Development and Characterization of 4 MS/s 8-bit Flash ADC

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Committee: Ulkuhan Guler, John McNeill

About Me

2024-2025

- CMOS Image Sensor MQP

May, 2025

- B.S. @ WPI
  - ECE & Data Science

Summer 2025

- ADC Characterization Independent Study

2026

- GlobTek Inc. Design Engineer, Northvale NJ

WPI

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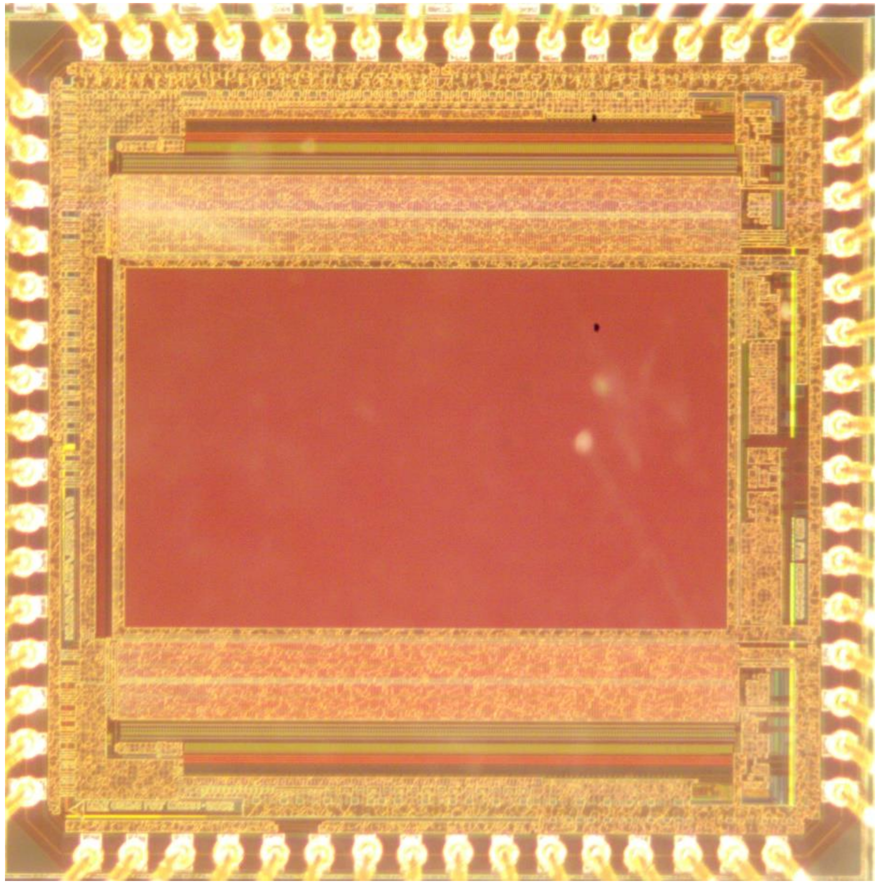
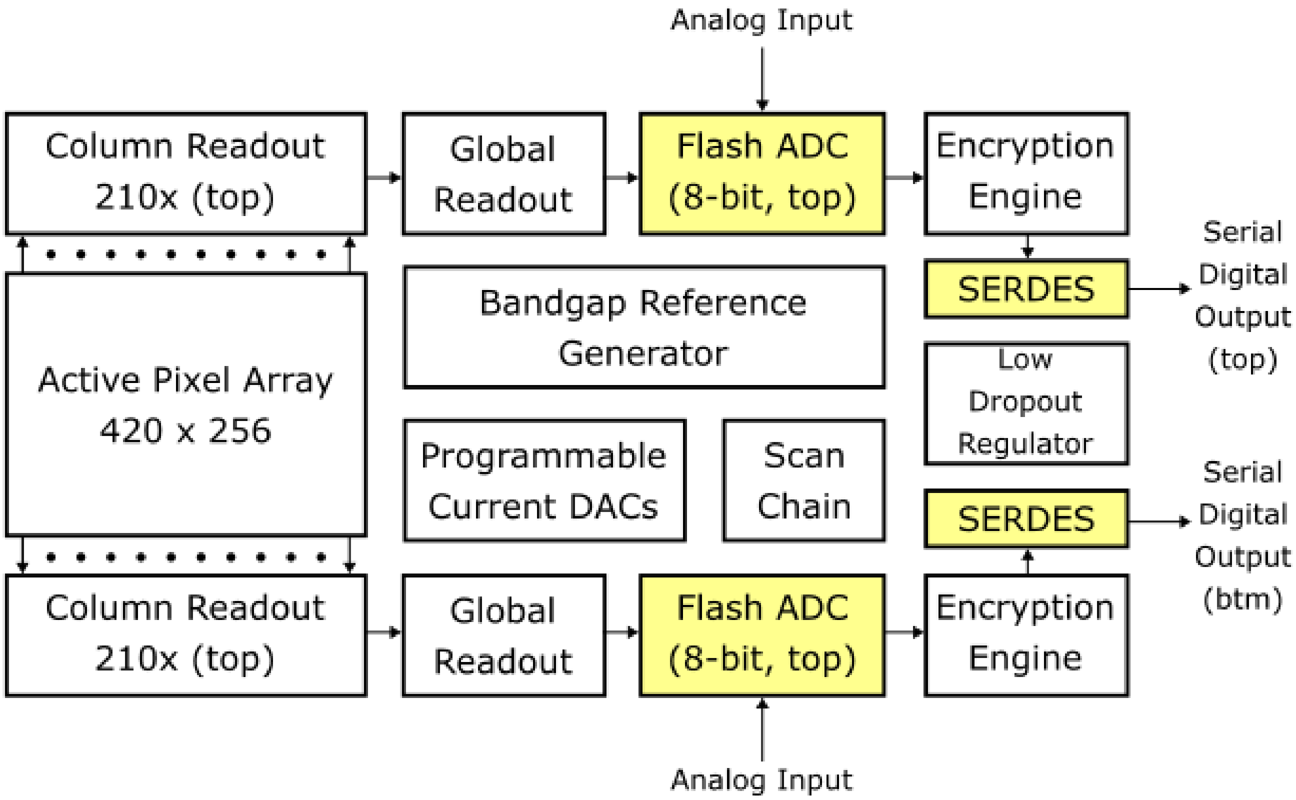
Background + Architecture

Worcester CMOS Image Sensor – WCIS MQP



2mm

2mm



TSMC 180nm 1P6M 3v3/1.8V CMOS

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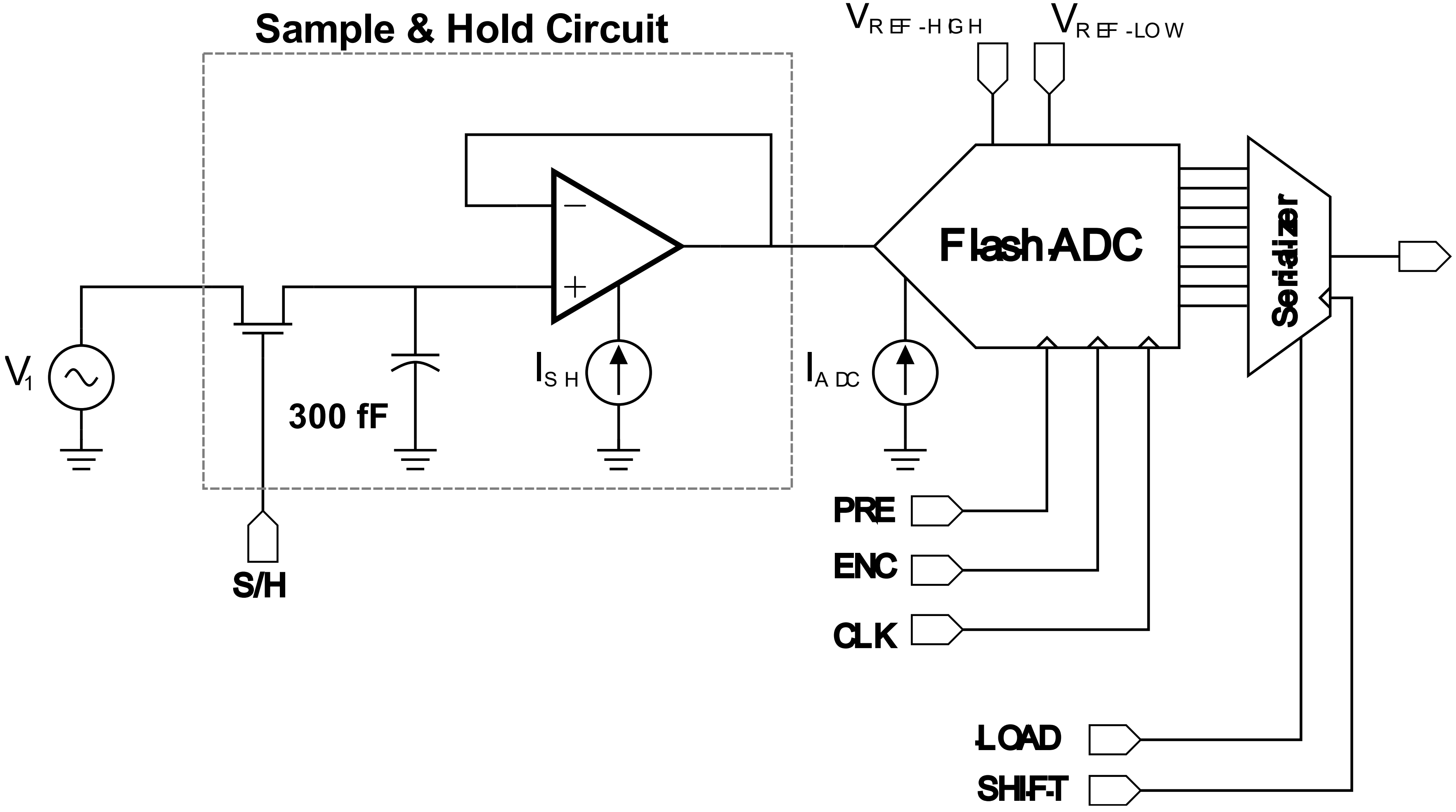
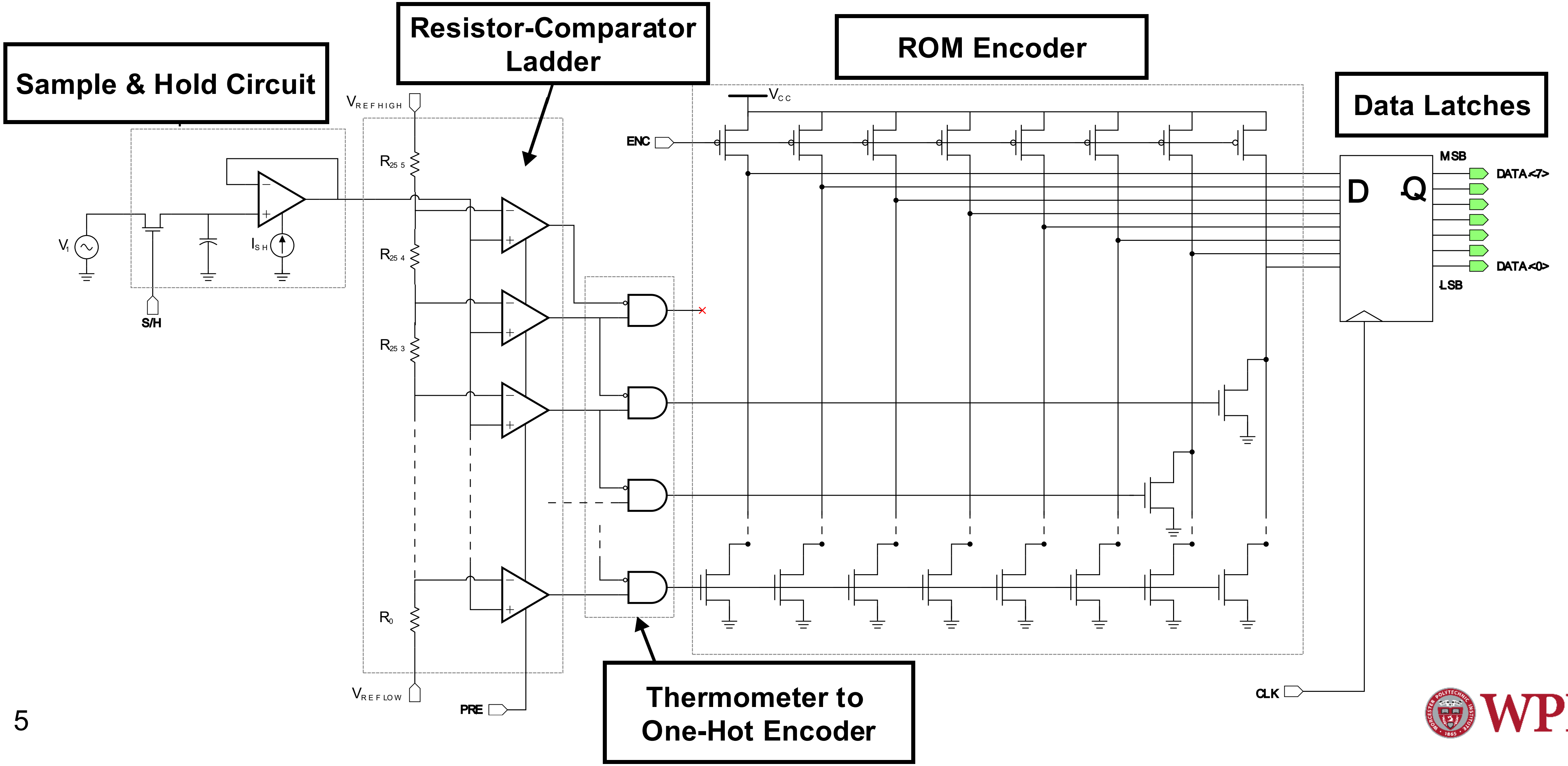
High Level Diagram



Flash ADC (FADC) Circuit Diagram



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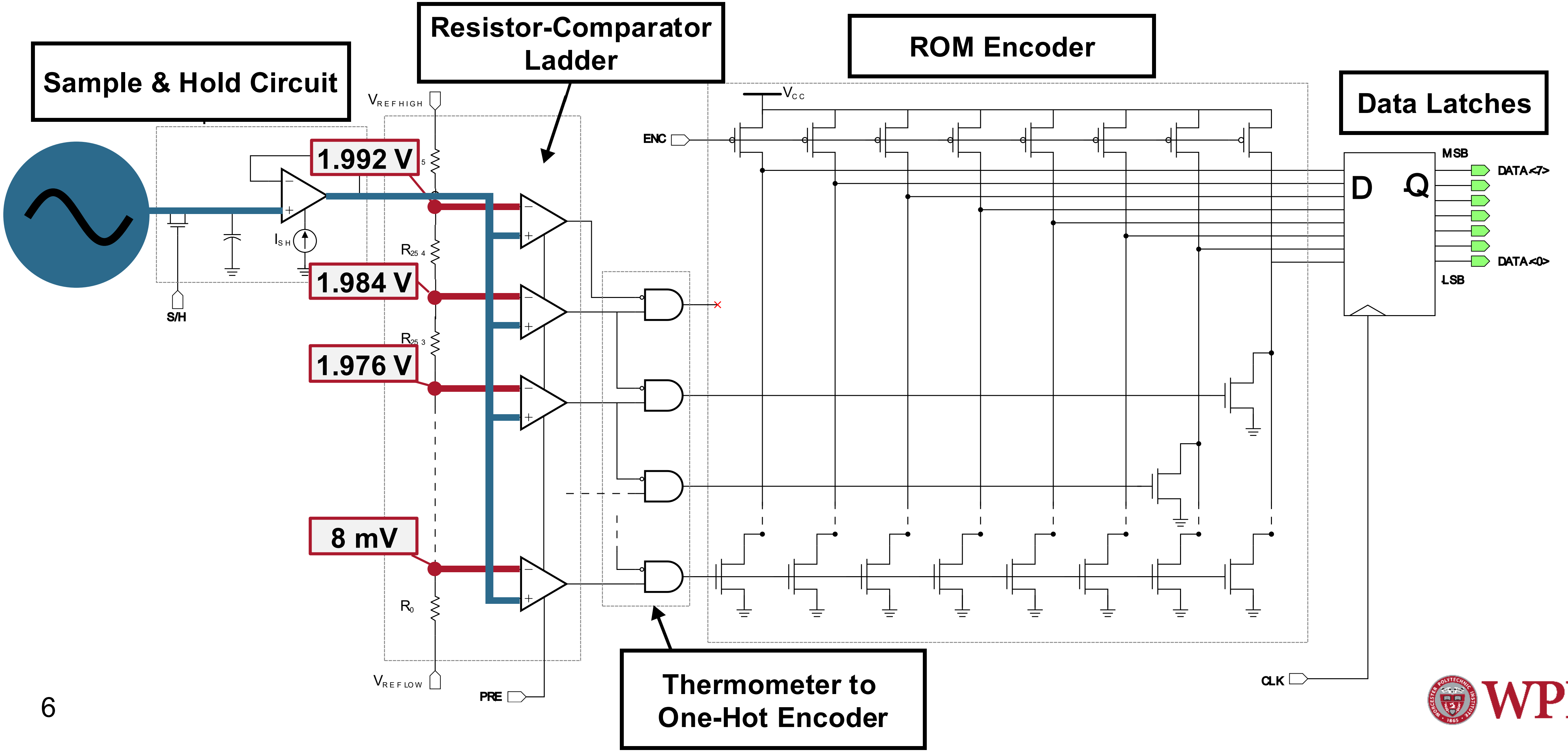

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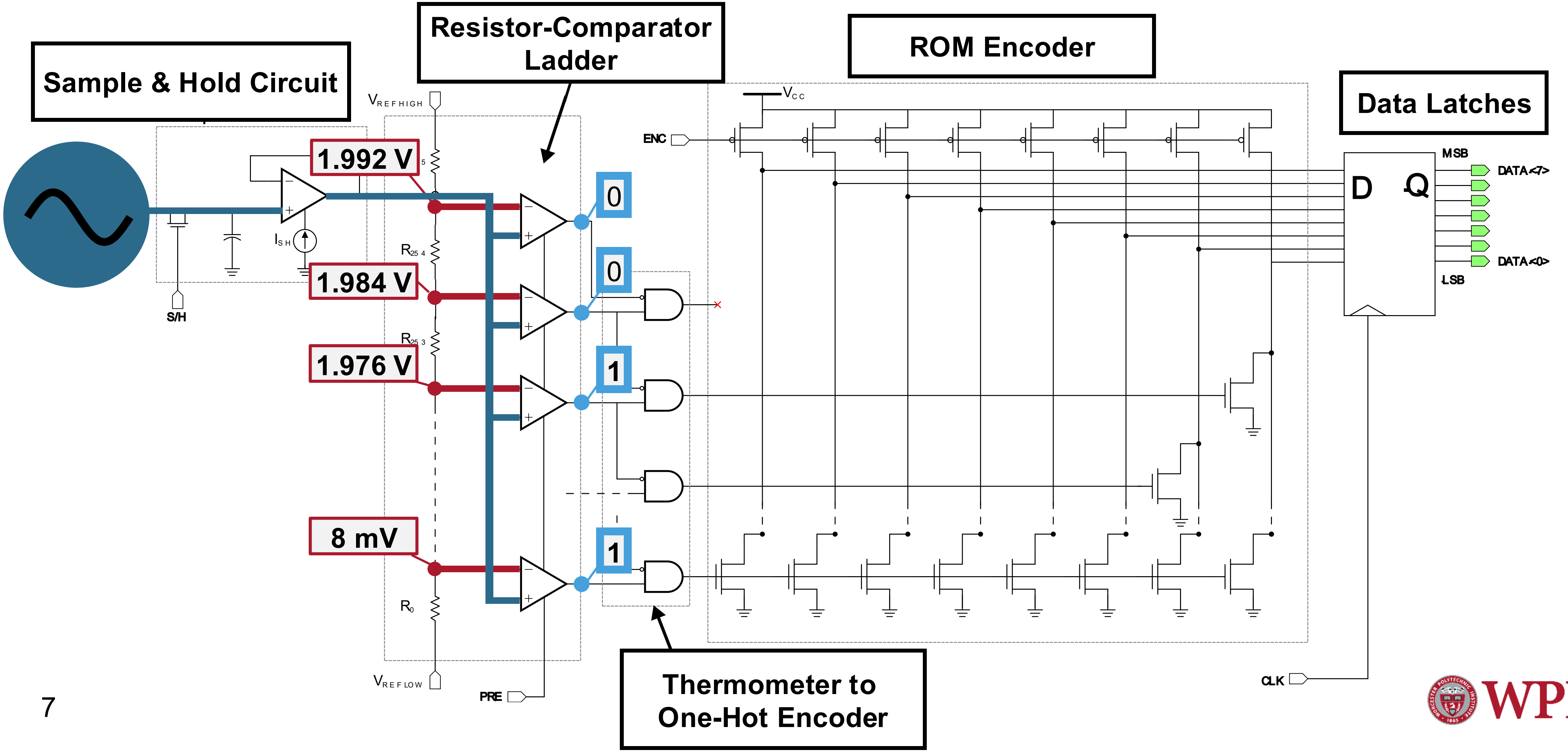

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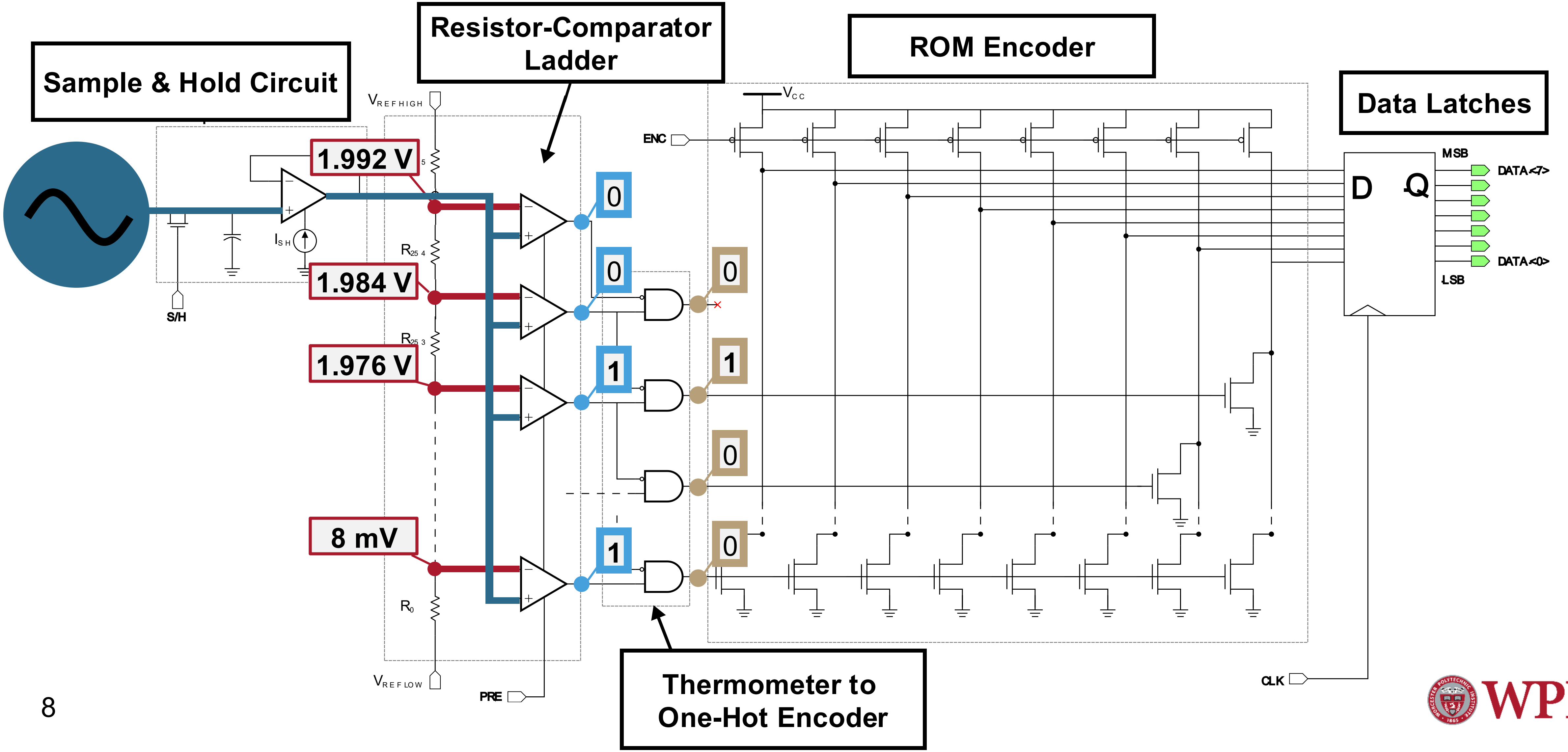

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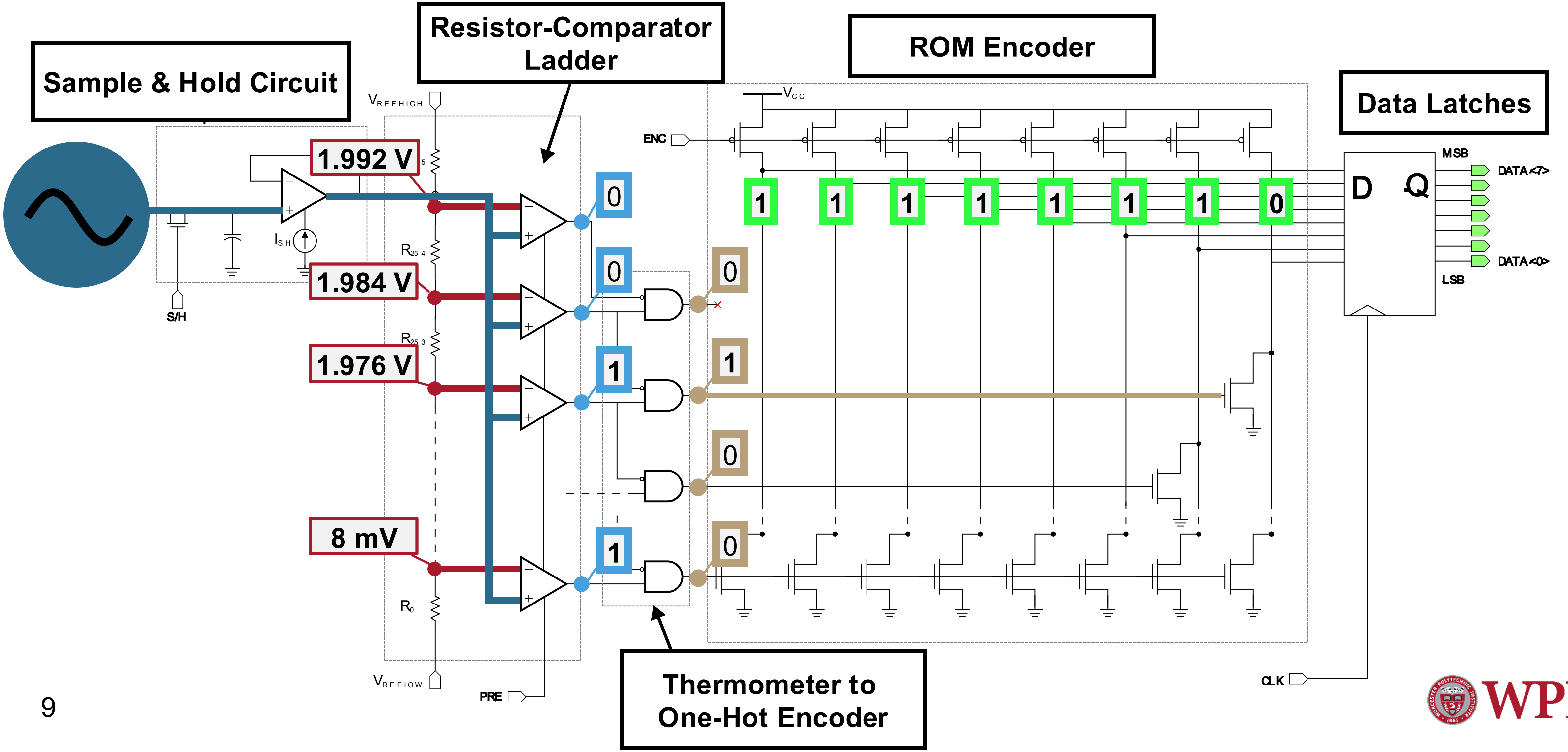

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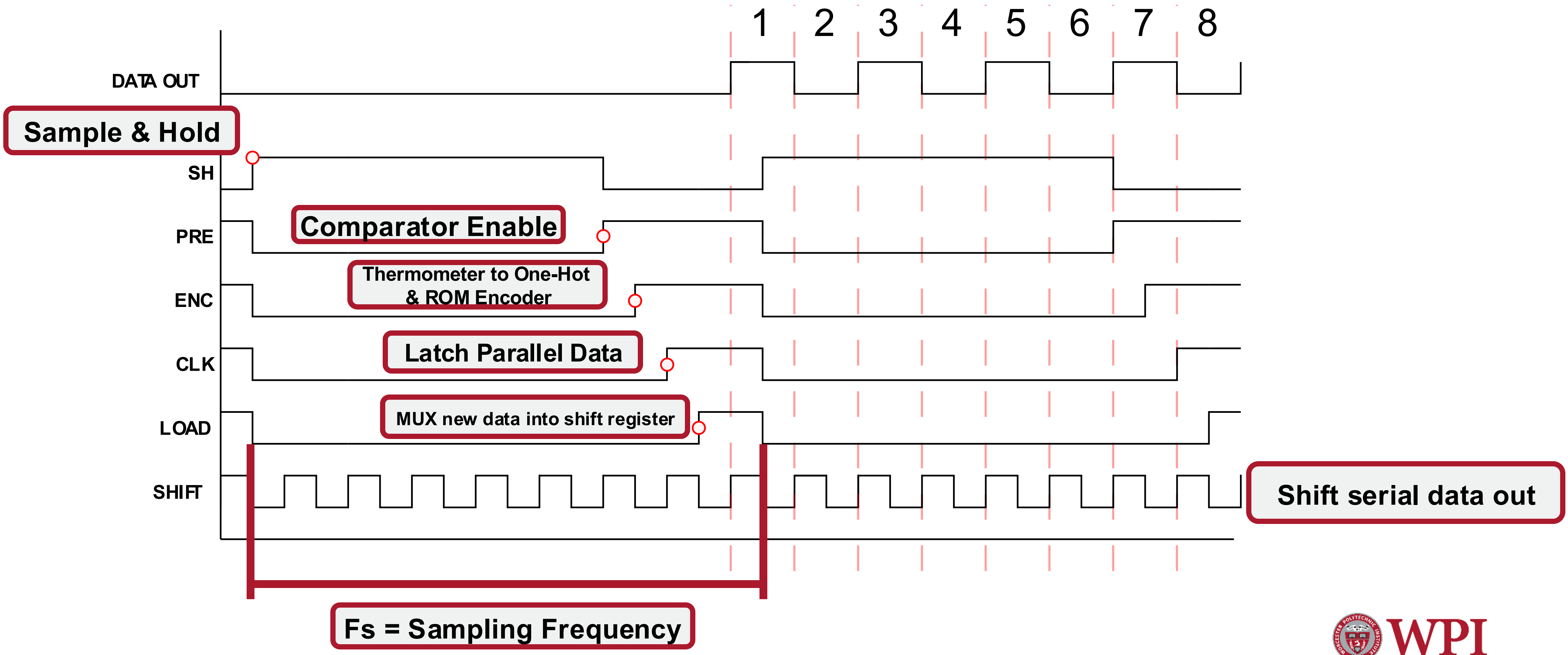
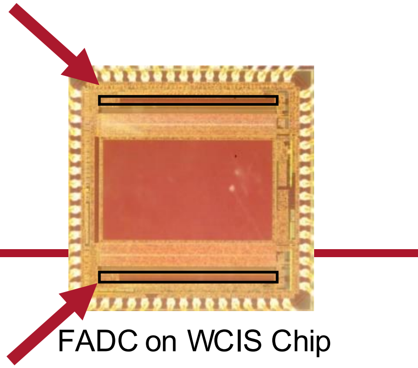
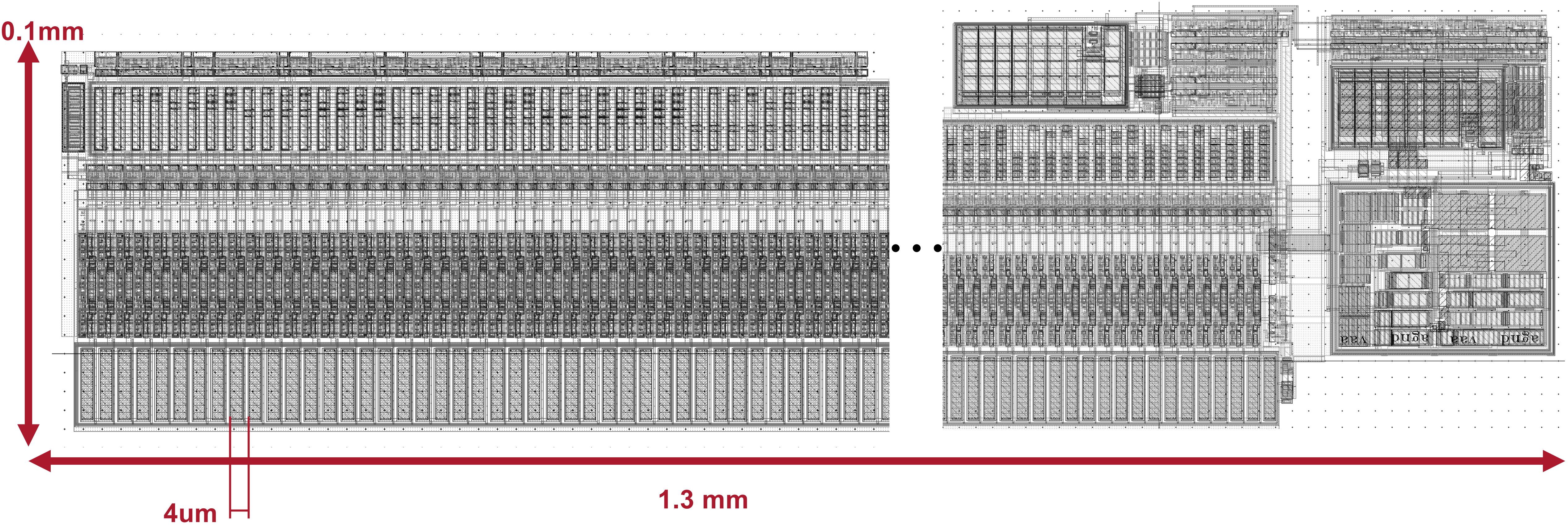
Timing Diagram



FADC Layout



FADC on WCIS Chip



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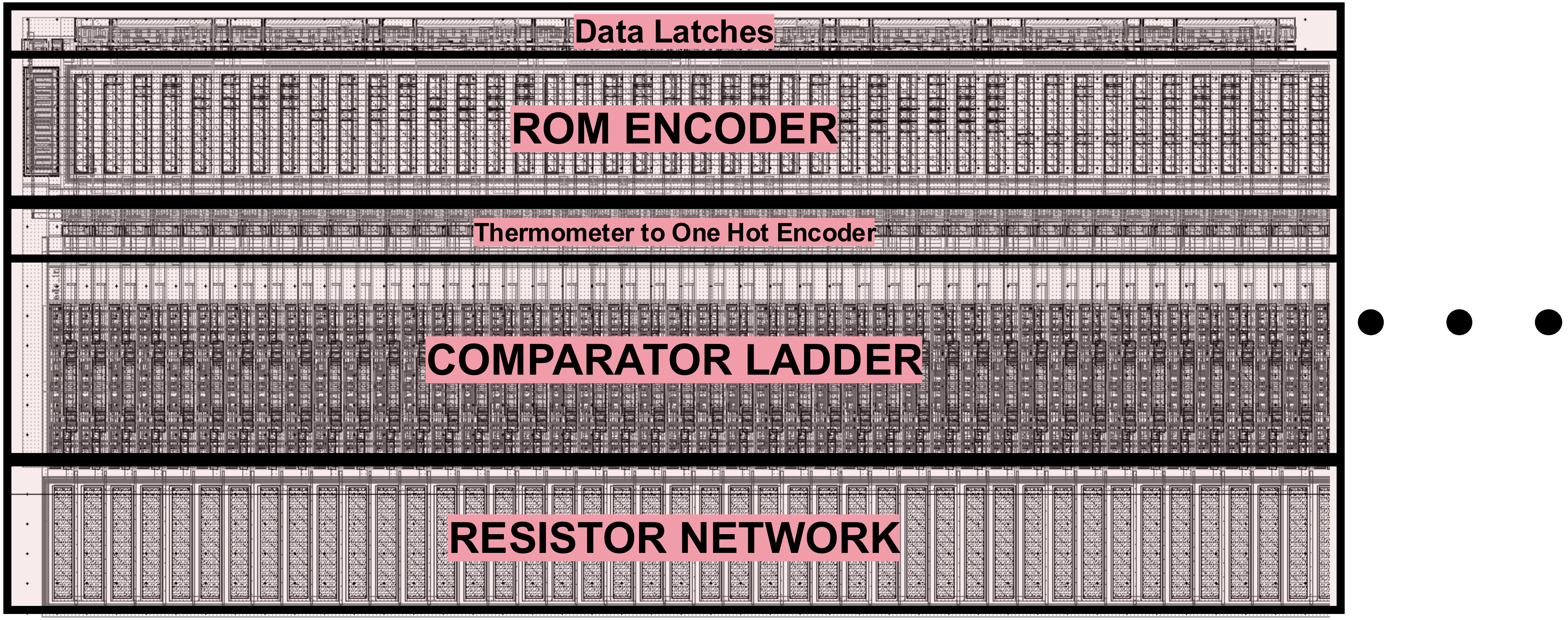
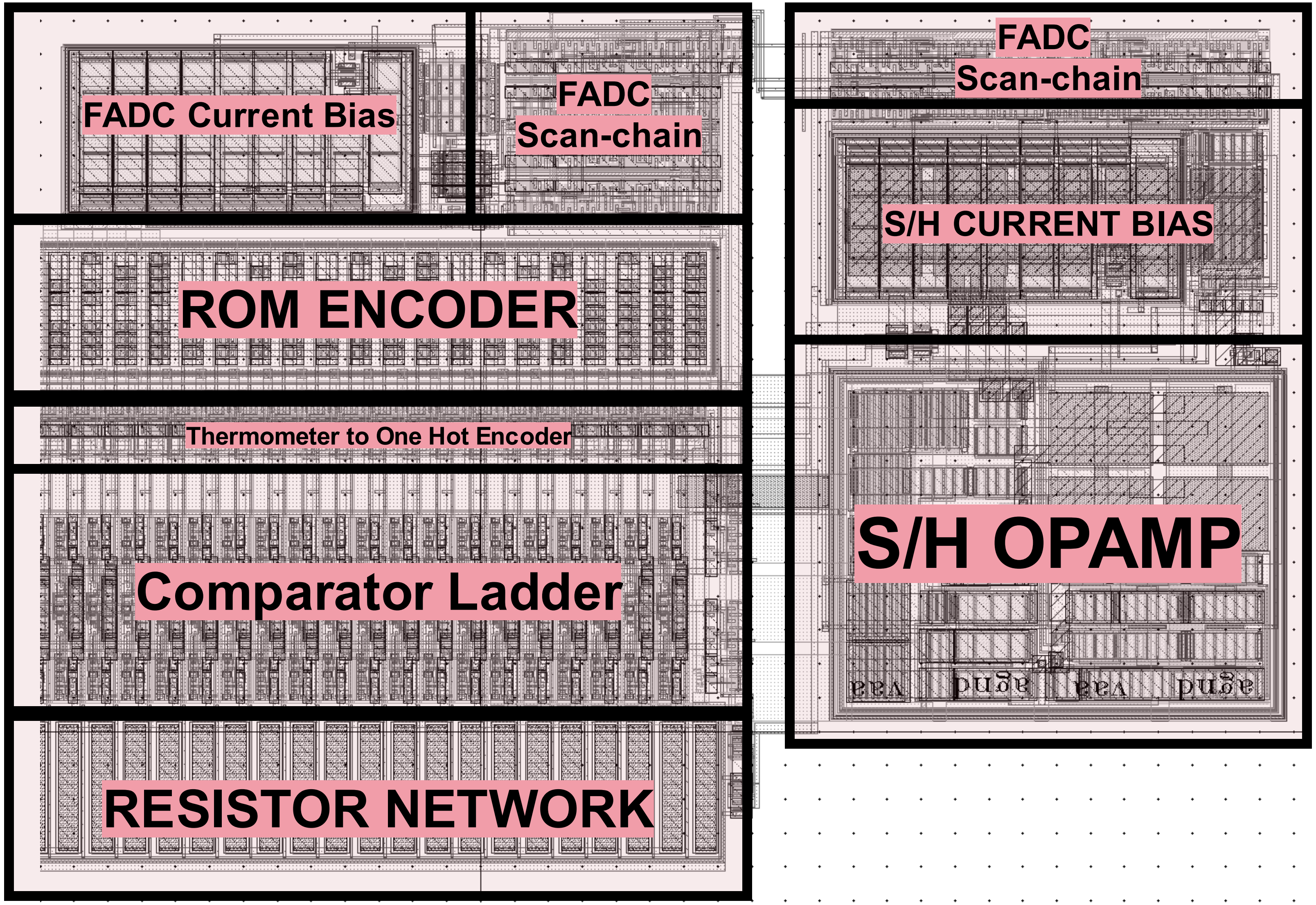

Data Latches
ROM ENCODER
Thermometer to One Hot Encoder
COMPARATOR LADDER
RESISTOR NETWORK

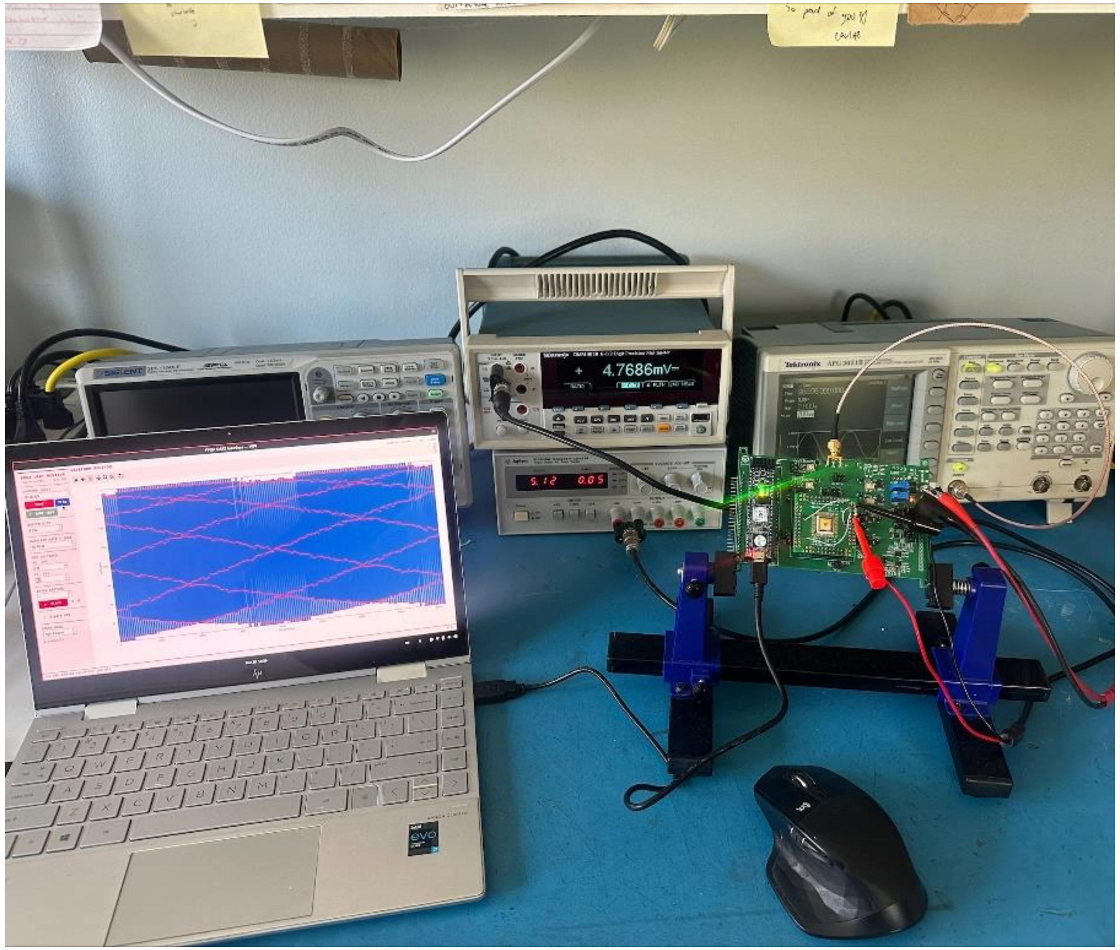
FADC Layout

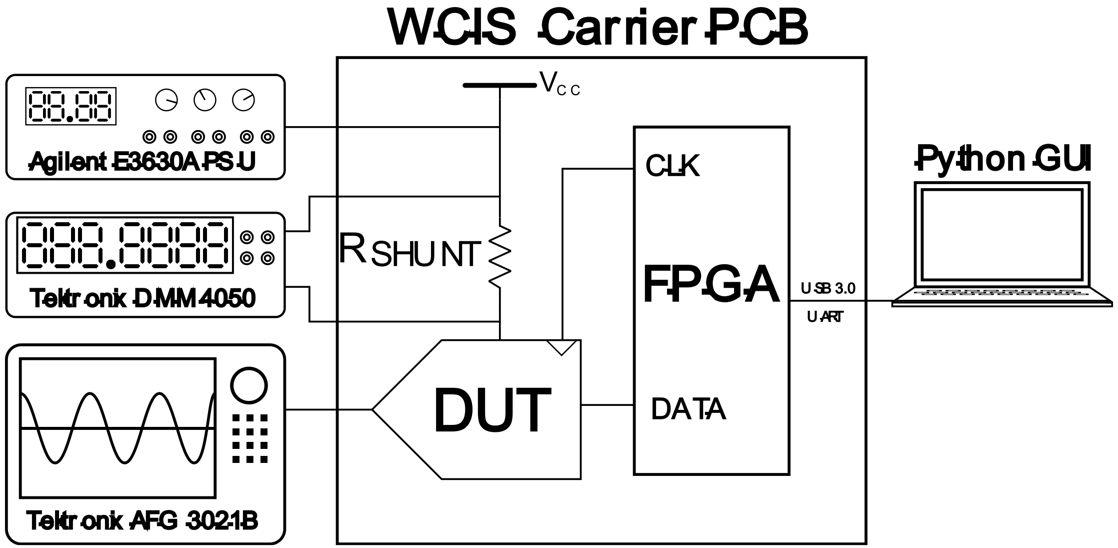

FADC Current Bias
FADC
Scan-chain
ROM ENCODER
Thermometer to One Hot Encoder
Comparator Ladder
RESISTOR NETWORK
FADC
Scan-chain
S/H CURRENT BIAS
S/H OPAMP

• • •

Test Methods

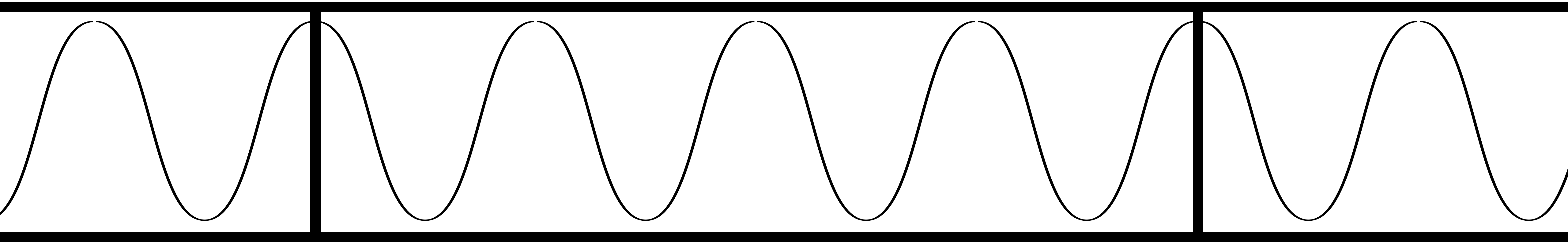
Test Setup





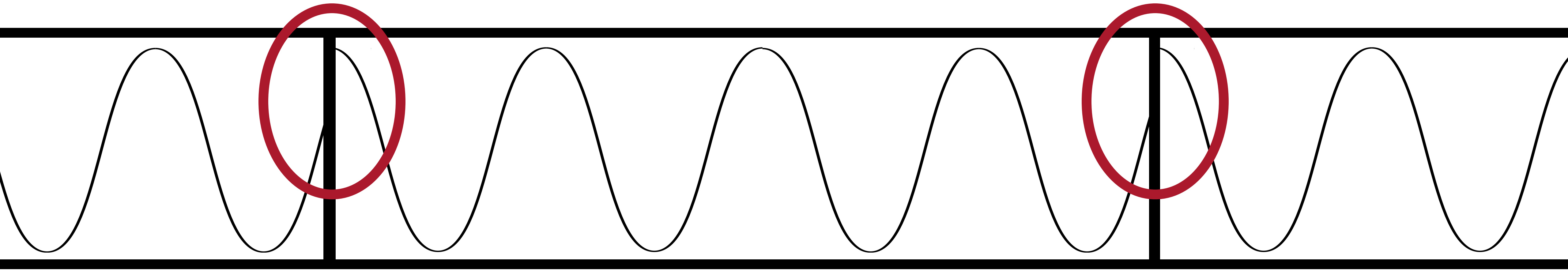
WCIS Carrier PCB
Agilent E3630A PSU
Tektronix DMM4050
Tektronix AFG 3021B
Vcc
RSHUNT
DUT
CLK
FPGA
DATA
USB 3.0
UART
Python GUI

Coherent Sampling Setup



*The **Fast Fourier Transform** lets us take a captured “epoch” of data and generate a frequency spectrum*

Coherent Sampling Setup



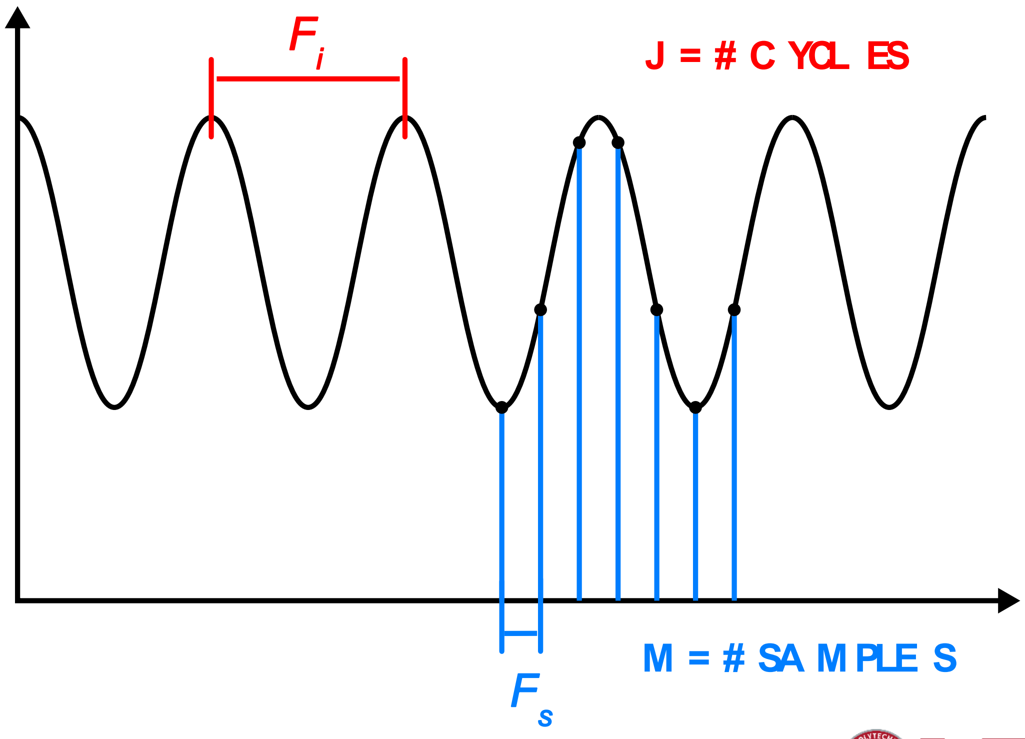
*But the "epoch" <u>MUST</u> be **coherently sampled** to generate accurate spectrum data and avoid <u>spectral leakage</u>*

Coherent Sampling Setup

"Sampling of a periodic signal such that there is an integer number of signal cycles in the waveform epoch" –*IEEE1241*

$$F_i M = J F_S$$

$\boldsymbol{F_i}$	Input Frequency
M	**Number of samples** in waveform epoch
J	**Integer number of cycles** of the signal in the epoch, which is **relatively prime to** $\boldsymbol{M}$
$\boldsymbol{F_S}$	Sampling Frequency



Coherent Sampling Setup

Parameter	Units	Value						
F_s	Hz	500.4k	1.0M	2.0M	3.0M	4.0M	5.0M	6.1M
J	—	1637	819	409	273	205	163	135
M	—	8192	8192	8192	8192	8192	8192	8192
F_i (ideal)	Hz	100.0k	100.0k	100.0k	100.0k	100.0k	100.0k	100.0k
F_s	Hz	500.0k	1.0M	2.0M	3.0M	4.0M	5.0M	6.0M
F_i (actual)	Hz	99.91k	99.98k	99.85k	99.98k	100.10k	99.49k	98.88k

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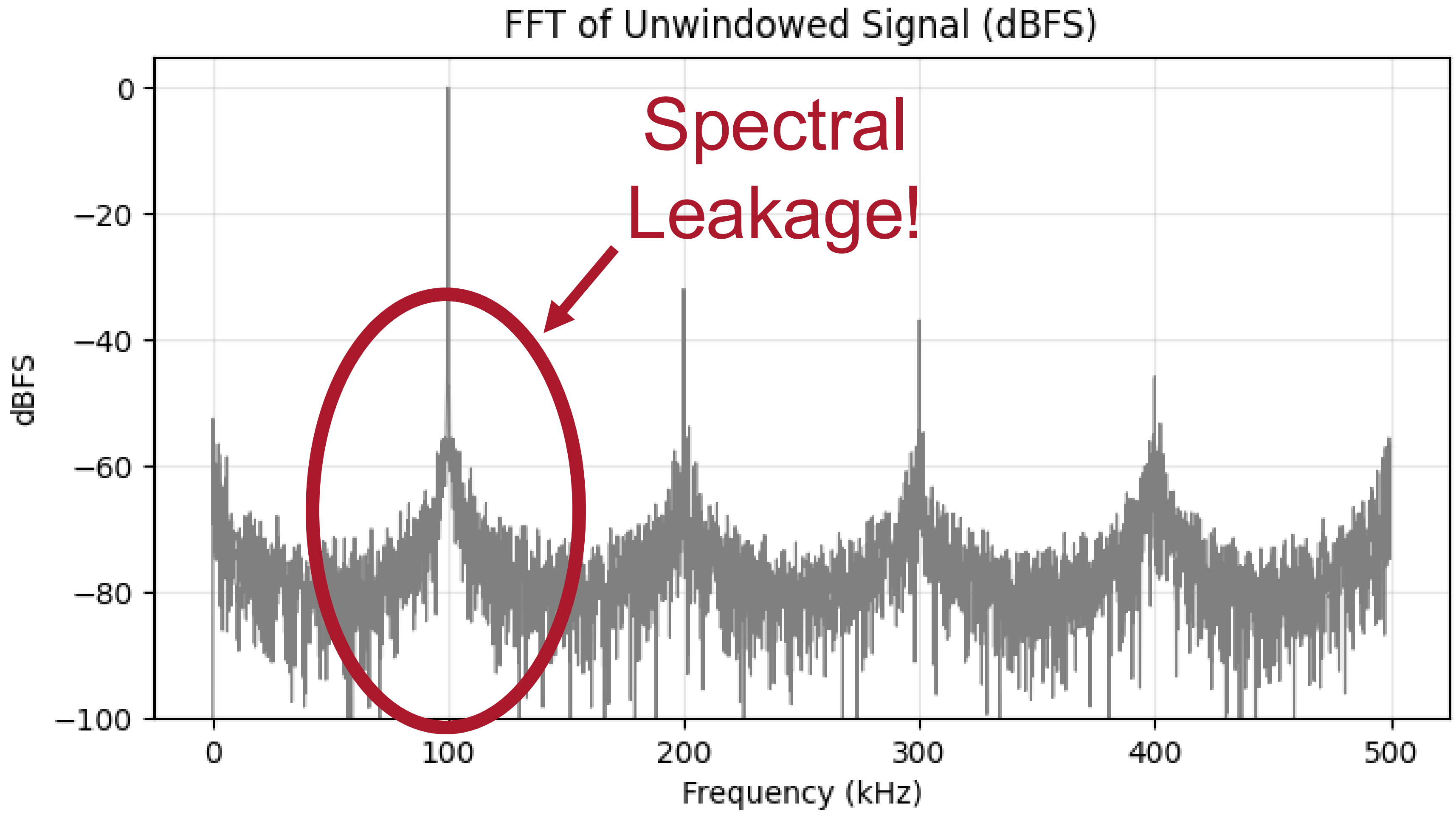
FFT Spectrum Analysis

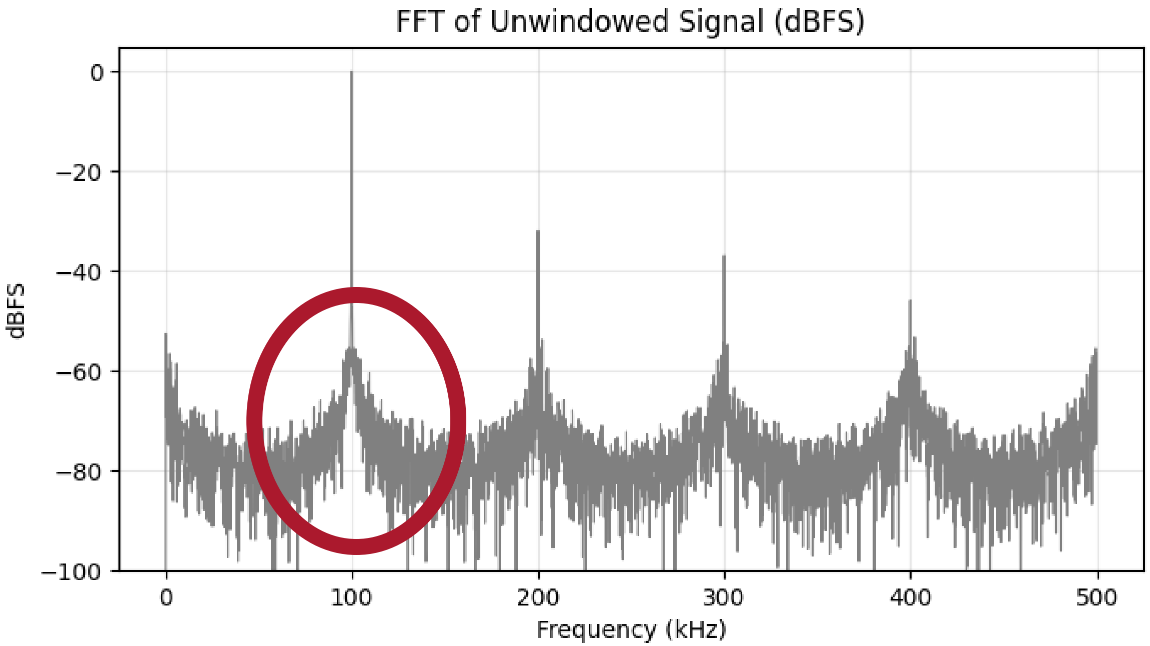
Initial FFT Measurement



Initial FFT spectrum showing spectral leakage around fundamental tone

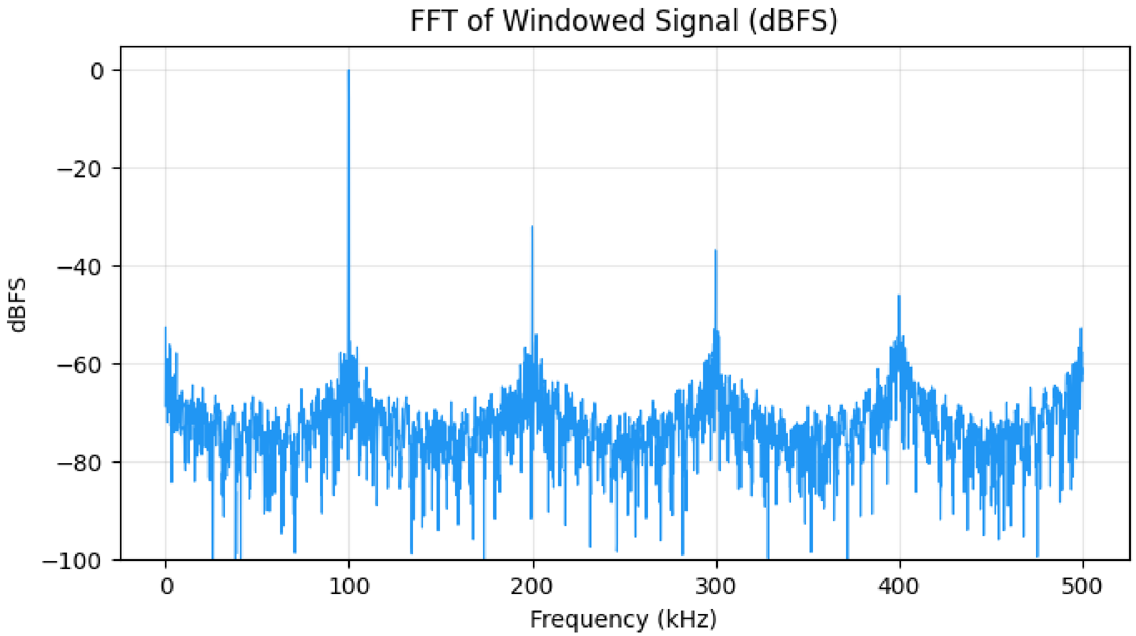
Hanning Window

BEFORE



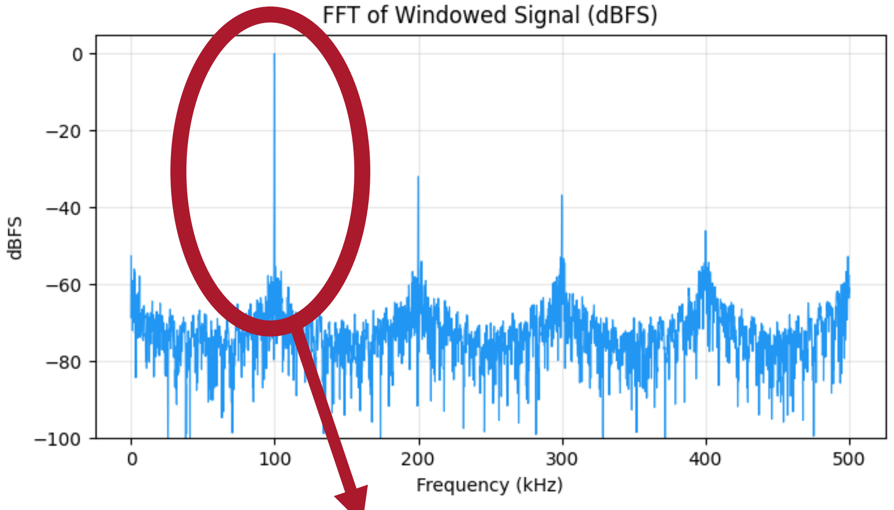
Initial FFT spectrum showing spectral leakage around fundamental tone

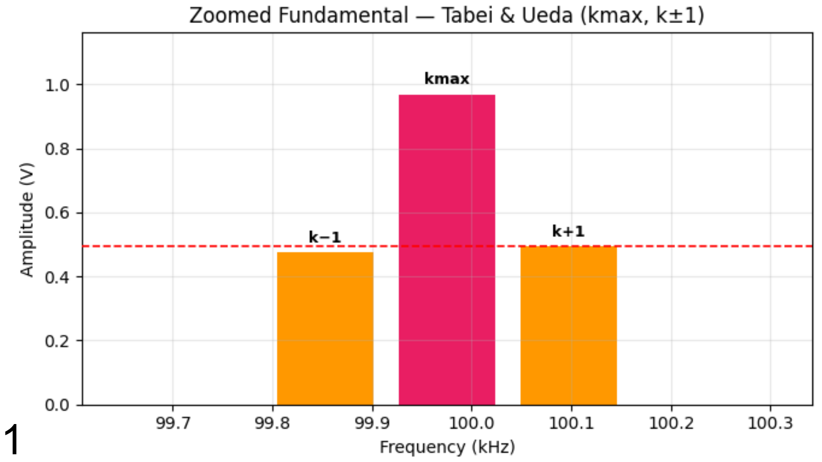
AFTER



FFT spectrum after applying Hanning window showing less spectral leakage

Signal Estimation - Tabei & Ueda Method






```python
def tabei_ueda(fft_full, fft_mag, N, hann_window):
    """Returns (A, fx, Po) — amplitude (V), fractional bin, phase (rad)."""
    fft_pos = fft_mag[:N//2]
    kmax    = np.argmax(fft_pos[1:]) + 1

    if fft_mag[kmax - 1] > fft_mag[kmax + 1]:
        r  = fft_mag[kmax - 1] / fft_mag[kmax]
        fx = kmax + (1.0 - 2.0*r) / (1.0 + r)
    else:
        r  = fft_mag[kmax + 1] / fft_mag[kmax]
        fx = kmax - (1.0 - 2.0*r) / (1.0 + r)

    dx   = fx - kmax
    dy   = np.pi * dx
    sinc = (dy / np.sin(dy)) if abs(dx) > 1e-10 else 1.0
    CG   = np.sum(hann_window) / N

    A  = (-fft_mag[kmax] / N) * sinc * (dx - 1.0) * (dx + 1.0) / CG * 2.0
    Po = (1 / (2*np.pi)) * np.angle(fft_full[kmax] * np.exp(-1j * dy))
    return A, fx, Po
```

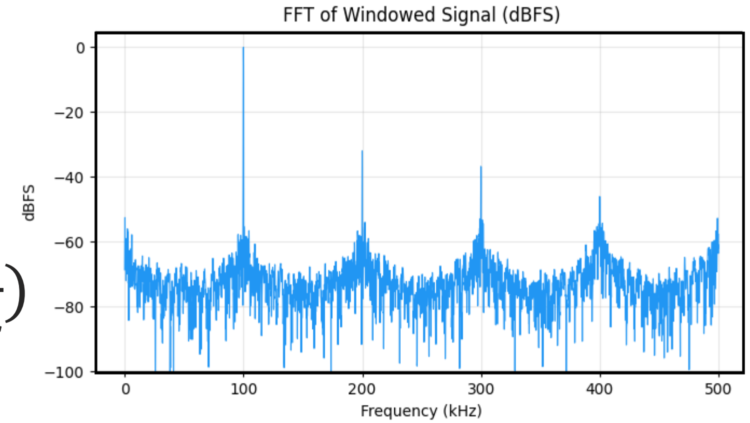
$$A = \frac{-2|G(k_{max})|}{N \cdot C_G} \frac{\pi(f - k_{max})}{\sin(\pi(f - k_{max}))} \times (f - k_{max} - 1)(f - k_{max} + 1)$$

$$P_o = \frac{1}{2\pi} Arg(G(k_{max}) e^{-j\pi(f - k_{max})})$$

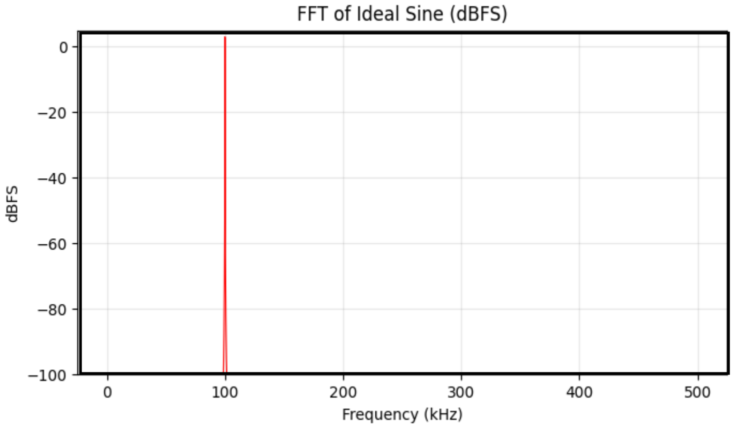
https://www3.advantest.com/documents/11348/f641a733-fcbe-43e8-b020-7799cd4c82bc

Breakdown Characterization Calculations

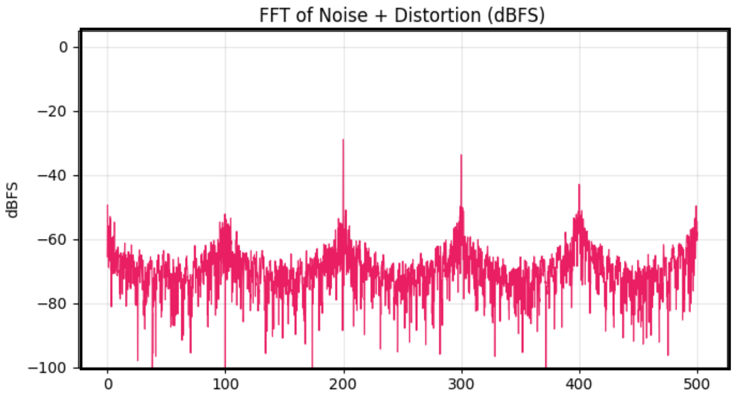
- $SNR = 20\log(\frac{V_{signal,RMS}}{V_{noise,RMS}})$
- $SINAD = 20\log(\frac{V_{signal,RMS}}{V_{noise+distortion,RMS}})$
- $THD = 20\log(\frac{V_{harmonic,RMS}}{V_{signal,RMS}})$
- $DR = 20\log(\frac{A_{signal}}{V_{noise,RMS}})$
- $SFDR = 20\log(\frac{A_{signal}}{A_{spur,max}})$
- $ENOB = \frac{SINAD - 1.76}{6.02}$



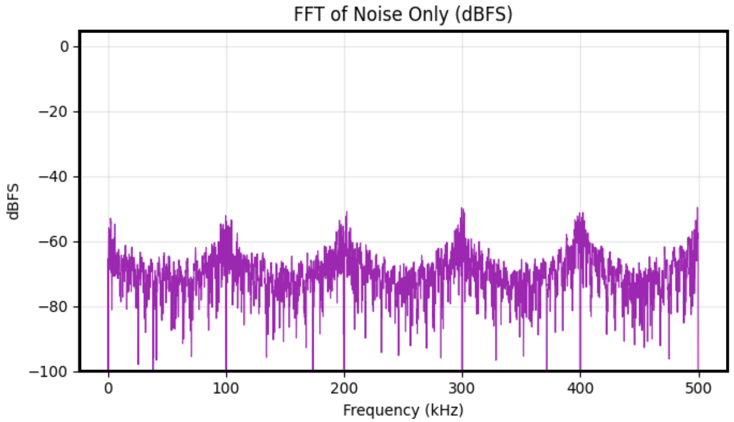
FFT with Hanning Window



Estimated fundamental tone



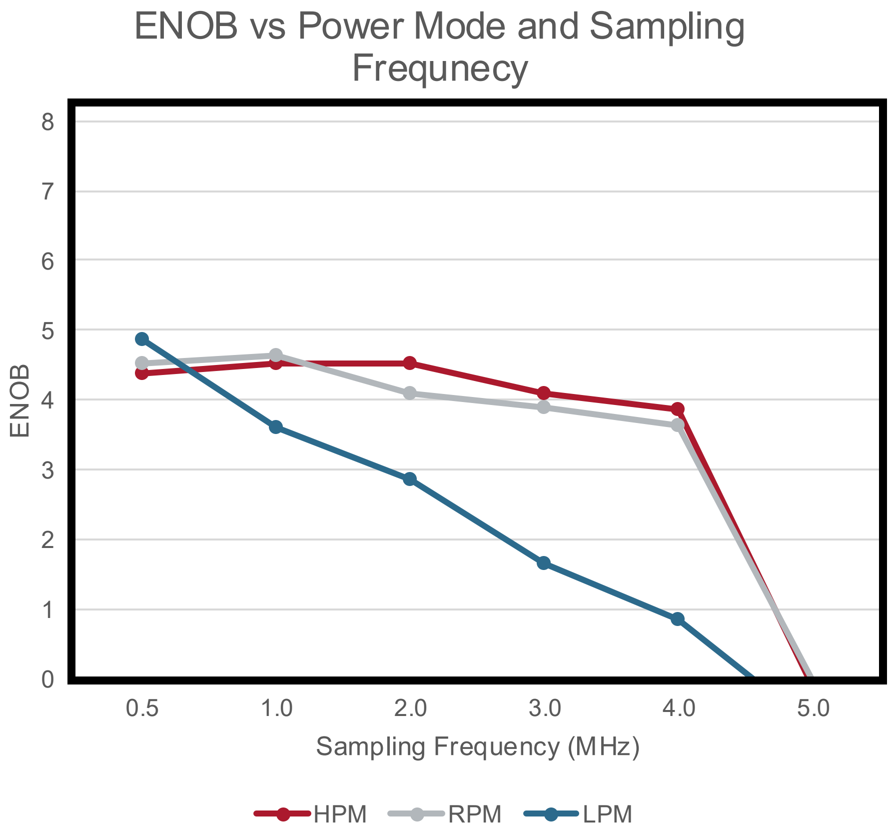
Noise + Distortion FFT

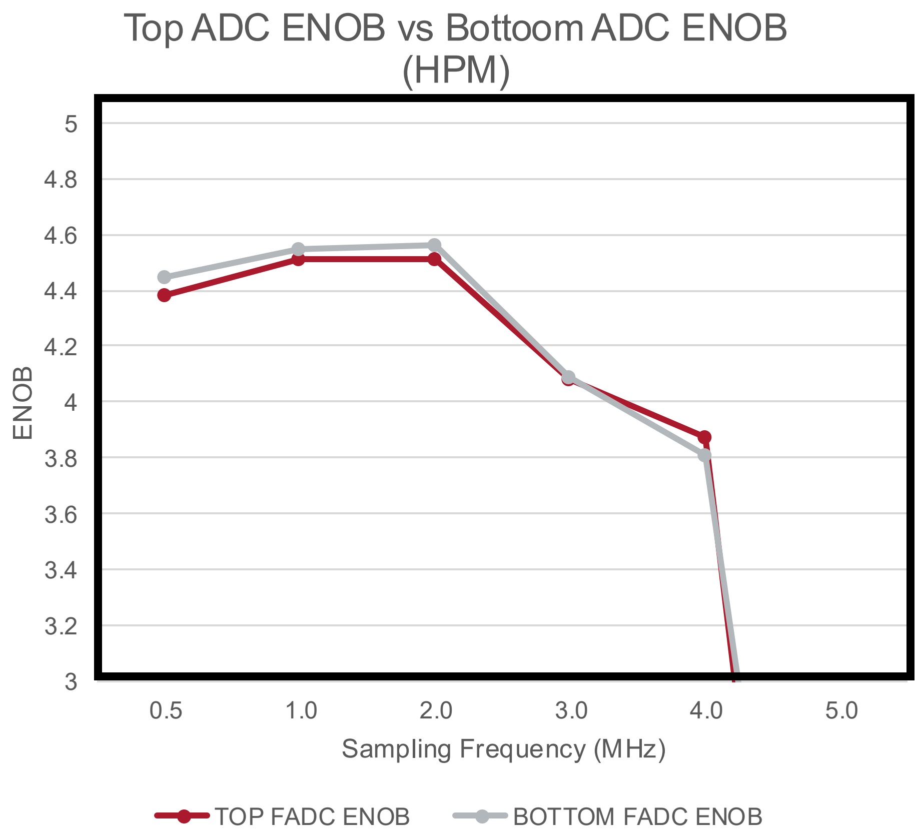


Noise FFT

Measured ENOB (Uncalibrated)

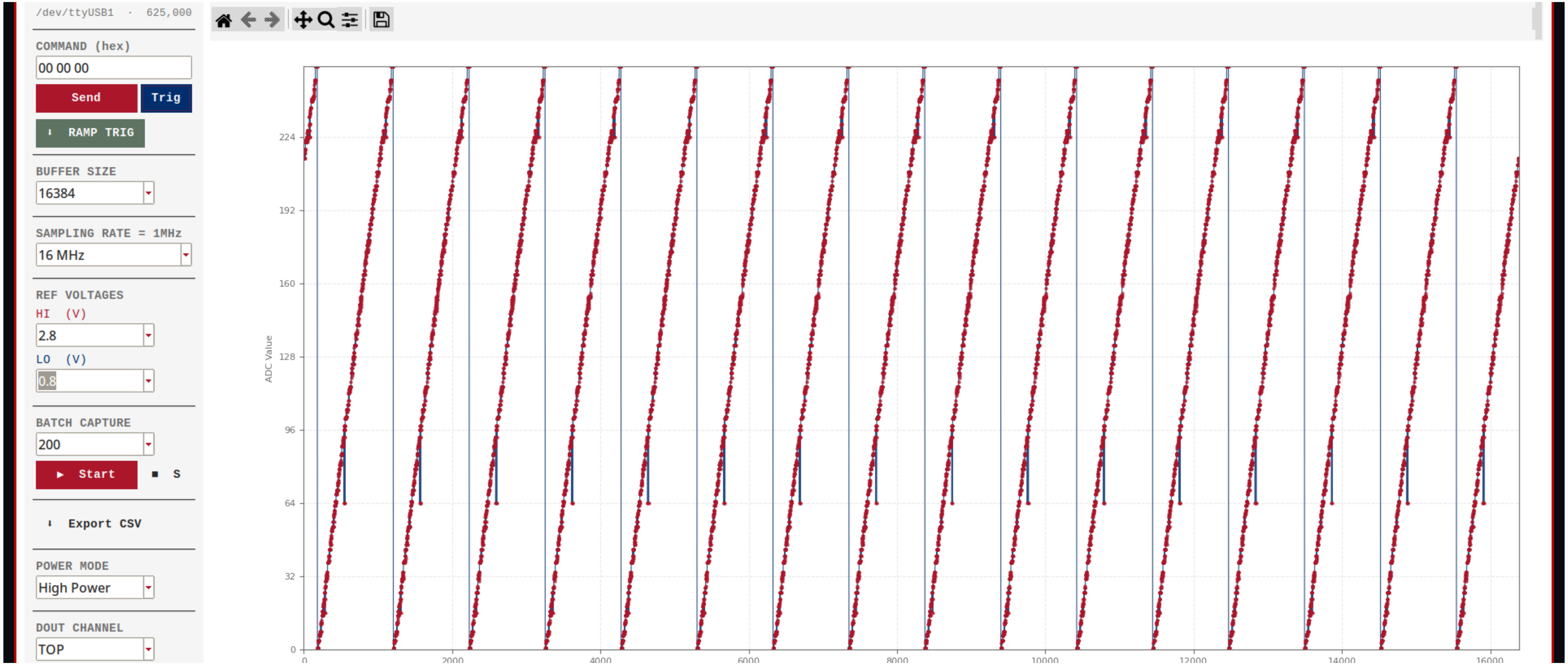
$$ENOB = \frac{SINAD - 1.76}{6.02}$$



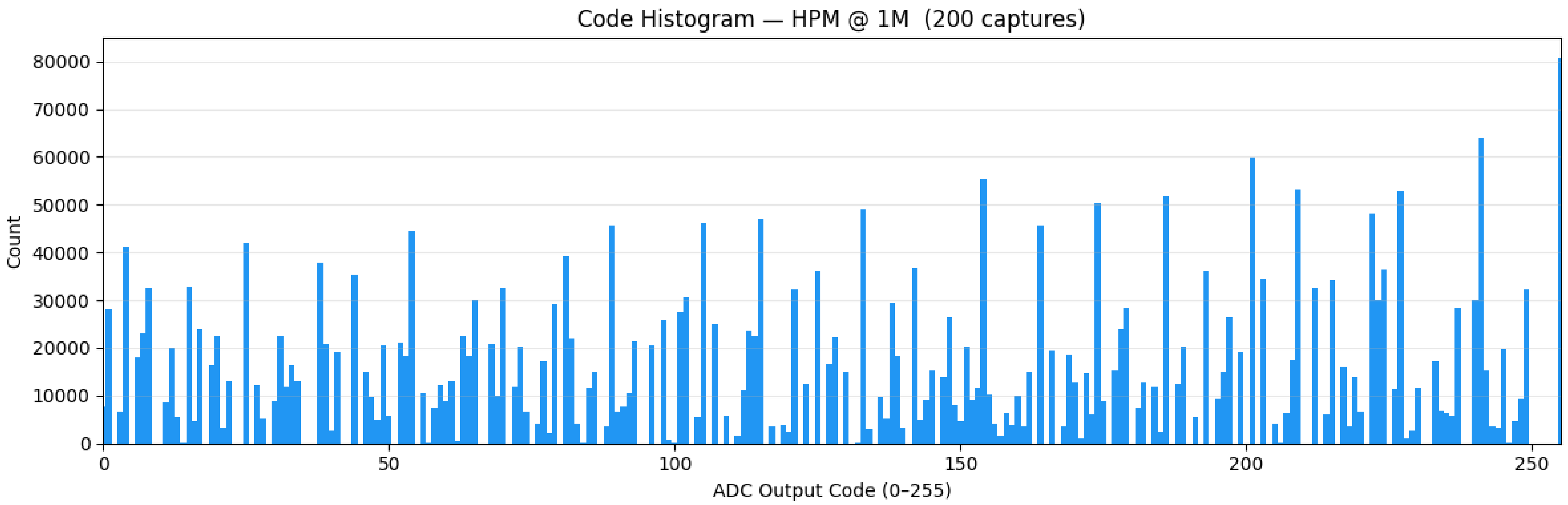


Static Characterization

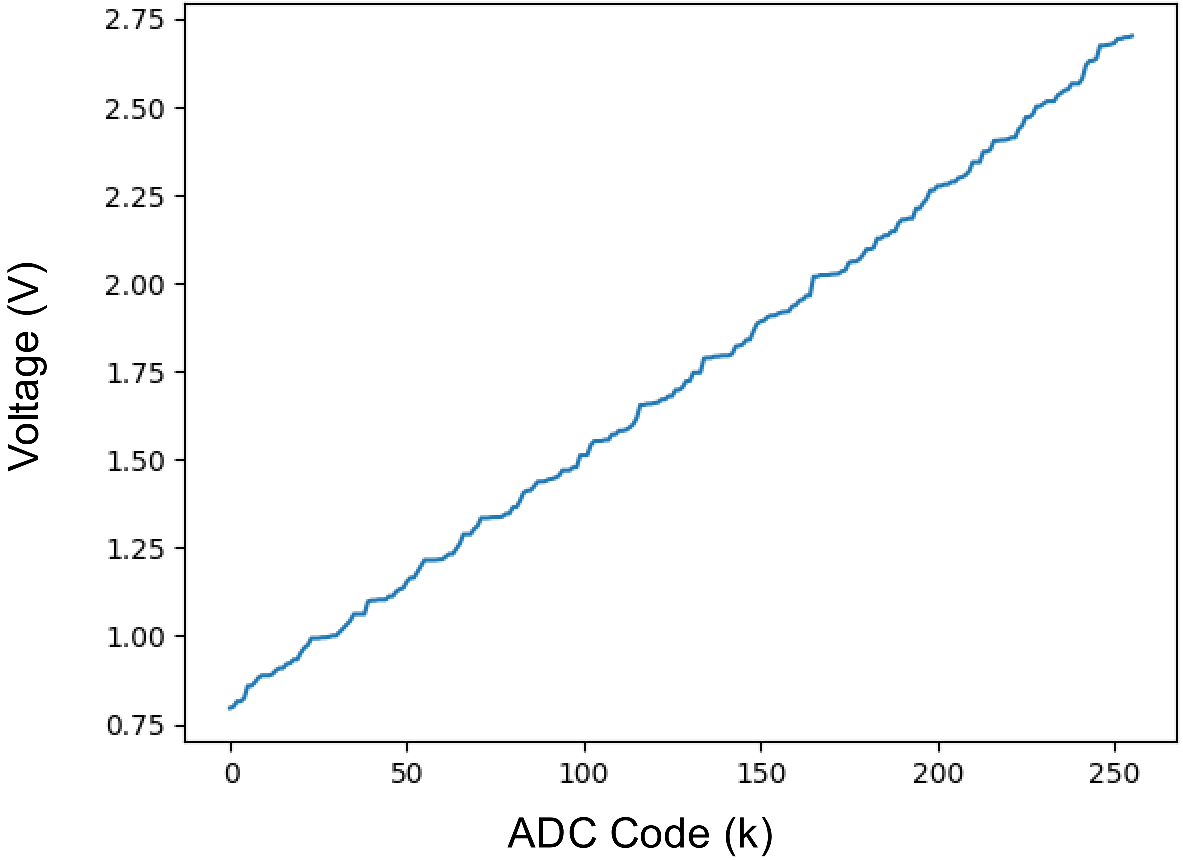
Static Characterization Capture



Static Characterization - Histogram Method



CTL Function (T[k])



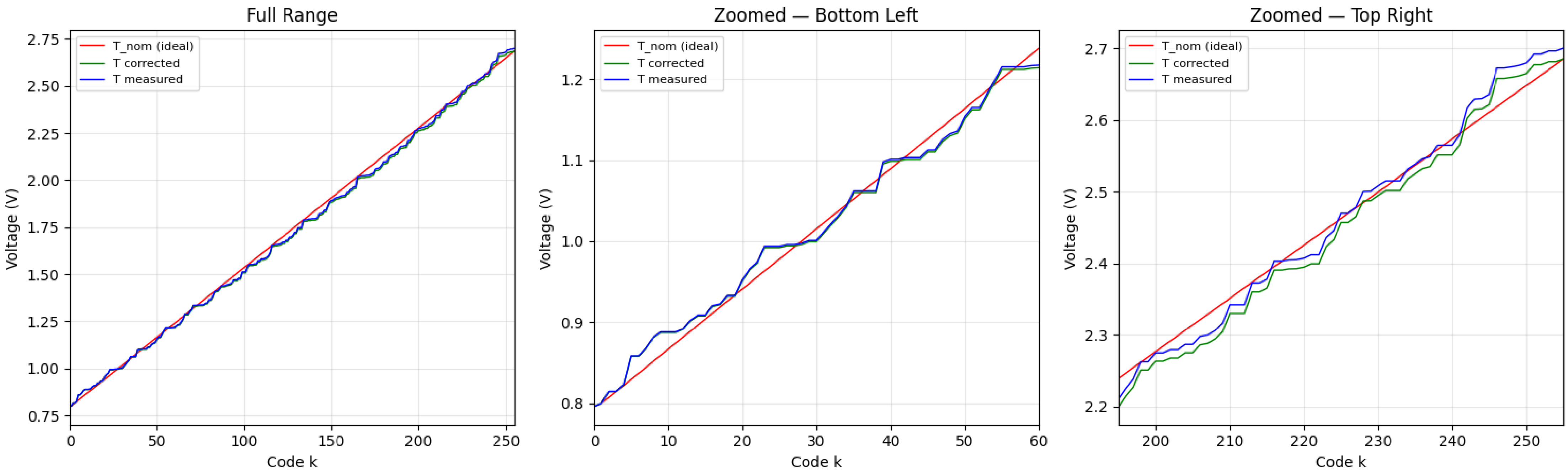
$$T[k] = C + G\sum_{i=0}^{k-1} \boldsymbol{H}[\boldsymbol{i}]\,, \text{ for } \mathrm{k} = 1, 2, \dots (2^N - 1)$$

$$C = V_{ref\ low}$$

$$G = \frac{V_{ref\ high} - V_{ref\ low}}{S}$$

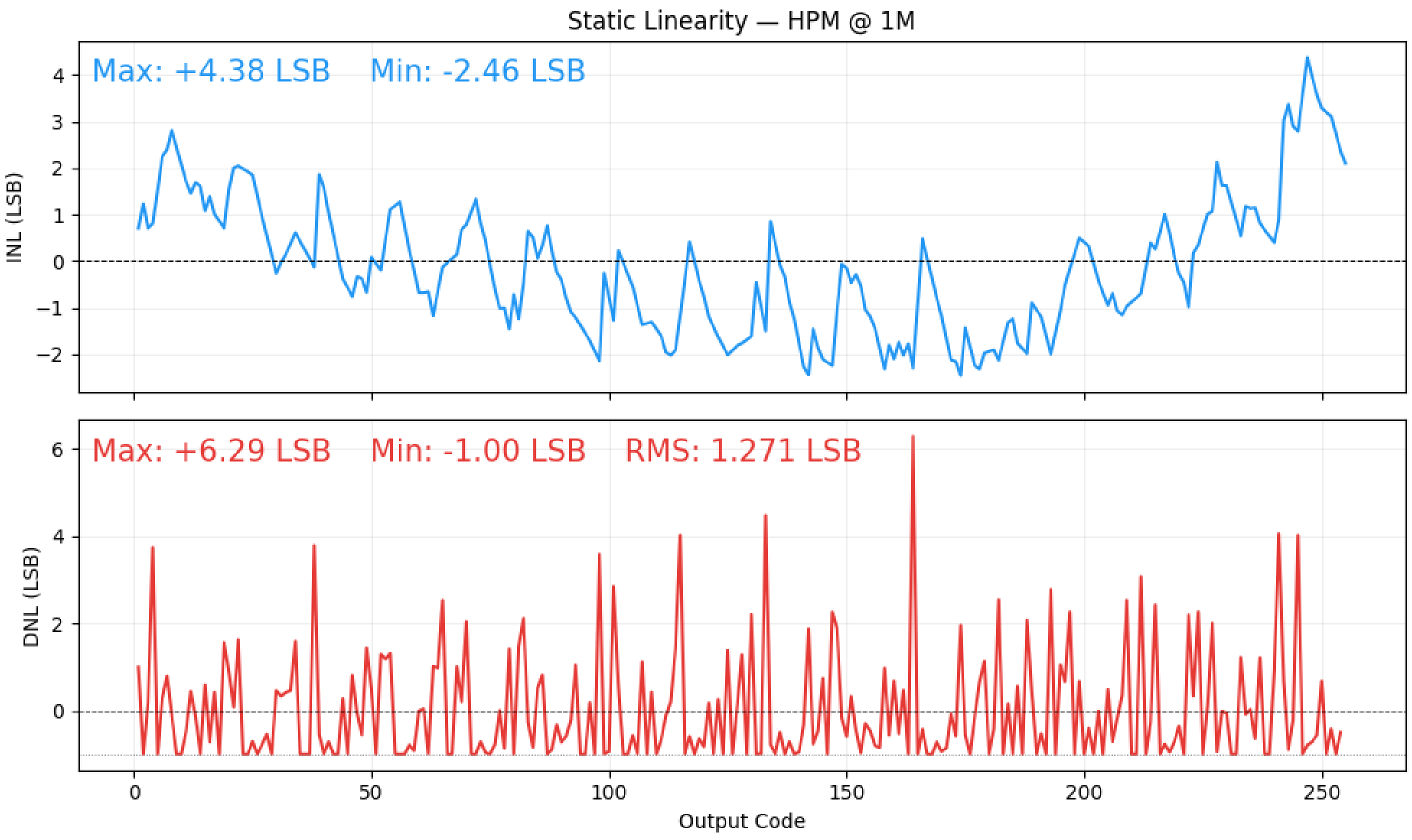
where **S** is the total number of samples

Static Gain and Offset *(IEEE-1241)*



*“Values by which the input values are **multiplied** and then to which the input values are **added**, to cause the deviations from the output values to be **zero at the terminal points**”*

Static Characterization - Results



$$INL[k] = \frac{A \cdot T[k] + V_{OS} - T_{nom}[k]}{Q \cdot V_{FS}}$$

$$DNL[k] = \frac{BIN\_WIDTH_{measured}[k] - BIN_{WIDTH_{ideal}}[k]}{BIN\_WIDTH_{ideal}[k]}$$

Results & Comparison

Comparison

Parameter	Units	WCIS FADC	MAX153	AD9057	CA3318	Lotfi et al.
Expected Resolution	Bits	8	8	8	8	5
Application	—	Video	Telecom	Video / Comms	Video	—
Year	—	2025	1994	2003	1992	2023
Topology	—	Flash, 180 nm CMOS	Half-Flash	Flash	Flash	Flash, 22 nm
f_{in}	kHz	100	195.8	10,000	100	4,700
f_s	MS/s	4	1	40	15	18,500
ENOB	Bits	4.1	7.7	6.7	7.2	3.9
SNR	dB	27.76	49.1	46.5	47.0	31.67
SINAD	dB	25.03	45.0	42.0	45.0	25.0
THD	dB	−28.34	−50.0	—	−46.0	−30.58
DNL	LSB	+6.22 / −1.0	+1.0 / −1.0	+2.0 / −2.0	+1.0 / −0.8	+1.5 / −0.95
INL	LSB	+2.29 / −4.08	+1.0 / −1.0	+2.0 / −2.0	+1.5 / −1.5	+0.76 / −0.95
Power	mW	0.35	40	260	150	3.2
FOM_W	fJ/step	6.00	192.37	62.52	68.01	0.01
FOM_S (SINAD)	dB	122.60	115.97	120.86	121.99	149.61

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Walden Figure of Merit

There are many metrics to characterize ADC's:

- **Power consumption**
- Aperture Bandwidth
- **Resolution**
- Size
- CMRR
- Yield
- **Speed**

How much energy is used per code step?

$$P = \frac{dE}{dt}$$

$$P = \frac{dE}{1/f_s}$$

$$E = \frac{P}{f_s}$$

$$FOM_W \text{ (fJ/conv step)} = E/2^{ENOB} = \frac{P}{f_s \cdot 2^{ENOB}}$$

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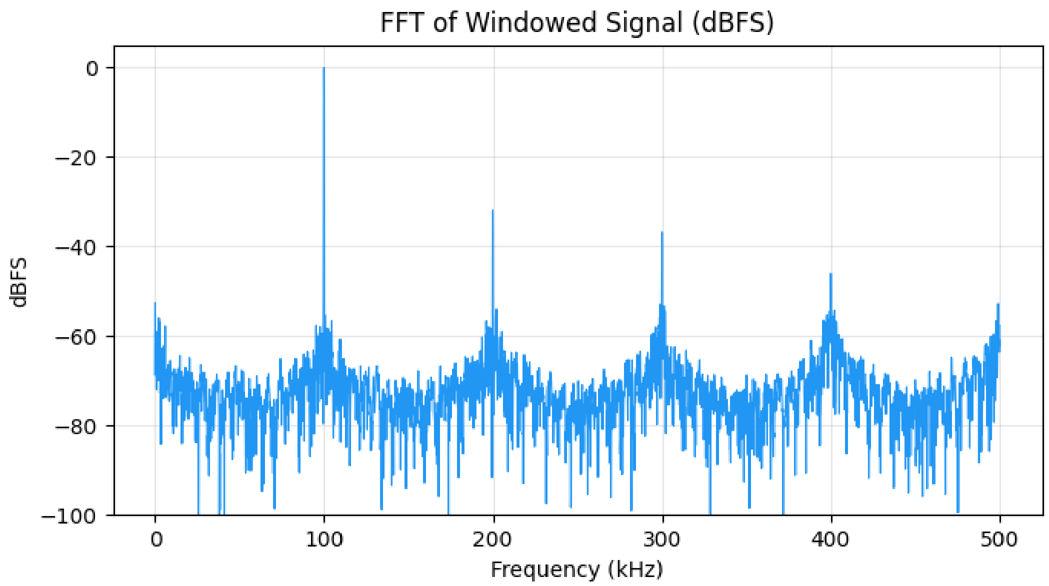
Schreier Figure of Merit

$$FOM_S\ (\mathrm{dB}) = SINAD + 10\log\frac{BW_{nyquist}}{P}$$

$$FOM_S\ (\mathrm{dB}) = DR + 10\log\frac{BW_{nyquist}}{P}$$



FFT with Hanning Window

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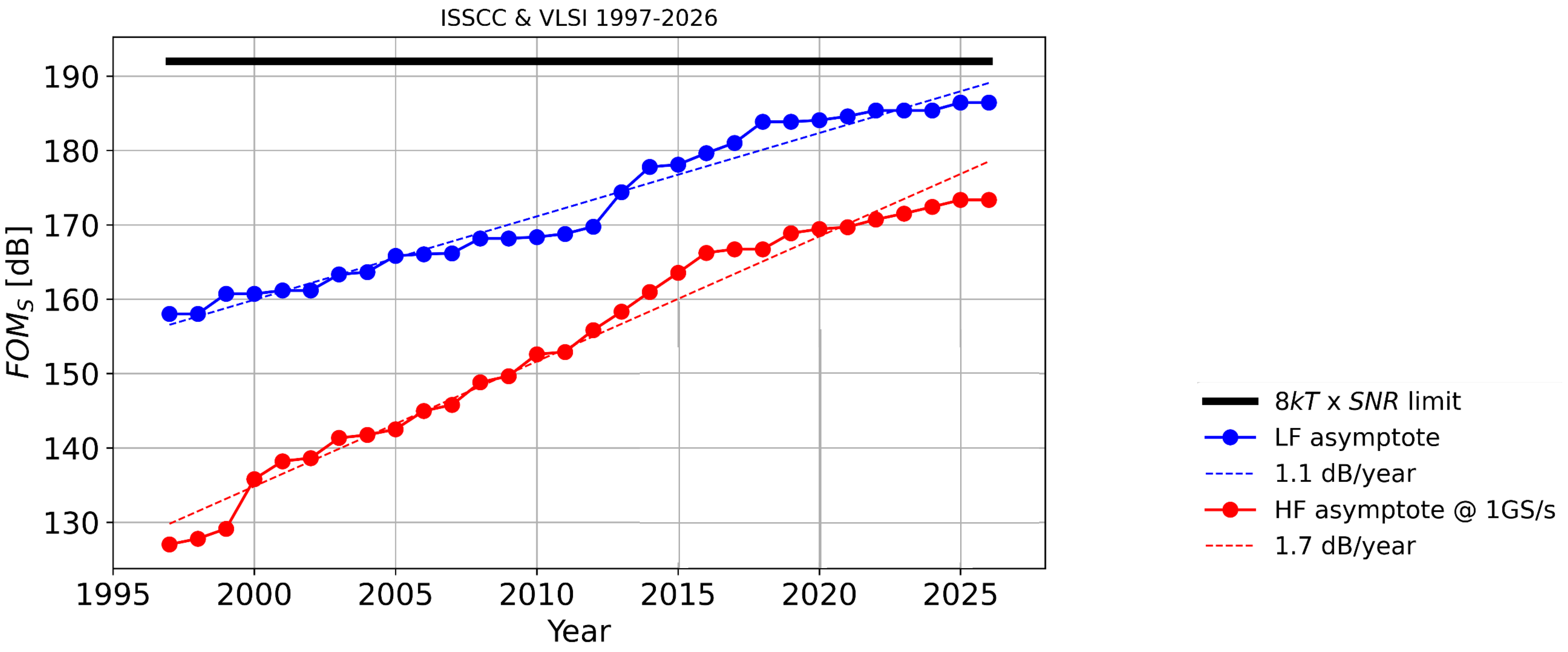
Schreier Figure of Merit

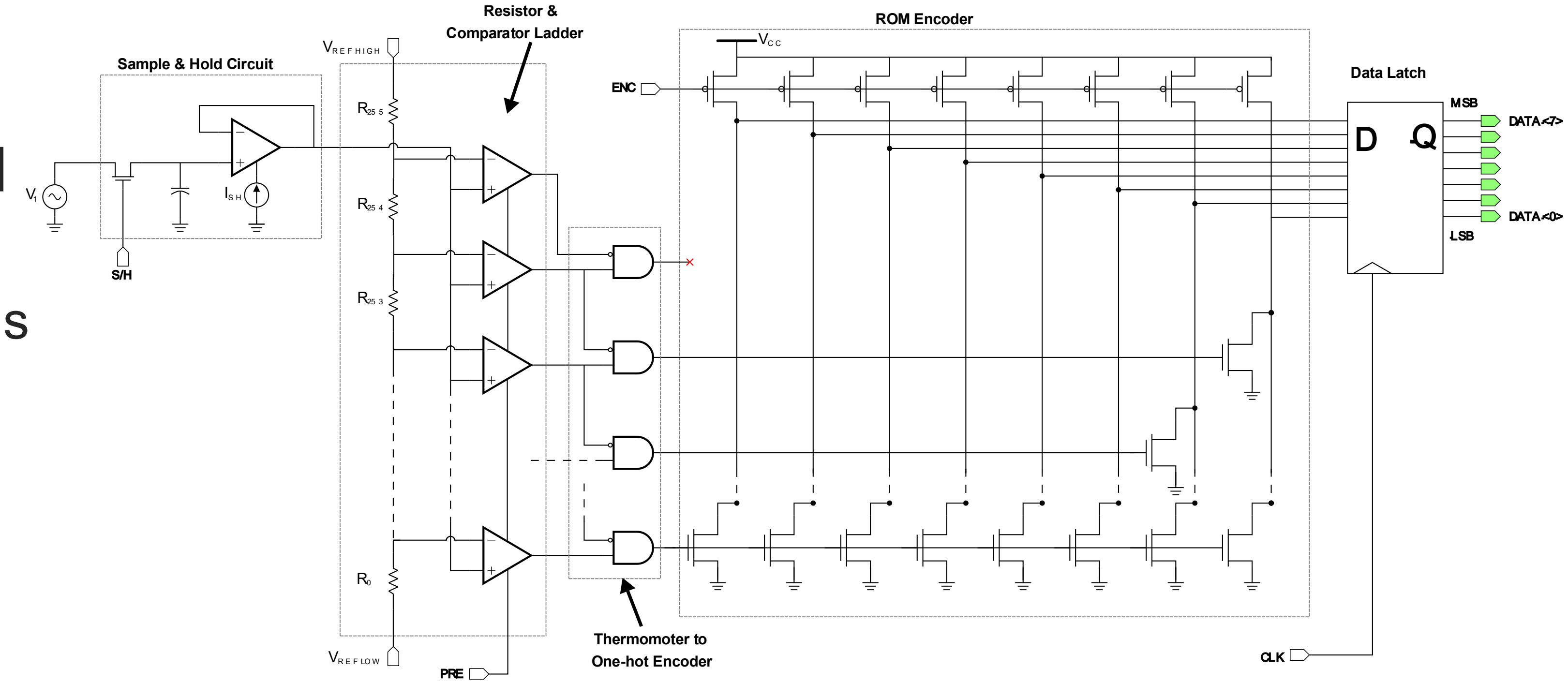


(Boris Murmann, University of Hawaii, ADC Survey)

Conclusions

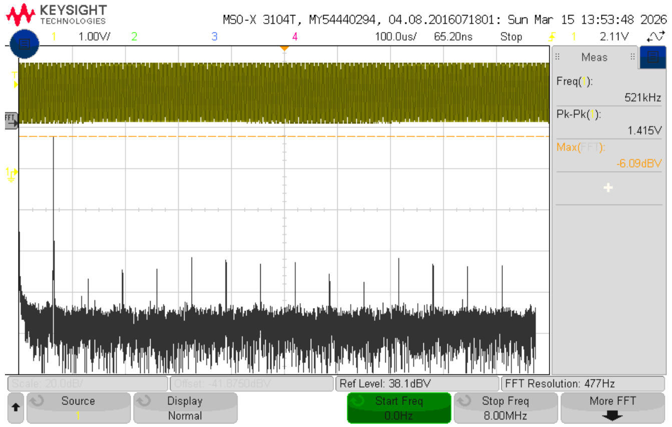
Reflection

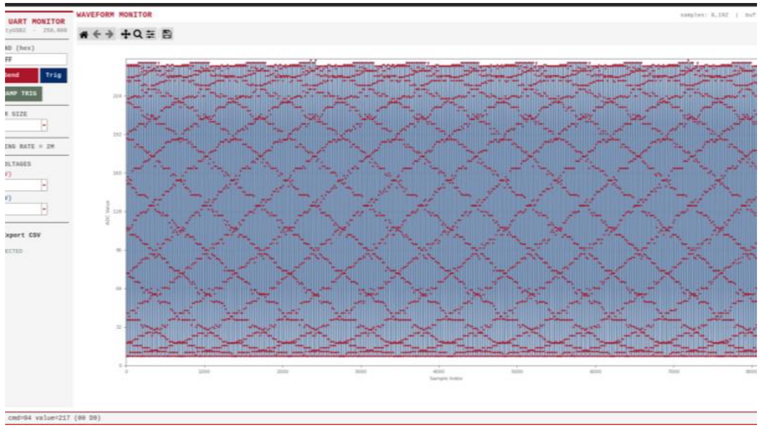
- Why was resolution limited but power exceptional?
  - General Flash ADC limitations
  - Resistor ladder
  - Comparator ladder
    - Skipped codes from offset mismatch

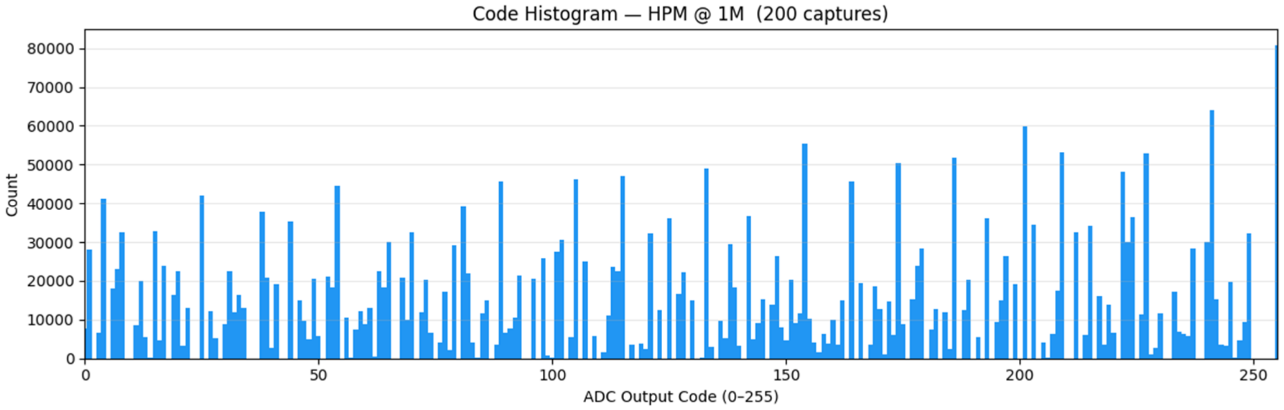


Limitations & Hindsight

- Unaccounted noise error
- Improvements Python GUI
- Background/ Foreground calibration







Next Steps

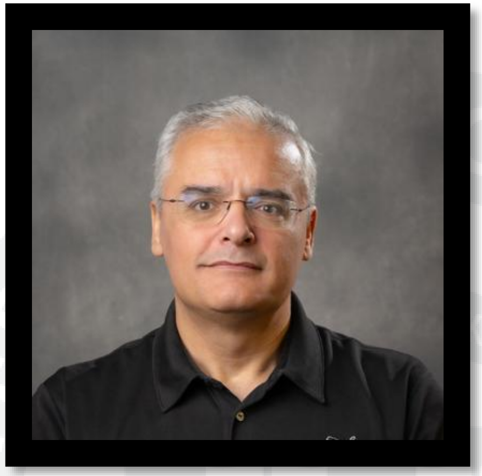
CHIPS DESIGN

STUDIO

- Parallel ADC calibration to remove thermal or jitter noise from FFT
- Characterize image sensor
- Associate researcher in WPI CHIPS Design Studio
- New classes at WPI!
- Moving to Boston!

Thank you!

Ibrahim Boyzel
Co-Advisor

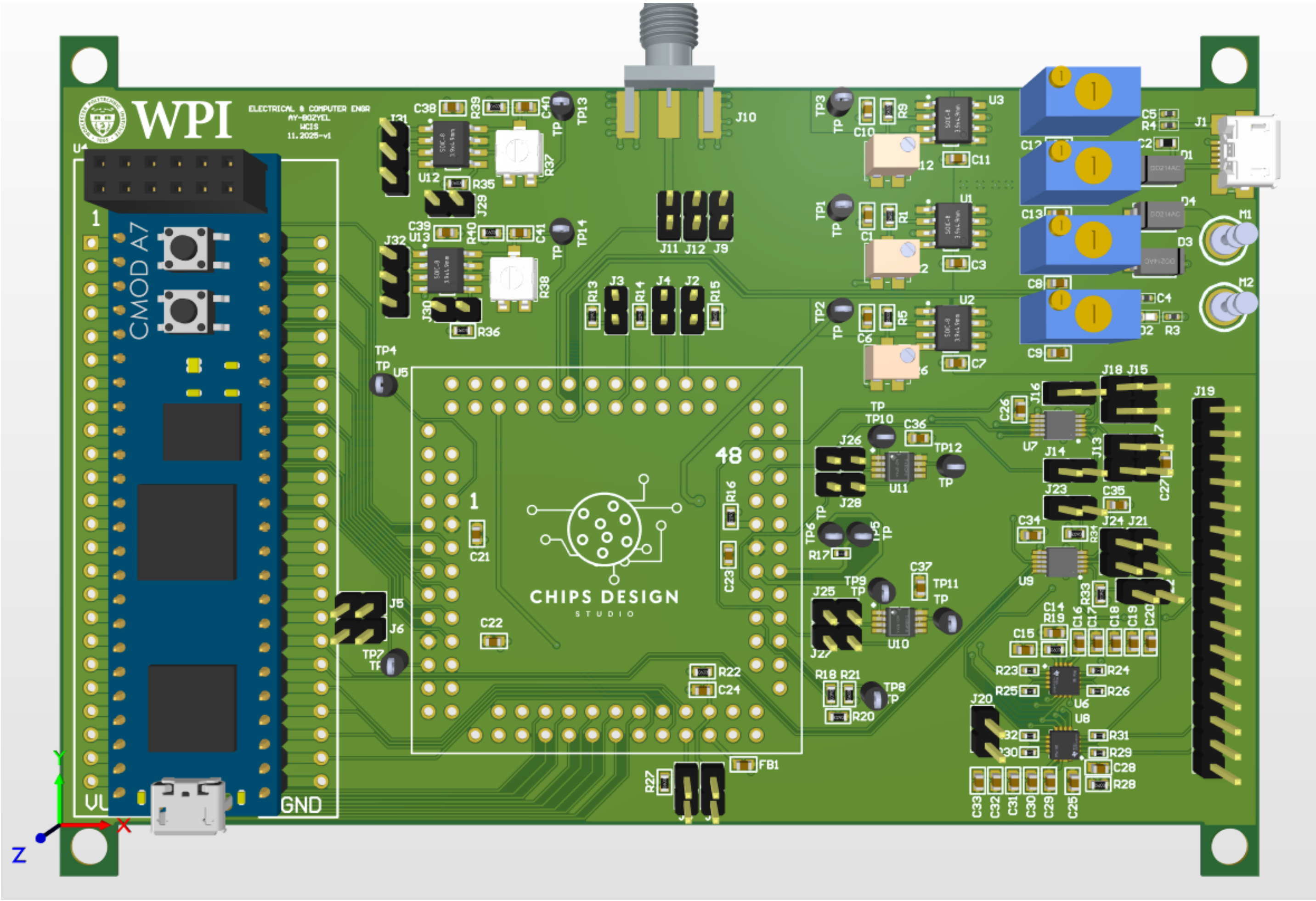


Suat Ay
Major Advisor

Thank you!

Any Questions?

CARRIER PCB


WPI
ELECTRICAL & COMPUTER ENGR
CMOD A7
CHIPS DESIGN
STUDIO
GND