User Manual for the Cosmic Ray Telescope

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Chapter 1

Quick start

The CRT Controller (CRTC) is the only application required for interacting with the CRT. It is a Labview application that handles CRT control, monitoring, and data acquisition. The CRTC is normally open and/or running, but if not, it can be found at the following path:

C:\Users\CRT Controller\CRTC Labview Application\Source\CRT Controller.vi

When the CRTC starts, it will take some time before it is responsive (~10s). This is due to the external permanent storage harddisks spinning up. Please be patient. The CRTC will be ready when you see the event display window open.

It is recommended that when manually sending commands to all ROBs, Usermessages are enabled (see next section). There is a probability that commands are not properly transmitted to the ROBs, and having usermessages enabled will notify the operator of this. When enabling "autoread", usermessages should be disabled, and MUST be disabled if the PC is to be left unmonitored.

1.1   Starting the CRTC

This section is only relevant if the CRTC was closed or stopped and you are starting it anew. Skip to the next section if you want to know how to get started on a datataking run.

Click the arrow button near the top right corner in the CRTC window to start the CRTC. When you do this, it will take about 10s before the CRTC is responsive, as explained in the previous section. You can then close the event display window if you wish, as it can be reponed later.

You must then enable ROB communications. Navigate to the last tab, called "Serial Ports control". The ROB network master is normally connected with USB to the COM3 port. It requires a baud rate of 115200. These are the default values. Click "Open" to enable ROB

communications.

NOTE: The ROBs may still be running even if the CRTC is not. Therefore, perform a single "report status" read of the ROBs after starting the CRTC to figure out what state they are in. The next paragraph is only relevant if the ROBs are in state "Standby".

Navigate to the "Control ROBs" tab. Select "All" from the "Board Selector" drop-down menu. Click "Go to READY" and wait for all ROBs to enter the Ready state. Then click "Go to RUNNING" and wait for all ROBs to enter the Running state.

Set your desired MPPC overvoltage and trigger threshold. See the next section for default recommended values. Enable autoread, and disable usermessages. The ROB infodisplay should start automatically updating within 10 seconds.

Navigate to the "Control TDC" tab. Click "Start". The time-to-digital converter is now running, and the CRTC is ready.

1.2   Taking data

To begin a period of uninterrupted data taking (a "run"), navigate to the "CRT CONTROL" tab. Here it is simply a matter of clicking "BEGIN RUN". However, this should not be done before you are sure that your settings are correct. First, navigate to the "Control ROBs" tab.

Make sure all ROBs are in their correct states and communicating. For a normal run, the following settings are recommended for all ROBs:

- State: RUNNING
- Trigger threshold: 170mV
- MPPC Overvoltage: 5V

Make sure that they are communication (check timestamps next to ID, are they up to date and all equal?). If some "15V Preamp" values are off by more than ± 0.15 V, they must be manually adjusted, see Section 3.2.1. If the ROB settings appear correct, you can then disable usermessages if they are not already disabled by clicking the big green "Usermessages enabled" button. This button is red if usermessages are already disabled.

Check that the TDC is running and that all channels are generating data by going to the "Charts" tab and checking that all the charts are updating. Also, the total pulse rate (white line) of every ROB should be around 1kpulses/s for the settings listed above. If they are not, this may indicate incorrect trigger threshold or overvoltage settings. The value depends somewhat on the value of the 15V rail, hence the need for manual adjustment to keep it near 15V.

If you wish to be informed in the case that the CRTC crashes, or one of the ROBs performs and auto-shutoff (or otherwise changes its state), insert your email address in the "Error email recipients" array in the "Low level" tab. This is recommended.

When everything seems fine, you may navigate back to the "CRT CONTROL" tab and click the "START RUN" button. Many settings will now be unavailable for editing.

1.3 Stopping the CRTC

You will normally not need to stop the CRTC. But if you have to, it can be stopped in two ways: Either by clicking the window cross like closing any other Windows window, or by navigating to the "Low-level" tab and clicking the "stop" button. The first method will stop the CRTC and close all windows, and the second method will only stop the CRTC but keeps the windows open afterwards.

Stopping the CRTC takes a very long time. The reason is unknown and should be investigated. It can take up to five minutes. Please be patient! Stopping the CRTC by killing its process is harmful. Doing so during a run will most likely corrupt the data file that CRT data is saved to.

1.4 CRT data

The CRTC will save two kinds of data: Coincidence timestamps and ROB information. The data is saved to the external harddisk, at the following path:

D:\2017

The datatype is HDF5. HDF5 files can be opened for viewing with the free software HDFVIEW. Libraries for manipulating HDF5 files exist for most programming languages.

The data is saved in weekly HDF5 files (hereon "data file"). The filenames tell you the year and week its data was recorded. A data file can contain more than one RUN group, each of which contains the data of a specific data run. A RUN group contain a dataset called "coincidences" and 16 ROB groups.

The "coincidences" dataset is a 2D array of timestamps and pixel IDs. Each row contains a timestamp and an ID. The timestamp is an unsigned 64-bit integer. It signifies the time of a potential crossing particle through the pixel denoted by the ID. Its value is the amount of intervals of length 32ps that has occurred since 00:00 01.01.2017. The pixel identification scheme is given as follows:
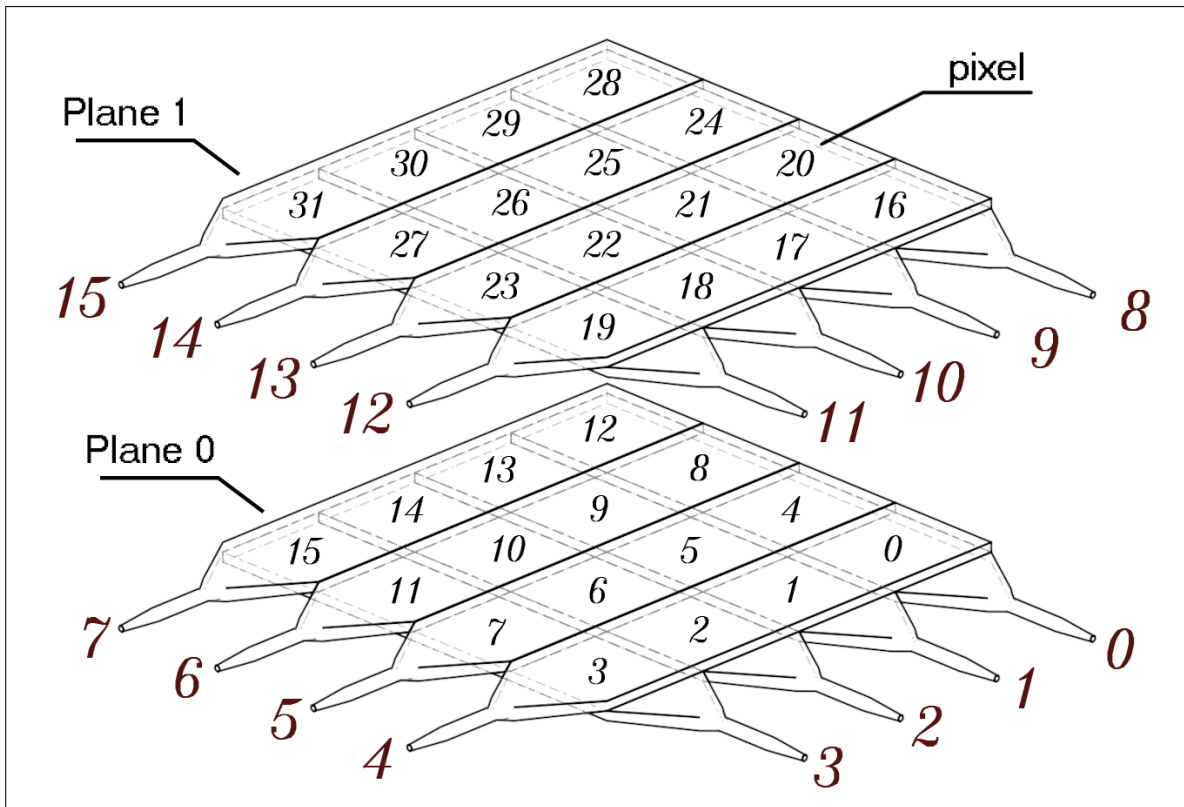
Figure 1.1: Plane and pixel identification scheme of the CRT.

There are 16 ROB groups within each RUN group. Each ROB group contains several data sets:

- Latch resets: Number of registered latch resets (currently not usable due to MCU bug)
- Rails: 2D array of voltage values of all monitored ROB voltage rails.
- Responding: Boolean denoting whether the ROB is responding to communications.
- SiPM bias: Bias voltage applied to the MPPC.
- SiPM temperature: The temperature of the MPPC.
- Trigger threshold: Value of the MPPC pulse discriminator trigger threshold.
- Timestamps: Timestamps of when each ROB info save was performed. Element N in each dataset was saved at the same time, denoted by element N in the timestamp data set. The timestamp format is the number of seconds since 01/01/1904 00:00:00.00 UTC.

The PC is set up to automatically back up the contents in the data path on the permanent external harddisks to a smaller portable harddisk once per day. If you need the CRT data, you can therefore unplug the small portable harddisk, bring it to your own PC, copy the files you need, and bring it back and plug it back into the CRT PC.

Chapter 2

ROBs control

Controlling the ROBs is the primary part of what it means to operate the CRT. The ROBs can be turned on or off, have its parameters adjusted, report information back to the CRTC, and many other things. This is done entirely from the "Control ROBs" tab of the CRTC, and will be explained in this chapter.

2.1   Introduction and basic commands

When interacting with the ROBs, one must first select which ROB the commands will be sent to. This done with the "Board selector" drop-down menu. The most used commands (those not in the "debug things" section) can be sent to all ROBs at once by selecting "all boards".

If there occurs an error as the command is sent to a ROB, an error message will be displayed to the user. To turn off these error messages, click the "Usermessages enabled" button.

The most commonly used commands will now be listed:

- **Go to standby**: Causes the ROB to enter STANDBY state. (See Section 2.2)
- **Go to ready**: Causes the ROB to enter READY state. (See Section 2.2)
- **Go to running**: Causes the ROB to enter RUNNING state. (See Section 2.2)
- **Report MPPC Temp**: ROB(s) returns temperature of MPPC.
- **Report voltages**: ROB(s) returns values of voltage rails and MPPC bias voltage.
- **Report status**: ROB(s) returns board state, rails and bias info (within nominal or warning, enabled or disabled), status of temperature (nominal, warning, or error), status of latch halt counter (nominal, warning, or error).
- **Rep. discr. latches**: ROB(s) returns the number of forced unlatches of the discriminator that the MCU has performed. The value is buggy and can be ignored.
- **Report trigger thres**: ROB(s) returns the value of the MPPC pulse discriminator trigger

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threshold.

- **Set trigger threshold**: Sets the value of the MPPC pulse discriminator trigger threshold.
- **Set MPPC Overvoltage**: Sets the value of the MPPC overvoltage. Maximum value is 5V. The default value is 1.5V.

2.2   Advanced commands

There are times when the basic commands are not enough, for example if one is performing debugging of a single ROB. For these tasks, there are a set of commands in the "debug things" section. These commands cannot be sent to more than one ROB at a time, and attempting to send to all will result in an error usermessage. Their functions will now be explained.

- **Echo**: Checks if the ROB is capable of receiving and sending messages by sending a small command which is echoed back. The result is displayed as a usermessage.
- **Reset Latch**: Forces the MCU to perform a reset of the discriminator latch. If it is already unlatched, this won't have much of an effect.
- **Set Voltage Ref**: Causes the MCU to switch between the internal low-accuracy default voltage reference, or the external high-accuracy voltage reference.
- **15V enable/disable**: Enables or disables the 15V rail. Do not use unless you are sure it will not damage components, or some part of the manual instructs you to do it.
- **3.3V enable/disable**:Enables or disables the 3.3V rail. Do not use unless you are sure it will not damage components, or some part of the manual instructs you to do it.
- **+-5V enable/disable**:Enables or disables the 5V rail. Do not use unless you are sure it will not damage components, or some part of the manual instructs you to do it.
- **Amplifiers enable/disable**:Enables or disables the primary amplifier. Do not use unless you are sure it will not damage components, or some part of the manual instructs you to do it.
- **Remove MPPC from amplifier chain**: Physically disconnects the MPPC from the preamplifier input. Can of course be reconnected.
- **Insert test charge**: Inserts a single test charge into the preamplifier input.
- **Continuous test charge**: Inserts 2000 test charges in rapid succession twice per second.
- **Disable automatic latch reset**: Disables the timed routine the MCU runs in order to check the discriminator latch status and unlatch it if necessary.
- **Disable rail monitor**: Disables the timed routine the MCU runs in order to monitor the voltage rails values. When disabled, the MCU will not auto-shutdown if a rail is out of range.
- **Disable automatic MPPC bias setting**: Disables the MCUs ability to perform automatic adjustment of the MPPC bias voltage based on a set overvoltage and MPPC temperature.
- **Set MPPC bias**: Sets a constant MPPc bias voltage. It will not be adjusted based on MPPC temperature. Only active when the automatic MPPC bias adjustment has been

disabled (previous command).

- **Set Debug Verbosity**: Sets the verbosity of the MCU. Given as integer from 0 (silent) to 6 (information overload).
- **Hard-reset ROB**: Pulls the MCU reset line down, forcing a hard reset of the ROB. Must only be used when it has become unresponsive, or cannot be taken to mode STANDBY as normal.

2.3 More detailed explanations

Some of the previous commands will now be explained in more detail.

2.3.1 Go to STANDBY

The ROB has three states: Standby, Ready, and Running. When in Standby, it is "off". All voltages are disables, except the digital 5V line (since it powers the MCU). When the MCU boots, it enters the Standby state. It can only enter the Standby state either when booting, or from the Ready mode.

Item	Status	Exec order (from Ready)
± 5V analog	Disabled	3
3.3V digital	Disabled	4
15V (preamp)	Disabled	
MPPC Bias	Disabled	2
Latch monitor	Disabled	
Auto bias adjustment	Disabled	
Rail monitor	Disabled	
Trigger threshold	0mV	1
Prim. amplifier	Disabled	
MPPC	Disconnected	

Table 2.1: Component status for the Standby state, and order of disabling.

2.3.2   Go to READY

The second ROB state is Ready. The Ready state can be reached from both the Standby or Running mode. When the ROB is requested to enter the Ready state from the Standby state, most of the voltage rails are enabled in a specific order, and checked to see if they are within nominal values. The MPPC is disconnected from the preamplifier. The preamplifier and primary amplifiers are disabled. The MPPC bias voltage is enabled and set to the lowest possible value ($\sim$46 V).

Item	Status	Exec. order (from Standby)	Exec. order (from Running)
$\pm$ 5V analog	Enabled	2	
3.3V digital	Enabled	1	
15V (preamp)	Disabled		3
MPPC Bias	Enabled	3	
Latch monitor	Enabled	5	
Auto bias adjustment	Enabled	6	
Rail monitor	Enabled	7	
Trigger threshold	$\sim$650mV	4	1
Prim. amplifier	Disabled		2
MPPC	Disconnected		4

Table 2.2: Component status for the Ready state, and order of enabling/disabling.

2.3.3   Go to RUNNING

In the Running state, the ROB is fully enabled. The Running state can only be reaced from the Ready state. All rails are on, the preamplifier and primary amplifier enabled, and the MPPC connected to the preamplifier. The trigger threshold is set to a default value of 400 mV.

Item	Status	Exec. order (from Ready)
± 5V analog	Enabled	
3.3V digital	Enabled	
15V (preamp)	Enabled	2
MPPC Bias	Enabled	
Latch monitor	Enabled	
Auto bias adjustment	Enabled	
Rail monitor	Enabled	
Trigger threshold	400mV	4
Prim. amplifier	Enabled	3
MPPC	Connected	1

Table 2.3: Component status for the Running state, and order of enabling.

2.3.4 Order of component enabling

This section relates to the enabling and disabling of individual voltage rails and other components, as listed in Section 2.2. They must be enabled in the following order (and disabled in the same reverse order):

1. 3.3V digital.
2. +-5V analogue, trigger threshold.
3. MPPC Bias voltage, primary amplifier, preamplifier.

Items on the same line may be enabled in any order.

Chapter 3

Debugging and known issues

The CRT is not flawless. In this chapter, a bit of information about how to debug the ROBs are presented.

3.1 Debugging

If a single ROB is misbehaving, the first thing to try is a hard reset. This can be done either by:

1. Clicking the power-button on the Arduino itself, or
2. Clicking "Control ROBs"->"Debug things"->"Hard-Reset ROB" in the CRTC (remember to select the correct ROB from the "Board selector" drop-down menu).

If the CRT network Master is functional and communications are enabled, these two actions are equal.

If it appears that none of the ROBs are responsive, it is more likely that there has occurred an error with the CRT network Master. This is an Arduino that connects to the PC via USB, and to the ROBs via RS-485 on cat5 ethernet cables. When it receives data from the PC, an onboard LED will light up. This is a good indication of whether the problem lies with the Master or not. You may attempt to fix communications by:

1. Closing and opening communications to the Master on the "Serial Ports Control" tab, or
2. Close communications and click the power button on the Master arduino.

If the Master still appears unable to receive or relay commands from the PC, the problem likely lies with the CRTC or PC. Attempt a restart of the CRTC. Remember that stopping the CRTC often takes up to 5 minutes, and it really should not be force-quit.

3.1.1   Execution listen

You can listen to the execution of the code on both the ROB MCUs and the Master MCU. This can provide you with useful information if you believe a problem to lie in the code. However, the text which is returned by the MCUs is not "nice". It is human-readable, but there is not much of a system to it. It will make little sense without cross-referencing with the Arduino code.

Master

Listening to the Master code execution is simple. In the CRTC, go to the "Serial Ports Control" tab. The "Master Serial Input Data" shows all data that is being returned from the Master to the PC. Interspersed with human-readable text are hex-commands for the CRTC. These can be ignored, or decoded (see my master thesis "A Silicon Photomultiplier Based Readout System For A Cosmic Muon Telescope; Design And Implementation" for a description of the hex command structure). You will want to disable autoread if it is not already disabled in order to not be swamped by text.

3.1.2   ROB

Listening to the ROB MCU code execution is a bit more difficult. You will need a USB to TTL cable. This cable must have its "TX" pin cut off on the TTL side, in order to prevent a short between the PC's TX and the MCU's RX. Since the MCU's RX is connected to the RS-485 receiver output, this could possibly cause damage.

When you have obtained such a cable, connect it to the ROB Arduino output pins. Plug the USB to TTL cable into the CRTC PC and go to the "Serial Ports Control" tab. Select the COM port you plugged it into from the "ROB Serial port" drop-down menu, and open the ROB communication with a baud rate of 38400.

The "ROB Serial Input Data" should now show commands being sent by the ROB onto the RS-485 network. To enable it to also print out information about its code execution, set its debug verbosity to a level between 1 and 6 (on the Control ROBs tab, debug section). Be aware that this will increase the probability that it does not register a command that you send to it. Disable autoread and send single commands to the ROB you are debugging, and keep usermessages enabled.

It can be helpful to disable various automatic procedures that the ROB MCU runs, and which will send lots and lots of data. You can do this by using the debug commands on the "Control ROBs" tab. Disable automatic latch reset, rail monitor and the automatic MPPC bias setting.

If the built-in serial monitor of the CRTC (as just described) proves too lacking, you will want to use the free software Realterm. I recommend this for anything more advanced than having a quick peek at what the ROB or Master is doing.

3.1.3 Data sniffer

There is a "Data sniffer" board connected on the RS-485 network. If not, it may lie somewhere else in the CRT room. The data sniffer "sniffs" the commands being sent back and forth on the RS-485 network and relays them over USB to a PC. It does not alter the commands in any way. Plug it into a free port on the PC and open up communications in the CRTC with baud rate 115200.

This can be useful to have a peek at what exactly the data packets which are sent on the network are. See the CRT master thesis for the command protocol, you will need this to understand the packets.

3.2 Known issues

There are a few known problems with the CRT. Some have temporary solutions, others do not.

3.2.1 15V rail drift

For unknown reasons, the 15V rail on every ROB has a tendency to drift over time. The 15V rail must therefore be manually adjusted from time to time (realistically at least once every 3 days).

To check if a ROB requires an adjustment of its 15V rail, look at the ROB info display in the CRTC (on the "Control ROBs" tab). All the "15V Preamp" values should be 15 ± 0.15 V. If a value is outside this range, it should be adjusted soon. If it is orange, it should be adjusted immediately. An orange cell means the 15V rail is close to the limit (15 ± 0.5 +volt) and a forced ROB shutdown is imminent.

Adjusting a ROB

To adjust the 15V rail value, you require a small screwdriver. Each ROB has a small potentiometer that must be turned slightly, see Figure 3.1.
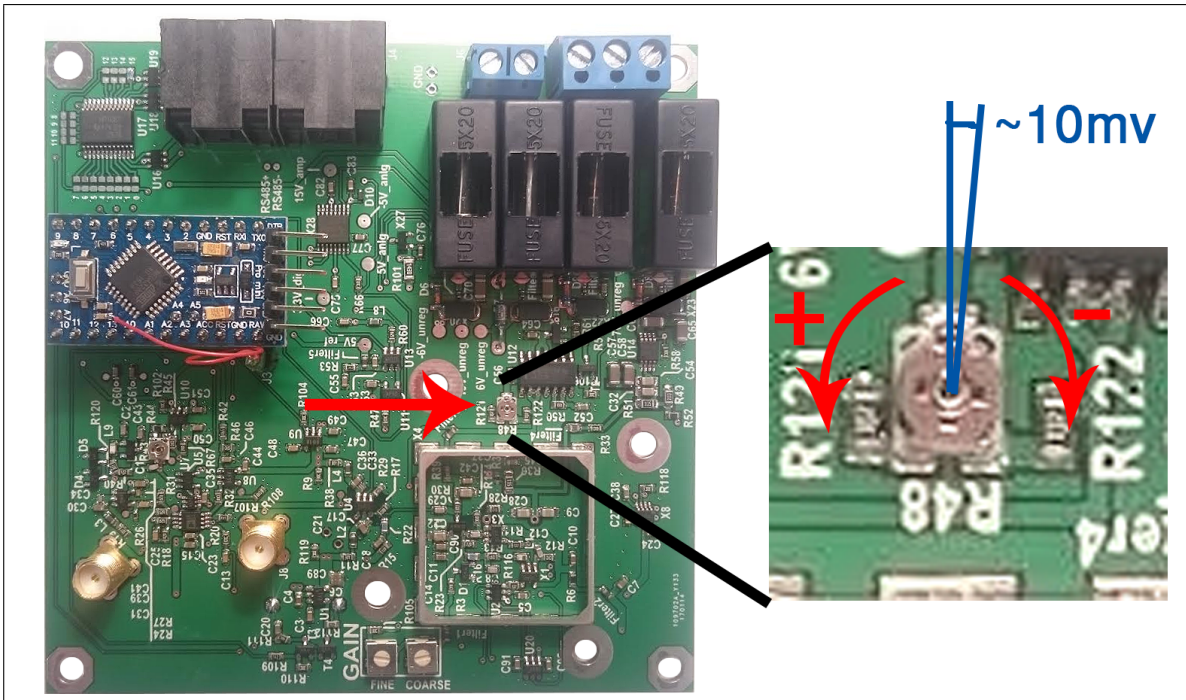
Figure 3.1: Adjust the 15V rail by turning the potentiometer.

Enter the CRT light-shielding enclosure. You can bring a source of light or keep the door flap open. It will not have a large impact on the false coincidence rate.

I recommend turning off the automatic rail monitor of the ROB that you are adjusting if you are new to it, especially if you are adjusting the ROB during a data run. This will prevent the ROB from automatically shutting down in the case that you accidentally adjust it outside the $\pm 0.5 +$volt limit.

You should try to adjust the 15V rail to within 15 ± 0.05 V. To check the value after an adjustment, either click "Report voltages" or more simply keep autoread enabled. The first time you adjust the ROB, it might help to have a colleague sitting at the CRTC that can tell you the value as you adjust.

3.2.2   The ROB will not enter state Running!

If you find that a ROB will not go from Ready to Running, this is most likely due to a 15V rail that has drifted too far (who let that happen...?). The ROB therefore requires an adjustment of its 15V rail, as explained in the previous section. But how can you know how much to adjust the 15V rail by if the ROB refuses to go turn it on?

Begin by disabling the automatic rail monitor. Then click "Enable 15V rail" and ignore the error message you get if usermessages is enabled. Perform a "Report voltages". You can now see what the value of the 15V rail is. Adjust it as explained in the previous section, and lastly re-enable the automatic rail monitor. Disable the 15V rail, and click "go to RUNNING". It should now be fine again.

3.2.3   The CRTC crashed!

That happens from time to time. Many different reasons have been observed, and none are reproducible. It appears to be entirely random when the CRTC decides it's had enough.

You can attempt to do some debugging by reading the error output which is sent to the email recipients on the "low-level" tab, and which is also printed in the "error out" object in the same tab.

3.2.4   Latch counter stuck at 50

The Latch Counter in the ROB info display is meant to display the number of times the discriminator latch was reset by the MCU within the last hour or so. A bug in the MCU software makes it unable to decrease the counter, and it therefore reaches its maximum value of 50 and stays there. The maximum value was set to 50 because the MCU has a tendency to crash at it nears 80, for unknown reasons. This value is therefore pretty much unusable, as the only way to reset the counter is by performing a hard reset of the MCU.

Chapter 4

Notes