Test Report: PMP41115

240W USB Type-C® and USB PD 3.1 Charger Reference Design

Description

This reference design is an integrated USB Type-C and USB power delivery (PD) charger for 10 to 12-cell batteries for applications such as e-bikes, high-capacity power banks, and portable power station applications.

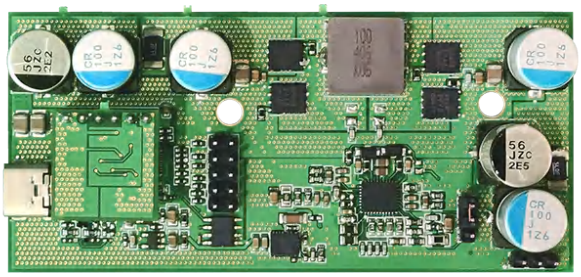
The design incorporates USB PD3.1 controllers TPS26750 and TPD4S480, a 48V extended power range (ERP) USB port protector together with BQ25756, a four-switch buck boost controller to fully achieve USB PD3.1 function with 240W power capability. The PD controller works with the battery charger controller BQ25756 through I2C communication. BQ25756 supports a wide-range input with four-switch buck-boost configuration, and supports seamless transition from buck, boost, and buck-boost operation mode to provide a highly efficient, highly accurate, and reliable charger design. TPD4S480 provides 48V short-to-VBUS, overvoltage, and electrostatic discharge (ESD) protection that allow reliable and safe operation. The design achieved 97.6% full load efficiency.

Features

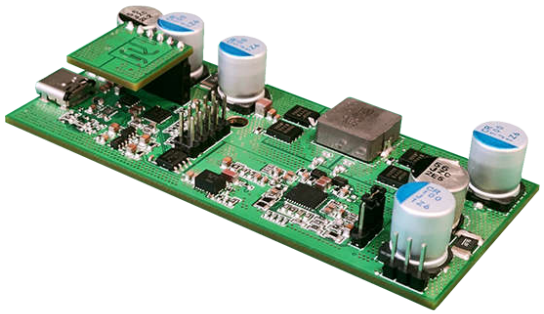
- Compatible with USB PD3.1 EPR protocol
- Supports 10 to 12 cell batteries
- Dual role power (DRP) with maximum 240W capability
- Provide short to 48V Vbus protection
- Seamless transition among buck, buck-boost, and boost across wide input and output range
- Full-load efficiency 97.6%

Applications

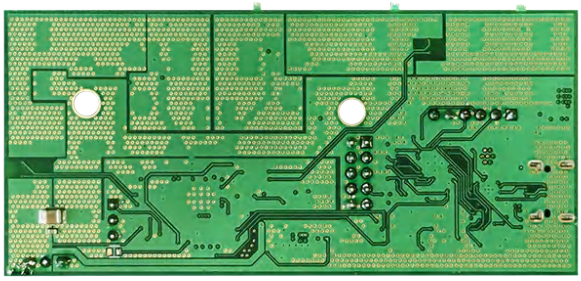
- Cordless power tool
- Vacuum robot
- Battery charger
- Cordless vacuum cleaner



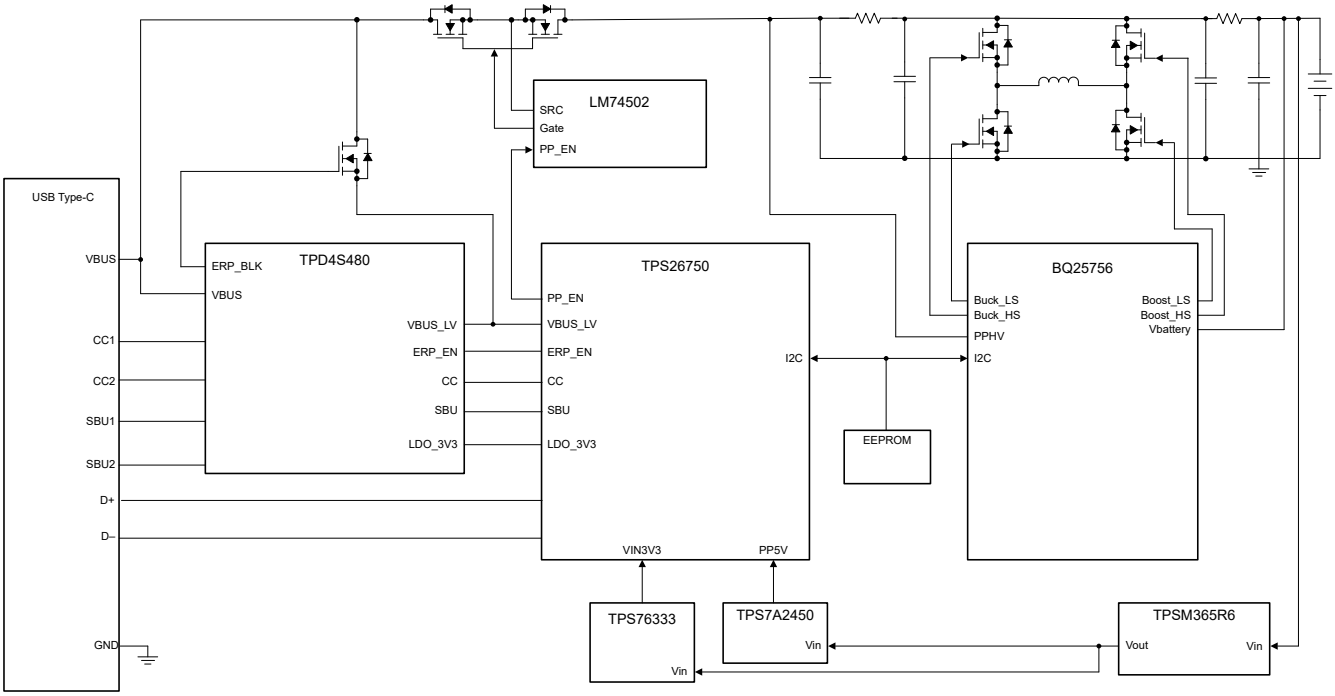
Top View



Angled View



Bottom View



PMP41115 Block Diagram

1 Test Prerequisites

Table 1-1 shows the USB Type-C PD bidirectional charger specification. The USB Type-C port can be either a source or sink depending on the equipment plug-in. The battery side supports 10 to 12 cells in OTG (On-The-Go) mode. The output voltage is configured to 5V, 9V, and 15V at 3A and 28V, 36V, and 48V at 5A. The maximum output power is limited to 240W.

1.1 Voltage and Current Requirements

Table 1-1. Voltage and Current Requirements

PARAMETER	SPECIFICATIONS
Sink input voltage range	5VDC to 48 VDC
Source output voltage range	5V, 9V, 15V, 20V, 36V, 48V
Battery cell configuration	10 to 12 Cells
Maximum input current	5A
Maximum power	240W
Switching frequency	300kHz
Efficiency	97.6% at full load

1.2 Required Equipment

1. DC source: GWinstek, GPS-3303C
2. Bidirectional power source: IT6010C-80-300
3. KM003C PD Emulator
4. 140W USB Type-C PD adapter
5. 1m USB Type-C cable (supports 5A)
6. Electronic load: Chroma, 6314A
7. Oscilloscope: Tektronix, DPO 3054
8. Infrared Thermal Camera: Fluke, TiS55
9. Ture-RMS-Multimeter: Fluke, 287C
10. Digital Power Meter: Yokogawa WT310
11. TPS65987 EVM board
12. USB Type-C DUO EVM board (Sink and Source Emulator)

1.3 Considerations

The reference design shows an example of how to implement a USB Type-C PD alongside a switching battery charger that is capable of handling high power and high current. This design can be used in power tool chargers, vacuum robot chargers, and portable power stations as well as various other personal electronic systems. This design assists with different functions, from the ability to charge a battery as well as providing power to the system or switching to OTG mode to source power to the connected device all through the USB Type-C connector.

1.4 Dimensions

PCB board size: 43mm × 94mm × 14.3m (open frame)

1.5 Test Setup

Place a 470µF, 100V bus capacitor physically close to the output terminal to avoid a long cable connection to the battery side when performing the test.

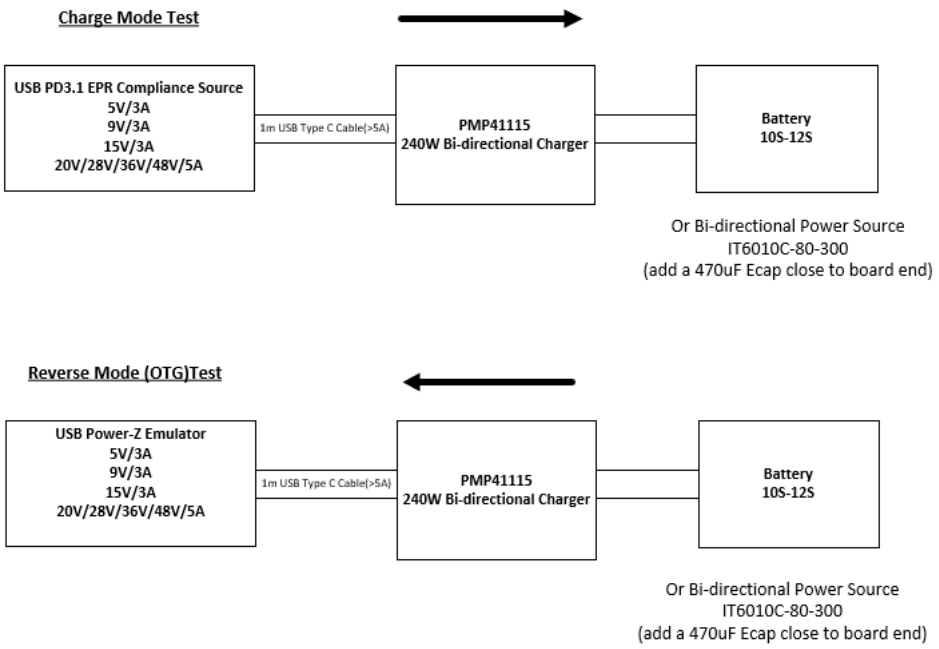


Figure 1-1. Test Setup

2 Testing and Results

2.1 Efficiency Graphs

The following figure show the charge mode efficiency across different input voltage conditions at 12S battery. Figure 2-1 and Figure 2-2 show the efficiency at OTG (reverse power) mode, output current is set to 3A for 5V, 9V, 15V input source, and 5A for 20V, 28V, 48V input source.

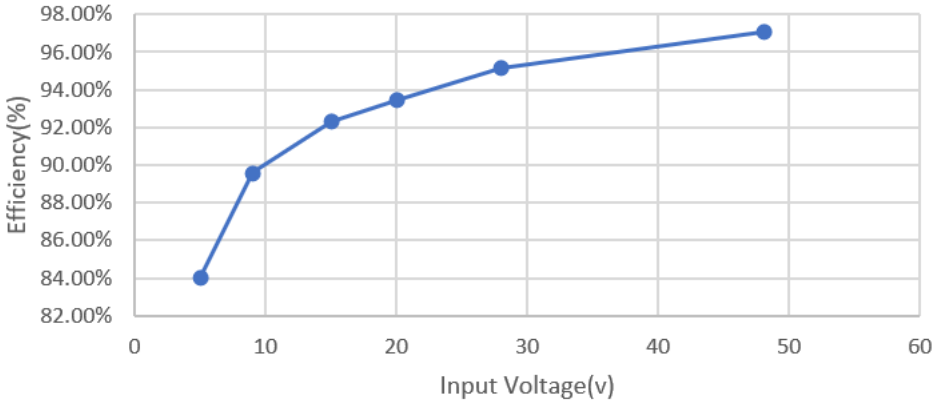


Figure 2-1. Charge Mode Efficiency Across Input Voltage

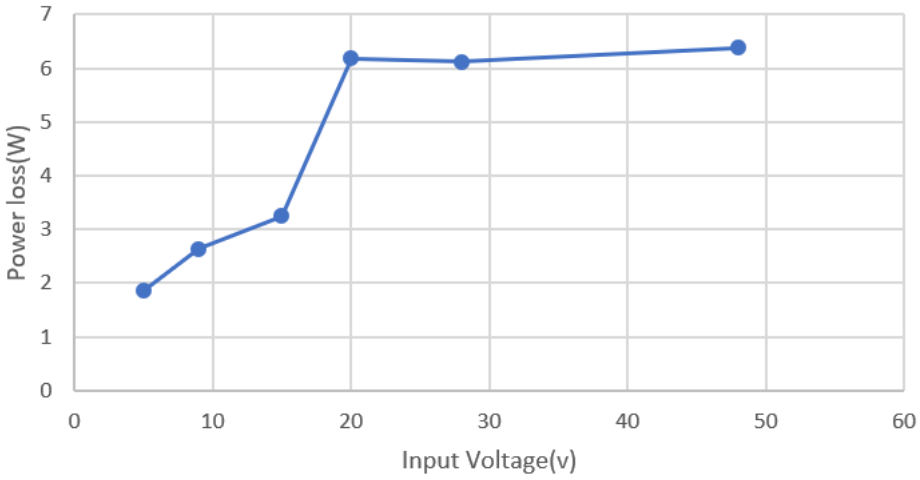


Figure 2-2. Power Loss Across Input Voltage

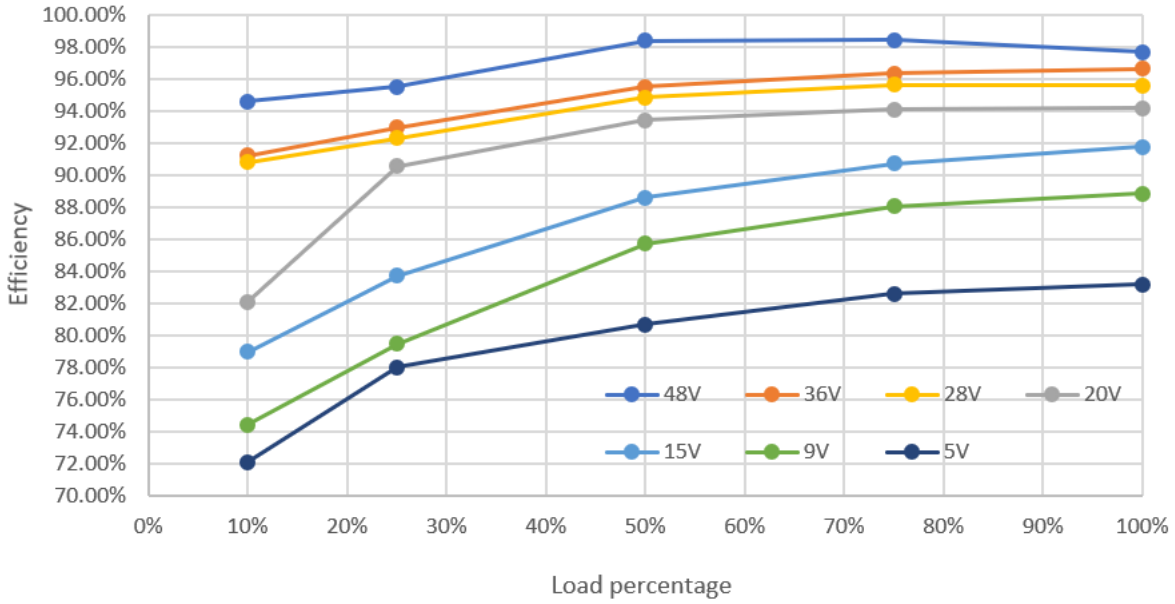


Figure 2-3. OTG Mode Efficiency at 12S Battery Across V_{out} and Load

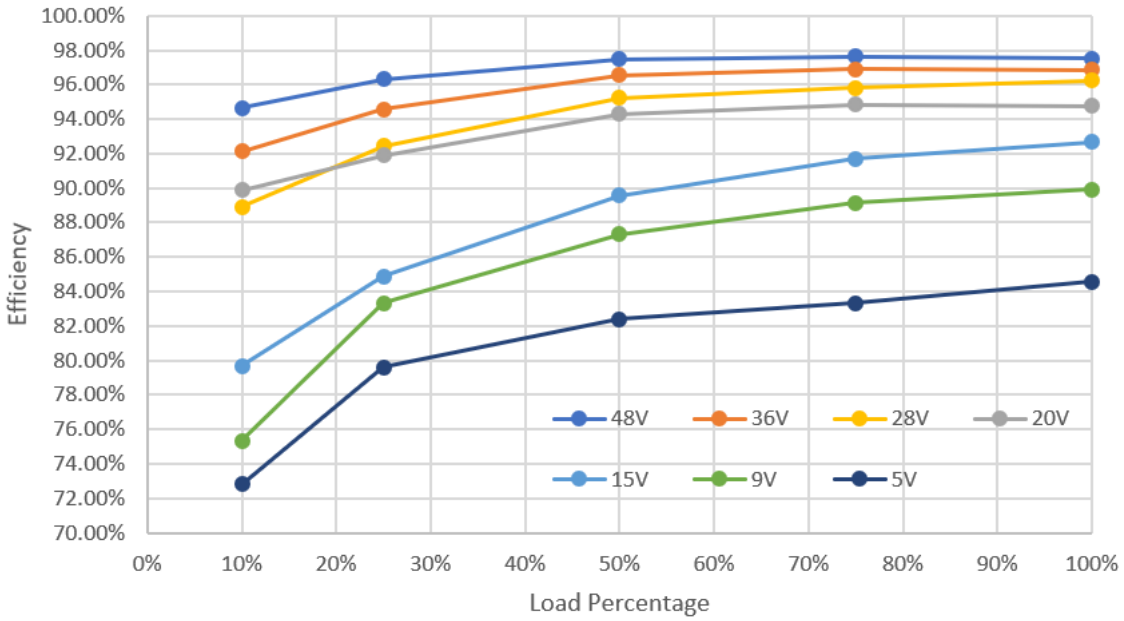


Figure 2-4. OTG Mode Efficiency at 10S Battery Across V_{out} and Load

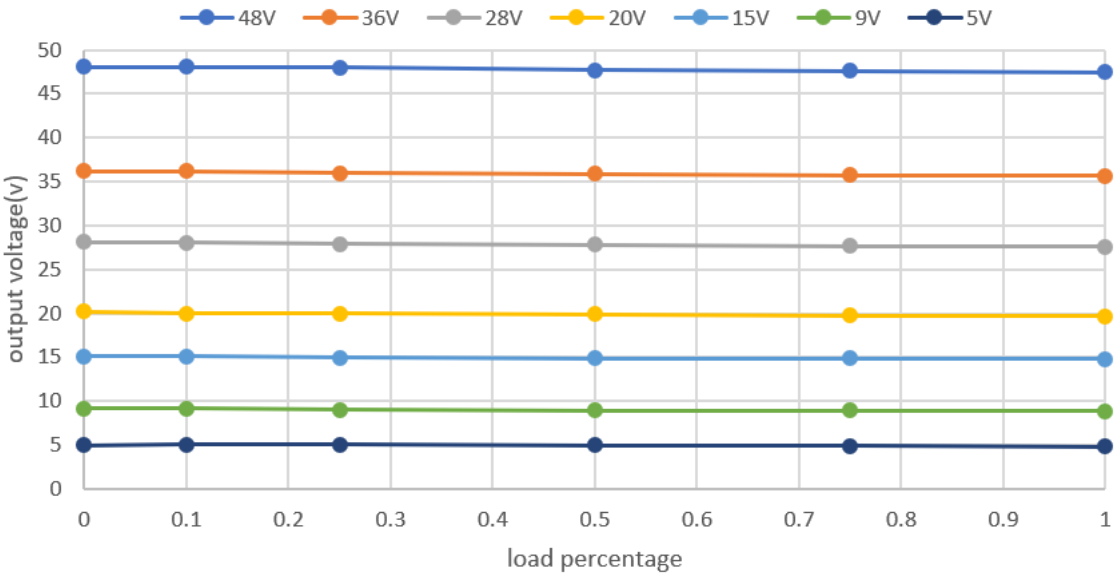


Figure 2-5. Vout Regulation at 12S Battery

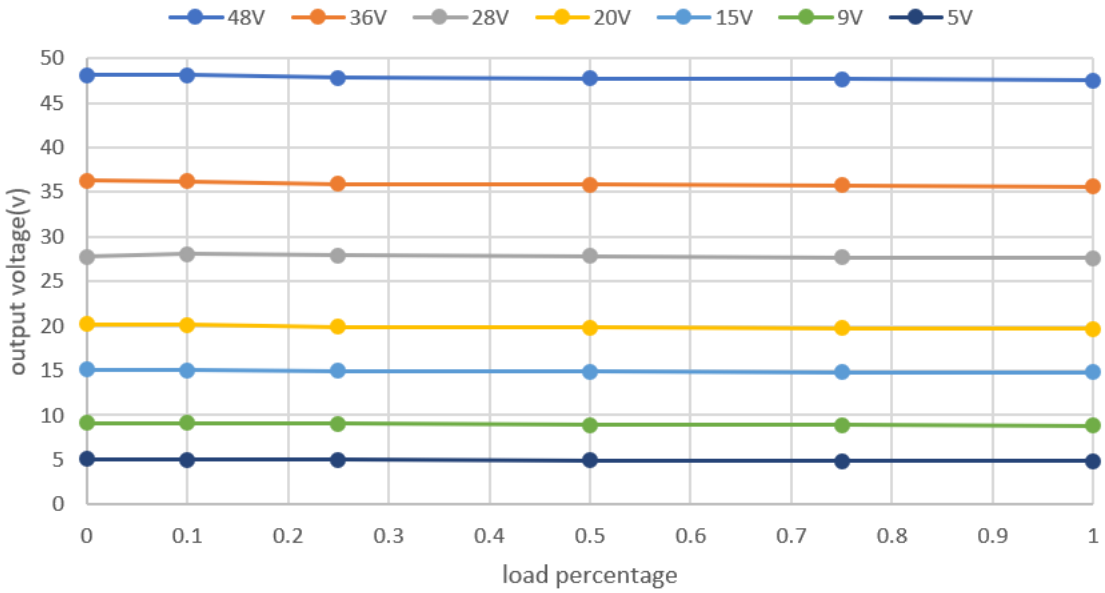


Figure 2-6. V_{out} Regulation at 10S Battery

2.2 Efficiency Data

Efficiency data is shown in Table 2-1 and Table 2-2.

Table 2-1. Charge Mode Efficiency Data

Vsys (V)	Iin (A)	Pin (W)	Vbat (V)	Ichg (A)	Pout (W)	Efficiency	Power Loss (W)
4.99	2.340	11.7	49.1	0.200	9.8	84.07%	1.9
9.20	2.760	25.4	49.8	0.457	22.7	89.59%	2.6
15.28	2.760	42.2	49.8	0.782	38.9	92.31%	3.2
20.48	4.600	94.2	49.8	1.768	88.0	93.44%	6.2
27.50	4.612	126.8	49.8	2.425	120.7	95.18%	6.1
47.25	4.605	217.6	49.8	4.242	211.2	97.07%	6.4

Table 2-2. OTG Mode Efficiency Data

Vbat (V)	Idisc (A)	Pin (W)	Vsys (V)	Iout (A)	Pout (W)	Efficiency	Power Loss (W)
49.9	0.512	25.6	48.1	0.503	24.2	94.6%	1.4
49.9	1.260	62.8	48.0	1.251	60.0	95.5%	2.8
49.8	2.441	121.6	47.7	2.506	119.6	98.4%	2.0
49.7	3.656	181.8	47.6	3.758	179.0	98.4%	2.9
49.7	4.902	243.5	47.5	5.010	237.8	97.7%	5.7
49.9	0.400	20.0	36.2	0.503	18.2	91.2%	1.8
49.9	0.970	48.4	35.9	1.251	45.0	92.9%	3.4
49.8	1.884	93.9	35.9	2.5	89.6	95.5%	4.2
49.8	2.802	139.5	35.8	3.757	134.4	96.3%	5.1
49.7	3.709	184.5	35.6	5.001	178.2	96.6%	6.3
49.9	0.317	15.9	28.0	0.502	14.1	89.0%	1.7
49.9	0.759	37.9	27.9	1.254	34.9	92.3%	2.9
49.9	1.471	73.4	27.8	2.505	69.6	94.8%	3.8
49.8	2.184	108.8	27.7	3.757	104.0	95.6%	4.8
49.8	2.902	144.4	27.6	5.001	138.0	95.6%	6.4
Vbat (V)	Idisc (A)	Pin (W)	Vsys (V)	Iout (A)	Pout (W)	Efficiency	Power Loss (W)
49.9	0.512	25.6	48.1	0.503	24.2	94.6%	1.4
49.9	1.260	62.8	48.0	1.251	60.0	95.5%	2.8
49.8	2.441	121.6	47.7	2.506	119.6	98.4%	2.0
49.7	3.656	181.8	47.6	3.758	179.0	98.4%	2.9
49.7	4.902	243.5	47.5	5.010	237.8	97.7%	5.7
49.9	0.400	20.0	36.2	0.503	18.2	91.2%	1.8
49.9	0.970	48.4	35.9	1.251	45.0	92.9%	3.4
49.8	1.884	93.9	35.9	2.5	89.6	95.5%	4.2
49.8	2.802	139.5	35.8	3.757	134.4	96.3%	5.1
49.7	3.709	184.5	35.6	5.001	178.2	96.6%	6.3
49.9	0.317	15.9	28.0	0.502	14.1	89.0%	1.7
49.9	0.759	37.9	27.9	1.254	34.9	92.3%	2.9
49.9	1.471	73.4	27.8	2.505	69.6	94.8%	3.8
49.8	2.184	108.8	27.7	3.757	104.0	95.6%	4.8
49.8	2.902	144.4	27.6	5.001	138.0	95.6%	6.4
49.9	0.245	12.2	20.0	0.502	10.0	82.1%	2.2
49.9	0.553	27.6	19.9	1.253	25.0	90.5%	2.6

Table 2-2. OTG Mode Efficiency Data (continued)

Vbat (V)	Idisc (A)	Pin (W)	Vsys (V)	Iout (A)	Pout (W)	Efficiency	Power Loss (W)
49.9	1.068	53.3	19.9	2.504	49.7	93.4%	3.5
49.8	1.583	78.9	19.8	3.7558	74.2	94.1%	4.7
49.8	2.101	104.7	19.7	5.007	98.5	94.2%	6.1
49.9	0.115	5.7	15.1	0.301	4.5	79.0%	1.2
49.9	0.269	13.4	14.9	0.752	11.2	83.7%	2.2
49.9	0.506	25.2	14.9	1.502	22.4	88.6%	2.9
49.9	0.738	36.8	14.8	2.251	33.4	90.7%	3.4
49.9	0.970	48.4	14.8	3.003	44.4	91.8%	4.0
49.9	0.074	3.7	9.1	0.301	2.7	74.4%	0.9
49.9	0.170	8.5	9.0	0.75	6.7	79.5%	1.7
49.9	0.314	15.7	8.9	1.502	13.4	85.7%	2.2
49.9	0.456	22.8	8.9	2.252	20.0	88.0%	2.7
49.9	0.599	29.9	8.8	3.003	26.5	88.8%	3.3
49.9	0.042	2.1	5.1	0.301	1.5	72.1%	0.6
49.9	0.097	4.8	5.0	0.752	3.8	78.0%	1.1
49.9	0.184	9.2	4.9	1.5	7.4	80.7%	1.8
49.9	0.267	13.3	4.9	2.251	11.0	82.6%	2.3
49.9	0.350	17.5	4.8	3.001	14.5	83.1%	2.9

2.3 Thermal Images

Figure 2-7 through Figure 2-16 show the thermal images at full power charge mode and OTG mode. All images were captured at 25ºC ambient temperature, after a 30-minute warm up.

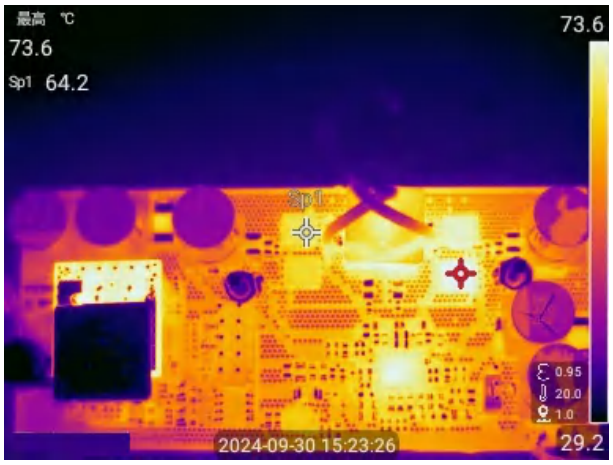


Figure 2-7. Charge Mode From 28Vin to 50V 12S Battery

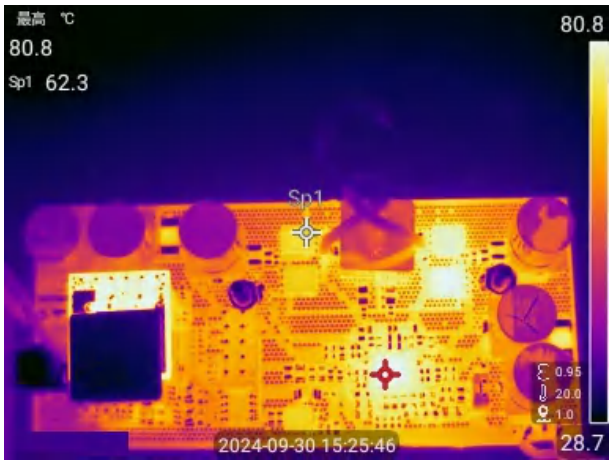


Figure 2-8. Charge Mode From 48V_{in} to 50V 12S Battery

Figure 2-9. OTG mode, 42V Battery 10S to 48V 5A

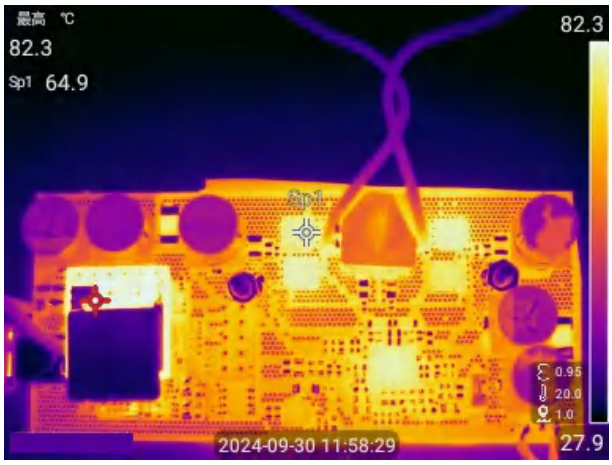


Figure 2-10. OTG Mode, 50V Battery 12S to 48V 5A

Figure 2-11. OTG Mode, 50V Battery 12S to 36V 5A

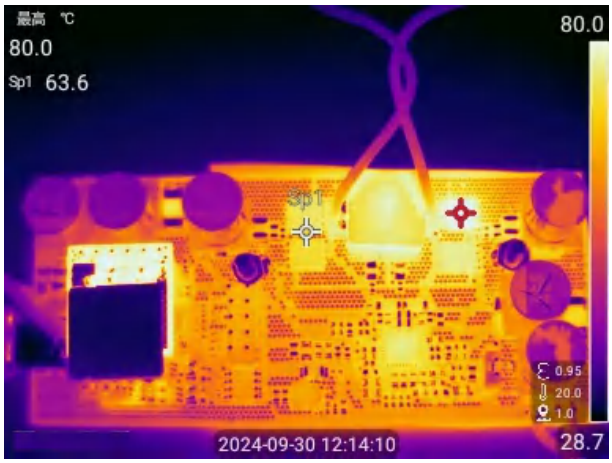


Figure 2-12. OTG Mode, 50V Battery 12S to 28V 5A

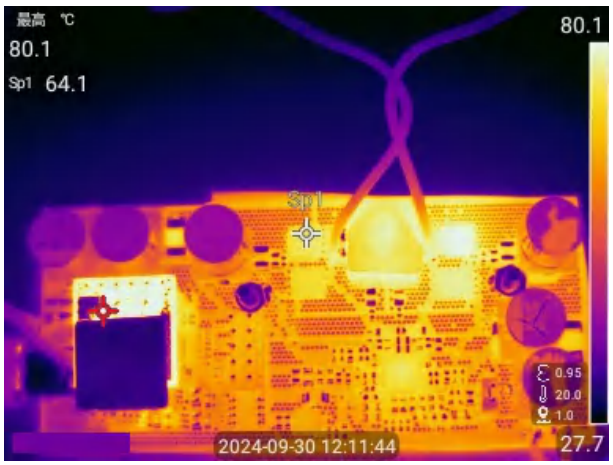


Figure 2-13. OTG Mode, 50V Battery 12S to 20V 5A

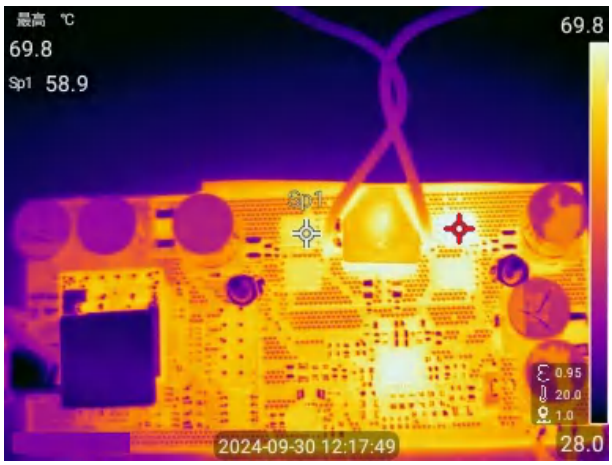


Figure 2-14. OTG Mode, 50V Battery 12S to 15V 3A

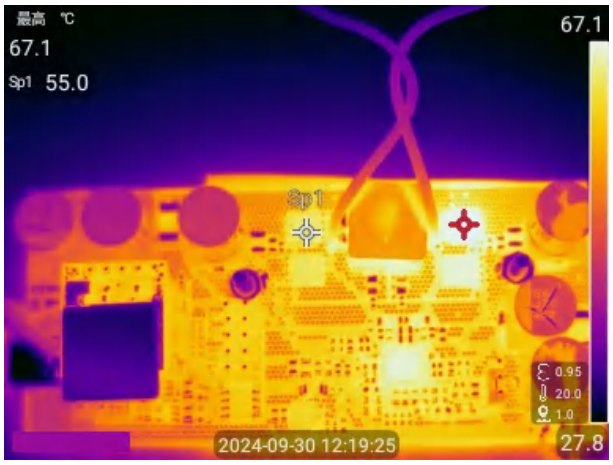


Figure 2-15. OTG Mode, 50V Battery 12S to 9V 3A

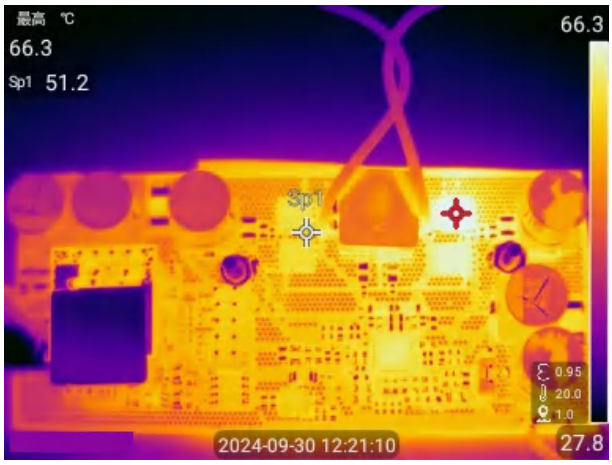


Figure 2-16. OTG Mode, 50V Battery 12S to 5V 3A

3 Waveforms

3.1 Charge Mode Start-Up Waveform

Figure 3-1 shows the power profile when using PD emulator KM003C. Figure 3-2 through Figure 3-7 show the charging waveform at different input source voltages negotiated on USB Type-C port, battery voltage, and charge current.

Figure 3-1. Power Profile

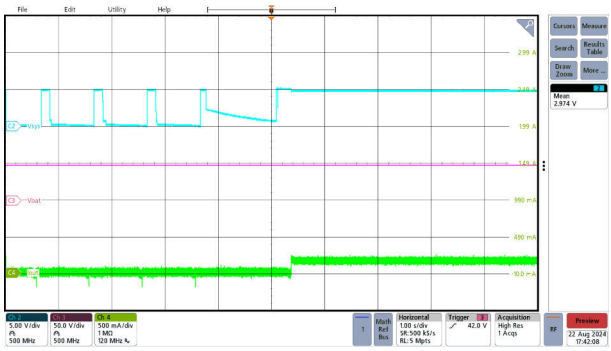


Figure 3-2. $5V_{sys}$ to 12S Battery voltage 50.4V Charge Mode

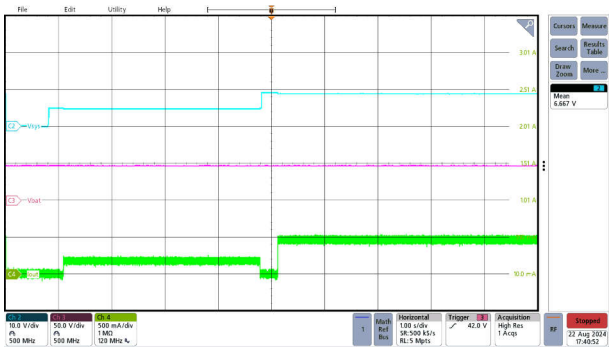


Figure 3-3. $9V_{sys}$ to 12S Battery Voltage 50.4V Charge Mode

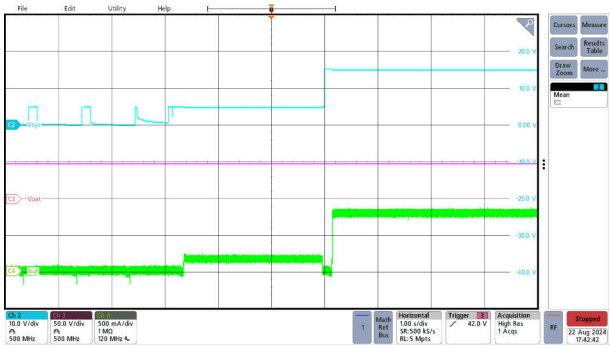


Figure 3-4. 15V_{sys} to 12S Battery Voltage 50.4V Charge Mode

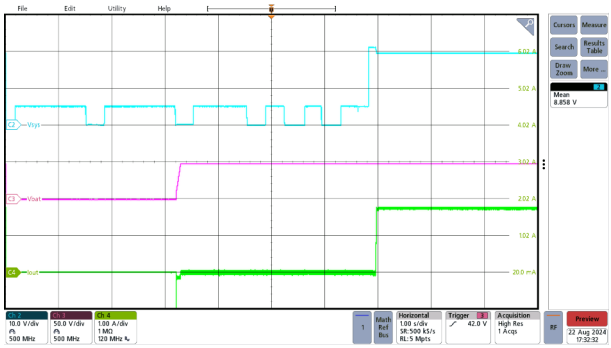


Figure 3-5. 20V_{sys} to 12S Battery Voltage 50.4V Charge Mode

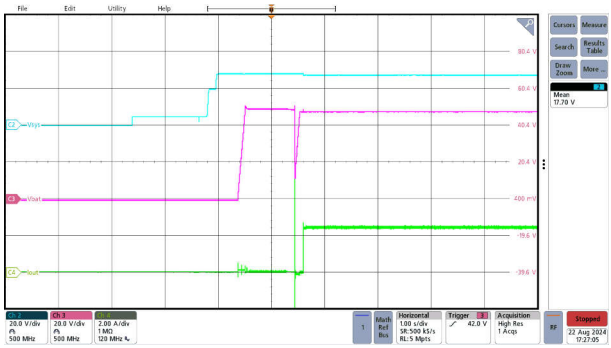


Figure 3-6. 28V_{sys} to 12S Battery Voltage 50.4V Charge Mode

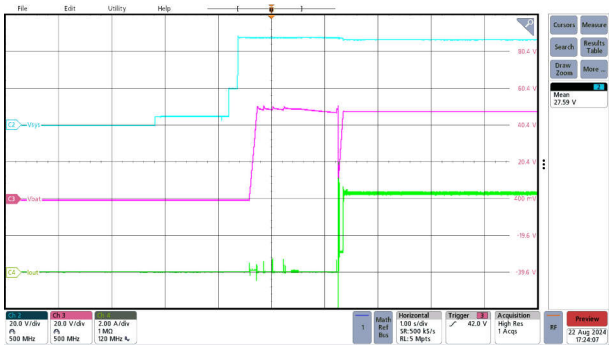


Figure 3-7. 48V_{sys} to 12S Battery Voltage 50.4V Charge Mode

3.2 OTG Mode Start-Up Waveform

Figure 3-8 through Figure 3-14 show the OTG mode start-up waveforms at different input source voltages.

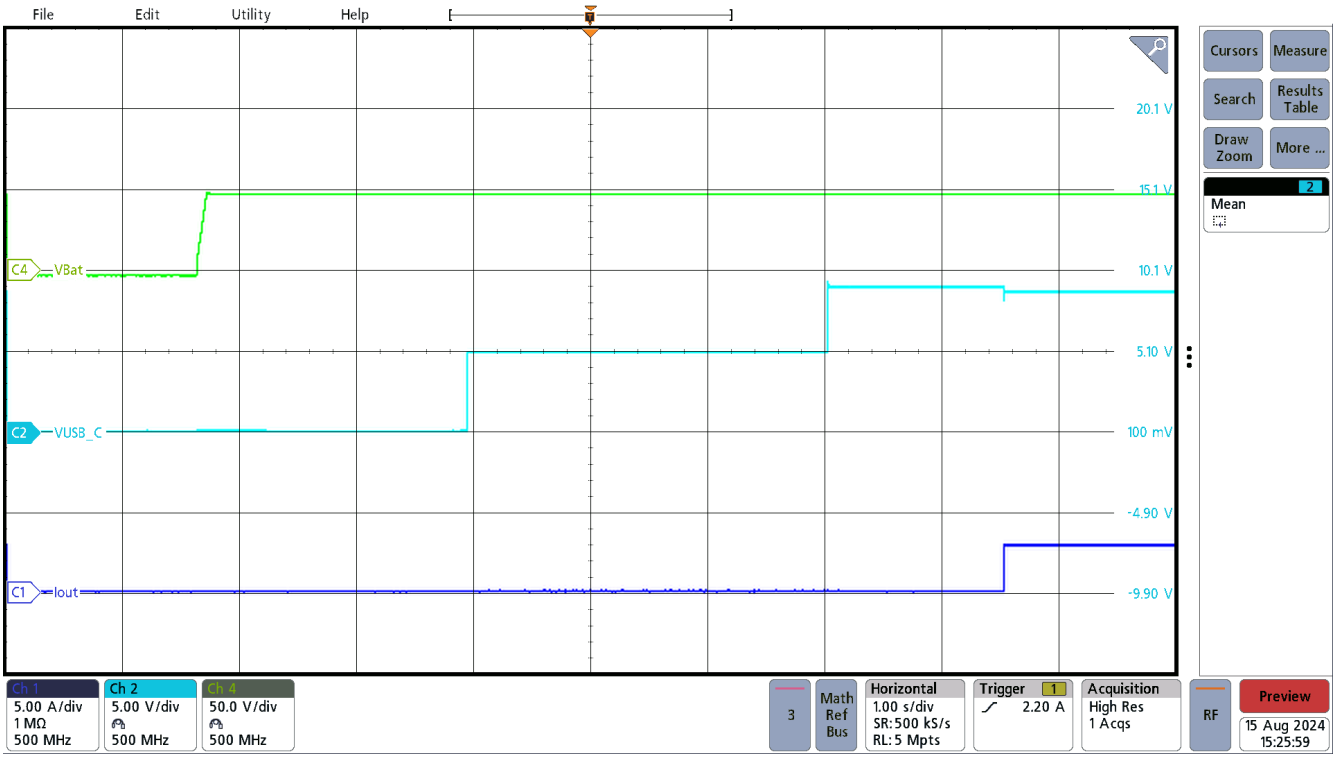


Figure 3-8. OTG Mode, 50.4Vbat, 5V/3A Output, Start-Up Waveform

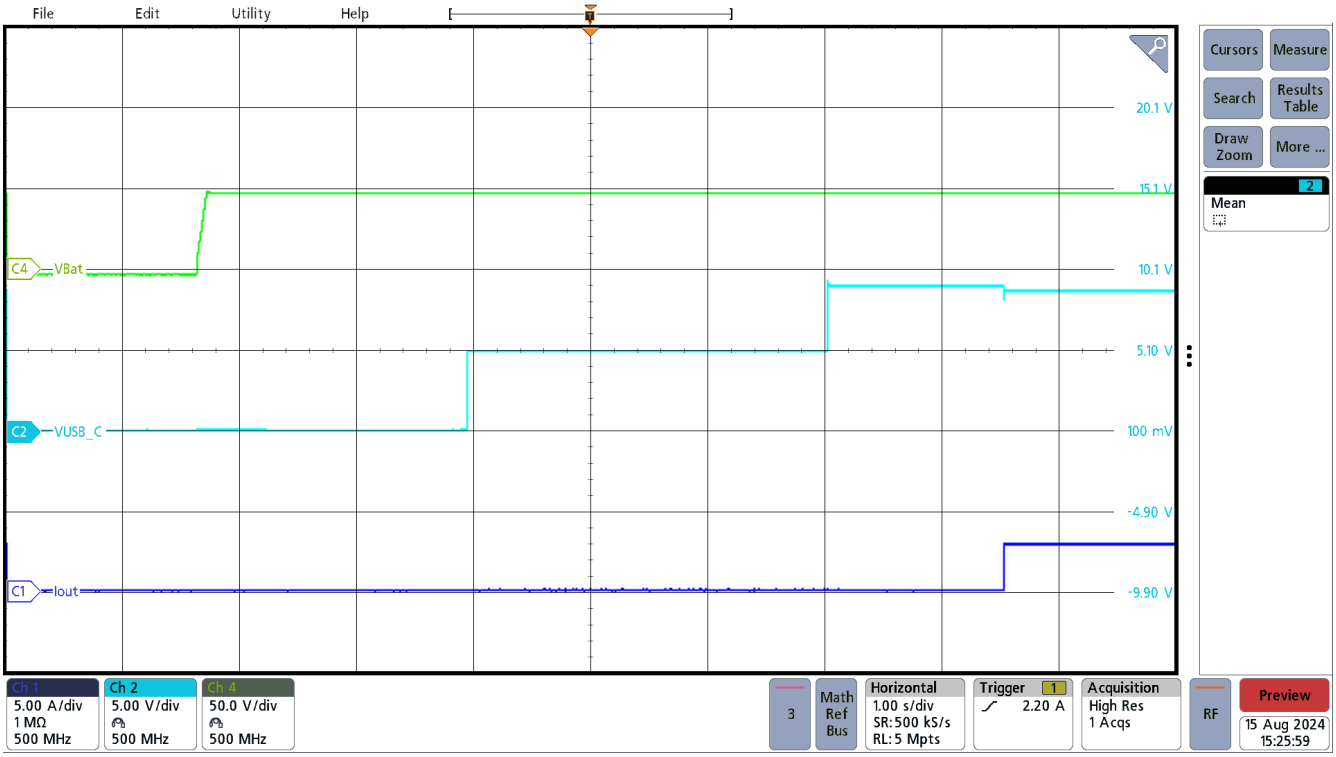


Figure 3-9. OTG Mode, 50.4Vbat, 9V/3A Output, Start-Up Waveform

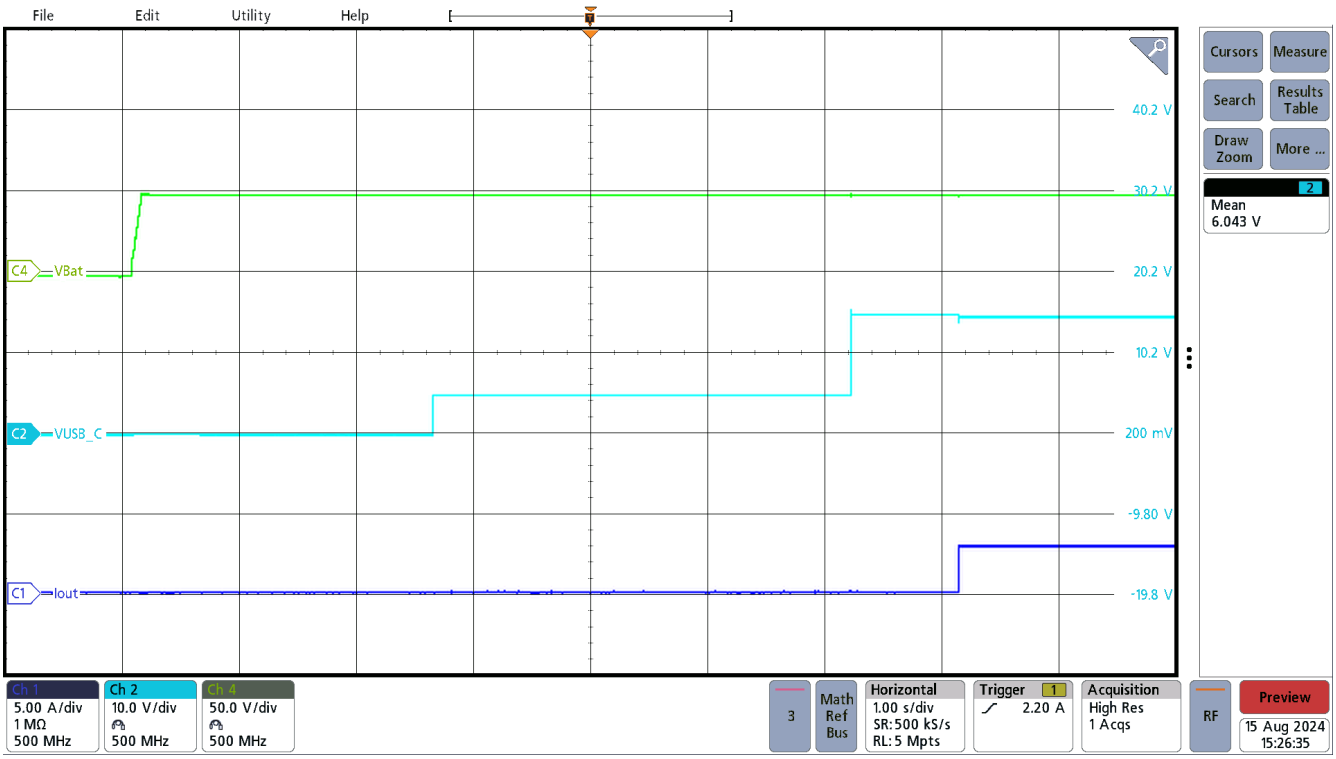


Figure 3-10. OTG Mode, 50.4Vbat, 15V/3A Output, Start-Up Waveform

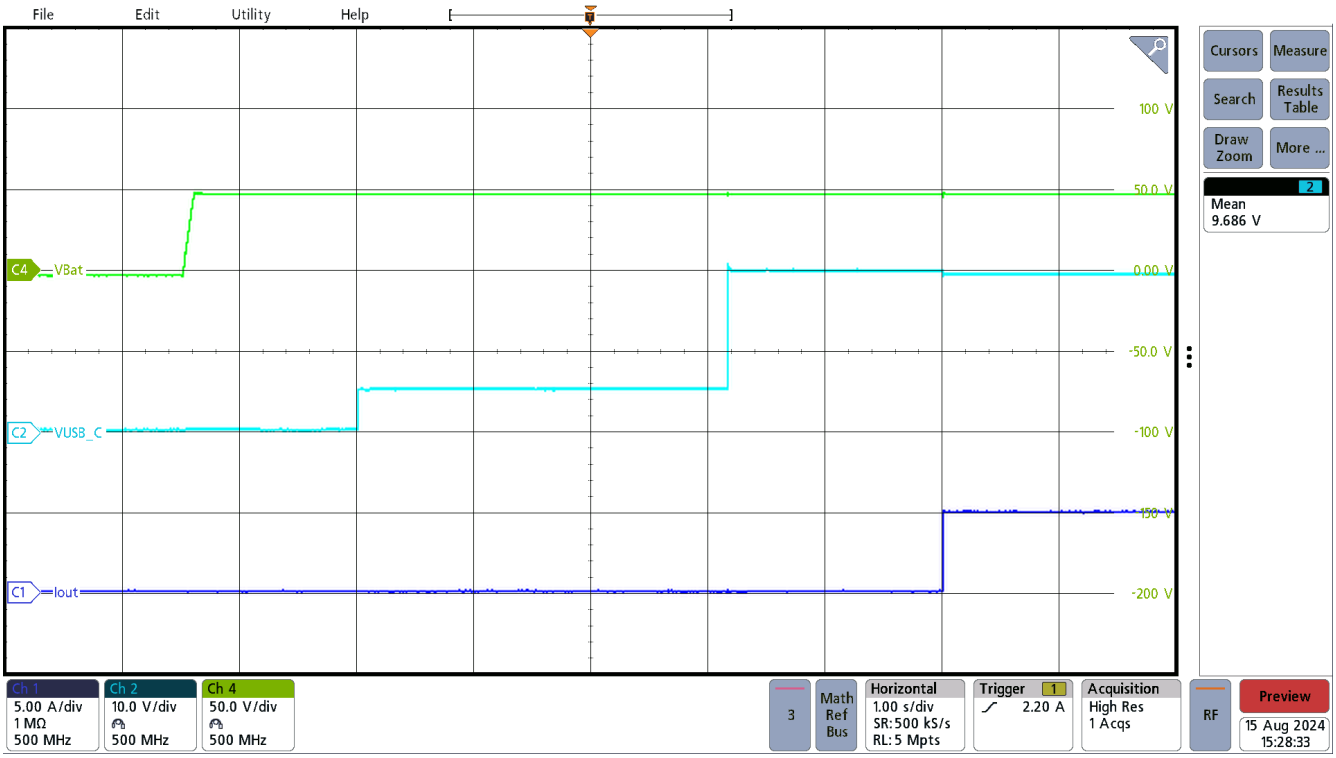


Figure 3-11. OTG Mode, 50.4Vbat, 20V/5A Output, Start-Up Waveform

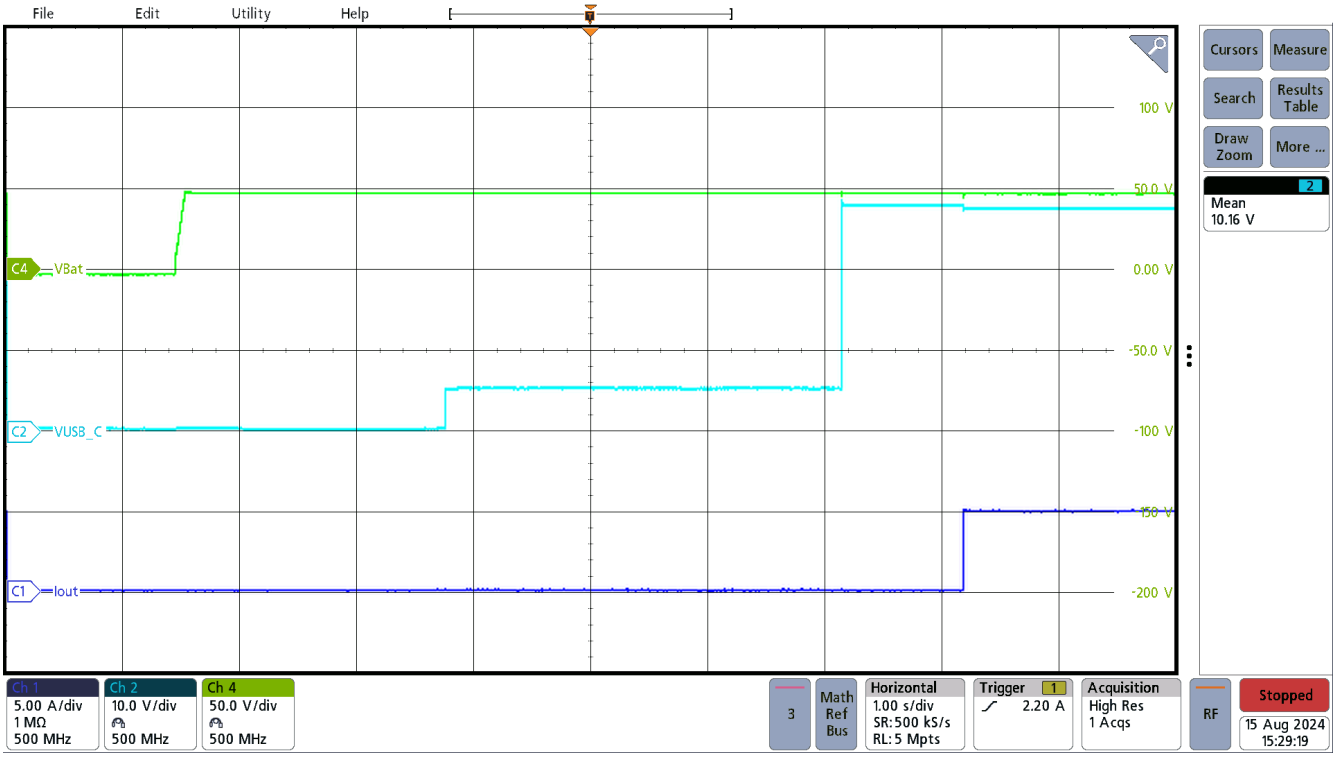


Figure 3-12. OTG Mode, 50.4Vbat, 28V/5A Output, Start-Up Waveform

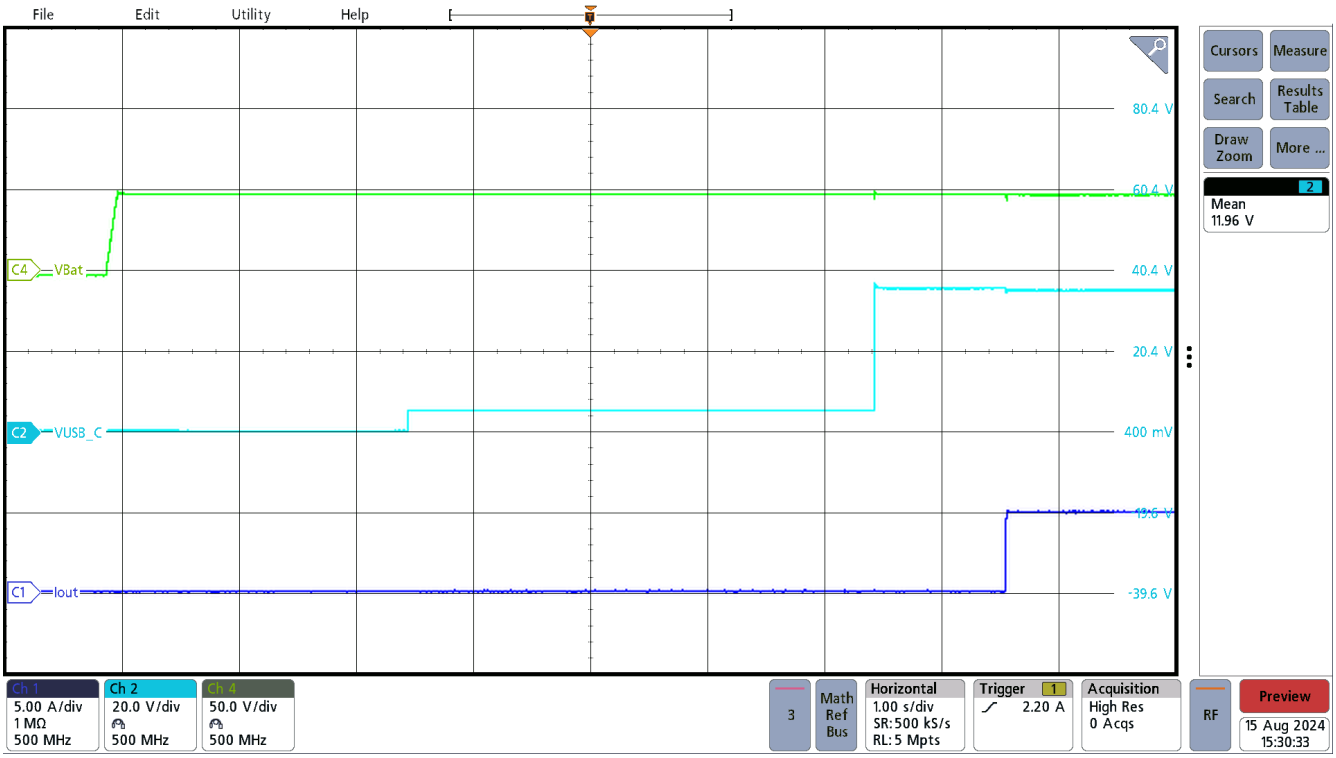


Figure 3-13. OTG Mode, 50.4Vbat, 36V/5A Output, Start-Up Waveform

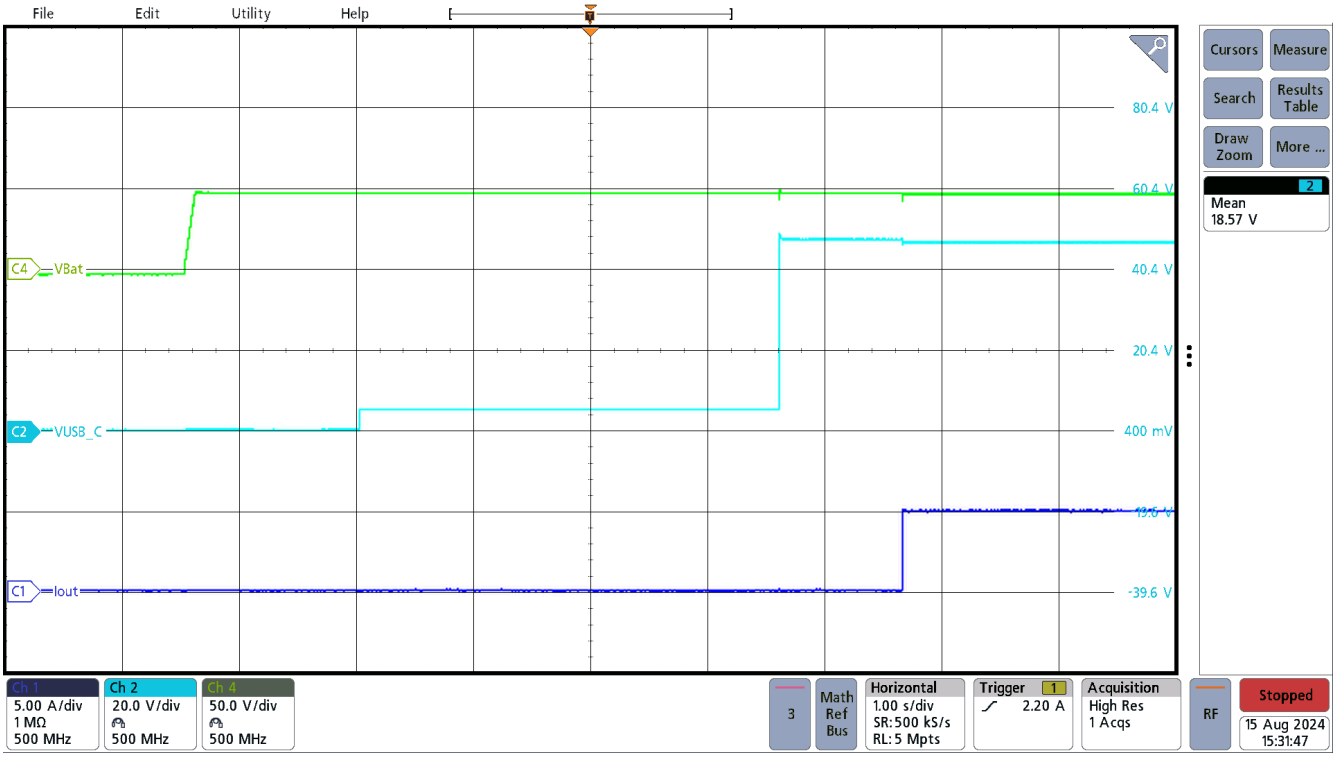


Figure 3-14. OTG Mode, 50.4Vbat, 48V/5A Output, Start-Up Waveform

3.3 Voltage Transition at OTG Mode

Figure 3-15 through Figure 3-18 shows a voltage full cycle transition from 5V to 48V at OTG mode at full load and open load condition.

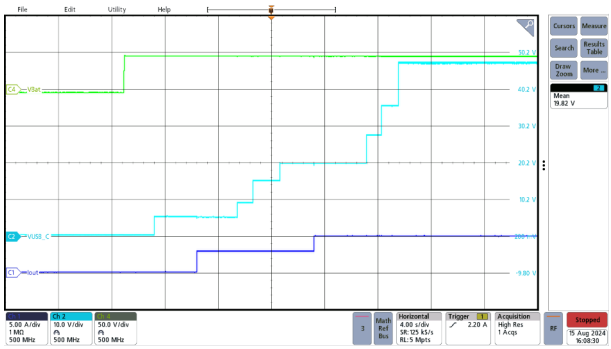


Figure 3-15. OTG Mode at 50.4Vbat, 5V to 48V Voltage Transition at Full Load

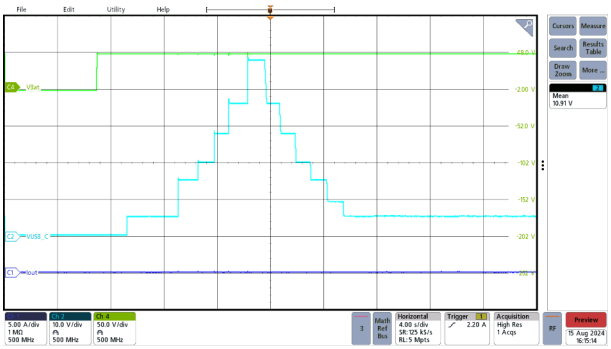


Figure 3-16. OTG Mode at 50.4Vbat, 5V to 48V Voltage Transition at Open Load

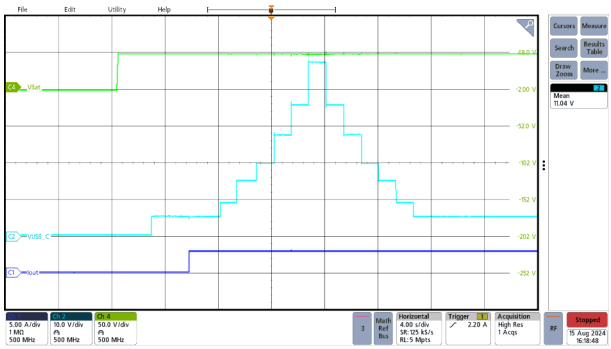


Figure 3-17. OTG Mode at 50.4Vbat, 5V to 48V Voltage Transition at 3A Load

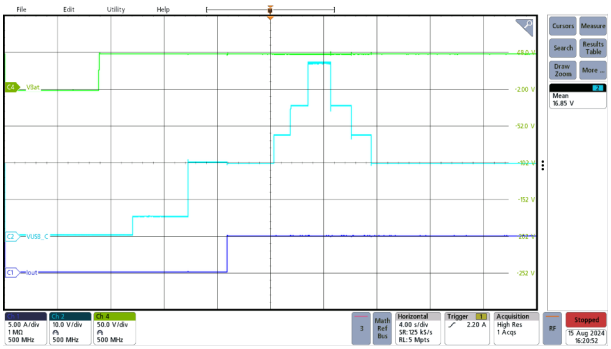


Figure 3-18. OTG Mode at 50.4Vbat, 20V to 48V Voltage Transition at 5A Load

3.4 Ripple and Noise at OTG Mode

Figure 3-19 through Figure 3-46 show the ripple and noise at full load, 50%, 25%, and open load at 5V, 9V, 15V, and 20V conditions.

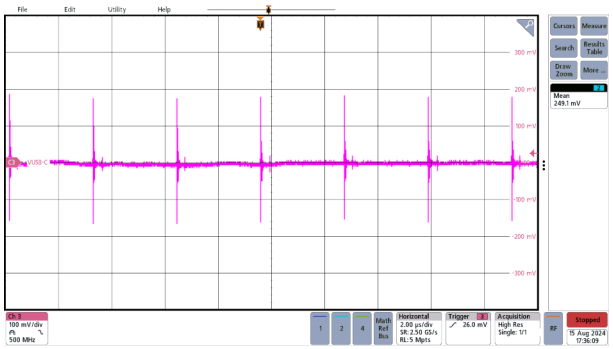


Figure 3-19. OTG Mode, 5V, 100% Load Ripple

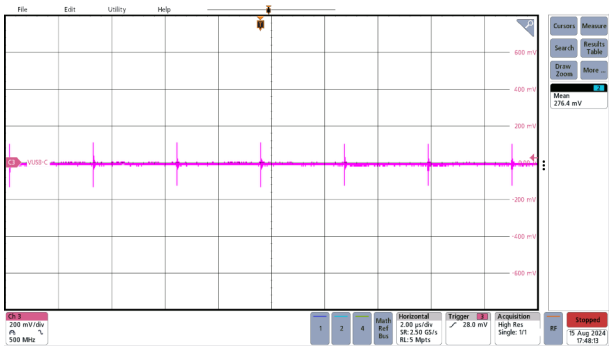


Figure 3-20. OTG Mode, 5V, 50% Load Ripple

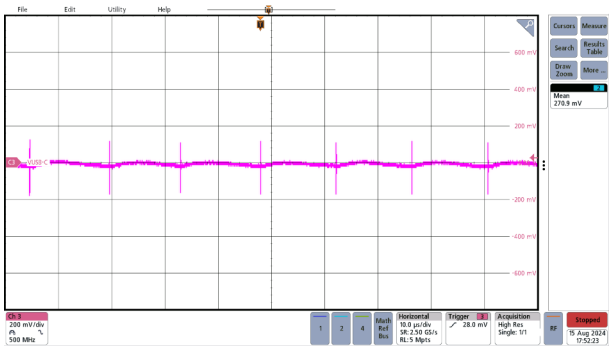


Figure 3-21. OTG Mode, 5V, 25% Load Ripple

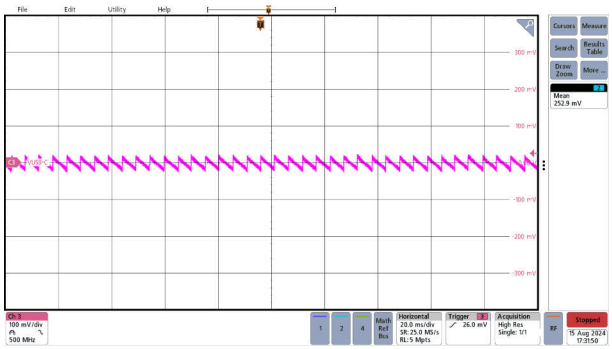


Figure 3-22. OTG Mode, 5V, Open Load Ripple

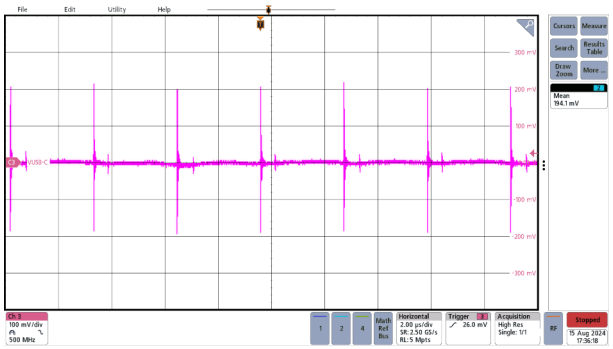


Figure 3-23. OTG Mode, 9V, 100% Load Ripple

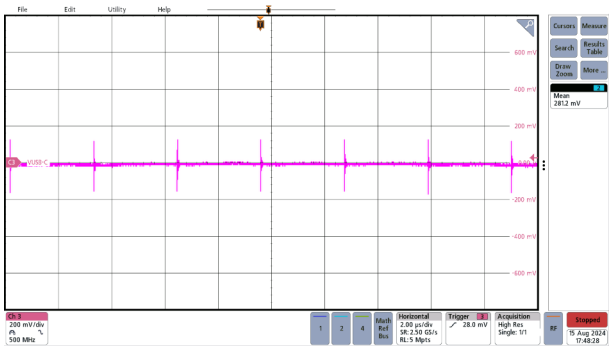


Figure 3-24. OTG Mode, 9V, 50% Load Ripple

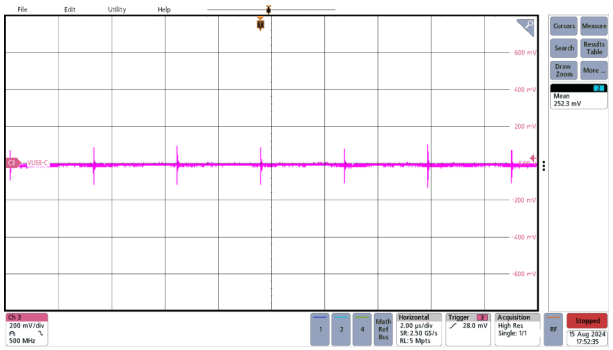


Figure 3-25. OTG Mode, 9V, 25% Load Ripple

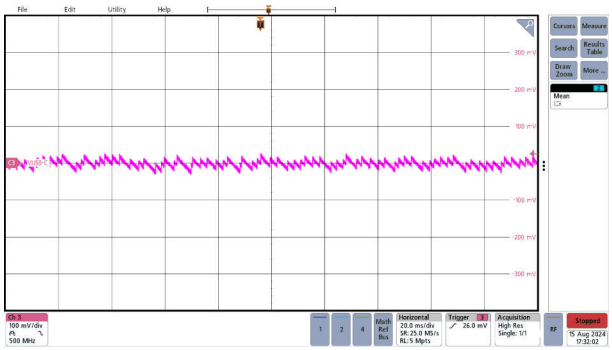


Figure 3-26. OTG Mode, 9V, Open Load Ripple

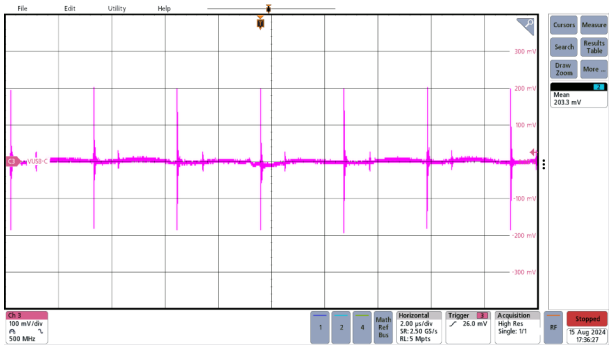


Figure 3-27. OTG Mode, 15V, 100% Load Ripple

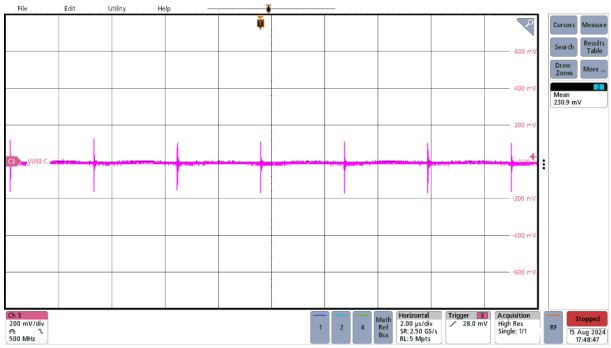


Figure 3-28. OTG Mode, 15V, 50% Load Ripple

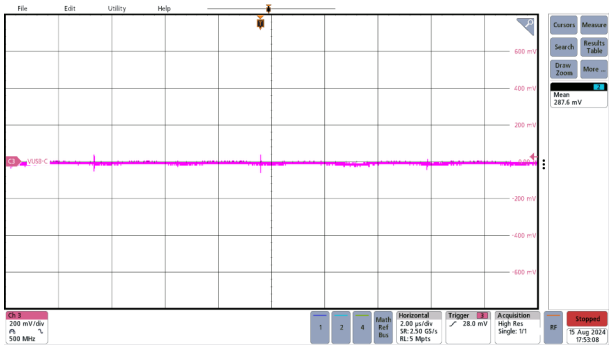


Figure 3-29. OTG Mode, 15V, 25% Load Ripple

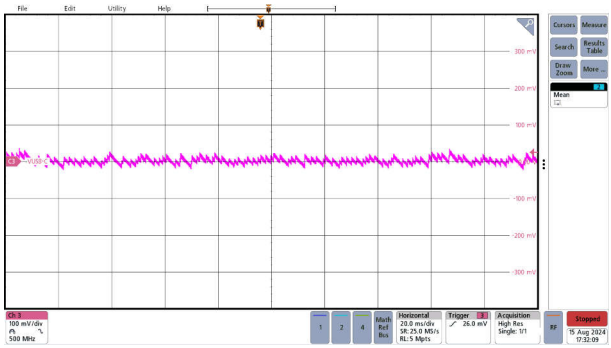


Figure 3-30. OTG Mode, 15V, Open Load Ripple

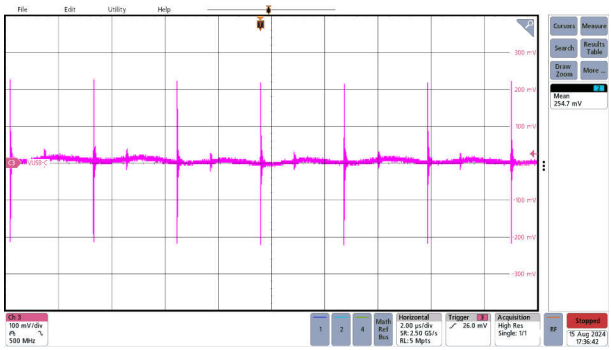


Figure 3-31. OTG Mode, 20V, 100% Load Ripple

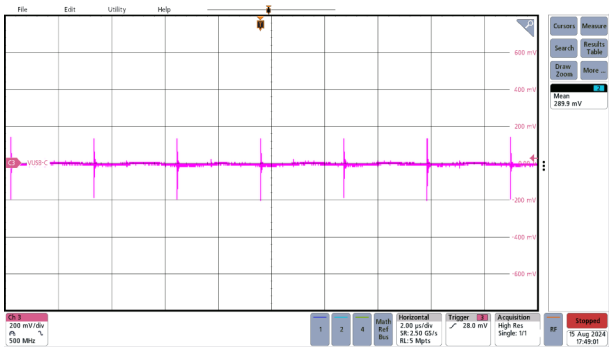


Figure 3-32. OTG Mode, 20V, 50% Load Ripple

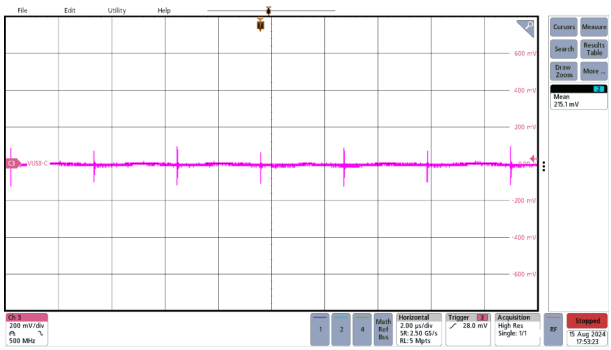


Figure 3-33. OTG Mode, 20V, 25% Load Ripple

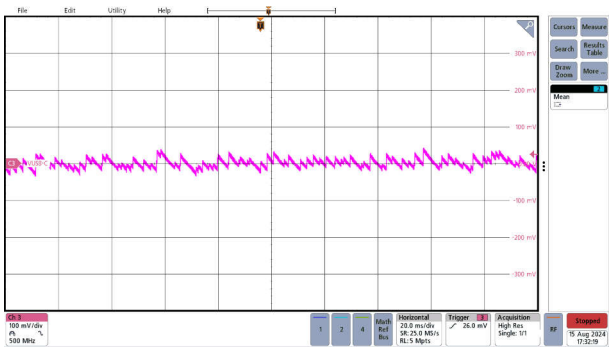


Figure 3-34. OTG Mode, 20V, Open Load Ripple

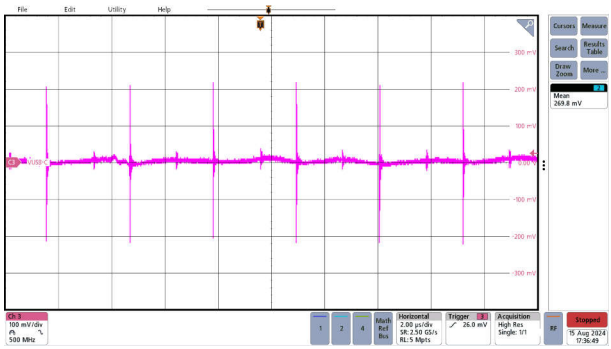


Figure 3-35. OTG Mode, 28V, 100% Load Ripple

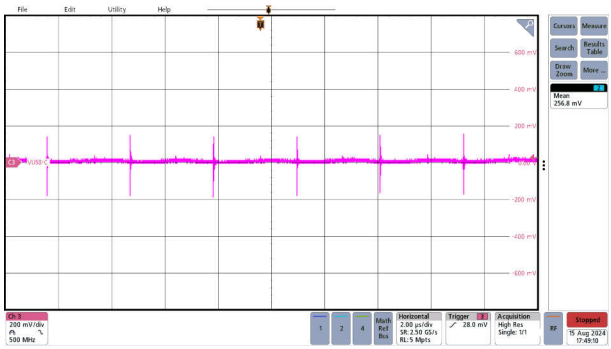


Figure 3-36. OTG Mode, 28V, 50% Load Ripple

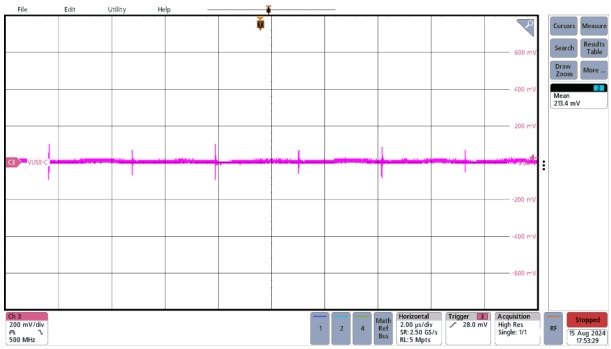


Figure 3-37. OTG Mode, 28V, 25% Load Ripple

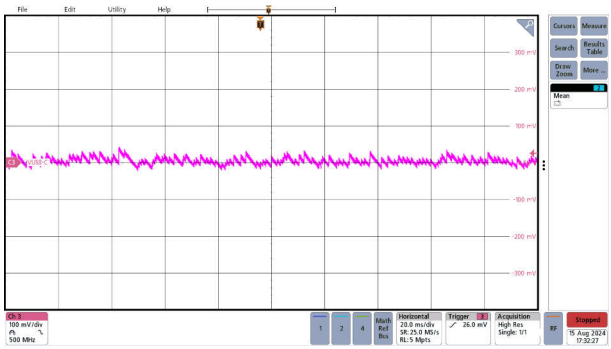


Figure 3-38. OTG Mode, 28V, Open Load Ripple

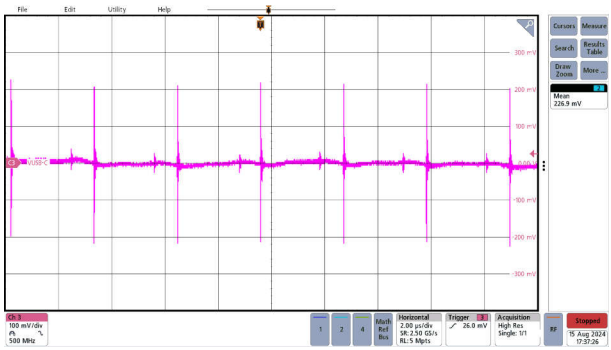


Figure 3-39. OTG Mode, 36V, 100% Load Ripple

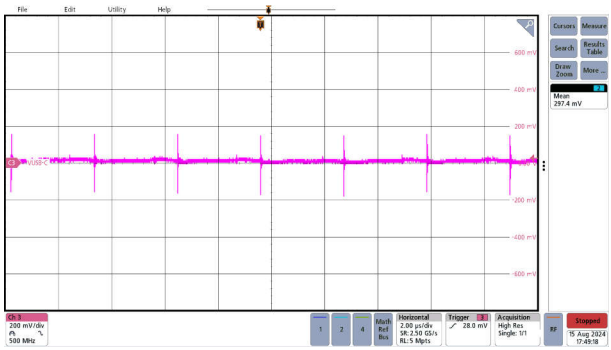


Figure 3-40. OTG Mode, 36V, 50% Load Ripple

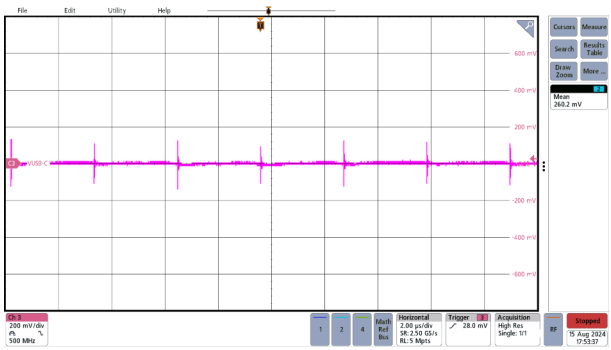


Figure 3-41. OTG Mode, 36V, 25% Load Ripple

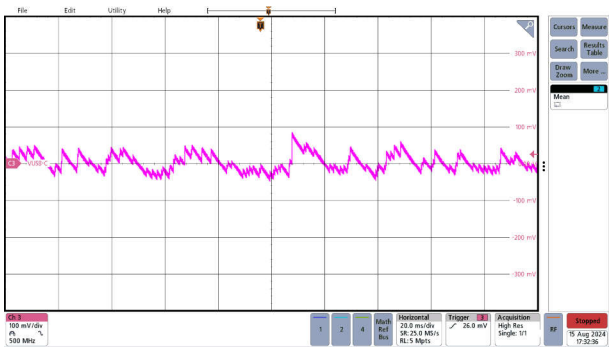


Figure 3-42. OTG Mode, 36V, Open Load Ripple

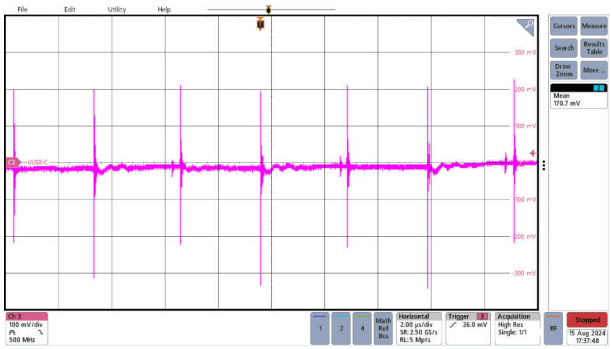


Figure 3-43. OTG Mode, 48V, 100% Load Ripple

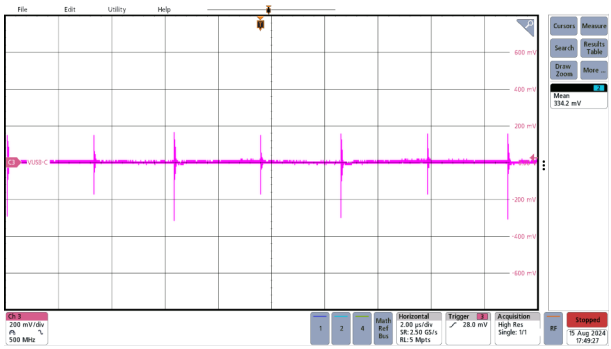


Figure 3-44. OTG Mode, 48V, 50% Load Ripple

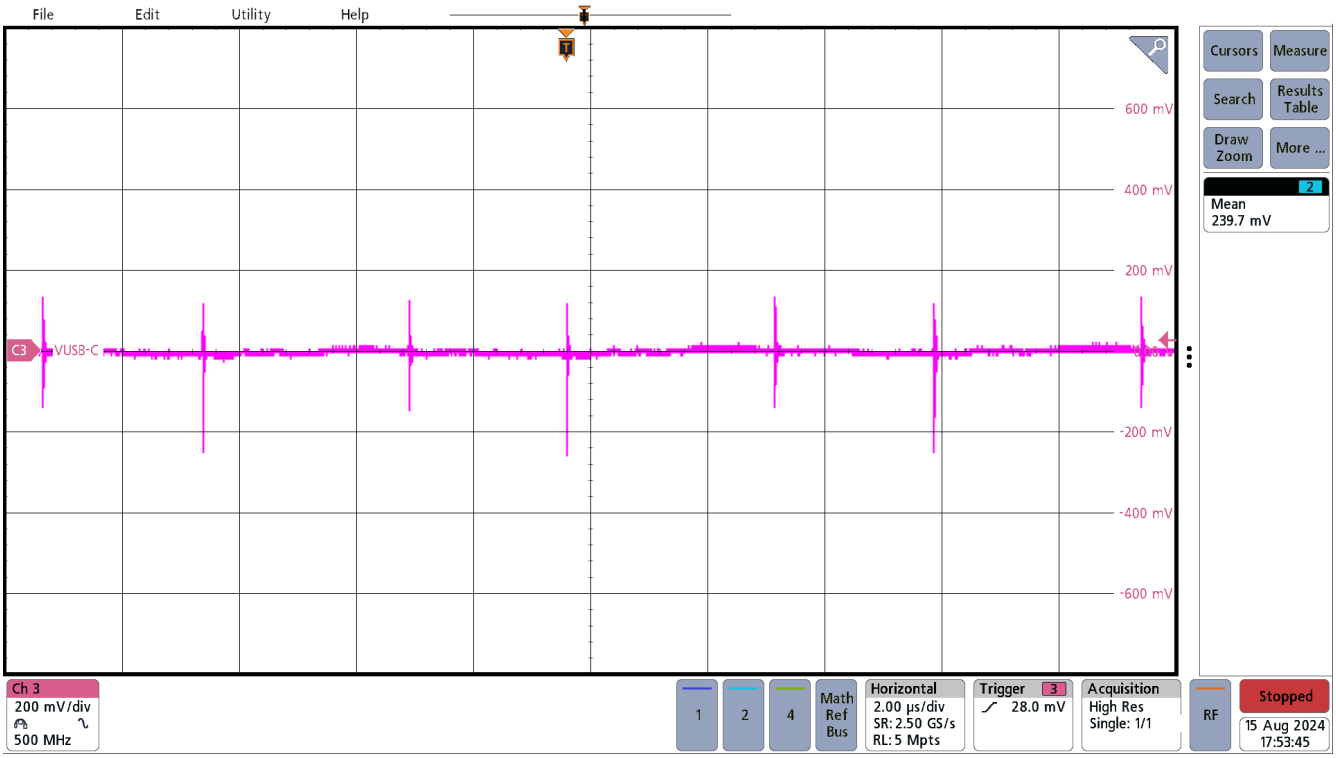


Figure 3-45. OTG Mode, 48V, 25% Load Ripple

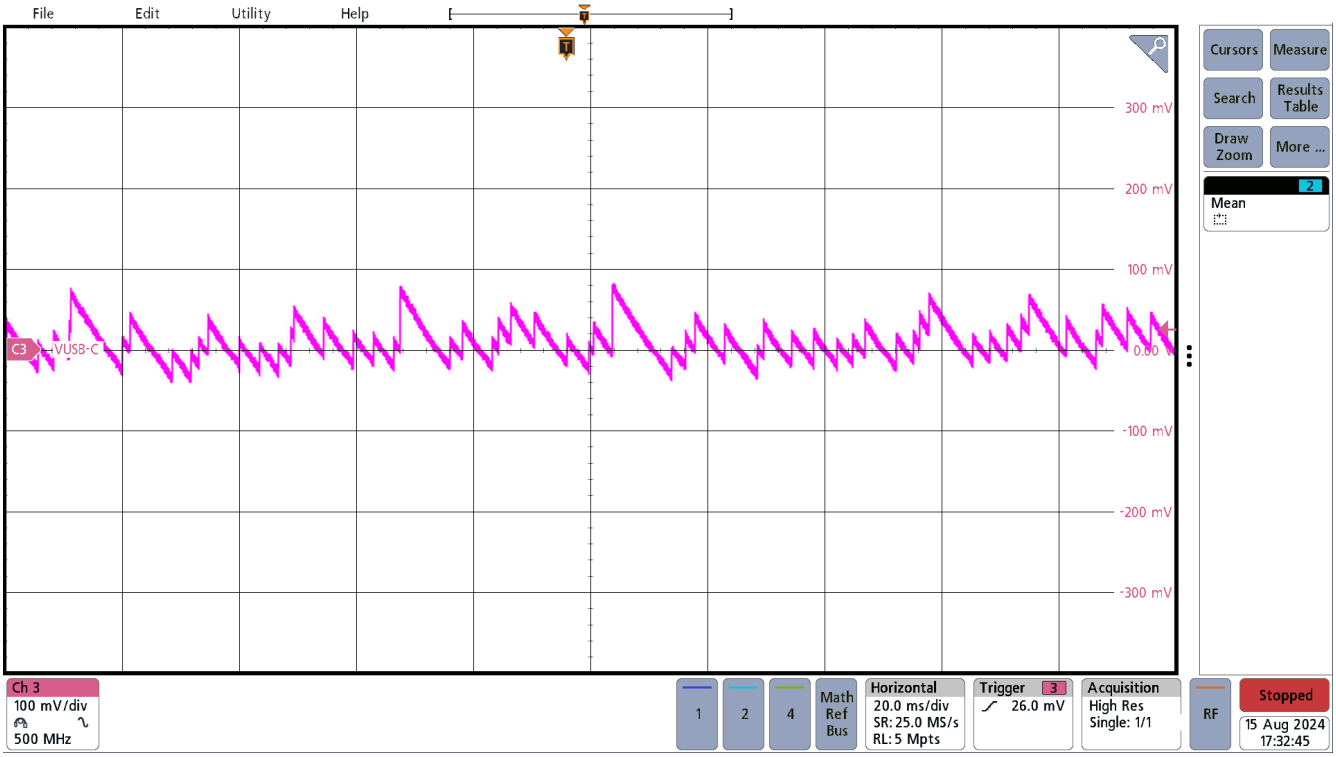


Figure 3-46. OTG Mode, 48V, Open Load Ripple

3.5 Load Transients at OTG Mode

The load dynamic test was performed from 10% to full load for 5V, 9V, 15V, 20V, 28V, 36V, 48V individually. The slew rate is set to 0.5Aμs. Output voltage was measured at the PCB end of the USB Type-C receptacle.

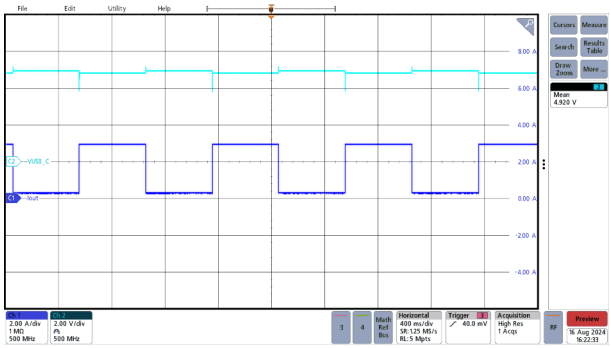


Figure 3-47. OTG Mode, 5V, 10% to 100% Load Dynamic

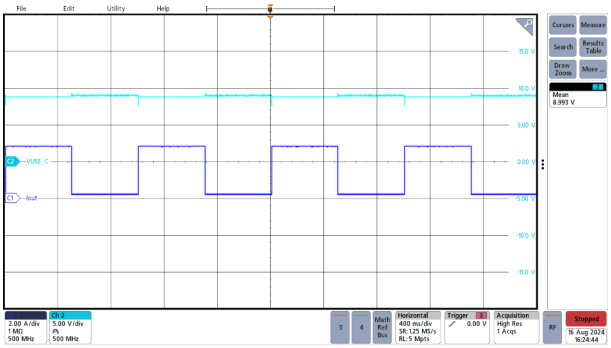


Figure 3-48. OTG Mode, 9V, 10% to 100% Load Dynamic

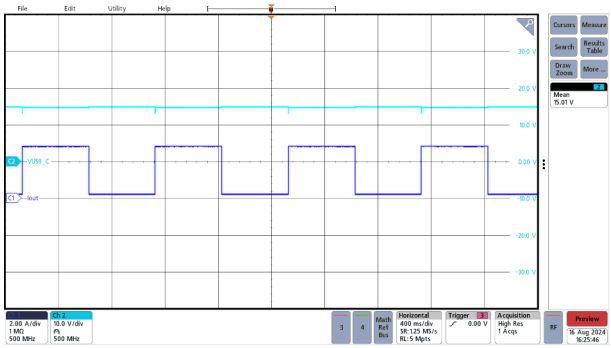


Figure 3-49. OTG Mode, 15V, 10% to 100% Load Dynamic

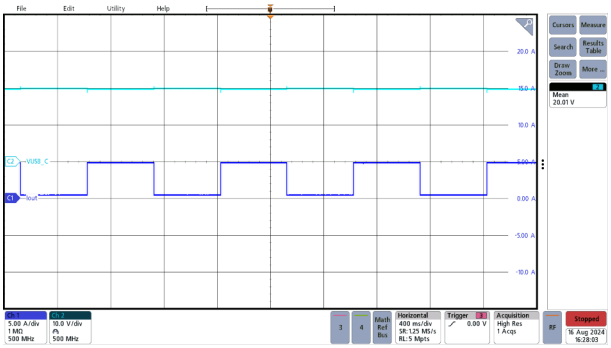


Figure 3-50. OTG Mode, 20V, 10% to 100% Load Dynamic

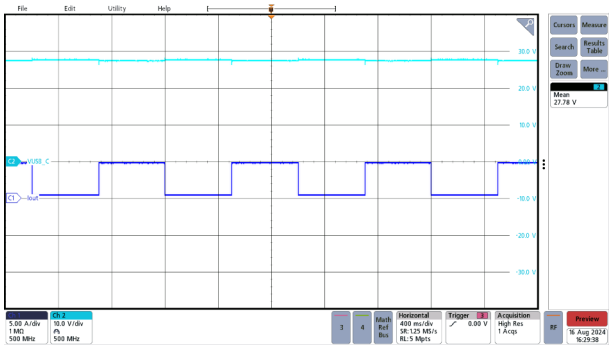


Figure 3-51. OTG Mode, 28V, 10% to 100% Load Dynamic

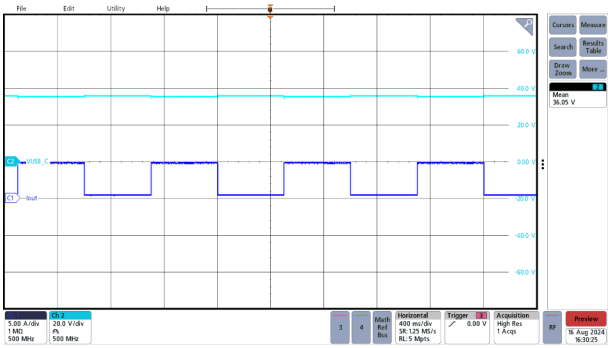


Figure 3-52. OTG Mode, 36V, 10% to 100% Load Dynamic

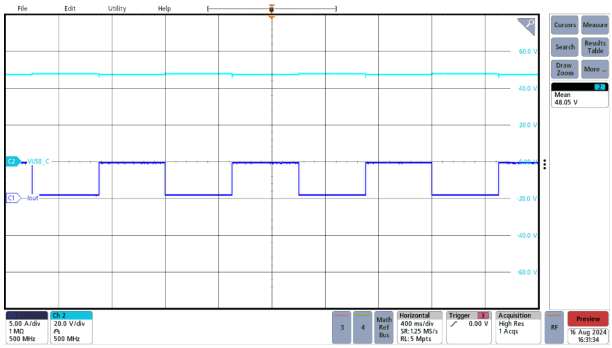


Figure 3-53. OTG Mode, 48V, 10% to 100% Load Dynamic

3.6 Switching Waveform

Figure 3-54 through Figure 3-56 show the power stage waveform at different working modes in BQ25756. The switching frequency is set to 300kHz.

- CH1: Buck leg high-side Vds
- CH2: Buck leg low-side Vds
- CH3: Boost leg High-side Vds
- CH4: Boost leg low-side Vds

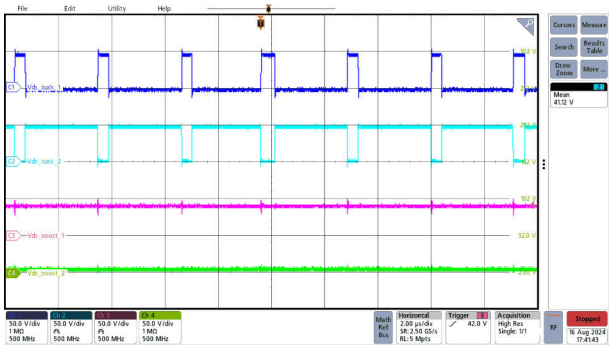


Figure 3-54. Buck Mode

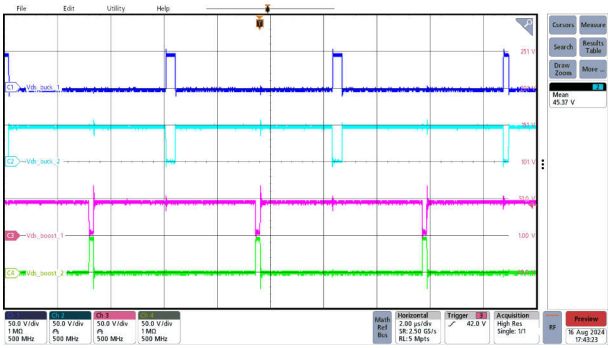


Figure 3-55. Buck-Boost Mode

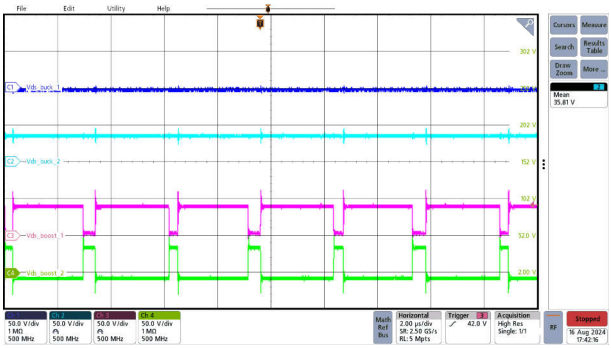


Figure 3-56. Boost Mode

3.7 Overcurrent Protection at OTG Mode

Overcurrent protection was performed at USB Cable end and gradually increase current of E-load at 5V, 9V, 15V, 20V, 28V, 36V, 48V output voltage individually. See Figure 3-57 through Figure 3-63, at OTG mode. BQ25756 regulates the output with Constant voltage and constant current profile, once output current triggers the current limit, the output voltage goes to auto restart.

CH2: Vout, CH4: output current

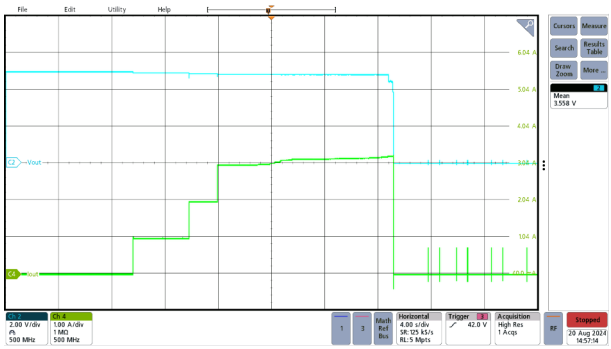


Figure 3-57. OTG mode, 50.4V battery, 5V OCP = 3.3A

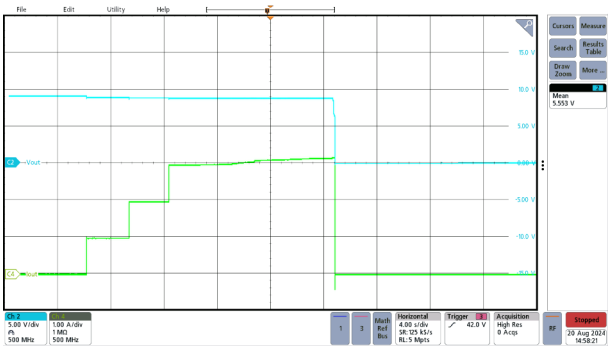


Figure 3-58. OTG Mode, 50.4V Battery, 9V OCP = 3.3A

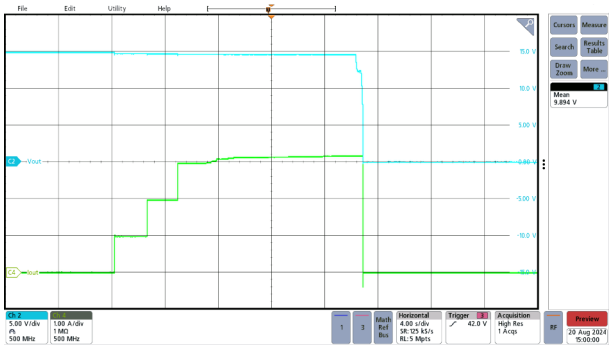


Figure 3-59. OTG Mode, 50.4V Battery, 15V OCP = 3.3A

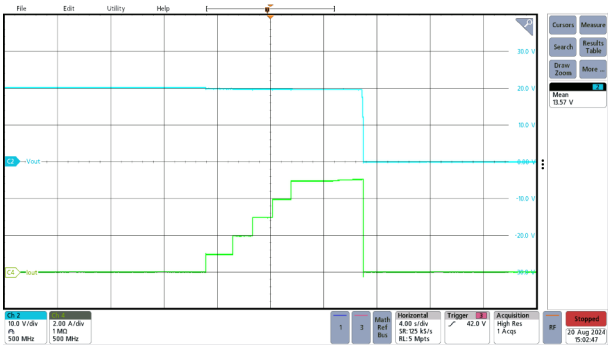


Figure 3-60. OTG Mode, 50.4V Battery, 20V OCP = 5.1A

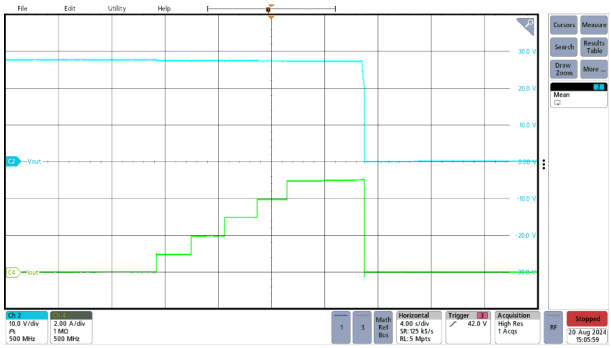


Figure 3-61. OTG Mode, 50.4V Battery, 28V OCP = 5.1A

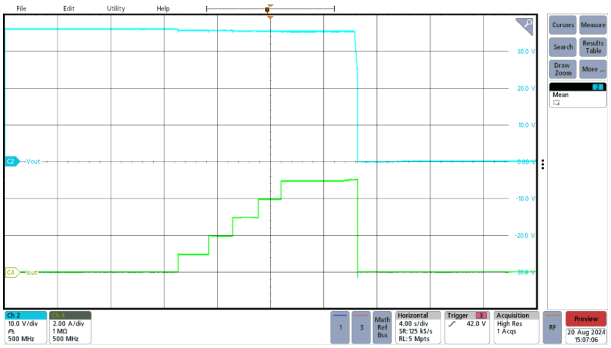


Figure 3-62. OTG Mode, 50.4V Battery, 36V OCP = 5.1A

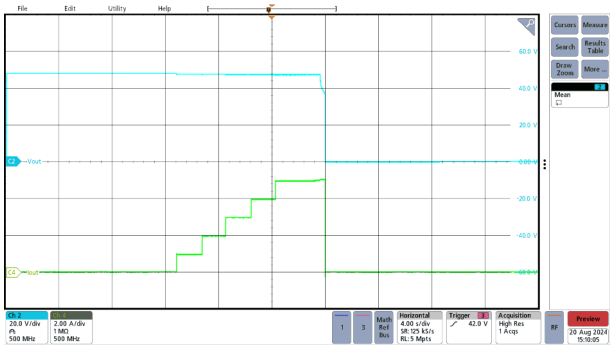


Figure 3-63. OTG Mode, 50.4V Battery, 48V OCP = 5.05A

3.8 Short-Circuit Protection

Short-circuit testing was performed at the USB Type-C cable end. Figure 3-64 through Figure 3-70 show the short-circuit test at 5V, 9V, 15V, 20V, 28V, 36V, 48V individually.

CH2: Vout, CH4: Output current

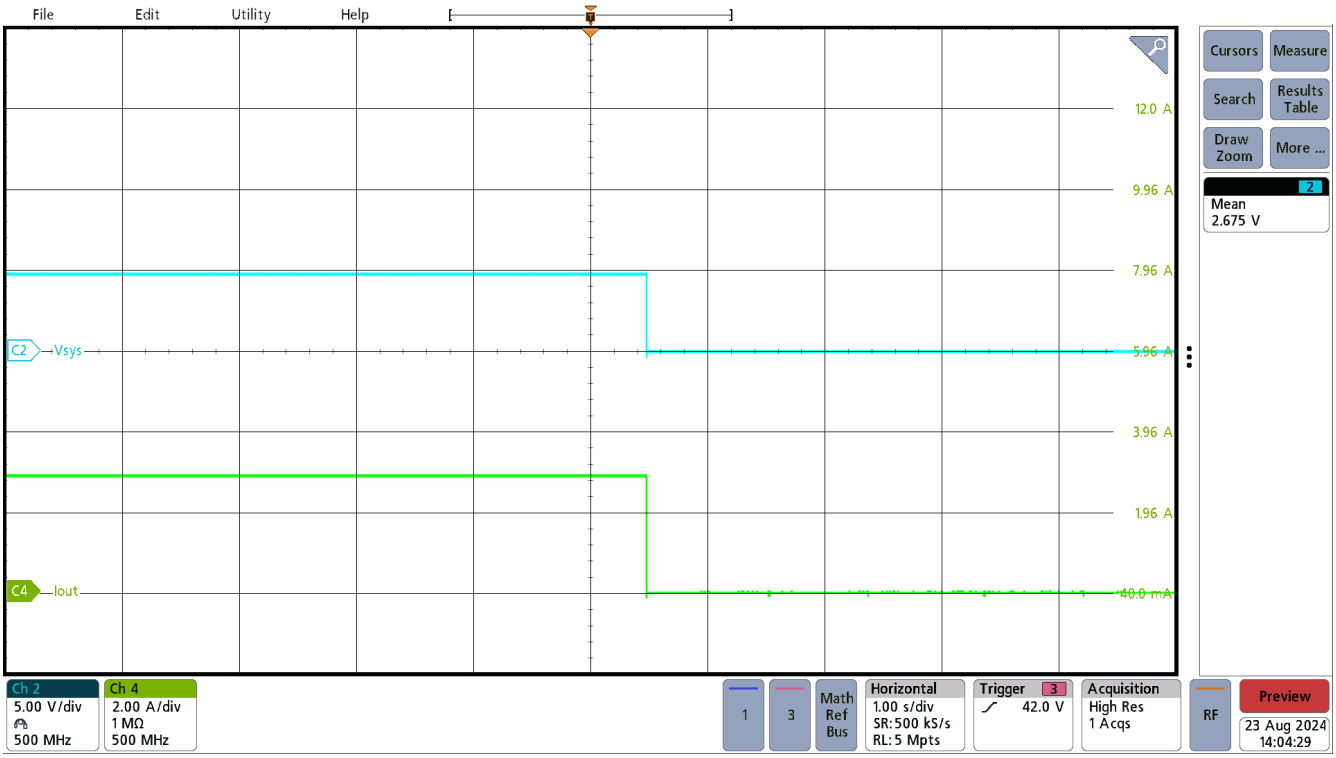


Figure 3-64. Short-Circuit Test at 5V Output

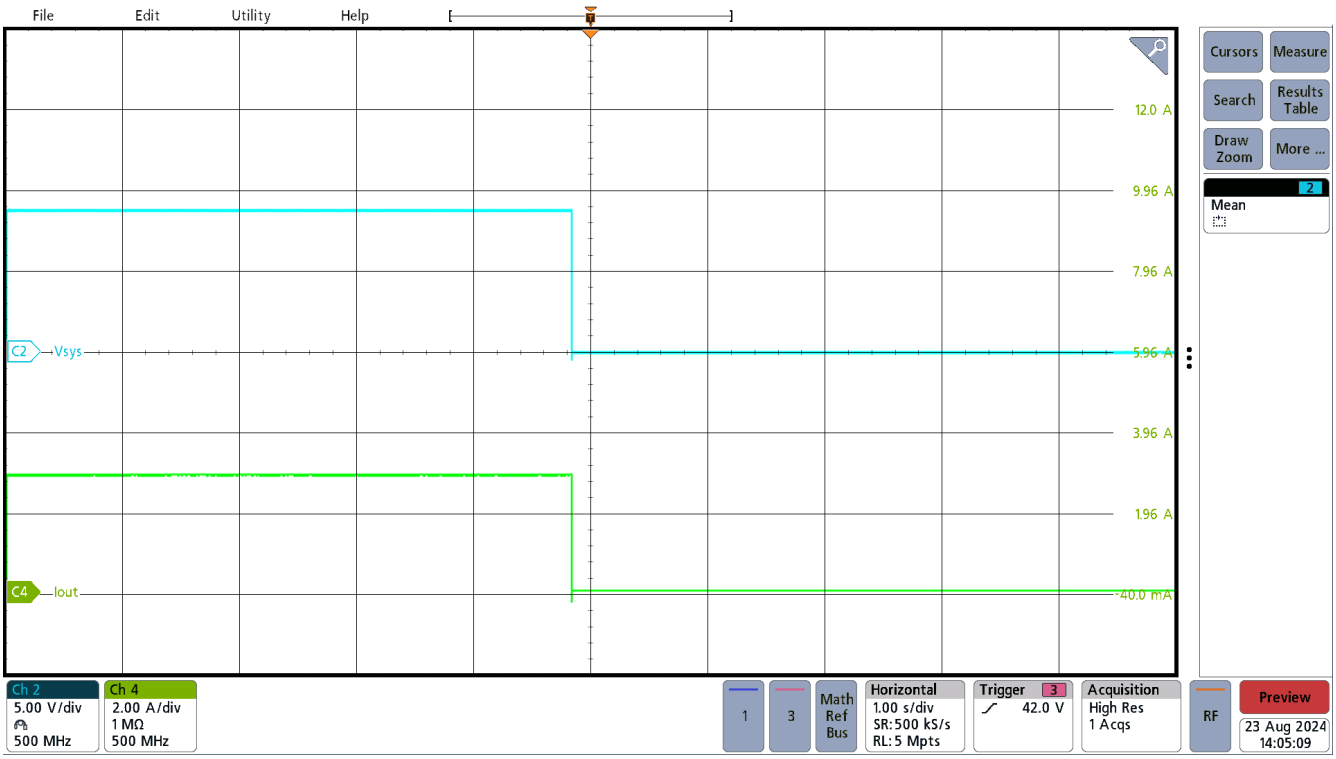


Figure 3-65. Short-Circuit Test at 9V Output

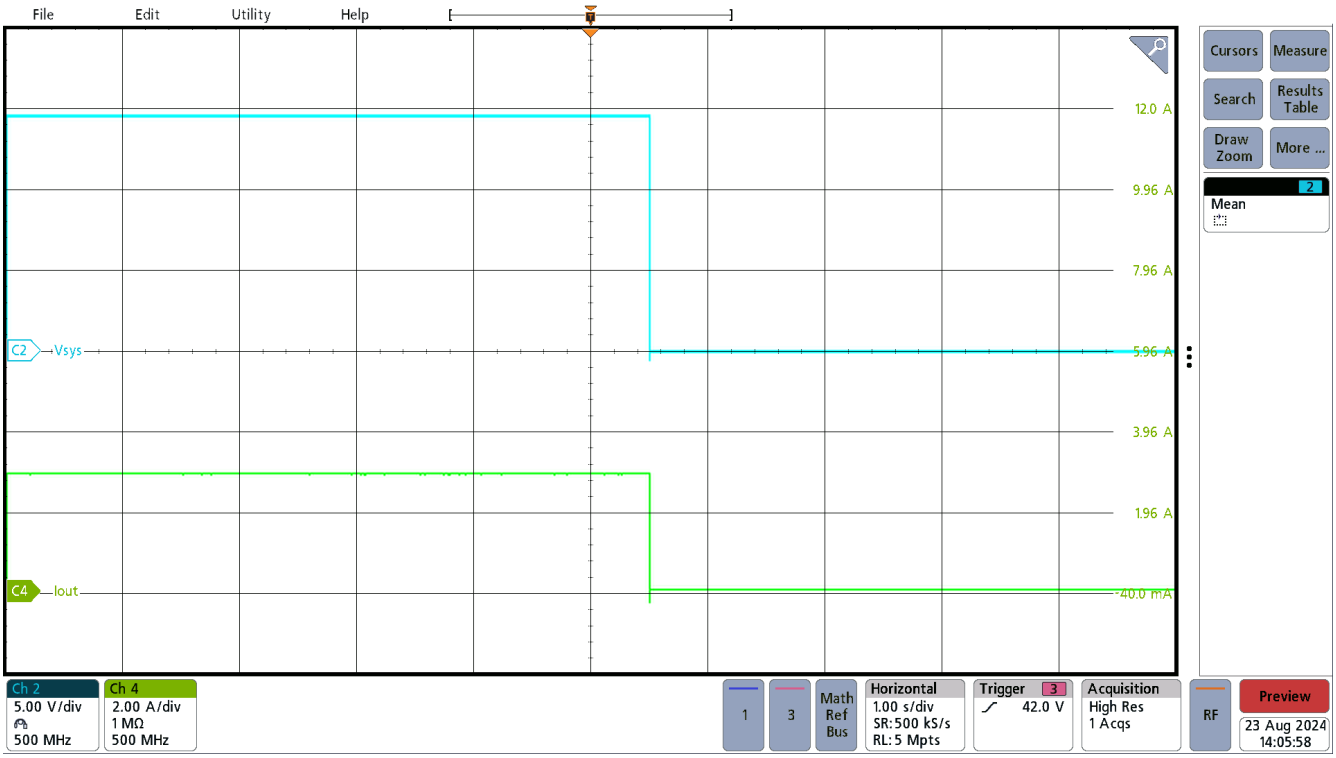


Figure 3-66. Short-Circuit Test at 15V Output

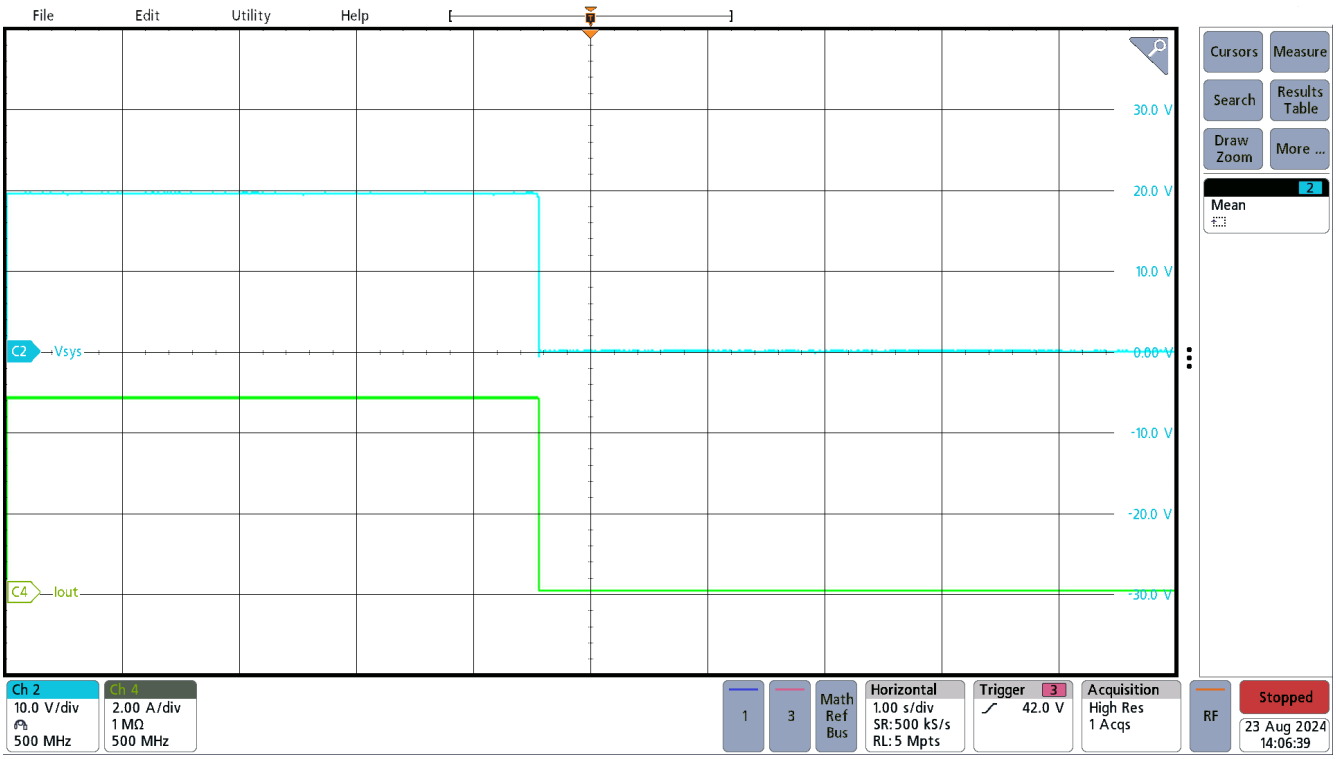


Figure 3-67. Short-Circuit Test at 20V Output

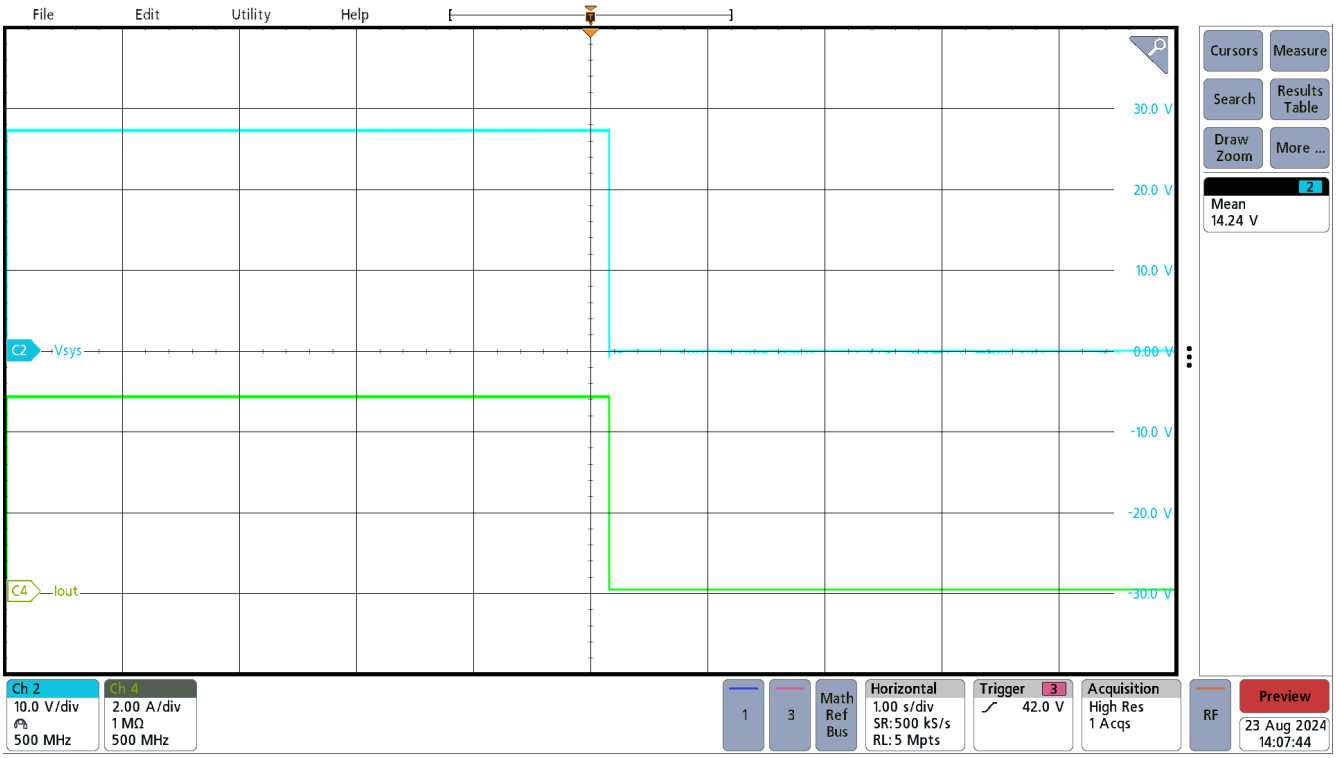


Figure 3-68. Short-Circuit Test at 28V Output

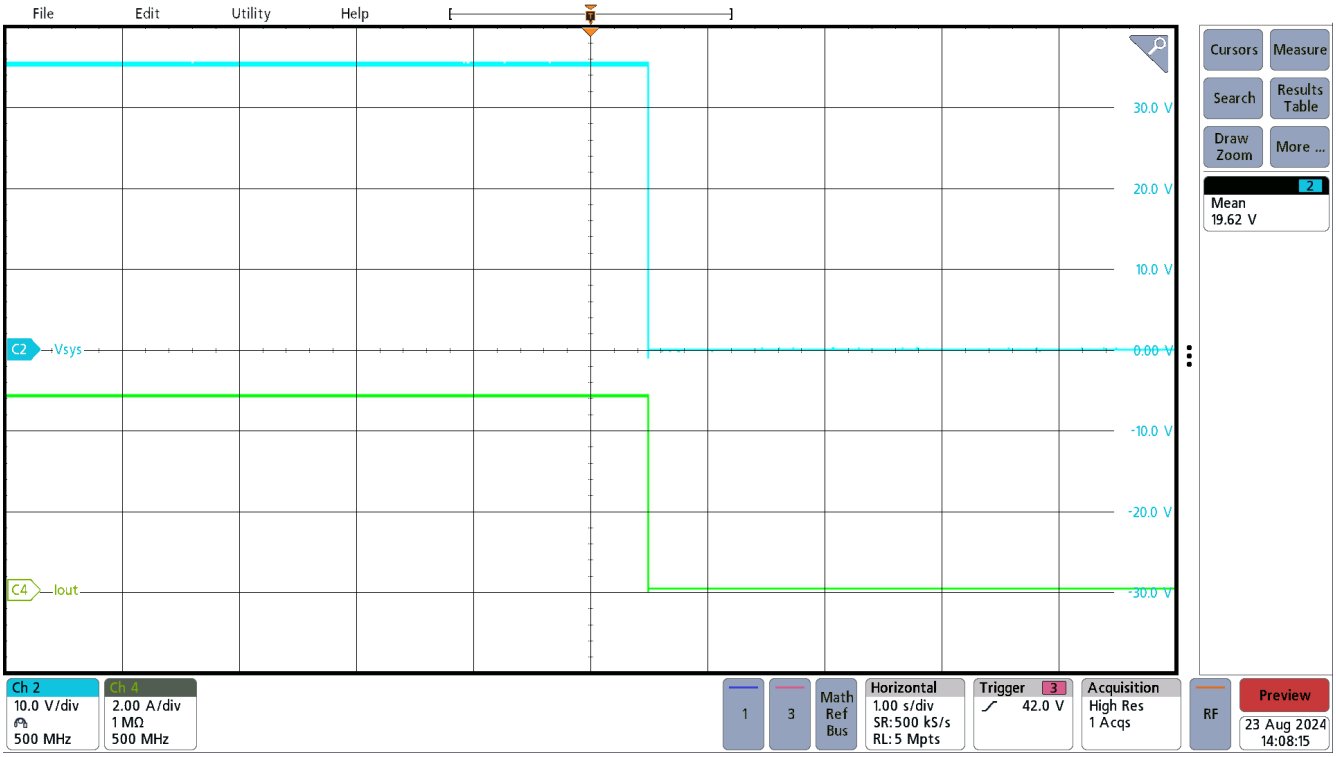


Figure 3-69. Short-Circuit Test at 36V Output

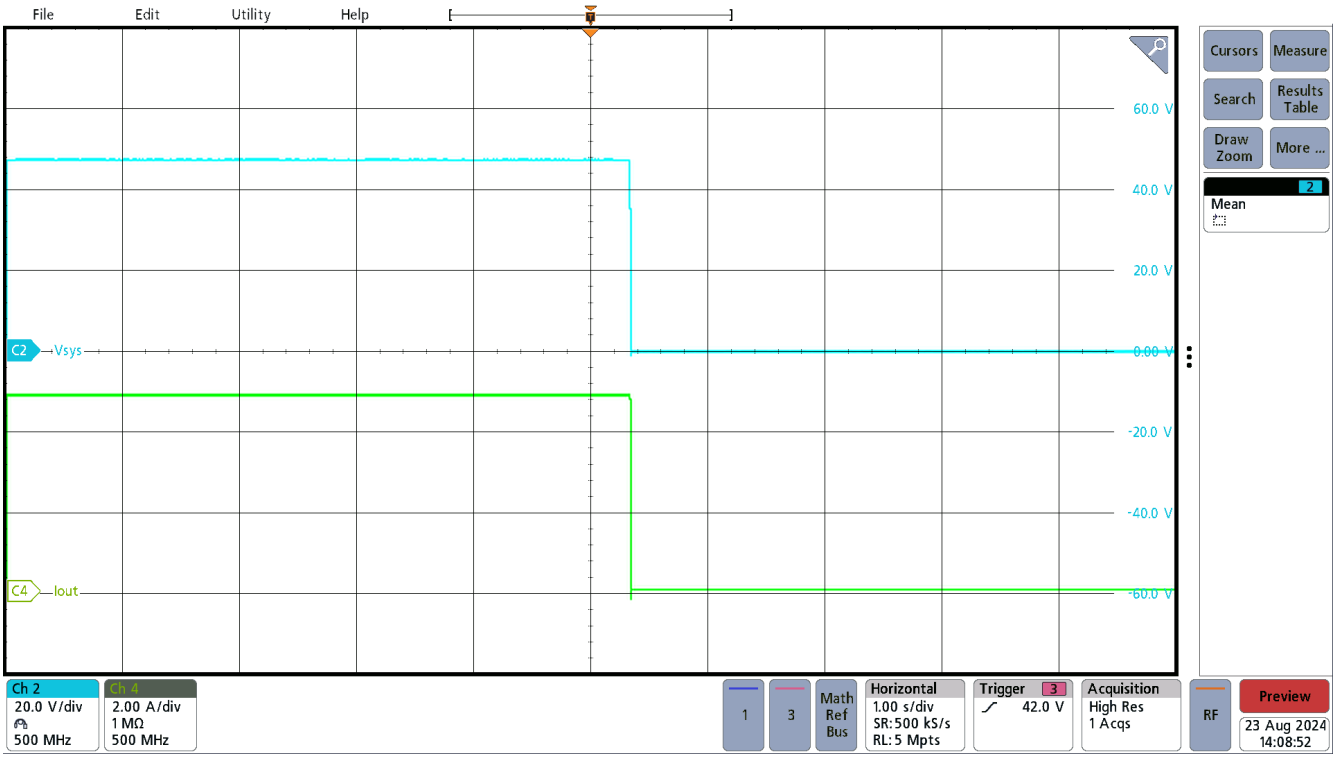


Figure 3-70. Short-Circuit Test at 48V Output

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