Signal Conditioning: RTD sub-module

Bartosz Pękosławski & Paweł Marciniak

About us

Bartosz PĘKOSŁAWSKI

Ph.D. Electrical Engineering

- Role:
  - HW (signal conditioning) designer
- Relevant Experience:
  - Projects on machine vibration monitoring – hardware engineer (2006 – 2011)
  - TULCOEMPA – hardware designer (2011 – 2015)
  - SPParTAN – hardware designer (2019 – 2022)
  - FOSREM – hardware designer (2021 – present)

Paweł MARCINIAK

Ph.D. Electrical Engineering

- Role:
  - HW (signal conditioning) designer
- Relevant Experience:
  - INNOREH – software designer (2017 – 2021)
  - SPParTAN – firmware designer (2019 – 2022)
  - ITER – hardware engineer (2021 – 2022)
  - FOSREM – hardware designer (2021 – present)

Agenda

- The RTD module requirements,
- The PoC version specification and scope
- The sub-module design details
- Implementation
- Test results discussion
- Full scale design plans
- Summary

The RTD sub-module requirements

- The RTD signals group: RTD 1, RTD 2
- Redundant temperature measurement based on PT-103 sensor (x4)
- Sensor current: up to 1 mA excitation, configurable (0 – 1 mA)
- Accuracy: 1 K; Resolution: 100 mK; Range: 275 – 300 K
- Radio-Frequency Interference (RFI) Immunity (4-wire sensing)
- GPIO and SPI signals isolation

Signal Name	Peripheral Need	IO Pins per Peripheral	IO Pins Per RFPI	Signal Type	Quantity	I/O	RFPI Response Time	Impedance	Signal Range	Cable Type
Temperature Probe RTD 1, (PT-103)	IO/SPI	4	16	Analog	1 per cavity/coupler	Input	<10 µs	100-110 Ω	10-110 mV, 0.1 - 1 mA excitation	Belden 1325A
Temperature Probe RTD 2, (PT-103)	IO/SPI	4	16	Analog	1 per cavity/coupler	Input	<10 µs	100-110 Ω	10-110 mV, 0.1 - 1 mA excitation	Belden 1325A

The PoC version specification and scope

- One PCB board which supports redundant temperature measurements: RTD 1, RTD 2
- 4 spare measurement inputs connected to ADC
- Sensor current range: 0 to 1 mA
- Input voltage amplification:
  Diffrence Amplifier (30 V/V) * Programmable Gain Amplifier (1 – 32 V/V)
- Management Block
- Power Supply Voltage: 12 V
- Management Block Supply Voltage: 3.3 V
- Isolation of SPI signals
- Temporary Connector type: BNC

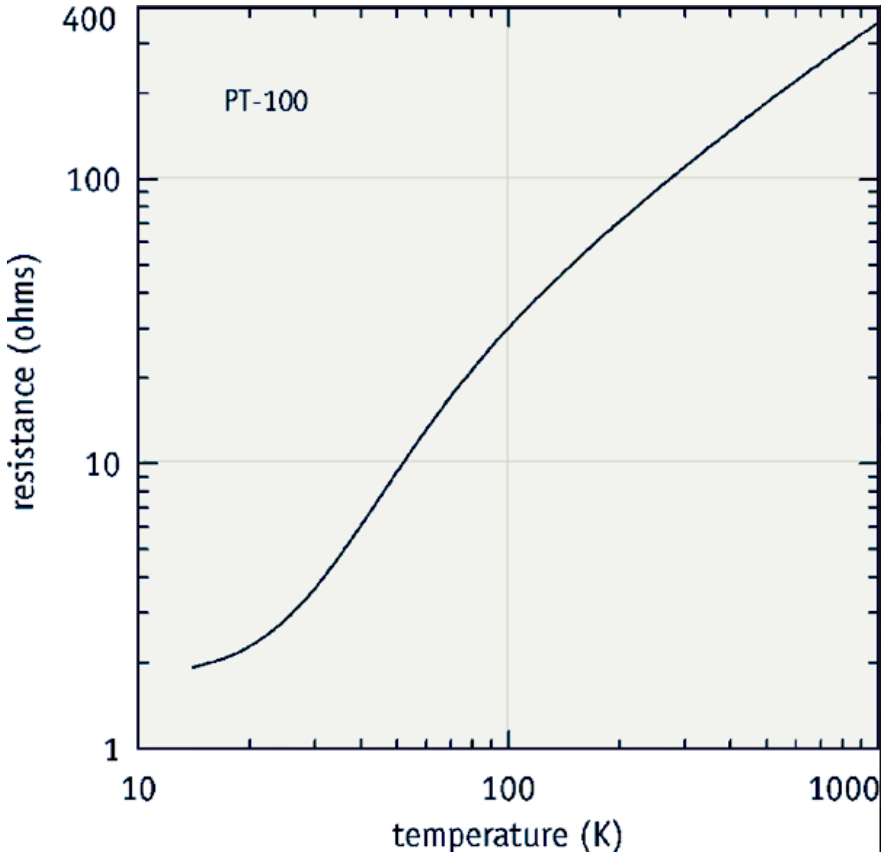
The PoC version specification and scope

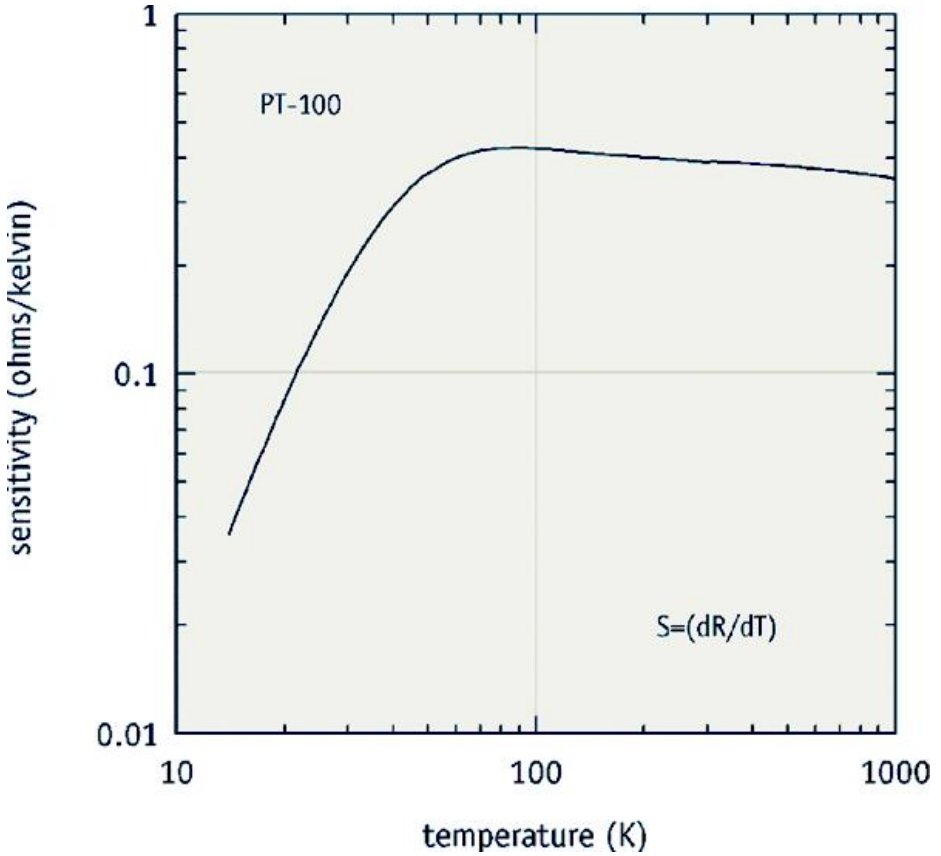
Management Block:

- I²C communication with Raspberry PI
- Current measurement
- Temperature and humidity measurements

The sub-module design details

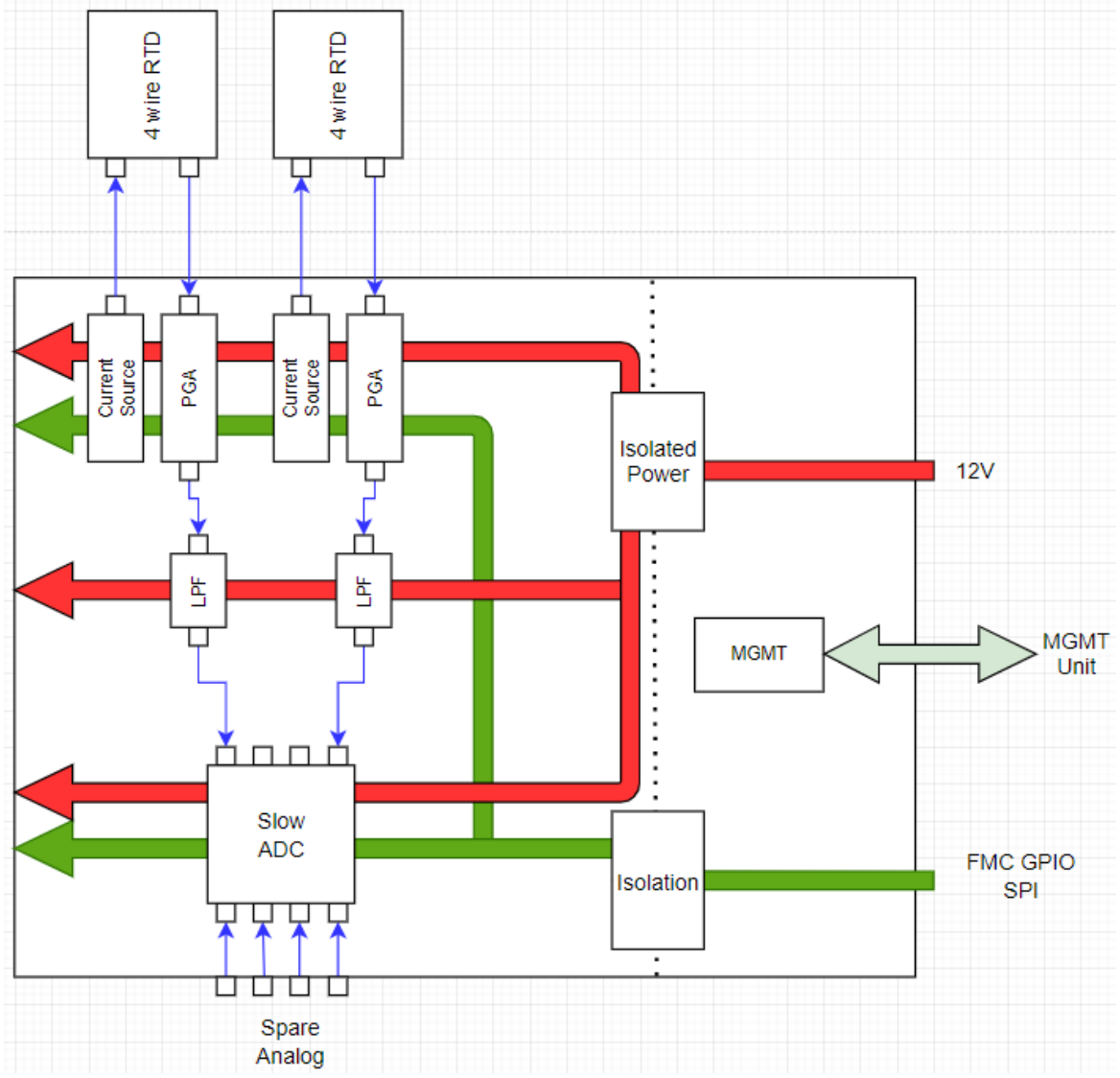
PT-103 sensor





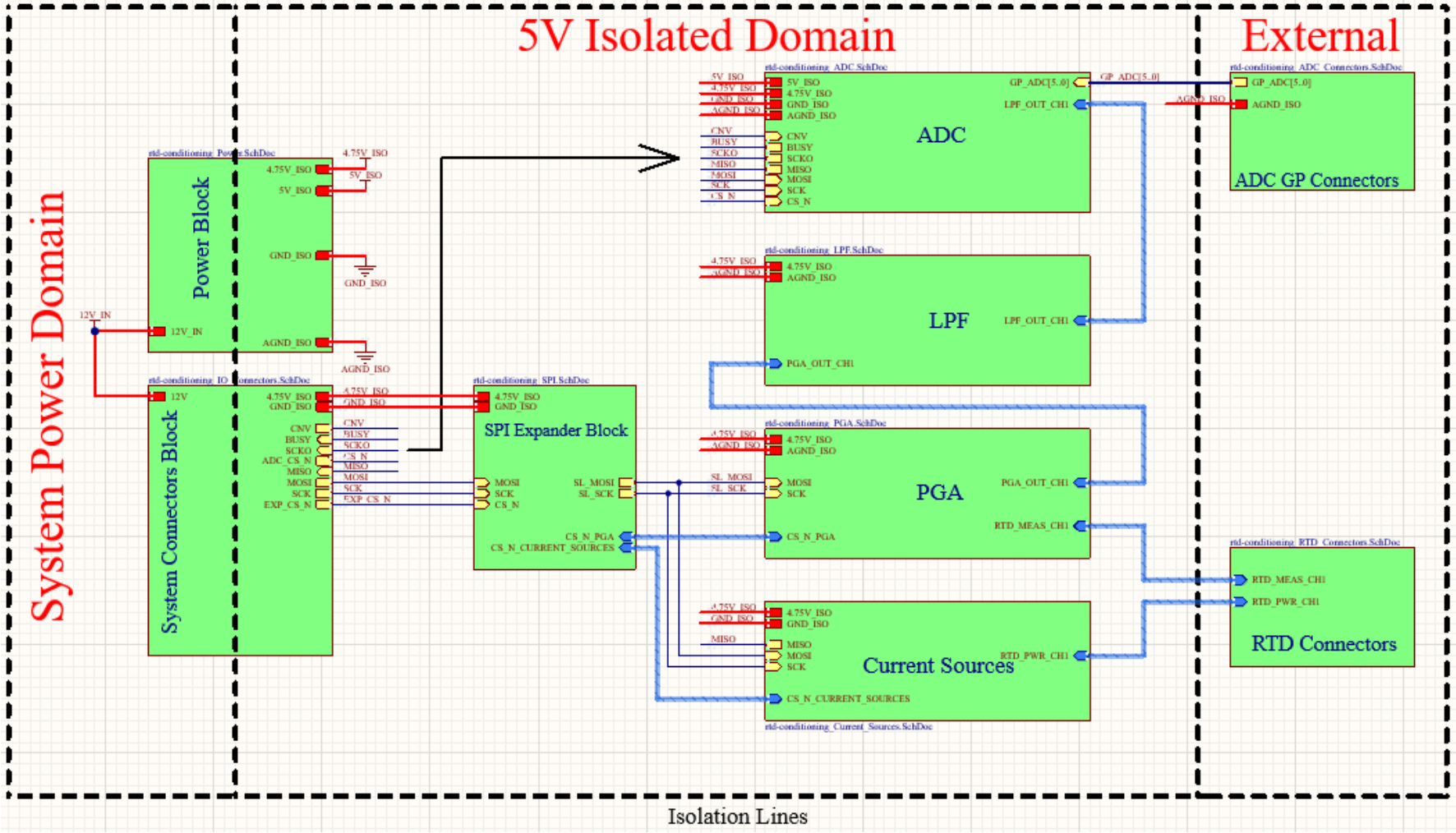
The sub-module design details

Conceptual diagram



The sub-module design details

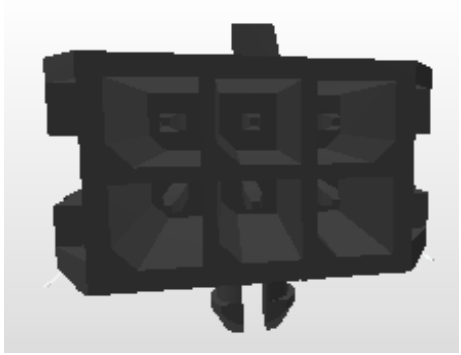
Block diagram



The sub-module design details

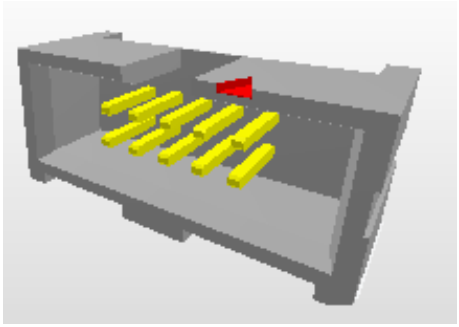
System Connectors Block

- Power Connector (12 V)



- MGMT Connector (I^2C) and sensors

- FMC GPIO Connector (SPI)

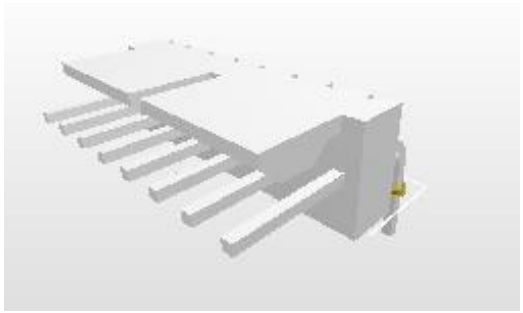


- Isolation of GPIO and SPI signals based on MAX22245BAWA+ and MAX22246CAWA+ digital isolators (2 channels, 7 ns delay, up to 25 / 200 Mbps, 868 V_{RMS} continous / 5 kV_{RMS} 60s / 12.8 kV_{RMS} surge galvanic isolation)

The sub-module design details

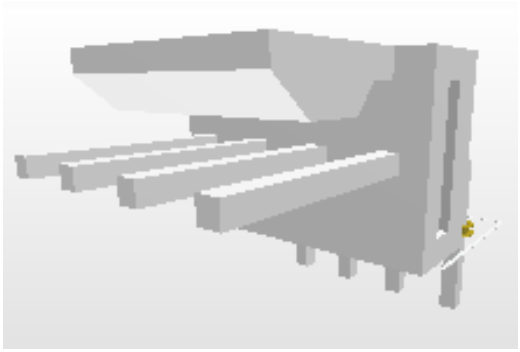
ADC GP Connectors

- One 8-pin connector (universal) for interconnecting with front panel connectors



RTD Connectors

- Two 4-pin connectors (universal) for interconnecting with front panel connectors



The sub-module design details

SPI Expander Block

- MAX7301 serial-interfaced I/O expander with 28 configurable (logic input or logic output) ports

Current Sources Block

- MCP48FEB24-20E quad, 12-bit resolution buffered voltage output Digital-to-Analog Converters (DAC), with volatile user memory
- MAX6138 bandgap voltage reference (4.096V),
  Operating Current Range: 60 µA to 15 mA, 28 μV_{RMS} Output Noise (0.01 to 10 kHz)
- MAX4165 operational amplifier (5 MHz Unity Gain Bandwidth , Input Voltage-Noise Density (26 nV/√Hz), Slew Rate of 2 V/µs)
- P-channel transistor (V_{GS} in negative feedback loop of the OPAMP)

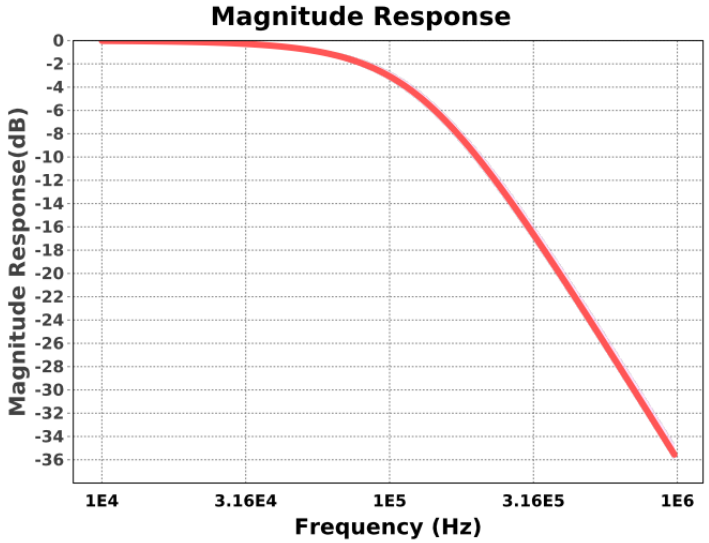
The sub-module design details

PGA Block

- MCP6S22-I/SN Programmable Gain Amplifiers (PGA) with SPI communication (gain from +1 V/V to +32 V/V) and two output channels

LPF Block

- Bessel LPF (Sallen-Key topology)
  - G = 1 V/V
  - f_{-3dB} = 100 kHz
  - G(500 kHz) = -24 dB
  - Group delay = 2.2 µs



- LMV721M7/NOPB operational amplifier (10 MHz Unity Gain Bandwidth , Input Voltage-Noise Density (8.5 nV/√Hz), Slew Rate of 5 V/µs)

The sub-module design details

ADC Block

- LTC2333CLX-18 18-bit, low noise 8-channel ADC, 800 ksps Throughput, 96.4 dB Single-Conversion SNR
- ADC Power supply
  - TPS65130 split-Rail Converter with dual, positive and negative Outputs (maximum output current: 300 mA)
  - LT3032 dual, low noise, positive and negative low dropout (300 mV) voltage linear regulator with 150 mA maximum output current

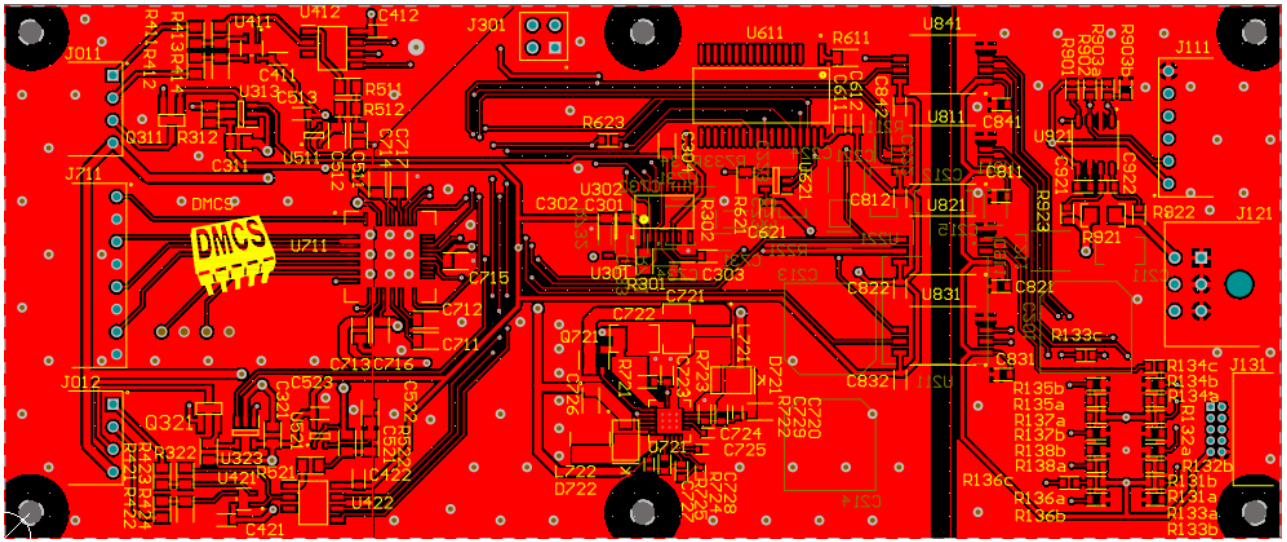
The sub-module design details

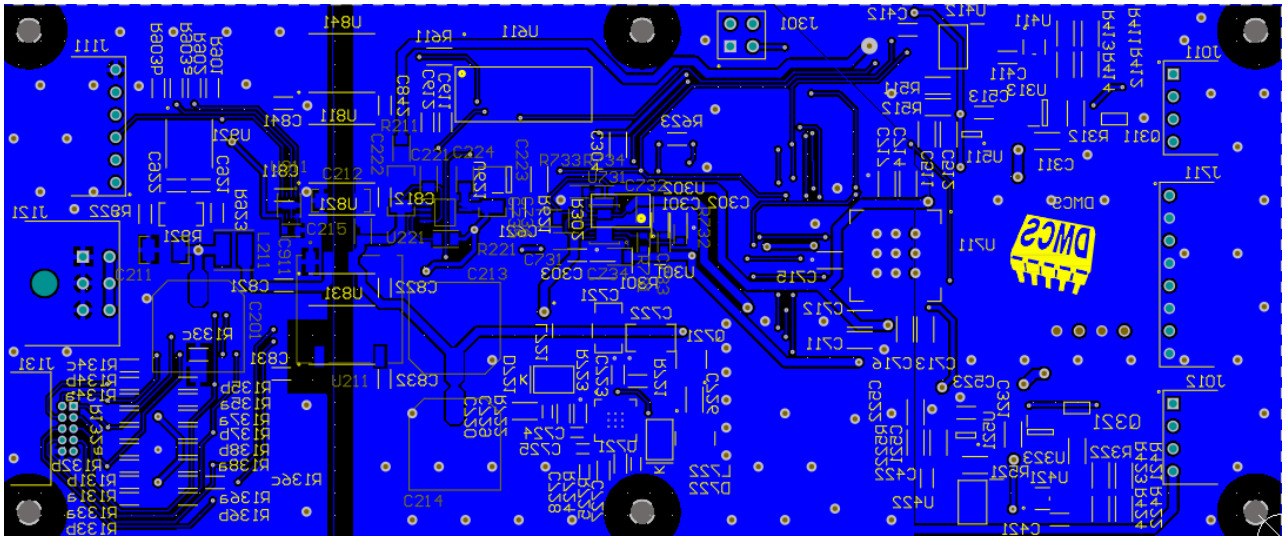
Power Block

- 12V → 5V SMPC module Traco Power TRS 2-1211 (isolated, 9-18 V input, max. 2 W output power, 80% efficiency, 1.6 kV isolation)
- EN 55032 class A external filter at the input for radiated and conducted emission
- 5V → 4.75V MAX1857EUA47+T Linear Voltage Regulator (up to 5.5 V supply, max. 500 mA load current, 120 mV typical dropout, output voltage accuracy ±1%)

Implementation

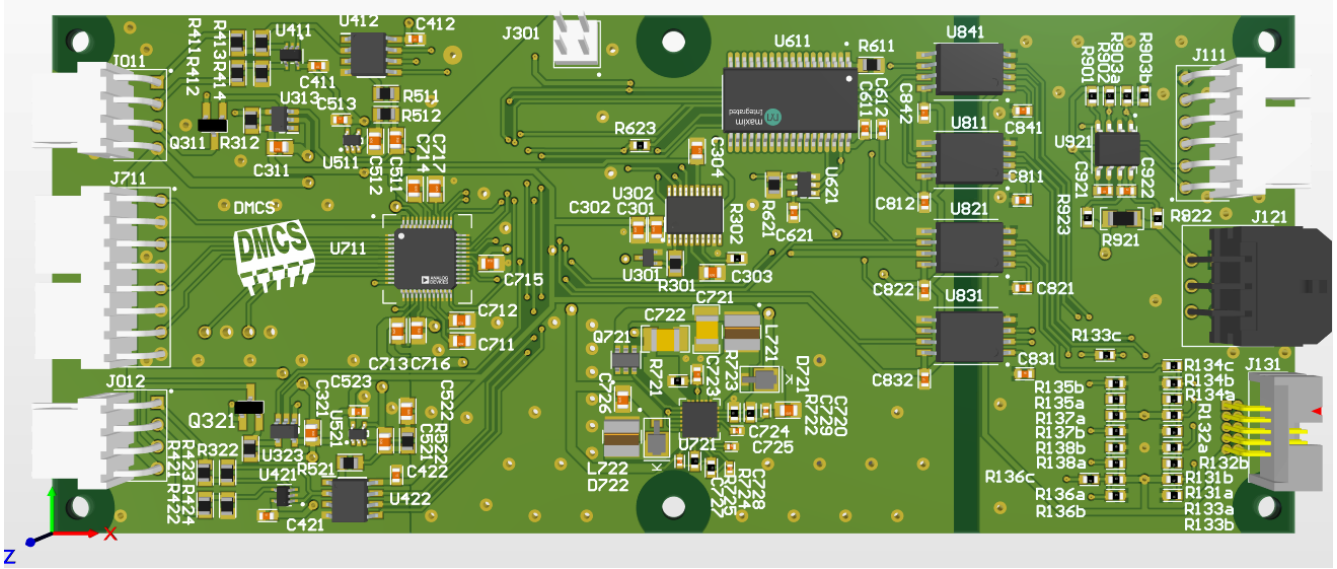
4-layer PCB, dimensions: 144 mm x 60 mm





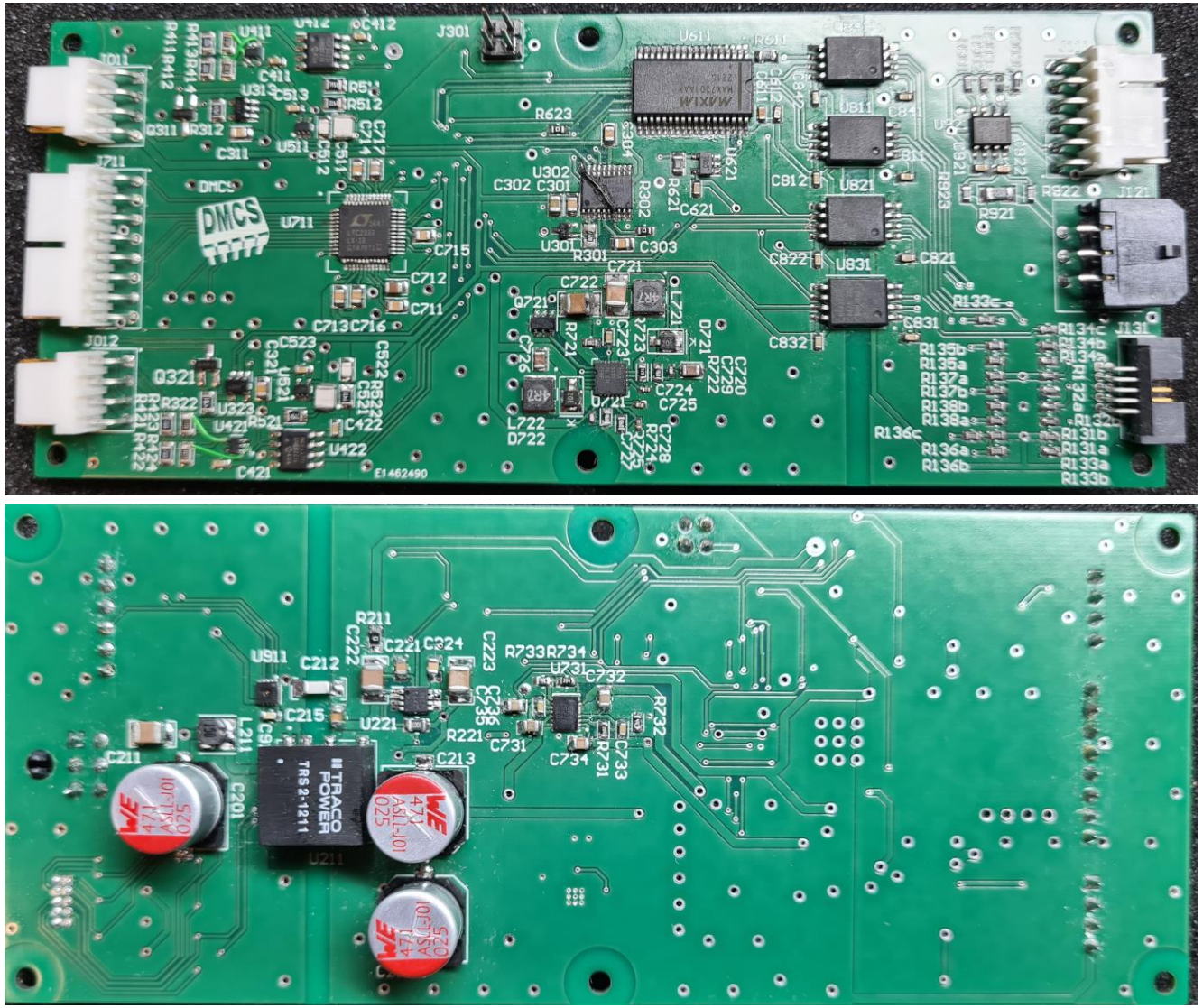
Implementation

3D model



Agenda

Real view

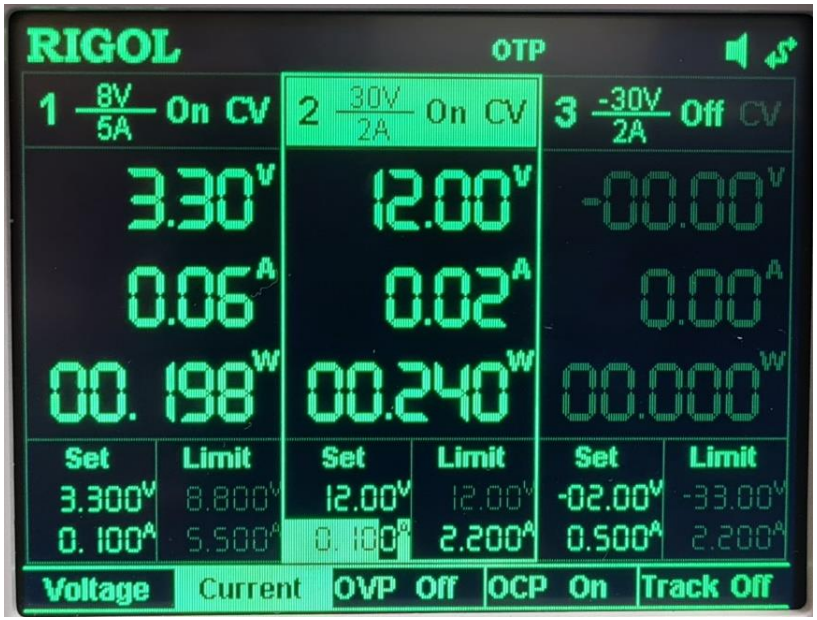


Test results discussion

- Detection of soldering faults (partially manual soldering)
  - Short circuits
  - Damaged tracks
  - Missing or broken connections
- Operation of the main power supply block and ADC power supply block (correct voltage levels)
- Current source block
- Temperature measurement in both channels (resistances: 102 Ω, 150 Ω)
- I^2C communication with temperature and supply current sensors

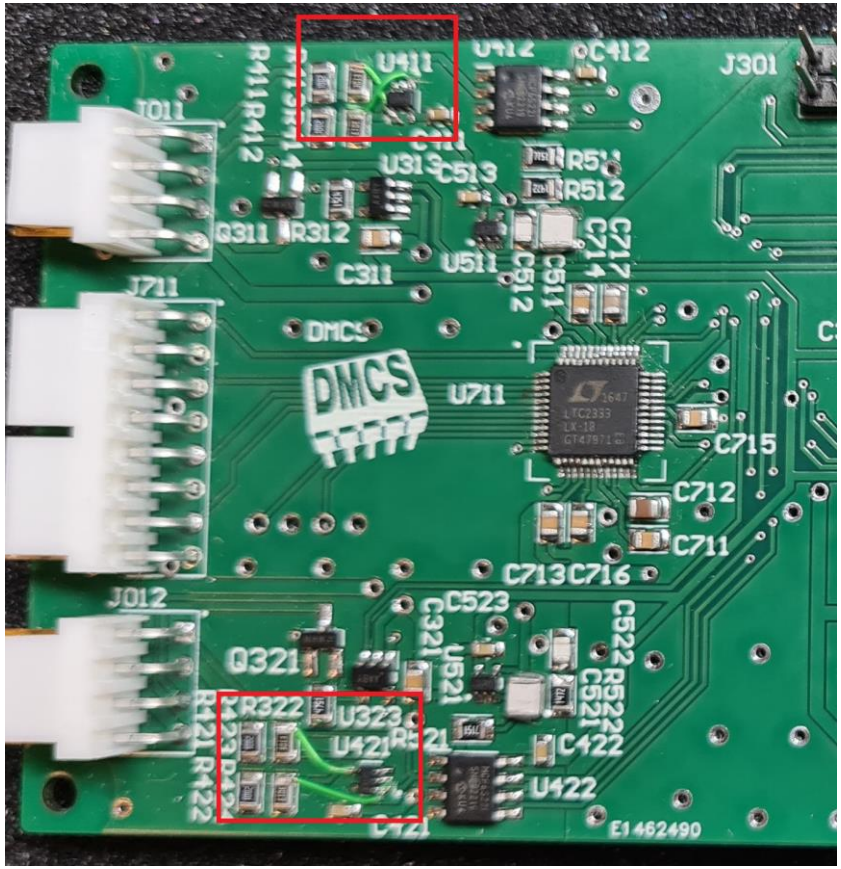
Test results discussion

- **Detection of soldering faults, e.g. short circuits, damaged tracks, missing or broken connections**
  - No errors were detected on the basis of the vision analysis.
- **Operation of the main power block (correct voltage levels)**
  - The power block works properly
  - Current consumptions are as expected (aprox. 60 mA for 3.3 V voltage domain, and 20 mA for 12 V voltage domain)



Test results discussion

- **Temperature measurement channel**
  - Error in signal gain was detected in the measurement circuit. The cause was a bad pinout in symbol of the operational amplifier.
  - The error was corrected by cutting the paths and soldering the wires correctly.



Test results discussion

- **Operation of the main power supply and ADC power supply blocks (correct voltage levels)**
  - Main power supply block works correct
  - ADC power supply block works correct

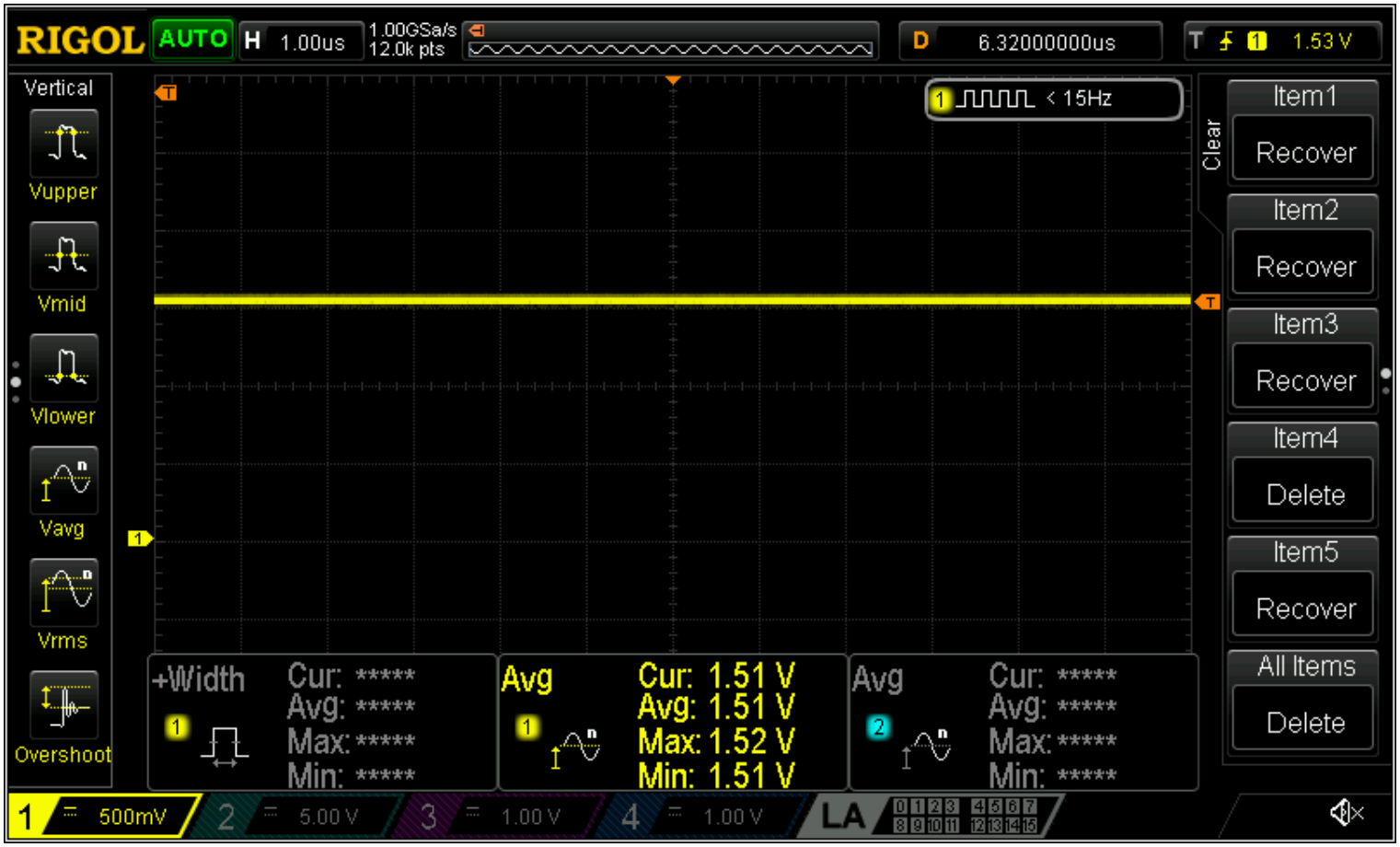
Test point	Value [V]
Main power converter output	4.94
Main LDO output	4.72
ADC power converter outputs	+10.30/-9.60
ADC LDO outputs	+8.88/-8.68

- **Current source block**
  - Reference voltage and DAC output voltage are correct

Test point	Value [V]
Reference voltage	4.08
DAC output	2.38

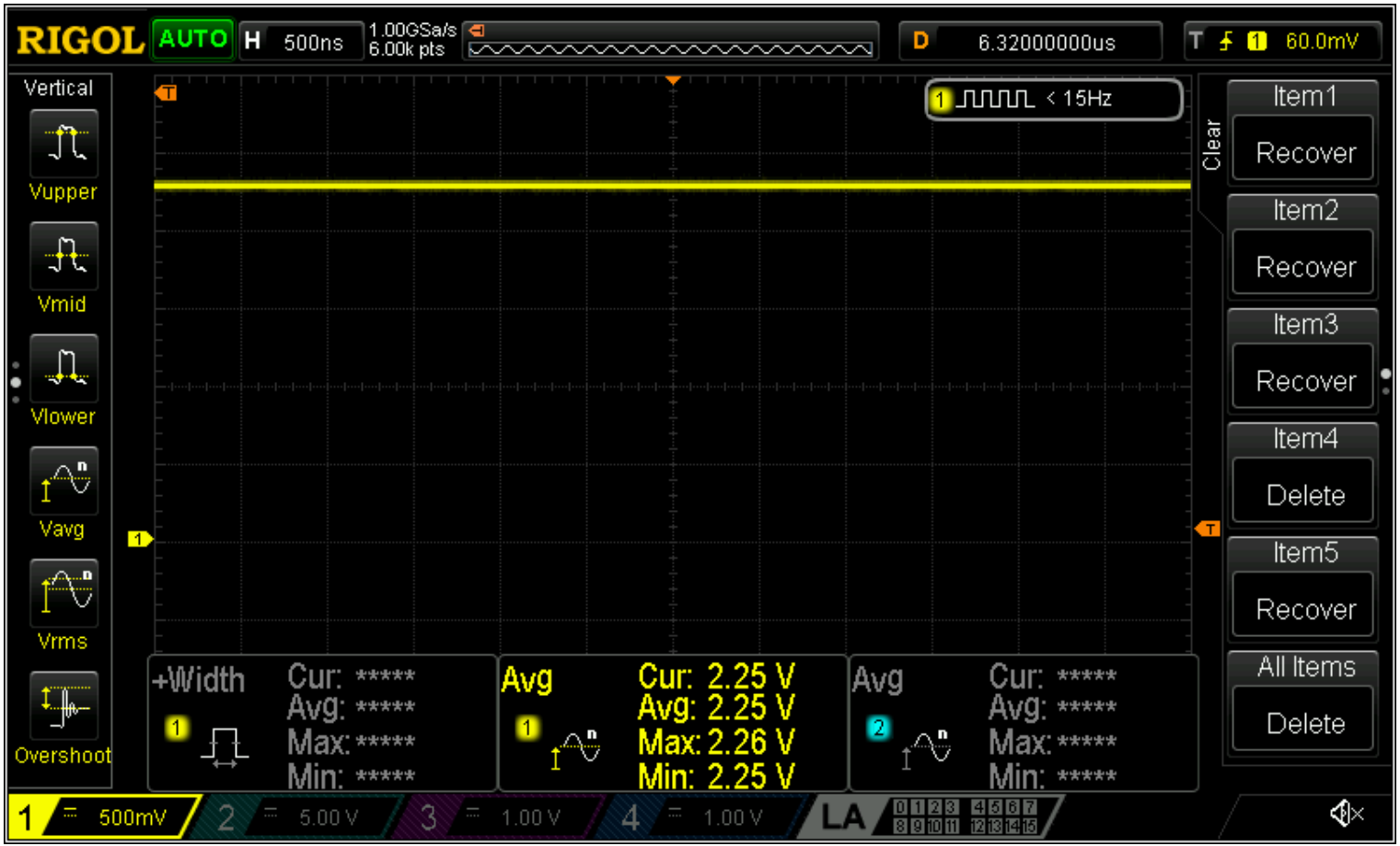
Test results discussion

- **Temperature measurement channel 1**
  - Measuring circuit works correctly (conditions: **sensor resistance = 102 Ω**, PGA gain = 1 V/V and sensor current = 0.497 mA). Measured voltage at ADC input is correct (102 Ω x 0.497 mA x 30 V/V = 1.521 V).



Test results discussion

- **Temperature measurement channel 1**
  - Measuring circuit works correctly (conditions: **sensor resistance = 150 Ω**, PGA gain = 1V/V and sensor current = 0.497 mA). Measured voltage at ADC input is correct (150 Ω x 0.497 mA x 30 V/V = 2.237 V).



Test results discussion

- **I²C communication with temperature and supply current sensors**
  - As part of the tests, the correctness of I²C communication with two sensors was checked:
    - STH31 - Connection with the temperature sensor was established and correct temperature was read.
    - INA219 – Connection with the sensor was established.

Full scale design plans

- The presented solution can be adopted in the final design
- Four redundant channels are needed in the final design

- Changes in schematic diagrams (duplication of selected blocks)
- PCB project redesign

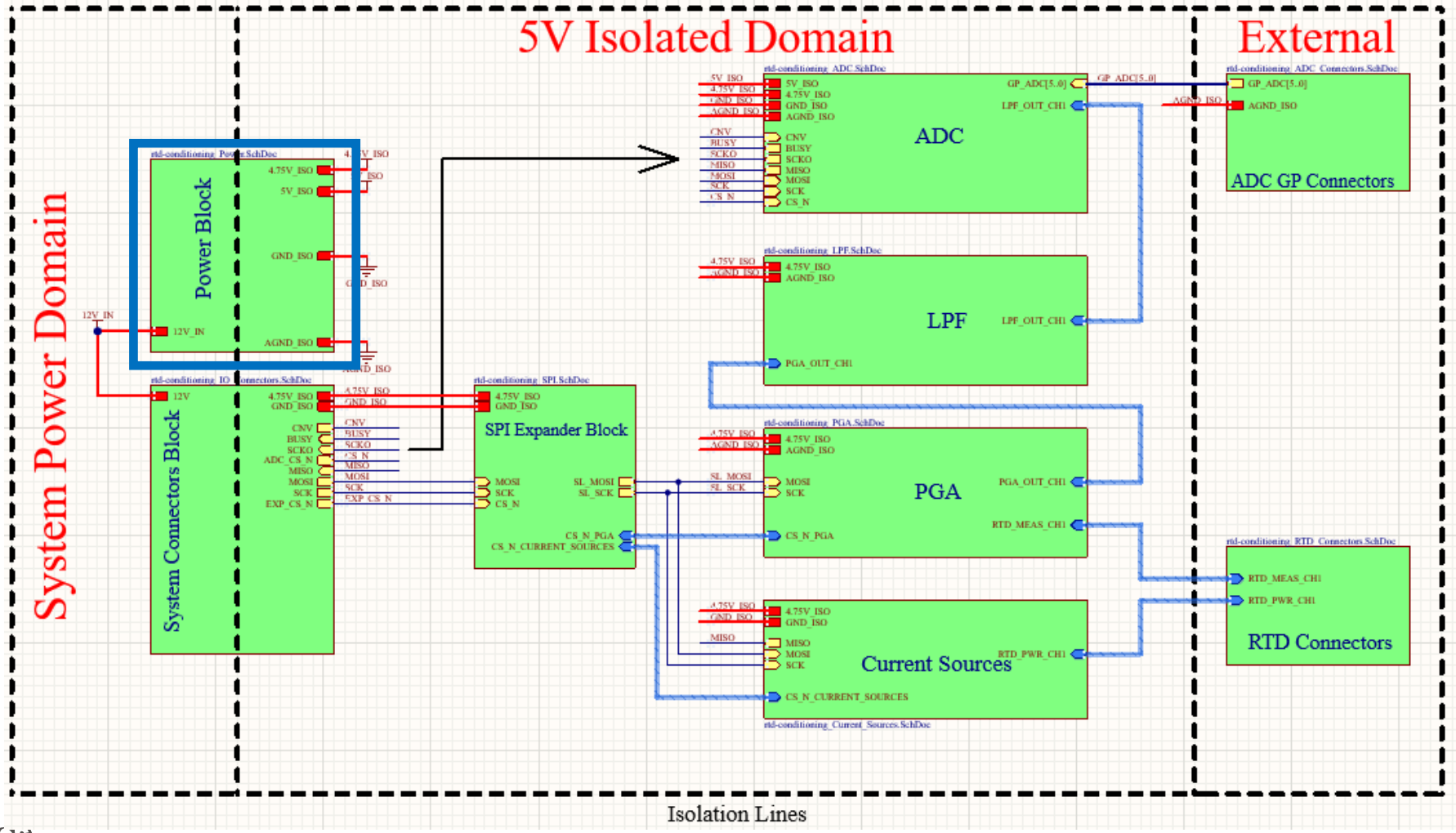
Summary

- Requirements
  - One redundant measurement channel per cavity => 4 redundant measurement channels per module = 8 measurement channels per module
  - Response time less then 10 μs
- PoC, implementation and verification
  - PCB board supporting one redundant measurement channel and four spare measurement inputs connected to ADC
  - 4-layer PCB
  - Correct operation of the main power block and ADC power supply block
  - Correct operation of the signal conditioning circuit
  - Configurable sensor current
- Full scale design plans
  - Extending the solution to 8 measurement channels

Thank You

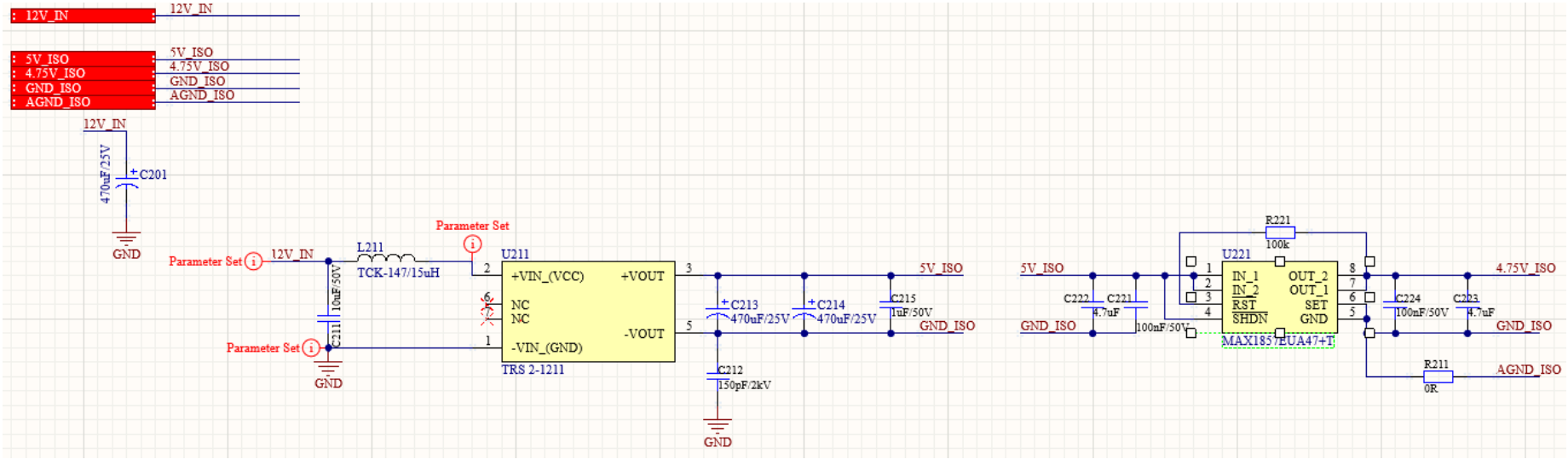
The sub-module design details

- Power Block



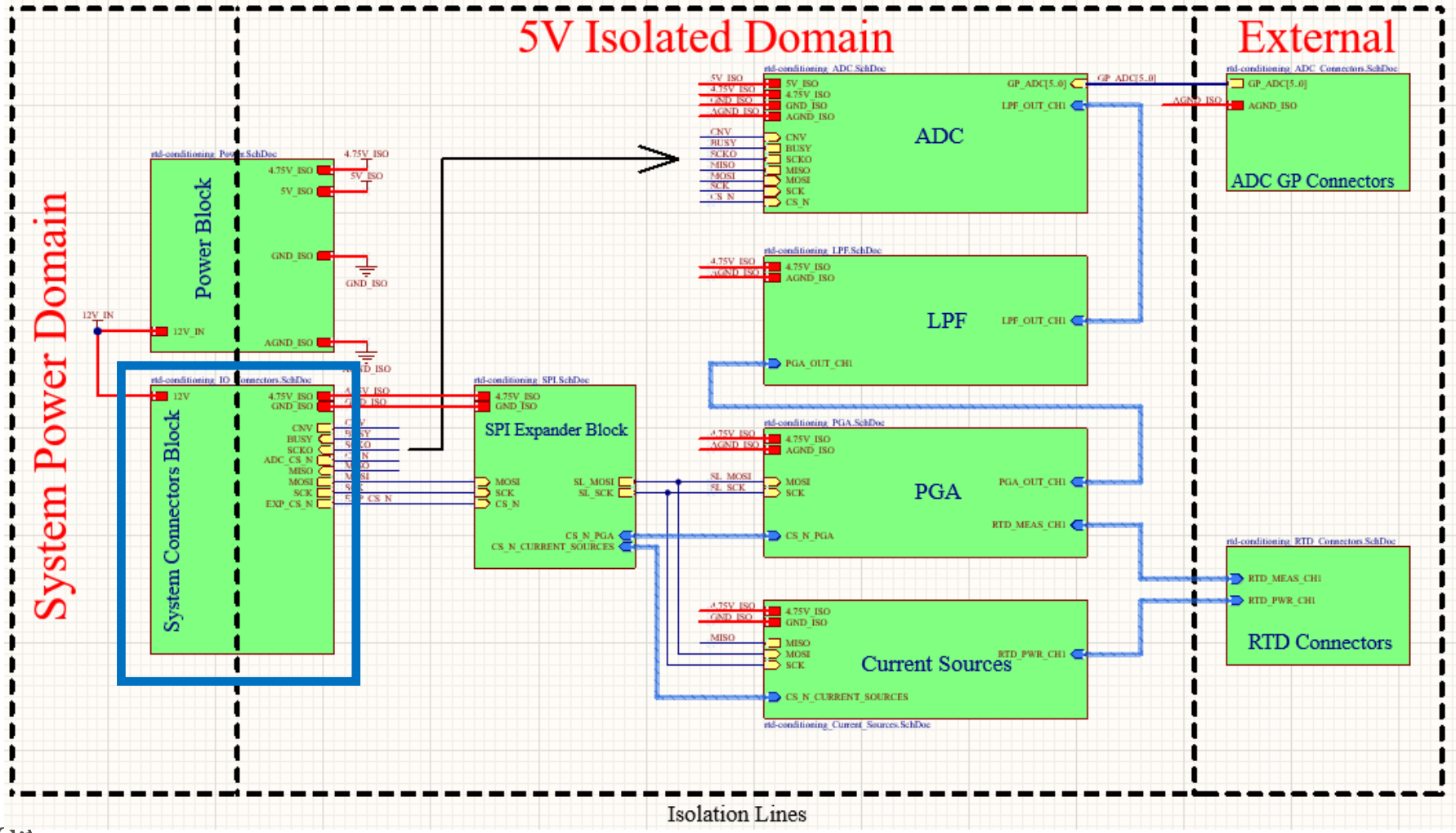
The sub-module design details

- Power Block



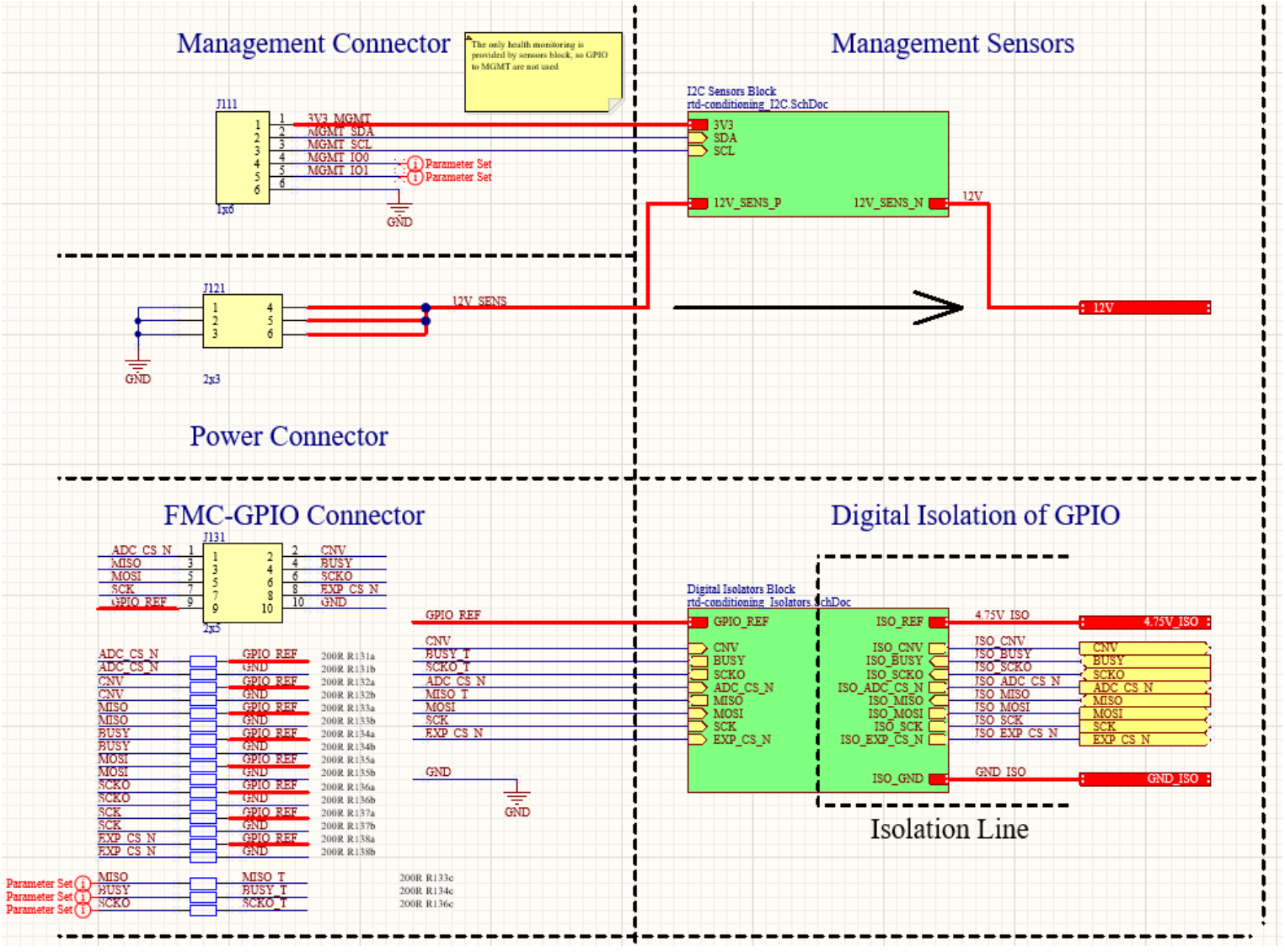
The sub-module design details

- System Connectors Block



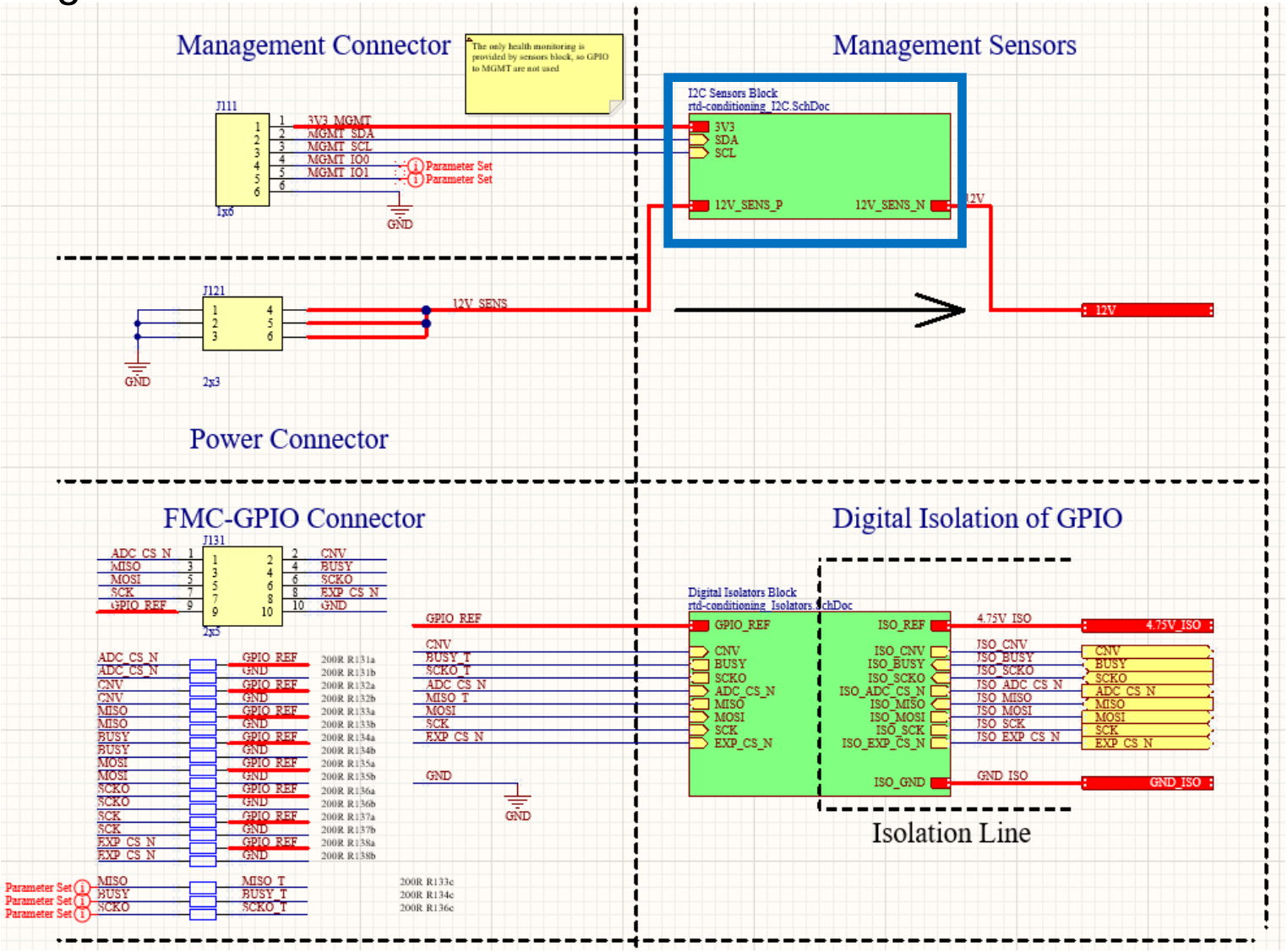
The sub-module design details

- System Connectors Block



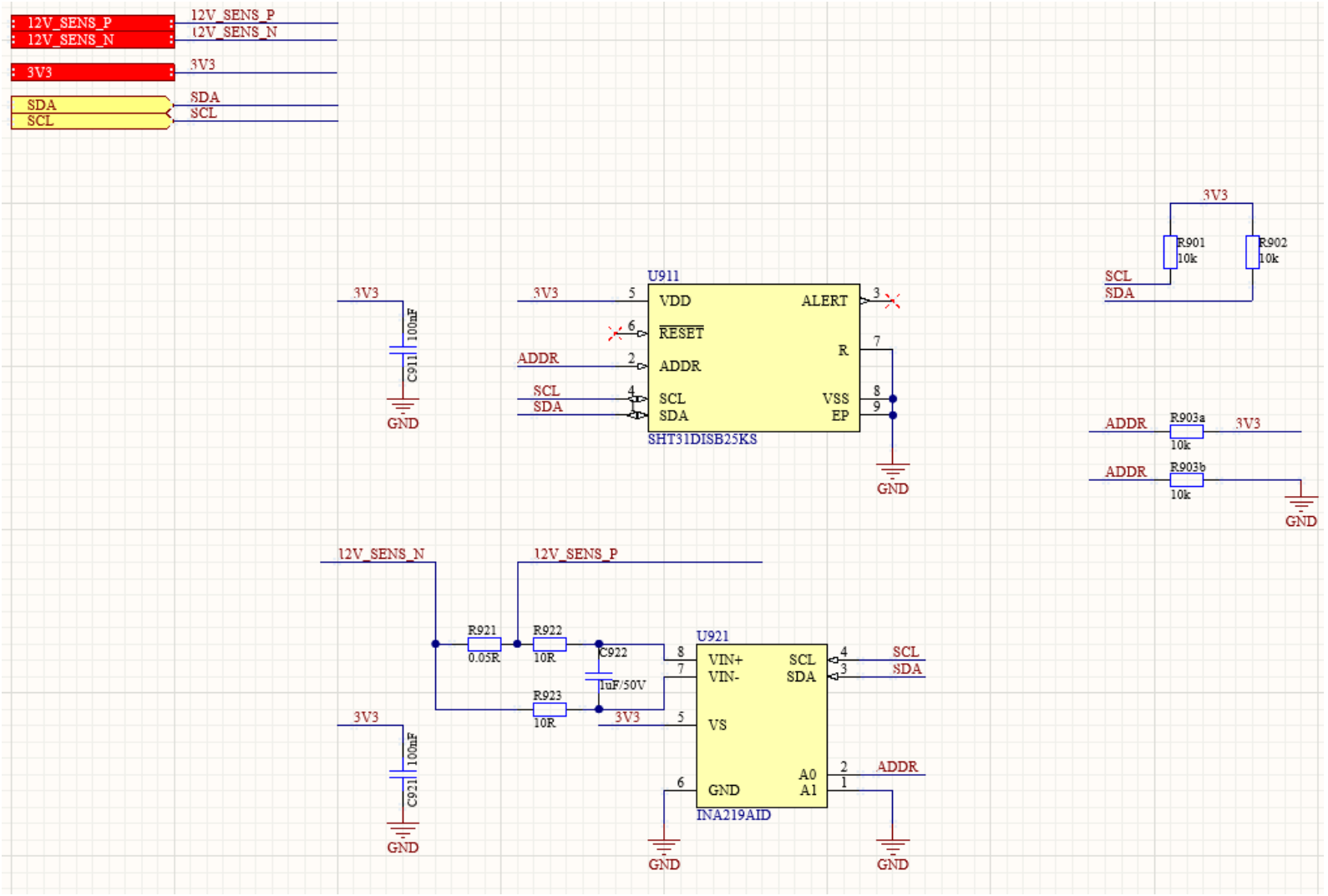
The sub-module design details

Management Sensors



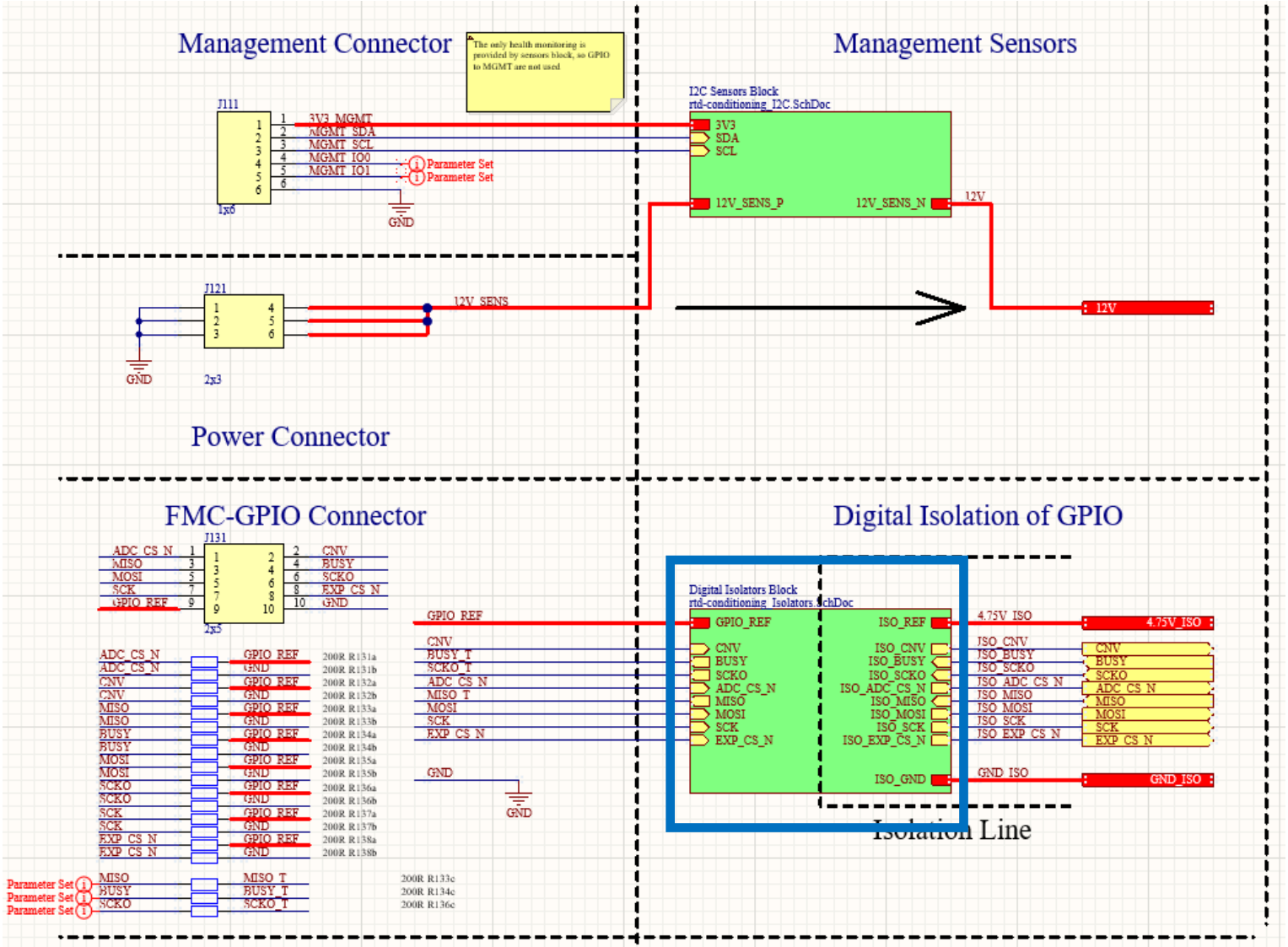
The sub-module design details

Management Sensors Schematic Diagram



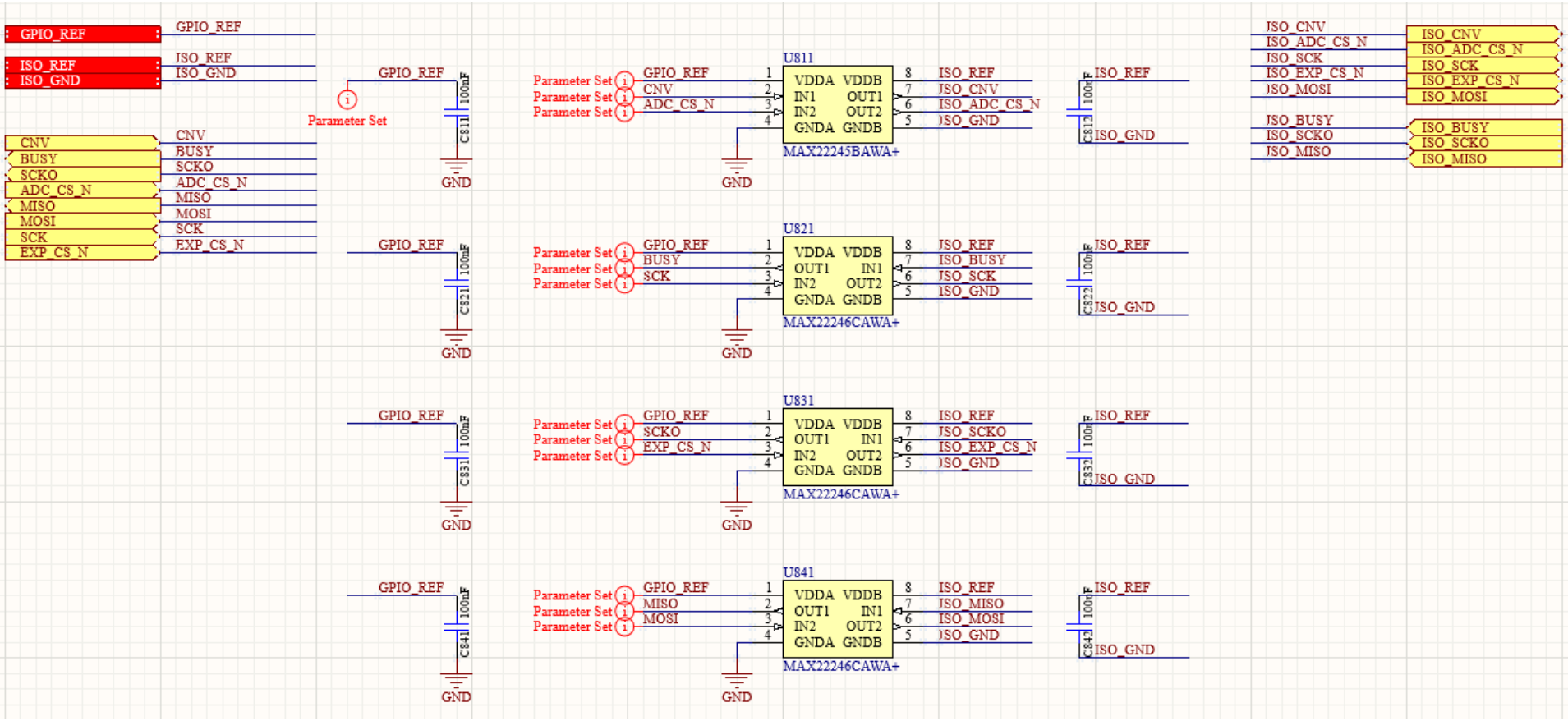
The sub-module design details

Digital Isolation of GPIO



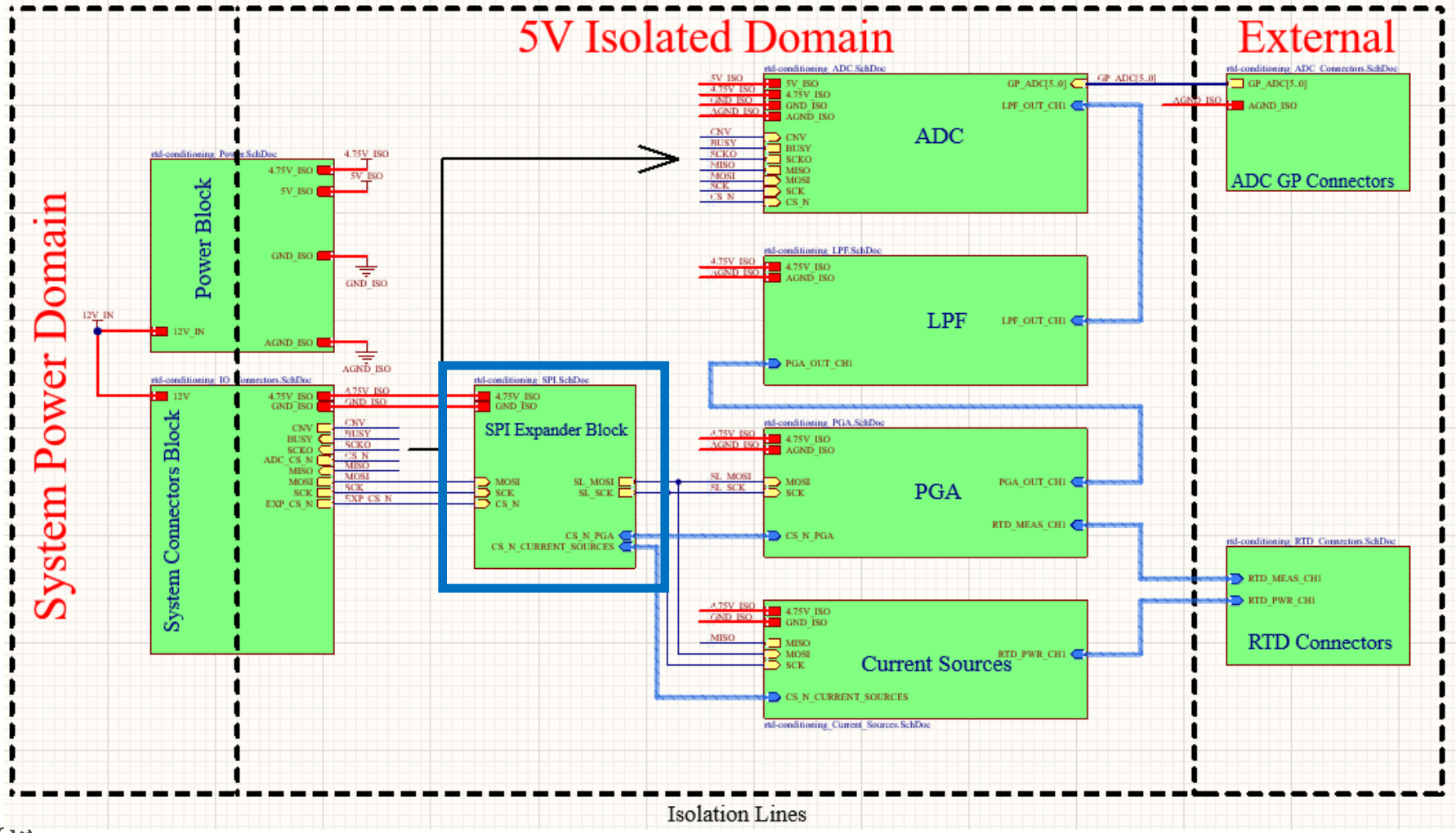
The sub-module design details

Digital Isolation of GPIO Schematic Diagram



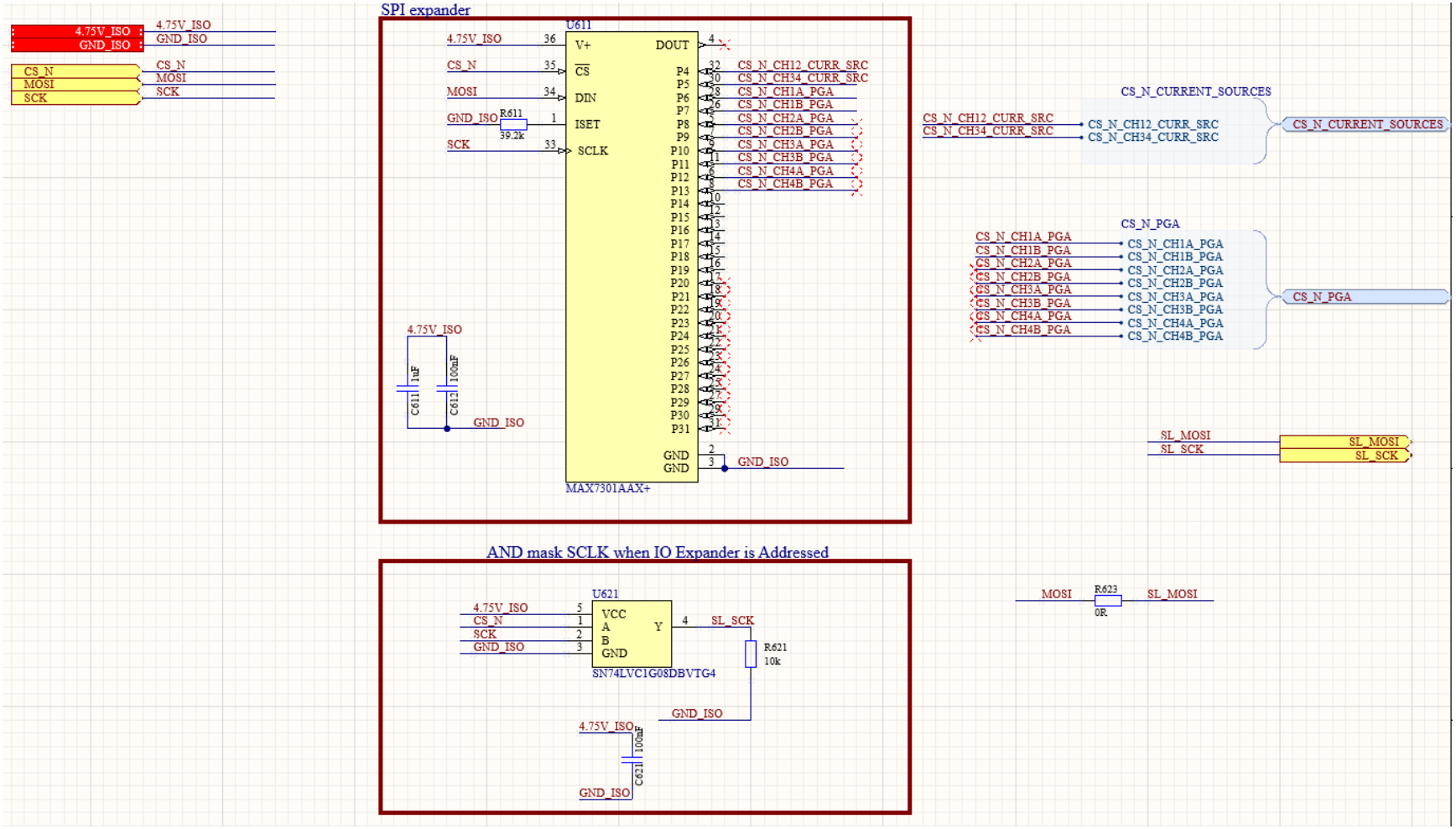
The sub-module design details

- SPI Expander Block



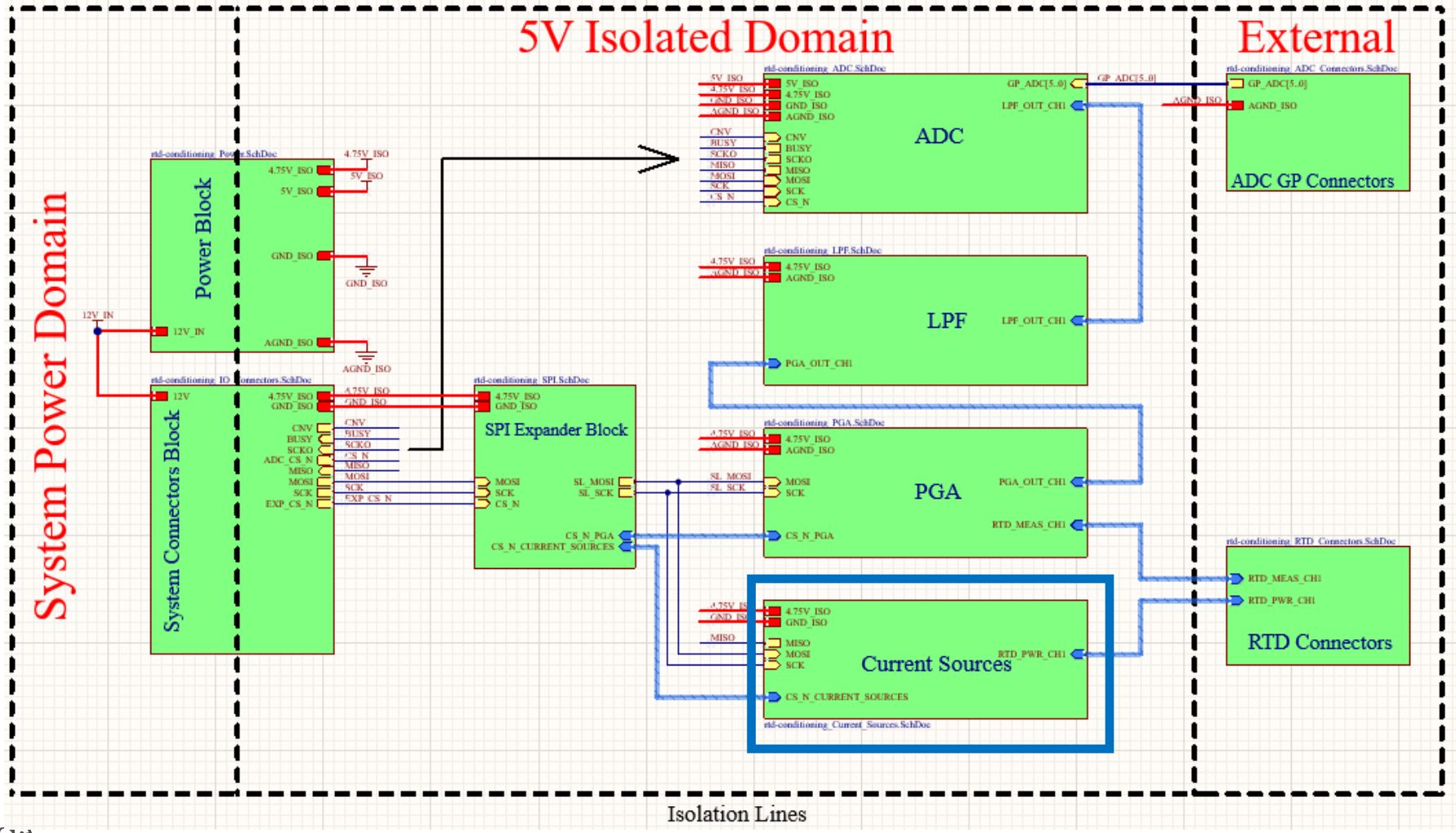
The sub-module design details

- SPI Expander Block



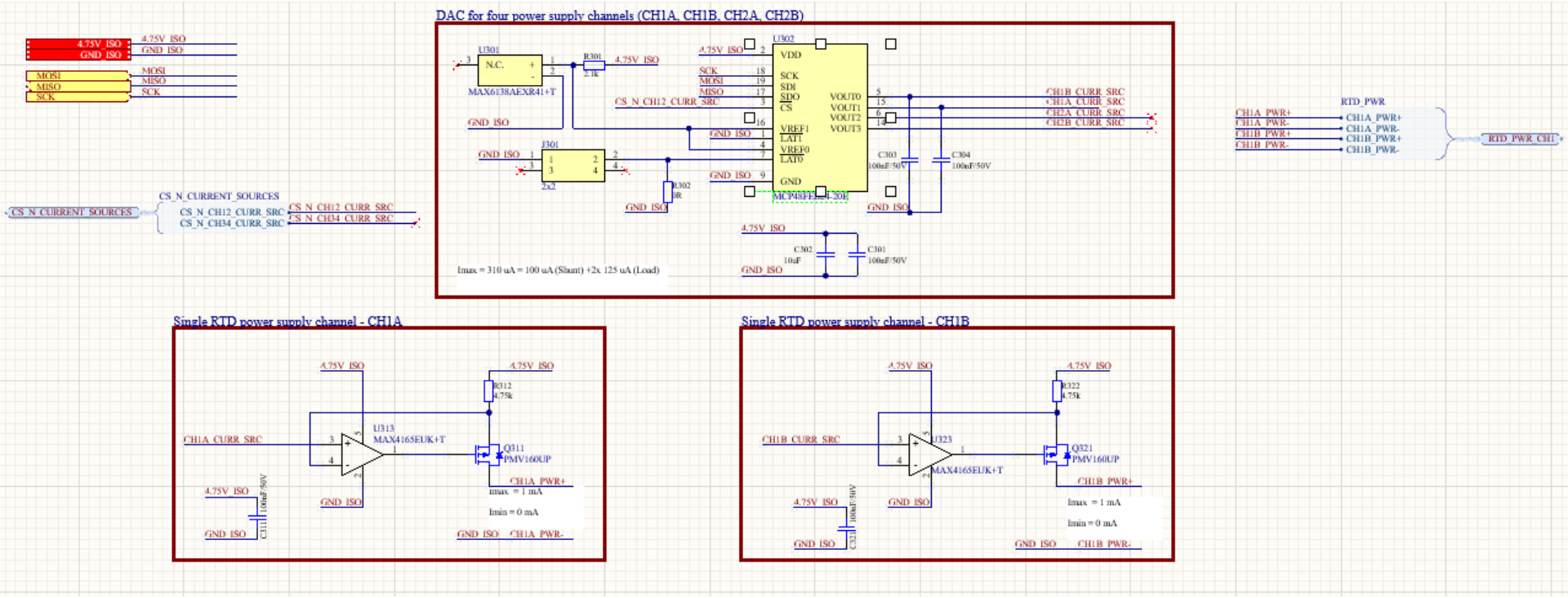
The sub-module design details

- Current Sources Block



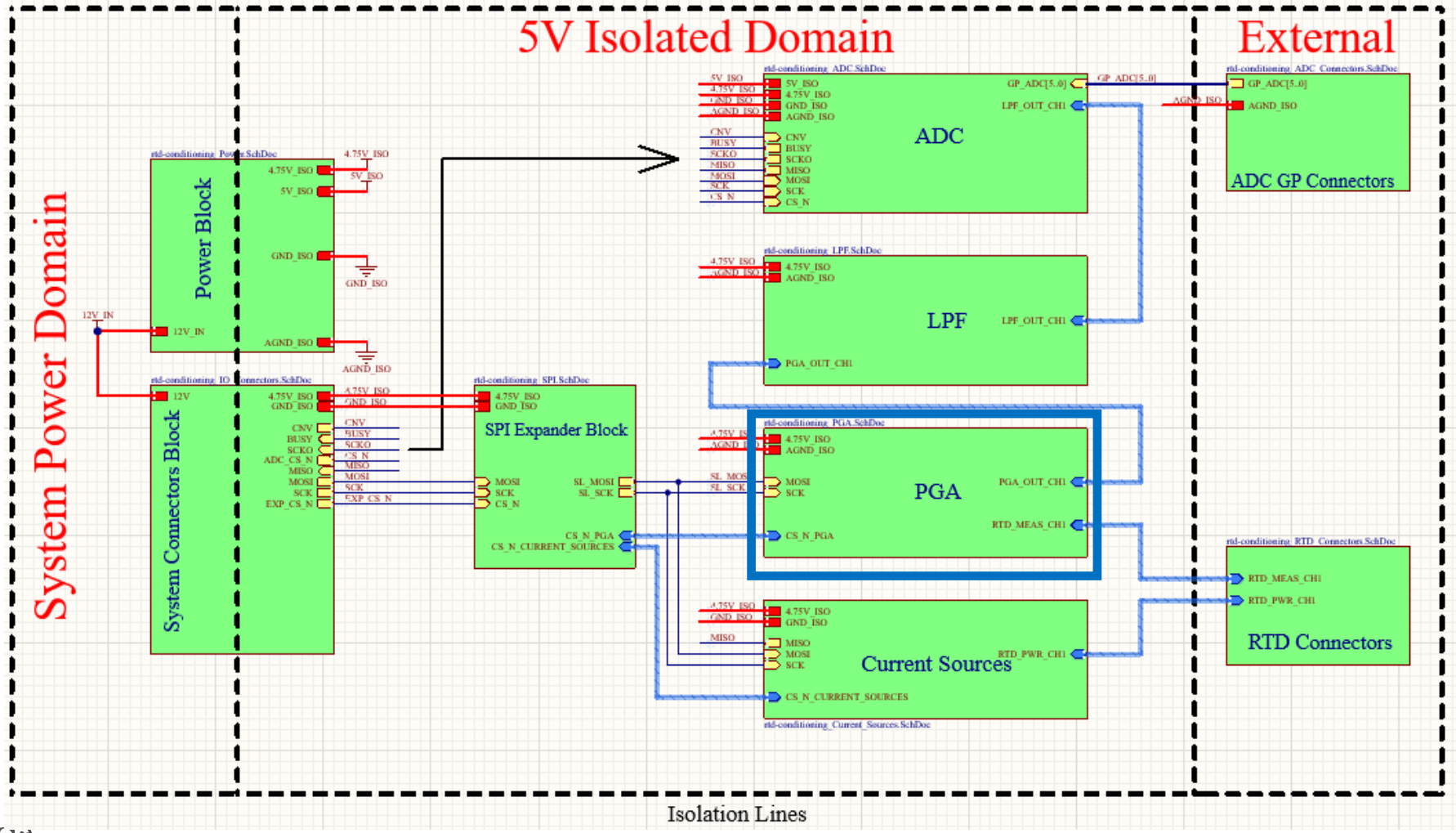
The sub-module design details

- Current Sources Block



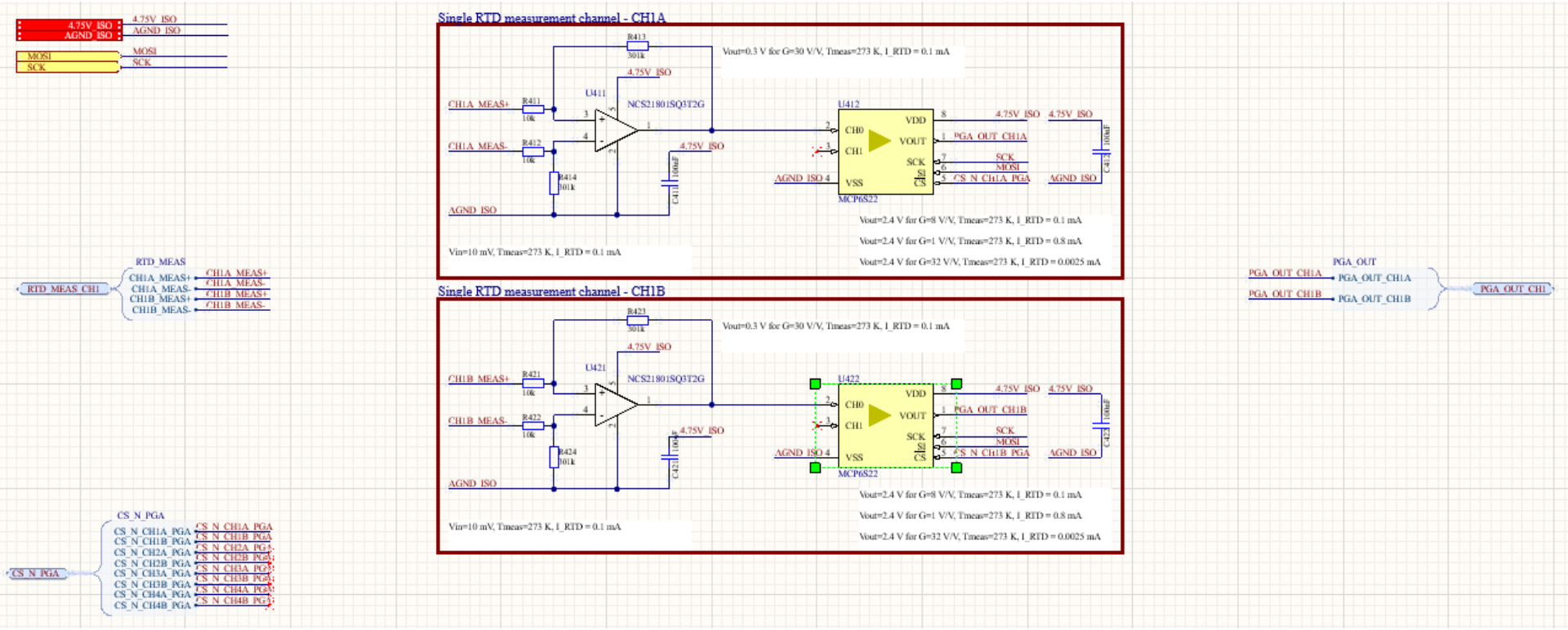
The sub-module design details

- PGA Block



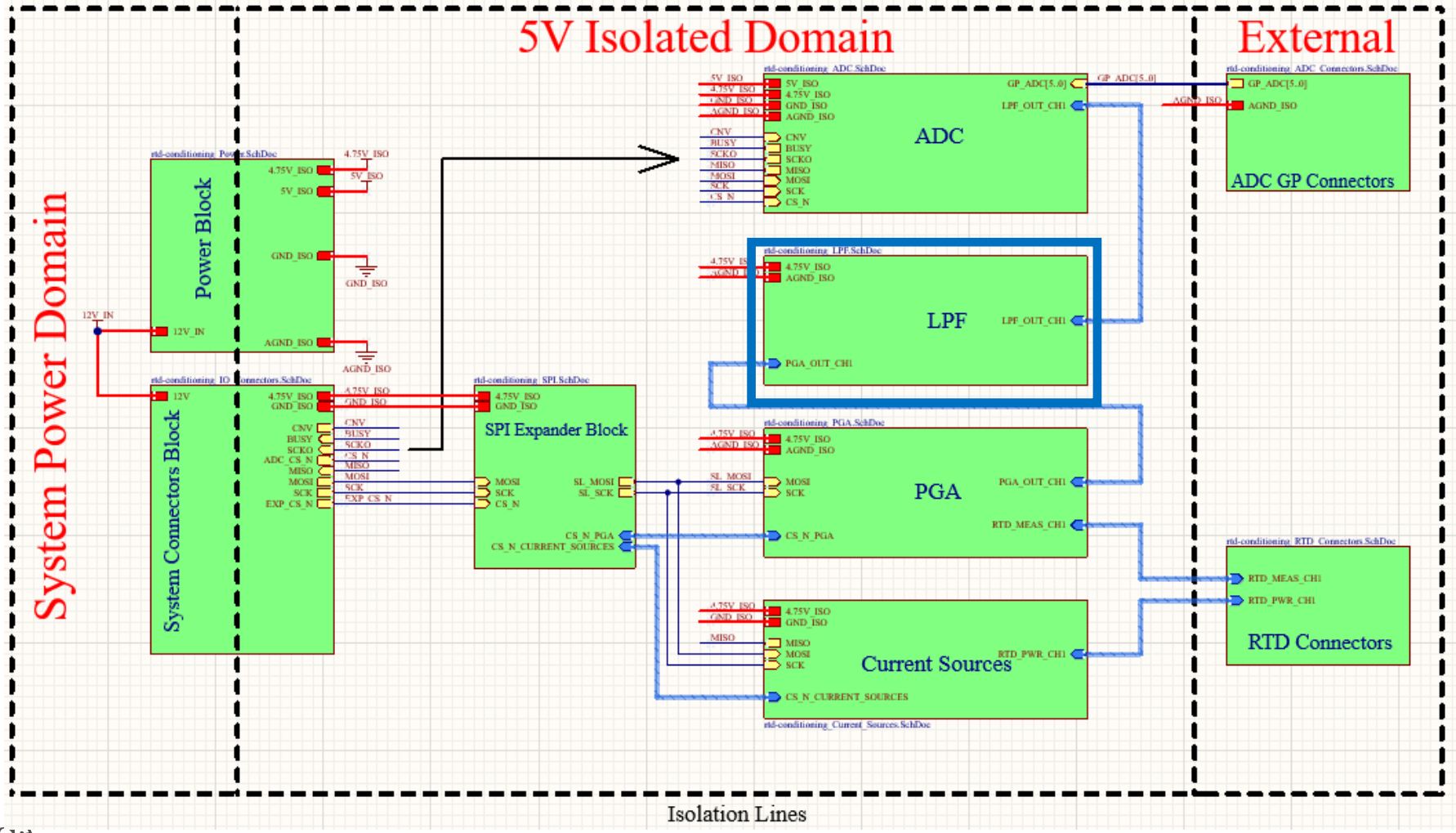
The sub-module design details

- PGA Block



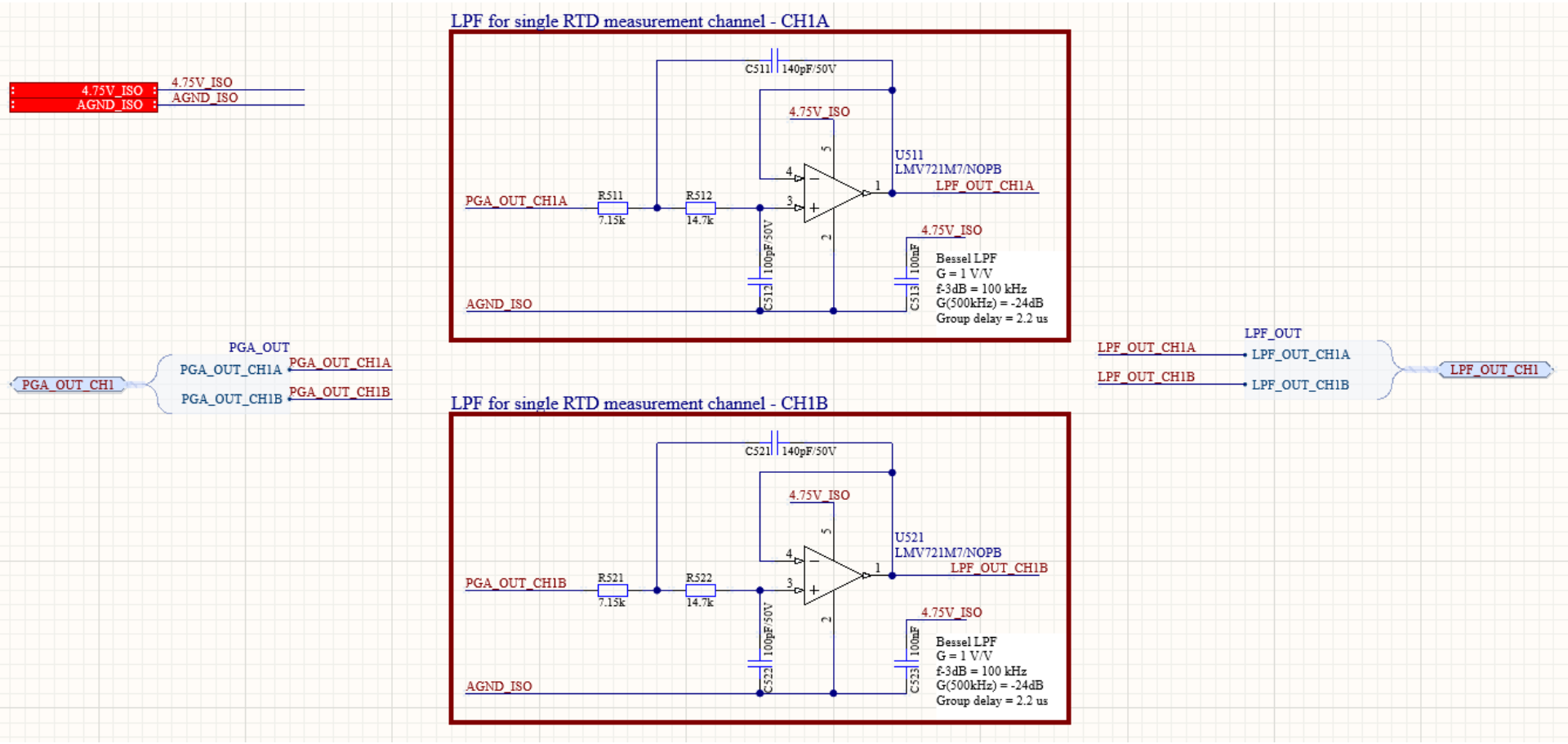
The sub-module design details

- LPF Block



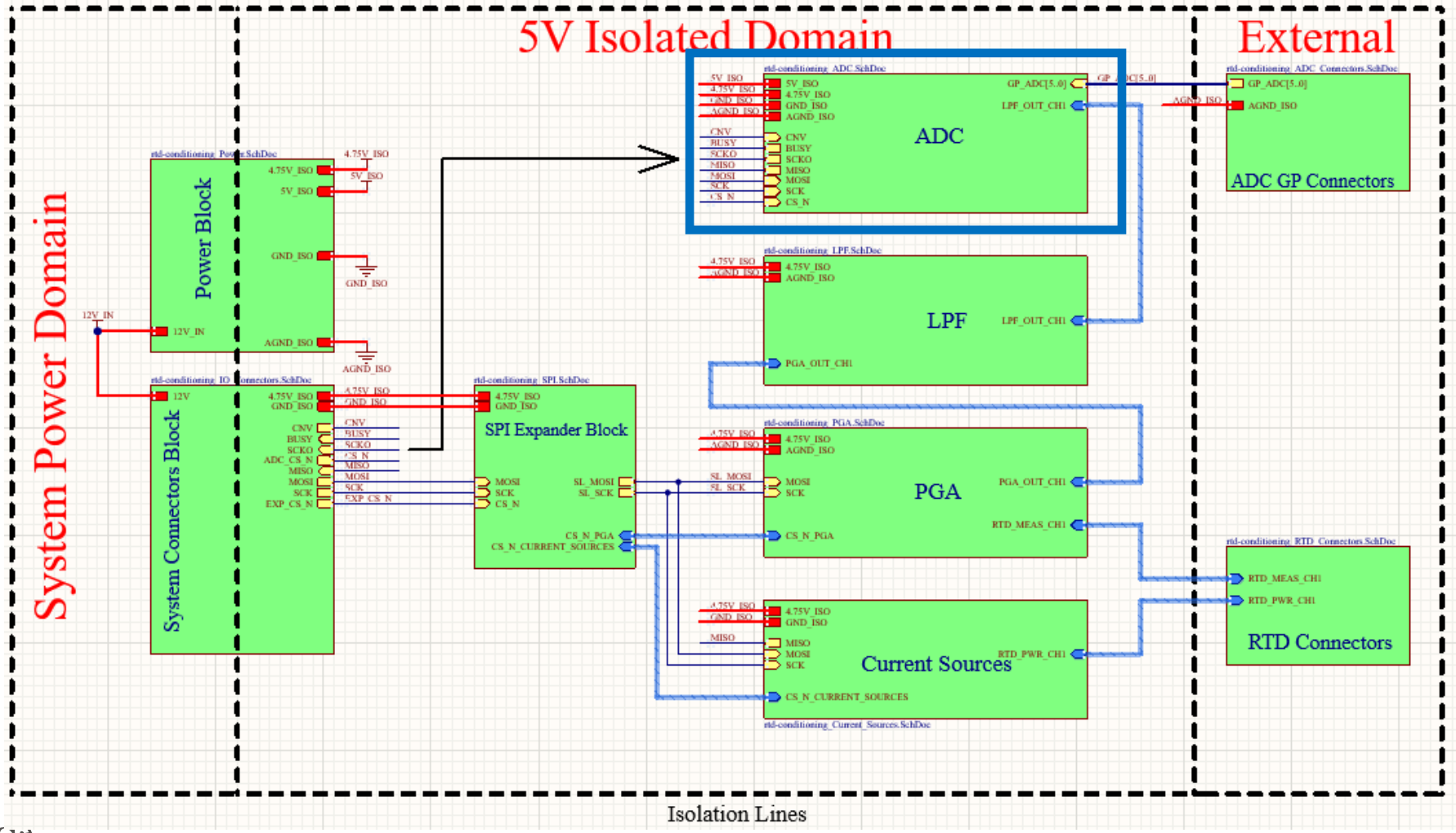
The sub-module design details

- LPF Block



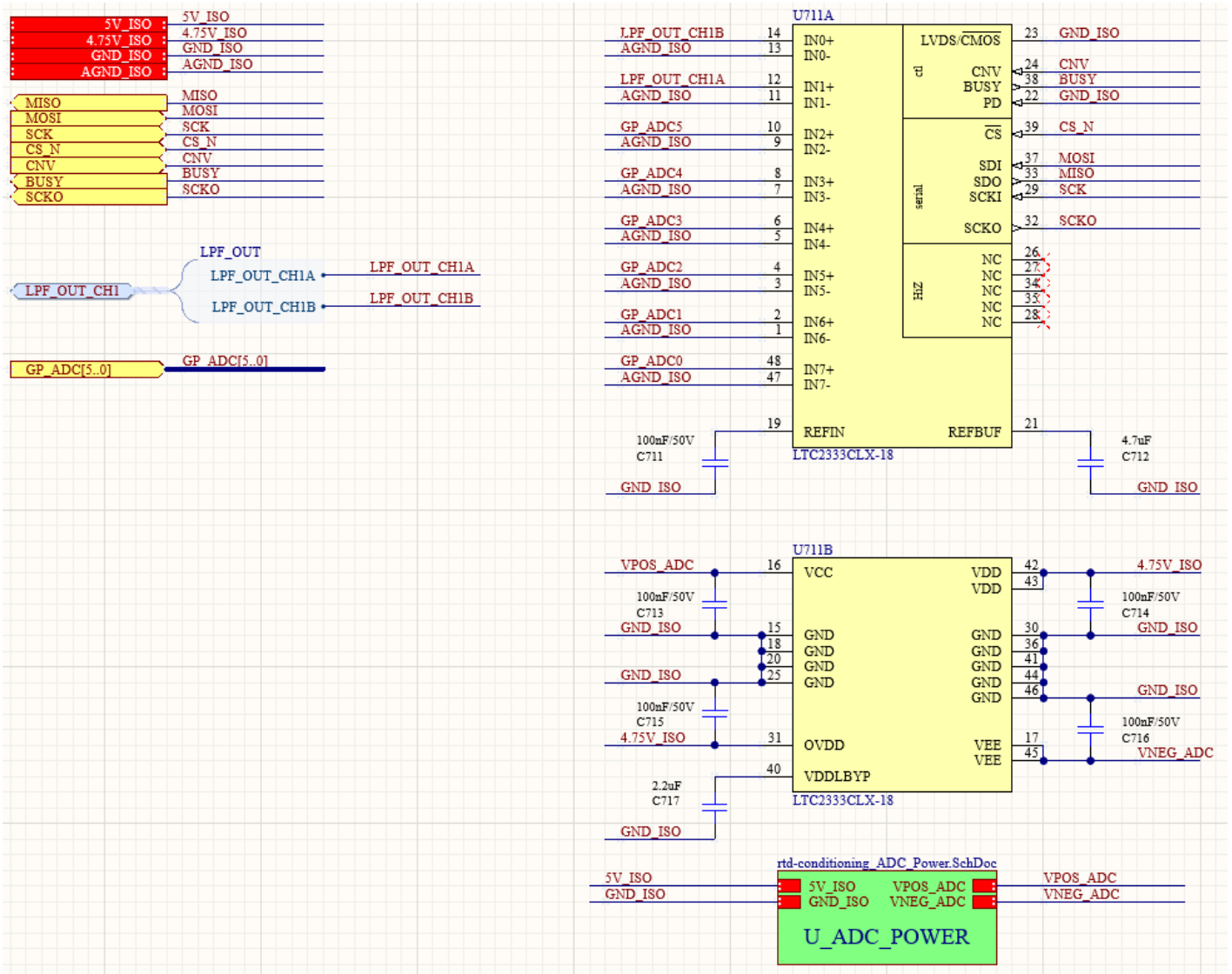
The sub-module design details

- ADC Block



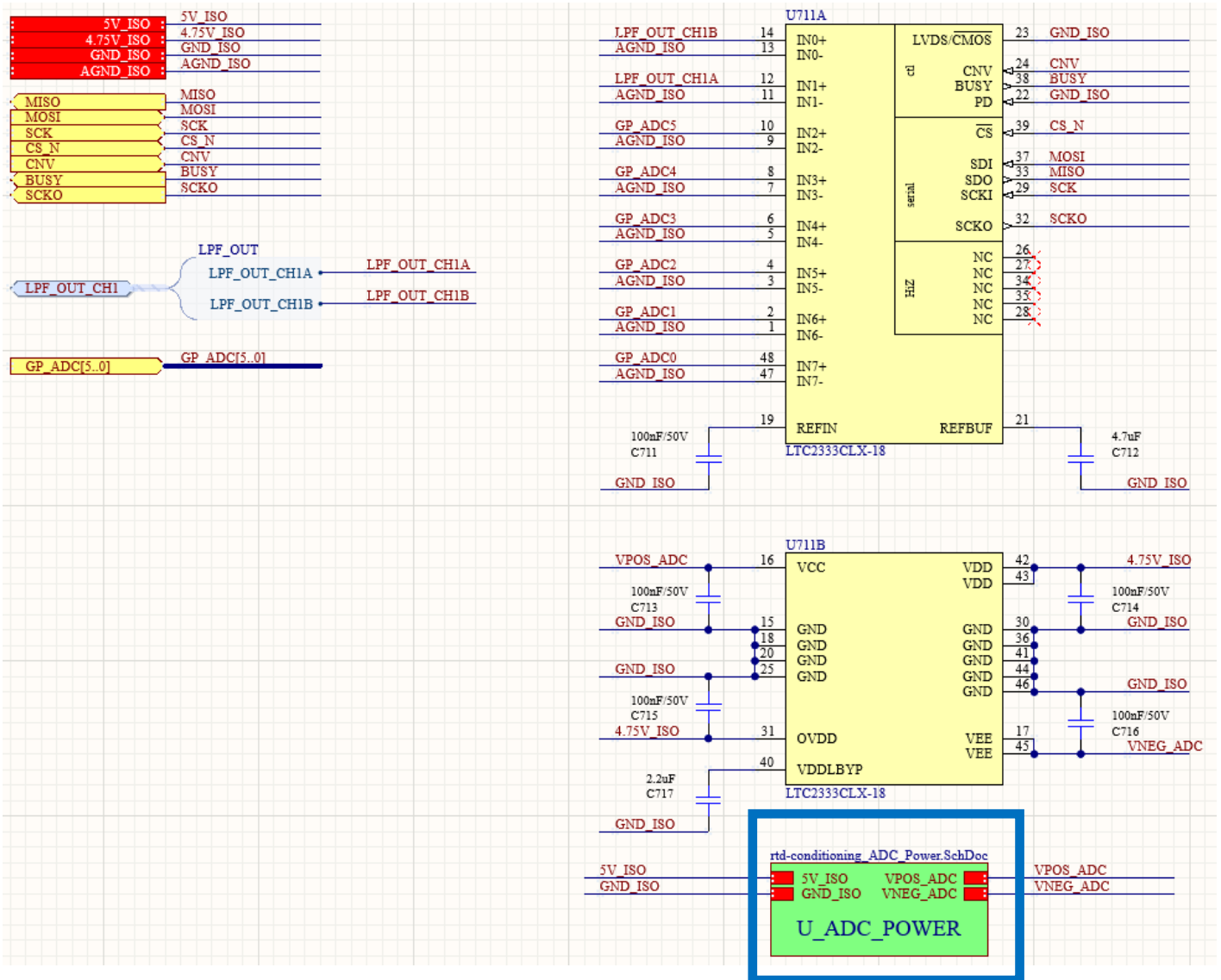
The sub-module design details

- ADC Block



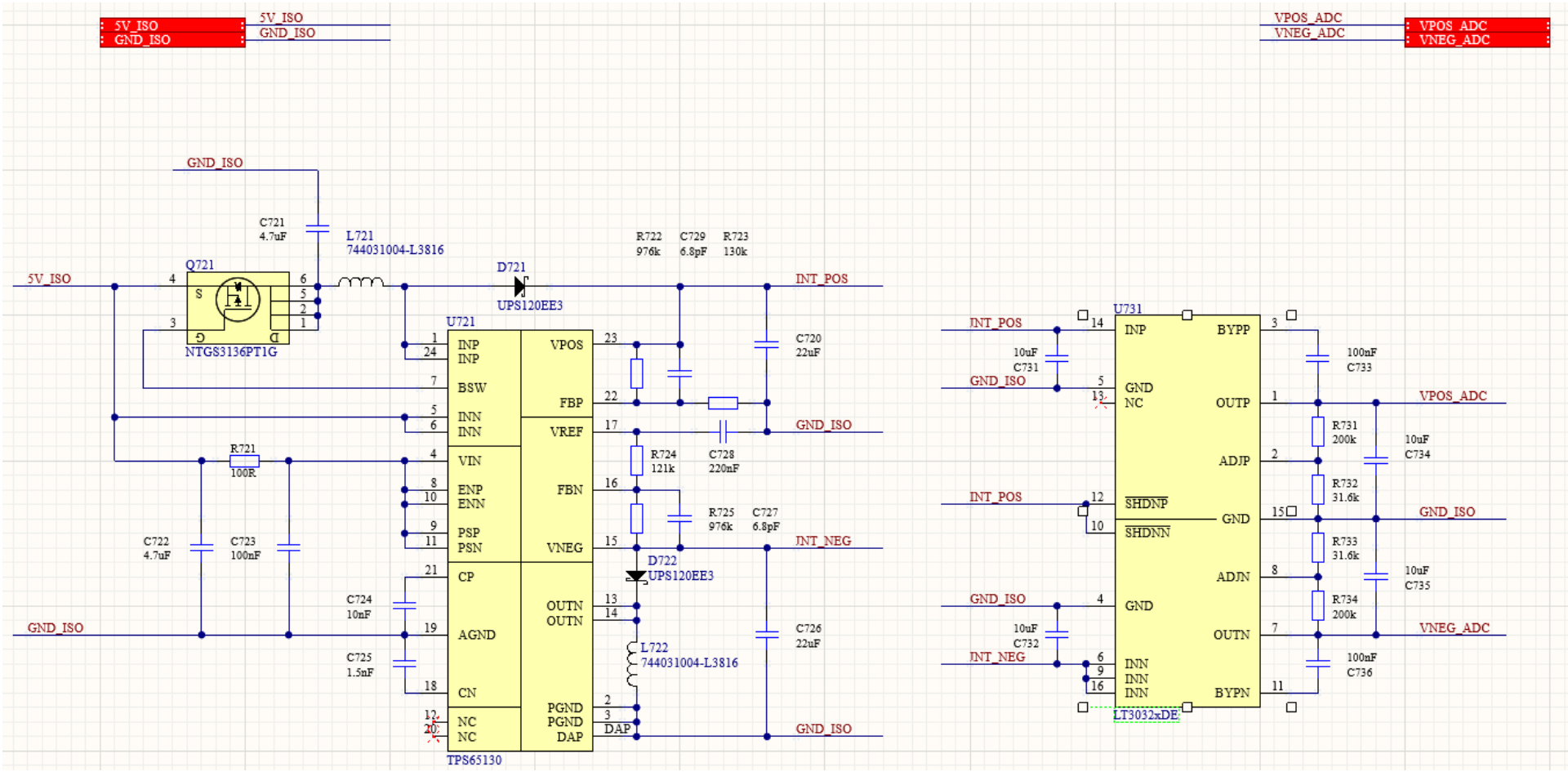
The sub-module design details

- ADC Block



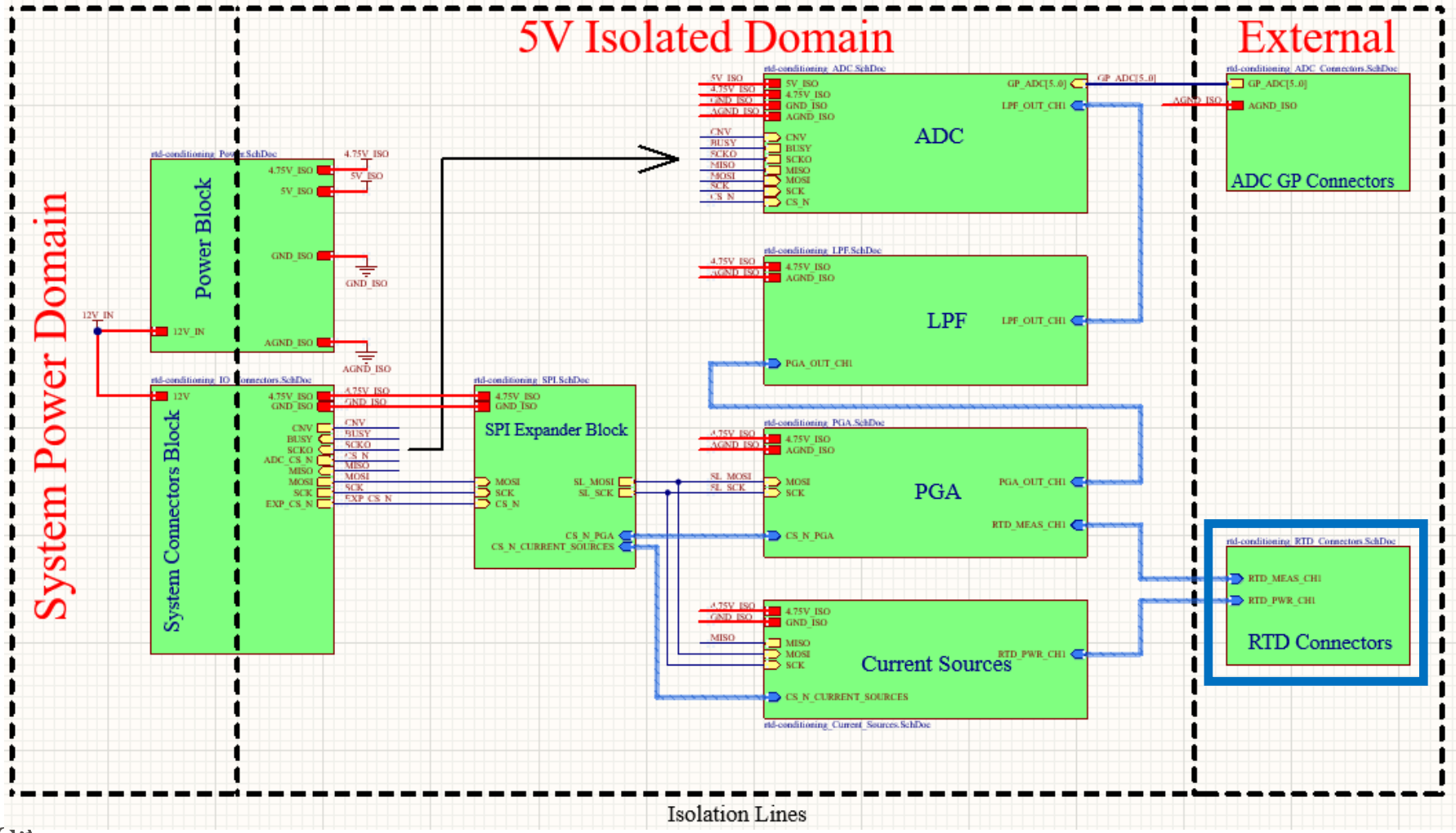
The sub-module design details

- ADC Power Block



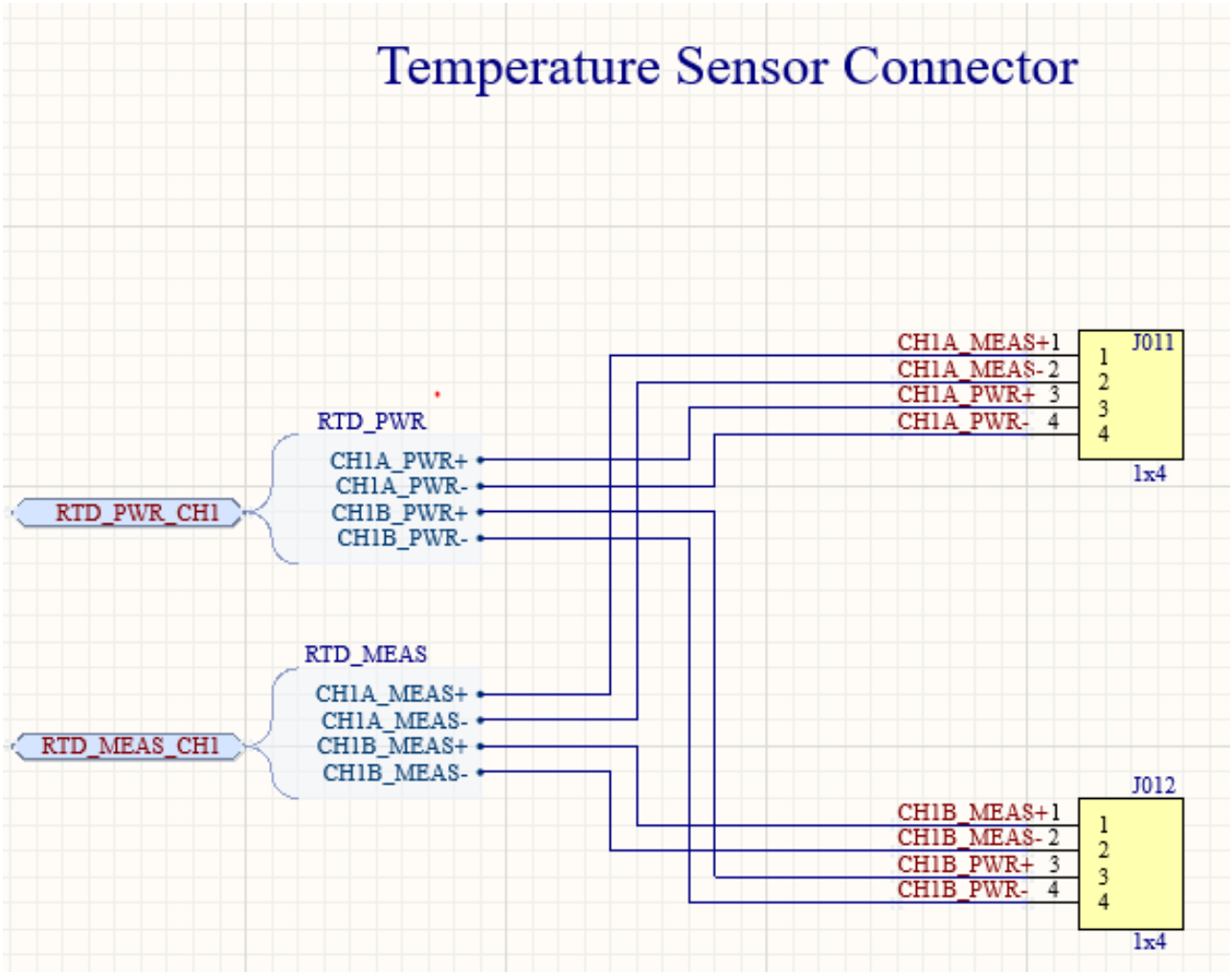
The sub-module design details

- RTD Connectors Block



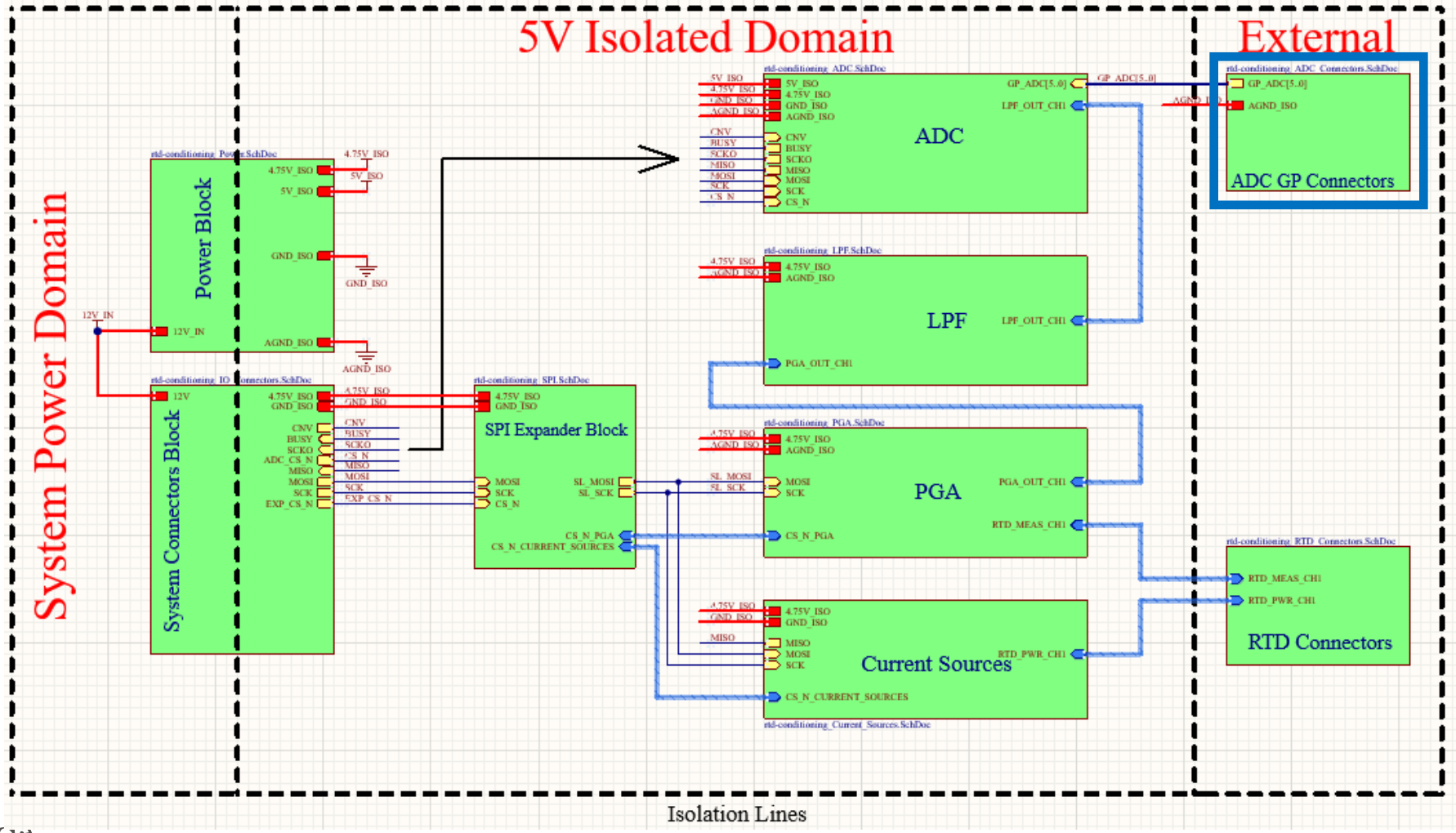
The sub-module design details

- RTD Connectors Block



The sub-module design details

- ADC GP Connectors Block



The sub-module design details

- ADC GP Connectors Block