

# FRIDA Design Review

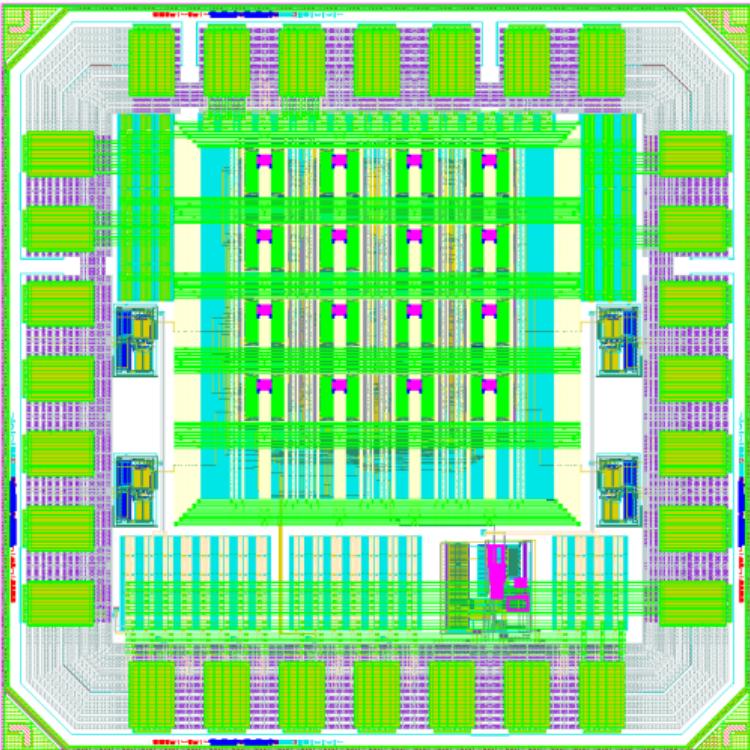
Kennedy Caisley

Wednesday, 28 January 2026

# Outline

1. ADC Target Specifications
2. ADC Floorplan Overview
3. OpenROAD Digital Flow
4. ADC Block Integration
5. Analog Building Blocks
6. Chip Assembly and Layout
7. Ongoing Work

# FRIDA Chip Overview



Parameter	Value
Die size	1 mm × 1 mm
Core area	600 μm × 600 μm
DUT array	4×4 grid (16 ADCs)
Technology	TSMC 65nm LP
Submitted	October 2025

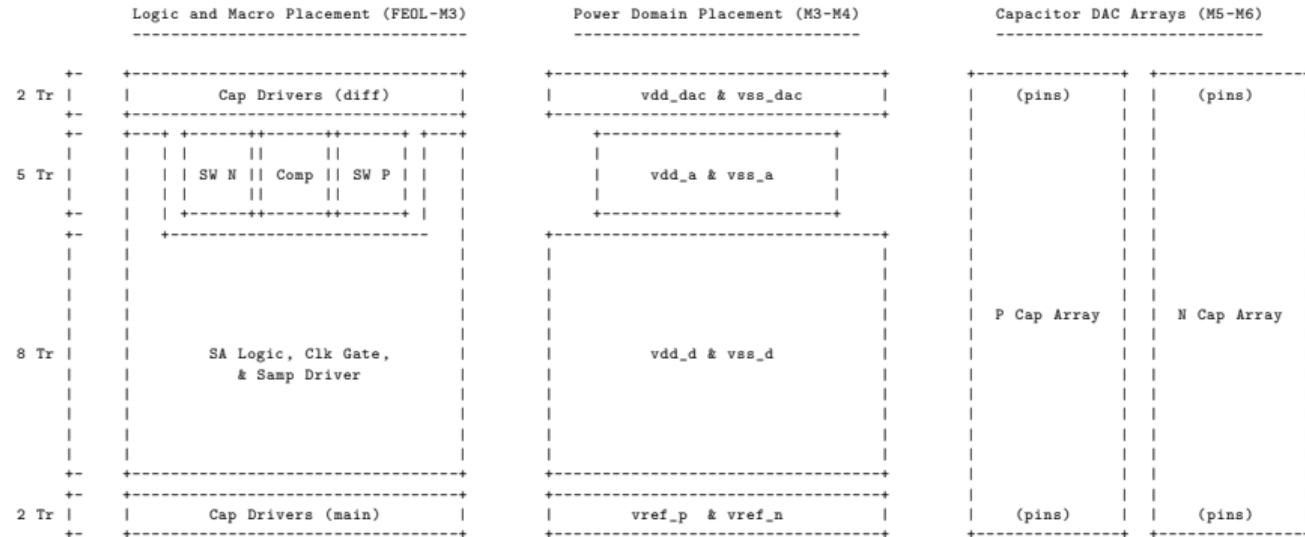
- ▶ Column-parallel SAR ADC array
- ▶ Mixed-signal integration
- ▶ Testing planned Spring 2026

# ADC Target Specifications

Parameter	CD v1	CoRDIA	M	H	F (target)
Resolution	8-bit	10-bit	8-bit	10-bit	12-bit
ENOB	8.3	8.8	8.0	9.5?	11.0?
Conversion rate	6.25 MHz	2.5 MHz	4.5 MHz	10 MHz	10 MHz
ADC dimensions	$40 \times 55 \mu\text{m}$	$80 \times 330 \mu\text{m}$	$60 \times 800 \mu\text{m}$	$15 \times 100 \mu\text{m}$	$50 \times 50 \mu\text{m}$
ADC area	$0.002 \text{ mm}^2$	$0.026 \text{ mm}^2$	$0.048 \text{ mm}^2$	$0.0015 \text{ mm}^2$	$0.0025 \text{ mm}^2$
Power per ADC	$960 \mu\text{W}$	$30 \mu\text{W}$	$700 \mu\text{W}$	$100 \mu\text{W}$	$200 \mu\text{W?}$
$\text{FOM}_{\text{csa}} (\text{Hz}/\mu\text{m}^2)$	3125	95	105	5000	5000
$\text{FOM}_{\text{wal}} (\text{fJ}/\text{conv-step})$	487	26	608	14	10

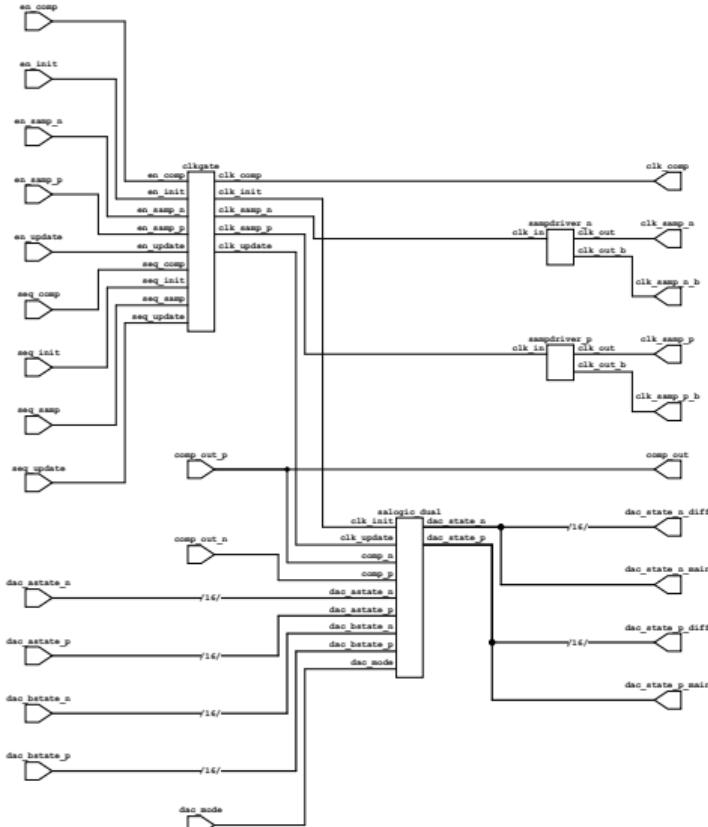
- ▶ F = FRIDA target: 12-bit, 10 MHz,  $50 \times 50 \mu\text{m}$  footprint
- ▶  $\text{FOM}_{\text{csa}}$  = conversion rate / area;  $\text{FOM}_{\text{wal}}$  = energy per conversion step

# Sketch of ADC Floorplan



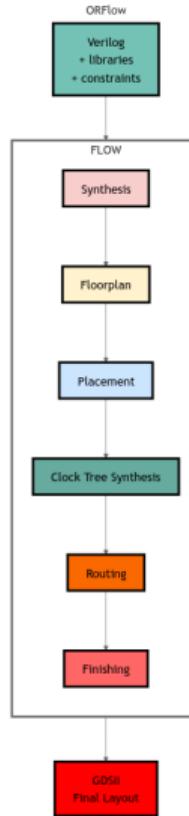
# ADC Digital Block Netlist

- ▶ **salogic**: SAR sequencing FSM
- ▶ **clkgate**: Clock gating for power
- ▶ **sampdriver\_p/n**: Sampling switch drivers
- ▶ Symmetric P/N halves for differential operation
- ▶ salogic and clkgate shared between halves



# OpenROAD Flow Scripts (ORFS)

- ▶ **Yosys:** RTL synthesis
  - ▶ Verilog parsing and elaboration
  - ▶ Logic optimization (ABC)
  - ▶ Technology mapping to standard cells
- ▶ **OpenROAD:** Physical design
  - ▶ Floorplanning and PDN
  - ▶ Placement (global + detailed)
  - ▶ Clock tree synthesis
  - ▶ Routing (global + detailed)
  - ▶ Timing analysis (OpenSTA)
- ▶ **KLayout:** Final verification
  - ▶ DRC and LVS checks
  - ▶ GDS export



# Yosys: Step 1 - RTL Synthesis

## Input Files

- ▶ adc\_digital.v (top module)
- ▶ clkgate.v, salogic.v, sampdriver.v
- ▶ cells\_tsmc65.v (cell wrappers)

## Synthesis Statistics

- ▶ Total cells: 350
- ▶ Total area: 893.88  $\mu\text{m}^2$
- ▶ Sequential elements: 49% of area
- ▶ 48 flip-flops (DFQD1, EDFD2)
- ▶ 5 clock gates (CKLNQD1LVT)

## Technology Mapping (ABC)

Module	Cells	Area
adc_digital	38	54.36
clkgate	6	33.48
salogic	302	798.84
sampdriver	2	3.60
Total	350	893.88

## Key Cell Types

EDFD2LVT (edge DFF)	32	334.08
DFQD1LVT (DFF)	16	109.44
NR2D0LVT (NOR2)	93	133.92
BUFFD0LVT (buffer)	69	99.36
CKLNQD1LVT (clkgate)	5	32.40

# OpenROAD Step 2.1: Floorplan



- ▶ Die and core area:  $60\mu\text{m} \times 49\mu\text{m}$
- ▶ Row height:  $2.8\mu\text{m}$  (17 rows)
- ▶ Blockages reserve space for analog macros
- ▶ I/O pin and routing grid ( $0.2\mu\text{m}$  pitch)

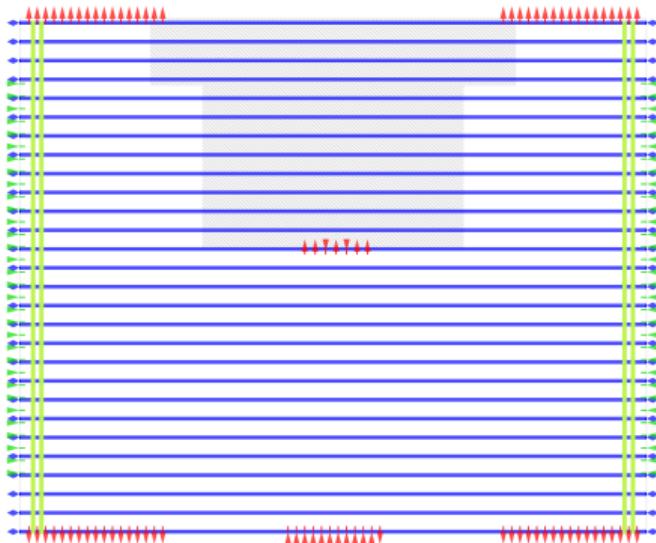
## config.mk

```
export DIE_AREA = 0 0 60 49
export CORE_AREA = 0 0 60 49
export CREATE_BLOCKAGES = .../create_blockages.tcl
```

## create\_blockages.tcl

```
# Reserve area for comparator
create_blockage -region {17.5 27.0 42.5 49}
# Reserve areas for sampling switches
create_blockage -region {12.5 42.6 21 49}
create_blockage -region {39 42.6 47.5 49}
```

# OpenROAD Step 2.2: Power Distribution Network



- ▶ M4 vertical stripes at edges for vdd\_d/vss\_d
- ▶ M1 horizontal stripes follow cell rows
- ▶ M1-M4 connections for power delivery

## pdn.tcl

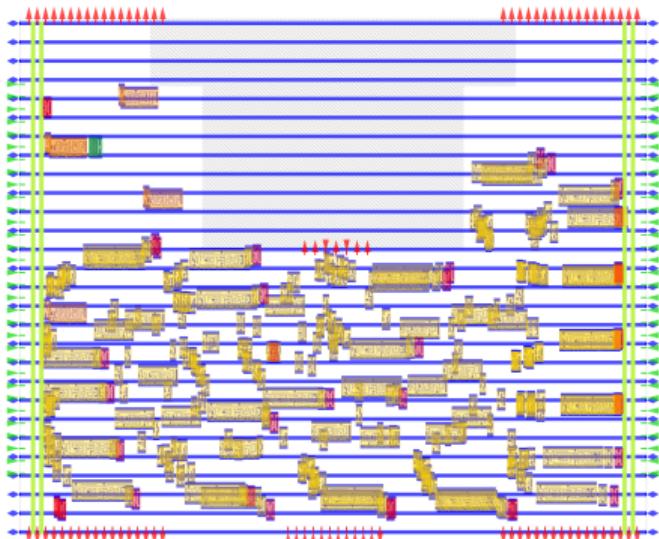
```
add_global_connection -net {vdd_d} \
    -inst_pattern {*} -pin_pattern VDD -power
add_global_connection -net {vss_d} \
    -inst_pattern {*} -pin_pattern VSS -ground

define_pdn_grid -name "Core" -pins {M4}

add_pdn_stripe -grid "Core" -layer M4 \
    -width 0.4 -offset 1.3 -nets {vdd_d}
add_pdn_stripe -grid "Core" -layer M4 \
    -width 0.4 -offset 2.1 -nets {vss_d}

add_pdn_stripe -grid "Core" -layer M1 \
    -followpins -width 0.33
add_pdn_connect -grid "Core" -layers {M1 M4}
```

# OpenROAD Step 3.1: Global Placement



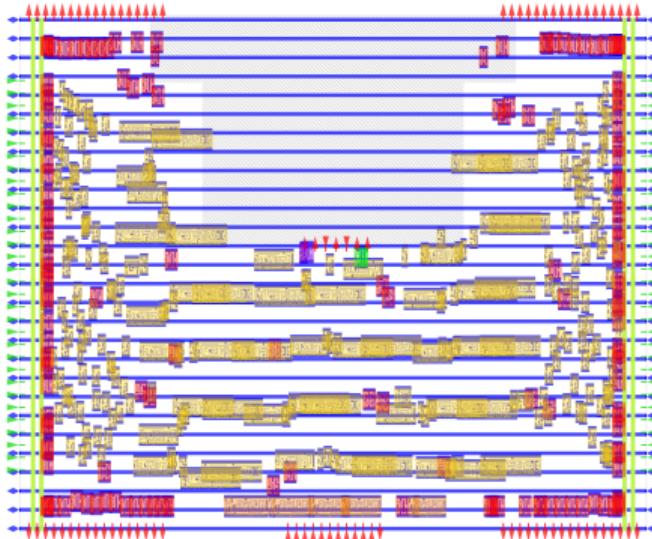
- ▶ Initial cell location doesn't consider I/O
- ▶ Instead routability-driven placement
- ▶ 60% target placement density
- ▶ Placement avoids blockages

## config.mk

```
# Standard cell placement density
export PLACE_DENSITY = 0.50

# I/O pin layers
export IO_PLACER_H = M3
export IO_PLACER_V = M2
```

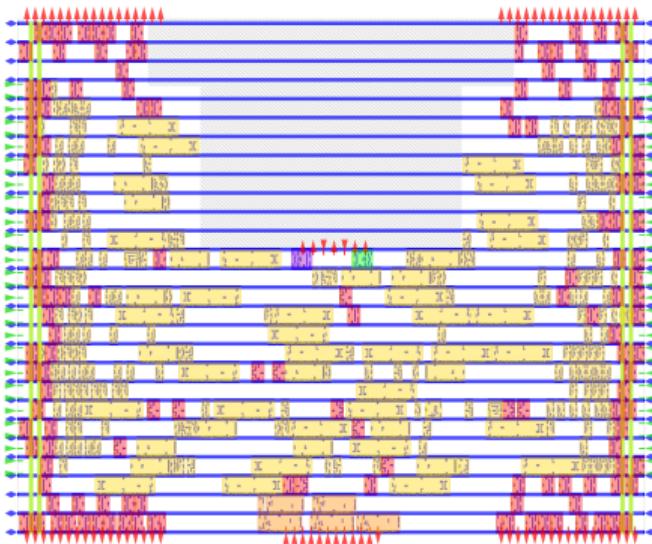
## OpenROAD Step 3.2: Global Placement (I/O Aware)



- ▶ Cells migrated toward connected IO pins
- ▶ 445 movable cells, 457 total instances
- ▶ Timing-driven with Nesterov solver
- ▶ 335 iterations to converge

Metric	Value
Core area	2916 $\mu\text{m}^2$
Cell area	1102 $\mu\text{m}^2$
Utilization	49%
Final HPWL	5125 $\mu\text{m}$
Worst slack	4.49 ns
fmax achievable	1975 MHz

# OpenROAD Step 3.3: Detailed Placement



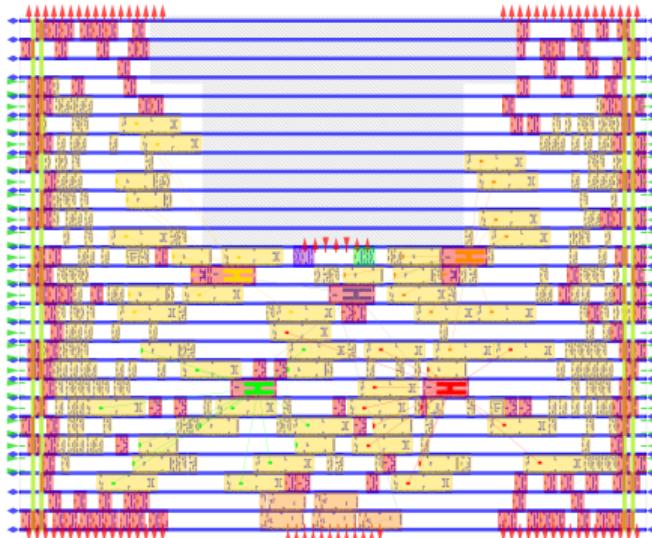
- ▶ 424 cells legalized to row sites
- ▶ Legalization adds 4% HPWL
- ▶ Optimization recovers 9.8% HPWL

## Optimization Passes

Independent set matching	0.35%
Global swaps	2.36%
Vertical swaps	0.34%
Reordering	0.96%
Random improvement	3.09%
Cell flipping	3.10%

Metric	Value
Final HPWL	4796 $\mu\text{m}$
Final area	1102 $\mu\text{m}^2$
Utilization	38%

# OpenROAD Step 4.1: Clock Tree Synthesis



- ▶ System clock: 10 MHz (100ns period)
- ▶ Samp/comp clock: 200 MHz (5ns period)
- ▶ 50ps clock uncertainty
- ▶ Balanced tree for minimal skew

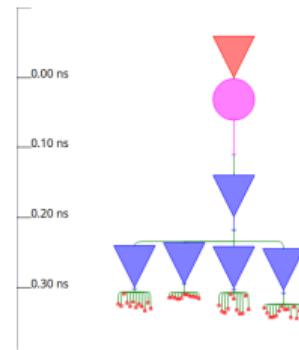
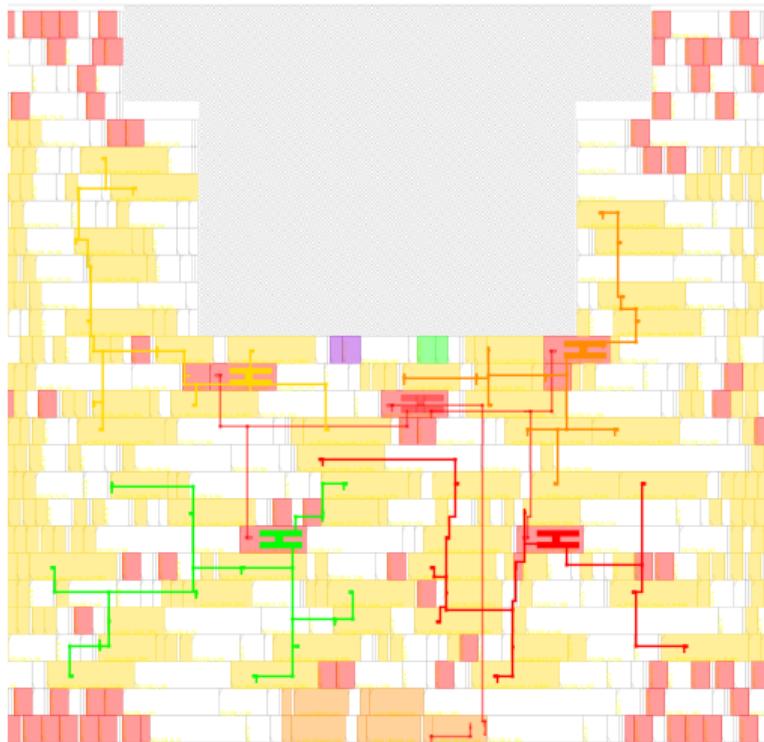
## constraint.sdc

```
current_design adc_digital

# Create clock for sequencing (200 MHz)
create_clock -name seq_update \
-period 5 [get_ports seq_update]

# Set clock uncertainties
set_clock_uncertainty 0.05 [all_clocks]
```

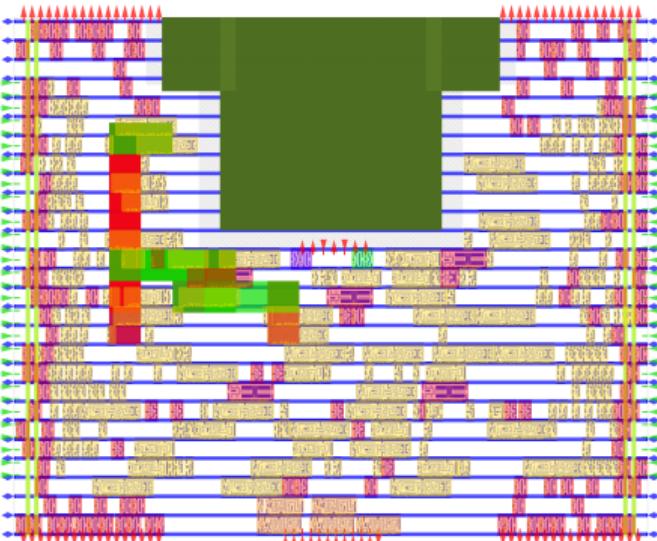
# OpenROAD Step 4.1: Clock Tree Views



## CTS Results:

- ▶ 31 BUFD2LVT cells across 4 clock paths
- ▶ Domains unsynchronized within ADC  
(relies on upstream sequencer)
- ▶ Clock power: 41% of total
- ▶ Setup skew: 0.07 ns

# OpenROAD Step 5.1: Global Routing



- ▶ Route guides shown for global routing
- ▶ M2-M3 routing layers only
- ▶ Routing obstructions for analog areas

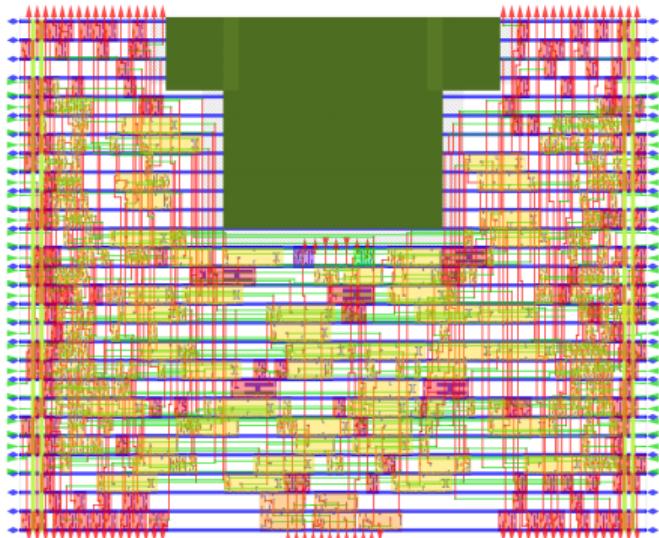
## config.mk

```
export MIN_ROUTING_LAYER = M2
export MAX_ROUTING_LAYER = M3
export PRE_GLOBAL_ROUTE_TCL = \
.../routing_blockages.tcl
```

## routing\_blockages.tcl

```
# Create obstructions on M1-M4 for analog
odb::dbObstruction_create $block $layer_M1 \
$comp_llx $comp_lly $comp_urx $comp_ury
odb::dbObstruction_create $block $layer_M2 \
$comp_llx $comp_lly $comp_urx $comp_ury
```

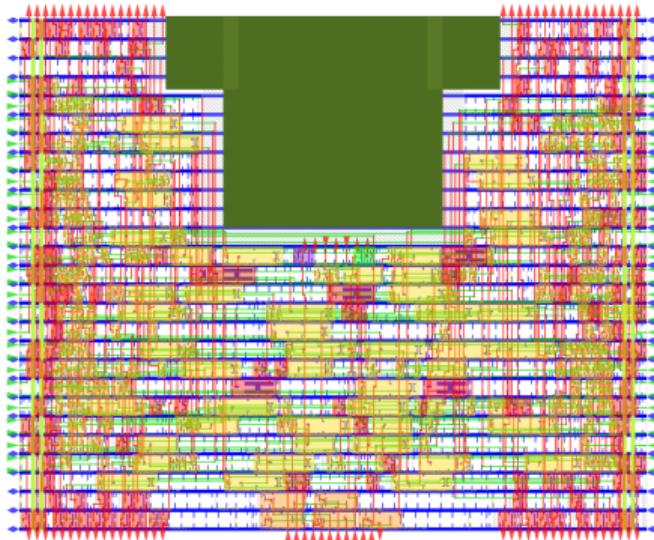
## OpenROAD Step 5.2: Detailed Routing



- ▶ Final metal routing on M2/M3
- ▶ All signals routed to I/O pins
- ▶ DRC-clean routing around blockages
- ▶ **Issue:** Multicut vias on large devices

Metric	Value
Nets routed	506
Total wire length	5717 $\mu\text{m}$
M2 wire length	3183 $\mu\text{m}$
M3 wire length	2625 $\mu\text{m}$
Total vias	2058
Clock skew	0.07 ns
Worst slack	4.37 ns

# OpenROAD Step 5.3: Fill Cells

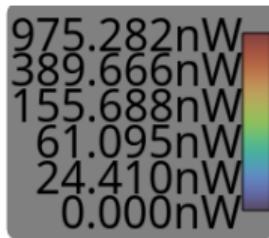
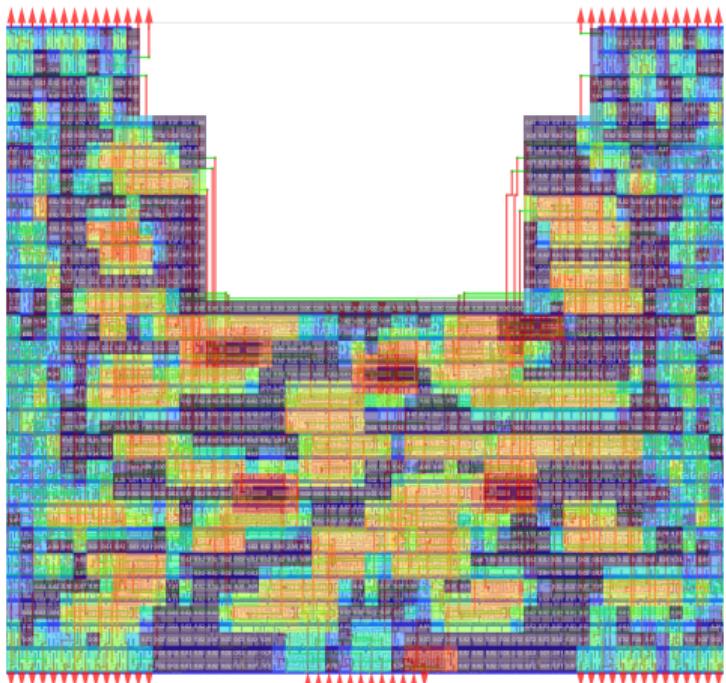


- ▶ Decap fill cells added (FEOL)
- ▶ Metal fill disabled (BEOL)
- ▶ Fills gaps in standard cell rows

## config.mk

```
# Only disables metal fill
# FILL_CELLS in routing step still
# adds FEOL decap fill cells
export USE_FILL = 0
```

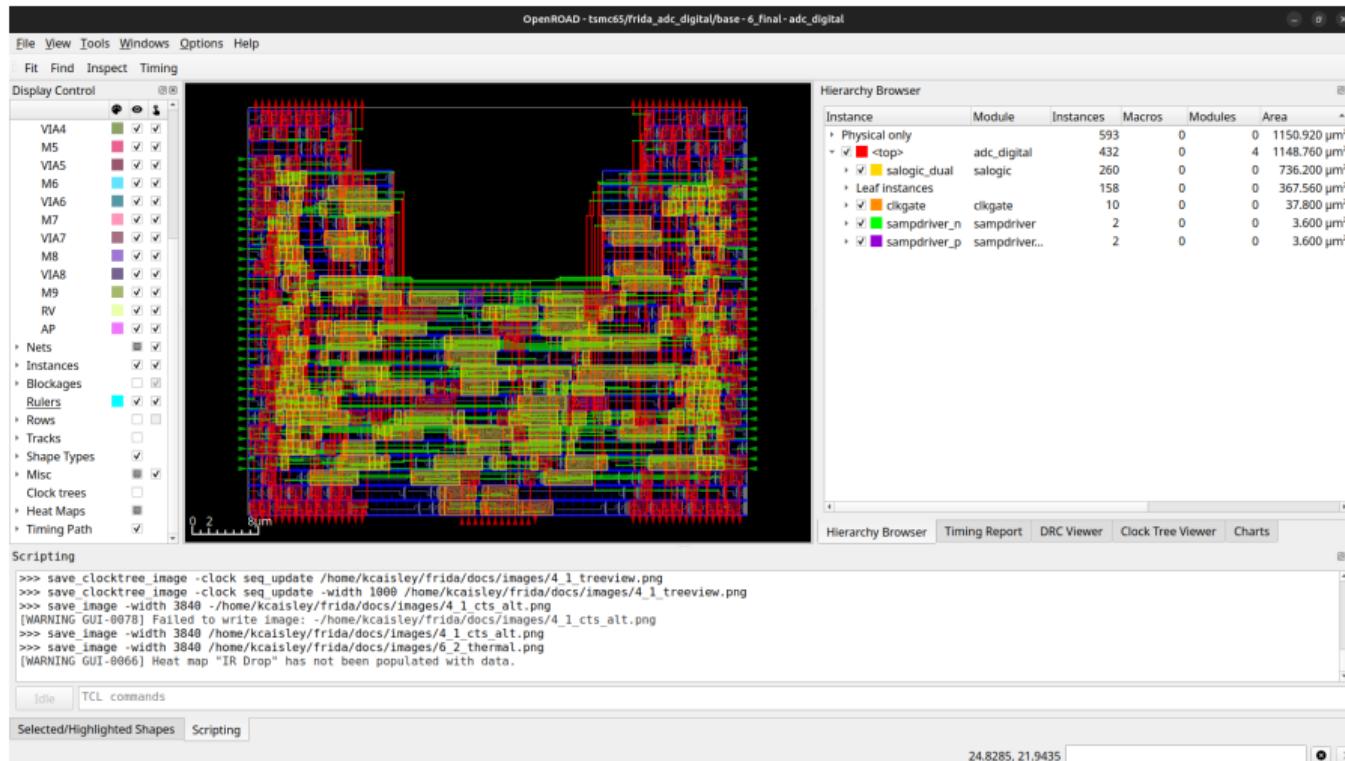
## OpenROAD Step 6.1: Heat Maps



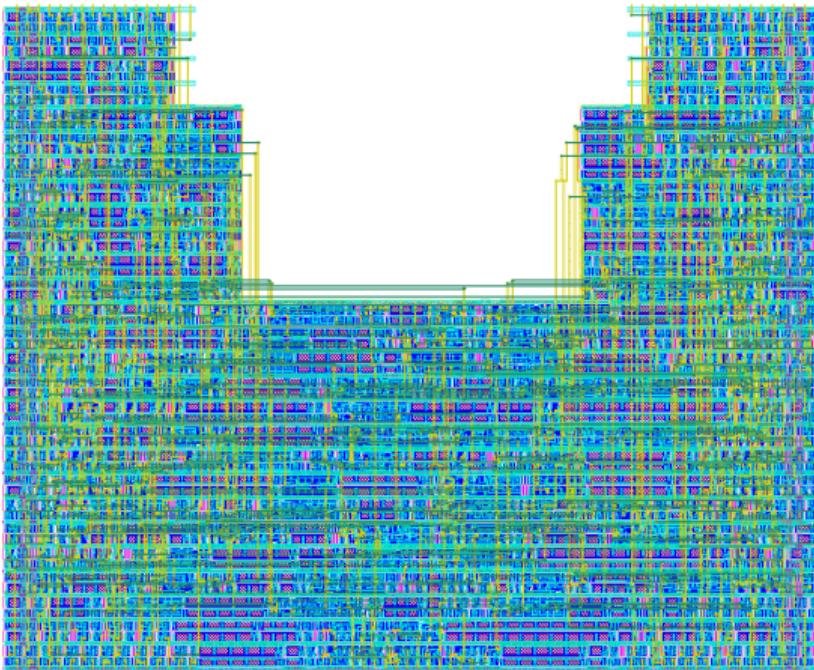
- ▶ Spatial visualizations for IR drop, thermal dissipation, placement density, pin density, and power consumption
- ▶ DRC and antenna violation views for debugging

# OpenROAD GUI

- ▶ Interactive GUI, net tracing, hierarchical cell grouping, timing reports, DRC viewer, heatmaps

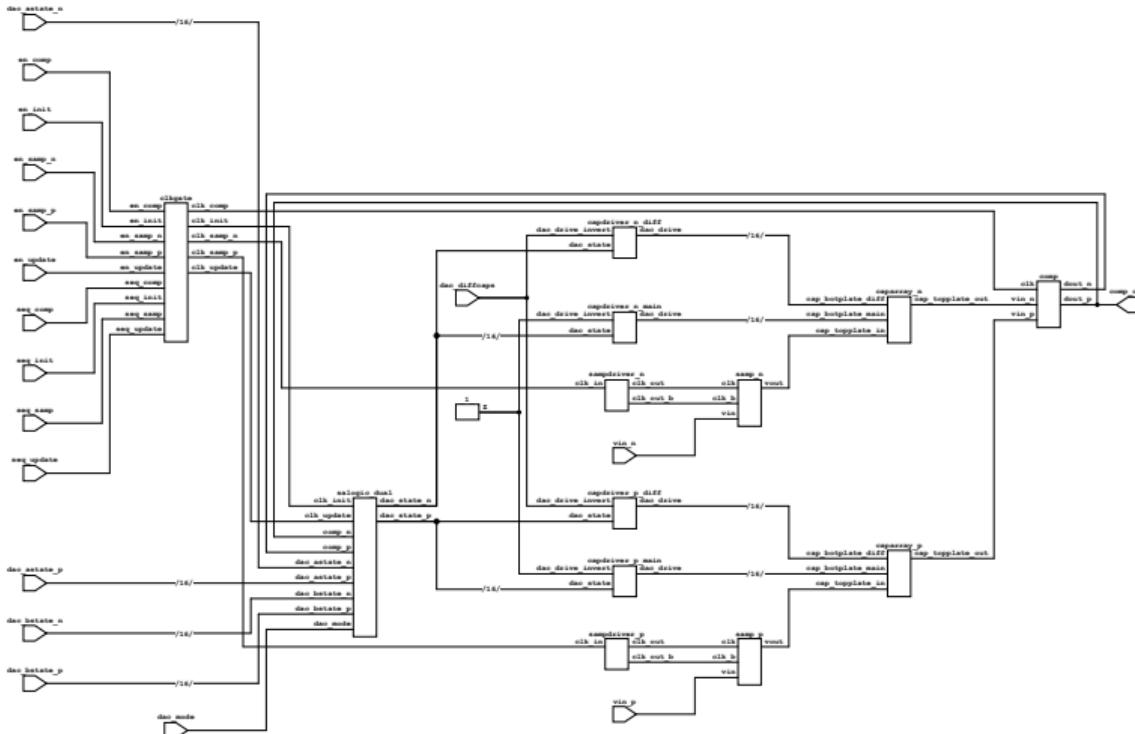


# ADC Digital Block Layout



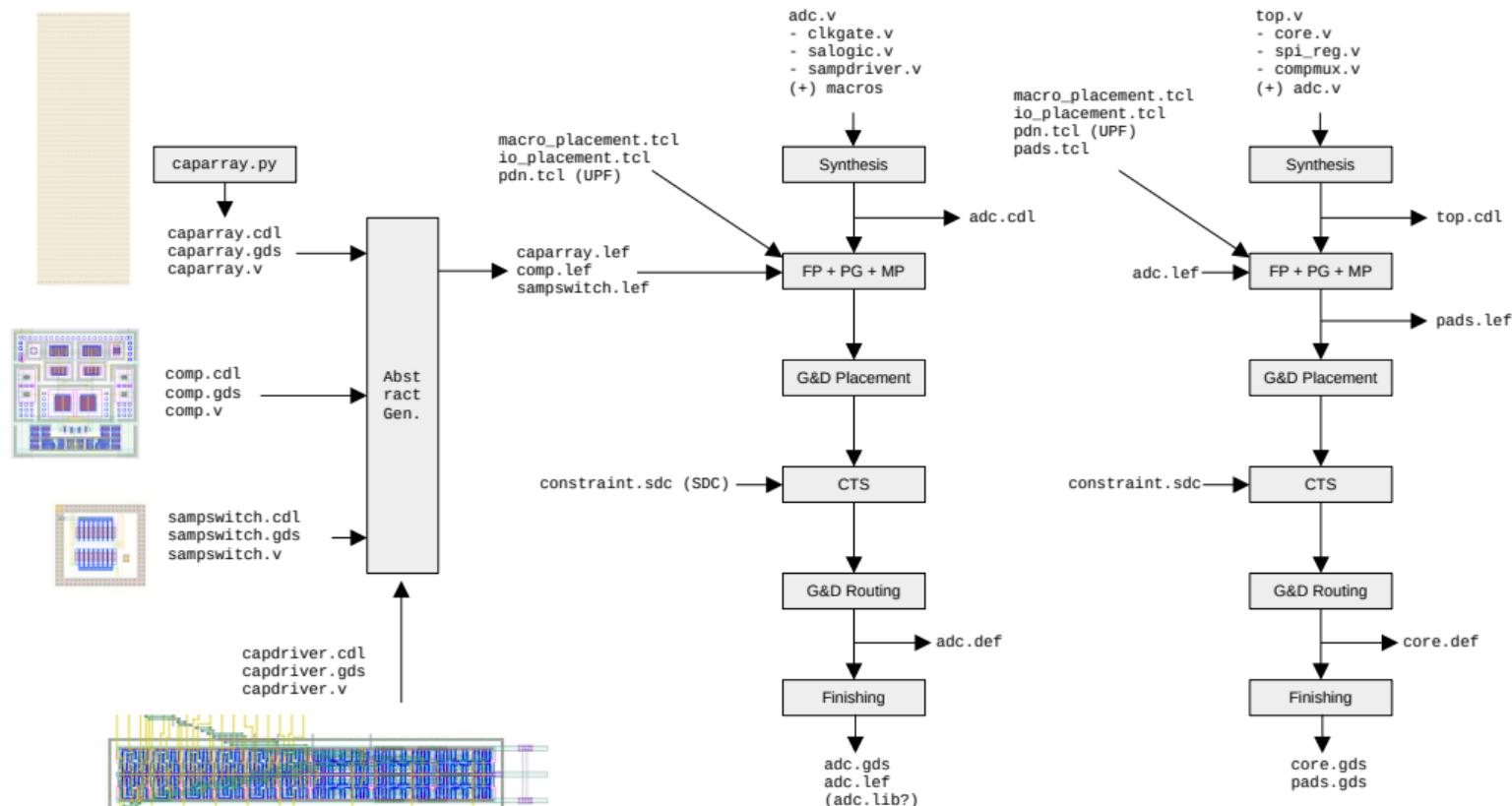
Metric	Value
Dimensions	$60 \times 49 \mu\text{m}$
Cell count	350
Area	$894 \mu\text{m}^2$
Flip-flops	48
Clock gates	5
Wire length	$5717 \mu\text{m}$
Vias	2058
Power	$18 \mu\text{W}$

# ADC Top-Level Assembly



- ▶ ADC assembled using hierarchical Verilog as well, with protected routing for sensitive analog nets

# ADC Level Integration



# Unit Fringe Capacitor

## Capacitance Density:

1 layer:  $0.31 \text{ fF}/\mu\text{m}^2$

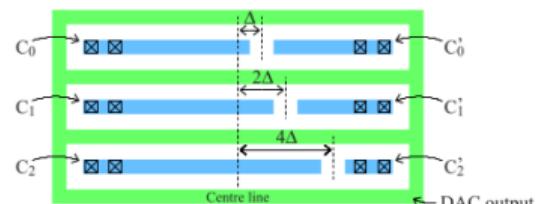
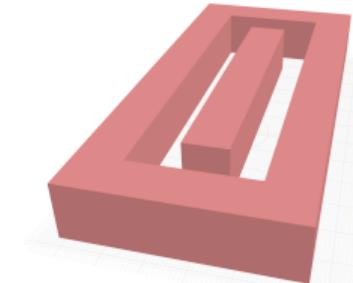
2 layers:  $0.62 \text{ fF}/\mu\text{m}^2$

3 layers:  $0.93 \text{ fF}/\mu\text{m}^2$

Matching:  $\sigma(\Delta C/C) = 0.85\%/\sqrt{C} \text{ [fF]}$

## Per-Bit Mismatch:

Bit	$C_{\text{main}}$	$C_{\text{diff}}$	uncorr	$\rho=0.9$
15 (768)	619 fF	4.8 fF	0.04%	0.03%
10 (64)	51.6 fF	0.4 fF	0.12%	0.11%
1 (1)	26.4 fF	25.6 fF	7.7%	2.4%



$$\frac{b_0}{b_0} \parallel \quad C_0 = C_m + C_\Delta \quad } \quad C_{0,\text{eff}} = 2C_\Delta$$

$$\frac{b_1}{b_1} \parallel \quad C_0' = C_m - C_\Delta \quad } \quad C_{1,\text{eff}} = 4C_\Delta$$

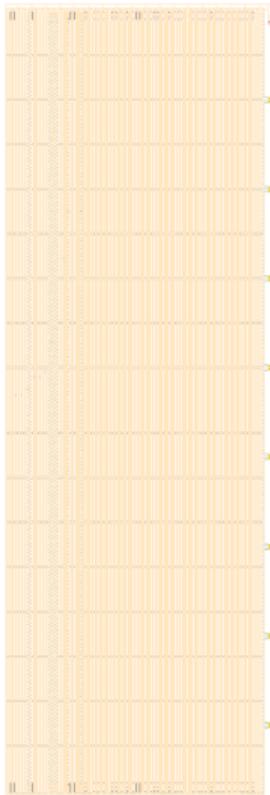
$$\frac{b_2}{b_2} \parallel \quad C_1 = C_m + 2C_\Delta \quad } \quad C_{2,\text{eff}} = 8C_\Delta$$

$$\frac{b_2}{b_2} \parallel \quad C_1' = C_m - 2C_\Delta \quad }$$

#units: 2N

[P. Harpe, ISSCC 2018]

# Capacitor Array Layout



Parameter	Value
Dimensions	$17 \times 50 \mu\text{m}$
$C_{\text{tot}}$	1.88 pF
$C_{\text{eff}}$	1.64 pF
Unit cap ( $C_u$ )	0.8 fF
Layers	M5–M6–M7 fringe

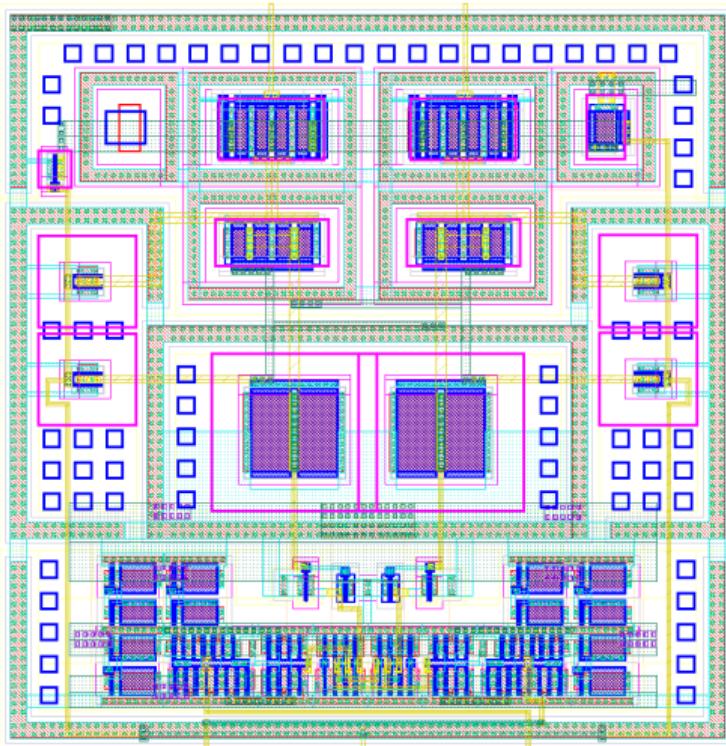
**Weights:** 768, 512, 320, 192, 96, 64, 32, 24, 12, 10, 5, 4, 4, 2, 1, 1

**Harpe Penalty Factor:**

$$\sigma_{\text{penalty}} = \sqrt{\frac{C_{\text{tot}}}{C_{\text{eff}}}} = \sqrt{\frac{1880}{1638}} \approx 1.07$$

Only 7% mismatch penalty — MSBs have  $C_{\text{diff}} \ll C_{\text{main}}$

# Comparator Layout



Parameter	Pre-Extract
Dimensions	$18 \times 18 \mu\text{m}$
Topology	StrongARM latch
Input noise	$\sim 77 \mu\text{V}$
Avg current	$\sim 4 \mu\text{A}$
Peak current	$\sim 500 \mu\text{A}$

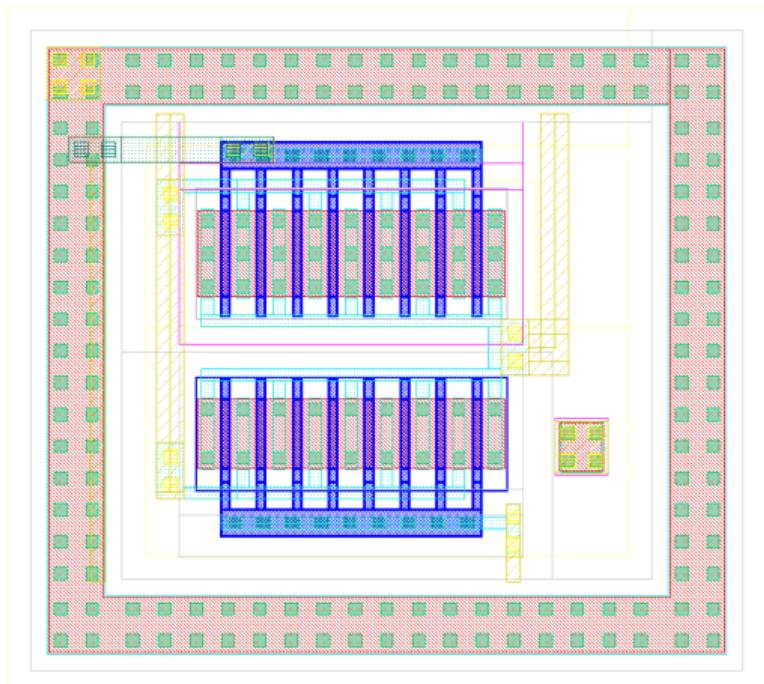
**Noise contribution to ENOB:**

$$V_{\text{LSB}} = \frac{2V_{\text{ref}}}{2^N} = \frac{1.2 \text{ V}}{4096} \approx 293 \mu\text{V}$$

$$\text{Comparator noise} \approx \frac{77 \mu\text{V}}{293 \mu\text{V}} \approx 0.26 \text{ LSB}$$

- ▶ Dynamic (no static power)
- ▶ Regenerative latch output

# Sampling Switch Layout



Parameter	Value
Dimensions	$12 \times 12 \mu\text{m}$
Device size	$W \approx 3 \mu\text{m}, L_{\min}$
Worst-case $R_{\text{on}}$	$\sim 1 \text{ k}\Omega$
$C_{\text{samp}}$	$\sim 1 \text{ pF}$

**Settling time:**

$$\tau = R_{\text{on}} \cdot C_{\text{samp}} = 1 \text{ k}\Omega \cdot 1 \text{ pF} = 1 \text{ ns}$$

For 12-bit accuracy ( $< 0.5 \text{ LSB}$ ):

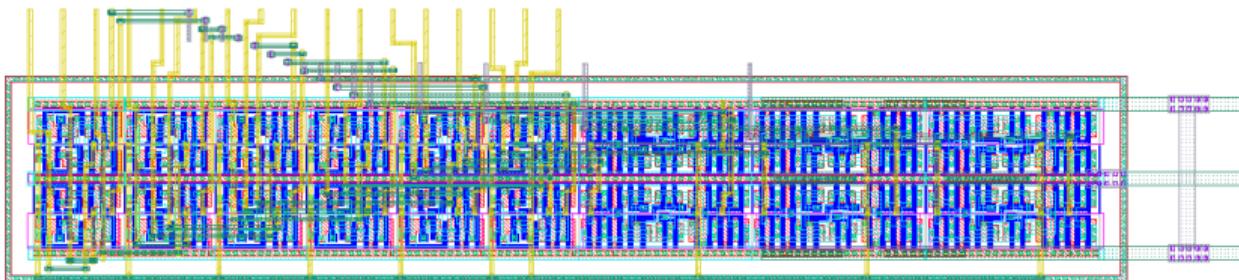
$$t_{\text{settle}} \approx 9\tau \approx 9 \text{ ns}$$

**kT/C sampling noise:**

$$\sigma_{\text{samp}} = \sqrt{\frac{kT}{C}} = \sqrt{\frac{4.14 \times 10^{-21}}{10^{-12}}} \approx 64 \text{ }\mu\text{V}$$

$$\text{Sampling noise} \approx \frac{64 \text{ }\mu\text{V}}{293 \text{ }\mu\text{V}} \approx 0.22 \text{ LSB}$$

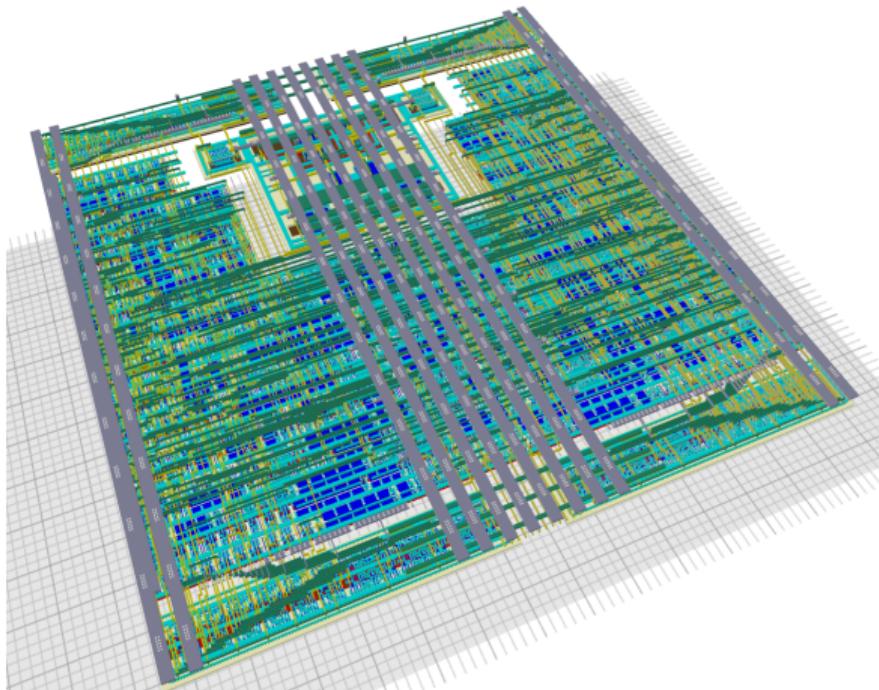
# Capacitor Driver Layout



Drivers scaled in width to match corresponding capacitor size (XOR gates for differential control):

Bits	Output W (NMOS)	Output W (PMOS)
15–14 (MSB)	3.12 $\mu\text{m}$	4.16 $\mu\text{m}$
13–12	1.56 $\mu\text{m}$	2.08 $\mu\text{m}$
11–0 (LSBs)	0.78 $\mu\text{m}$	1.04 $\mu\text{m}$

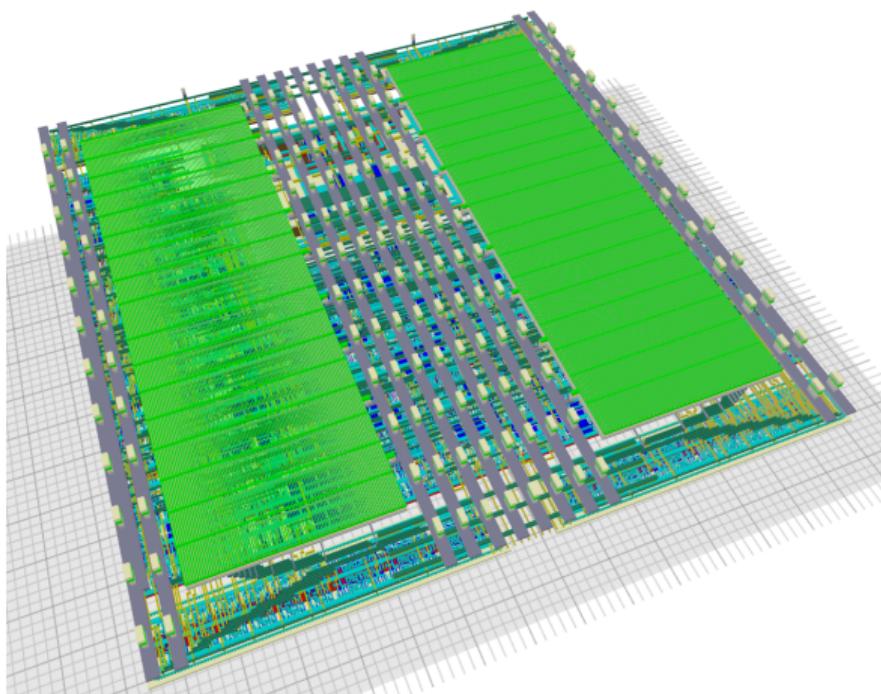
## ADC Layout: Lower Metals (3D)



Layer	Usage
M1	Standard cell routing
M2–M3	Signal routing
M4	Power distribution

- ▶ Digital logic in center/bottom
- ▶ Comparator at top center
- ▶ Sampling switches on sides
- ▶ Cap drivers at top/bottom edges

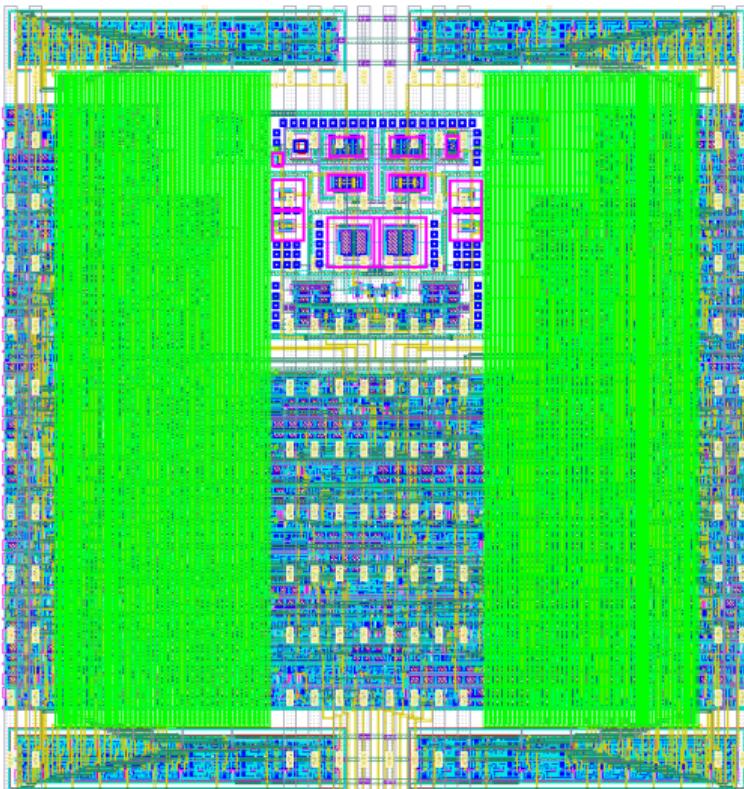
## ADC Layout: With Cap Arrays (3D)



Layer	Usage
M5–M6	CDAC fringe caps

- ▶ P and N cap arrays on left/right
- ▶ Stacked above digital/analog
- ▶ Vertical fringe capacitors
- ▶ Direct connection to sampling nodes

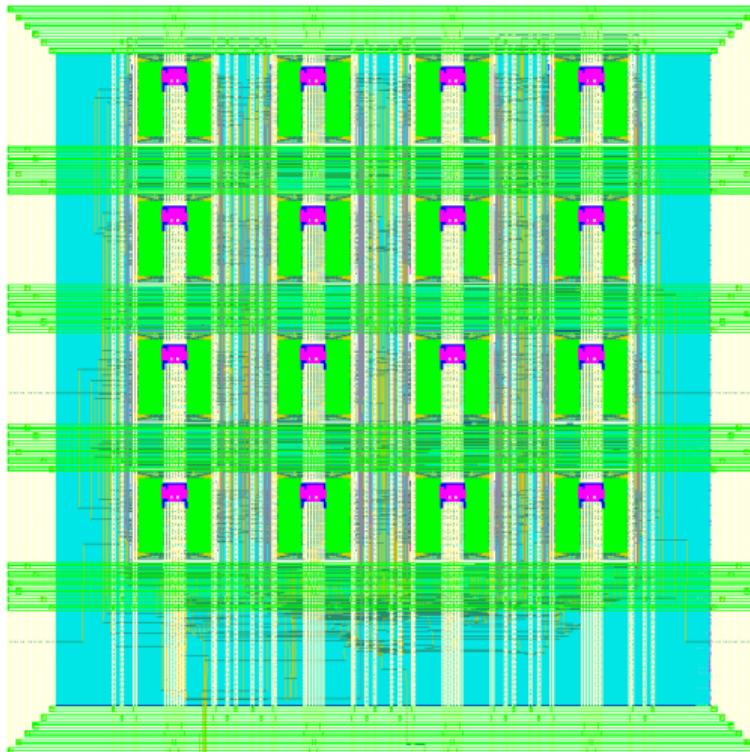
# Full ADC Layout



Parameter	Value
Dimensions	$60 \times 60 \mu\text{m}$
Area	$0.0036 \text{ mm}^2$
Resolution	12-bit
Sample rate	10 MS/s
Power	$\sim 200 \mu\text{W}$

- ▶ Fully differential SAR ADC
- ▶ Mixed-signal integration
- ▶ Column-parallel compatible

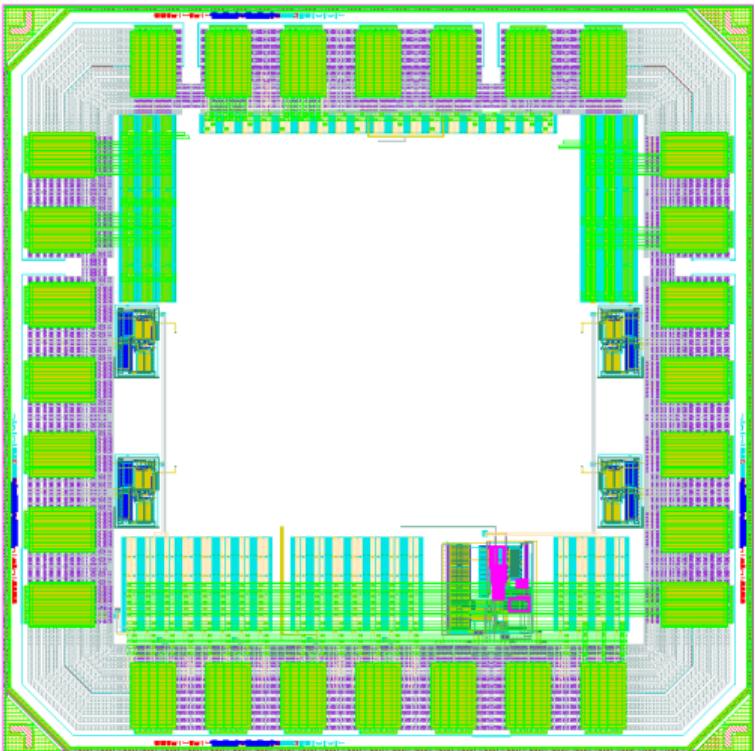
# ADC Core Array (4×4)



Parameter	Value
Array size	4×4 ADCs
Dimensions	240×240 $\mu\text{m}$
Total ADCs	16
Aggregate rate	160 MS/s
Total power	~3.2 mW

- ▶ Tiled ADC instances
- ▶ Shared clock distribution
- ▶ Column-parallel readout

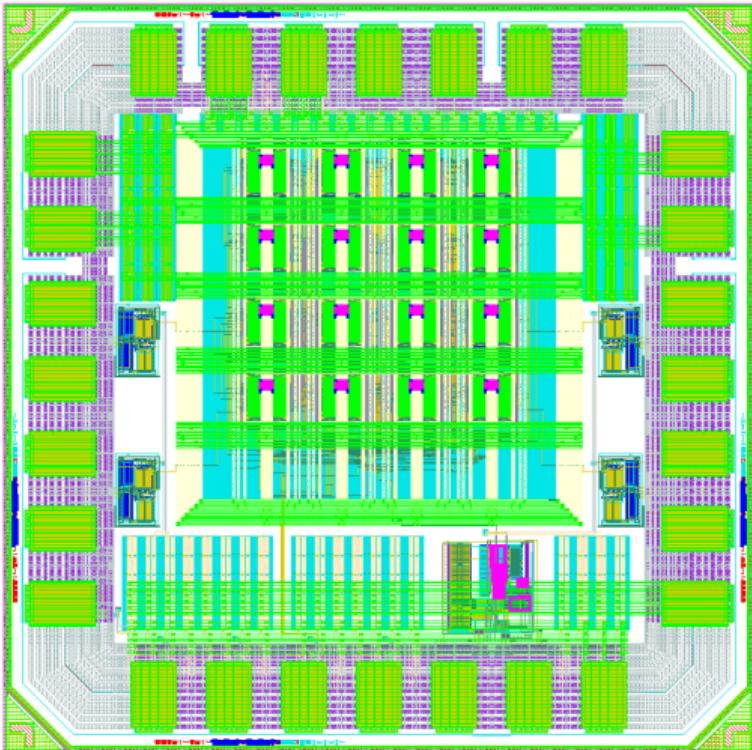
# Pad Ring Layout



Pad Type	Count	Purpose
LVDS_RX	4	Sequencing clocks
LVDS_TX	1	Comparator output
CMOS_IO	5	SPI interface + reset
PASSIVE	2	Analog input (diff)
POWER	4	VDD (A, D, IO, DAC)
GROUND	4	VSS (A, D, IO, DAC)
<b>Total</b>	<b>22</b>	

- ▶ Separate analog/digital supplies
- ▶ ESD protection on all pads

# Full Chip Layout (FRIDA 65A)



Parameter	Value
Die size	1×1 mm
Process	TSMC 65nm LP
ADC count	16 (4×4)
Decoupling	~100 pF/rail

- ▶ MOS capacitor decoupling on all power rails (~100 pF each)
- ▶ Submitted Oct 2025
- ▶ Testing planned Spring 2026

## Ongoing Work: PCB Design

*[Placeholder for PCB image]*

## Ongoing Work: Test System

*[Placeholder for test system image]*

# Analog Automation: CDAC Weight Strategies

Five strategies in blocks/cdac.py:

Strategy	Description	Radix
rdx2	Standard binary	2.0
subrdx2	Sub-radix-2 rounded	<2.0
subrdx2lim	Sub-radix-2 w/ floor	<2.0
subrdx2rdst	MSB redistribution	~2.0
rdx2rpt	Binary w/ repeated	2.0

Weight calculation:

$$\beta = 2^{N/M} \quad W_i = \max(1, \lfloor \beta^{M-1-i} \rfloor)$$

**Coarse-Fine Partitioning** (threshold  $T = 64$ ):

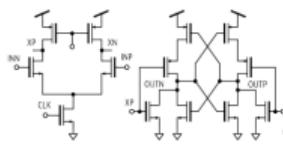
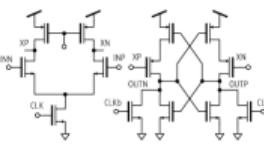
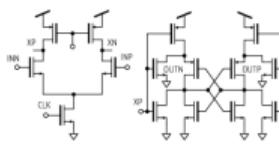
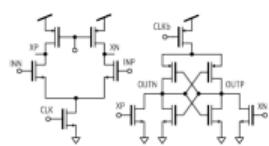
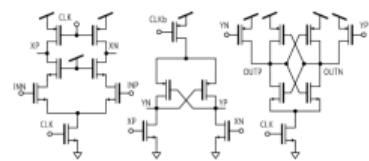
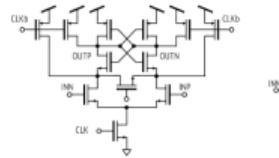
$$W = q \cdot T + r \quad \text{where } q = \lfloor W/T \rfloor$$

**Difference Capacitor Split:**

- ▶ Coarse:  $C_{\text{main}} = T \cdot C_u, m = q$
- ▶ Coarse diff:  $C_{\text{diff}} = 1 \cdot C_u, m = q$
- ▶ Fine:  $C_{\text{main}} = (T + 1 + r),$   
 $C_{\text{diff}} = (T + 1 - r)$

**Effective:**  $C_{\text{eff}} = C_{\text{main}} - C_{\text{diff}}$

# Analog Automation: Comparator Topologies



## Topology Parameters:

Parameter	Options
preamp_diffpair	nmos, pmos
preamp_bias	std, dyn
comp_stages	1, 2
latch_pwrgate_ctl	clk, sig
latch_pwrgate_node	ext, int
latch_RST_ext_ctl	clk, sig, none
latch_RST_int_ctl	clk, sig

- ▶ Cartesian product of combinations
- ▶ Auto netlist from `blocks/comp.py`
- ▶ Sweep device params & corners