Performance Evaluation of the ESS Phase Reference Line

Krzysztof Czuba

On behalf of the WUT and ESS PRL Team

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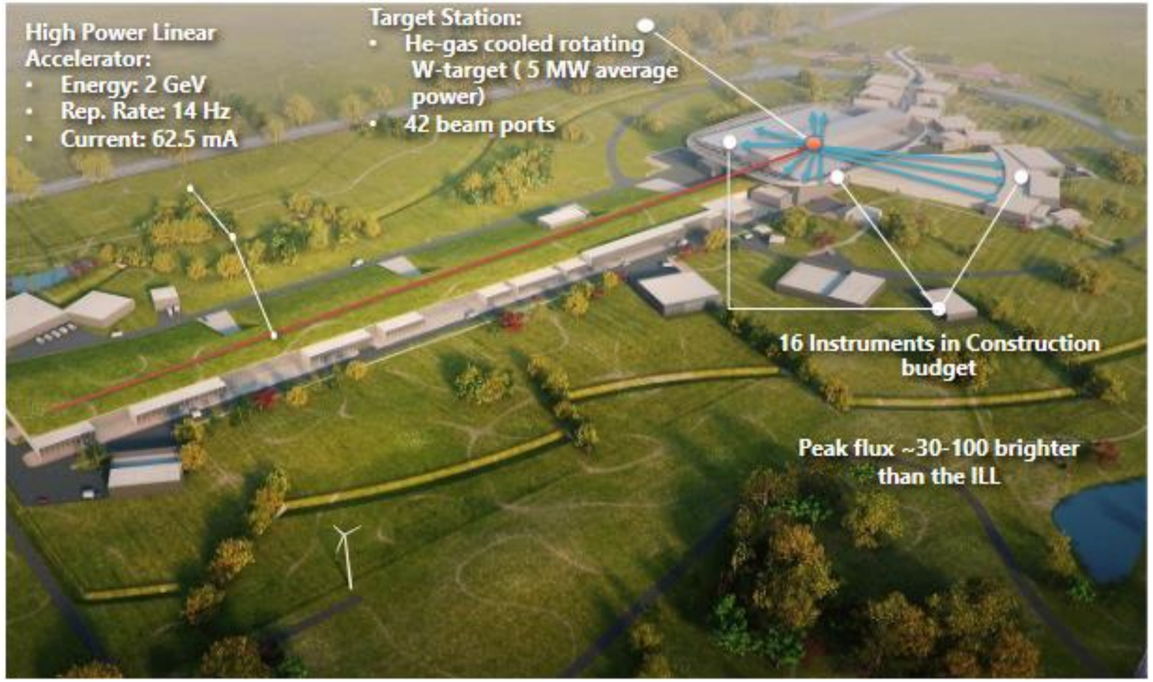
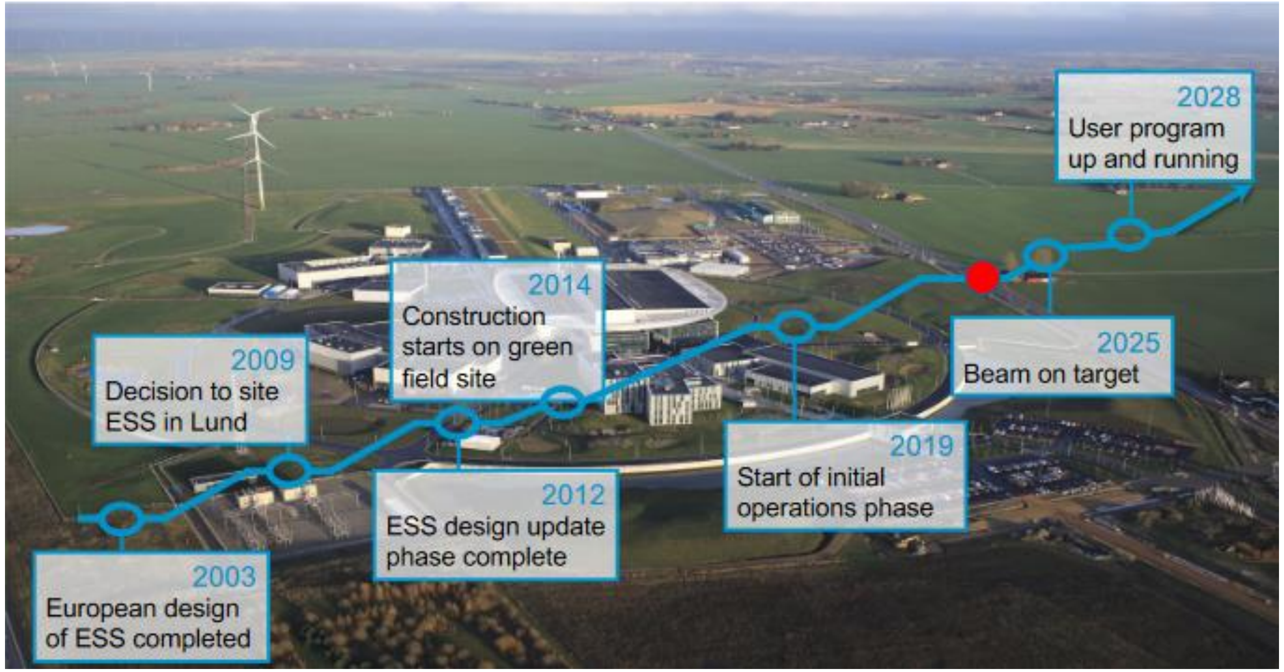
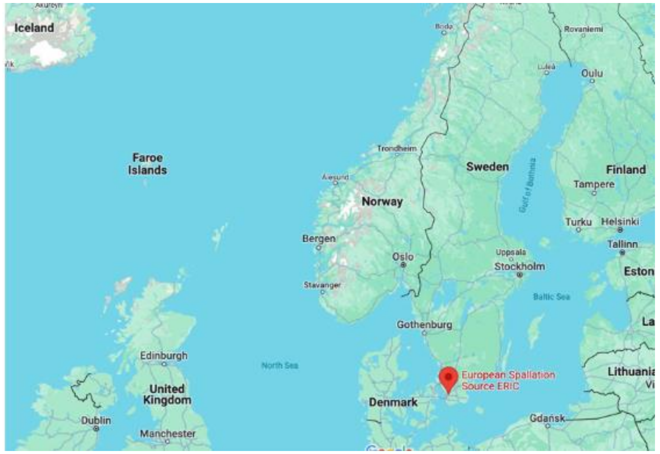
European Spallation Source

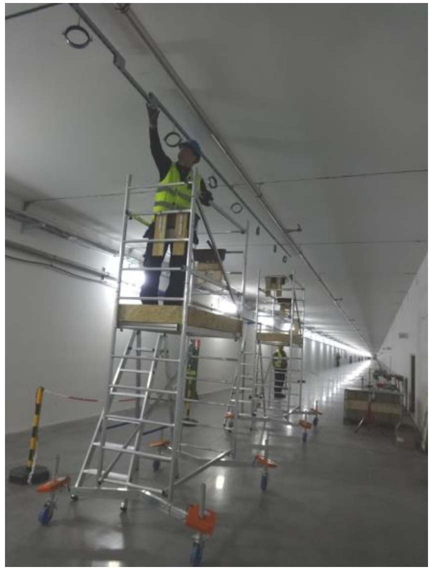




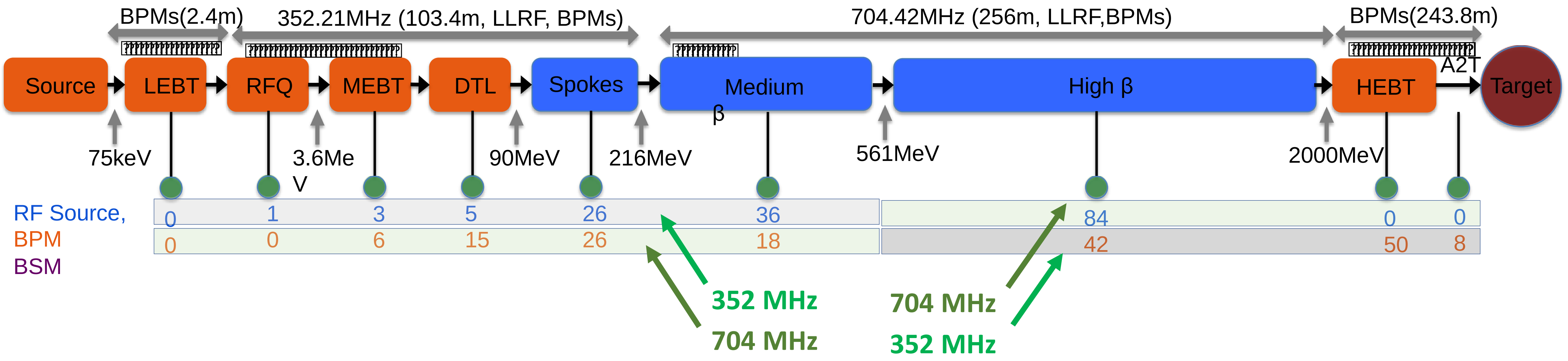


A Brief History of WUT Contribution to ESS PRL

- Officially started in October 2016
- Basic concept by ESS (general requirements) and the Lund University (temp. control)
- Originally planned a single frequency distribution line with a simple power splitter at each Tap Point, **well …**
- Developed to the final shape after building **18.7m** long **prototype in a WUT corridor**
- WUT team was the first to start installations in the ESS tunnel in July 2017
- Installations were completed in 2022/2023 (SAR in Dec. 2023)
- Final performance tests (above the In-Kind scope) possible in 2024 due to energization of racks with PRL equipment



ESS RF Phase Synchronization Requirements

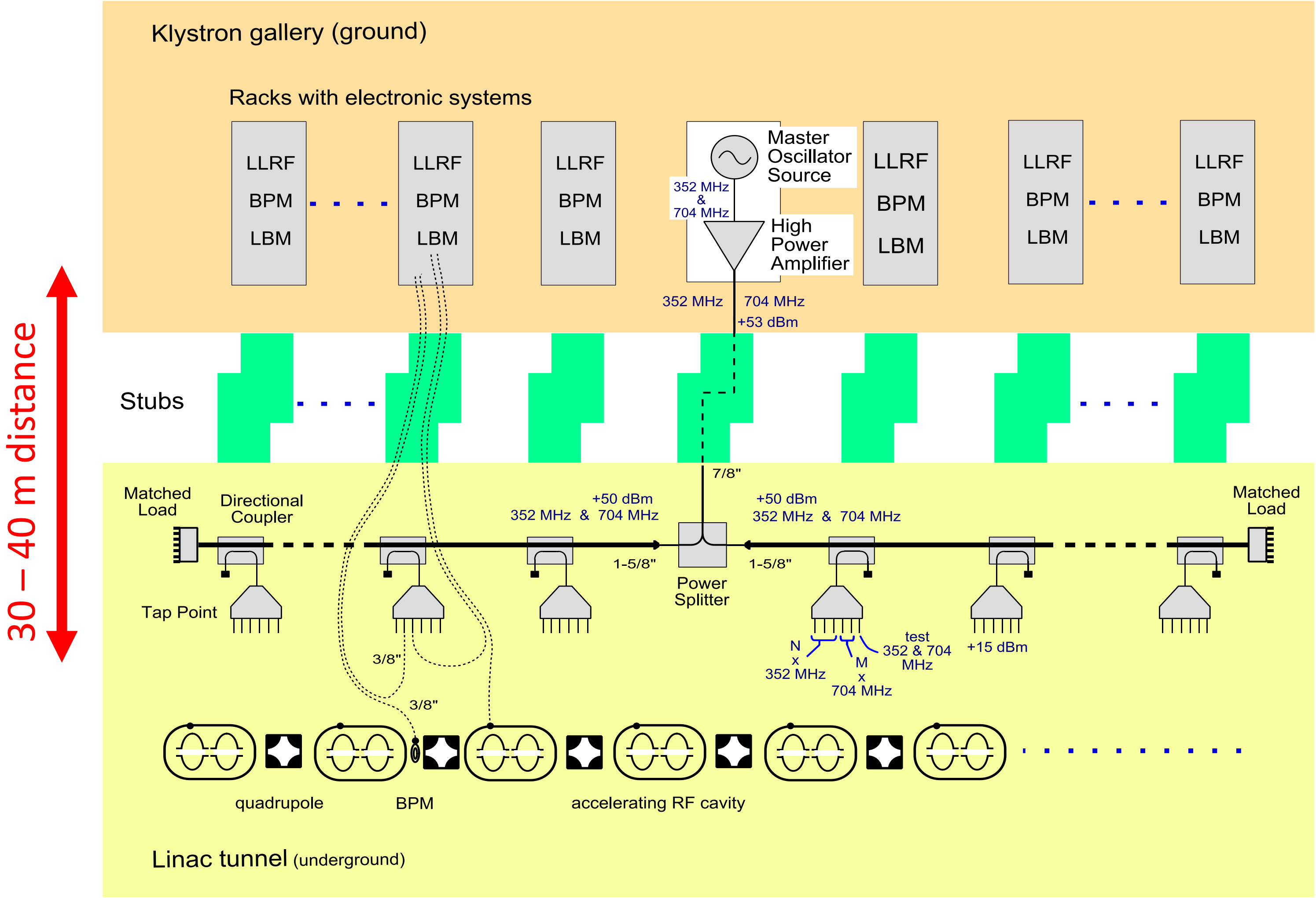


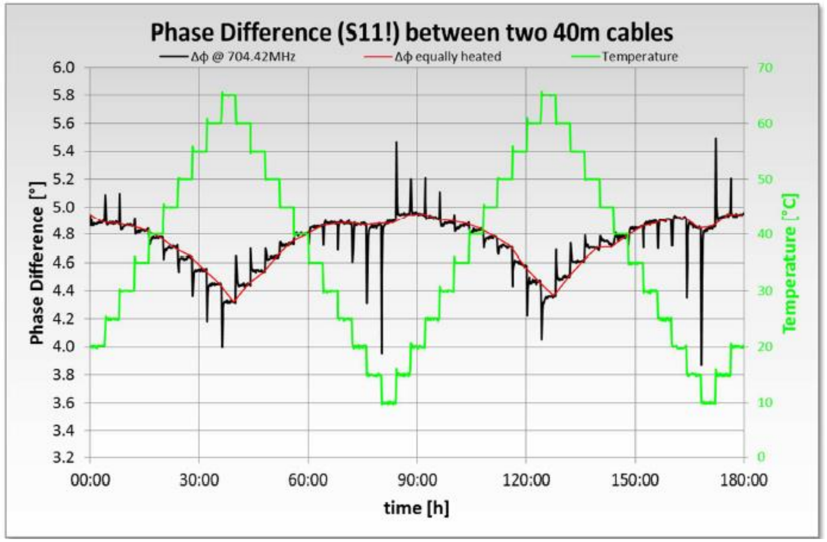
- Both 352 MHz and 704 MHz required along the entire linac **(drift reduction)**
- Required phase synchronization:
  - 0.1° for short term (during 3.5 ms pulse),
  - 0.1° for long term between adjacent outputs
  - 2.0° for long term (hours to days)

Main Assumptions for the Phase Reference Line

- Passive distribution along the accelerator tunnel (radiation)
- **Single** 1 $^5/_8$” coaxial rigid line **for 352 MHz and 704 MHz**
- 58 signal taps (3 or 6 way), 294 total outputs
- Frequency selective, configurable tap outputs
- Equal power level at each output (+17 dBm +/- 1 dBm), at both frequencies – **min. +14 dBm for most of devices**
- Temperature and internal gas (Nitrogen) pressure control
- All active electronics in the Klystron Gallery hall

PRL RF Scheme





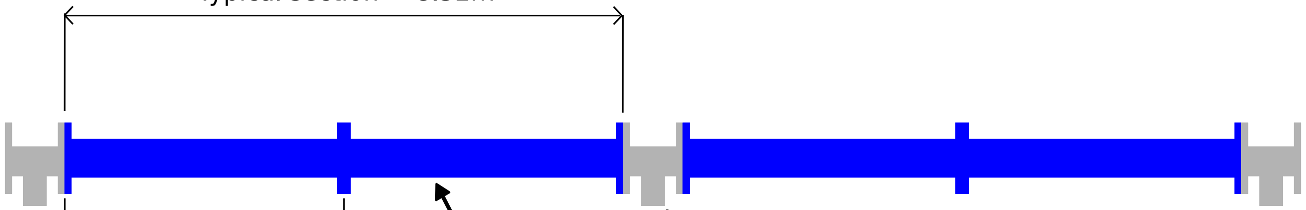
Two 40 m long SCF38-50J-TC cables @ 704 MHz

- **Δφ = 0.7° p-p** for **ΔT = 55 °C** <+10 oC, +65 °C>
- **Δφ = 0.38° p-p** for **ΔT = 20 °C** <+25 oC, +55 °C>

  - expected max. temp. change in the STUB

Measurement by Michael Schubert SPINNER GmbH

Main Line Design

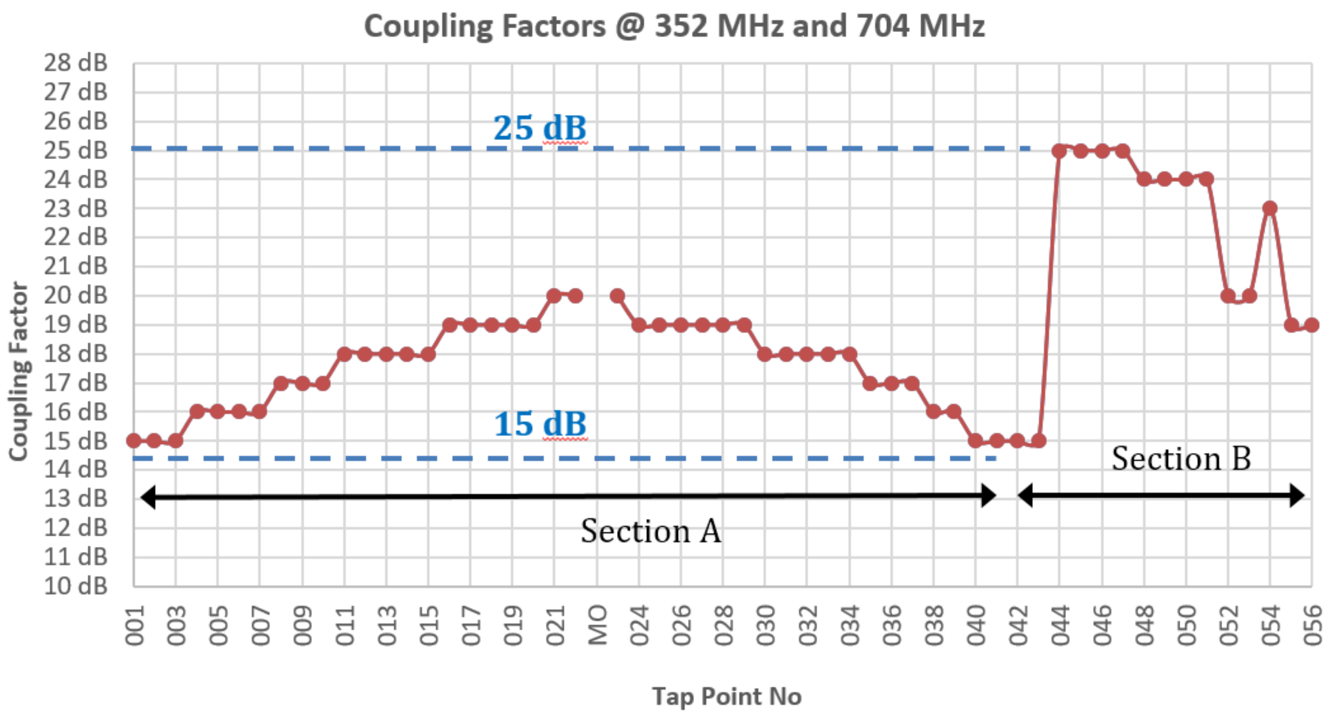


No of 4.135m segments in section	No. of sections	Total no of segments	Total segment length [m]
2	37	74	305,990
3	3	9	37,215
4	7	28	115,780
5	2	10	41,350
6	2	12	49,620
	51	133	549,955
Irregular segments	5		38,700

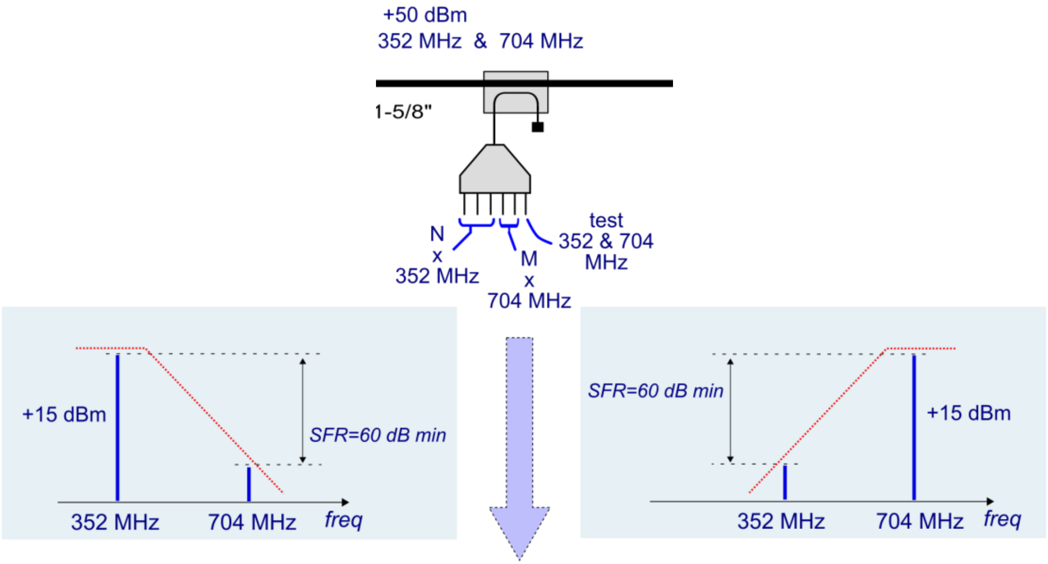
- Modular design to simplify production and assembly
- Minimized of number of various segment types
- Teflon free line supports
- Gas tight system

Directional Couplers

- Directional coupler with adjustable coupling factor, the same @ both 352 MHz and 704 MHz
- Minimized number of coupling factors along the tunnel

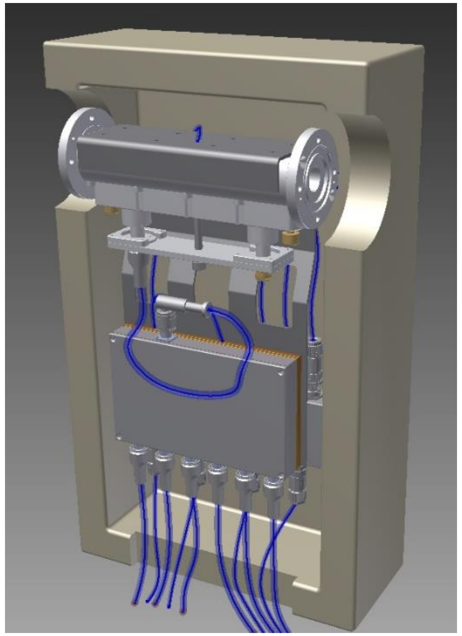


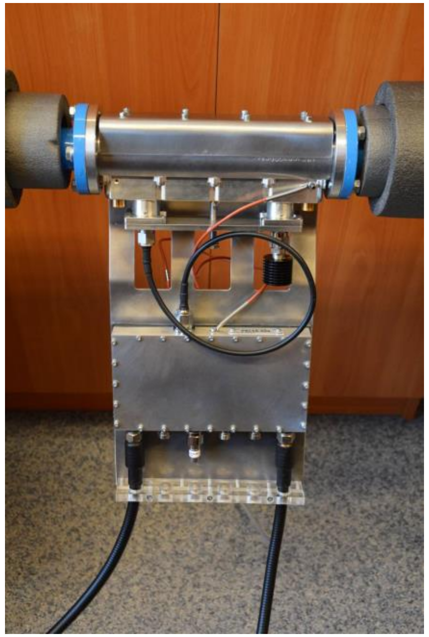
Design by the Space Forest company

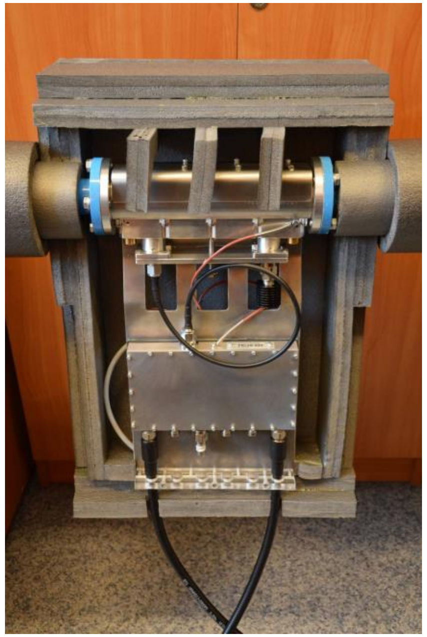


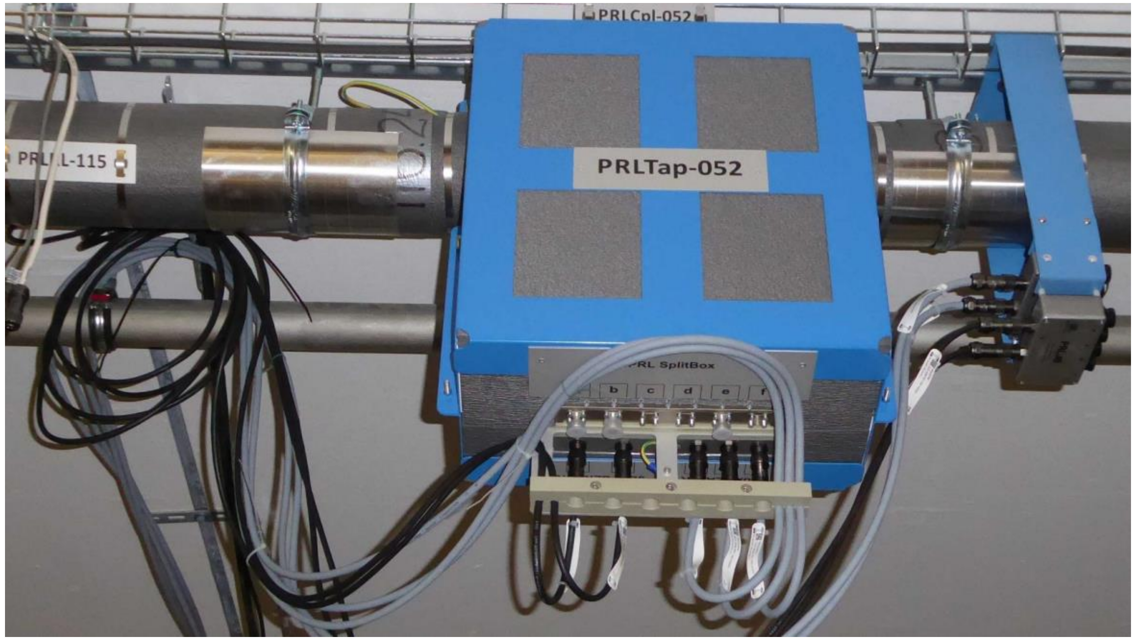
Tap Point

1. Coaxial directional coupler + PRL Split Box + Junction Boxes (J-Box)
2. Temperature stabilization (+/- 0.1 ^{o}C)
3. Mechanics for temperature stabilization and mechanical stress relief
4. Produced and installed 58 pieces



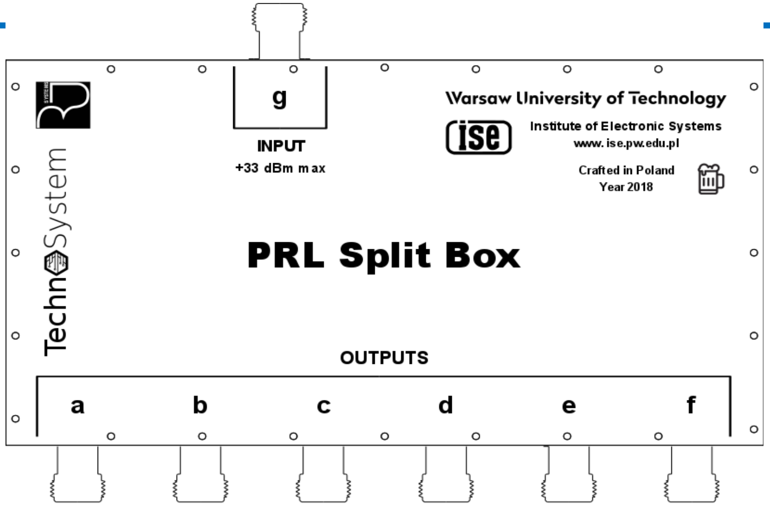


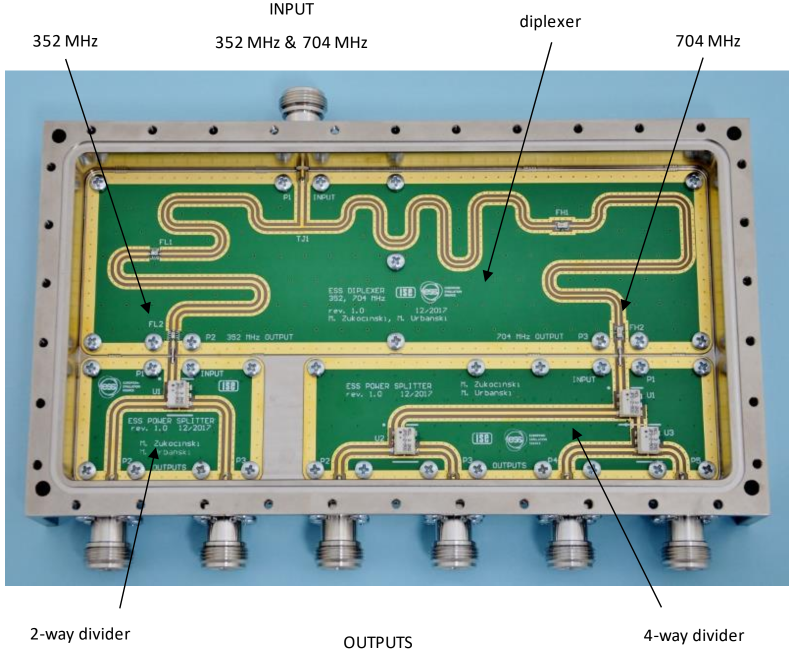


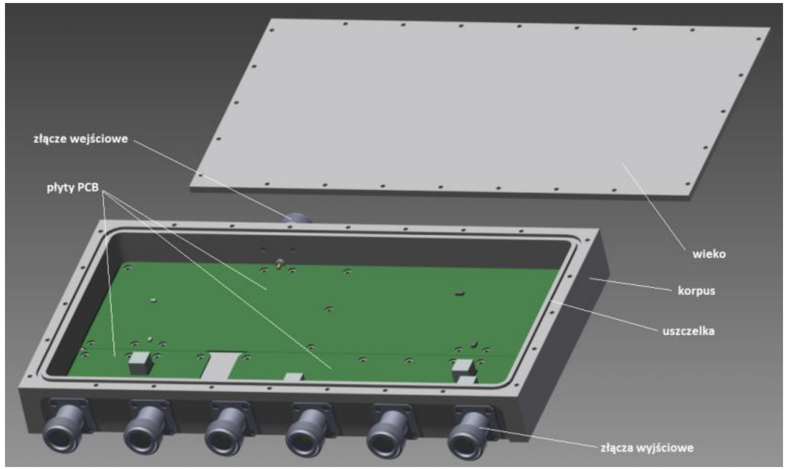


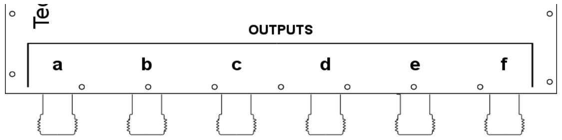
PRL Split Box for TapPoints

- Passive (RF diplexer + power splitter) structure allowing for flexible configuration of output frequencies for up to 6 outputs
- Produced 60 pieces









RF Split Box	assembly configuration (PCBs)	a	b	c	d	e	f
RF Split Box-001	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 352 MHz	BPM 704 MHz	BPM 704 MHz
RF Split Box-002	2+4	LLRF 352 MHz	LBM 352 MHz	spare 704 MHz	spare 704 MHz	BPM 704 MHz	BPM 704 MHz
RF Split Box-003	2+4	LLRF 352 MHz	spare 352 MHz	spare 704 MHz	BPM 704 MHz	BPM 704 MHz	BPM 704 MHz
RF Split Box-004	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-005	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-006	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-007	1+1	LLRF 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-008	1+1	LBM 352 MHz	X	X	X	BPM 704 MHz	X
RF Split Box-009	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-010	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-011	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-012	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-013	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-014	4+2	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	LLRF 352 MHz	spare 704 MHz	BPM 704 MHz
RF Split Box-015	4+1	LLRF 352 MHz	LLRF 352 MHz	LBM 352 MHz	spare 352 MHz	spare 704 MHz	X
....	....	....	....	....	....	....	....

PRL Output Power Levels

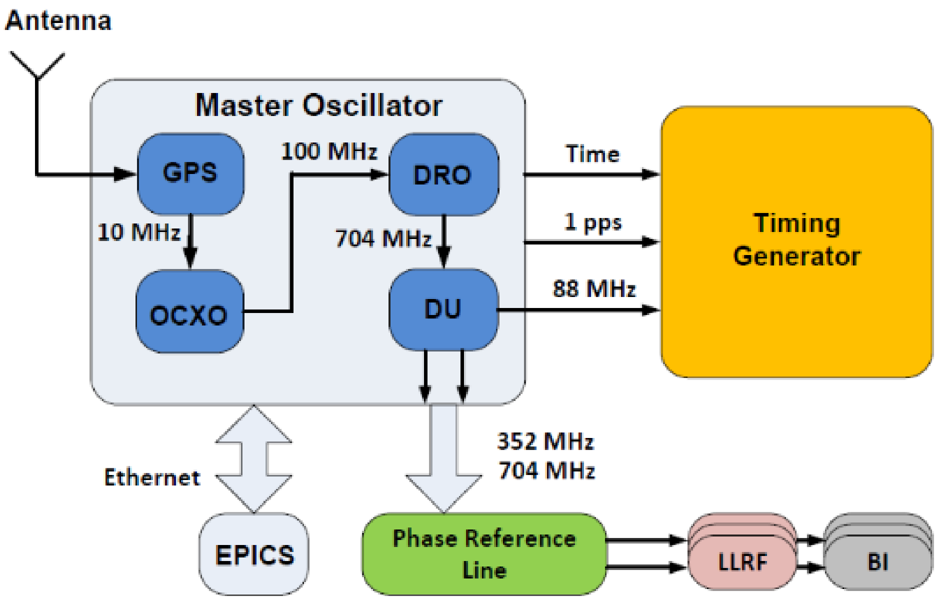
Output type	Required power levels [dBm]		Measured power levels [dBm]	
	Minimum	Maximum	Minimum	Maximum
BPM 352.21 MHz	14.0	25.0	22.7	23.7
BPM 352.21 MHz @PRLTap-046 – 058	10.8	25.0	11.0	16.2
BPM 704.42 MHz	14.0	25.0	17.7	18.4
BPM 704.42 MHz @PRLTap-005 – 008	10.8	25.0	13.0	13.5
BPM 704.42 MHz @PRLTap-004	7.7	25.0	8.8	9.1
LLRF 352.21 MHz	14.0	18.0	15.5	16.2
LLRF 704.42 MHz	14.0	18.0	13.7*	15.0
LBM 352.21 MHz	14.0	25.0	15.7	23.5

- *Power level at 7 outputs 0,3 dBm below specs - additional outputs were requested during installation
- No issue, there is still a safety margin

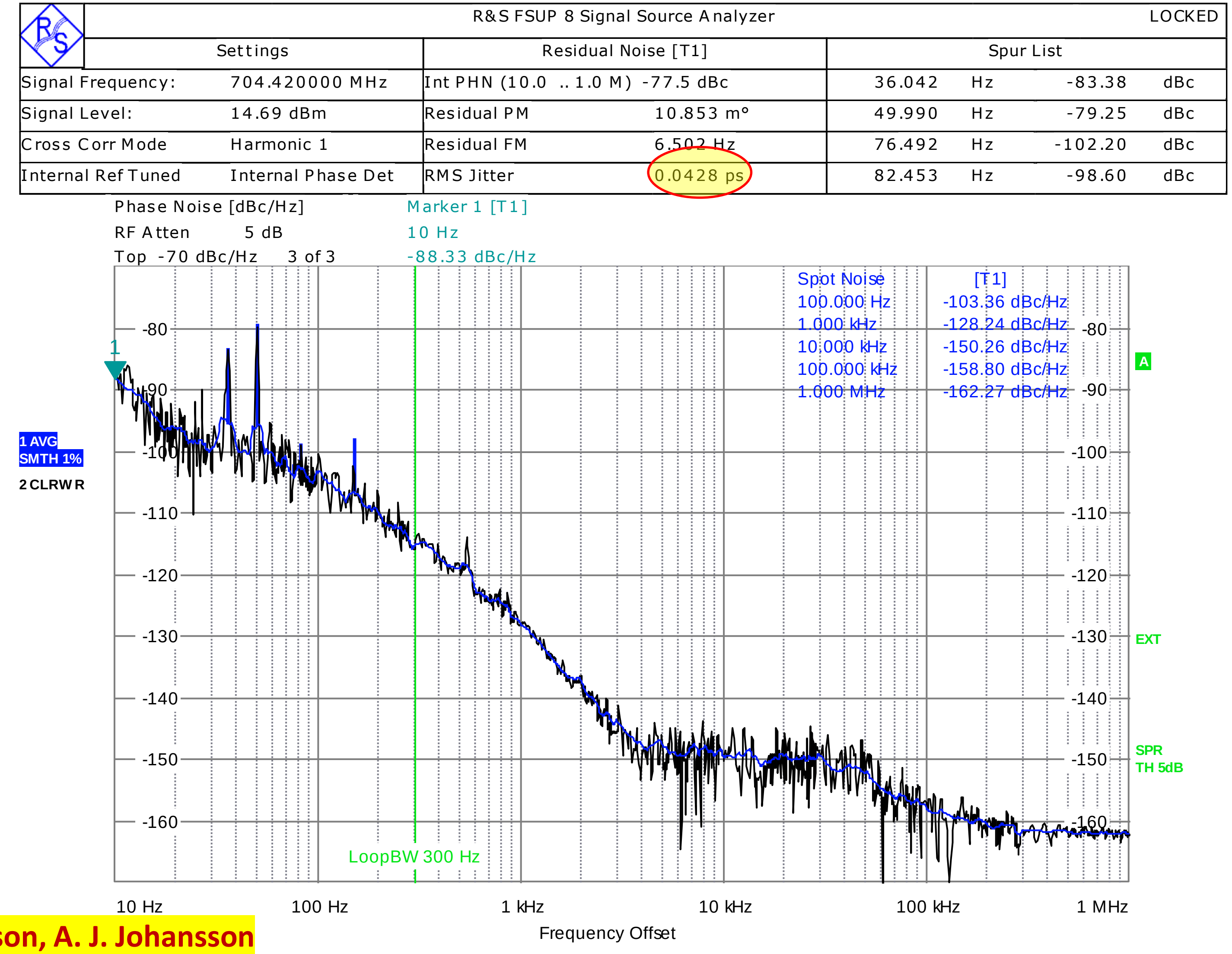
Harmonics of all output signals within specs (< -60 dBc):

- worst case: 63.0 dBc
- best case: 69.4 dBc

Master Oscillator



- Design by Lund University and ESS
- Output power +6.3 dBm
- RMS Jitter **laboratory** test (10 Hz – 1 MHz):
  - ~ 80 fs @ 352 MHz
  - ~43 fs @ 704 MHz



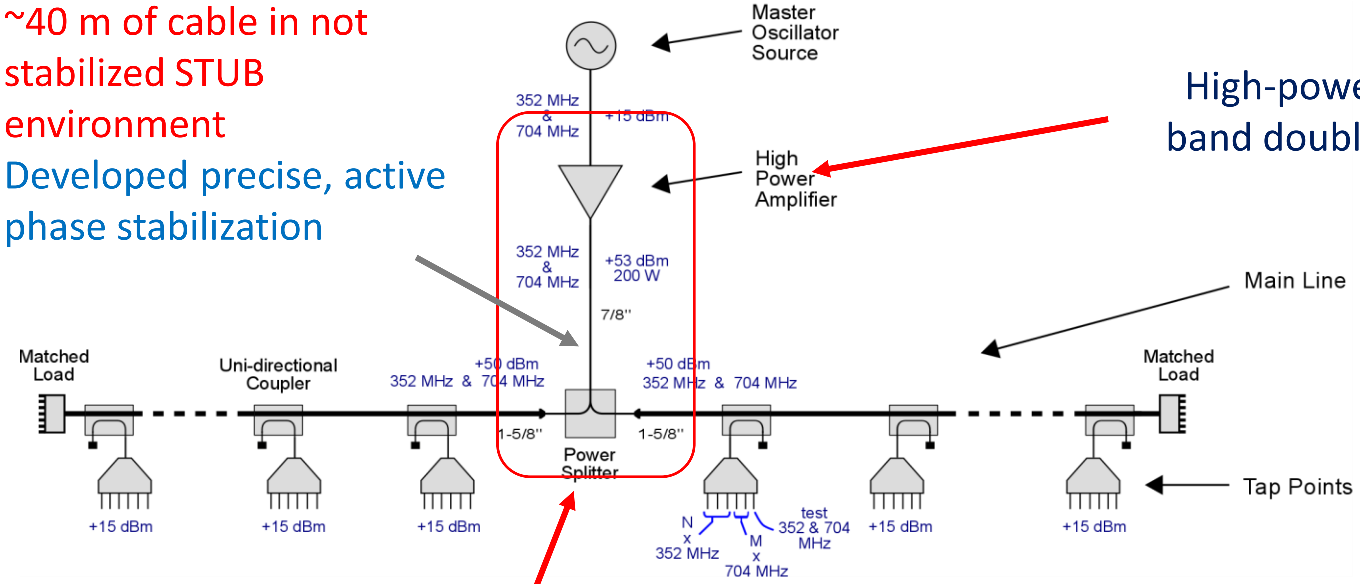
R&S FSUP 8 Signal Source Analyzer — LOCKED

Settings		Residual Noise [T1]		Spur List	
Signal Frequency:	704.420000 MHz	Int PHN (10.0 .. 1.0 M)	-77.5 dBc	36.042 Hz	-83.38 dBc
Signal Level:	14.69 dBm	Residual PM	10.853 m°	49.990 Hz	-79.25 dBc
Cross Corr Mode	Harmonic 1	Residual FM	6.502 Hz	76.492 Hz	-102.20 dBc
Internal Ref Tuned	Internal Phase Det	RMS Jitter	0.0428 ps	82.453 Hz	-98.60 dBc

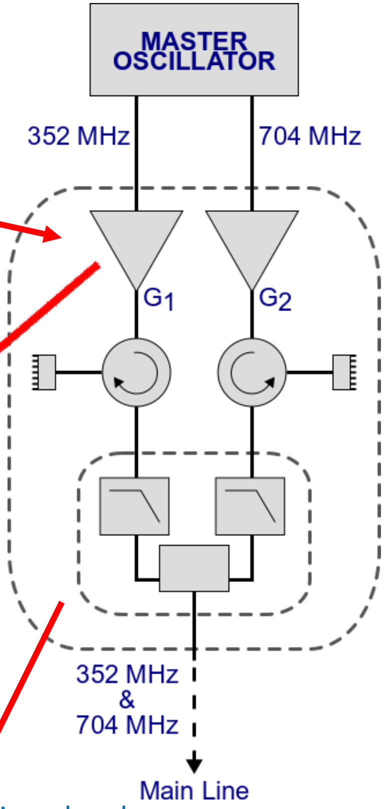
Courtesy of A. Svensson, A. J. Johansson

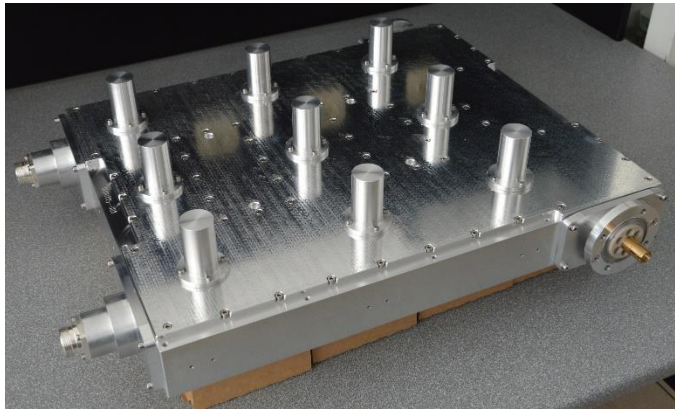
PRL Input Section

- ~40 m of cable in not stabilized STUB environment
- Developed precise, active phase stabilization



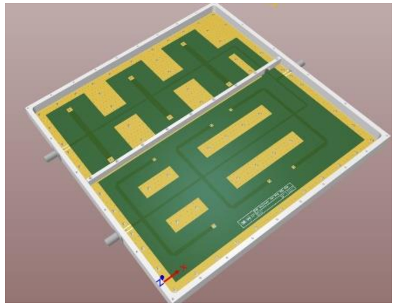
High-power (~200W) broad band double amplifier system



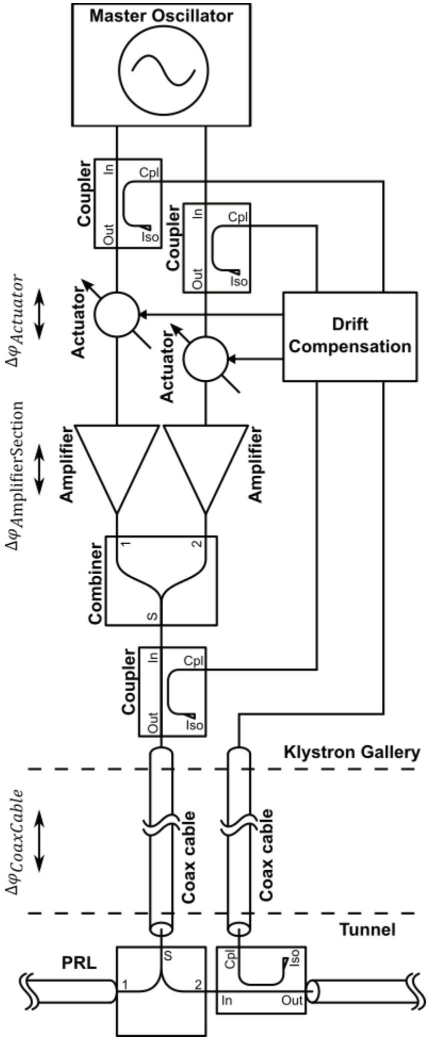


Input power splitter by the Space Forest company

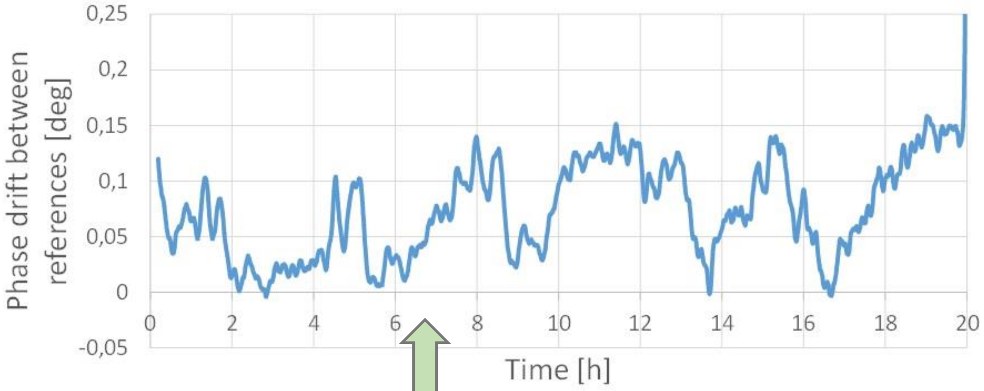
Bandpass combiner designed and produced at WUT

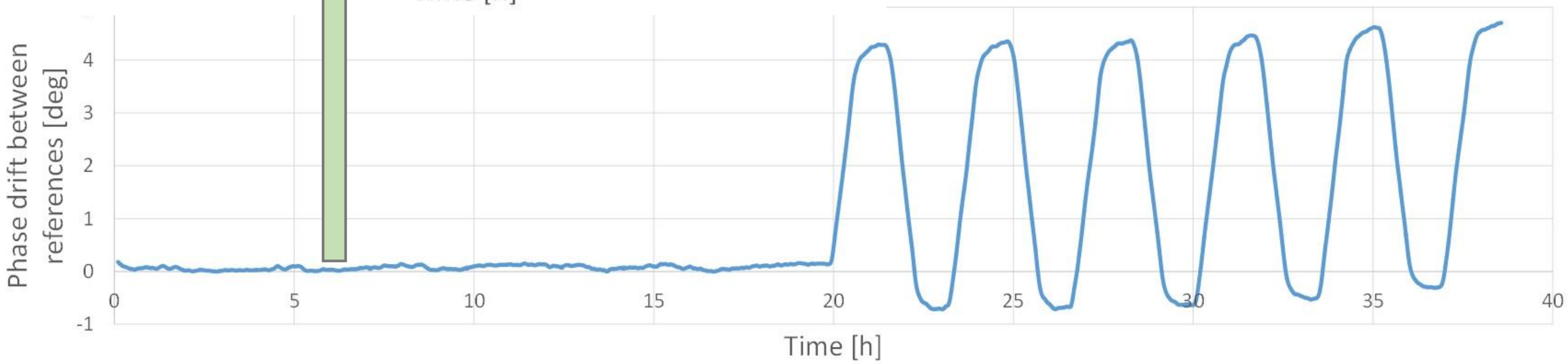


PRL Input Section Drift Compensation



- PRL PDC – compensation of phase drift between the MO and PRL line in the tunnel (**long cable, no temperature stabilization**)
- Laboratory tests: 0.15 deg p-p of phase stability

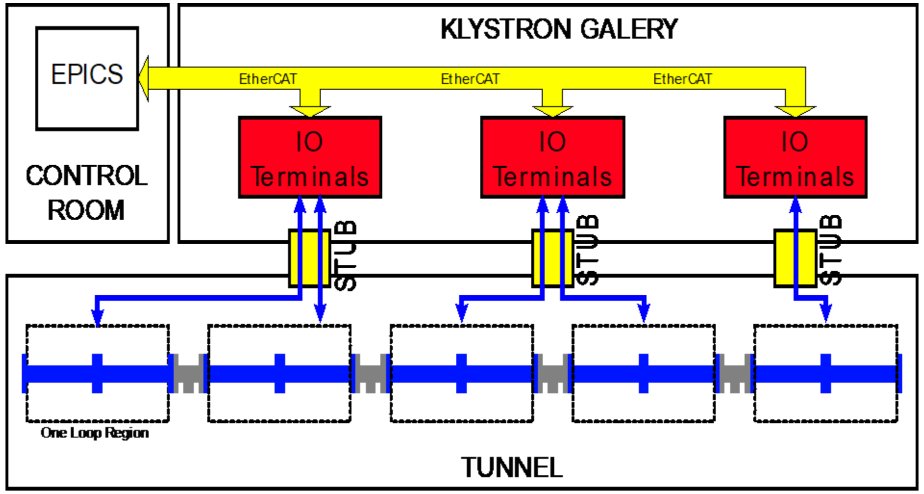


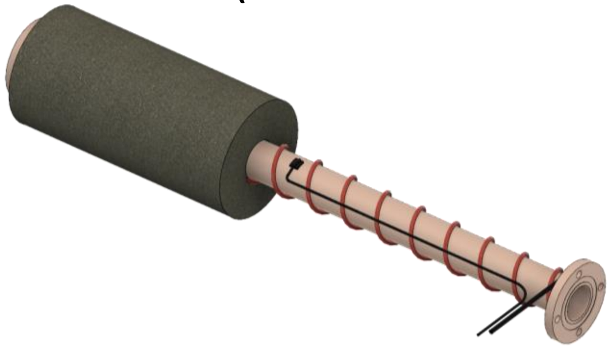


D. Sikora et al.: „Phase drift compensating RF link for femtosecond synchronization of E-XFEL", IEEE Transactions on Nuclear Science 2020
D. Sikora et al.: „RF Connection from Master Oscillator to Phase Reference Line in European Spallation Source", MIKON 2020

Temperature Control System

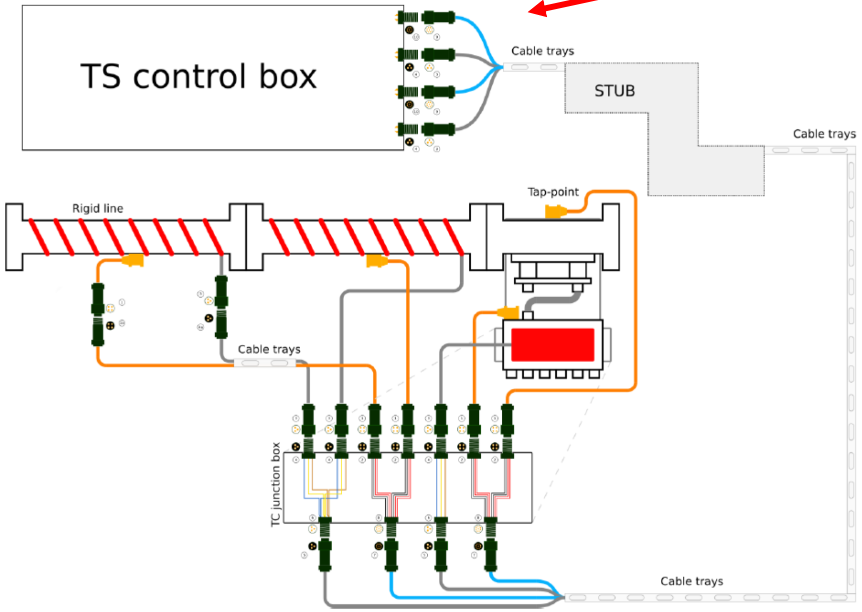
- Regulation to +/- 0.1 °C, 600 m line + 58 Tap Points!
- Line is wrapped with a **heating tape and a thermal insulation**
- Industrial temperature controllers – basic selection and general concept by Lund University (Björn Olofsson)
- 202 independent temperature control loops
- Control software running on EPICS servers
- Concept successfully tested in PRL prototype at WUT
- A lot of logistics, tests and quality control needed (over 6000 internal cable connections …)



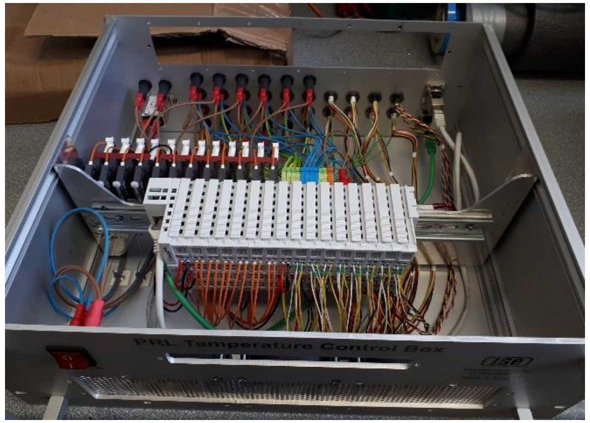


Temperature Control System Components

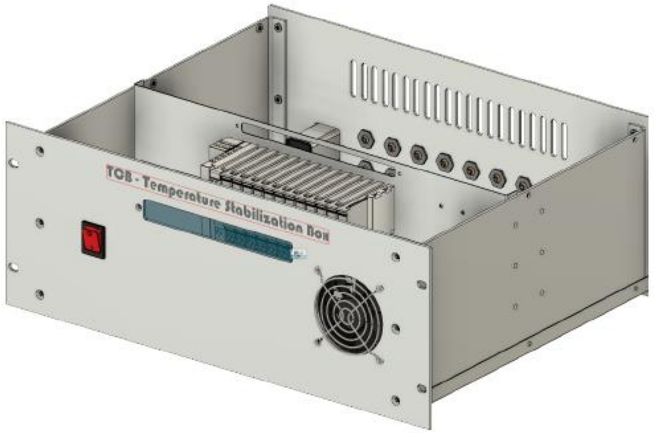
Simplified scheme of 1 section temperature control



202 systems
~26 km of cables



Temperature Control Box



Produced 19 pieces

EPICS Implementation

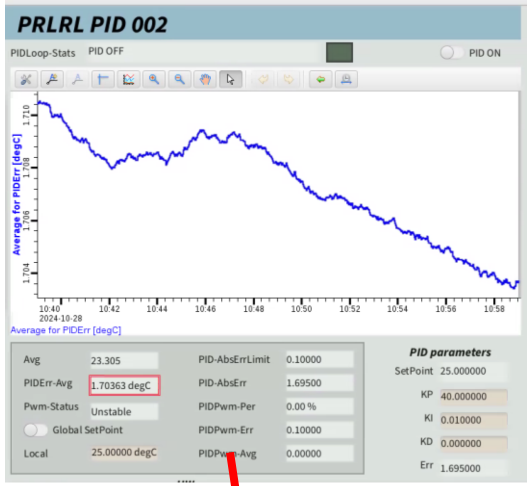
EPICS IOC

- EPID record -> temperature control
- EtherCAT master for communication

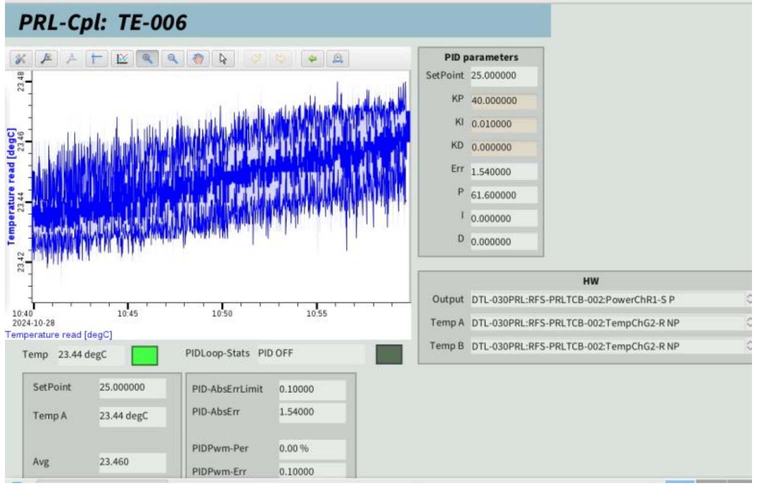
EPICS OPI

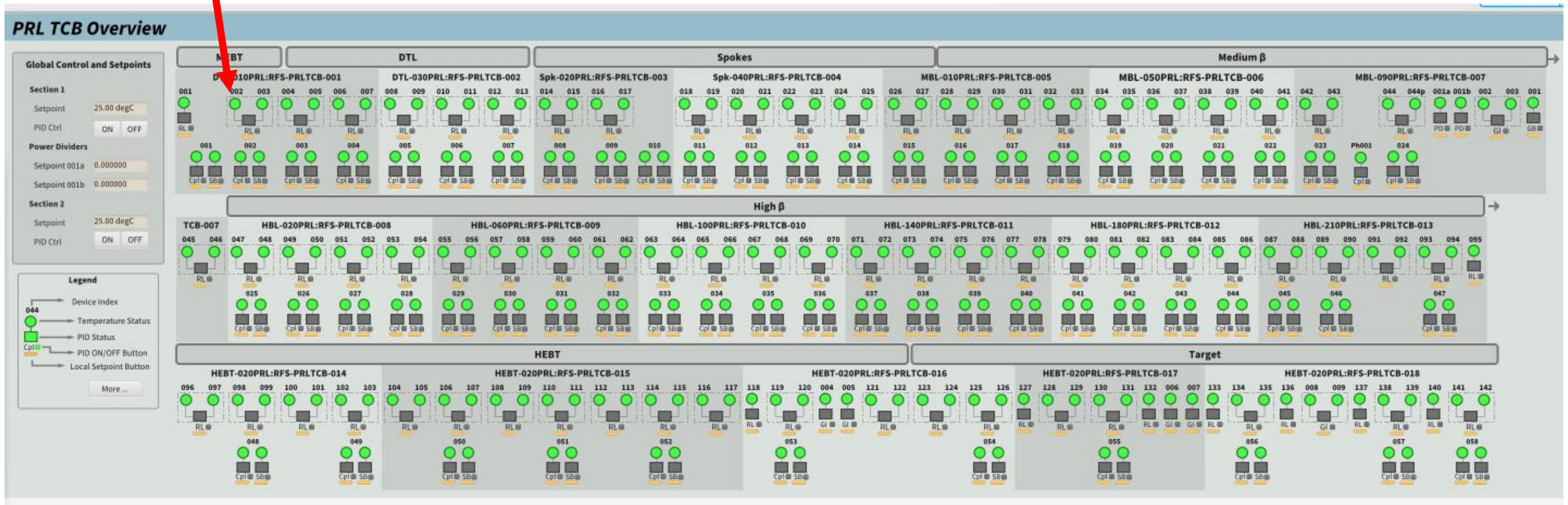
- Status of all sensors
- Temperature stabilization loop status
- Set-point
- Temperature history plot

Single control loop panel



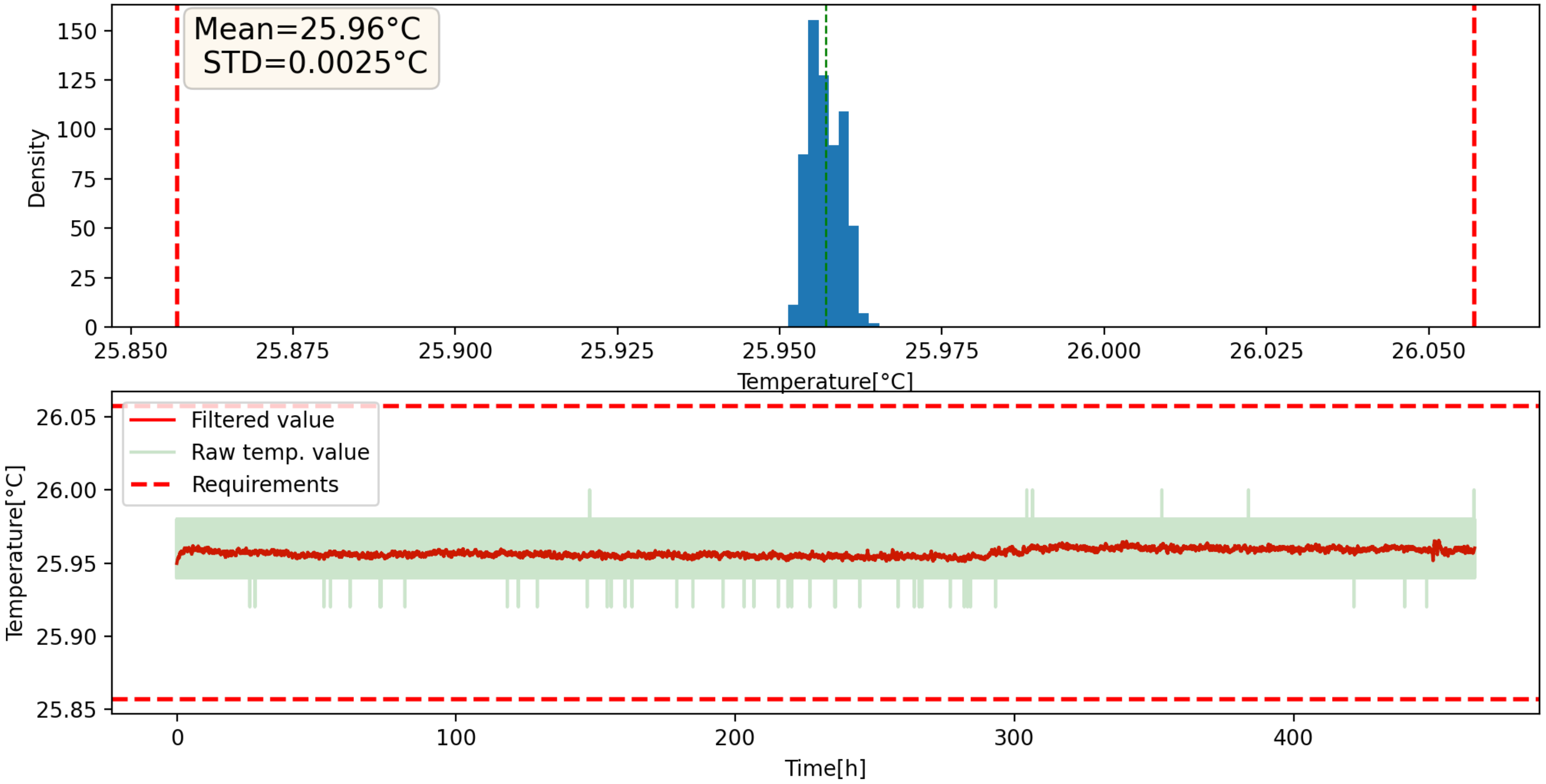
Temperature sensor panel





Temperature Control Tests Example – MBL-090

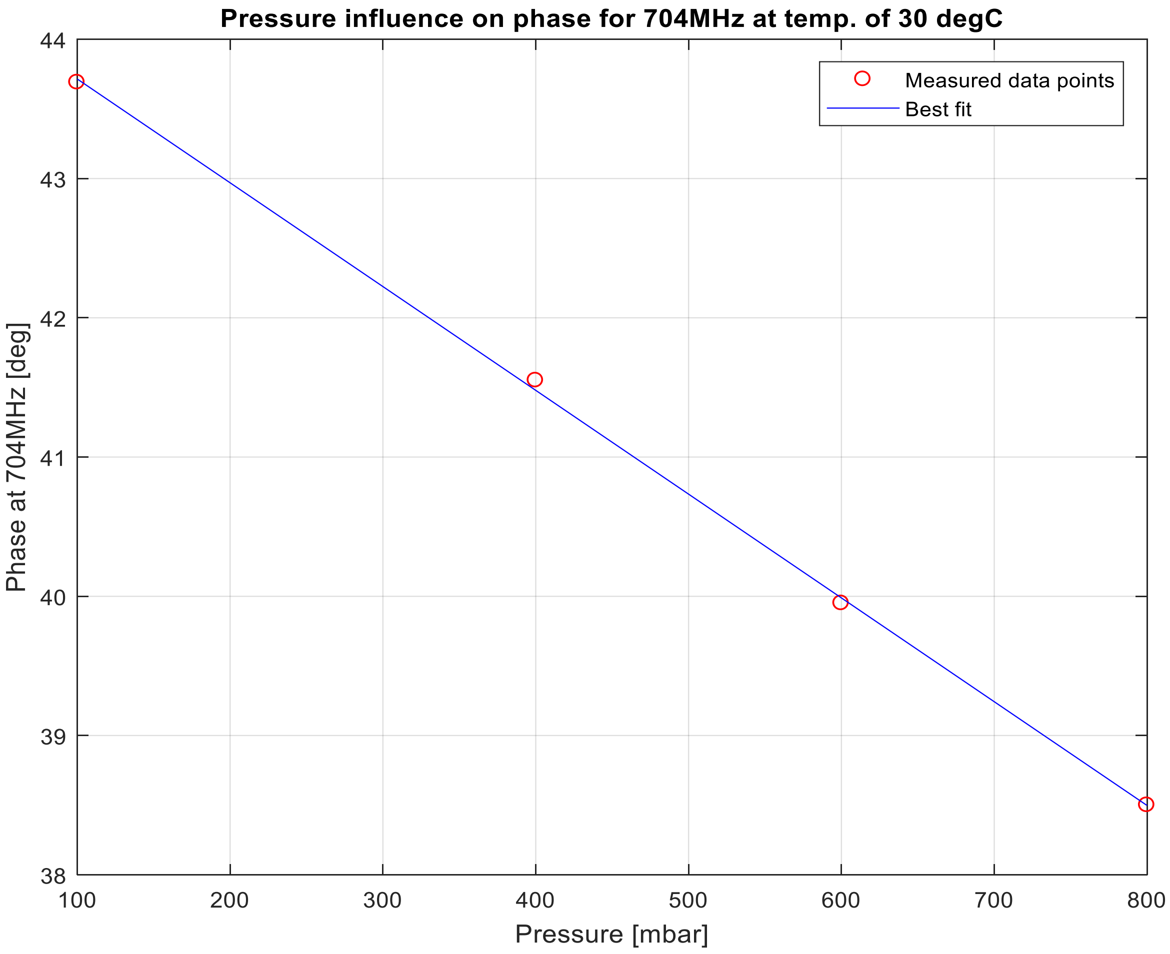
- Example of **one week** test - all control loops running simultaneously
- Typical result for most sections **~0,015°C p-p**
- Required +/- 0.1°C p-p
- Meets requirements

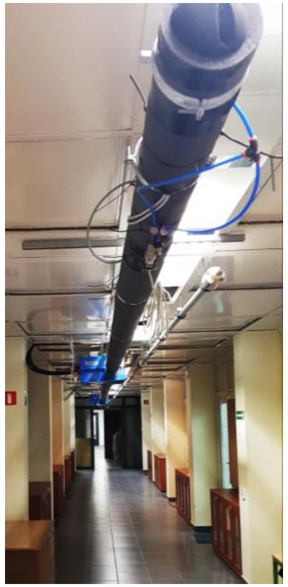


Humidity Issue

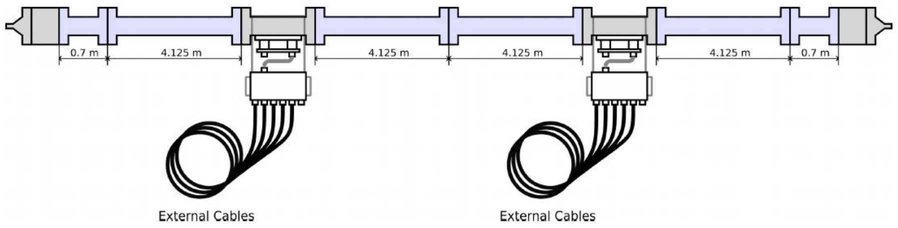
- Tested at the WUT prototype (18.7 m)
- Result: 20^o of phase change @ 704 MHz for 600m (not sure!)
- Difficult to measure:
  - probably too short line
  - difficult to precisely control humidity in a long line
  - sensitivity to temperature and pressure changes
- Calculated air dielectric constant change influence on phase due to humidity
- Result: ~130 deg of phase change @ 704 MHz for 600m (not sure…)
- Rigid line can be sealed but internal pressure will be constant – external will change…
- Decision: stabilize pressure of a dry Nitrogen inside the line

Internal Pressure Influence on Phase



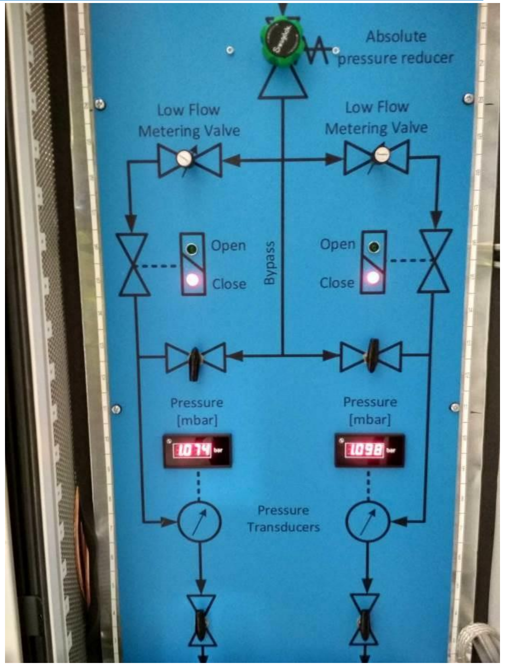


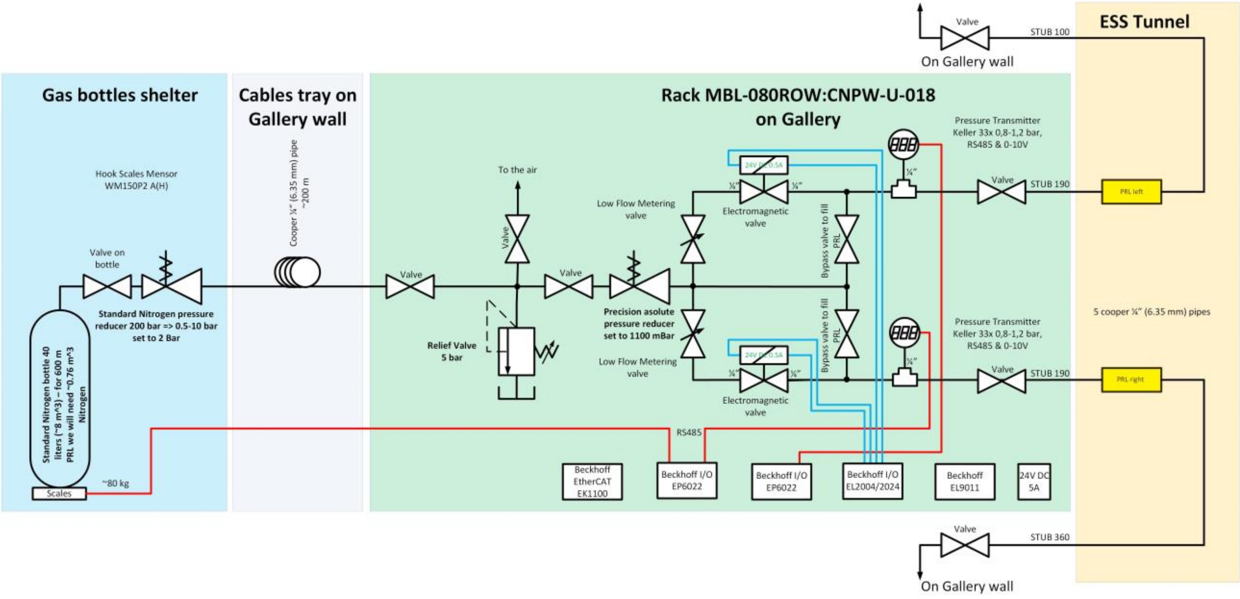
- **Measured round trip phase change in the PRL prototype (2x18.7 m)**
- Temperature Stabilized
- **700 mbar pressure change applied**
- **~5 ° p-p phase change for 37.4 m**
- Estimated ~0.11 °/mbar for 600 m
- Max allowed pressure change ~18 mbar
- Assumed 5 mbar for the design



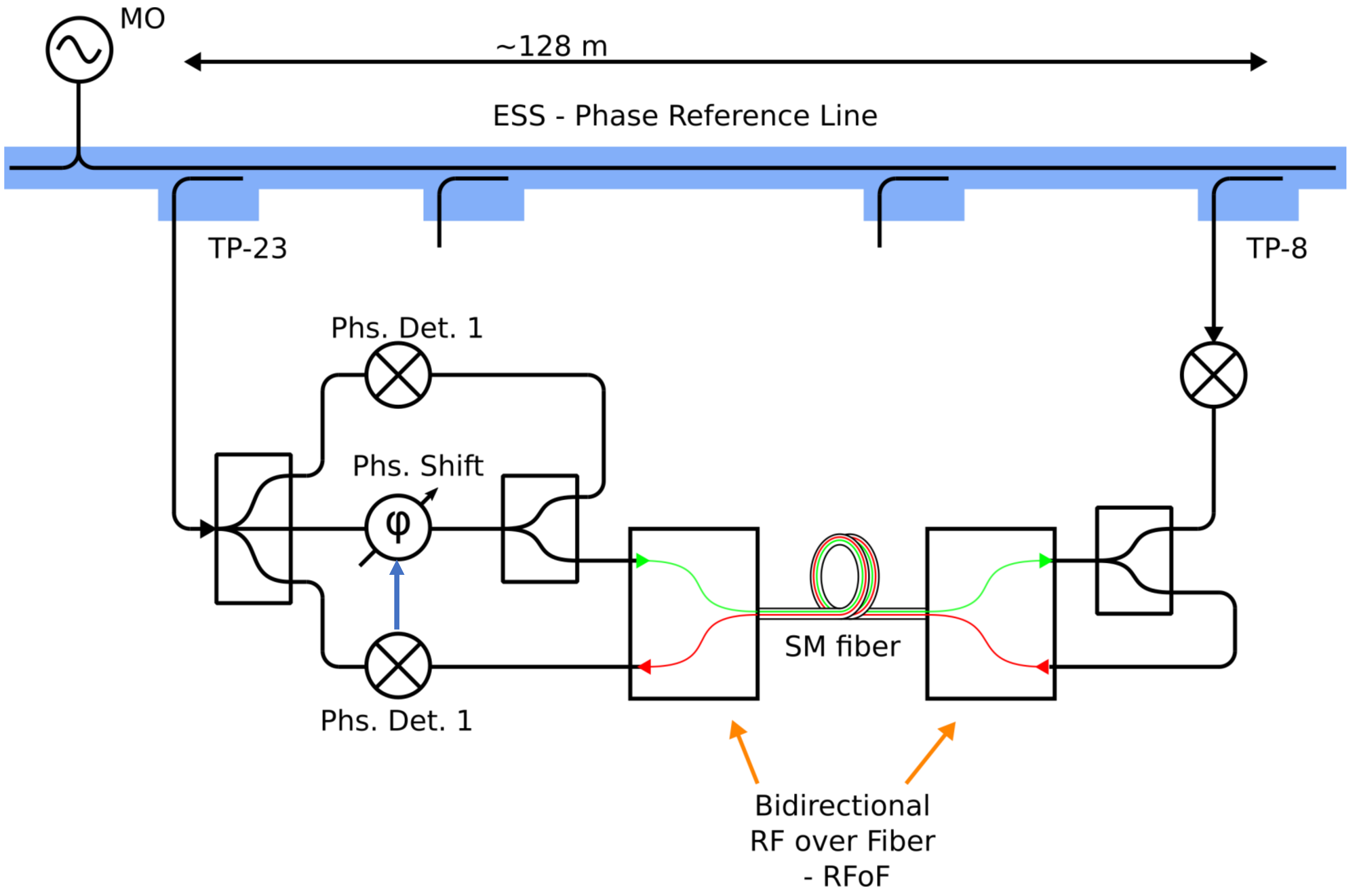
Nitrogen Pressure Stabilization

- Line filled with Nitrogen to remove humidity
- Achieved +/- 1 mbar pressure stability
- Gas bottles and valves allowing to separately stabilize and fill in both PRL branches



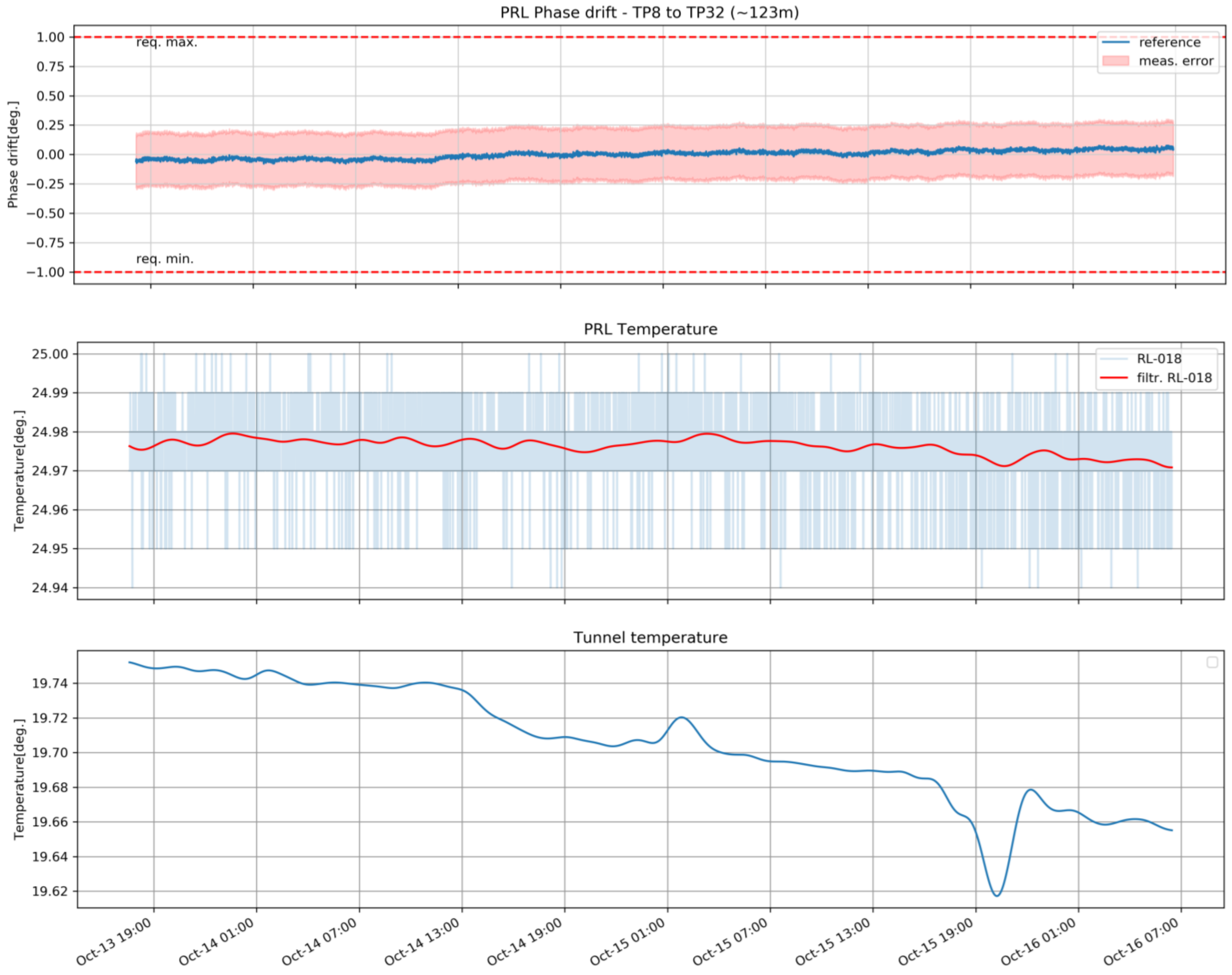


PRL Drift Performance Test Setup



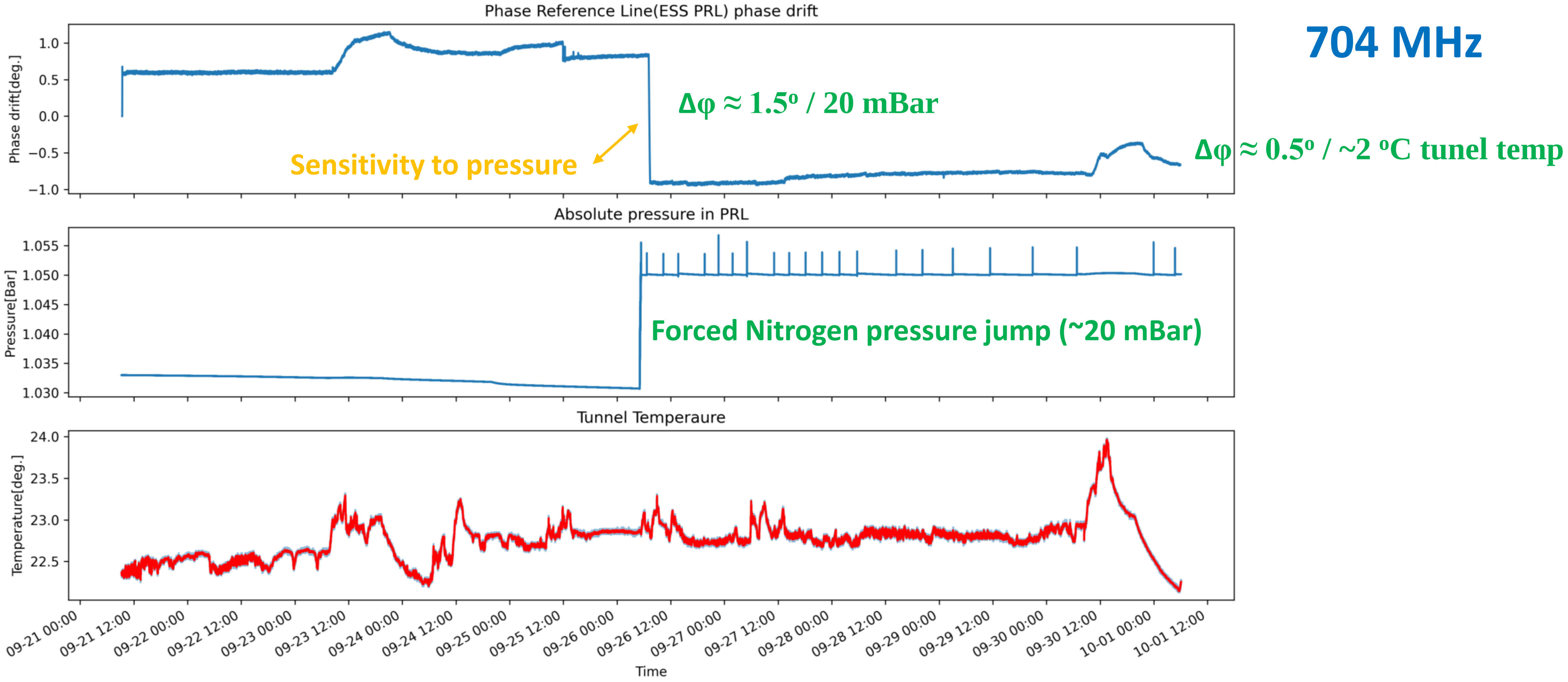
- Phase change measured between TP8 and TP32 (123 m distance
- Installed temporary low-drift (but noisy!) fiber link

Temperature Stability and Phase Drift @ 704 MHz (128m)



- Fairly stable tunnel temperature
- Duration 60h
- **Temperature change (mid section) 0.01 ºC p-p**
- **Phase drift: 0.12 º p-p**
- Requirement: 2.0 º p-p

Phase vs Pressure and Tunnel Temperature, STUB190-to-Dogleg, 406m, 10 Days



704 MHz

Performance Summary

- Power levels within specs
- Drift compensation in the link between MO and tunnel 0.15 °C p-p
- **Phase drift: 0.12 ° p-p** and **temperature change of 0.01 °C p-p** at 123 m distance
- Phase drift **0.5 ° p-p @704 MHz vs tunnel temp. change of 2°C p-p over 10 days at 406 m distance** (required 2 ° p-p)
- Tests still ongoing
- Planned installation of permanent drift monitoring system (?)

Thank you for attention!

Thanks to all contributors to the system design and installations!

Adam Abramowicz, Anirban Krishna Bhattacharyya, Jerzy Berliński, Bo Bernhardsson, Łukasz Czuba, Grażyna Fistek, Luciano Carneiro Guedes, Paweł Jatczak, Morten Jensen, Michał Kalisiak, Mateusz Lipiński, Maria Mielnik, Krzysztof Oliwa, Björn Olofsson, Radosław Papis, Dominik Sikora, Anders Sunesson, Maciej Urbański, Wojciech Wierba, Rihua Zeng, Mateusz Żukociński, (hope nobody was forgotten…)