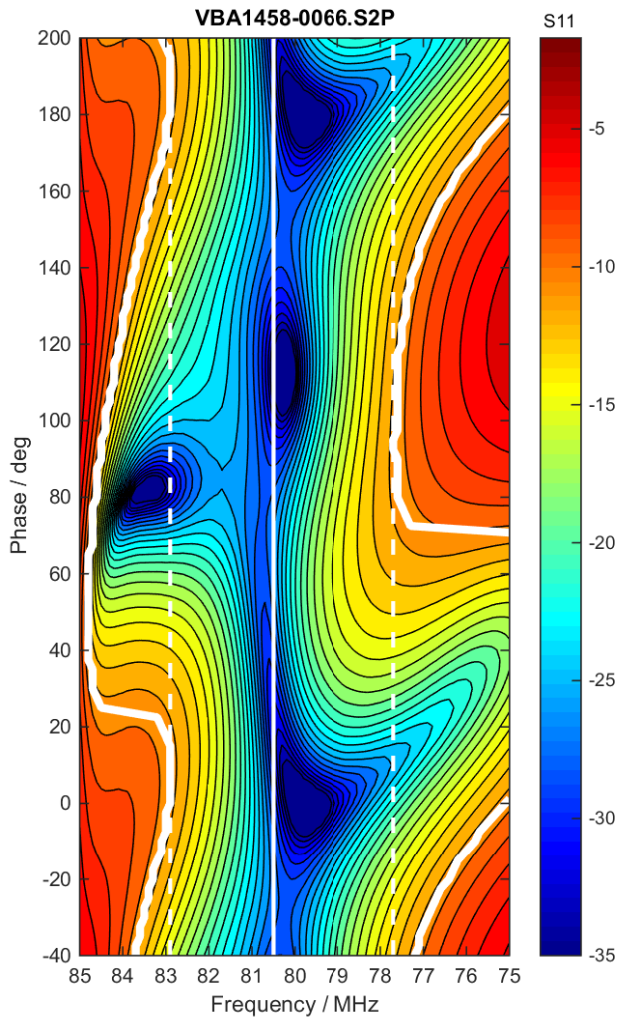
- Protection of the amplifier transistors is necessary because of 100% reflection requirement at any phase angle – Long term CW operation under full power

- At low frequencies circulator return loss, insertion loss and isolation change dramatically with temperature and RF power

- **No practical solution at this frequency available prior to this amplifier development**

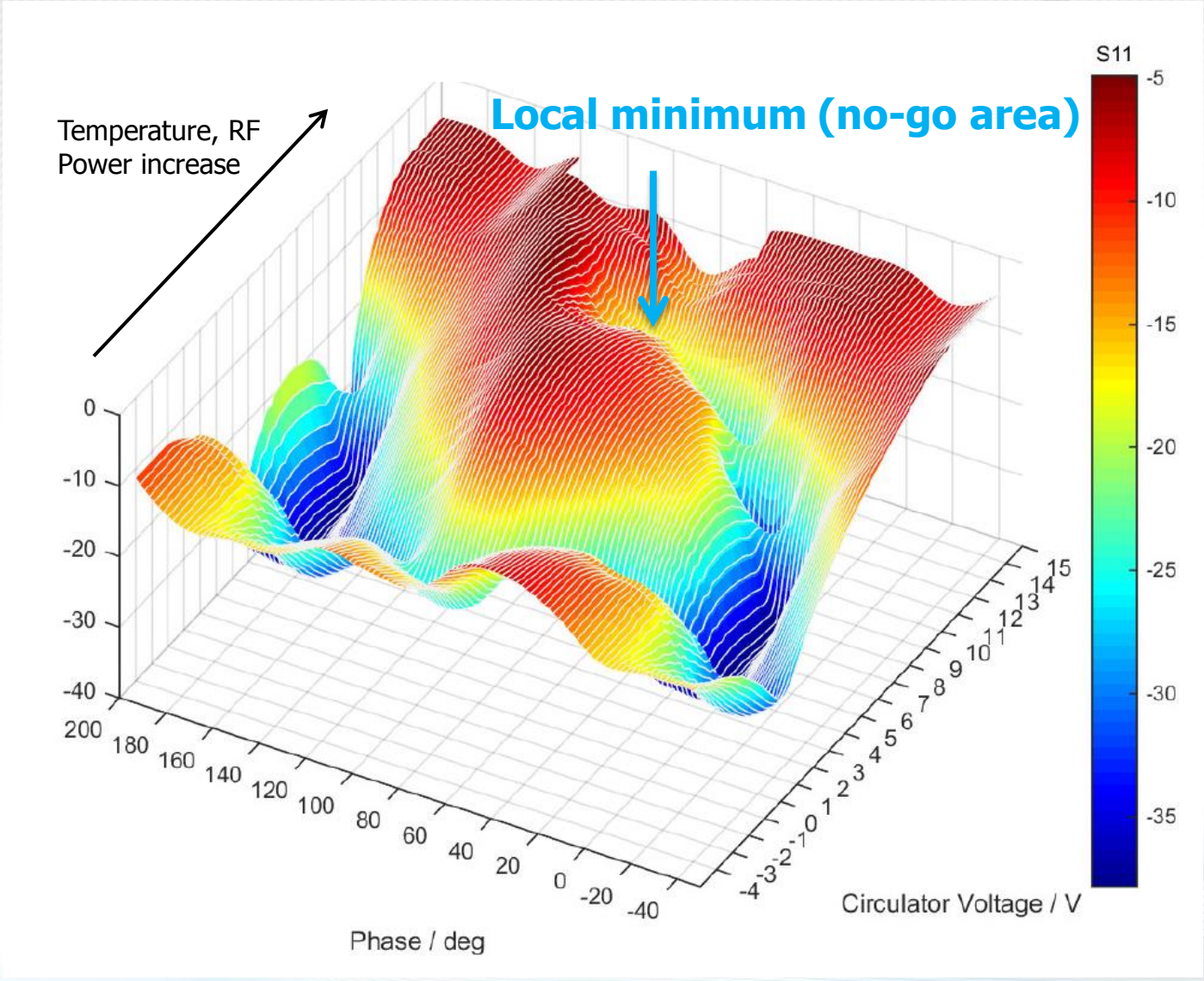
Circulator Characterization – Small signal



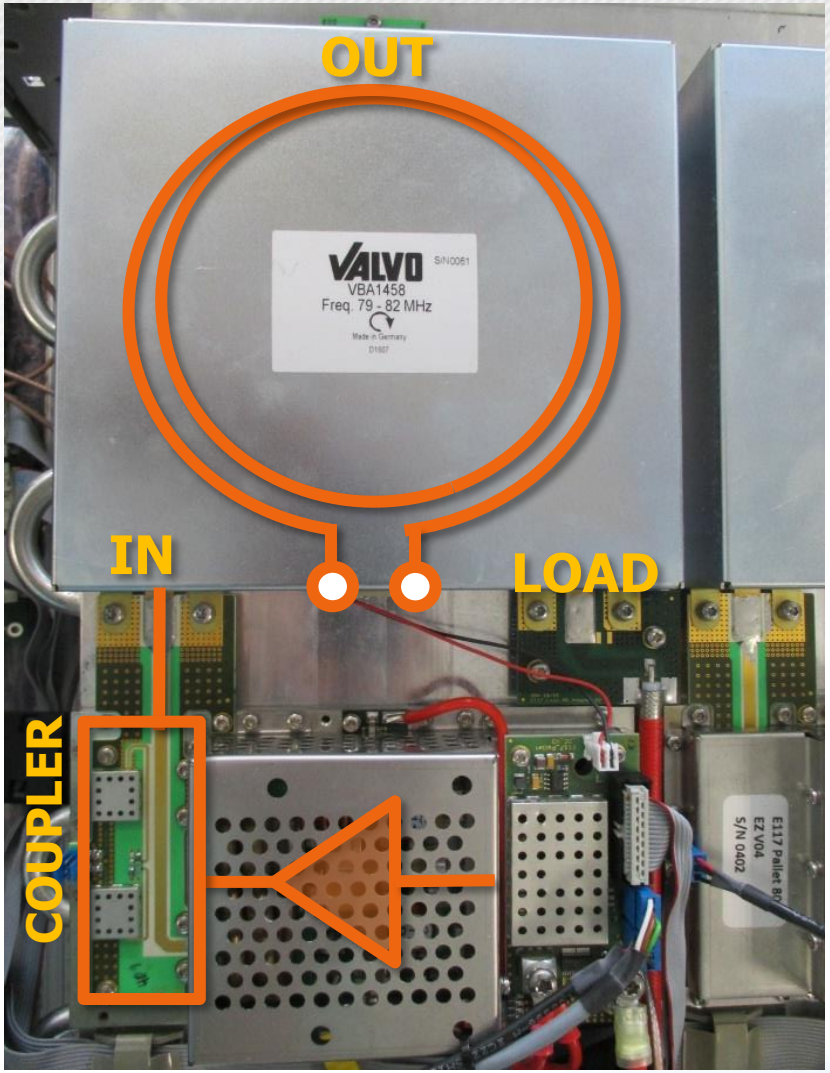


S11 from Real Circulator and Isolation Effect with full reflection

Circulator characterization - 3D view, Large signal



Circulator tracking solution



Circulator specifications:

Frequency : 79 – 82 MHz

Isolation: min 25 dB (@ center frequency)

Insertion loss: max 0.4 dB (@ center frequency)

VSWR: 1.12

Power: 1600W CW forward, 1200W CW reflected

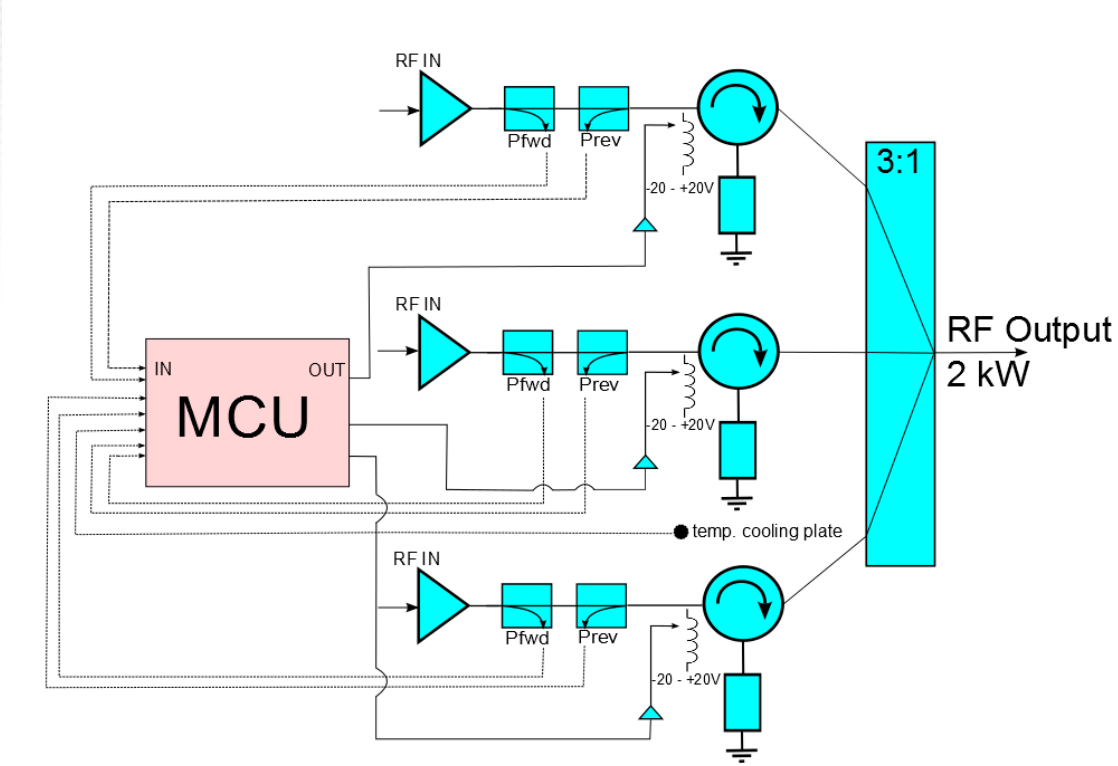
Temp. Range: 0…+60 ° C

Dimensions: 150x160x42 mm

System Overview

8kW AMPLIFIER

2kW UNIT Setup



MCU – Microcontroller unit

Limits of the tuning voltage - Channel of safe operation

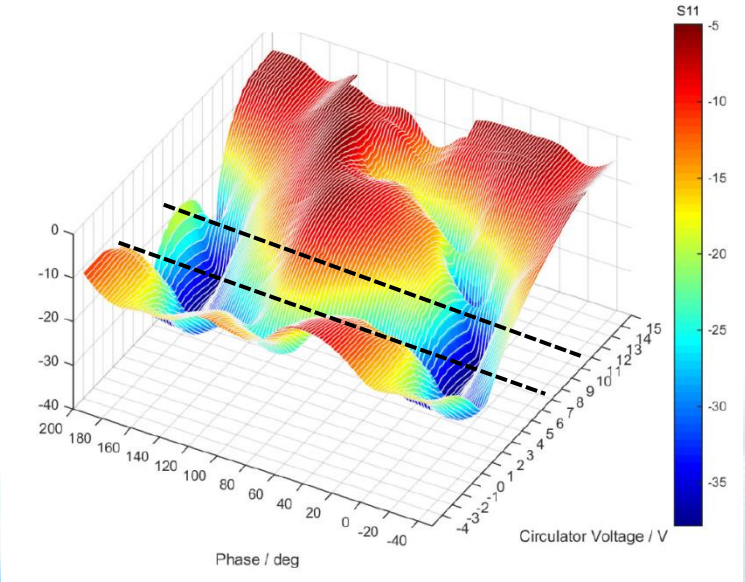
Channel of safe operation with -13 dB as the limits, temperature held constant

Channel of safe operation

- Limit of the channel mathematically defined from a calibration measurement

  Upper Limit = Maximum – RF Factor(P_FWD) – Temp Factor(T)
  Lower Limit = Minimum – RF Factor(P_PWD) – Temp Factor(T)

  - Limits are dynamic because circulator behavior changes with RF power and temperature
- Equation coefficients saved into EEPROM of the microcontroller (Factors are nonlinear equations)



Software Control

- Circulator tracking is realized with software code running on a microcontroller

- Input parameters
  - forward and reverse power at the input of circulator (Calculates S11)
  - Temperature of the cooling plate (water temperature)

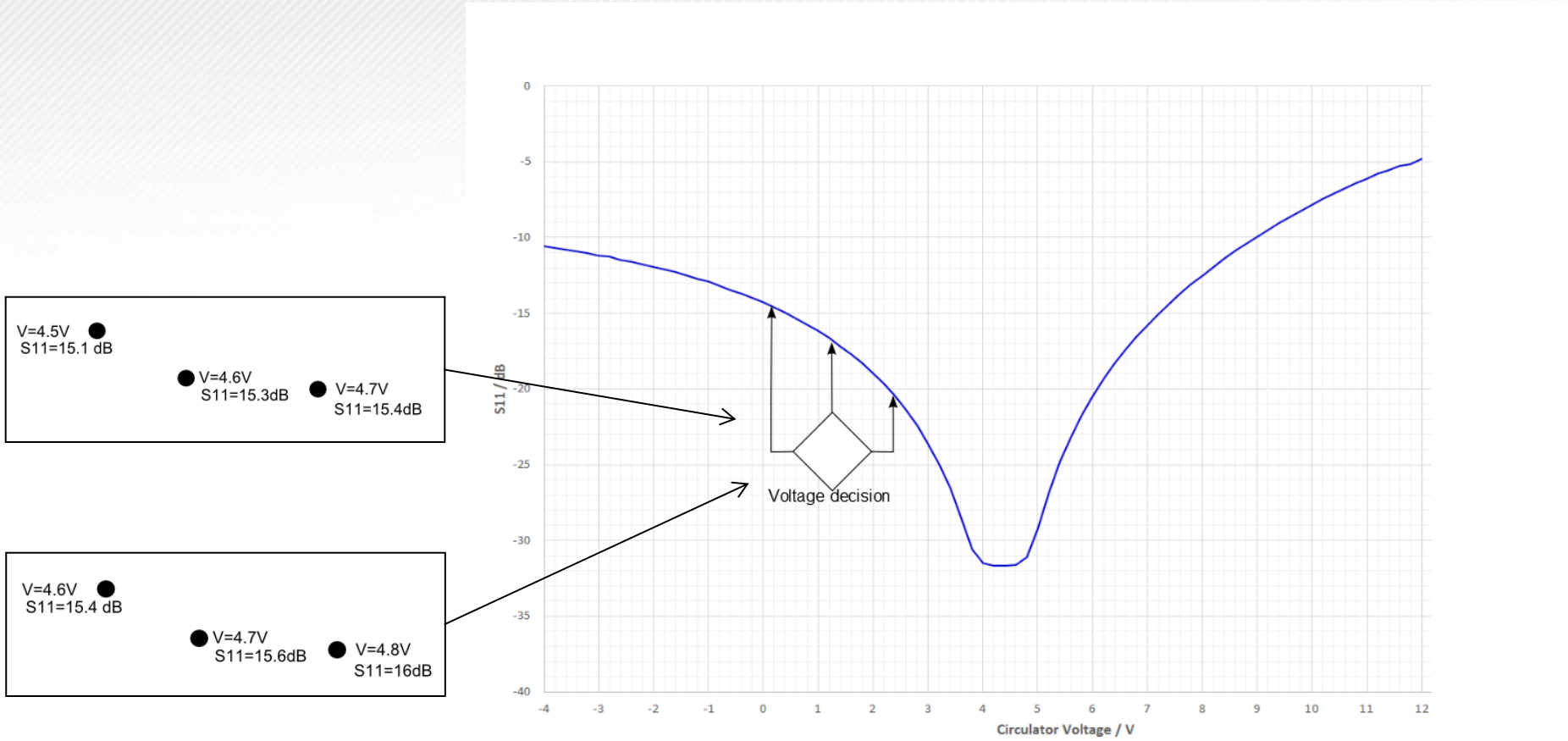
- Output parameters
  - Microcontroller generates tuning voltage for the optimal S11 of the circulator

- Goal is keeping S11 as low as possible
  - 0% to 100% reflection termination at any phase

- Temperature compensation when RF is off
  - Allows a good start voltage at power-on moment

Tracking Algorithm

– When S11 moves with temperature or RF power, voltage moves accordingly, speed of decision process is 200ms



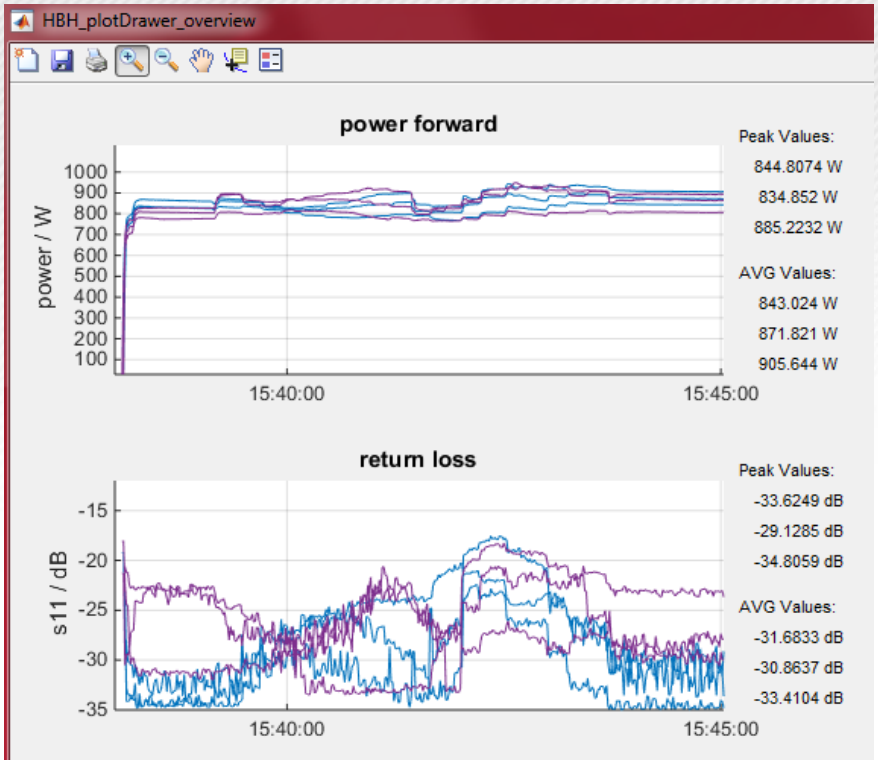
Tracking Algorithm

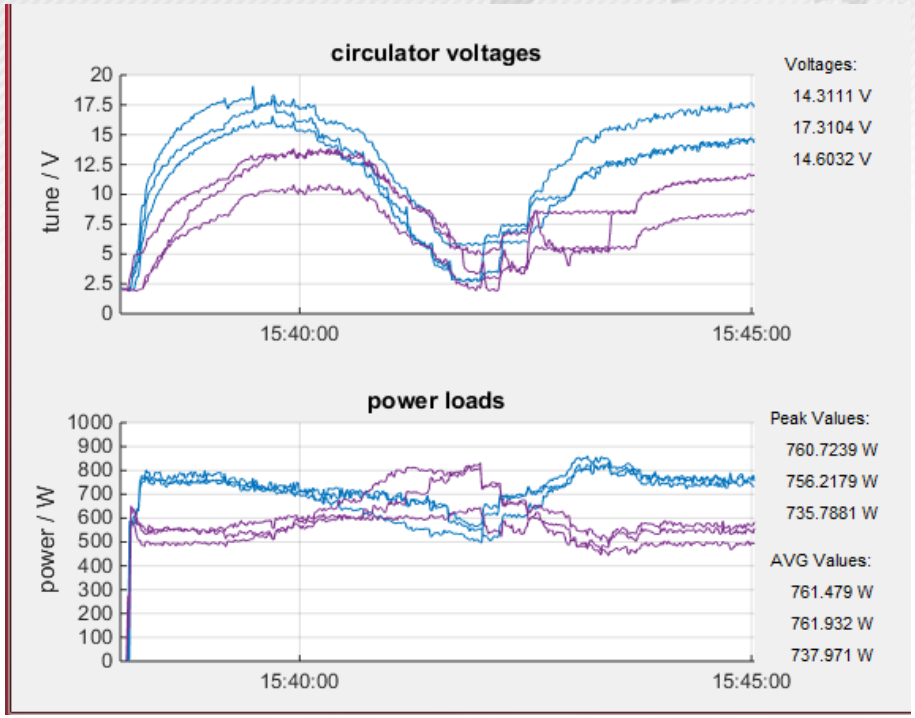
- **RF Power tracking**
  - RF power change causes quick changes in the required voltages
  - Implemented with S11 information from directional coupler

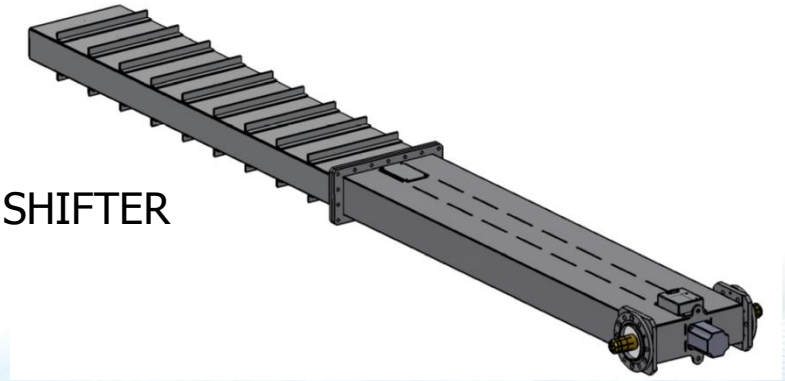
- **Temperature tracking**
  - Implemented with heat sink temperature sensor data
  - Defines starting point voltage when RF power is off
    - If set wrong, circulators S11 can be almost 0 dB and circulator has no isolation
    - **Enables operation without any ramp-up and inhibition time**
  - When RF power is applied, temperature tracking is also present

- **Circulator is phase dependent too**
  - Different reflection phases, different S11 curves
  - Phase shift causes breakdown – **Channel of safe operation** needed
    - Channel allows operation at any phase at any moment in time
    - Channel prevents getting stuck in second minimum

Real Time Operation – Phase Shift







3-1/8 COAXIAL PHASE SHIFTER

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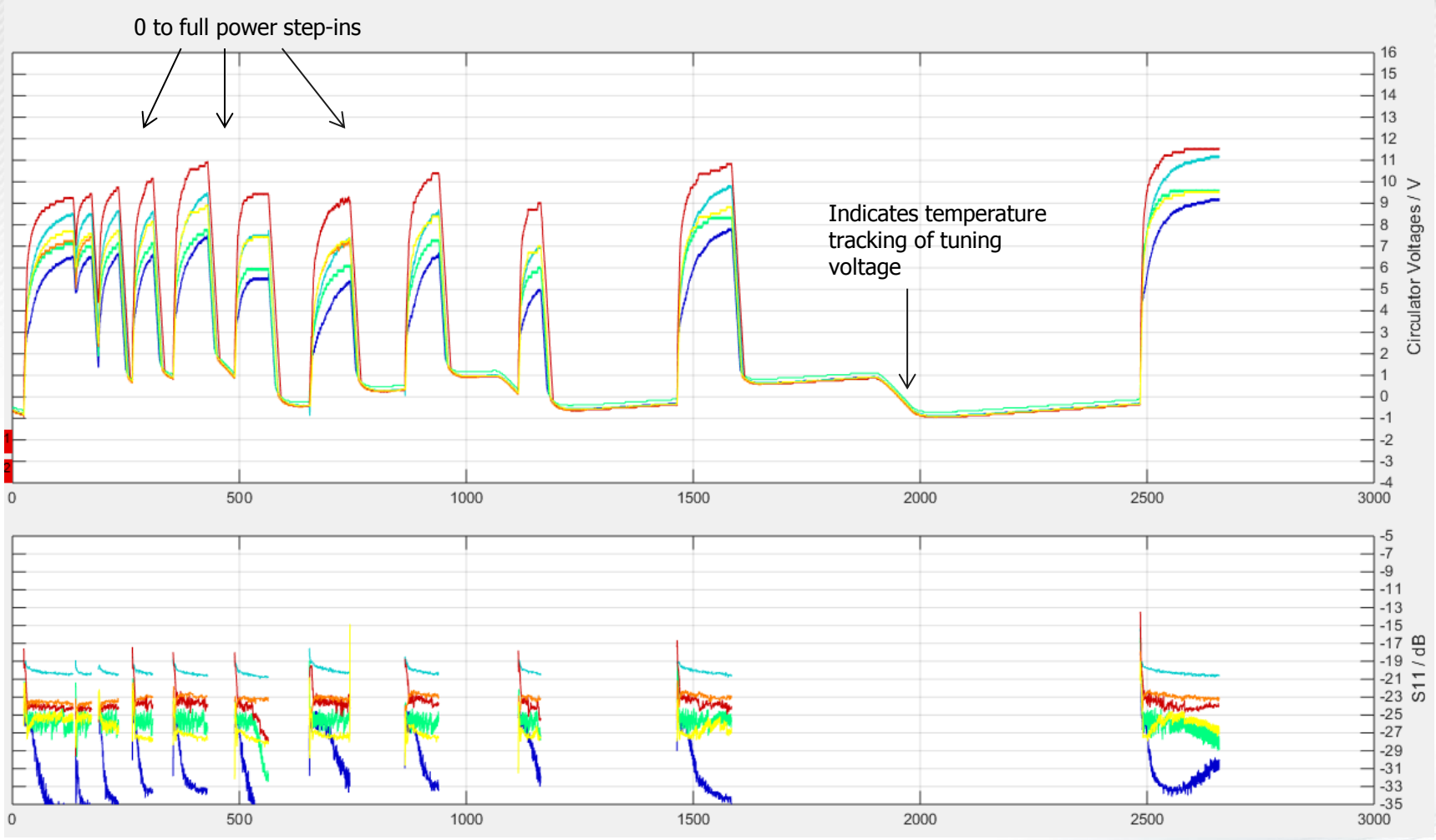
Real Time Operation – Power On



Summary

- A new solution for circulator tracking at low frequencies has been developed and successfully implemented by HBH Microwave

- Circulator parametrization and a robust tracking algorithm are the key elements for outstanding system performance

- Series production has started for 80.5 MHz 2kW and 4kW solid-state power amplifiers with circulator tracking for FRIB linear accelerator in Michigan, USA

- Tracking solution can be applied for similar applications at different frequencies and power levels

Acknowledgments

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Thank you!

Time for questions

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