Stress tests for Raspberry Pi 4 and 3B+

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This is a test abstract.

Contents

1 Introduction

The aim of this notebook is to stress the Raspberry Pi 4 for deciding between different cases and cooling types.

Sources:

- https://github.com/nschloe/stressberry
- https://www.pragmaticlinux.com/2020/06/check-the-raspberry-pi-cpu-temperature/

2 Implementation of helper functions

2.1 Load globally used libraries and set plot parameters

```
[1]: import subprocess
     import os
     import threading
     import time

     import smbus2
     import bme280

     import pandas as pd
     import numpy as np
     import prettytable as pt

     import matplotlib.pyplot as plt
     import matplotlib.dates as mdates
     %matplotlib inline

     # FutureWarning: Using an implicitly registered datetime converter for a matplotlib
      ↪plotting method.
     # The converter was registered by pandas on import.
     # Future versions of pandas will require you to explicitly register matplotlib
      ↪converters.
     from pandas.plotting import register_matplotlib_converters
     register_matplotlib_converters()

     from IPython.display import set_matplotlib_formats
     set_matplotlib_formats('pdf', 'png')

     plt.rcParams['savefig.dpi'] = 80
     plt.rcParams['savefig.bbox'] = "tight"

     plt.rcParams['figure.autolayout'] = False
     plt.rcParams['figure.figsize'] = 10, 6
     plt.rcParams['axes.labelsize'] = 18
     plt.rcParams['axes.titlesize'] = 20
     plt.rcParams['font.size'] = 16
     plt.rcParams['lines.linewidth'] = 2.0
     plt.rcParams['lines.markersize'] = 8
     plt.rcParams['legend.fontsize'] = 14

     # Need to install dependent package first via 'apt install cm-super'
     plt.rcParams['text.usetex'] = True
     plt.rcParams['font.family'] = "serif"
     plt.rcParams['font.serif'] = "cm"
```

/home/bk/jupyter-env/lib/python3.7/site-packages/ipykernel_launcher.py:24:
DeprecationWarning: `set_matplotlib_formats` is deprecated since IPython 7.23,
directly use `matplotlib_inline.backend_inline.set_matplotlib_formats()`

2.2 Variant 1: Function for reading the CPU core temperature

This implementation retrieves the temperature information from the system file
/sys/class/thermal/thermal_zone0/temp.

```
[2]:   # Function for reading the CPU core temperature
       # Found here: https://www.pragmaticlinux.com/2020/06/
       ↪check-the-raspberry-pi-cpu-temperature/
       def get_cpu_temp_old():
           """
           Obtains the current value of the CPU temperature.
           :returns: Current value of the CPU temperature if successful, zero value␣
       ↪otherwise.
           :rtype: float
           """
           # Initialize the result.
           result = 0.0
           # The first line in this file holds the CPU temperature as an integer times␣
       ↪1000.
           # Read the first line and remove the newline character at the end of the string.
           if os.path.isfile('/sys/class/thermal/thermal_zone0/temp'):
               with open('/sys/class/thermal/thermal_zone0/temp') as f:
                   line = f.readline().strip()
               # Test if the string is an integer as expected.
               if line.isdigit():
                   # Convert the string with the CPU temperature to a float in degrees␣
       ↪Celsius.
                   result = float(line) / 1000
           # Give the result back to the caller.
           return result
```

2.3 Variant 2: Function for reading the CPU core temperature (used here)

This implementation retrieves the temperature information from the command line tool `vcgencmd`. In the bash console you can get the same result by issuing:

```
$ vcgencmd measure_temp
```

```
[5]:   # Function for reading the CPU core temperature
       # Found here: https://github.com/nschloe/stressberry/blob/main/stressberry/main.py
       def get_cpu_temp(filename=None):
           """Returns the core temperature in Celsius."""
           if filename is not None:
               with open(filename) as f:
                   temp = float(f.read()) / 1000
           else:
               # Using vcgencmd is specific to the raspberry pi
               out = subprocess.check_output(["vcgencmd", "measure_temp"]).decode("utf-8")
               temp = float(out.replace("temp=", "").replace("'C", ""))

           return temp
```

2.4 Function for reading the CPU core frequency

The frequency information is retrieved from the command line tool `vcgencmd` also. In the bash console you can get the same result by issuing:

```
$ vcgencmd measure_clock arm
```

Issue regarding the **Raspberry Pi 3B+** (2021-06-01):
With the latest Raspbian updates there seems to be a bug in reading the CPU frequency with the otherwise propagated command line call `vcgencmd measure_clock arm`. With this call only frequencies

around 600 MHz are displayed even under full load of the CPU. The direct query of the `/sys` device tree provides the correct results for the first core:

```
$ cat /sys/devices/system/cpu/cpu0/cpufreq/scaling_cur_freq
```

Therefore, the function has been extended to first query which Raspberry Pi hardware is present. If it is a **RPi 3B+**, the current CPU frequency is queried directly from the device tree instead of via the `vcgencmd` tools.

```python
[6]: # Function for reading the CPU core frequency
     def get_cpu_freq(filename=None):
         if os.path.isfile('/sys/firmware/devicetree/base/model'):
             with open('/sys/firmware/devicetree/base/model') as f:
                 hw_version = f.readline().strip()

         # RPi 3B+: there seems to be a bug in reading CPU frequency with 'vcgencmd'
         if (hw_version.startswith('Raspberry Pi 3 Model B Plus')):
             if os.path.isfile('/sys/devices/system/cpu/cpu0/cpufreq/scaling_cur_freq'):
                 with open('/sys/devices/system/cpu/cpu0/cpufreq/scaling_cur_freq') as f:
                     line = f.readline().strip()
                 # Test if the string is an integer as expected.
                 if line.isdigit():
                     # Convert the string with the CPU frequency to a float in MHz.
                     frequency = float(line) / 1000
         # RPi 4B: 'vcgencmd' does work as expected ...
         else:
             """Returns the CPU frequency in MHz"""
             if filename is not None:
                 with open(filename) as f:
                     frequency = float(f.read()) / 1000
             else:
                 # Only vcgencmd measure_clock arm is accurate on Raspberry Pi.
                 # Per: https://www.raspberrypi.org/forums/viewtopic.php?
     ↪f=63&t=219358&start=25
                 out = subprocess.check_output(["vcgencmd", "measure_clock arm"]).
     ↪decode("utf-8")
                 frequency = float(out.split("=")[1]) / 1000000

         return frequency
```

2.5 Function for reading the ambient temperature

In order to compare the recorded CPU core temperatures of the different housing and cooling scenarios, the temperature curves must be normalized with the curves of the simultaneously measured ambient temperature.
However, only the curves of the so-called "overtemperature" are comparable, which is the difference between the curves of the CPU core temperature and the ambient temperature.

The external Bosch sensor *BME280* is used to measure the ambient temperature. This is connected to the Raspberry Pi via a USB-I2C adapter. The installation of the required kernel module is described in the Jupyter notebook BME280.ipynb.

```python
[7]: # i2c bus on /dev/i2c-11
     port = 11
     # i2c address of BME280
     address = 0x76
     bus = smbus2.SMBus(port)

     # Function for reading the ambient temperature
```

```python
# Found here: https://github.com/nschloe/stressberry/blob/main/stressberry/main.py
def get_ambient_temp():
    """Returns the ambient temperature in Celsius."""

    calibration_params = bme280.load_calibration_params(bus, address)

    # the sample method will take a single reading and return
    # a compensated_reading object
    data_obj = bme280.sample(bus, address, calibration_params)

    return data_obj.temperature
```

2.6 Helper functions for stressing all cores of the CPU

Stress is created by the command line tool `stress`. It has to be installed first by issuing:

```
$ sudo apt install stress
```

```python
[8]: # Helper function to call the 'stress' command line tool
     def stress_cpu(num_cpus, time):
         subprocess.check_call(["stress", "--cpu", str(num_cpus), "--timeout",
     →f"{time}s"])
         return
```

```python
[9]: # Function for stressing all cores of the CPU
     # Found here: https://github.com/nschloe/stressberry/blob/main/stressberry/main.py
     def run_stress(stress_duration=300, idle_duration=120, cores=None):
         """Run stress test for specified duration with specified idle times
         at the start and end of the test.
         """
         if cores is None:
             cores = os.cpu_count()

         print(f"Preparing to stress [{cores}] CPU Cores for [{stress_duration}]
     →seconds")
         print(f"Idling for {idle_duration} seconds...")
         time.sleep(idle_duration)

         print(f"Starting the stress load on [{cores}] CPU Cores for [{stress_duration}]
     →seconds")
         stress_cpu(num_cpus=cores, time=stress_duration)

         print(f"Idling for {idle_duration} seconds...")
         time.sleep(idle_duration)
```

2.7 Helper function to let the CPU cool down

This function is used to let the CPU cool down first to find a stable baseline.

```python
[10]: def cpu_cooldown(interval=60, filename=None):
          """Lets the CPU cool down until the temperature does not change anymore."""
          prev_tmp = get_cpu_temp()
          while True:
              time.sleep(interval)
              tmp = get_cpu_temp()
              print(
```

```
            f"Current temperature: {tmp:4.1f}°C - "
            f"Previous temperature: {prev_tmp:4.1f}°C"
        )
        if abs(tmp - prev_tmp) < 0.2:
            break
        prev_tmp = tmp
    return tmp
```

2.8 Helper function for handling dataframes

First, a dataframe is created and at the same time the column headers are set. The function `dataframe_add_row()` is used to add the measured values to the dataframe in the form of new rows.

```
[11]: # Dataframe for the measuring values
      df_meas_values = pd.DataFrame(columns=['Time', 'CPU Temperature', 'CPU Frequency',␣
       ↪'Ambient Temperature'])
```

```
[12]: def dataframe_add_row(df=None, row=[]):
          if (df is None):
              return

          # Add a row
          df.loc[-1] = row

          # Shift the index
          df.index = df.index + 1

          # Reset the index of dataframe and avoid the old index being added as a column
          df.reset_index(drop=True, inplace=True)
```

2.9 Main worker function

```
[13]: # Function for running the stress test in another thread while measuring CPU␣
      ↪temperature and frequency
      # Found here: https://github.com/nschloe/stressberry/blob/main/stressberry/cli/run.
      ↪py
      def run(argv=None):
          # Cool down first
          print("Awaiting stable baseline temperature ...")
          cpu_cooldown(interval=60)

          # Start the stress test in another thread
          t = threading.Thread(
              target=lambda: run_stress(stress_duration=900, idle_duration=300, cores=4),␣
      ↪args=()
          )
          # Init event handler for killing the thread
          t.event = threading.Event()
          # Start the thread
          t.start()

          # Init row array
          values_row = []
          # Get starting time
          start_time = time.time()
          while t.is_alive():
```

```python
        try:
            # Get time relative to starting time and round to 1 decimal
            timestamp = float("{:.1f}".format(time.time() - start_time))
            # Get CPU temperature and round to 1 decimal
            temperature_cpu = float("{:.1f}".format(get_cpu_temp()))
            # Get ambient temperature and round to 1 decimal
            temperature_ambient = float("{:.1f}".format(get_ambient_temp()))
            # Get CPU frequency and round to 1 decimal
            frequency = float("{:.1f}".format(get_cpu_freq()))

            values_row = [ timestamp,
                           temperature_cpu,
                           frequency,
                           temperature_ambient
                         ]

            dataframe_add_row(df_meas_values, values_row)

            print(
                    f"Time: {timestamp} s,\t"
                    f"CPU Temperature: {temperature_cpu} °C,\t"
                    f"Ambient Temperature: {temperature_ambient} °C,\t"
                    f"Frequency: {frequency} MHz"
                 )

            # Choose the sample interval such that we have a respectable number of
↪data points
            t.join(2.0)

        except:
            print("Keyboard Interrupt ^C detected.")
            print("Bye.")
            # Stop the thread by calling the event
            t.event.set()
            break

    # Normalize times so we are starting at '0 s'
    #time0 = df_meas_values['Time'][0]
    # It's a really fancy oneliner - but not necessary at all ...
    #df_meas_values['Time'] = [tm - time0 for tm in df_meas_values['Time']]
```

3 Run the heating test

```python
[ ]: # Clear all data in dataframe
    df_meas_values = df_meas_values.iloc[0:0]

    run()
```

```python
[25]: display(df_meas_values)
```

	Time	CPU Temperature	CPU Frequency	Ambient Temperature
0	0.0	45.7	900.2	24.6
1	2.1	45.7	700.2	24.6
2	4.3	46.2	900.2	24.5
3	6.4	45.2	800.2	24.5
4	8.5	45.7	800.2	24.6

```
..   ...          ...         ...                 ...
692  1491.6       51.1        1500.4              24.6
693  1493.7       49.6        1000.2              24.7
694  1495.8       48.7         800.2              24.6
695  1498.0       50.1        1000.3              24.6
696  1500.1       49.6         900.2              24.6

[697 rows x 4 columns]
```

4 Save all to CSV files

```
[26]: # Write dataframe to CSV file
      str_file_prefix_b4 = 'RaspiB4JupyterLab_stress_measurement'
      str_file_prefix_b3plus = 'RaspiB3plusEPaper_stress_measurement'

      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_woHeatSinks.csv', sep ='\t', index = False, header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinks.csv', sep ='\t', index = False, header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinksAndFan5V.csv', sep ='\t', index = False, header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinksAndFan3V.csv', sep ='\t', index = False, header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinksAndFan5Vrev.csv', sep ='\t', index = False, header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_pinkRaspiCase_wHeatSinks.csv', sep ='\t', index = False, header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinksAndNoctuaFan5V.csv', sep ='\t', index = False,␣
      ↪header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinksAndNoctuaFan3V.csv', sep ='\t', index = False,␣
      ↪header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_PlasticCase_wHeatSinksAndNoctuaFan5Vrev.csv', sep ='\t', index = False,␣
      ↪header=True)
      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_woCase_wHeatSinksAndCtrlFan5V_70C.csv', sep ='\t', index = False, header=True)
      df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b4 +␣
       ↪'_woCase_wHeatSinksAndCtrlFan5V_65C.csv', sep ='\t', index = False, header=True)

      #df_meas_values.to_csv(r'./data_files/' + str_file_prefix_b3plus +␣
       ↪'_PlasticCase_wHeatSinks.csv', sep ='\t', index = False, header=True)
```

5 Read in the CSV files and display it

5.1 Read in the CSV files in dataframes

```
[2]: # Helper function for creating dataframes from CSV files
     def create_dictionary_from_csv(filename, offset=0, cols_wanted=1):
         my_dataframe = pd.read_csv(filename, sep='\t', index_col=False, decimal='.',␣
     ↪header=offset)
```

```
    # Delete all cloumns after the desired ones
    my_dataframe.drop(my_dataframe.columns[cols_wanted:], axis=1, inplace=True)

    return my_dataframe
```

```
[3]: str_file_prefix_b4 = 'RaspiB4JupyterLab_stress_measurement'
     str_file_prefix_b3plus = 'RaspiB3plusEPaper_stress_measurement'

     str_file_name_1 = str_file_prefix_b4 + '_PlasticCase_woHeatSinks.csv'
     str_file_name_2 = str_file_prefix_b4 + '_PlasticCase_wHeatSinks.csv'
     str_file_name_3 = str_file_prefix_b4 + '_PlasticCase_wHeatSinksAndFan5V.csv'
     str_file_name_4 = str_file_prefix_b4 + '_PlasticCase_wHeatSinksAndFan3V.csv'
     str_file_name_5 = str_file_prefix_b4 + '_PlasticCase_wHeatSinksAndFan5Vrev.csv'
     str_file_name_6 = str_file_prefix_b4 + '_pinkRaspiCase_wHeatSinks.csv'
     str_file_name_7 = str_file_prefix_b4 + '_PlasticCase_wHeatSinksAndNoctuaFan5V.csv'
     str_file_name_8 = str_file_prefix_b4 + '_PlasticCase_wHeatSinksAndNoctuaFan3V.csv'
     str_file_name_11 = str_file_prefix_b4 + '_PlasticCase_wHeatSinksAndNoctuaFan5Vrev.
      ↪csv'

     str_file_name_10 = str_file_prefix_b4 + '_woCase_wHeatSinksAndCtrlFan5V_70C.csv'
     str_file_name_12 = str_file_prefix_b4 + '_woCase_wHeatSinksAndCtrlFan5V_65C.csv'

     str_file_name_9 = str_file_prefix_b3plus + '_PlasticCase_wHeatSinks.csv'

     df_1_PC_woHeatSinks = create_dictionary_from_csv(filename="./data_files/" +␣
      ↪str_file_name_1, offset=0, cols_wanted=4)
     df_2_PC_wHeatSinks = create_dictionary_from_csv(filename="./data_files/" +␣
      ↪str_file_name_2, offset=0, cols_wanted=4)
     df_3_PC_wHeatSinksAndFan5V = create_dictionary_from_csv(filename="./data_files/" +␣
      ↪str_file_name_3, offset=0, cols_wanted=4)
     df_4_PC_wHeatSinksAndFan3V = create_dictionary_from_csv(filename="./data_files/" +␣
      ↪str_file_name_4, offset=0, cols_wanted=4)
     df_5_PC_wHeatSinksAndFan5Vrev = create_dictionary_from_csv(filename="./data_files/"␣
      ↪+ str_file_name_5, offset=0, cols_wanted=4)
     df_6_RC_wHeatSinks = create_dictionary_from_csv(filename="./data_files/" +␣
      ↪str_file_name_6, offset=0, cols_wanted=4)
     df_7_PC_wHeatSinksAndNoctuaFan5V = create_dictionary_from_csv(filename="./
      ↪data_files/" + str_file_name_7, offset=0, cols_wanted=4)
     df_8_PC_wHeatSinksAndNoctuaFan3V = create_dictionary_from_csv(filename="./
      ↪data_files/" + str_file_name_8, offset=0, cols_wanted=4)
     df_11_PC_wHeatSinksAndNoctuaFan5Vrev = create_dictionary_from_csv(filename="./
      ↪data_files/" + str_file_name_11, offset=0, cols_wanted=4)

     df_10_woC_wHeatSinksAndCtrlFan5V_70C = create_dictionary_from_csv(filename="./
      ↪data_files/" + str_file_name_10, offset=0, cols_wanted=4)
     df_12_woC_wHeatSinksAndCtrlFan5V_65C = create_dictionary_from_csv(filename="./
      ↪data_files/" + str_file_name_12, offset=0, cols_wanted=4)

     df_9_PC_wHeatSinks = create_dictionary_from_csv(filename="./data_files/" +␣
      ↪str_file_name_9, offset=0, cols_wanted=4)
```

```
[4]: #df_1_PC_woHeatSinks.head(6)
     #df_2_PC_wHeatSinks.head(6)
     #df_3_PC_wHeatSinksAndFan5V.head(6)
     #df_4_PC_wHeatSinksAndFan3V.head(6)
     #df_5_PC_wHeatSinksAndFan5Vrev.head(6)
```

```python
#df_6_RC_wHeatSinks.head(6)
#df_7_PC_wHeatSinksAndNoctuaFan5V.head(6)
#df_8_PC_wHeatSinksAndNoctuaFan3V.head(6)
#df_11_PC_wHeatSinksAndNoctuaFan5Vrev.head(6)

#df_10_woC_wHeatSinksAndCtrlFan5V_70C.head(6)
df_12_woC_wHeatSinksAndCtrlFan5V_65C.head(6)

df_9_PC_wHeatSinks.head(6)
```

```
[4]:    Time  CPU Temperature  CPU Frequency  Ambient Temperature
    0   0.0             47.8          800.0                 23.2
    1   2.2             47.8          800.0                 23.2
    2   4.3             47.8          800.0                 23.2
    3   6.5             48.3         1400.0                 23.2
    4   8.6             47.8          800.0                 23.2
    5  10.8             47.8          800.0                 23.2
```

```python
[5]: #df_1_PC_woHeatSinks.dtypes
    #df_2_PC_wHeatSinks.dtypes
    #df_3_PC_wHeatSinksAndFan5V.dtypes
    #df_4_PC_wHeatSinksAndFan3V.dtypes
    #df_5_PC_wHeatSinksAndFan5Vrev.dtypes
    #df_6_RC_wHeatSinks.dtypes
    #df_7_PC_wHeatSinksAndNoctuaFan5V.dtypes
    #df_8_PC_wHeatSinksAndNoctuaFan3V.dtypes
    #df_11_PC_wHeatSinksAndNoctuaFan5Vrev.dtypes

    #df_10_woC_wHeatSinksAndCtrlFan5V_70C.dtypes
    #df_12_woC_wHeatSinksAndCtrlFan5V_65C.dtypes

    df_9_PC_wHeatSinks.dtypes
```

```
[5]: Time                   float64
    CPU Temperature        float64
    CPU Frequency          float64
    Ambient Temperature    float64
    dtype: object
```

5.2 Smoothing with a moving average filter

```python
[6]: # Smooth temperature column only!
    df_1_PC_woHeatSinks['CPU Temperature'] = df_1_PC_woHeatSinks['CPU Temperature'].
     ↪rolling(window=3).mean()
    df_2_PC_wHeatSinks['CPU Temperature'] = df_2_PC_wHeatSinks['CPU Temperature'].
     ↪rolling(window=3).mean()
    df_3_PC_wHeatSinksAndFan5V['CPU Temperature'] = df_3_PC_wHeatSinksAndFan5V['CPU
     ↪Temperature'].rolling(window=3).mean()
    df_4_PC_wHeatSinksAndFan3V['CPU Temperature'] = df_4_PC_wHeatSinksAndFan3V['CPU
     ↪Temperature'].rolling(window=3).mean()
    df_5_PC_wHeatSinksAndFan5Vrev['CPU Temperature'] =
     ↪df_5_PC_wHeatSinksAndFan5Vrev['CPU Temperature'].rolling(window=3).mean()
    df_6_RC_wHeatSinks['CPU Temperature'] = df_6_RC_wHeatSinks['CPU Temperature'].
     ↪rolling(window=3).mean()
    df_7_PC_wHeatSinksAndNoctuaFan5V['CPU Temperature'] =
     ↪df_7_PC_wHeatSinksAndNoctuaFan5V['CPU Temperature'].rolling(window=3).mean()
```

```
df_8_PC_wHeatSinksAndNoctuaFan3V['CPU Temperature'] =␣
 ↪df_8_PC_wHeatSinksAndNoctuaFan3V['CPU Temperature'].rolling(window=3).mean()
df_11_PC_wHeatSinksAndNoctuaFan5Vrev['CPU Temperature'] =␣
 ↪df_11_PC_wHeatSinksAndNoctuaFan5Vrev['CPU Temperature'].rolling(window=3).mean()

df_10_woC_wHeatSinksAndCtrlFan5V_70C['CPU Temperature'] =␣
 ↪df_10_woC_wHeatSinksAndCtrlFan5V_70C['CPU Temperature'].rolling(window=3).mean()
df_12_woC_wHeatSinksAndCtrlFan5V_65C['CPU Temperature'] =␣
 ↪df_12_woC_wHeatSinksAndCtrlFan5V_65C['CPU Temperature'].rolling(window=3).mean()

df_9_PC_wHeatSinks['CPU Temperature'] = df_9_PC_wHeatSinks['CPU Temperature'].
 ↪rolling(window=3).mean()
```

```
[7]: df_12_woC_wHeatSinksAndCtrlFan5V_65C
```

```
[7]:        Time  CPU Temperature  CPU Frequency  Ambient Temperature
     0        0.0              NaN          900.2                 24.6
     1        2.1              NaN          700.2                 24.6
     2        4.3        45.866667          900.2                 24.5
     3        6.4        45.700000          800.2                 24.5
     4        8.5        45.700000          800.2                 24.6
     ..       …                …              …                     …
     692   1491.6        50.266667         1500.4                 24.6
     693   1493.7        50.266667         1000.2                 24.7
     694   1495.8        49.800000          800.2                 24.6
     695   1498.0        49.466667         1000.3                 24.6
     696   1500.1        49.466667          900.2                 24.6

     [697 rows x 4 columns]
```

5.3 Display / Plot data from dataframes

5.3.1 Comparative representation of the temperature curves

This is a comparative representation of the temperature curves over all examined cooling variants for
Raspberry Pi B4 and 3B+.

```
[8]: # figsize: a tuple (width, height) in inches
     plt.figure(num=0, figsize=(20, 10), dpi=80, facecolor='w', edgecolor='k')
     axes = plt.gca()

     plt.title('RaspiB4JupyterLab / RaspiB3plusEPaper stress measurements with different␣
      ↪cooling types')

     plt.plot(df_1_PC_woHeatSinks['Time'], df_1_PC_woHeatSinks['CPU Temperature'], '-',␣
      ↪label='R4, Plastic Case wo heat sinks or fan, AVG')
     plt.plot(df_2_PC_wHeatSinks['Time'], df_2_PC_wHeatSinks['CPU Temperature'], '-',␣
      ↪label='R4, Plastic Case with heat sinks and wo fan, AVG')
     #plt.plot(df_3_PC_wHeatSinksAndFan5V['Time'], df_3_PC_wHeatSinksAndFan5V['CPU␣
      ↪Temperature'], '-', label='R4, Plastic Case with heat sinks and cheap fan (5 V),␣
      ↪AVG')
     #plt.plot(df_4_PC_wHeatSinksAndFan3V['Time'], df_4_PC_wHeatSinksAndFan3V['CPU␣
      ↪Temperature'], '-', label='R4, Plastic Case with heat sinks and cheap fan (3.3␣
      ↪V), AVG')
```

```python
#plt.plot(df_5_PC_wHeatSinksAndFan5Vrev['Time'], df_5_PC_wHeatSinksAndFan5Vrev['CPU␣
 ↪Temperature'], '-', label='R4, Plastic Case with heat sinks and cheap fan␣
 ↪reverted (5 V), AVG')
plt.plot(df_6_RC_wHeatSinks['Time'], df_6_RC_wHeatSinks['CPU Temperature'], '-',␣
 ↪label='R4, pink Raspi Case with heat sinks and wo fan, AVG')
plt.plot(df_7_PC_wHeatSinksAndNoctuaFan5V['Time'],␣
 ↪df_7_PC_wHeatSinksAndNoctuaFan5V['CPU Temperature'], '-', label='R4, Plastic Case␣
 ↪with heat sinks and Noctua fan (5 V), AVG')
plt.plot(df_8_PC_wHeatSinksAndNoctuaFan3V['Time'],␣
 ↪df_8_PC_wHeatSinksAndNoctuaFan3V['CPU Temperature'], '-', label='R4, Plastic Case␣
 ↪with heat sinks and Noctua fan (3.3 V), AVG')
plt.plot(df_11_PC_wHeatSinksAndNoctuaFan5Vrev['Time'],␣
 ↪df_11_PC_wHeatSinksAndNoctuaFan5Vrev['CPU Temperature'], '-', label='R4, Plastic␣
 ↪Case with heat sinks and Noctua fan reverted (5 V), AVG')

plt.plot(df_10_woC_wHeatSinksAndCtrlFan5V_70C['Time'],␣
 ↪df_10_woC_wHeatSinksAndCtrlFan5V_70C['CPU Temperature'], '-', label='R4, wo Case␣
 ↪with one big sink and controlled fan (5 V, 70°C), AVG')
plt.plot(df_12_woC_wHeatSinksAndCtrlFan5V_65C['Time'],␣
 ↪df_12_woC_wHeatSinksAndCtrlFan5V_65C['CPU Temperature'], '-', label='R4, wo Case␣
 ↪with one big sink and controlled fan (5 V, 65°C), AVG')

plt.plot(df_9_PC_wHeatSinks['Time'], df_9_PC_wHeatSinks['CPU Temperature'], '-',␣
 ↪label='R3+, Plastic Case with heat sinks and wo fan, AVG')

plt.plot(df_12_woC_wHeatSinksAndCtrlFan5V_65C['Time'],␣
 ↪df_12_woC_wHeatSinksAndCtrlFan5V_65C['Ambient Temperature'], '-', label='Ambient␣
 ↪Temperature')

plt.xlabel('Time [s]')
plt.ylabel('CPU core temperature [°C]')

plt.ylim(0, 100)

plt.grid(True)

plt.setp(plt.gca().xaxis.get_majorticklabels(), 'rotation', 50)

plt.legend()

# Save plot to PNG and PDF
str_image_name = 'RaspiB4JupyterLab_RaspiB3plusEPaper_stress_measurement'
#plt.savefig(r'./data_files/' + str_image_name + '.png')
plt.savefig(r'./data_files/' + str_image_name + '.pdf')

plt.show()
```
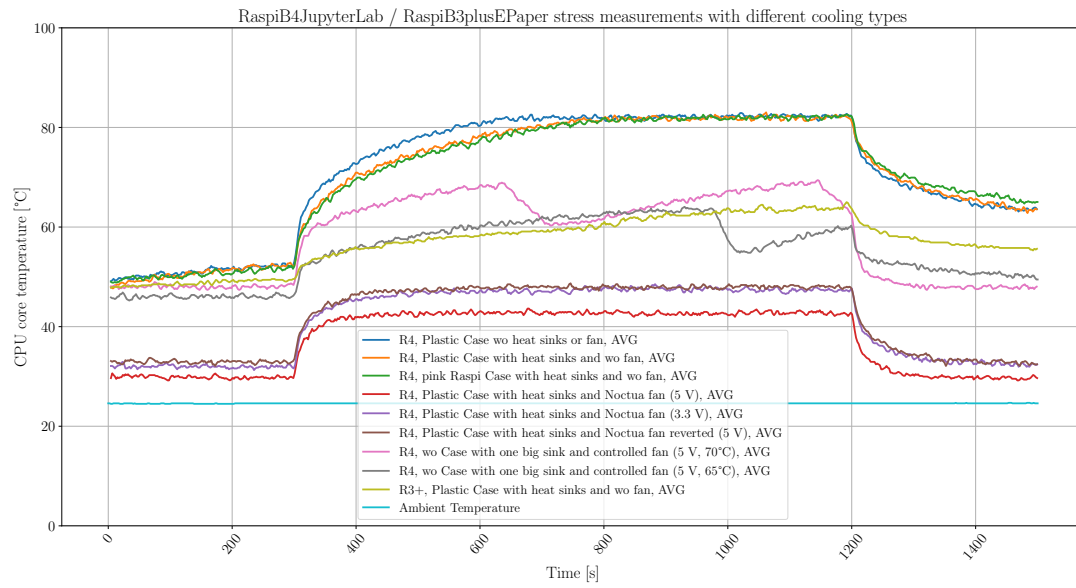
RaspiB4JupyterLab / RaspiB3plusEPaper stress measurements with different cooling types

Legend:
- R4, Plastic Case wo heat sinks or fan, AVG
- R4, Plastic Case with heat sinks and wo fan, AVG
- R4, pink Raspi Case with heat sinks and wo fan, AVG
- R4, Plastic Case with heat sinks and Noctua fan (5 V), AVG
- R4, Plastic Case with heat sinks and Noctua fan (3.3 V), AVG
- R4, Plastic Case with heat sinks and Noctua fan reverted (5 V), AVG
- R4, wo Case with one big sink and controlled fan (5 V, 70°C), AVG
- R4, wo Case with one big sink and controlled fan (5 V, 65°C), AVG
- R3+, Plastic Case with heat sinks and wo fan, AVG
- Ambient Temperature

5.3.2 RaspiB3plusEPaper: Temperature curve compared with the curve of the CPU frequency (passive cooling)

The following thermal images show the **Raspberry Pi 3B+** in idle (1) state and under CPU full load (2). The images were taken with the thermal camera *Ti 480 Thermal Imager (Fluke)*:
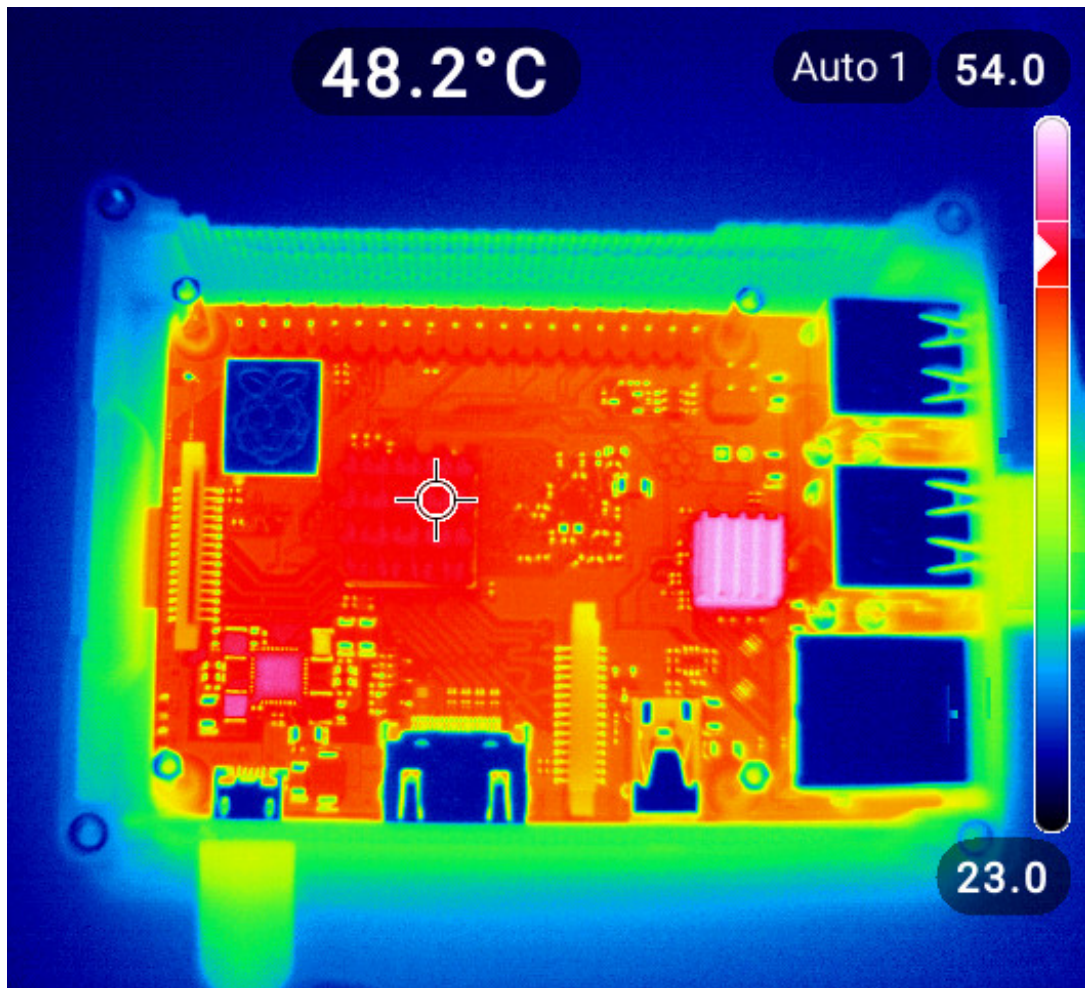
(1) Thermal image of the RPi 3B+ in idle state
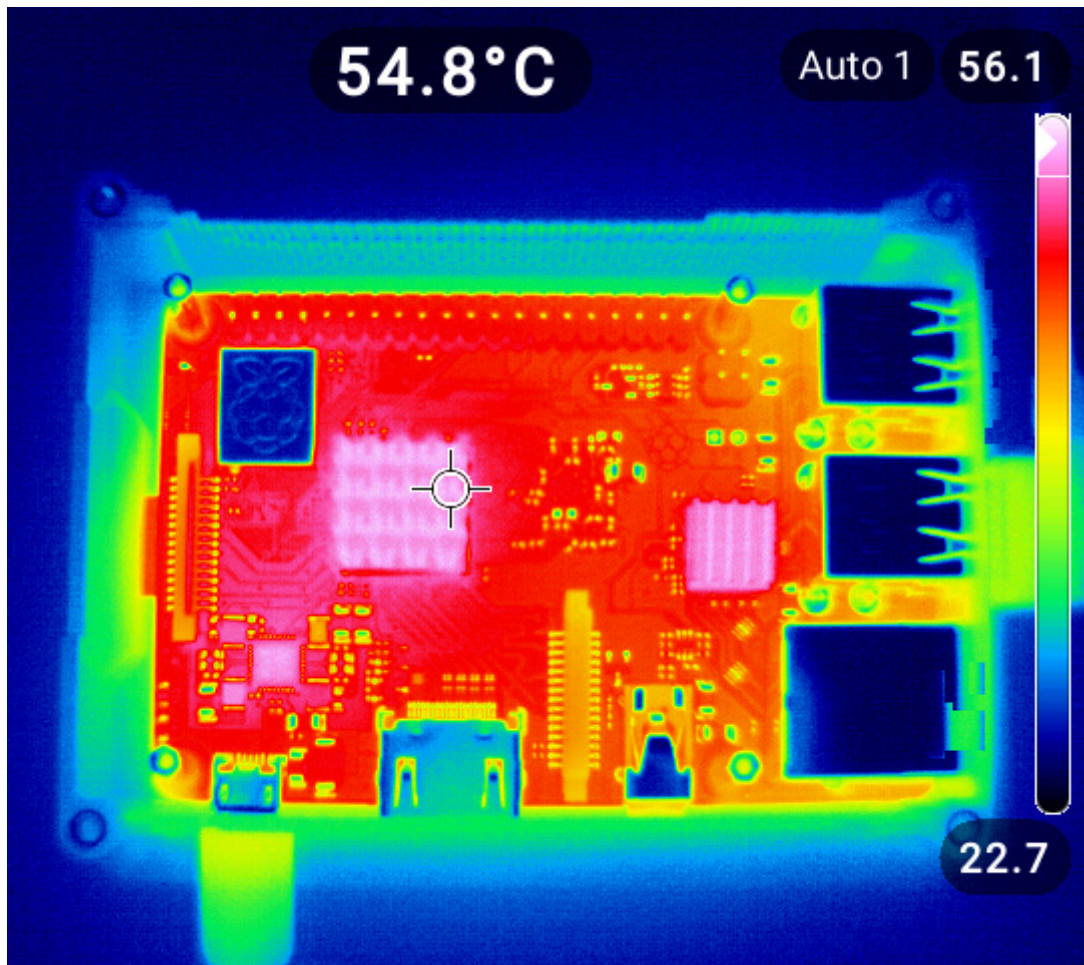
(2) Thermal image of the RPi 3B+ under CPU full load

This is the plot of the temperature curve compared with the CPU frequency curve for the Raspberry Pi 3B+ with the cooling variant "glued-on heat sinks without fan".

```
[9]: # Figsize: a tuple (width, height) in inches
     # Create figure and axis objects with subplots()
     fig, ax1 = plt.subplots(num=0, figsize=(20, 10), dpi=80, facecolor='w',␣
     ↪edgecolor='k')

     axes = plt.gca()

     plt.title('RaspiB3plusEPaper: passive cooling (glued-on heat sinks without fan)')

     line1 = ax1.plot(df_9_PC_wHeatSinks['Time'], df_9_PC_wHeatSinks['CPU Temperature'],␣
     ↪color='navy', label='CPU Temperature')
     line2 = ax1.plot(df_9_PC_wHeatSinks['Time'], df_9_PC_wHeatSinks['Ambient␣
     ↪Temperature'], color='lightseagreen', label='Ambient Temperature')

     # Set x-axis label
     ax1.set_xlabel('Time [s]', fontsize=14)
     # Set y-axis label
     ax1.set_ylabel('CPU core temperature [°C]', fontsize=16)
     ax1.set_ylim(0, 102)
     ax1.grid(True)
     plt.xticks(rotation=50)

     # Twin object for two different y-axis on the same plot
```

```
ax2 = ax1.twinx()

line3 = ax2.plot(df_9_PC_wHeatSinks['Time'], df_9_PC_wHeatSinks['CPU Frequency'],␣
 ↪color='limegreen', label='CPU Frequency')

# Set y-axis label
ax2.set_ylabel('CPU core frequency [MHz]', fontsize=16)
ax2.set_ylim(500, 1510)
ax2.grid(True)

# Add all lines to the same legend box
lines_all = line1+line2+line3
labels = [l.get_label() for l in lines_all]
ax1.legend(lines_all, labels, loc='lower center')

# Save plot to PNG and PDF
str_image_name = 'RaspiB3plusEPaper_stress_measurement_PC_wHeatSinks'
#plt.savefig(r'./data_files/' + str_image_name + '.png')
plt.savefig(r'./data_files/' + str_image_name + '.pdf')

plt.show()
```
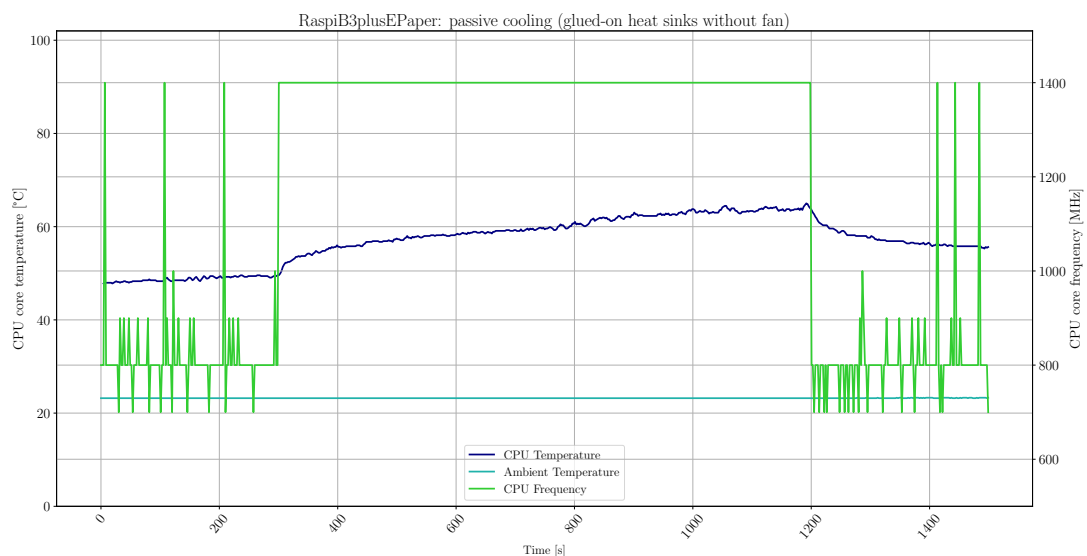

RaspiB3plusEPaper: passive cooling (glued-on heat sinks without fan)

5.3.3 RaspiB4JupyterLab: Temperature curve compared with the curve of the CPU frequency (passive cooling: without heat sinks or fan)

This is the plot of the temperature curve compared with the CPU frequency curve for the Raspberry Pi B4 with the cooling variant "passive cooling: without heat sinks or fan".

```
[10]:  # Figsize: a tuple (width, height) in inches
       # Create figure and axis objects with subplots()
       fig, ax1 = plt.subplots(num=0, figsize=(20, 10), dpi=80, facecolor='w',␣
        ↪edgecolor='k')

       axes = plt.gca()
```

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```python
plt.title('RaspiB4JupyterLab: passive cooling (passive cooling: without heat sinks␣
 ↪or fan)')

line1 = ax1.plot(df_1_PC_woHeatSinks['Time'], df_1_PC_woHeatSinks['CPU␣
 ↪Temperature'], color='navy', label='CPU Temperature')
line2 = ax1.plot(df_1_PC_woHeatSinks['Time'], df_1_PC_woHeatSinks['Ambient␣
 ↪Temperature'], color='lightseagreen', label='Ambient Temperature')

# Set x-axis label
ax1.set_xlabel('Time [s]', fontsize=14)
# Set y-axis label
ax1.set_ylabel('CPU core temperature [°C]', fontsize=16)
ax1.set_ylim(0, 102)
ax1.grid(True)
plt.xticks(rotation=50)

# Twin object for two different y-axis on the same plot
ax2 = ax1.twinx()

line3 = ax2.plot(df_1_PC_woHeatSinks['Time'], df_1_PC_woHeatSinks['CPU Frequency'],␣
 ↪color='limegreen', label='CPU Frequency')

# Set y-axis label
ax2.set_ylabel('CPU core frequency [MHz]', fontsize=16)
ax2.set_ylim(500, 1510)
ax2.grid(True)

# Add all lines to the same legend box
lines_all = line1+line2+line2
labels = [l.get_label() for l in lines_all]
ax1.legend(lines_all, labels, loc='lower center')

# Save plot to PNG and PDF
str_image_name = 'RaspiB4JupyterLab_stress_measurement_PC_woHeatSinks'
#plt.savefig(r'./data_files/' + str_image_name + '.png')
plt.savefig(r'./data_files/' + str_image_name + '.pdf')

plt.show()
```
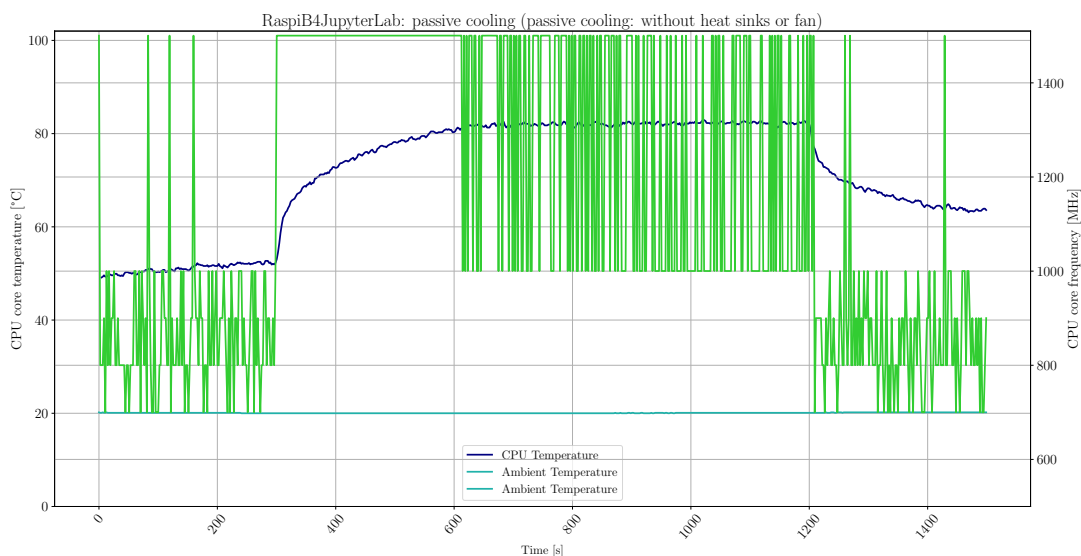
5.3.4 RaspiB4JupyterLab: Temperature curve compared with the curve of the CPU frequency (passive cooling: with heat sinks, but without fan)

This is the plot of the temperature curve compared with the CPU frequency curve for the Raspberry Pi B4 with the cooling variant "glued-on heat sinks without fan".

```python
[11]:  # Figsize: a tuple (width, height) in inches
       # Create figure and axis objects with subplots()
       fig, ax1 = plt.subplots(num=0, figsize=(20, 10), dpi=80, facecolor='w',
        ↪edgecolor='k')

       axes = plt.gca()

       plt.title('RaspiB4JupyterLab: passive cooling (glued-on heat sinks without fan)')

       line1 = ax1.plot(df_2_PC_wHeatSinks['Time'], df_2_PC_wHeatSinks['CPU Temperature'],
        ↪color='navy', label='CPU Temperature')
       line2 = ax1.plot(df_2_PC_wHeatSinks['Time'], df_2_PC_wHeatSinks['Ambient
        ↪Temperature'], color='lightseagreen', label='Ambient Temperature')

       # Set x-axis label
       ax1.set_xlabel('Time [s]', fontsize=14)
       # Set y-axis label
       ax1.set_ylabel('CPU core temperature [°C]', fontsize=16)
       ax1.set_ylim(0, 102)
       ax1.grid(True)
       plt.xticks(rotation=50)

       # Twin object for two different y-axis on the same plot
       ax2 = ax1.twinx()

       line3 = ax2.plot(df_2_PC_wHeatSinks['Time'], df_2_PC_wHeatSinks['CPU Frequency'],
        ↪color='limegreen', label='CPU Frequency')

       # Set y-axis label
       ax2.set_ylabel('CPU core frequency [MHz]', fontsize=16)
       ax2.set_ylim(500, 1510)
       ax2.grid(True)

       # Add all lines to the same legend box
       lines_all = line1+line2+line2
       labels = [l.get_label() for l in lines_all]
       ax1.legend(lines_all, labels, loc='lower center')

       # Save plot to PNG and PDF
       str_image_name = 'RaspiB4JupyterLab_stress_measurement_PC_wHeatSinks'
       #plt.savefig(r'./data_files/' + str_image_name + '.png')
       plt.savefig(r'./data_files/' + str_image_name + '.pdf')

       plt.show()
```
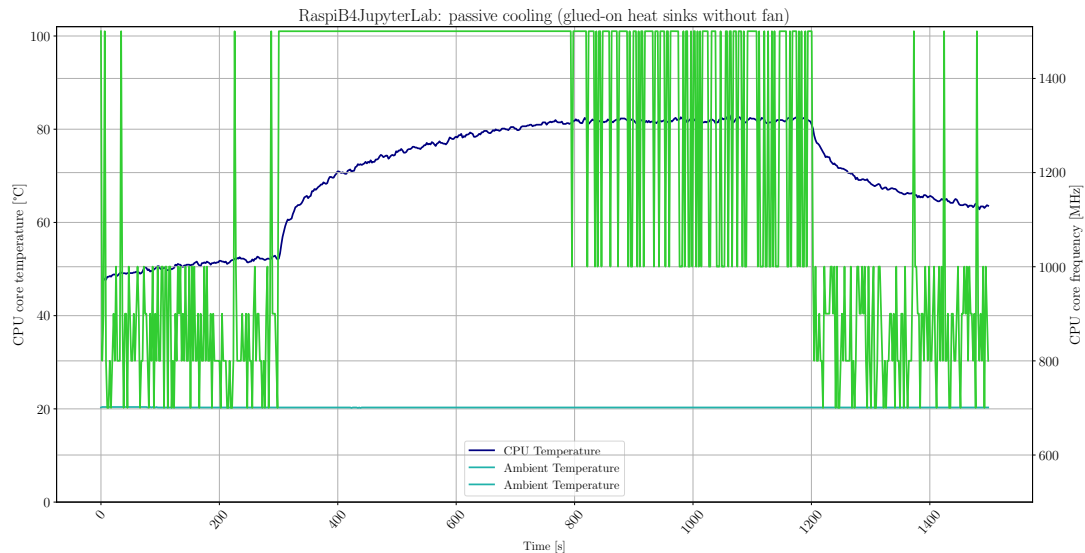
RaspiB4JupyterLab: passive cooling (glued-on heat sinks without fan)

5.3.5 RaspiB4JupyterLab: Temperature curve compared with the curve of the CPU frequency (active cooling)

This is the plot of the temperature curve compared with the CPU frequency curve for the Raspberry Pi B4 with the cooling variant "glued-on heat sinks with Noctua fan (driven by 3.3 V)".

```
[12]:  # Figsize: a tuple (width, height) in inches
       # Create figure and axis objects with subplots()
       fig, ax1 = plt.subplots(num=0, figsize=(20, 10), dpi=80, facecolor='w',␣
        ↪edgecolor='k')

       axes = plt.gca()

       plt.title('RaspiB4JupyterLab: active cooling (glued-on heat sinks with Noctua fan,␣
        ↪3.3 V)')

       line1 = ax1.plot(df_8_PC_wHeatSinksAndNoctuaFan3V['Time'],␣
        ↪df_8_PC_wHeatSinksAndNoctuaFan3V['CPU Temperature'], color='navy', label='CPU␣
        ↪Temperature')
       line2 = ax1.plot(df_8_PC_wHeatSinksAndNoctuaFan3V['Time'],␣
        ↪df_8_PC_wHeatSinksAndNoctuaFan3V['Ambient Temperature'], color='lightseagreen',␣
        ↪label='Ambient Temperature')

       # Set x-axis label
       ax1.set_xlabel('Time [s]', fontsize=14)
       # Set y-axis label
       ax1.set_ylabel('CPU core temperature [°C]', fontsize=16)
       ax1.set_ylim(0, 102)
       ax1.grid(True)
       plt.xticks(rotation=50)

       # Twin object for two different y-axis on the same plot
       ax2 = ax1.twinx()
```

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```python
line3 = ax2.plot(df_8_PC_wHeatSinksAndNoctuaFan3V['Time'],␣
 ↪df_8_PC_wHeatSinksAndNoctuaFan3V['CPU Frequency'], color='limegreen', label='CPU␣
 ↪Frequency')

# Set y-axis label
ax2.set_ylabel('CPU core frequency [MHz]', fontsize=16)
ax2.set_ylim(500, 1510)
ax2.grid(True)

# Add all lines to the same legend box
lines_all = line1+line2+line3
labels = [l.get_label() for l in lines_all]
ax1.legend(lines_all, labels, loc='lower center')

# Save plot to PNG and PDF
str_image_name = 'RaspiB4JupyterLab_stress_measurement_PC_wHeatSinksAndNoctuaFan3V'
#plt.savefig(r'./data_files/' + str_image_name + '.png')
plt.savefig(r'./data_files/' + str_image_name + '.pdf')

plt.show()
```
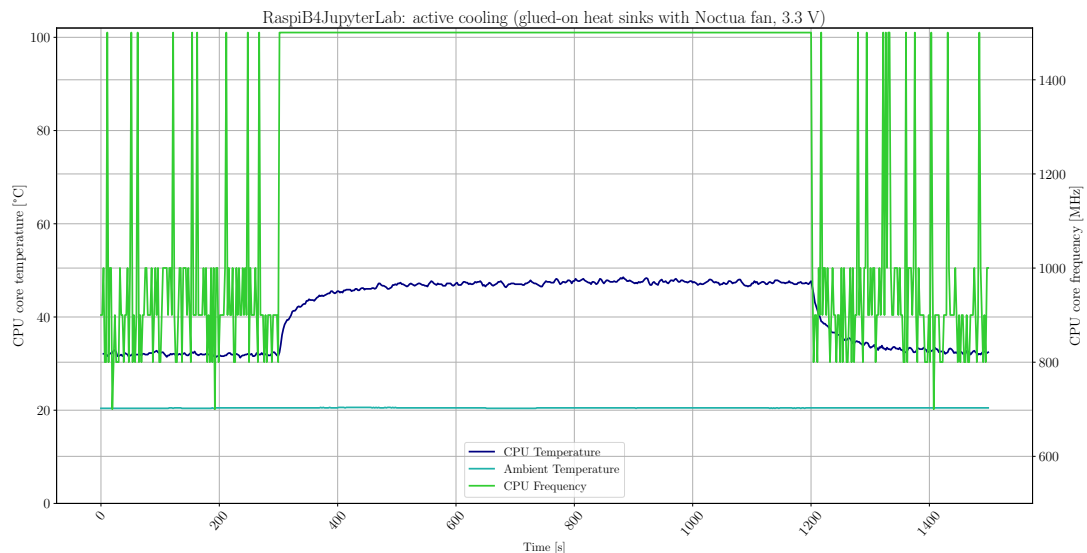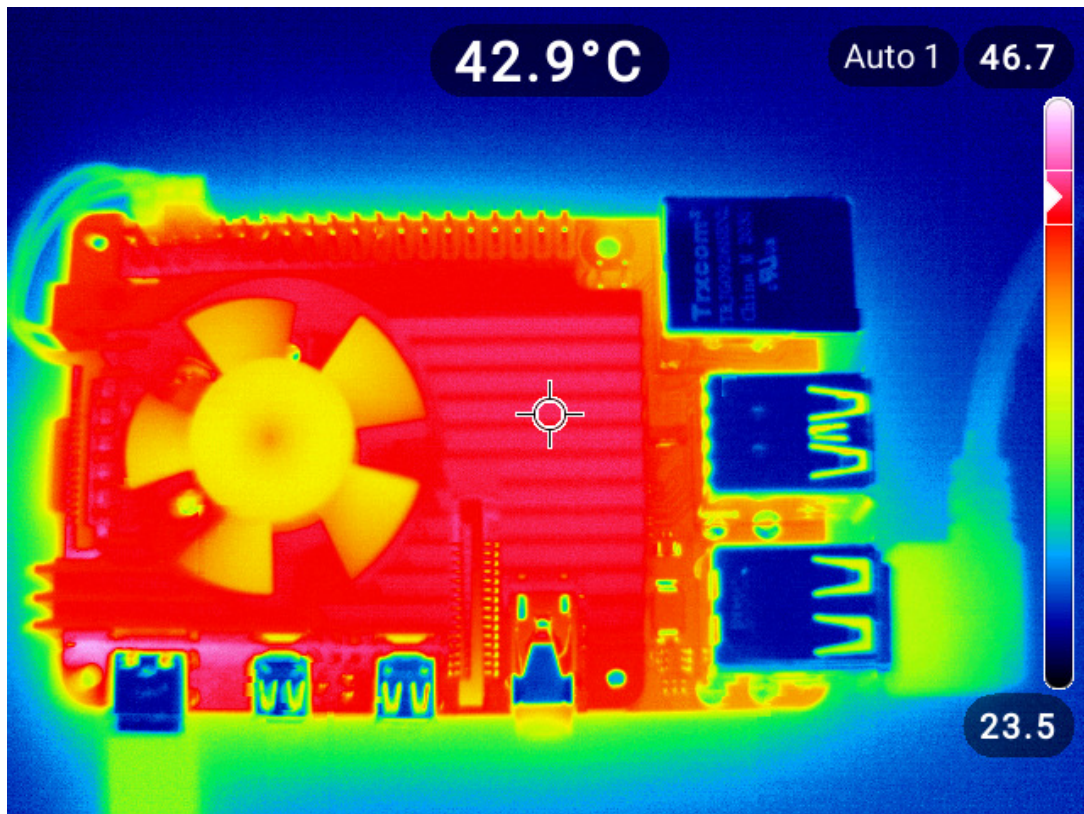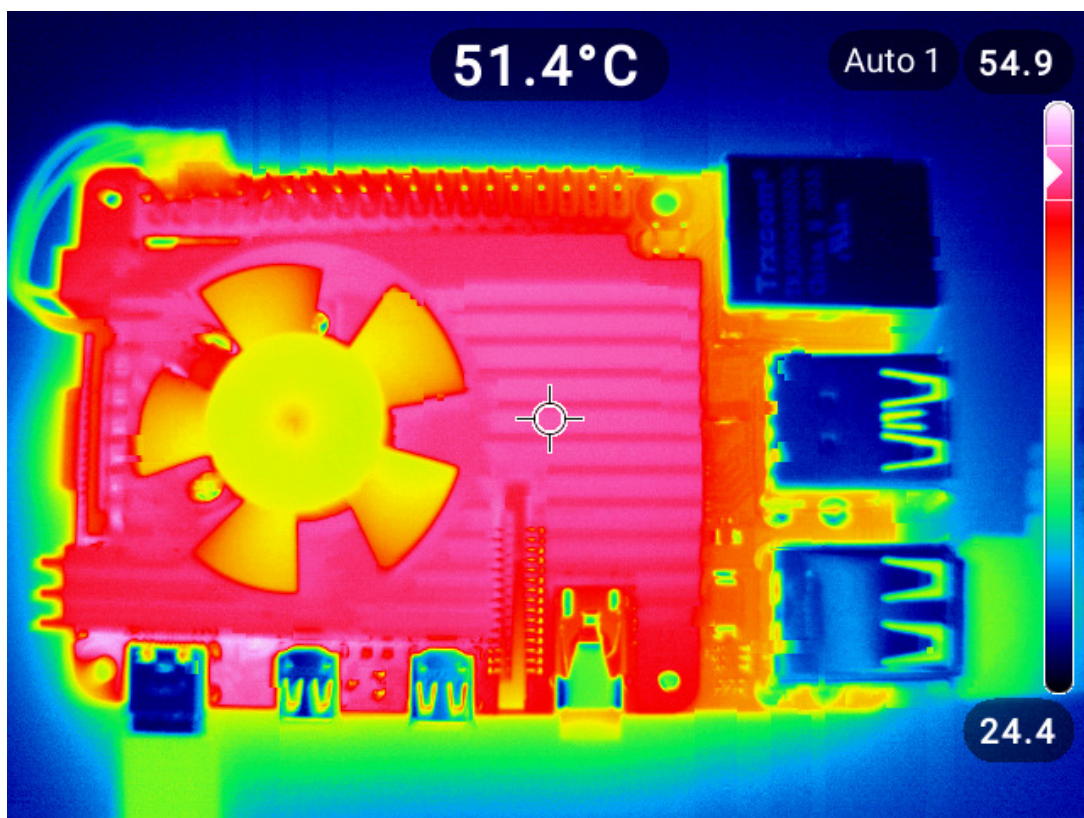

5.3.6 RaspiB4JupyterLab: Temperature curve compared with the curve of the CPU frequency (active cooling by controlled fan)

The following thermal images show the **Raspberry Pi 4B** in idle (1) state and under CPU full load (2). The images were taken with the thermal camera *Ti 480 Thermal Imager (Fluke)*:

(1) Thermal image of the RPi 4B in idle state

(2) Thermal image of the RPi 4B under CPU full load

This is the plot of the temperature curve compared with the CPU frequency curve for the Raspberry Pi B4 with the cooling variant "wo Case and one big heat sink with controlled fan (driven by 5 V and 65°C switch-on temperature)".

```
[15]:  # Figsize: a tuple (width, height) in inches
       # Create figure and axis objects with subplots()
       fig, ax1 = plt.subplots(num=0, figsize=(20, 10), dpi=80, facecolor='w',␣
        ↪edgecolor='k')

       axes = plt.gca()

       plt.title('RaspiB4JupyterLab: active cooling (wo Case and one big heat sink with␣
        ↪controlled fan, 5 V, 65°C switch-on temperature)')

       # List of named colors: https://matplotlib.org/stable/gallery/color/named_colors.
        ↪html
       line1 = ax1.plot(df_12_woC_wHeatSinksAndCtrlFan5V_65C['Time'],␣
        ↪df_12_woC_wHeatSinksAndCtrlFan5V_65C['CPU Temperature'], color='navy', label='CPU␣
        ↪Temperature')
       line2 = ax1.plot(df_12_woC_wHeatSinksAndCtrlFan5V_65C['Time'],␣
        ↪df_12_woC_wHeatSinksAndCtrlFan5V_65C['Ambient Temperature'],␣
        ↪color='lightseagreen', label='Ambient Temperature')

       #df_10_woC_wHeatSinksAndCtrlFan5V_70C
       #df_12_woC_wHeatSinksAndCtrlFan5V_65C

       # Set x-axis label
       ax1.set_xlabel('Time [s]', fontsize=14)
       # Set y-axis label
       ax1.set_ylabel('CPU core temperature [°C]', fontsize=16)
       ax1.set_ylim(0, 102)
       ax1.grid(True)
       plt.xticks(rotation=50)

       # Twin object for two different y-axis on the same plot
       ax2 = ax1.twinx()

       line3 = ax2.plot(df_12_woC_wHeatSinksAndCtrlFan5V_65C['Time'],␣
        ↪df_12_woC_wHeatSinksAndCtrlFan5V_65C['CPU Frequency'], color='limegreen',␣
        ↪label='CPU Frequency')

       # Set y-axis label
       ax2.set_ylabel('CPU core frequency [MHz]', fontsize=16)
       ax2.set_ylim(500, 1510)
       ax2.grid(True)

       # Add all lines to the same legend box
       lines_all = line1+line2+line3
       labels = [l.get_label() for l in lines_all]
       ax1.legend(lines_all, labels, loc='lower center')

       # Save plot to PNG and PDF
       str_image_name =␣
        ↪'RaspiB4JupyterLab_stress_measurement_woCase_wHeatSinksAndCtrlFan5V_65C'
       #plt.savefig(r'./data_files/' + str_image_name + '.png')
       plt.savefig(r'./data_files/' + str_image_name + '.pdf')

       plt.show()
```
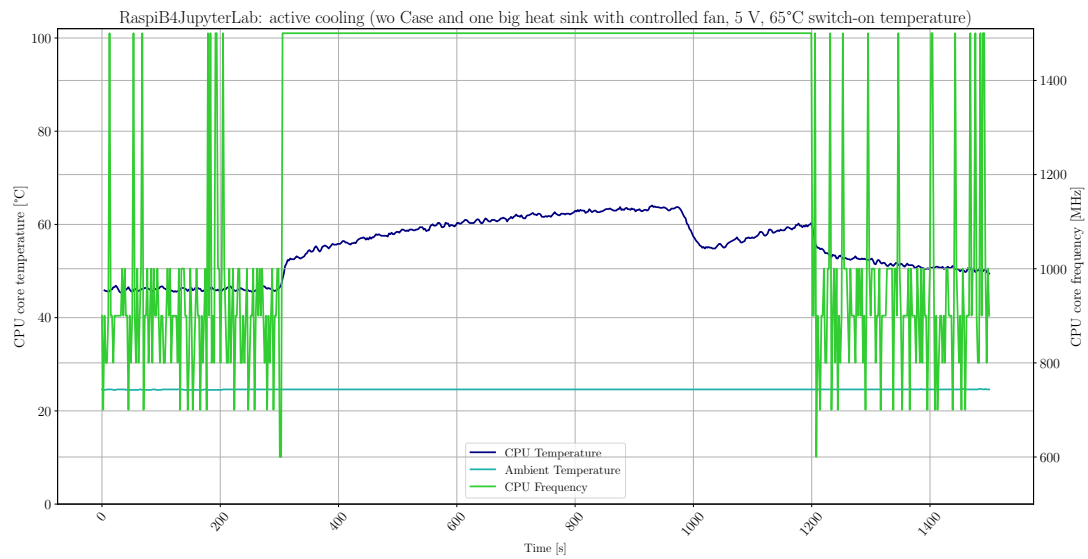
RaspiB4JupyterLab: active cooling (wo Case and one big heat sink with controlled fan, 5 V, 65°C switch-on temperature)

```
[ ]:
```