Development of a Ruggedized Rubidium CPT Clock Platform

A Leading Provider of Smart, Connected and Secure Embedded Control Solutions

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Presentation Overview

- **Background and motivation**
- **Concept**
- **Preliminary test results**
  - Power consumption
  - Short-term stability / phase noise
- **Prototype test results**
  - Radiation testing
- **Summary**

Coherent Population Trapping (CPT) Background

- **Technology: Coherent Population Trapping (CPT) architecture enables simplification / power reduction of physics package**
- **Key features: Low SWaP, with atomic clock accuracy and precision**
- **History: First demonstrated in 1978. 1990s VCSEL technology provided a path toward commercialization**
- **Development: Initiated in 2001 with Draper and Sandia Laboratories (DARPA contract) to create a CSAC**
- **Improved: manufacturability 2009 to 2013 (Army / ManTech Contract)**

CSAC Released in 2011

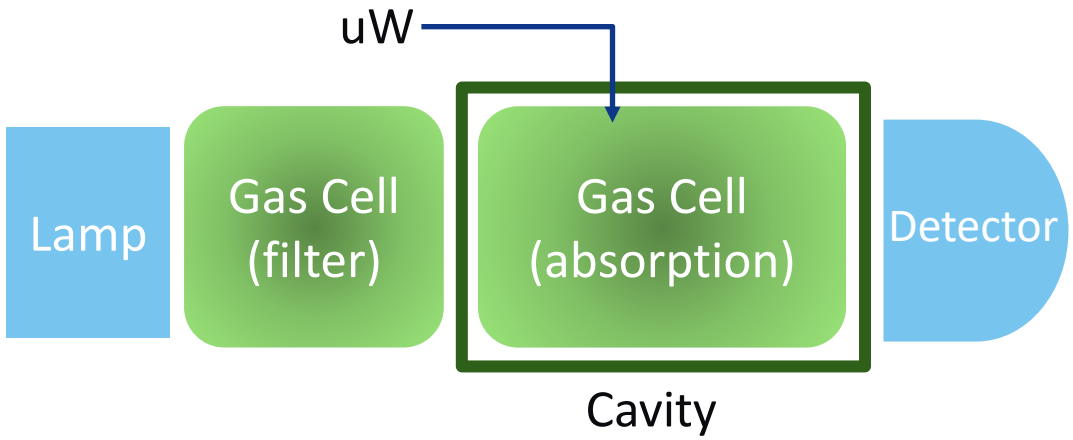
CSAC-SA65 Released in 2022

MAC Released in 2009

MAC-SA55 Released in 2020

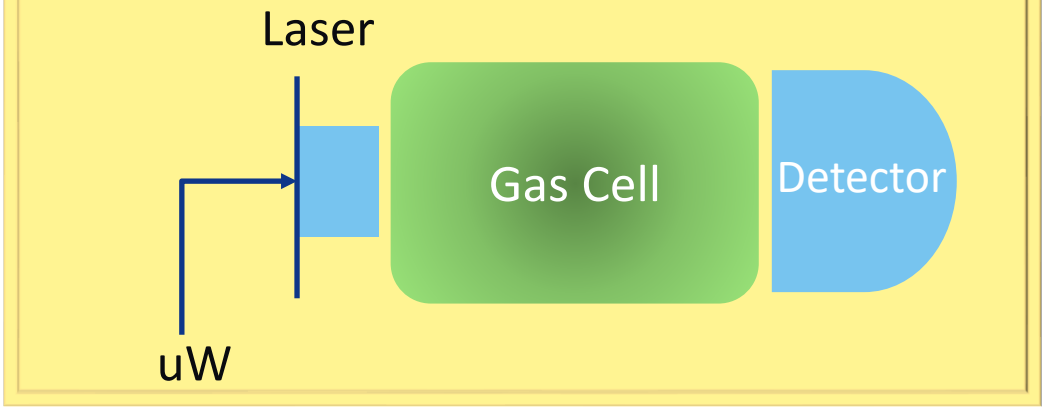
Legacy approach:

Optical-microwave Double Resonance (OMDR)



Current approach:

Coherent Population Trapping (CPT)



Replaces lamp with VCSEL, uW directly applied to VCSEL, low SWaP

Requires resonant uW cavity, RF discharge lamp (1W), multiple cells , ovens, controllers

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Motivation

*Low Earth Orbit

Shorter / more frequent / low-cost missions in LEO*

→ Require COTS availability with radiation tolerance and a desire for latest technology

- **Defense / Commercial applications**
  - ✓ LEO space defense
  - ✓ Optical time transfer
  - ✓ Inter-satellite communications
  - ✓ Earth observation
  - ✓ Ionosphere weather monitoring
  - ✓ Radio Frequency (RF) geolocation
  - ✓ Interferometry
  - ✓ Tactical MILSATs

Some missions require higher stability than Space CSAC → Space MAC (Rb) desired

Space CSAC Heritage

- **> 740 units shipped since 2018**
- **> 40 unique clients**
  - Multiple NASA Science missions (CAPSTONE cislunar, CHOMPTT)

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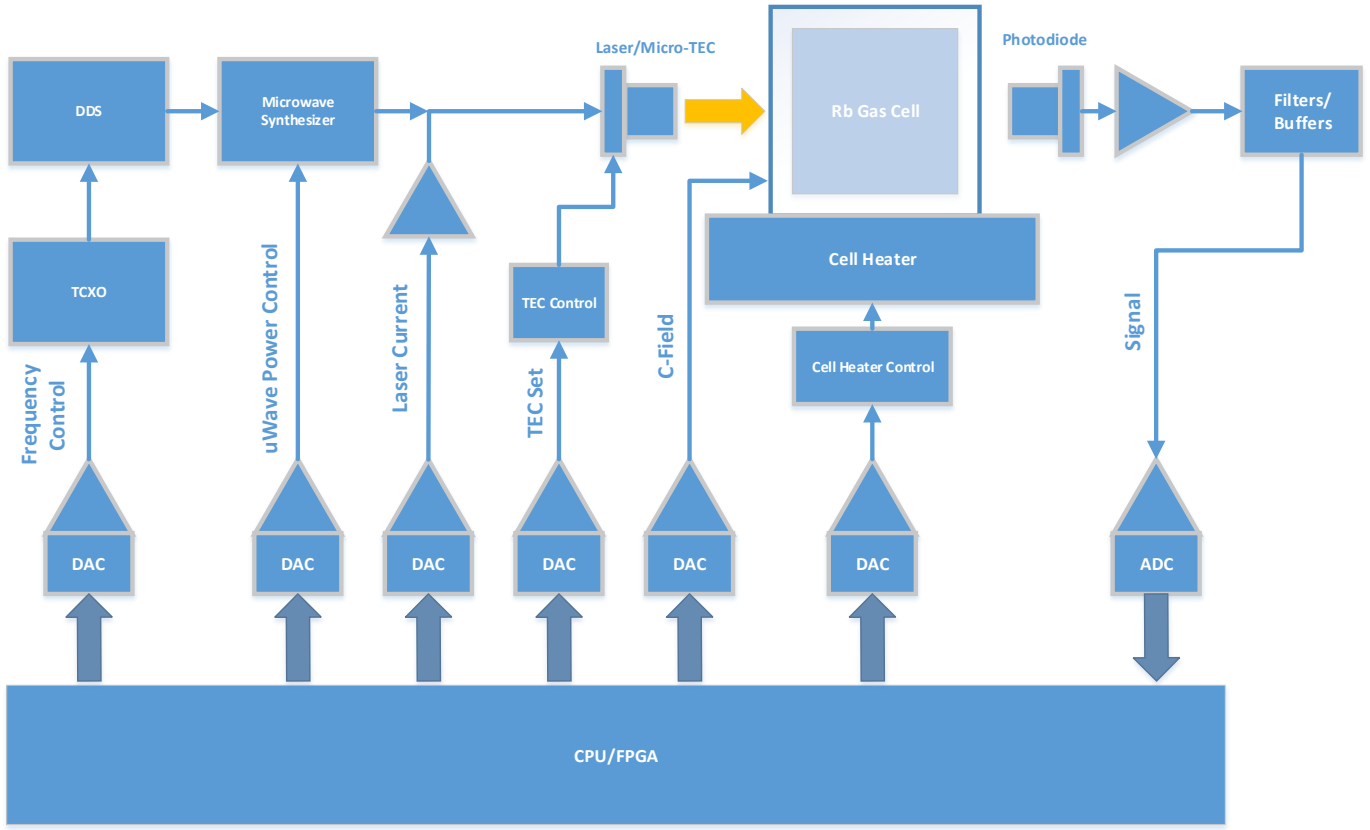
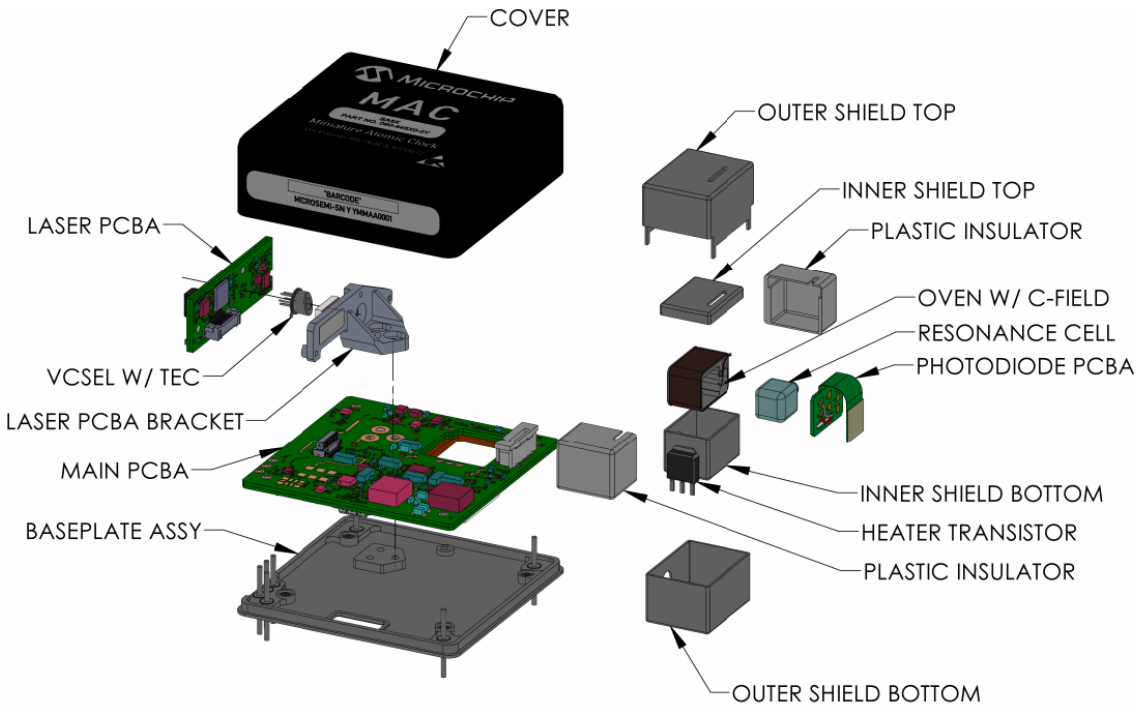
Architecture

Simple Block Diagram



Assembly



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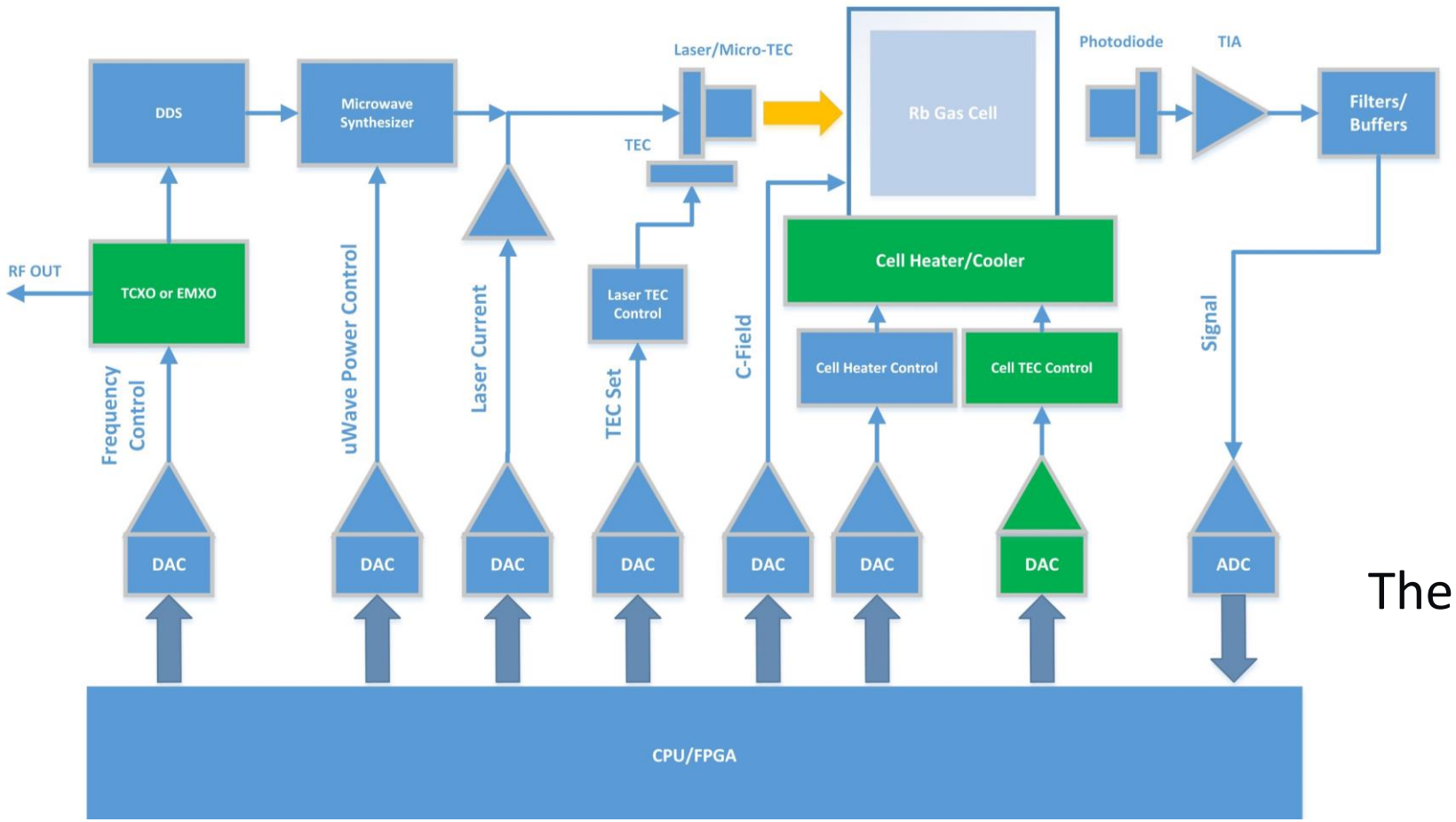
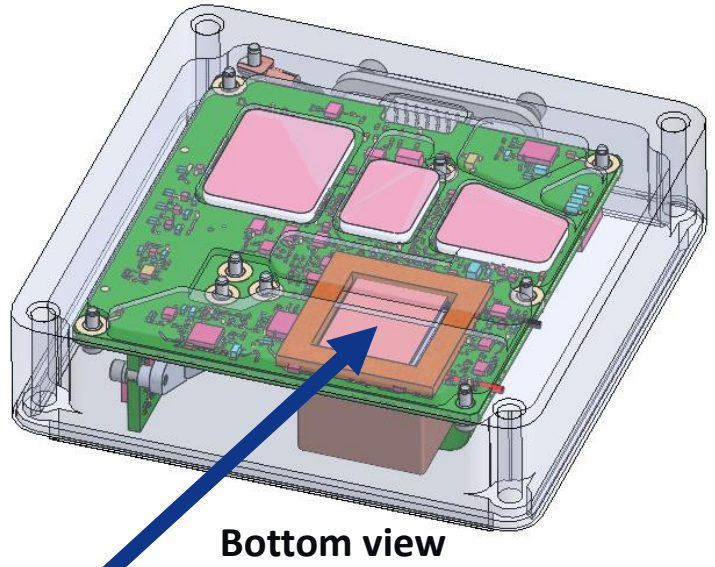
New Architecture





Bottom view

Thermo-Electric Cooler

Limitation: upper operating temperature predicated by cell temperature

Solution: use TEC to help maintain cell temperature

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Ruggedization and Improvement Goals

Ruggedization

- **Increased temperature range**
  - -40 to > +85 °C
- **Packaging**
  - Hermetic
    - Vented space variant
  - Rugged I/O (D-sub, SMA)
  - Height < 0.7 in.

Performance and Features

- **Features**
  - Low Noise
    - ADEV (1S) < 2E-12 [Goal]
    - Phase Noise (1Hz) < -100 dBc/Hz [Goal]
  - Radiation-tolerant option
    - >30 Krad [Goal]
- **Maintain key features**
  - 1 PPS disciplining
  - Robust telemetry diagnostics
- **Maintain (or improve) key stability metrics**
  - TempCo < 5E-11
  - ADEV floor ~ ppE-13
  - Aging < 5E-11 /month (freq. drift rate)

Ruggedized Rb *Model 8300C LN*

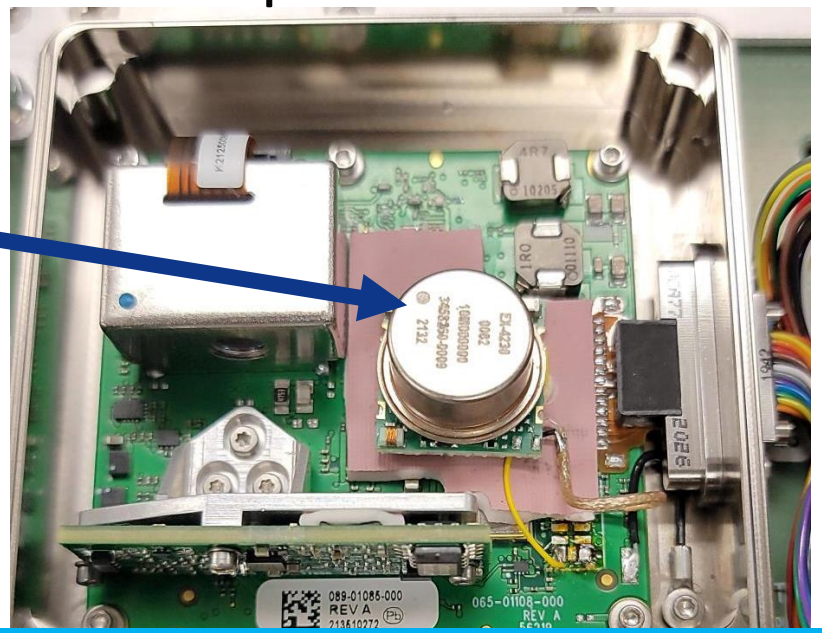
Experimental Results

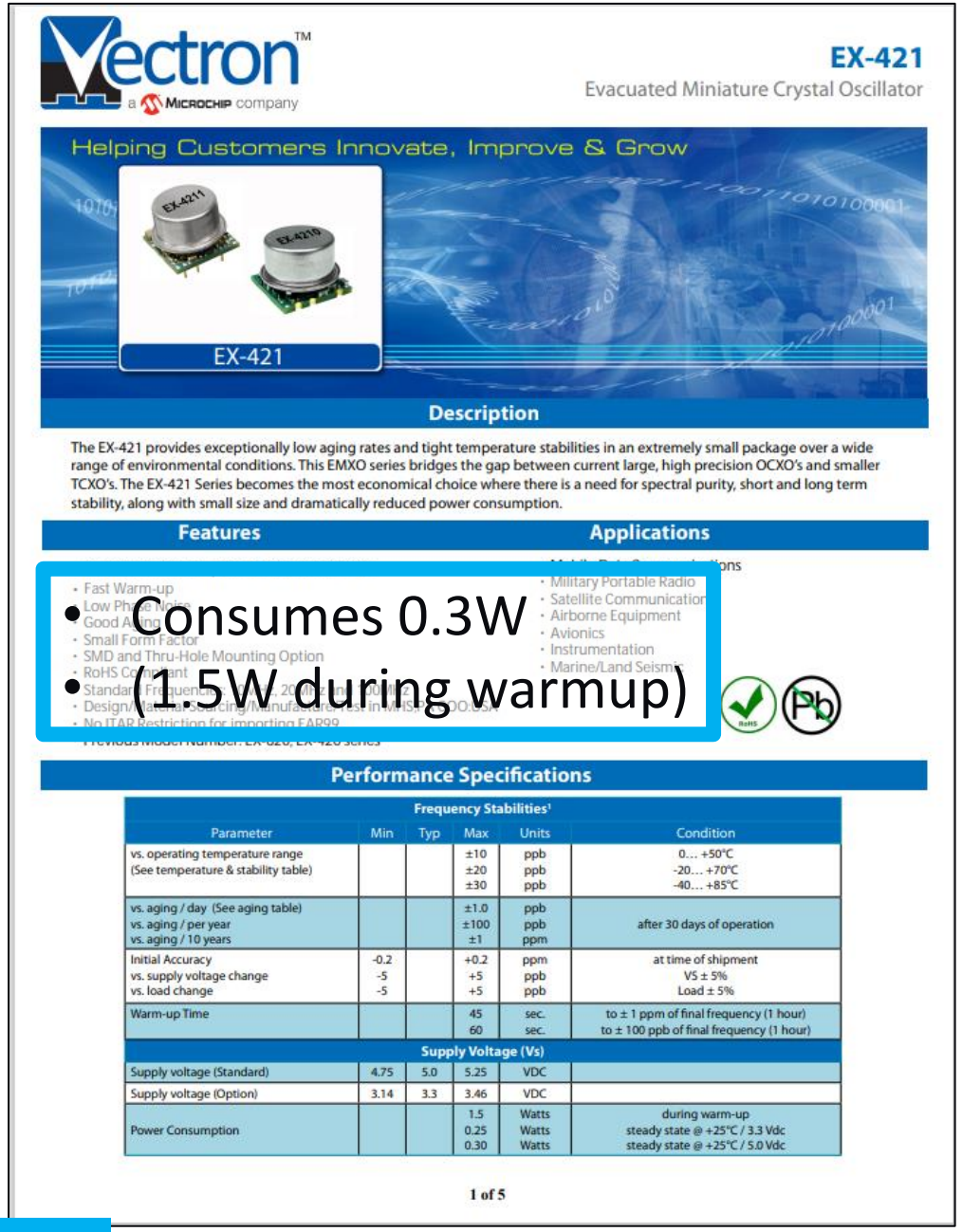
Low-Noise Configuration

8300C LN

- **Goals**
  1. Improve ADEV < 100s
  2. Improve Phase Noise
  3. Minimize added power

EMXO "Dead-bugged" into assembly





- Consumes 0.3W
- (1.5W during warmup)

Projected <6W at maximum operating temperature

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Combined Power Draw of 8300C, TEC and EMXO

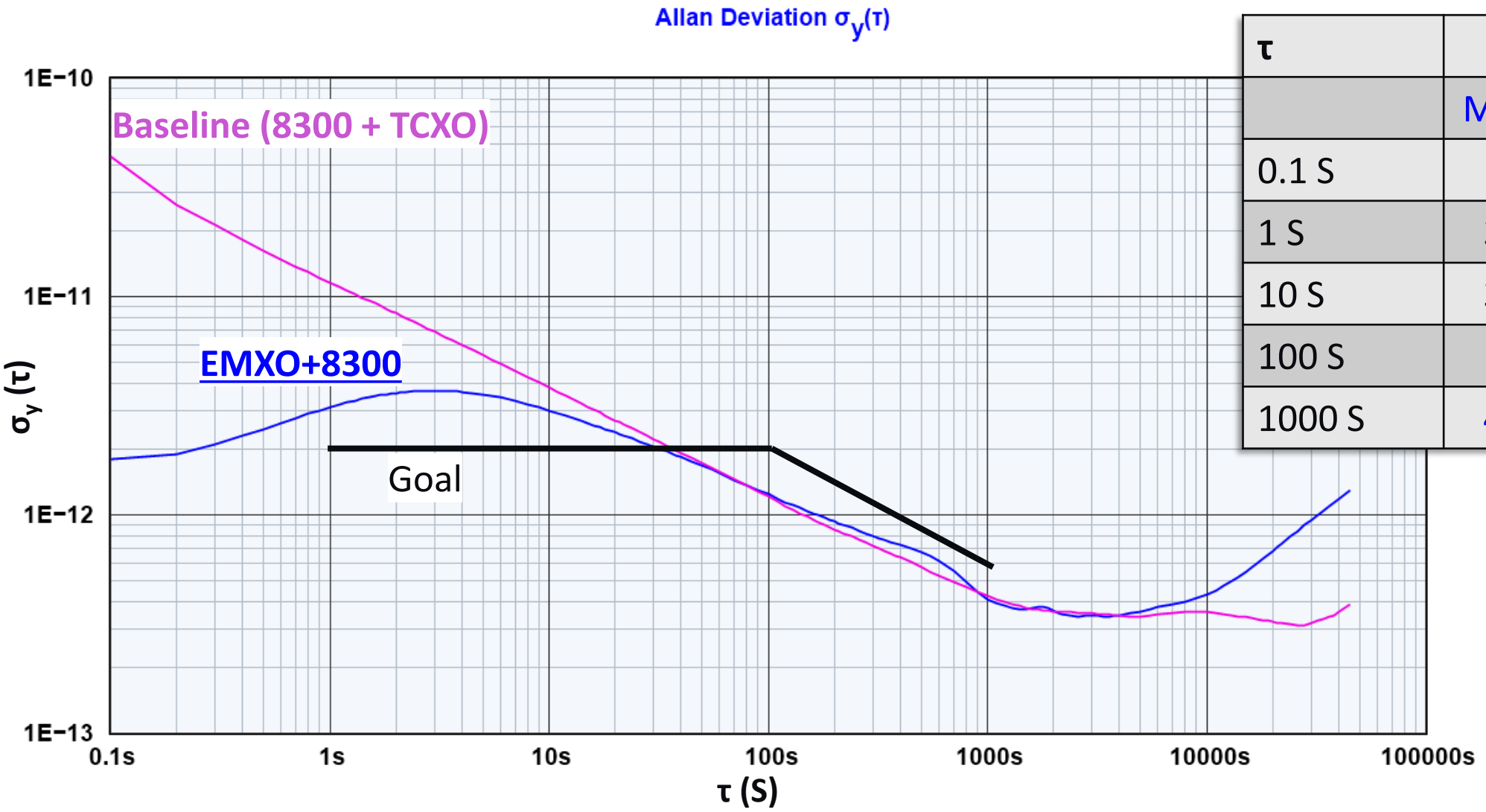
Projected <6W at maximum operating temperature

	Goal	**TOTAL (calculated)**	EMXO (typical)	TEC + 8300b (calculated)
Warm-up power (W)	20	15.5	1.5	14
Power @ -40°C (W)*	16	10.3	0.3	10
Power @ 25°C (W)	12	6.8	0.3	6.5
Power @ 65°C (W)		4.8	0.3	4.5
Power @ 75°C (W)		<5.1	0.3	<4.8
Power @ 80°C (W)		<5.3	0.3	<5
Power @ 85°C (W)	**8**	**<5.8**	0.3	<5.5
Power @ 90°C (W)		<6.6	0.3	<6.3

*temperature measured at the baseplate

Conclusion: High temperature and LN operation is attainable, without breaching power goal

ADEV of 8300 LN Option



τ	σ_y (τ)	
	Measured	Goal
0.1 S	1.9E-12	-
1 S	3.1E-12	2E-12
10 S	3.0E-12	2E-12
100 S	1.2E-12	2E-12
1000 S	4.1E-13	6E-13

Conclusion: ADEV < 30s is improved with EMXO (blue trace)

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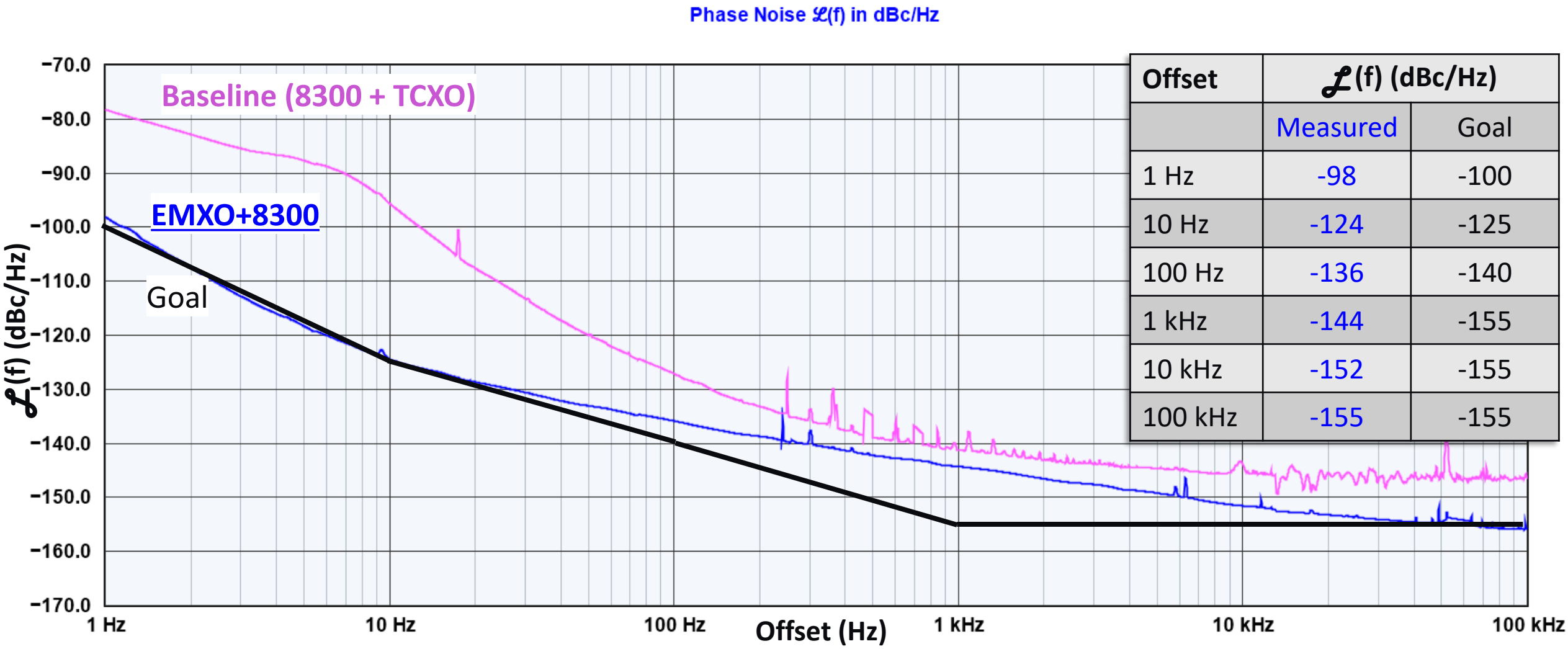
Phase Noise of 8300 LN Option



Offset	ℒ(f) (dBc/Hz)	
	Measured	Goal
1 Hz	-98	-100
10 Hz	-124	-125
100 Hz	-136	-140
1 kHz	-144	-155
10 kHz	-152	-155
100 kHz	-155	-155

Conclusion: Phase Noise is improved with EMXO (blue trace)

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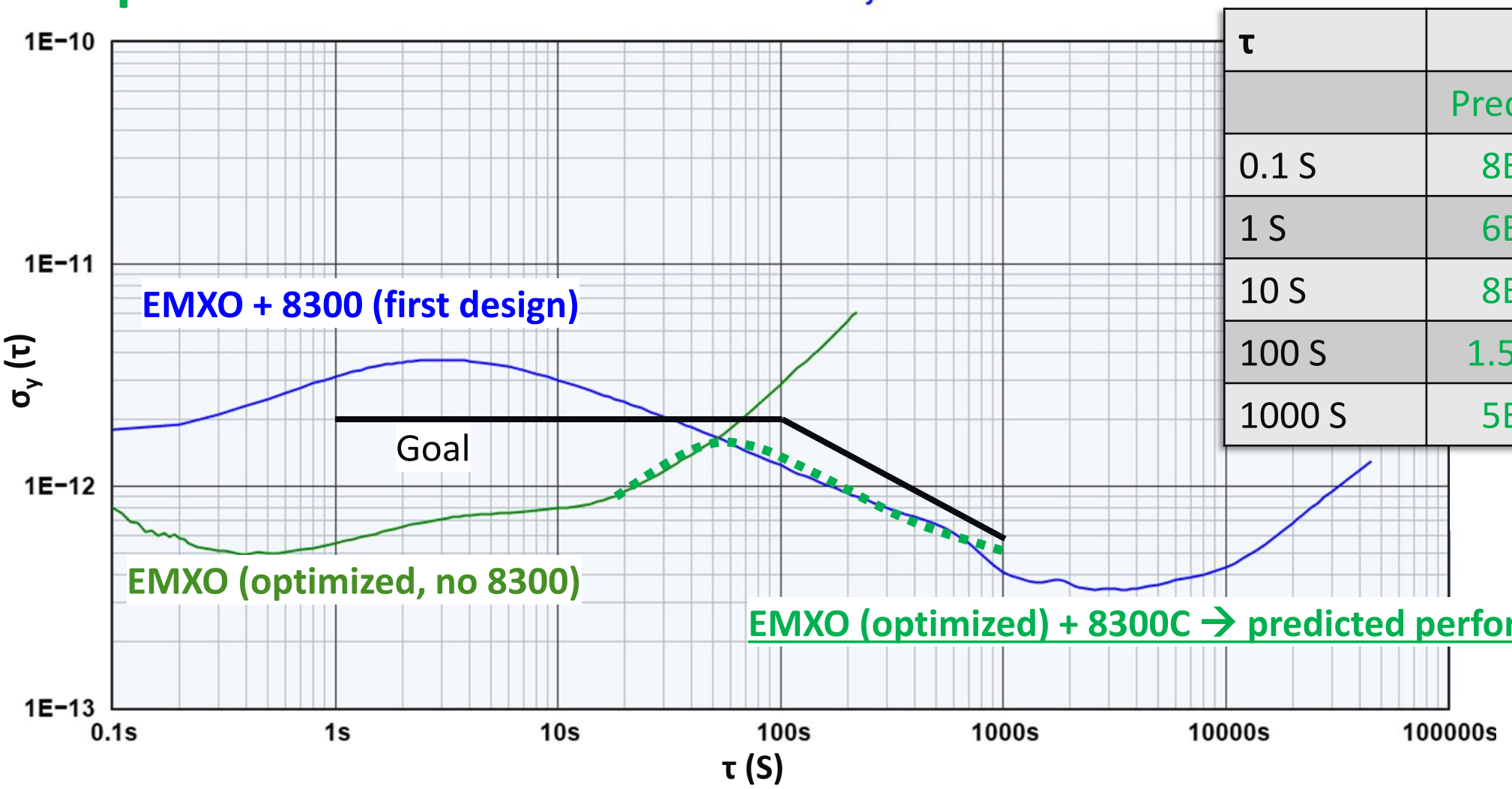
EMXO Optimization

- **Effort is underway to optimize the EMXO control circuit and later embed into the 8300C**
- **Preliminary results are shown next**

EMXO breadboard

Predicted ADEV of 8300C LN Option*

*Optimized EMXO

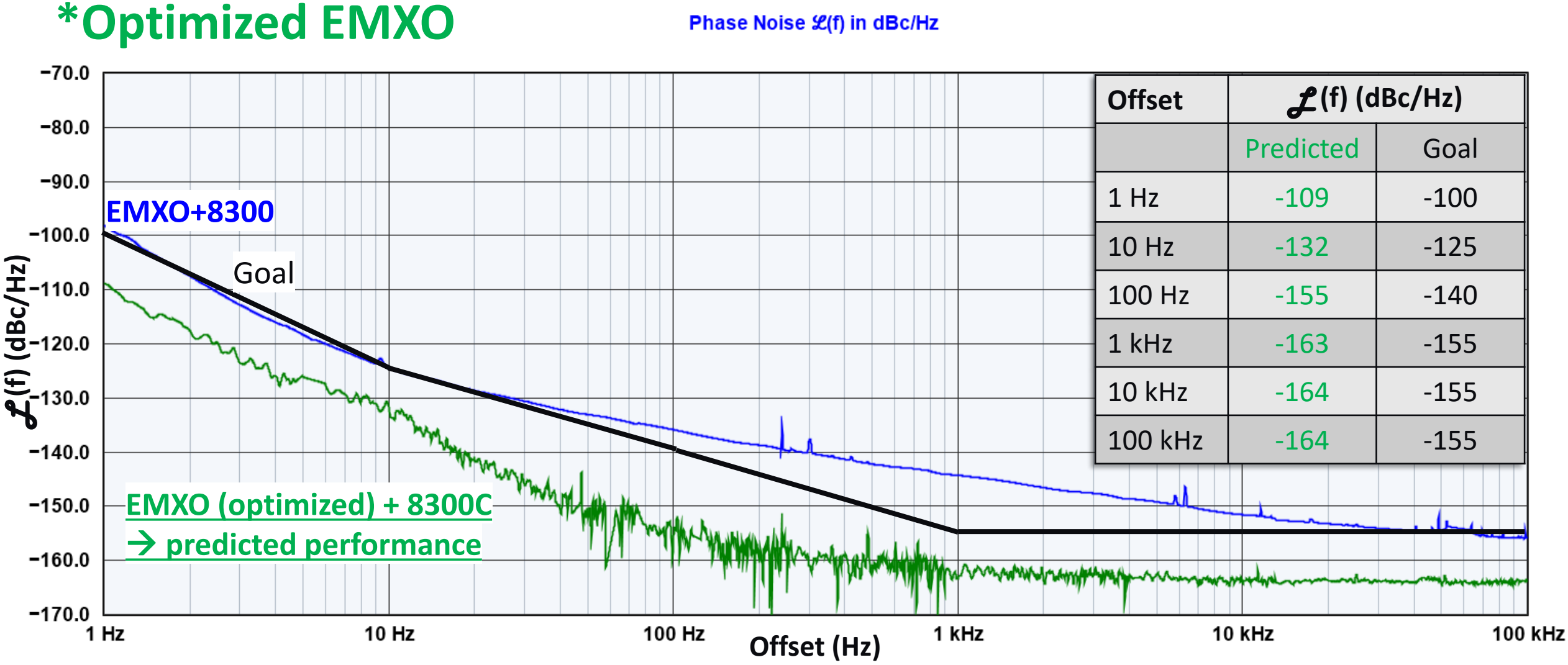


τ	σ_y (τ)	
	Predicted	Goal
0.1 S	8E-13	-
1 S	6E-13	2E-12
10 S	8E-13	2E-12
100 S	1.5E-12	2E-12
1000 S	5E-13	6E-13

Conclusion: potential improvement for σ_y (1s) < 6E-13

Predicted Phase Noise of 8300C LN Option*

*Optimized EMXO



Offset	ℒ(f) (dBc/Hz)	
	Predicted	Goal
1 Hz	-109	-100
10 Hz	-132	-125
100 Hz	-155	-140
1 kHz	-163	-155
10 kHz	-164	-155
100 kHz	-164	-155

Conclusion: potential improvement to phase noise

Ruggedized Rb *Model 8300C*

Radiation Testing

Radiation Testing

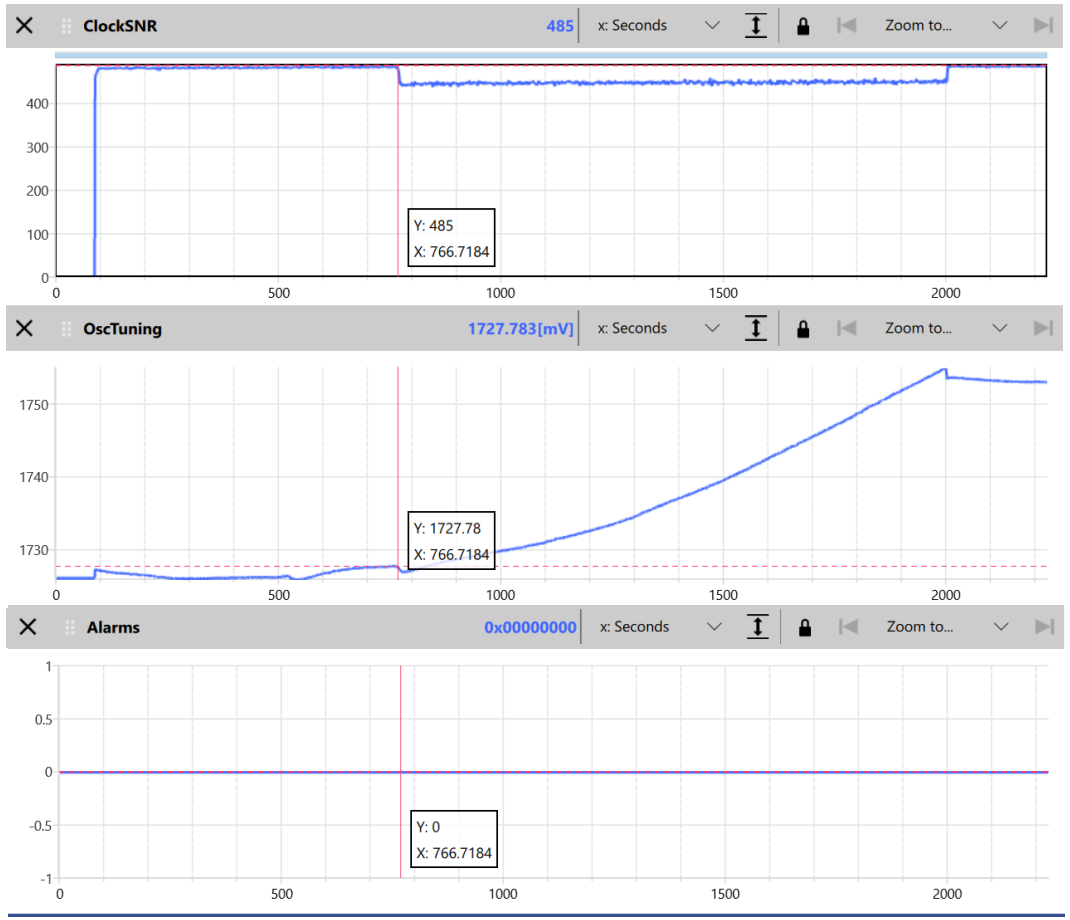
- **Performed at UMASS-Lowell "Gamma Cave"**
- **Calibration: initial 10-minute dosimetry exposure was performed on an empty box to verify the dose rate**
- **DUT was exposed in two phases**
  1. To 20 Krad
     - Power-cycle and health check
  2. Until failure
     - Power-cycle and failure analysis
- **Goal: achieve > 30 Krad**

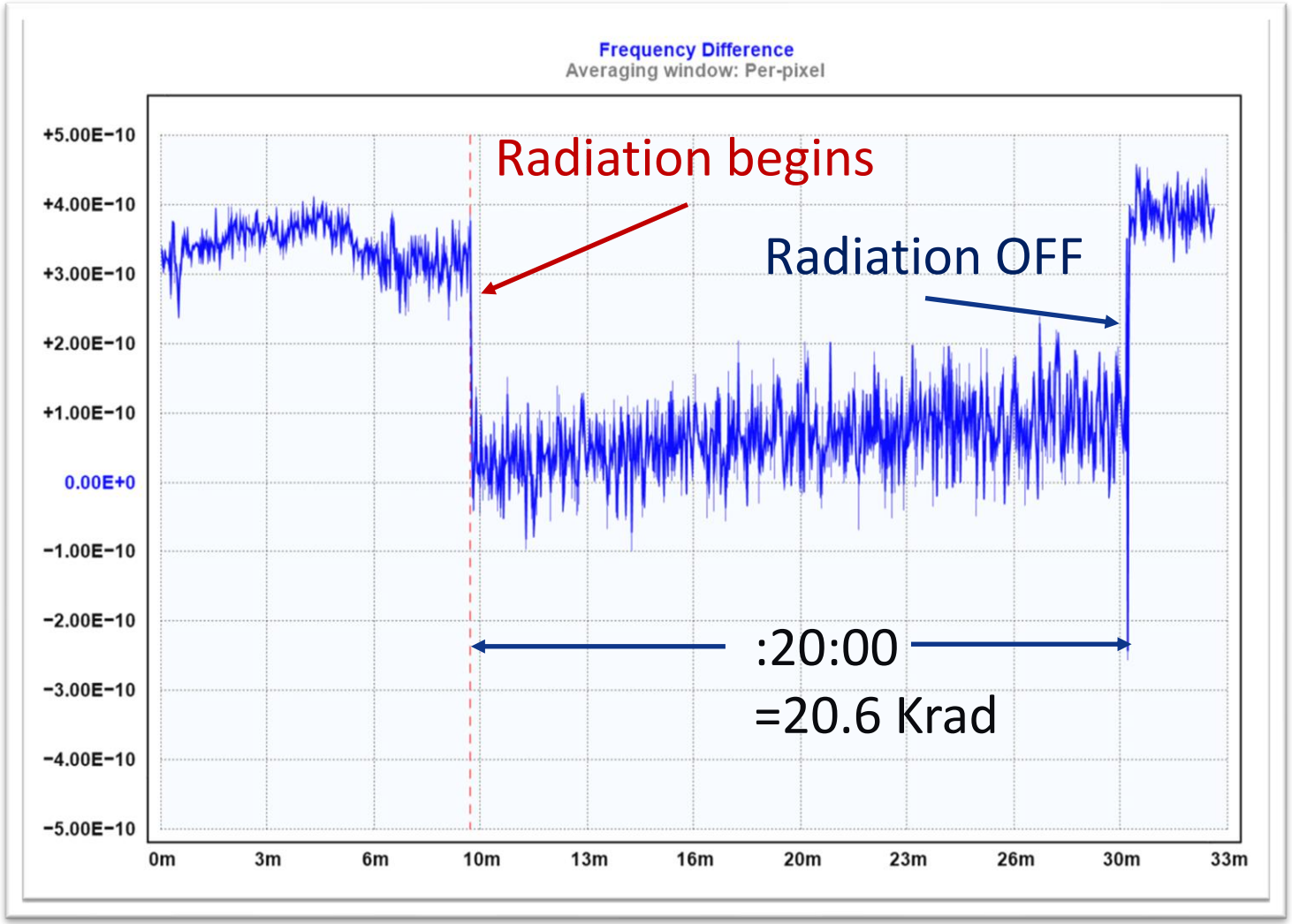
Dosimetry orientation with empty box. Dosimeters are attached on the back. (Rear Pb/Al shield not shown in picture.)

8300C samples positioned within the Pb/Al shields.

Performance During 1st Exposure: To 20 Krad

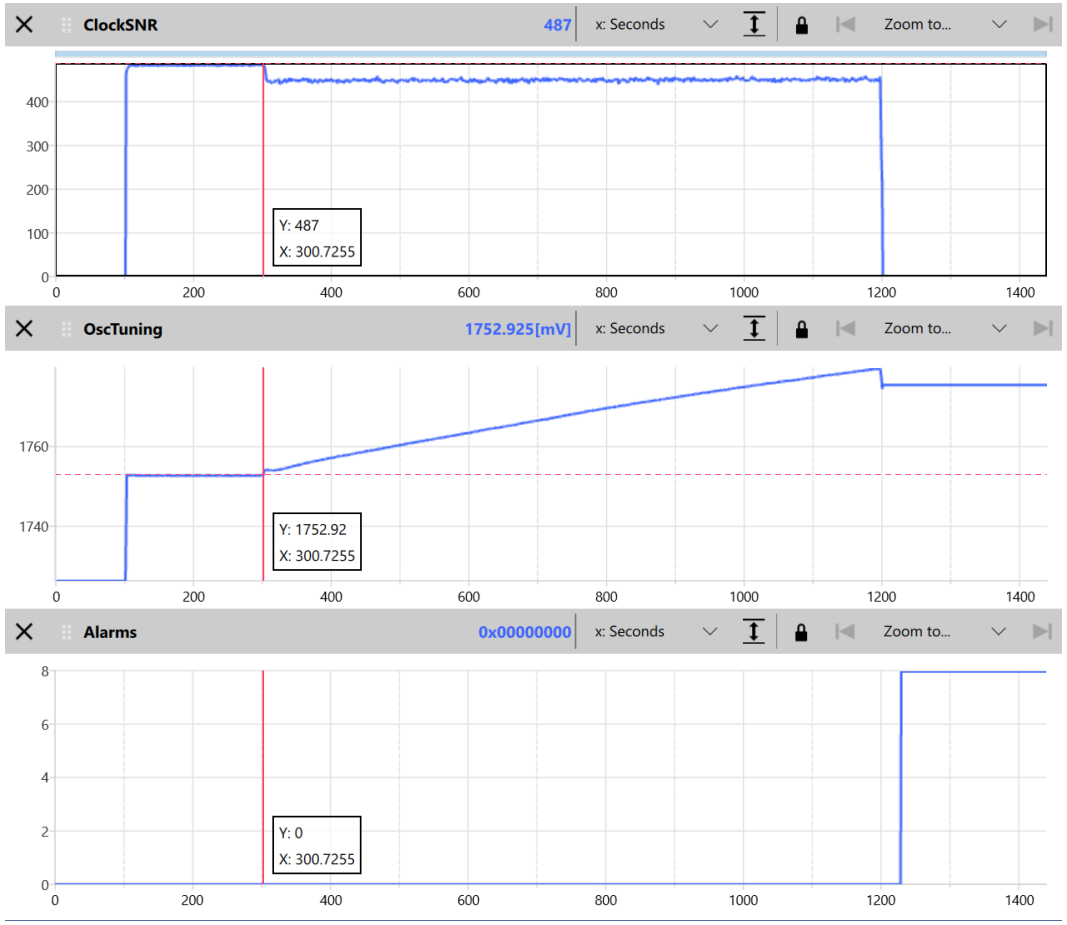
- **Frequency output →**
- **Telemetry:**

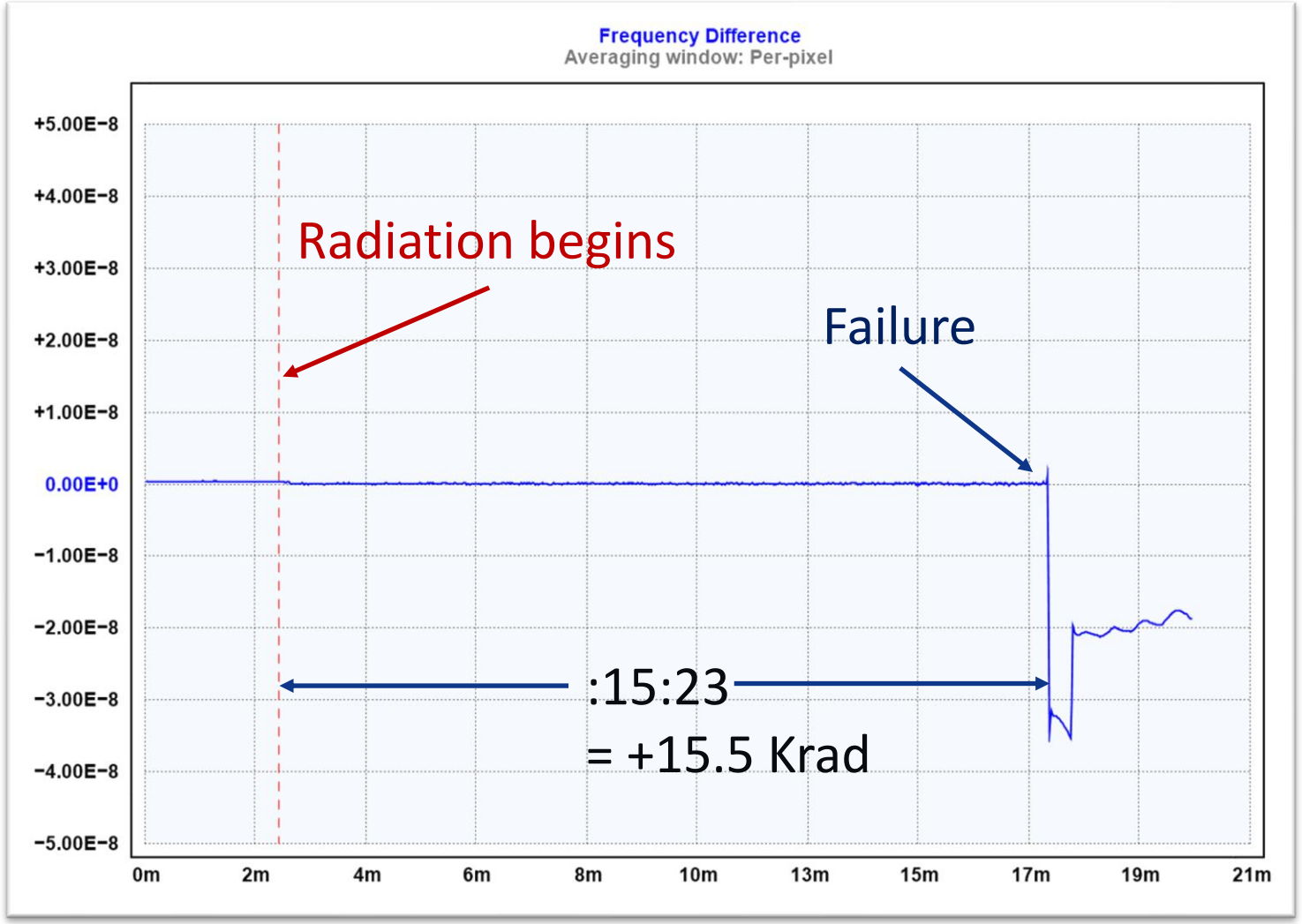




Performance During 2nd Exposure: Until Failure

- **Frequency output →**
- **Telemetry:**





Total Radiation Dosage - TID = 36.1 Krad

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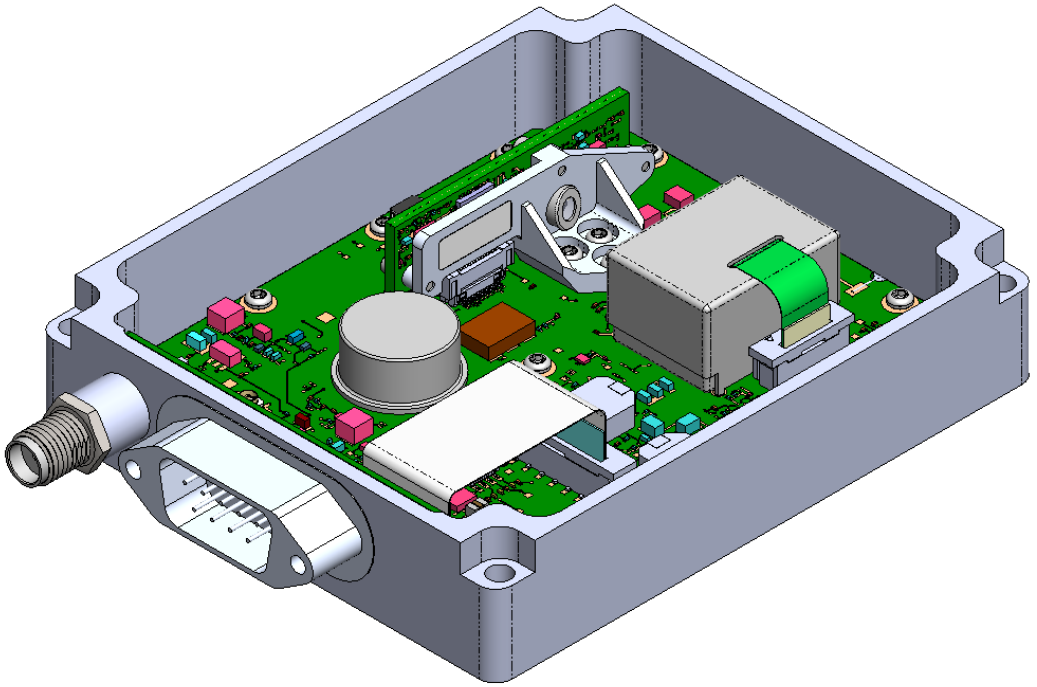
Space MAC-8300C and EMXO Test Results

- **Space MAC-8300C prototype survived 36.1 Krad TID (Si)**
- **Post-mortem diagnosis: Initial analysis points to failures of the ADC and FPGA as a result of radiation exposure**
- **EMXO breadboard survived > 37 Krad TID**
  - Test stopped due to time constraints
- **Breadboard still functional post radiation**

Summary Table

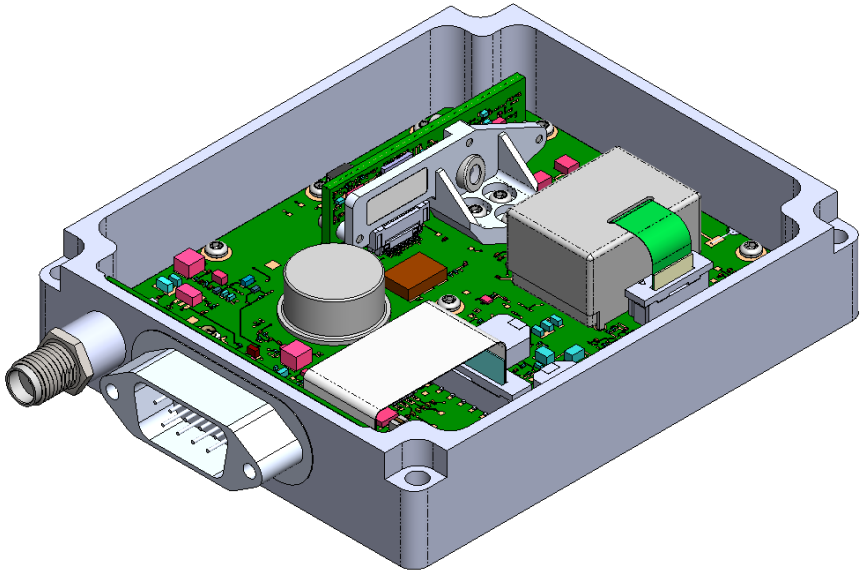
	MAC-8300C LN
Technology	CPT Rb clock
Key Metrics	
Power	7W
L x W x H	3.25 x 2.75 x 0.69”
Temperature Range	-40 to +85 °C
Performance	Goals
ADEV at 1s	2×10^{-12}
ADEV at 1,000s	6×10^{-13}
Freq Drift (Aging)	1.7×10^{-12} /day
TempCo	5×10^{-11} (max)
Phase Noise at 1 Hz	-100 dBc/Hz
Measured Radiation tolerance	*Prototype*
TID	36.1 Krad



Planned Availability: Spring 2026

Conclusions and Next Steps

- **Experimental Results proved design feasibility toward a wide temperature and low-noise Rb**



- **Next steps**
  1. Integration into ruggedized package ✓
  2. Optimization and integration of EMXO
  3. Optimization of TEC set points
  4. Environmental testing
     (hermeticity, shock, vibration, radiation, TempCo, TVAC)

- **Verify performance on prototype design**

Thank You

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