Politechnika Warszawska

Phase Reference Line for PIP-II Beam Instrumentation

Maciej Grzegrzółka, Bartosz Gąsowski, Paweł Jatczak, Radosław Papis, Andžej Šerlat, Dominik Sikora, Maciej Urbański,Krzysztof Czuba
(Institute of Electronic Systems, Warsaw University of Technology)

Jeremiah Holzbauer, and Nathan Eddy
Fermi National Accelerator Laboratory (FNAL)

This work was supported in part by Fermilab/Warsaw University of Technology Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics Facility under Grant CRADA FRA-2020-0026; and in part by Fermilab is managed by Fermi Forward Discovery Group, LLC, under Contract 89243024CSC000002
Project co-financed by the funds of the Polish Ministry of Education and Science under the program titled 'International Co-financed Projects (6121/PIP-II/2025/0).

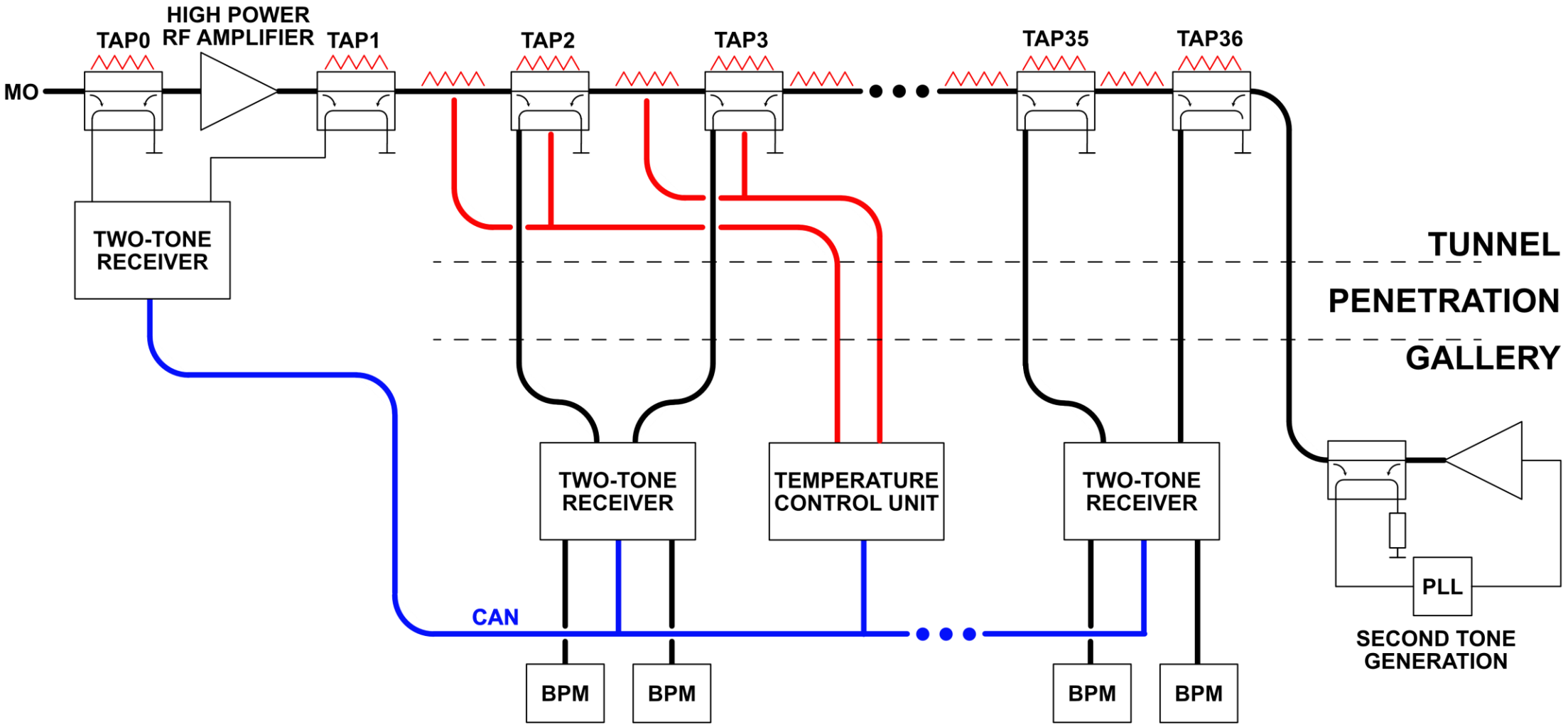
Proton Improvement Plan II (PIP-II)

- PIP-II is a high-intensity proton accelerator under construction at Fermilab to support the the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE).
- The central component of PIP-II is a 220 meter linac, designed to accelerate negative hydrogen ions (H^-) to an energy of 800 MeV.
- The linac's accelerating cavities operate at: 162.5 MHz, 325 MHz, and 650 MHz.
- 36 Beam Position Monitor (BPM) systems are placed along the linac.
- BPMs require a phase-stable 162.5 MHz RF reference signal throughout the accelerator.
- A Beam Instrumentation Reference Line (BIRL) will distribute the signal to 36 BPM systems.
- BIRL will be designed by the Insitute of Electronic Systems at Warsaw University of Technology.

Beam Instrumentation Reference Line (BIRL)

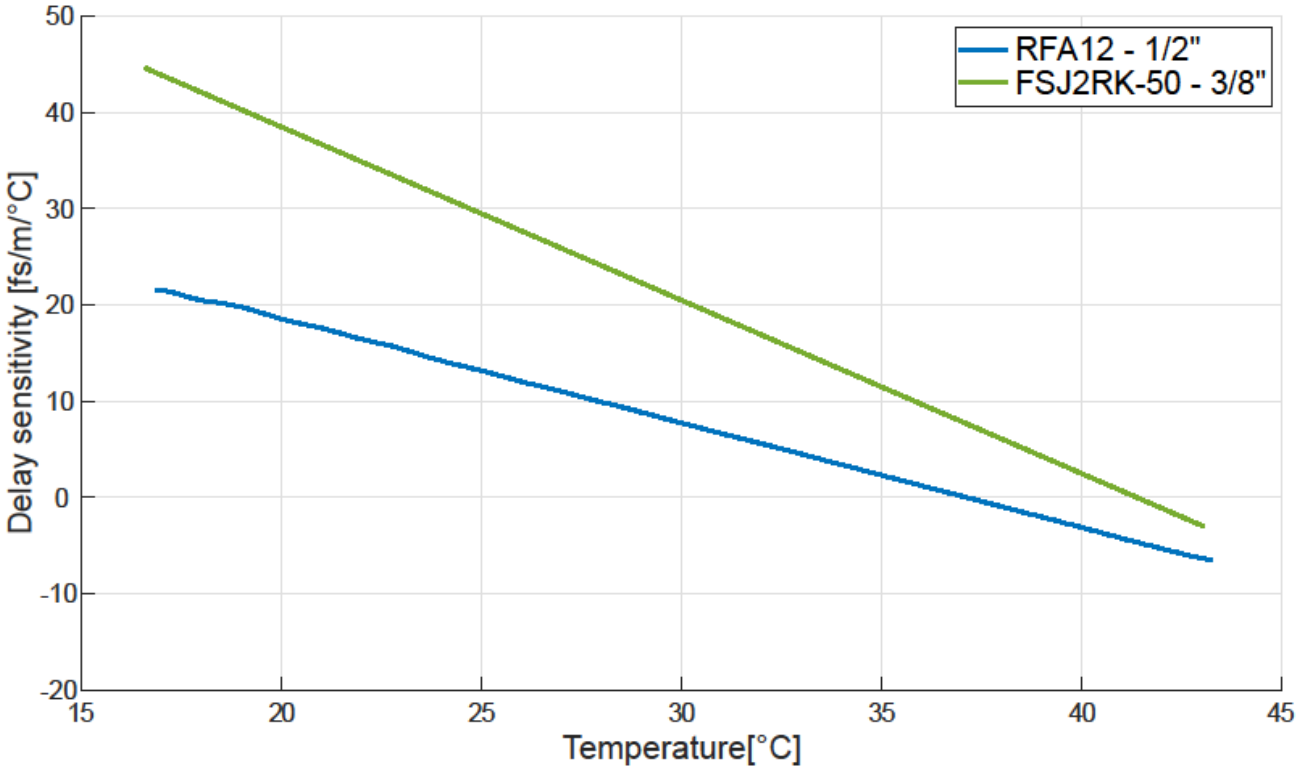
- The reference signal is distributed using a coaxial RF cable.
- Phase drift is actively compensated using a two-tone measurement system.
- Additional stabilization by temperature control of the RF cable and couplers.
- Two-tone receivers provide phase-compensated signals to the BPM systems.
- Requirements:
  - Distribution of a 162.5 MHz RF signal to 36 BPM systems,
  - Long-term phase stability <1 ps over temperature range of 19–34°C,
  - Minimum RF output power of +3 dBm at each tap-point,
  - RMS jitter < 1 ps,
  - Spurious-free dynamic range of at least 80 dBc.

General Concept



Cabling

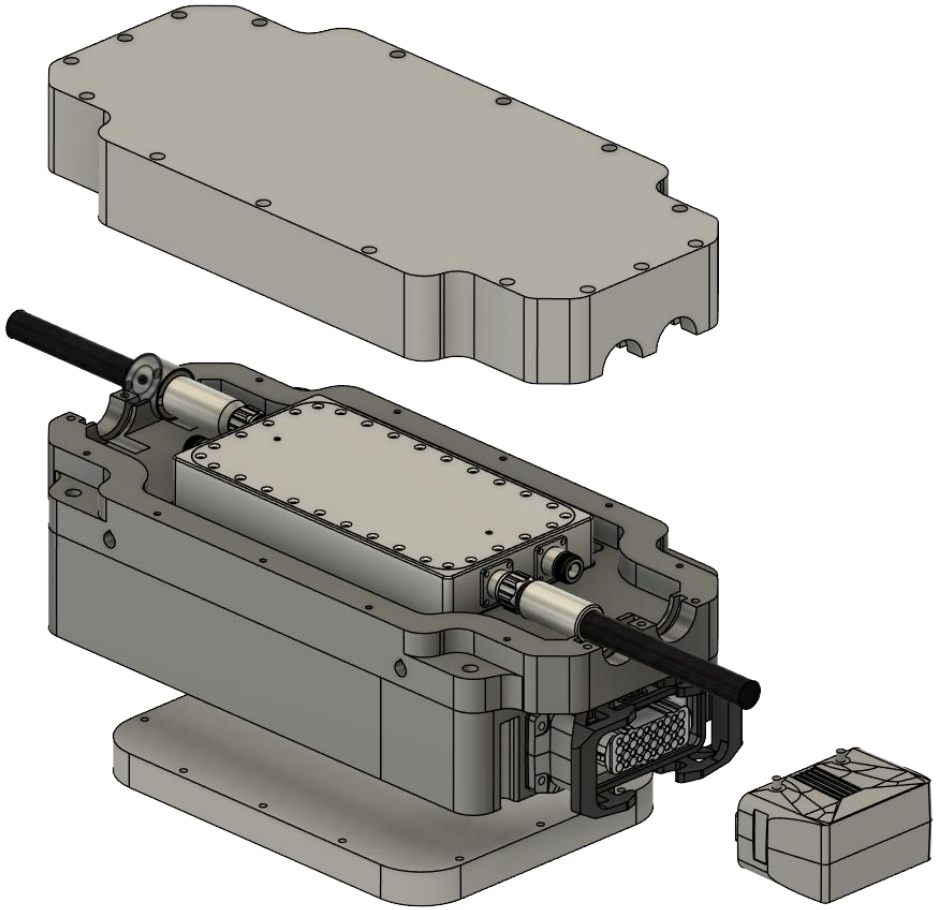
- Several coaxial cables were evaluated
- Draka RFA12 (1/2") was selected for the main reference line.
  - Attenuation: 2.8 dB/100 m
- The main line will be thermally stabilized near 37°C.
- Connections between the tap-points and BPM racks will use 3/8" FSJ2-50 Superflex cables.



- More information in:
  - **A. Šerlat, et al., "Phase Drifts and Signal Dispersion in Coaxial Cables," IEEE Access, vol. 14, pp. 40261–40271, 2026. DOI: 10.1109/ACCESS.2026.3670751.**

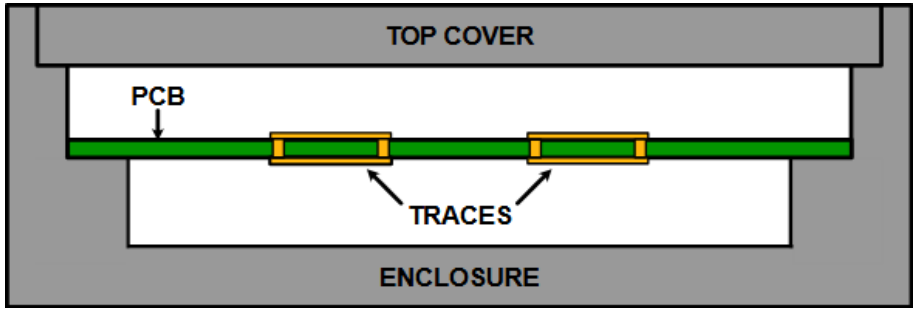
Tappoints

- 36 tap-points will be placed along the linac.
- Each tap-point contains a custom-designed directional coupler and connections for temperature control.
- The 3D-printed PETG V0 enclosure provides mechanical protection, thermal insulation, and flame resistance.
- The couplers will be temperature-stabilized at 37°C.



Tappoints - couplers

- Custom-designed directional couplers.
- Two coupling variants, 19 dB and 25 dB.
- The couplers use a symmetrical stripline structure with air as the main dielectric to minimize losses and temperature-induced phase drift.
- Custom RF connectors with PEI dielectric replace conventional PTFE-based connectors to improve radiation resistance.

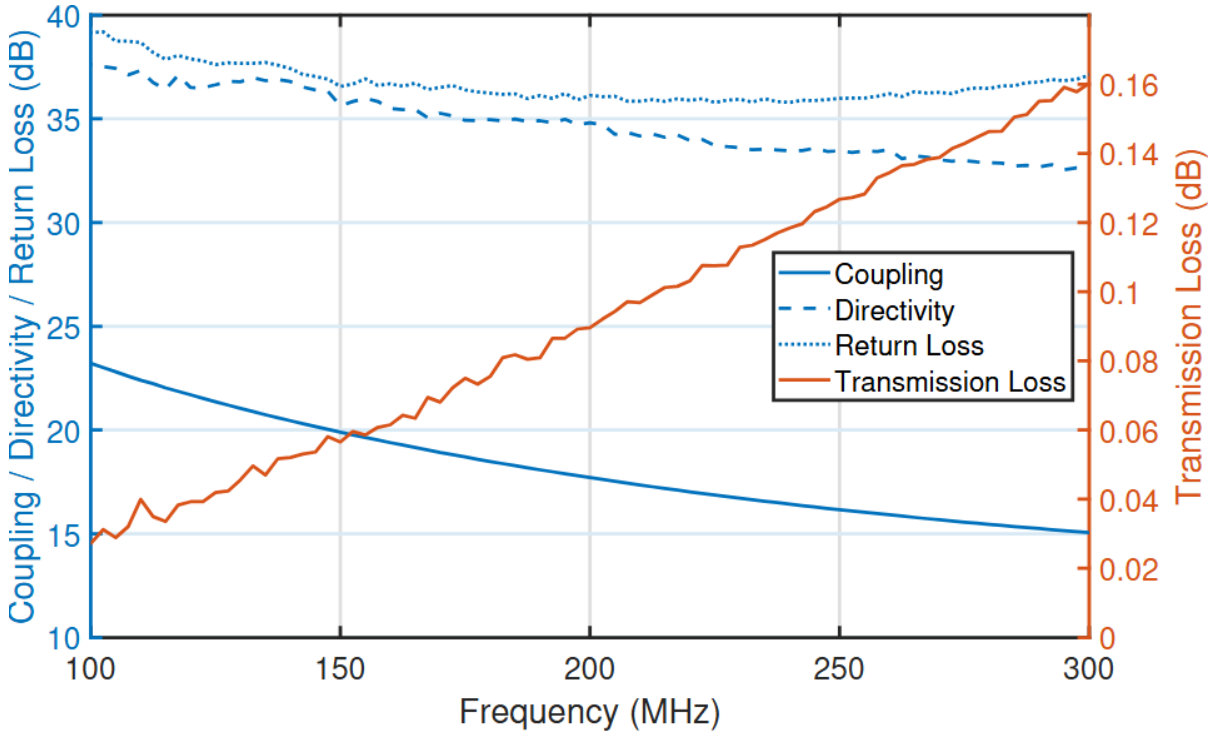




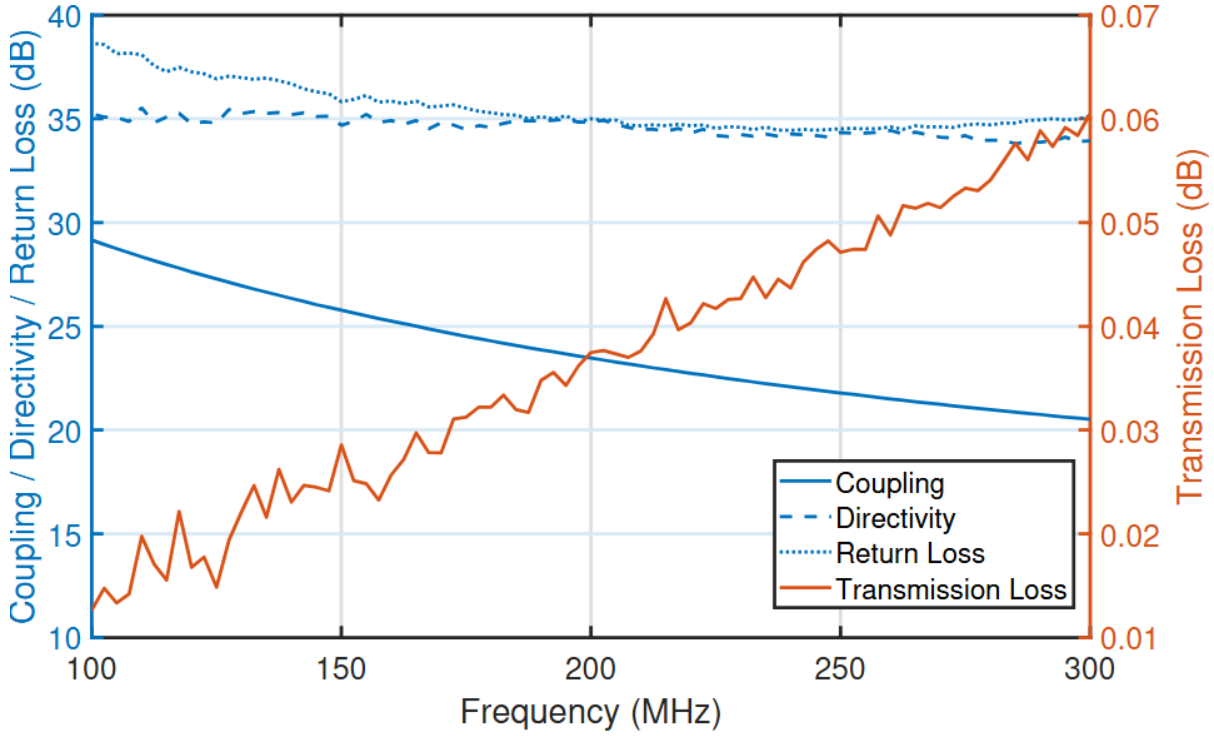
Tappoints - couplers

Directivity > 35 dB Insertion Loss < 0.1 dB Return Loss > 35 dB

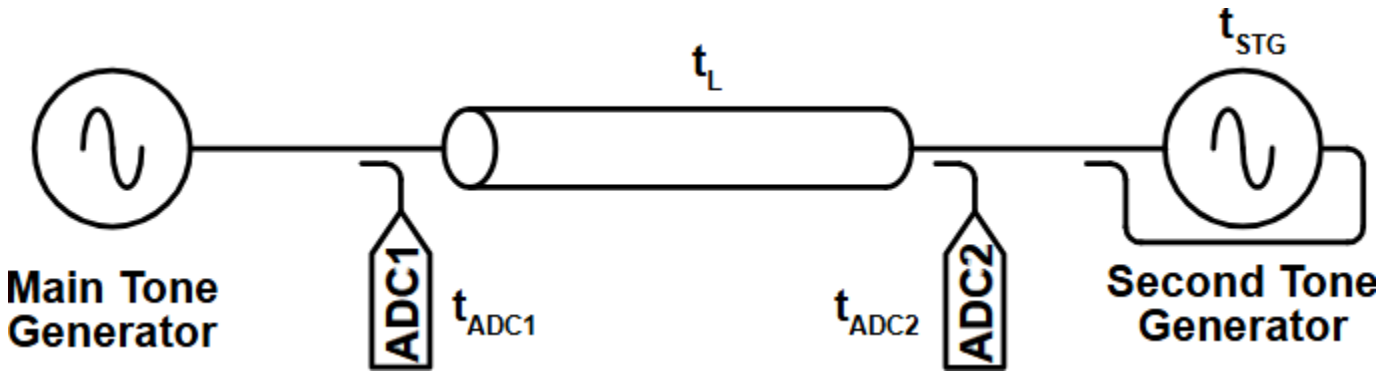
19 dB



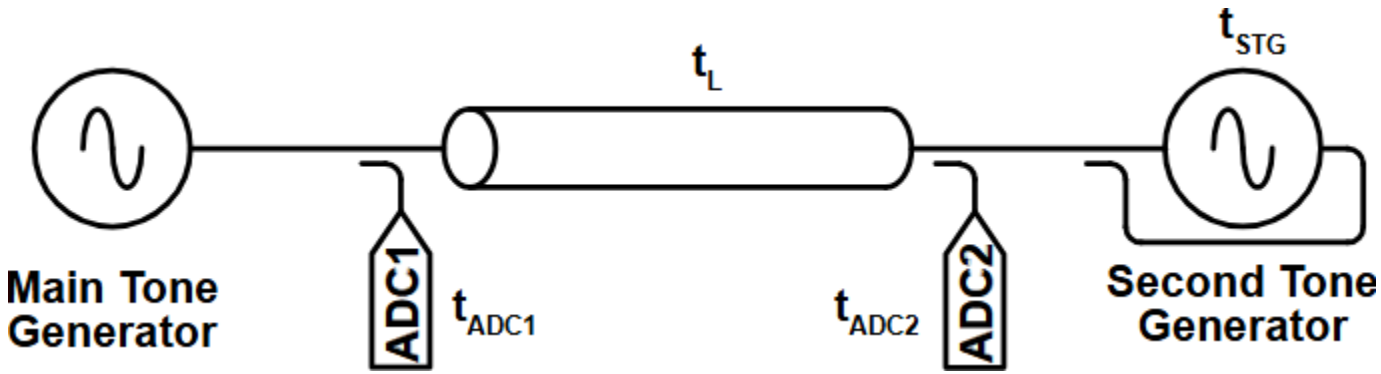
25 dB



Two-tone link

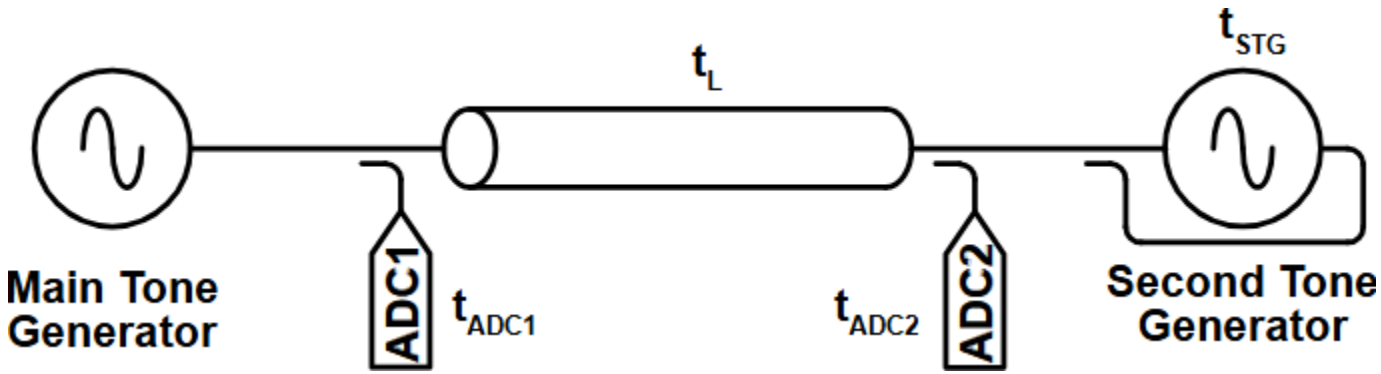


Two-tone link



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

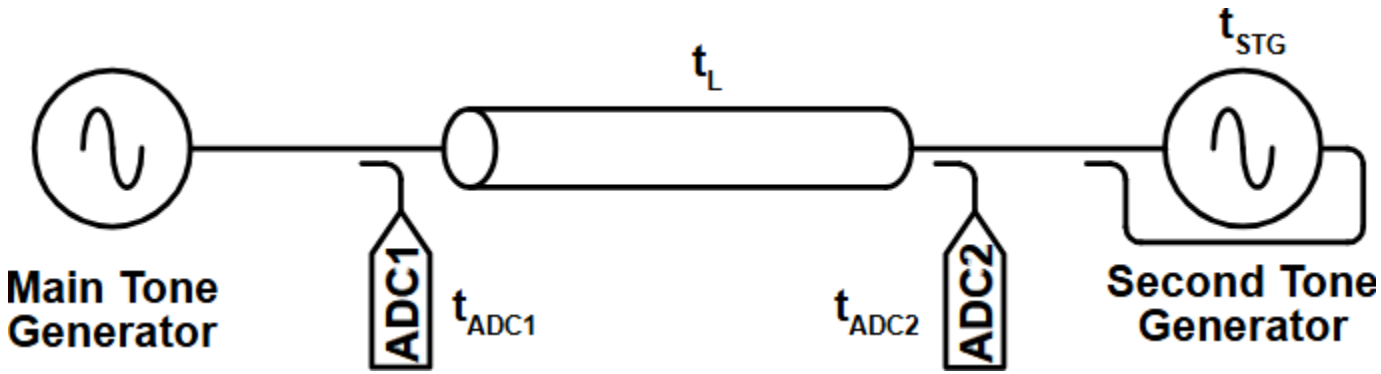
Two-tone link



$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

$$\Delta\varphi_{ST1} = (\Delta t_{STG} + 2\Delta t_L + \Delta t_{ADC1}) f_{ST}$$

Two-tone link

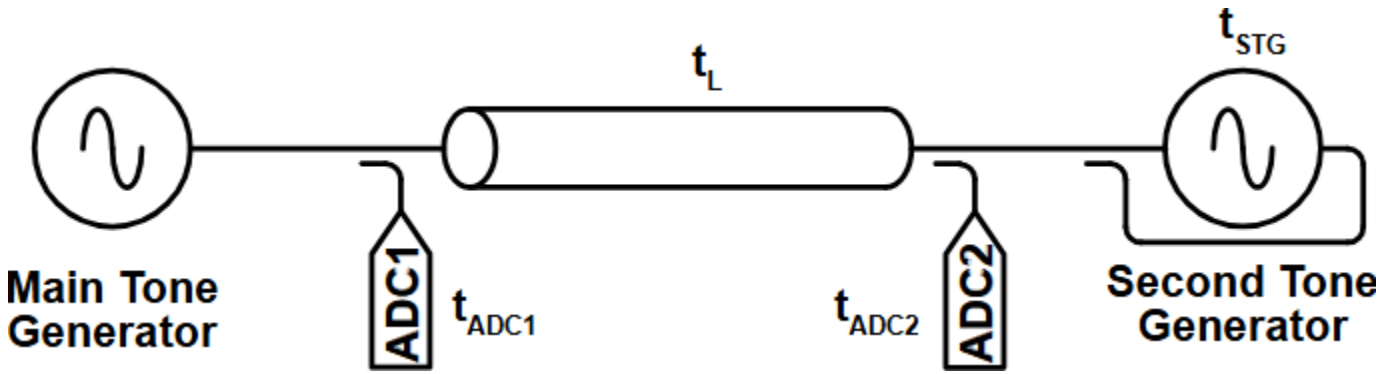


$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

$$\Delta\varphi_{ST1} = (\Delta t_{STG} + 2\Delta t_L + \Delta t_{ADC1}) f_{ST}$$

$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

Two-tone link



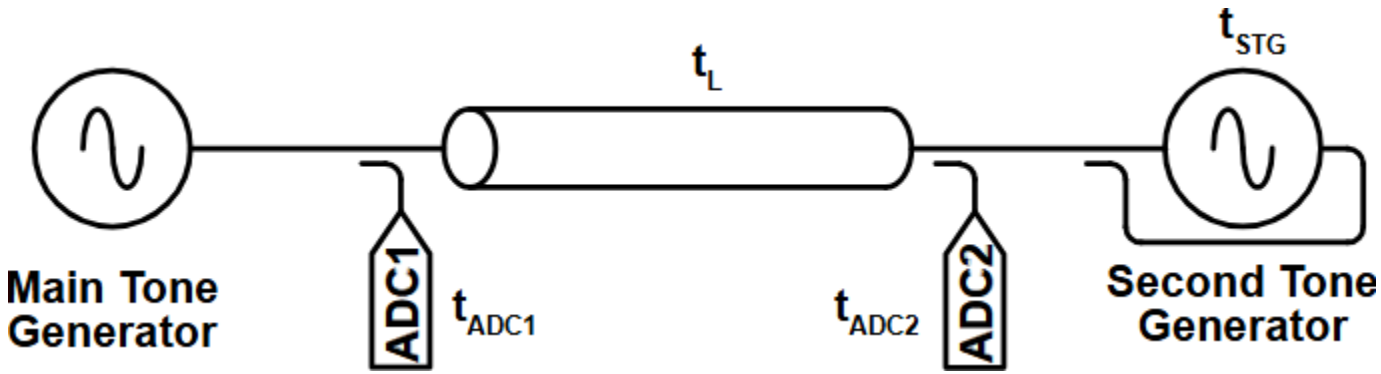
$$\Delta\varphi_{MT1} = (\Delta t_{ADC1}) f_{MT}$$

$$\Delta\varphi_{ST1} = (\Delta t_{STG} + 2\Delta t_L + \Delta t_{ADC1}) f_{ST}$$

$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

$$\Delta\varphi_{ST2} = (\Delta t_{STG} + \Delta t_L + \Delta t_{ADC2}) f_{ST}$$

Two-tone link

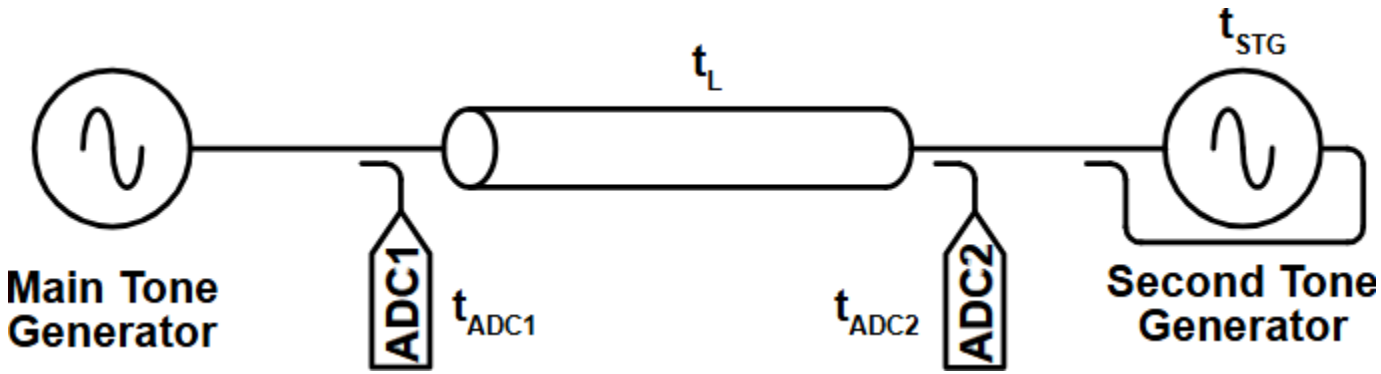


$$\Delta t_{STG} + 2\Delta t_L = \frac{\Delta\varphi_{ST1}}{f_{ST}} - \frac{\Delta\varphi_{MT1}}{f_{MT}}$$

$$\Delta\varphi_{MT2} = (\Delta t_L + \Delta t_{ADC2}) f_{MT}$$

$$\Delta\varphi_{ST2} = (\Delta t_{STG} + \Delta t_L + \Delta t_{ADC2}) f_{ST}$$

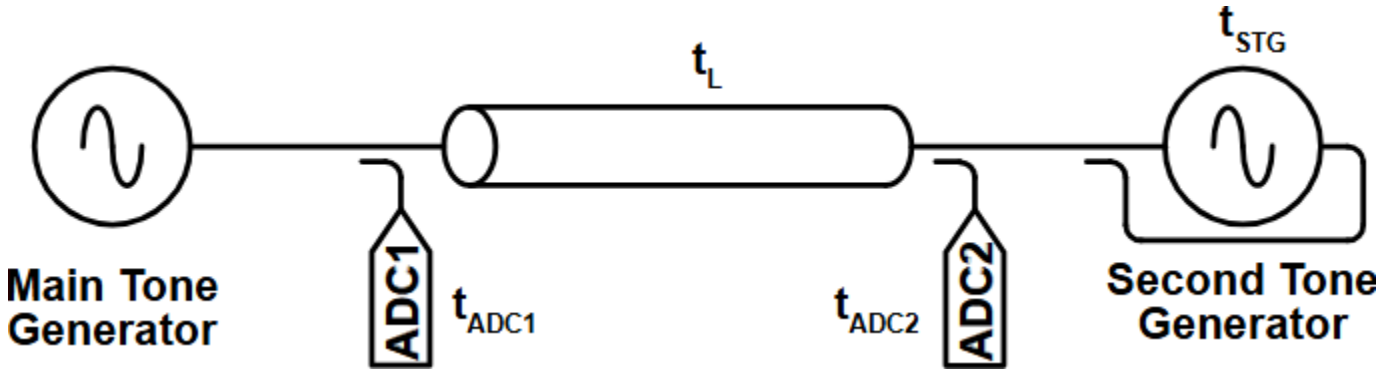
Two-tone link



$$\Delta t_{STG} + 2\Delta t_L = \frac{\Delta\varphi_{ST1}}{f_{ST}} - \frac{\Delta\varphi_{MT1}}{f_{MT}}$$

$$\Delta t_{STG} = \frac{\Delta\varphi_{ST2}}{f_{ST}} - \frac{\Delta\varphi_{MT2}}{f_{MT}}$$

Two-tone link

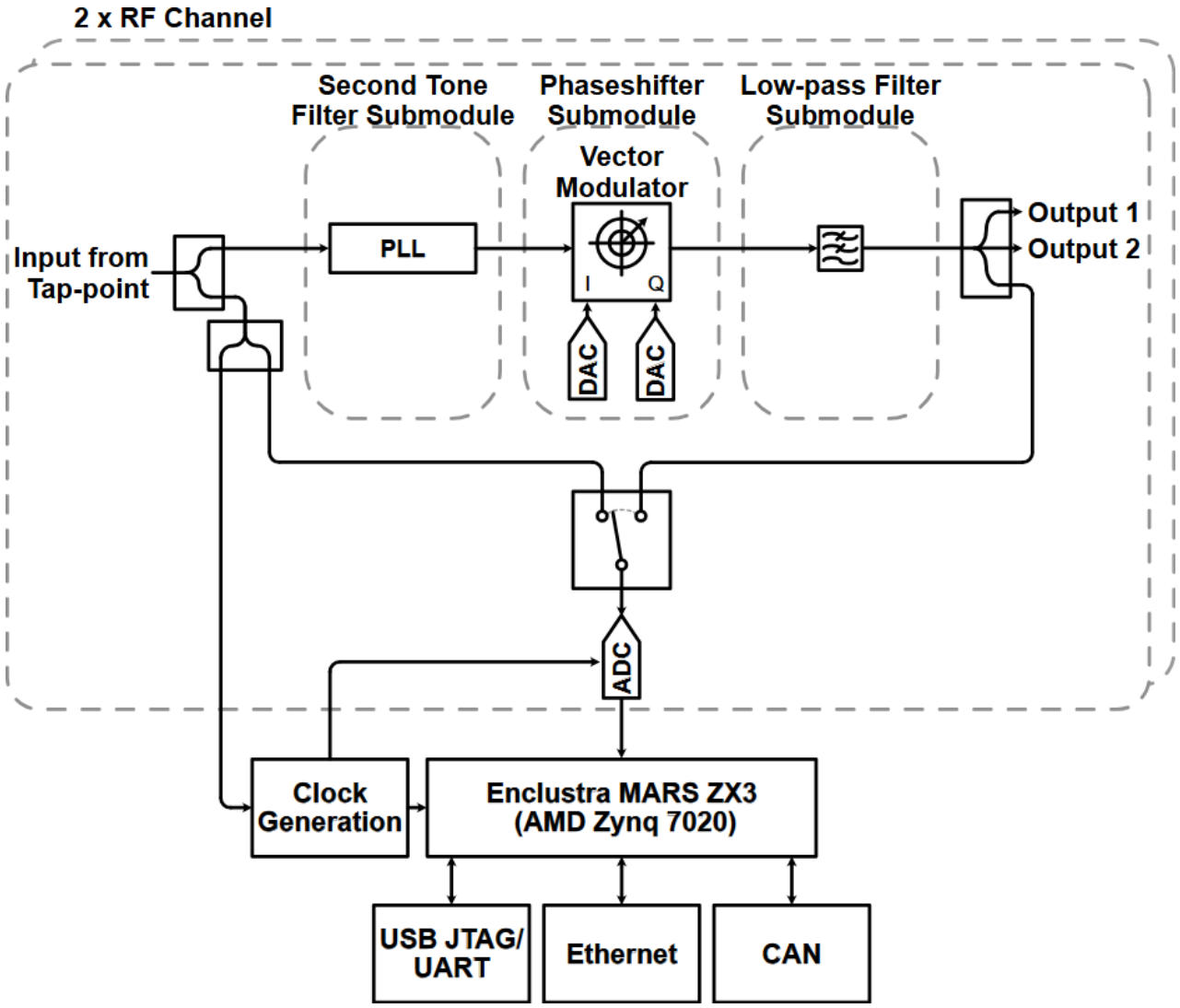


$$\Delta t_L = \frac{\Delta\varphi_{ST1} - \Delta\varphi_{ST2}}{2f_{ST}} - \frac{\Delta\varphi_{MT1} - \Delta\varphi_{MT2}}{2f_{MT}}$$

- More information in:
  - **A. Šerlat, M. Grzegrzółka, and K. Czuba, "Two-Tone RF Signal Phase Drift Measurement System," Measurement, vol. 243, Art. no. 116183, 2025, doi: 10.1016/j.measurement.2024.116183.**

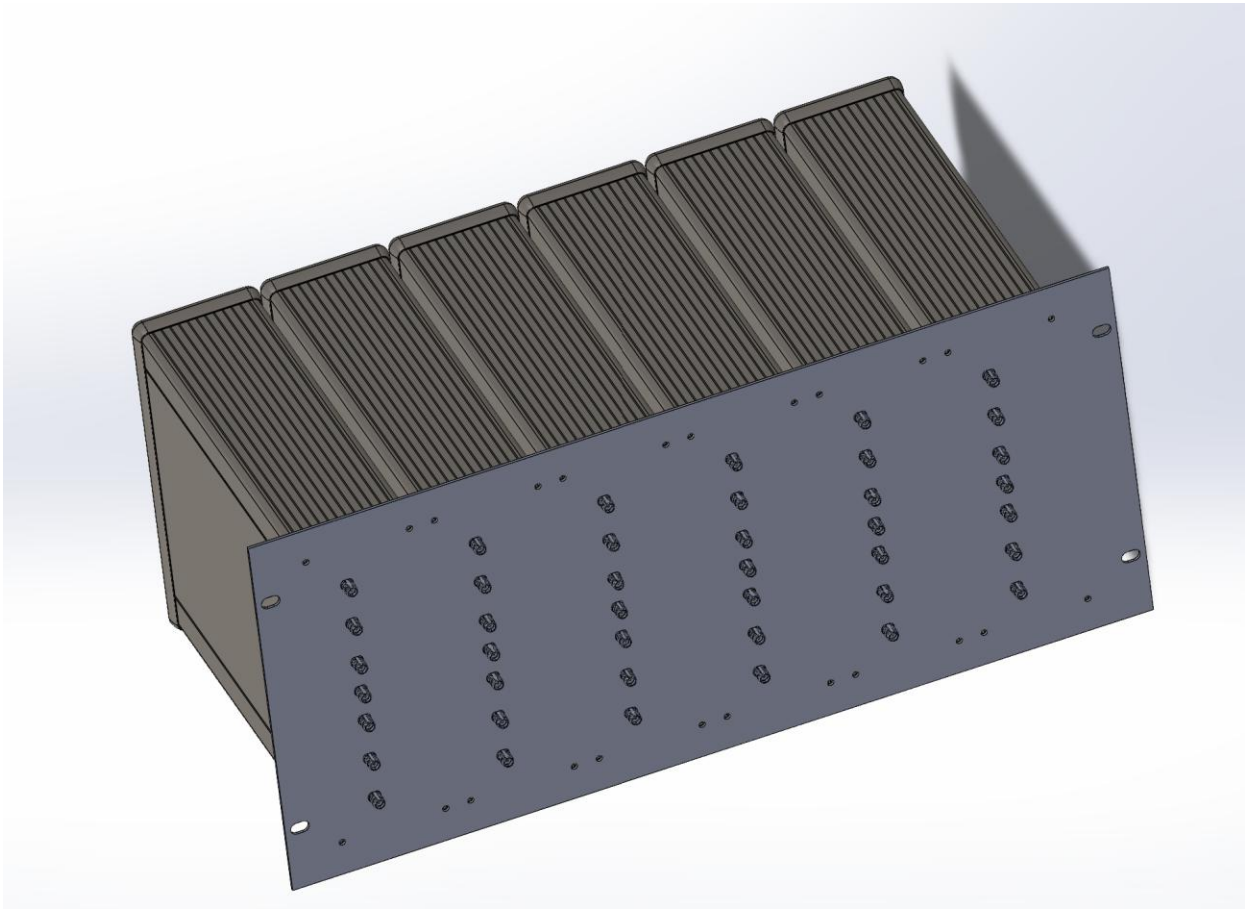
Two-tone receiver

- Measures phase drift and provides active compensation.
- Two RF channels per receiver.
- ADCs and non-IQ digital demodulation used for phase measurements.
- Compensation based on PLL with vector modulator.



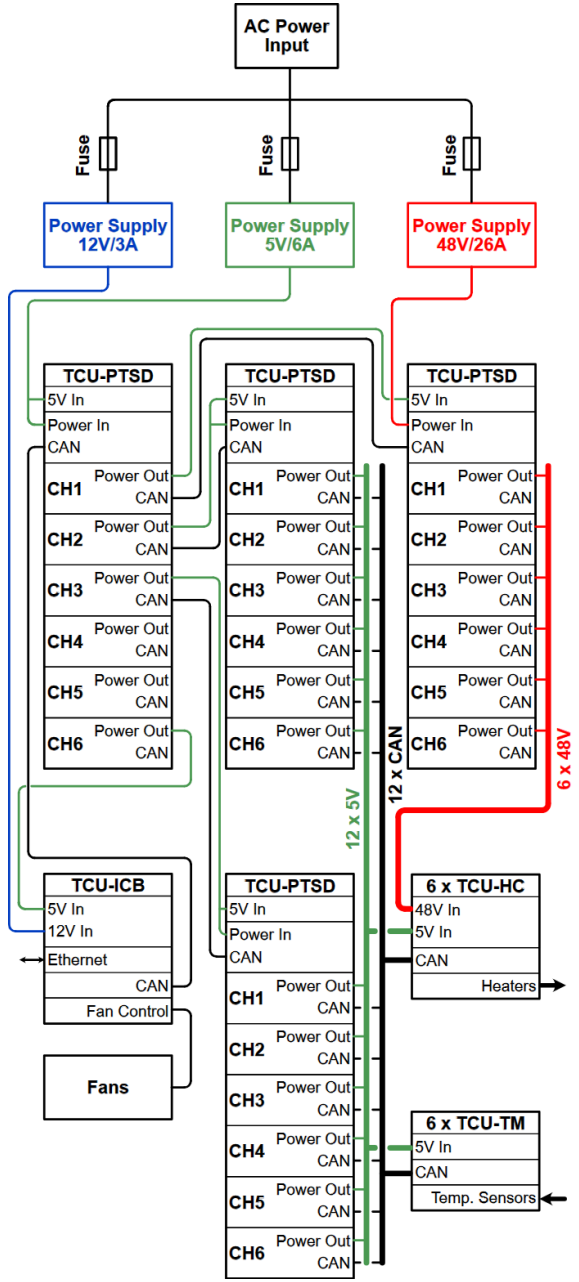
Two-tone receiver



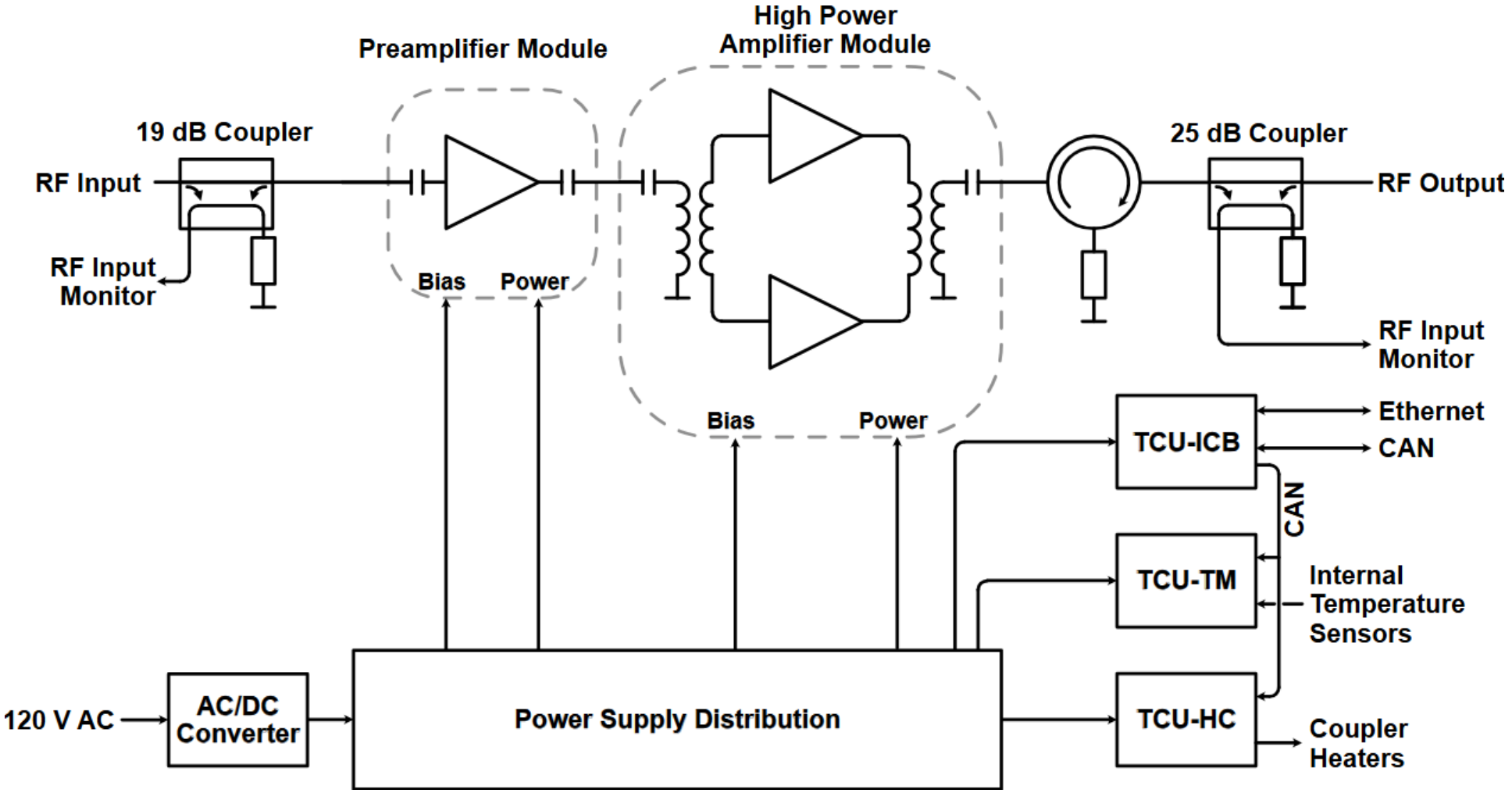


Temperature Control System

- Stabilizes the temperature of the main RF cable and directional couplers.
- Target temperature: 37°C.
- Temperature is measured using PT100 sensors with 4-wire connections.
- Each Temperature Control Unit (TCU) supports up to 18 heaters and 36 temperature sensors.
- PID-based regulation with CANopen communication and Ethernet monitoring.

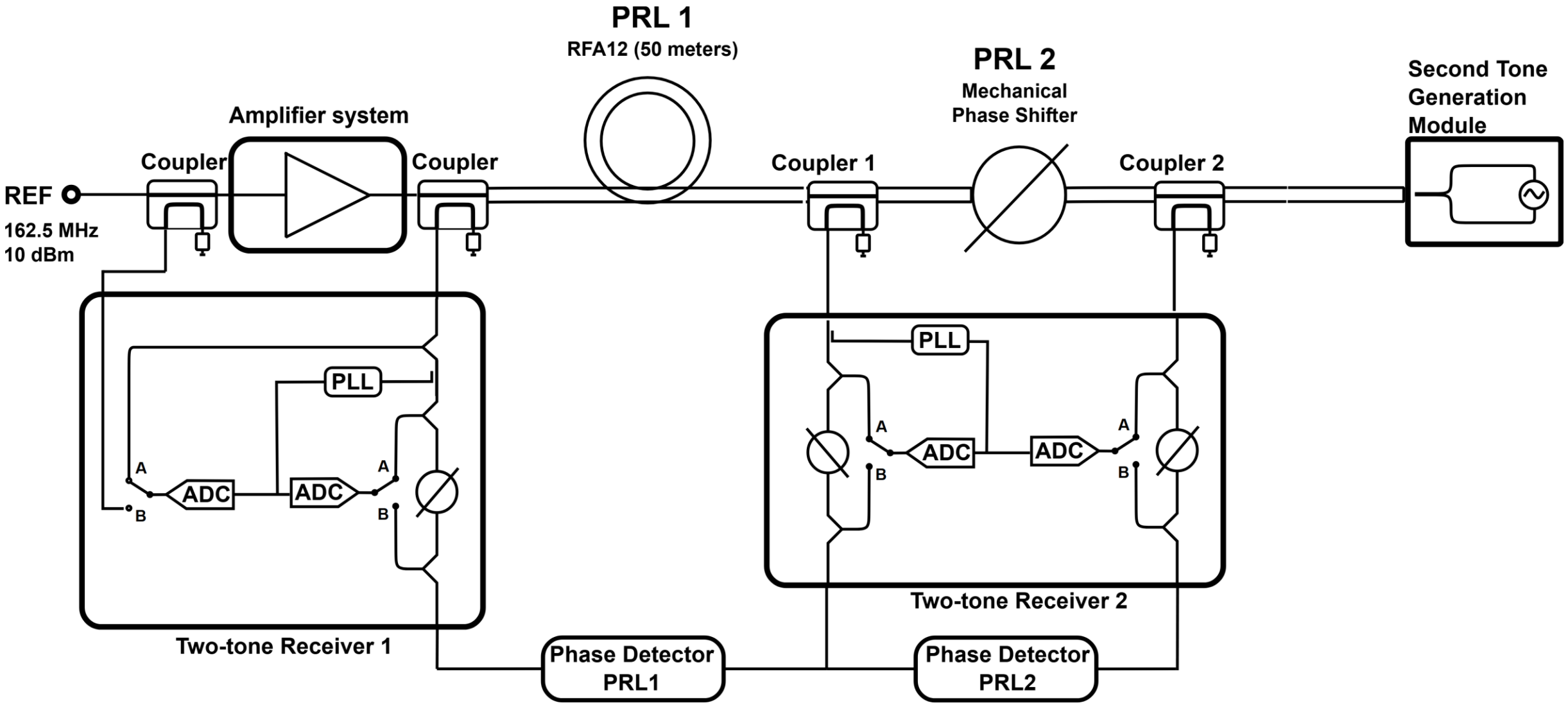


High-power Amplifier

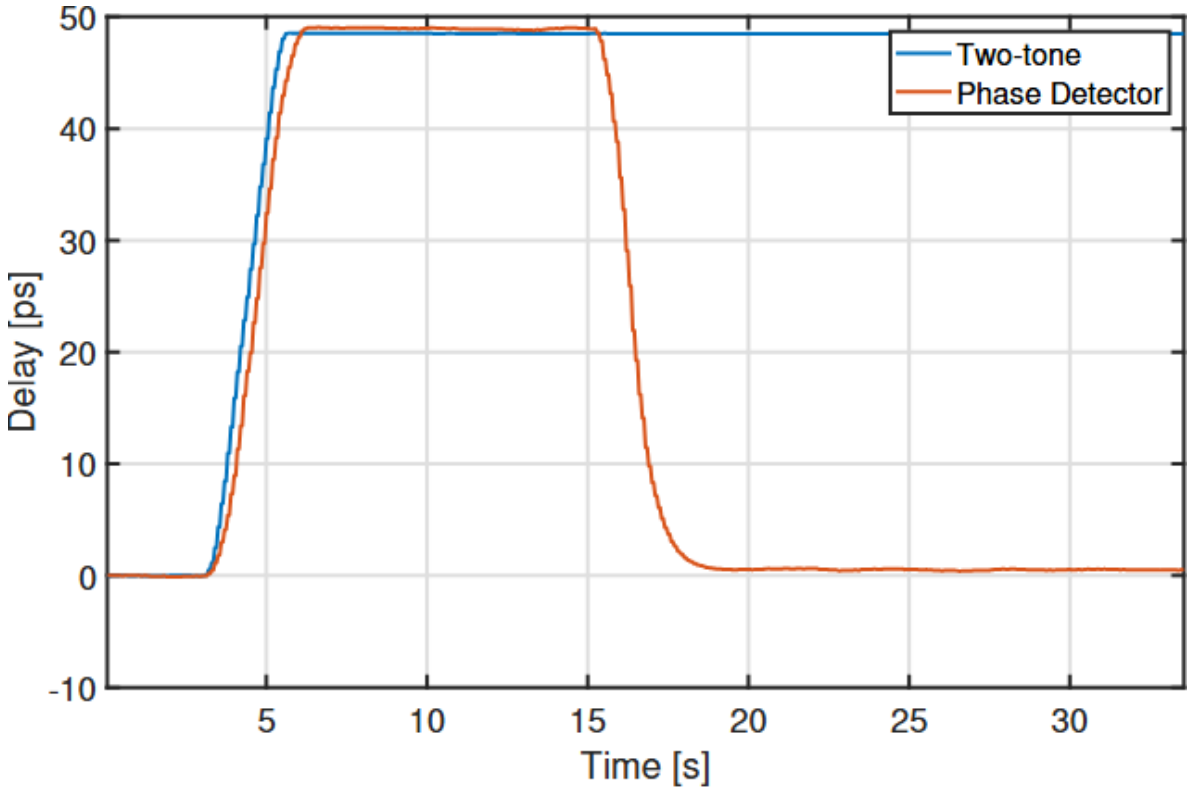


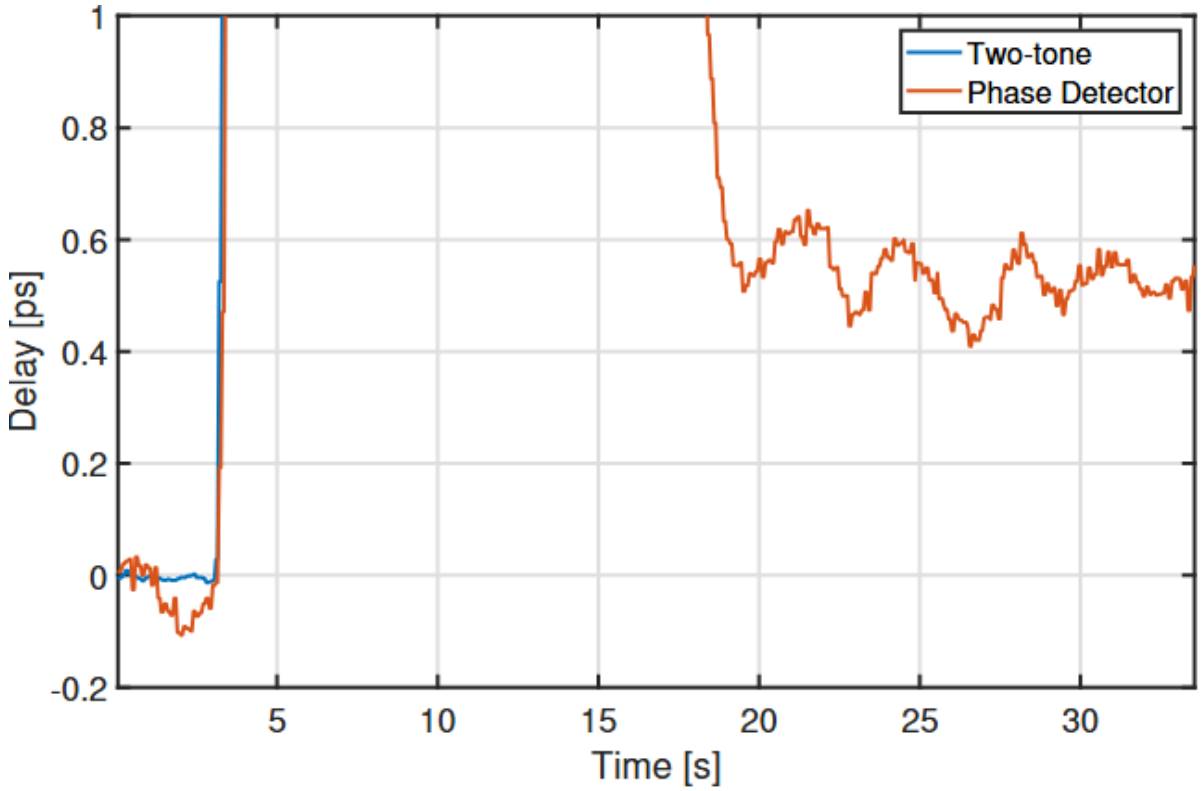
- 37 dB gain
- +47 dBm (50 W) output power
- RF Couplers and output circulator are temperature stabilized

Teststand


PRL 1
RFA12 (50 meters)
PRL 2
Mechanical
Phase Shifter
Second Tone
Generation
Module
Amplifier system
Coupler
Coupler
Coupler 1
Coupler 2
REF
162.5 MHz
10 dBm
PLL
A
B
ADC
ADC
Two-tone Receiver 1
PLL
A
B
ADC
ADC
Two-tone Receiver 2
Phase Detector
PRL1
Phase Detector
PRL2

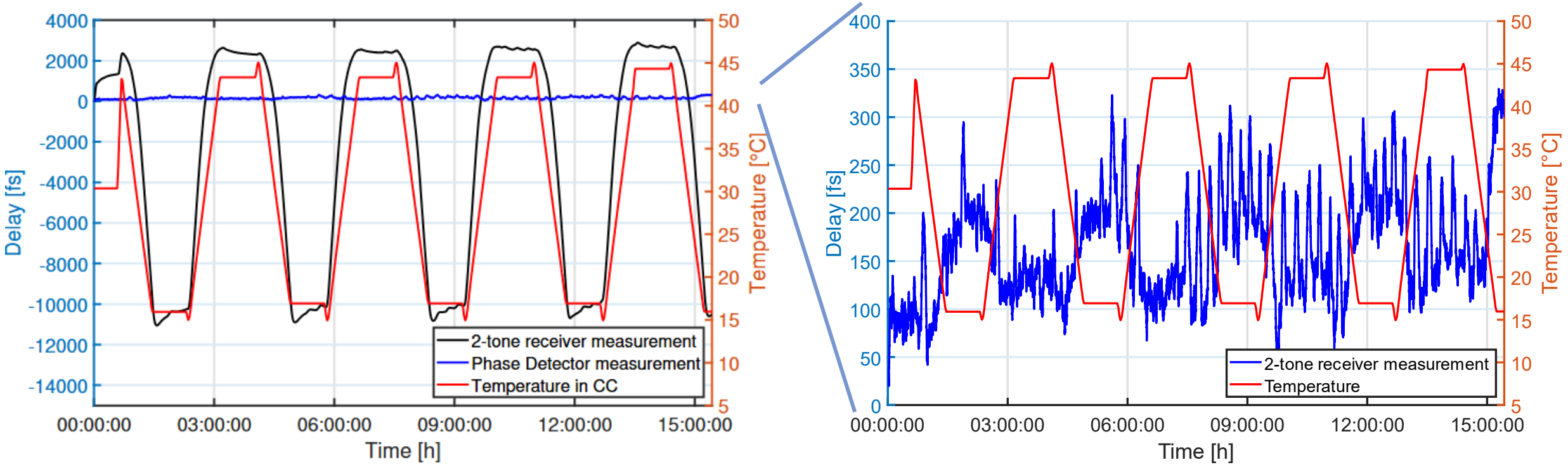
Teststand





48.5 ps phase change was reduced to 0.6 ps. 82-times reduction.

Teststand



14 ps cable phase drift was reduced to 310 fs. 45-times reduction.

Status

- System architecture and hardware design of all major BIRL components completed.
- First hardware prototypes manufactured and preliminary tests performed.
- Two-tone phase drift compensation successfully demonstrated on a dedicated test stand.
- Further optimization and integration tests, including the temperature stabilization system, are in progress.
- Main reference line installation scheduled to begin in Q1 2027.
- Full system operation expected in Q3 2027.

Summary

- The Beam Instrumentation Reference Line (BIRL) was designed to distribute a phase-stable 162.5 MHz RF reference signal to 36 BPM systems in the PIP-II linac.
- The proposed architecture combines active two-tone phase drift compensation with passive temperature stabilization.
- The main system components, including RF couplers, two-tone receivers, temperature control units, and a high-power amplifier, have been developed.
- Preliminary measurements demonstrated an 82-times reduction in phase steps and a 45-times reduction in long-term cable drift.
- The results indicate that the proposed system can achieve the required sub-picosecond phase stability.

Politechnika Warszawska

Thank you!