Radiation tolerant instrumentation for the LHC cryogenic system

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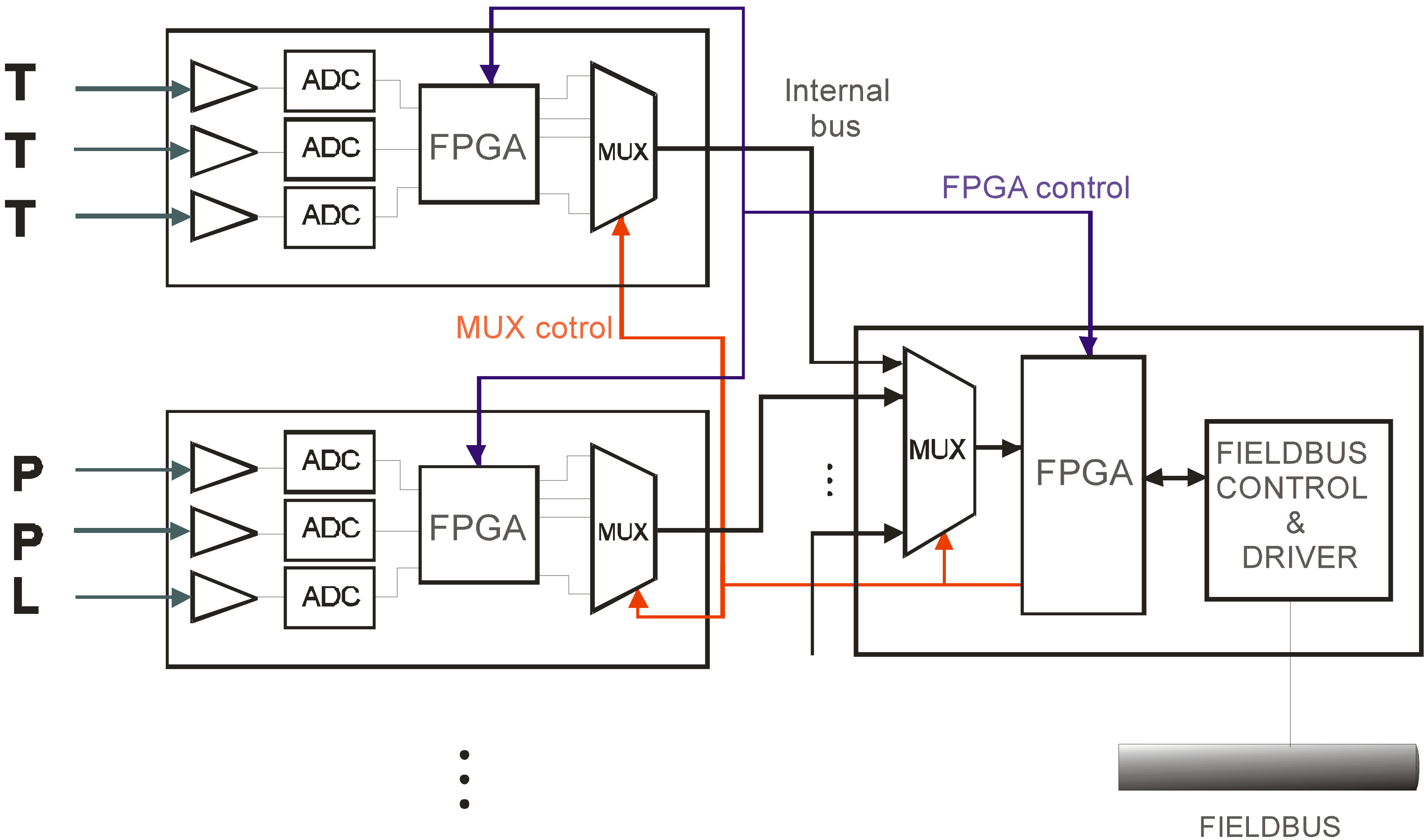
LHC/ACR/IN

Introduction

- The LHC machine will need more than 10 000 cryogenic sensors and actuators to control the temperature of the superconductor magnets, beam screen, HTS current leads …
- The cryogenic instrumentation will be distributed uniformly along the 27 Km long machine.
- The low signal amplitude obtained when measuring cryogenic sensors requires signal conditioning in close proximity to the sensors.
- The electronic system for signal conditioning and transmission will be located in crates placed under the main dipoles and will thus be exposed to the accelerator environmental radiation.

Instrumentation crates



Radiation constrains

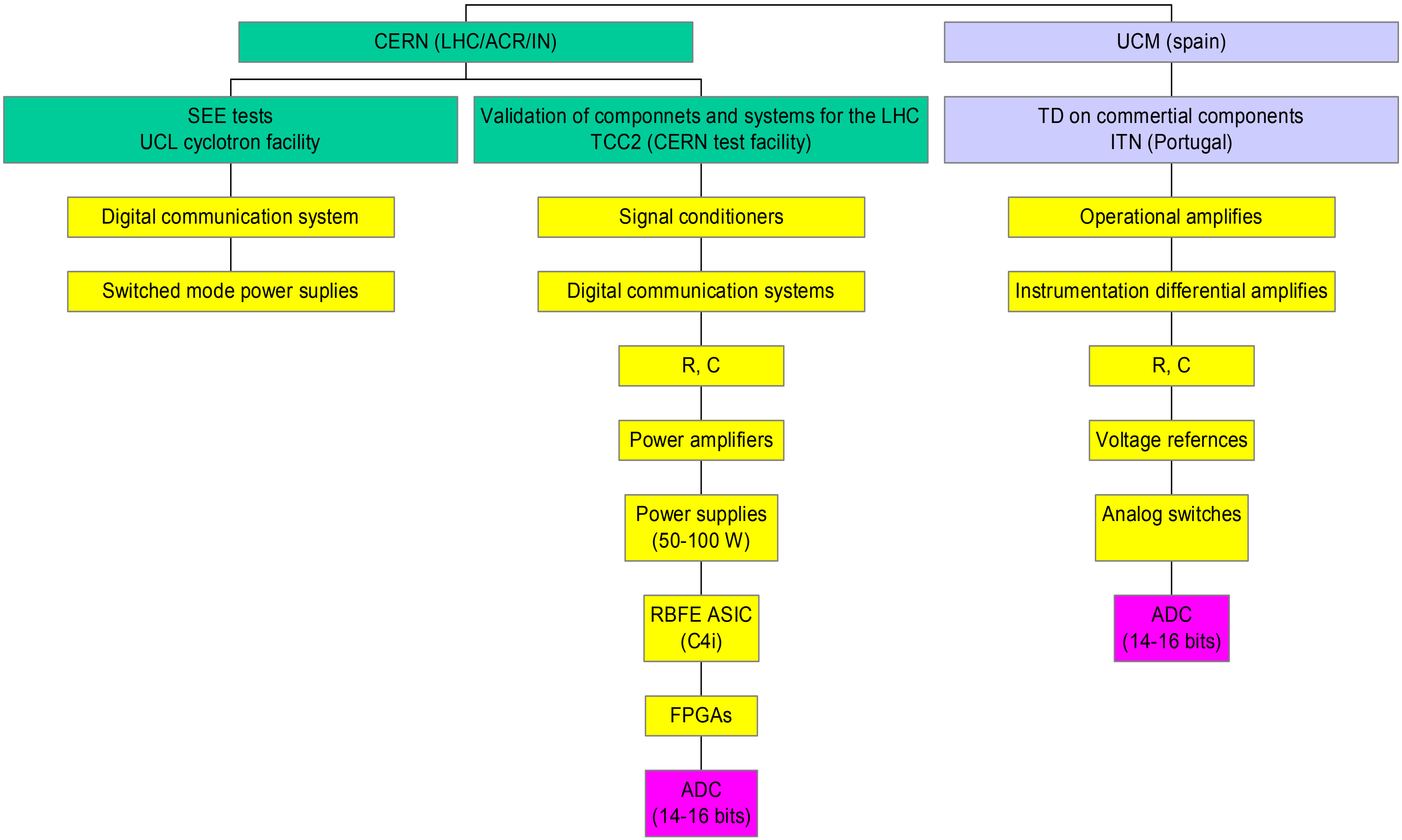
- In the LHC regular arcs low radiation dose are expected (2-6 Gy per year) and it should be straightforward to find radiation-tolerant commercial components.

- Along Dispersion Suppressor the dose may reach 60-200 Gy per year for which commercial components can still be used after careful selection.

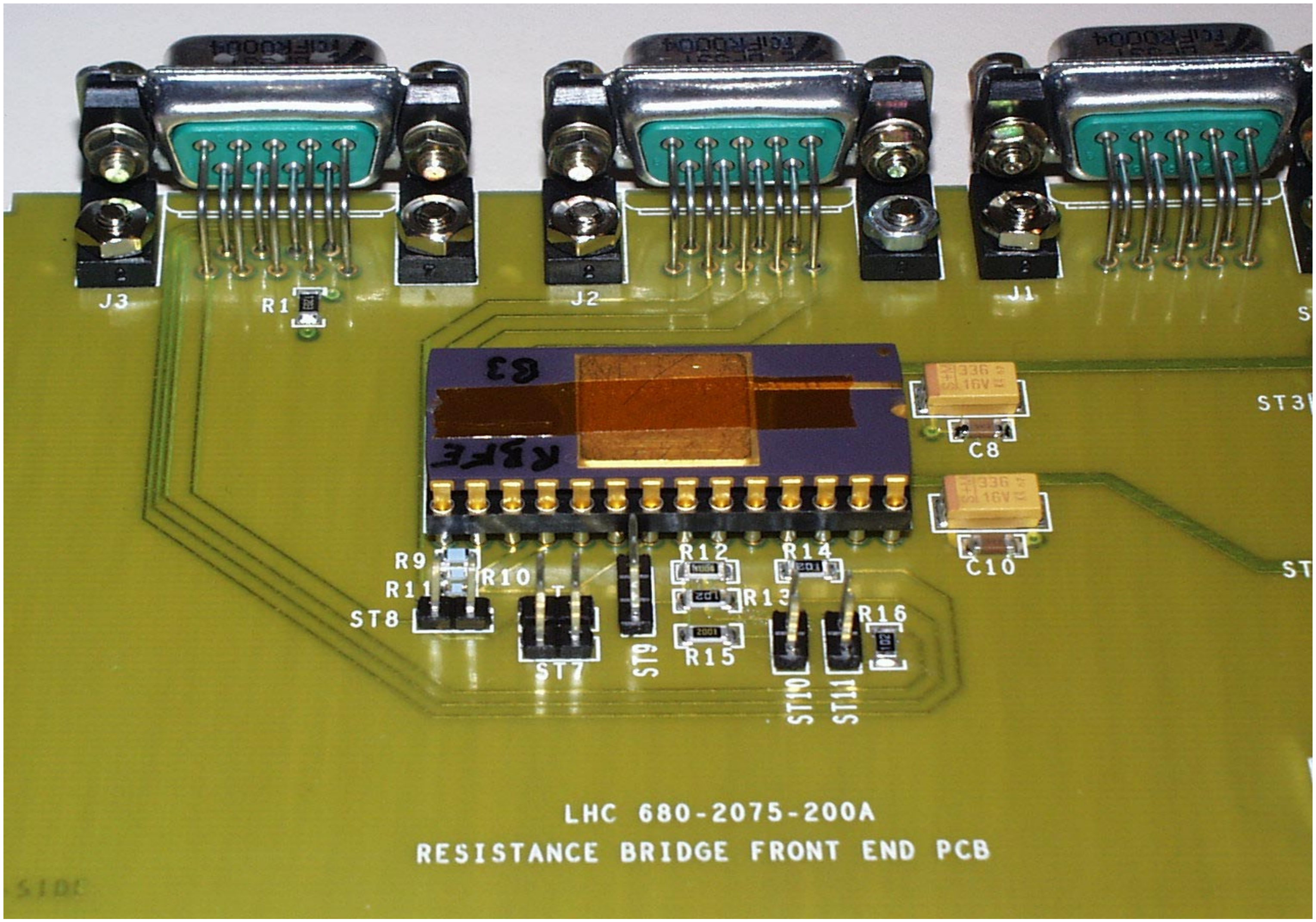
- Around the LHC points 1,3,5, and 7 the expected dose will exceed 1000 Gy per year, the degradation in the electronic components will be severe and many commercial components will not survive. (in this difficult zones the positioning of the electronic is critical and whenever possible access galleries should be used)

- Only a few radiation test per year can be performed because they are expensive and the access to the facility is not always possible.

Radiation test protocol for electronics



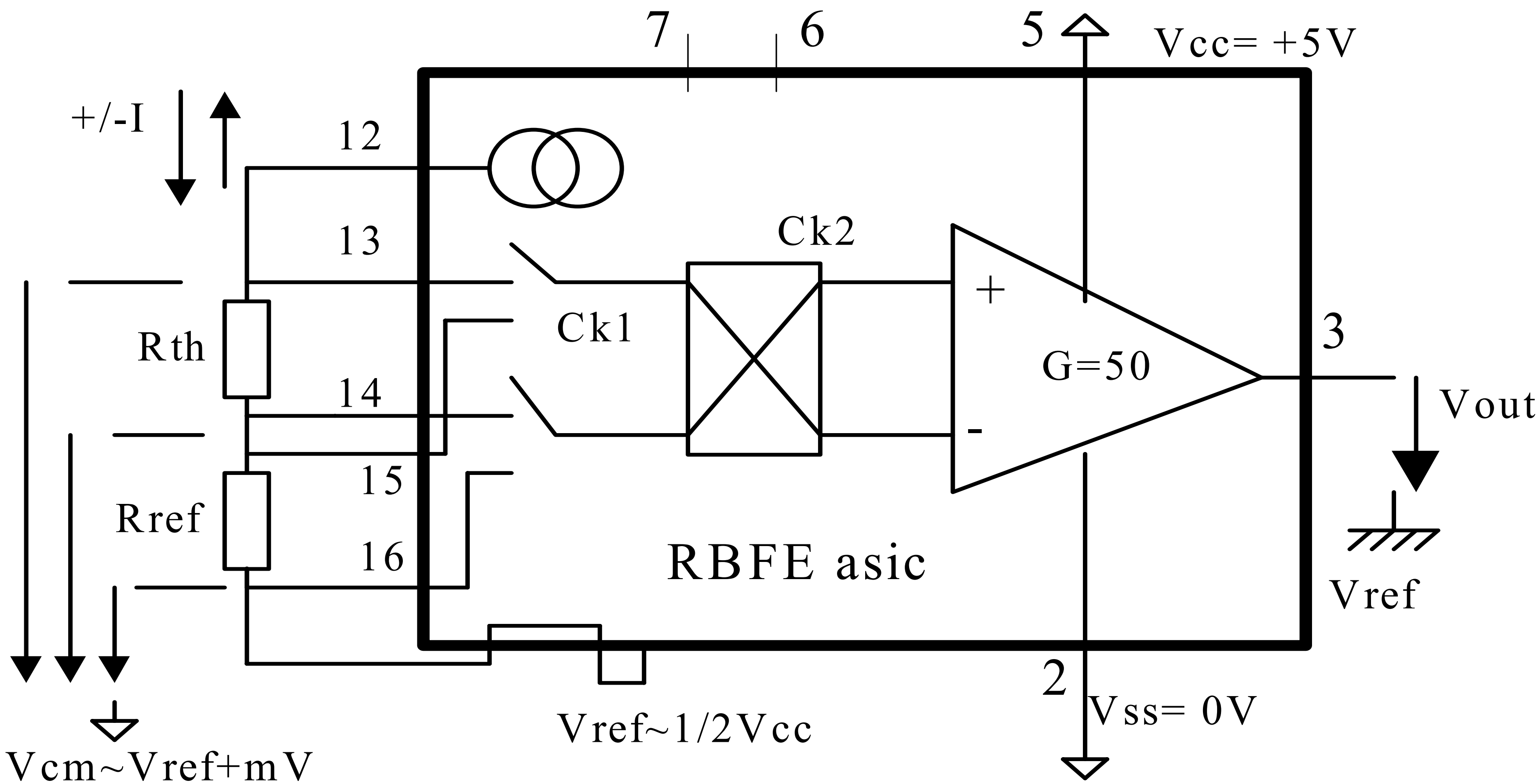
RBFE ASIC

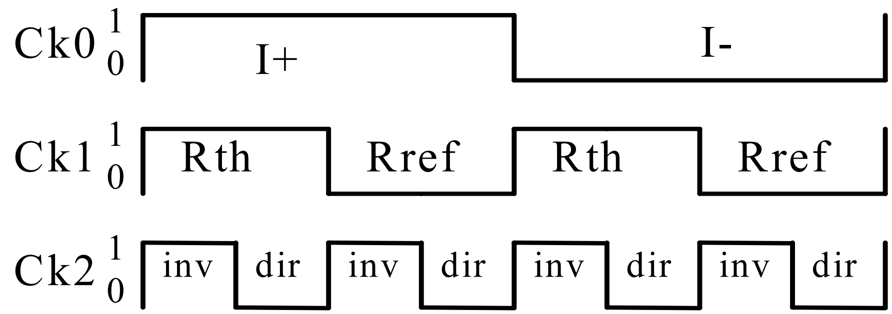

J3
R1
J2
J1
ST3
C8
C10
R9
R11
R10
ST8
ST7
ST9
R12
R13
R14
R15
R16
ST10
ST11
LHC 680-2075-200A
RESISTANCE BRIDGE FRONT END PCB

- RBFE is an ASIC developed by the French institution **C4i** for CERN in DMILL technology (25 - 30 CHF / unit).
- The RBFE is designed to work with semiconductor behavior temperature sensors.
- The ASIC implements four basic functions:
  - Bi-directional programmable current source (100 uA, 10 uA, 1 uA).
  - Analog switches.
  - Voltage reference 2.5 V.
  - Differential amplifier.
- The device has passed all functionality tests and its precision falls within the design constrains imposed by CERN.
- By using a reference (high precision thin-film resistor) the thermocouples effects, the ASIC offset voltage, power supply and ambient temperature dependences are compensated => auto-calibration system.
- Up to a certain limit the auto-calibration system correct also the effect of radiation on the device.
- The possibility to use the RBFE with Pressure sensors is under study.

RBFE ASIC

Fig. 1. RBFE chip doing 8 measurements of sensing and reference resistances.





$$WORD1(111) = V_{err} + A_{cm}.V_{cm1} - A_{dm}(R_{th}.I_{+} + V_{tc})$$

$$WORD2(110) = V_{err} + A_{cm}.V_{cm1} + A_{dm}(R_{th}.I_{+} + V_{tc})$$

$$WORD3(101) = V_{err} + A_{cm}.V_{cm2} - A_{dm}(R_{ref}.I_{+})$$

$$WORD4(100) = V_{err} + A_{cm}.V_{cm2} + A_{dm}(R_{ref}.I_{+})$$

$$WORD5(011) = V_{err} + A_{cm}.V_{cm1} - A_{dm}(R_{th}.I_{-} + V_{tc})$$

$$WORD6(010) = V_{err} + A_{cm}.V_{cm1} + A_{dm}(R_{th}.I_{-} + V_{tc})$$

$$WORD7(001) = V_{err} + A_{cm}.V_{cm2} - A_{dm}(R_{ref}.I_{-})$$

$$WORD8(000) = V_{err} + A_{cm}.V_{cm2} + A_{dm}(R_{ref}.I_{-})$$

$$WORD2 - WORD1 = 2A_{dm}(R_{th}.I_{+} + V_{tc})$$

$$WORD4 - WORD3 = 2A_{dm}(R_{ref}.I_{+})$$

$$WORD6 - WORD5 = 2A_{dm}(R_{th}.I_{-} + V_{tc})$$

$$WORD8 - WORD7 = 2A_{dm}(R_{ref}.I_{-})$$

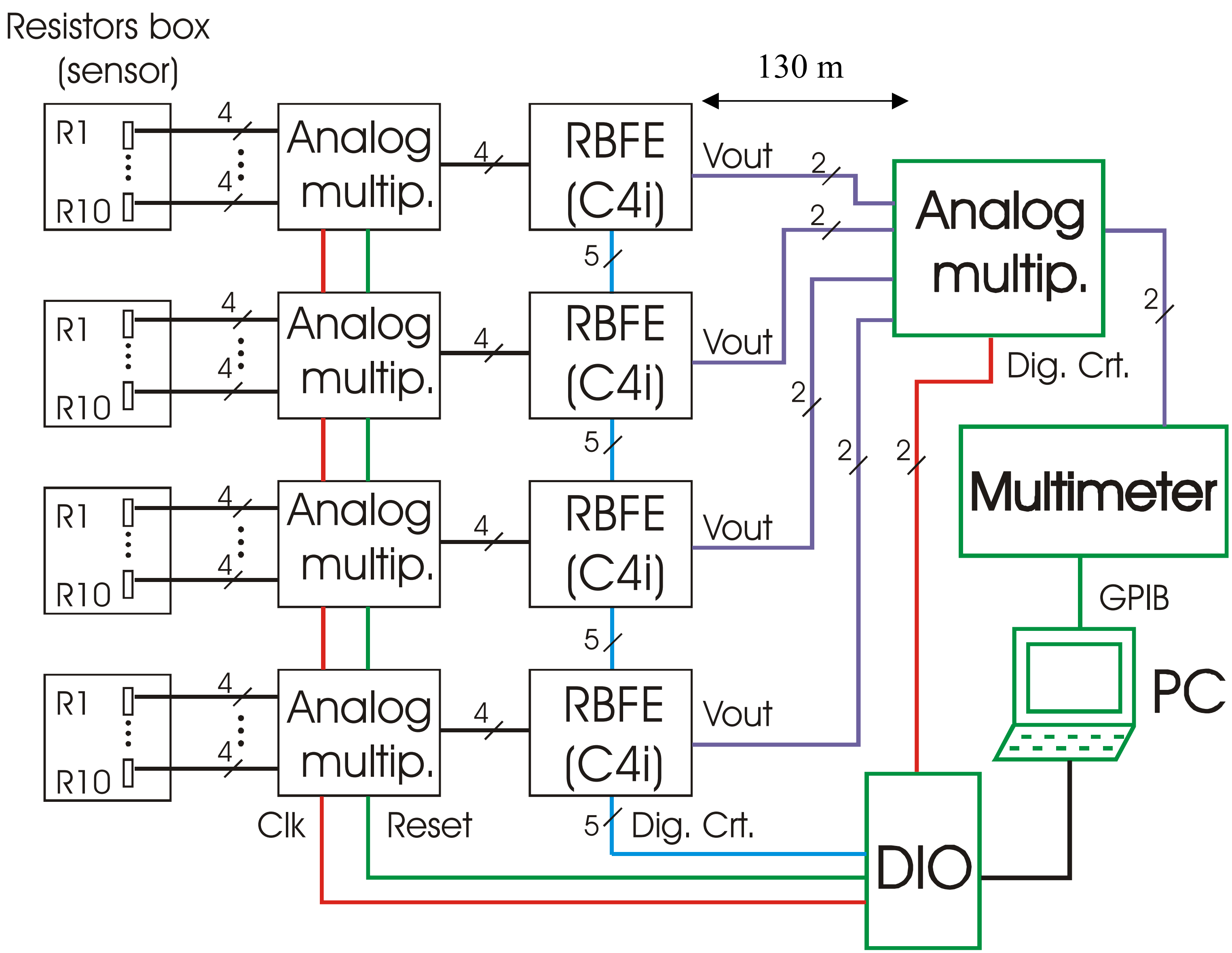
$$(WORD4 - WORD3) - (WORD8 - WORD7) = 2A_{dm}.R_{ref}(I_{+} - I_{-})$$

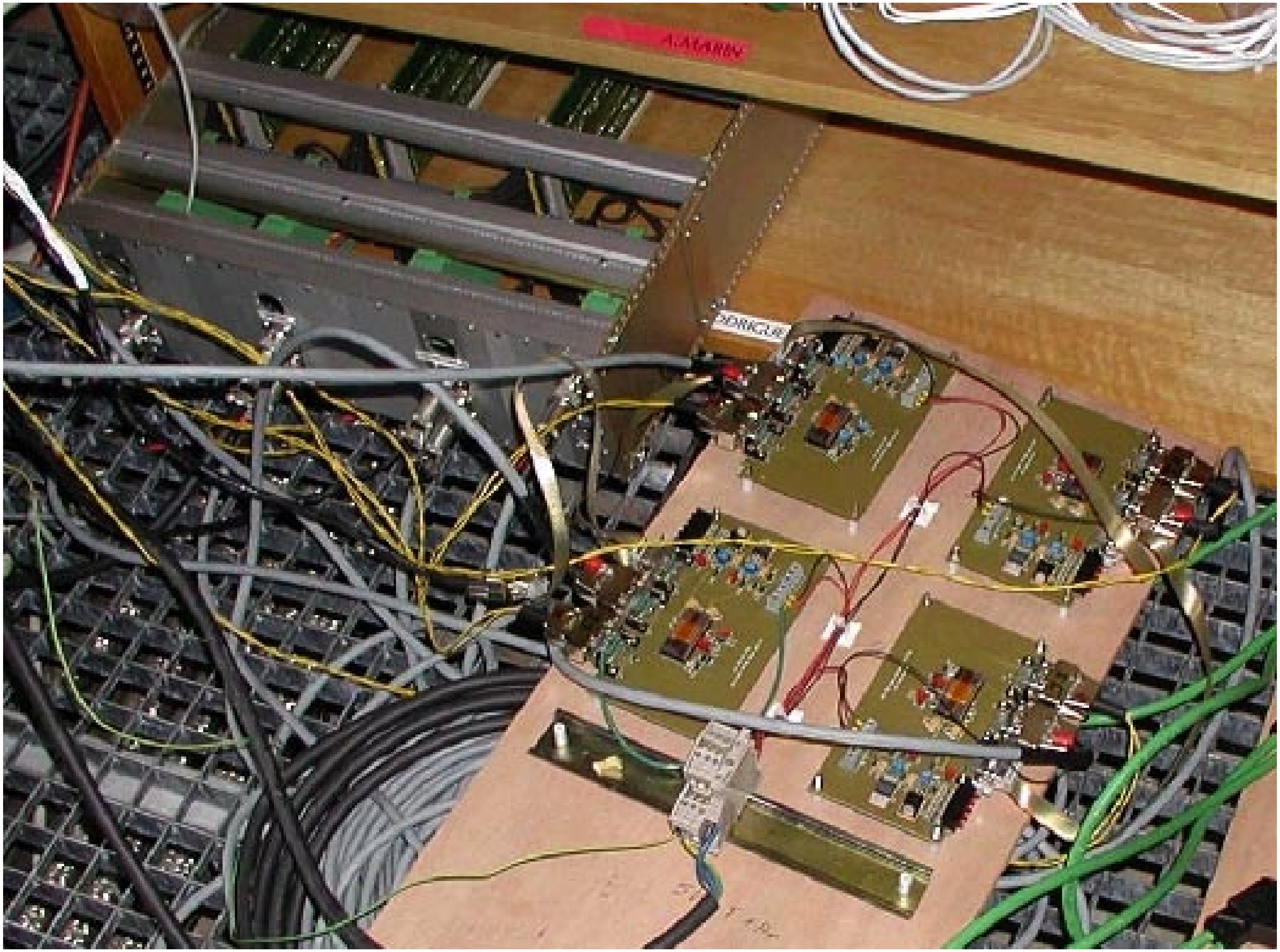
$$(WORD2 - WORD1) - (WORD6 - WORD5) = 2A_{dm}.R_{th}(I_{+} - I_{-})$$

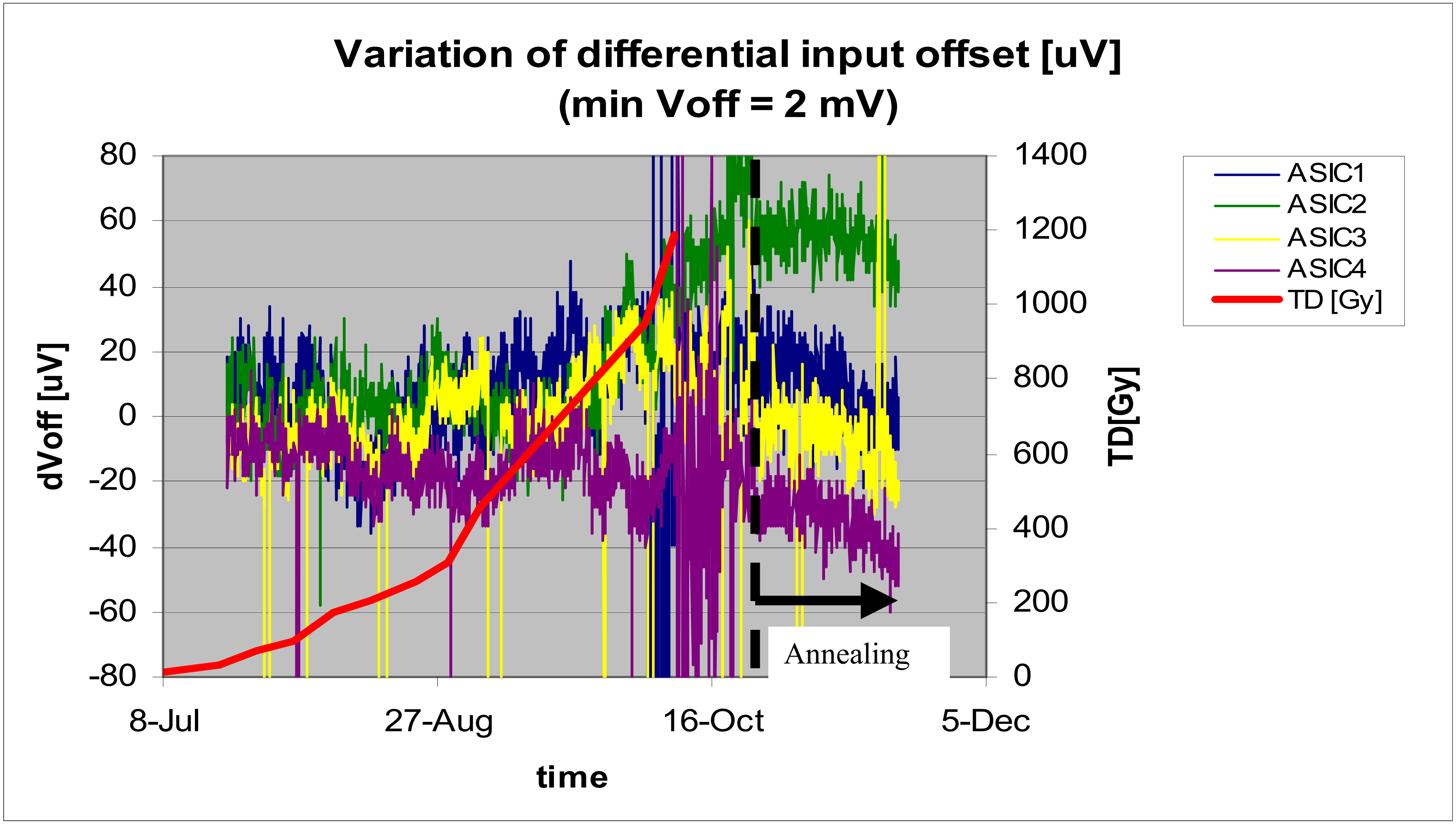
$$R_{th} = \frac{(WORD2 - WORD1) - (WORD6 - WORD5)}{(WORD4 - WORD3) - (WORD8 - WORD7)}.R_{ref}$$

RBFE radiation tests

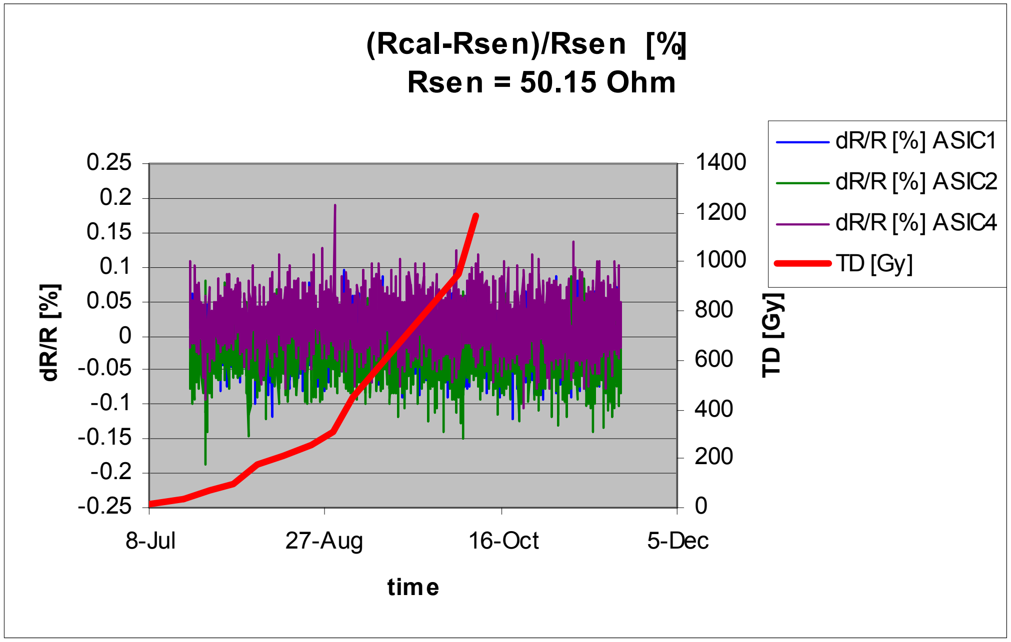
TCC2 RBFE experimental set-up

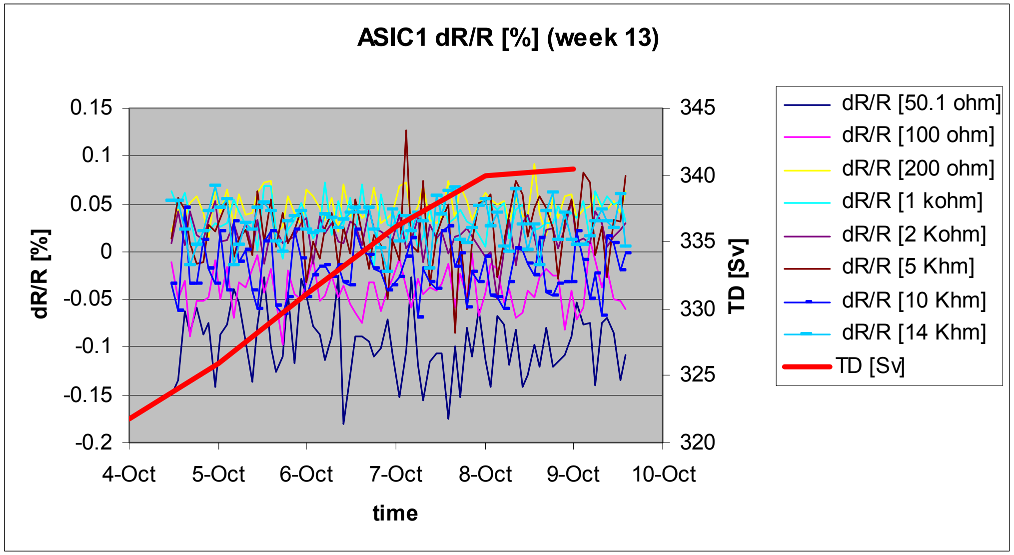



A.MARIN

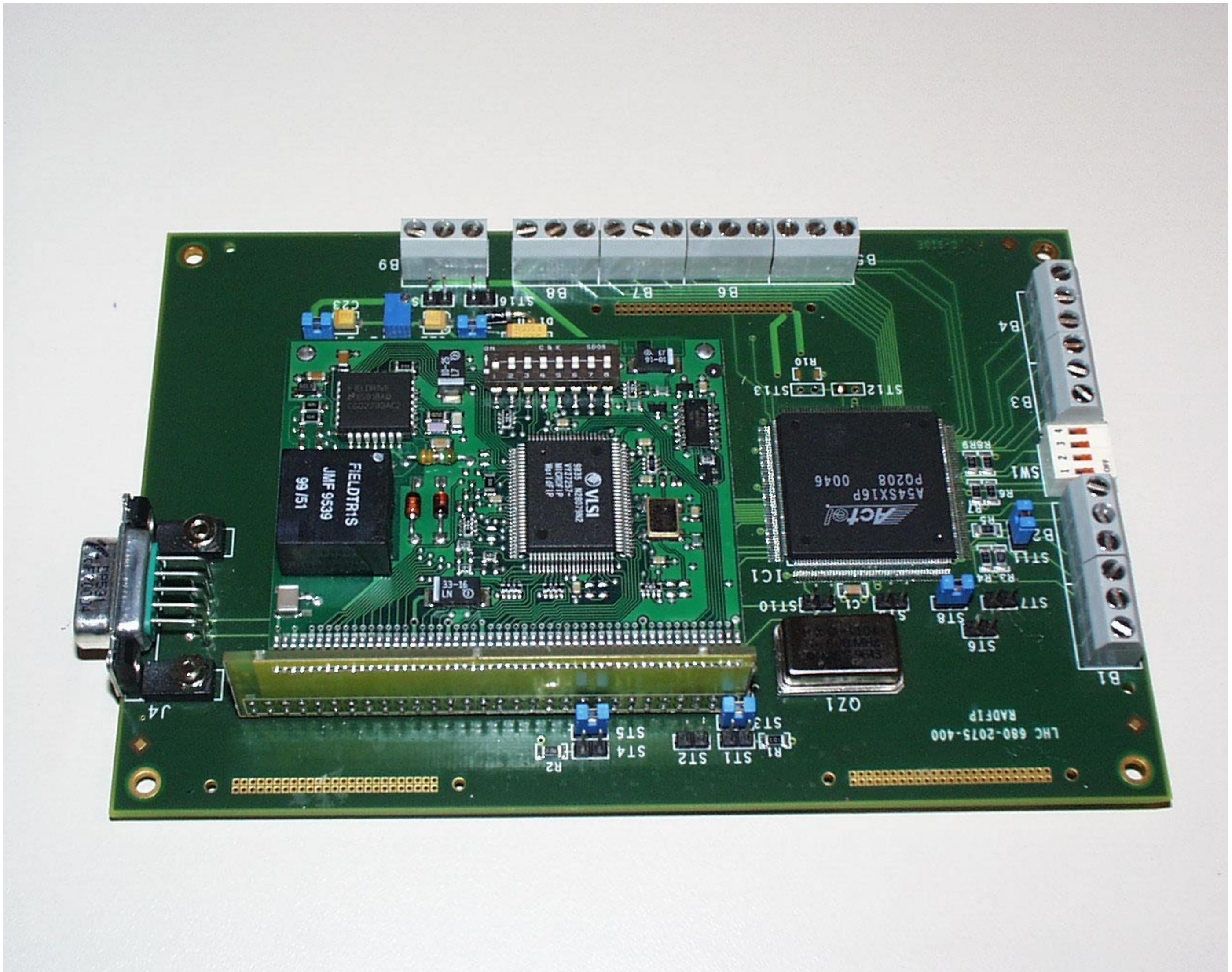


Voltage offset didn't reject after the ASIC auto-calibration operations


(Rcal-Rsen)/Rsen [%]
Rsen = 50.15 Ohm
dR/R [%] ASIC1
dR/R [%] ASIC2
dR/R [%] ASIC4
TD [Gy]
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
1400
1200
1000
800
600
400
200
0
dR/R [%]
TD [Gy]
8-Jul
27-Aug
16-Oct
5-Dec
time


ASIC1 dR/R [%] (week 13)
dR/R [50.1 ohm]
dR/R [100 ohm]
dR/R [200 ohm]
dR/R [1 kohm]
dR/R [2 Kohm]
dR/R [5 Khm]
dR/R [10 Khm]
dR/R [14 Khm]
TD [Sv]
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
345
340
335
330
325
320
dR/R [%]
TD [Sv]
4-Oct
5-Oct
6-Oct
7-Oct
8-Oct
9-Oct
10-Oct
time

Radfip



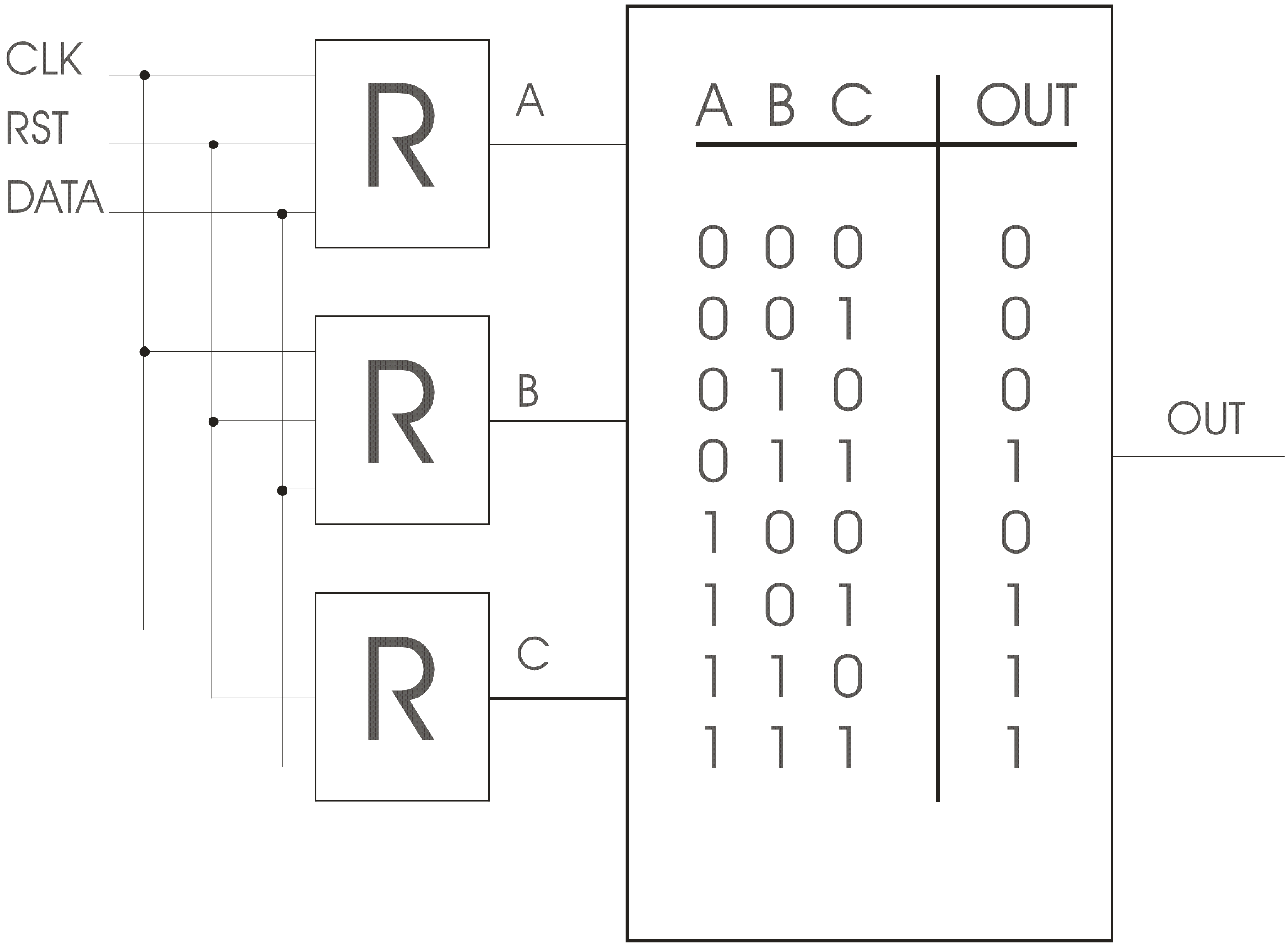
- Radfip is a digital communication system developed by LHC/ACR/IN based on the MICROFIP C131 board (Worldfip fieldbus protocol) and the ACTEL anti-fuse FPGA 54SX family used as micro-controller (40 – 80 CHF / channel).

- In order to avoid SEU on the digital system the FPGA has been programmed with a voting system (Triple Module Redundancy) and the MICROFIP memory will be rewritten every 10-20 ms.

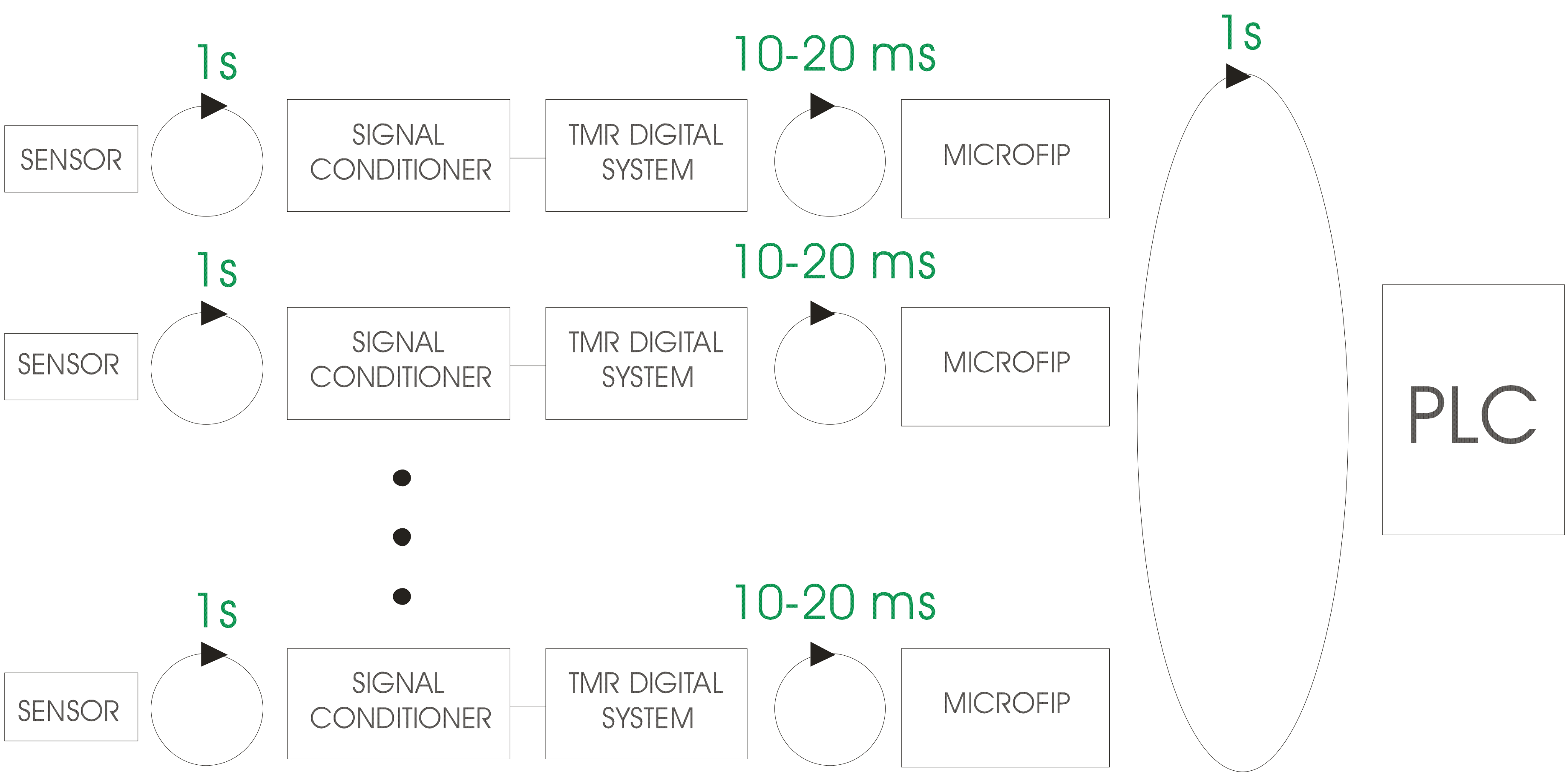
- Radiation test has been performed, with very promising results, at UCL cyclotron facilities (SEE) and CERN's TCC2 (TD).

- The net increase of current consumption versus the Total Ionizing Dose is the only adverse result. Direct consequence is the increment of power consumption leading to higher operating temperatures thus reducing the component lifetime.

FPGA Triple Module Redundancy



Memory refreshment strategy

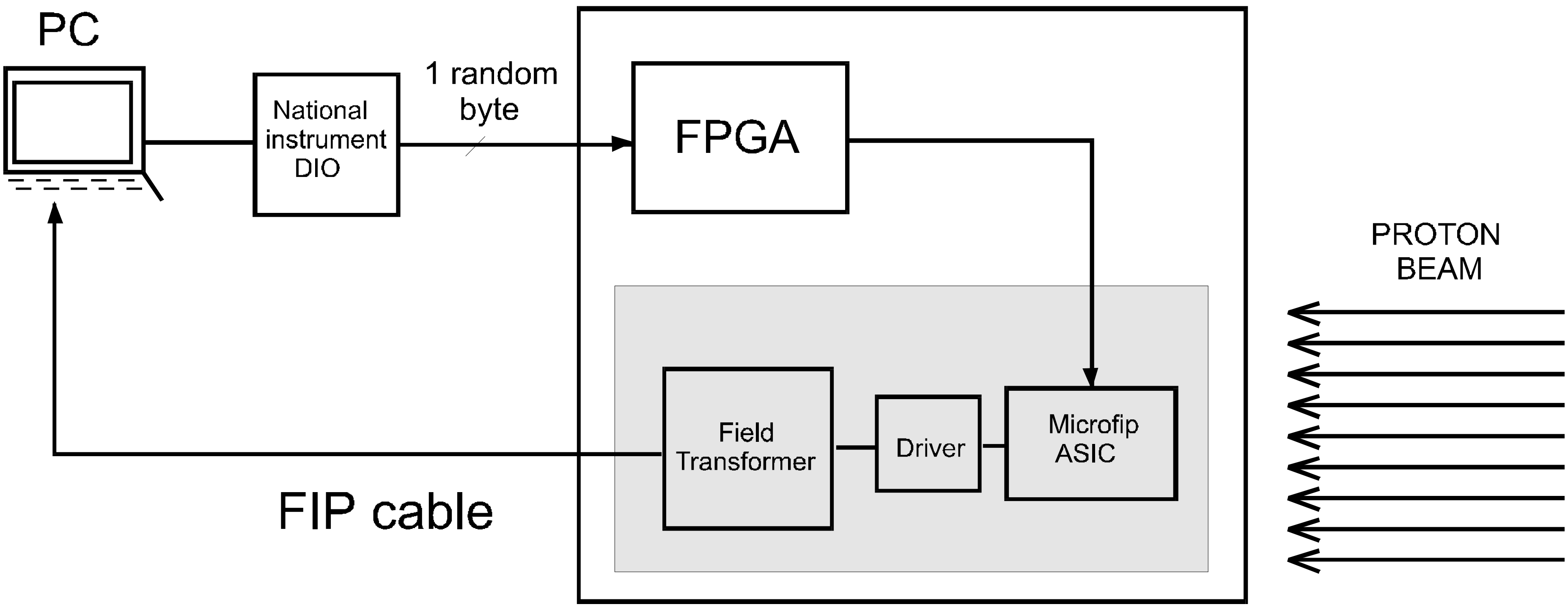


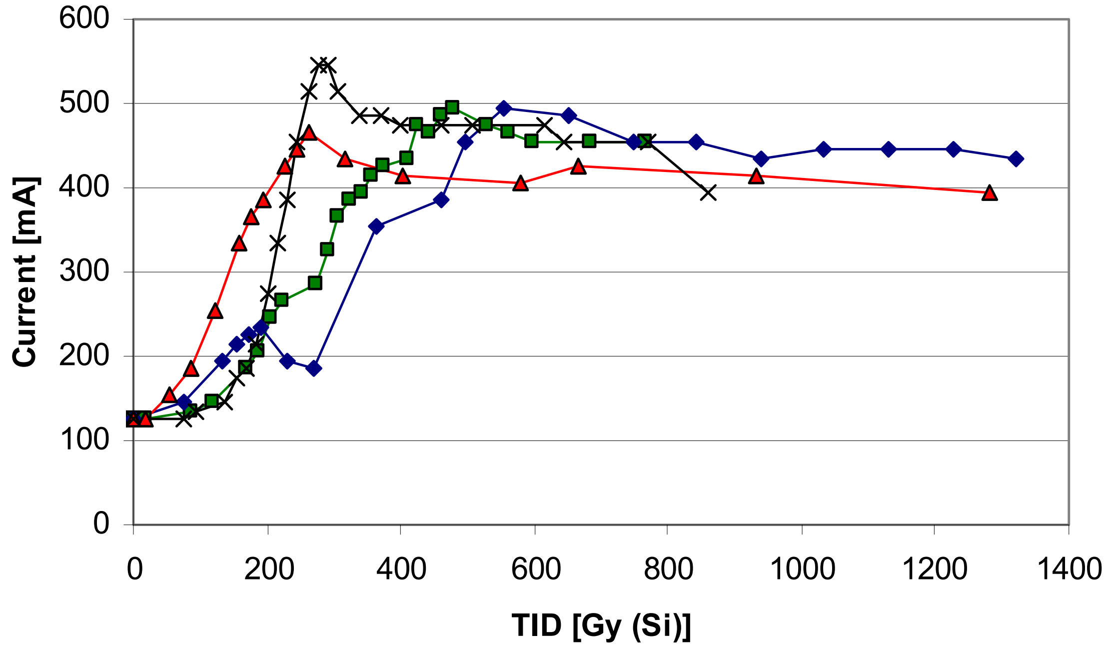
Radfip radiation tests

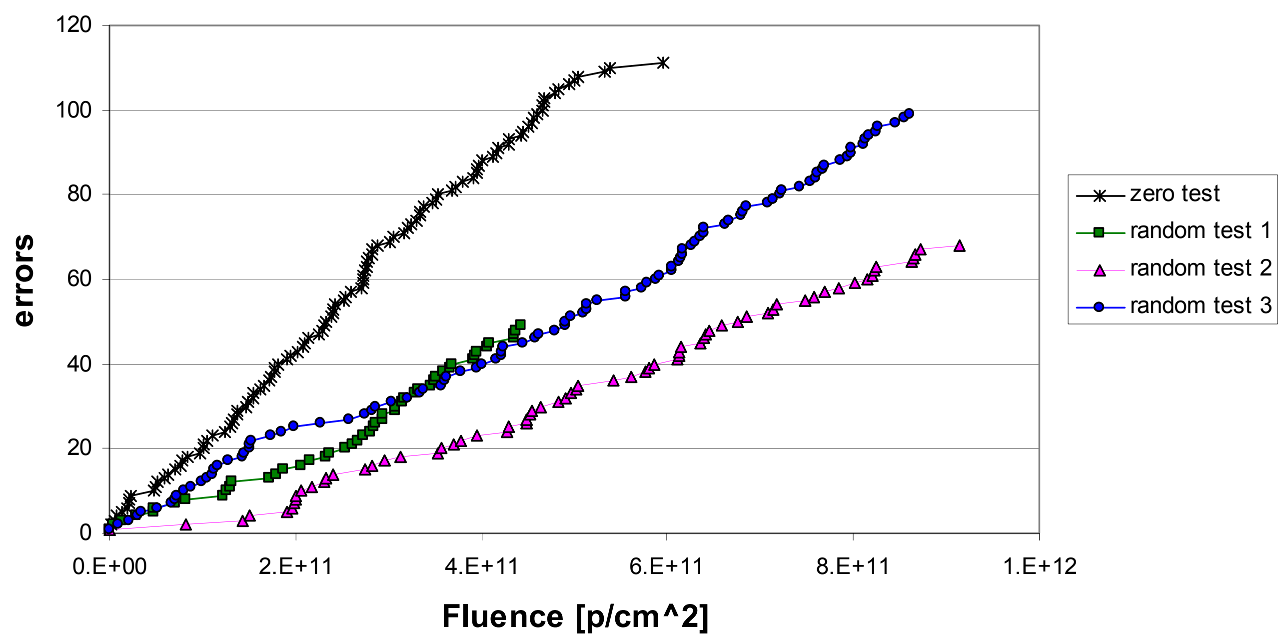
SEE test

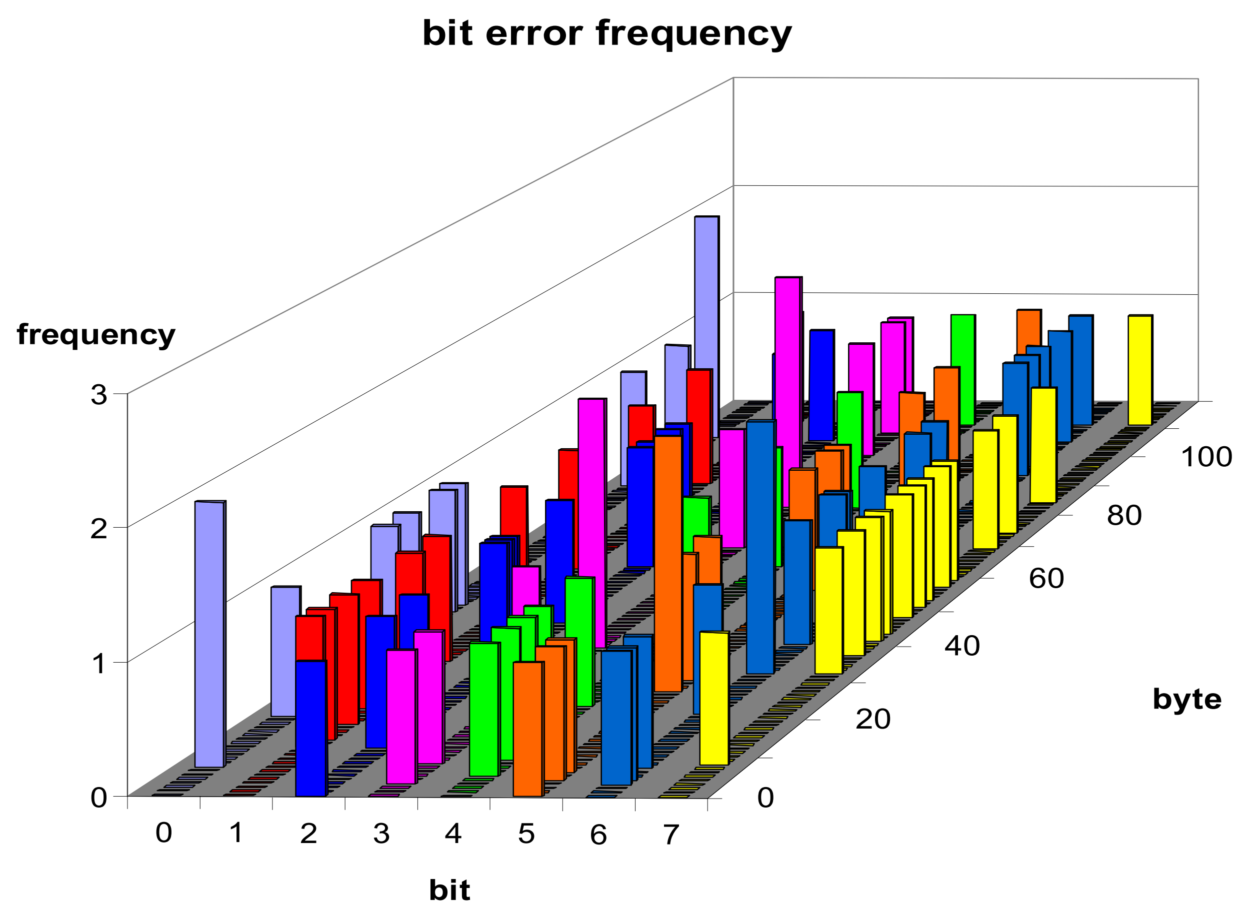
- SEE tests have been performed at the UCL cyclotron in Belgium.
- The proton beam intensity was adjusted to 2 10^{8} p. cm^{-2}.s^{-1} and the energy to 60 Mev.
- Four C131 MICROFIP boards were tested. Three of them used random bytes and the last one was forced to all-zero memory.
- In the experimental set-up all bytes of the memory zone for dynamic variables were investigated.
- Each board was tested during approximately one hour. All boards survive a TID of 700 Gy and only one dead at 800 Gy.
- Only one SEU involving the reset of the MICROFIP unit was obtained (SEU in a configuration register).
- No Latch-Up detected in any tested unit.
- In some memory cells 1 to 0 transitions were observed but the 97% were transitions from 0 to 1.

SEU experimental set-up

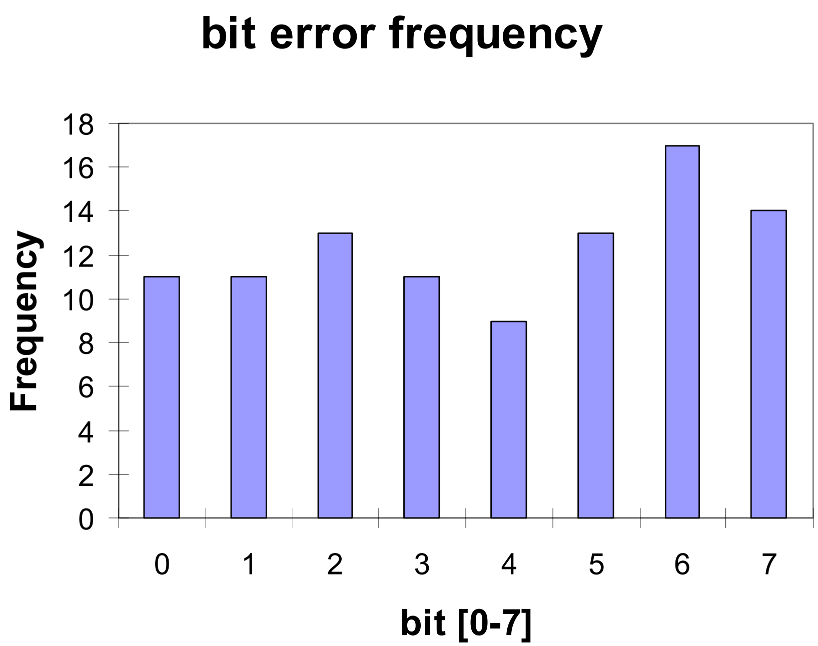


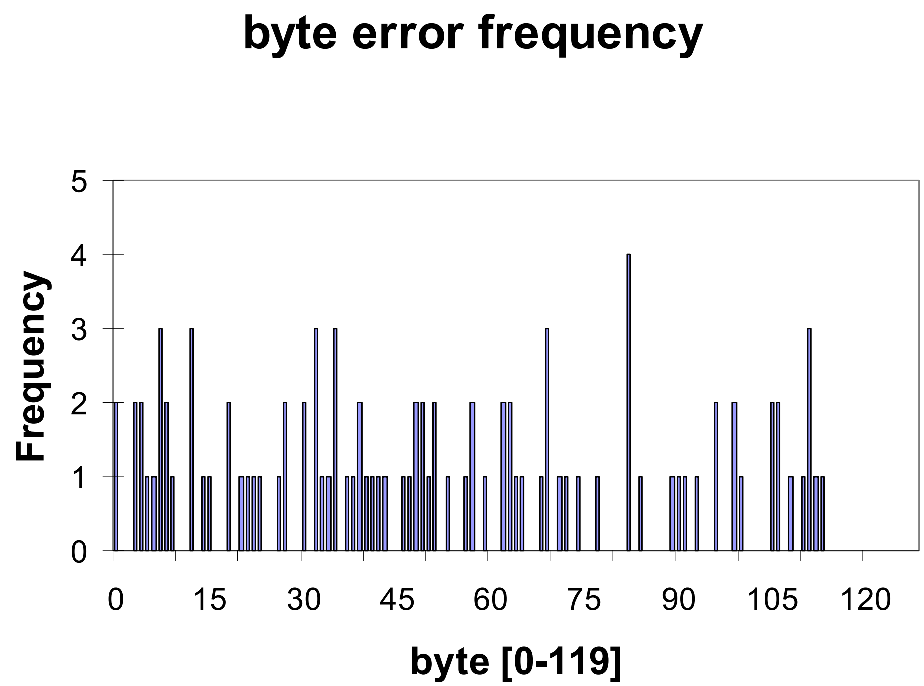

600
500
400
300
200
100
0
Current [mA]
0
200
400
600
800
1000
1200
1400
TID [Gy (Si)]


120
100
80
60
40
20
0
errors
0.E+00
2.E+11
4.E+11
6.E+11
8.E+11
1.E+12
Fluence [p/cm^2]
zero test
random test 1
random test 2
random test 3



Number of SEU errors detected through MICROFIP dynamic memory indicating the exact byte and bit position (Board 3).

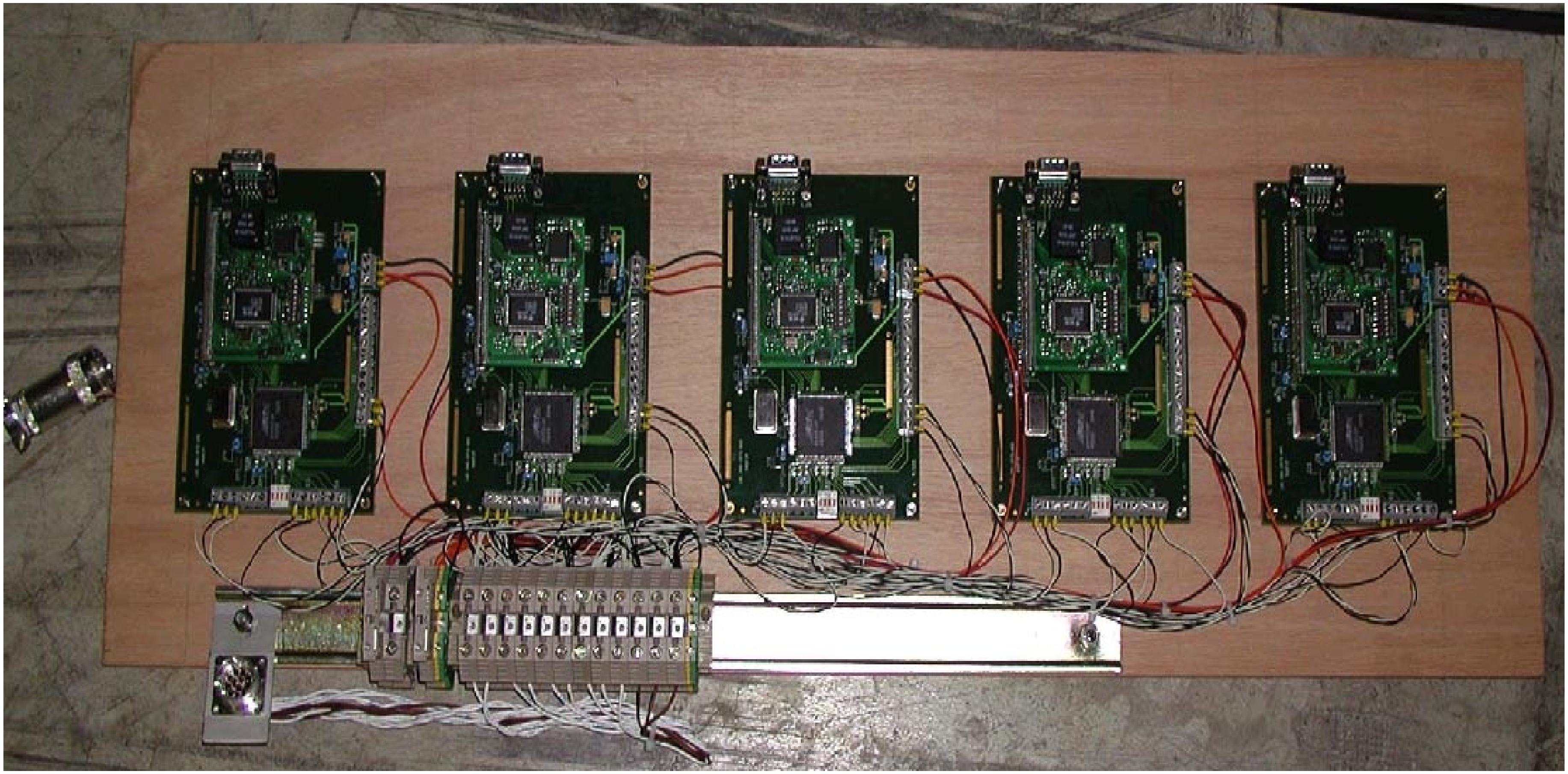




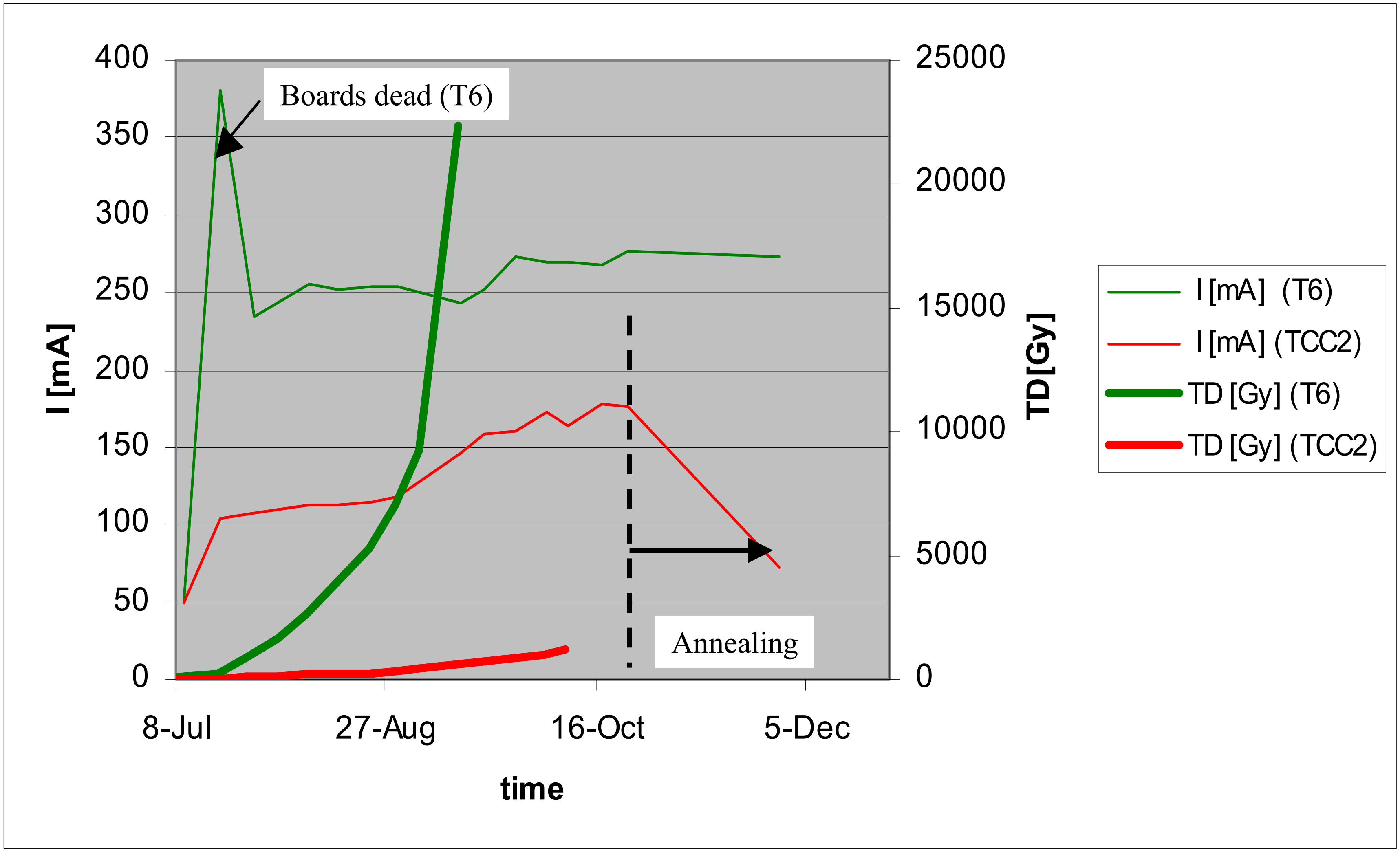
Projection of the SEU errors detected in terms of bit and byte position.

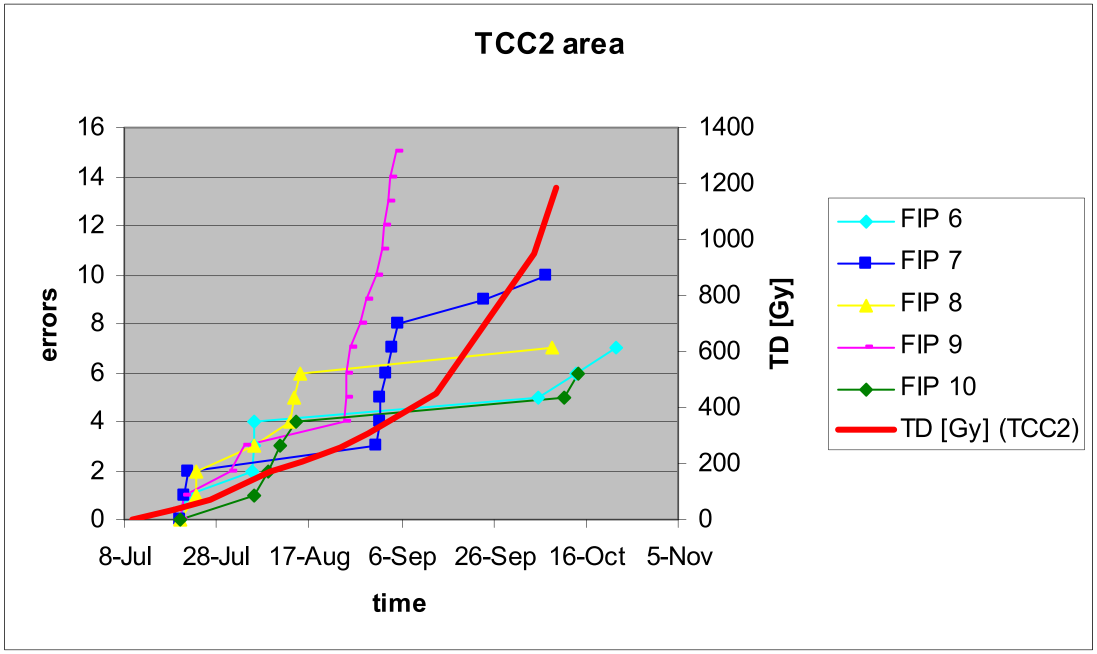
Radfip TCC2 tests

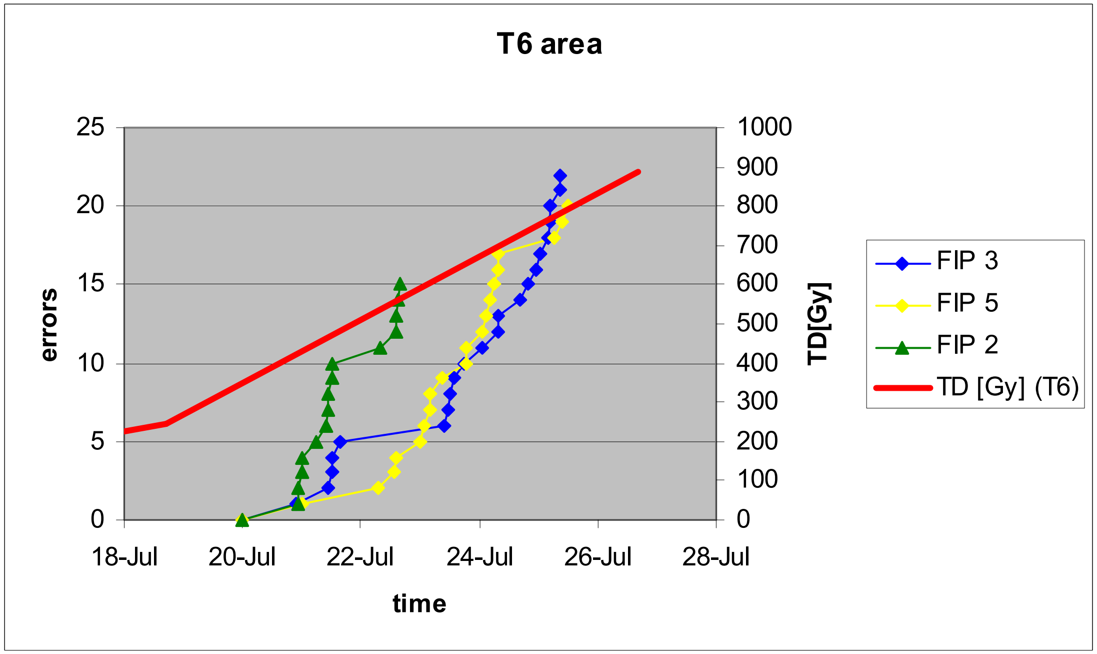
- 5 electronic boards were placed in TCC2 area (low dose rate).
- 5 electronic boards were placed in T6 area (high dose rate).
- As expected direct dependence of the current consumption with the dose rate was observed.
- All boards placed in TCC2 area are still running without problems (1400 Gy and 6 10^{13} n/cm2).
  - **8 errors per week and board predicted but only 0.6 per week and board detected.**
  - **The board current consumption increase by a factor 3.2 versus the initial value.**
- All boards placed in T6 area dead during the first month of radiation (900 Gy).
  - 48 **errors per week and board detected.**
  - **The board current consumption increase by a factor 5.6 versus the initial value.**



Radfip current consumption



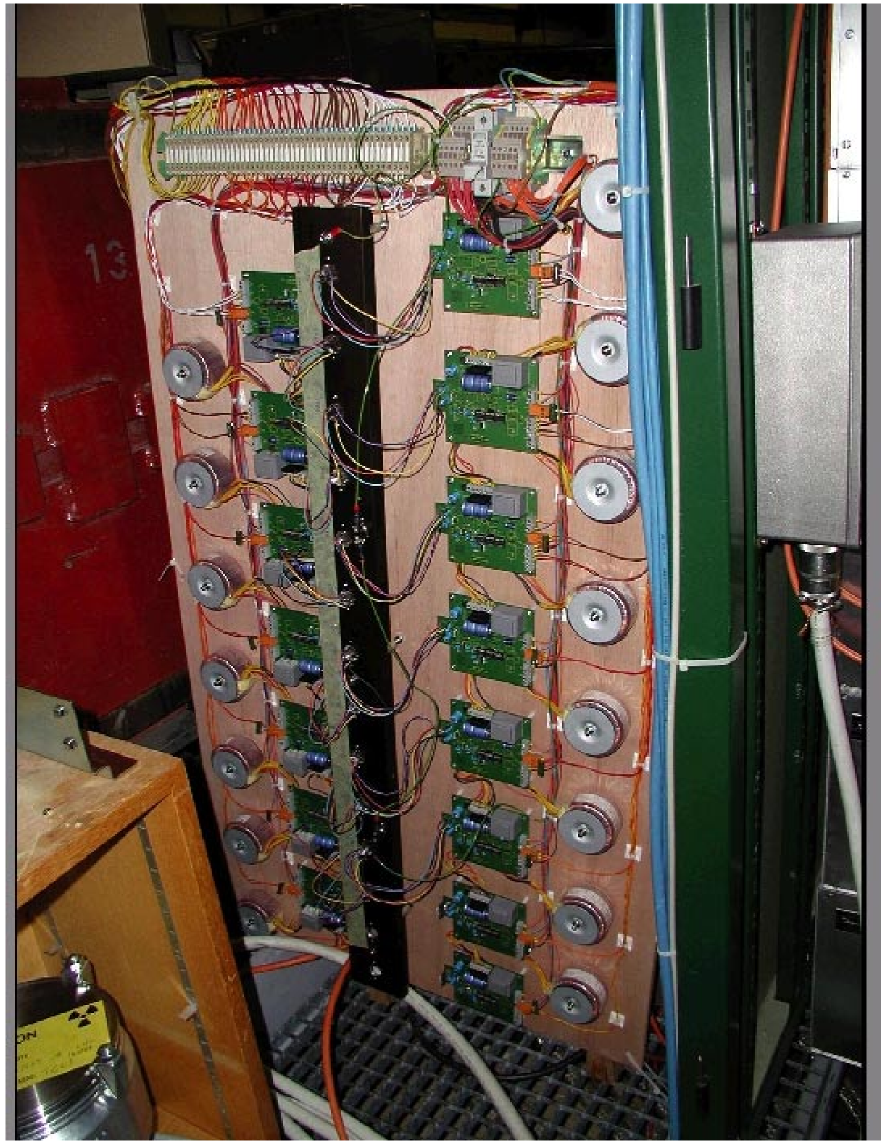

TCC2 area
errors
16
14
12
10
8
6
4
2
0
1400
1200
1000
800
600
400
200
0
TD [Gy]
8-Jul
28-Jul
17-Aug
6-Sep
26-Sep
16-Oct
5-Nov
time
FIP 6
FIP 7
FIP 8
FIP 9
FIP 10
TD [Gy] (TCC2)


T6 area
errors
25
20
15
10
5
0
1000
900
800
700
600
500
400
300
200
100
0
TD[Gy]
18-Jul
20-Jul
22-Jul
24-Jul
26-Jul
28-Jul
time
FIP 3
FIP 5
FIP 2
TD [Gy] (T6)

SEU predictions for the LHC

- From the experimental results the error cross section is estimated to 1.04 10^{-10} errors.cm ^{2}.
- The device error cross section (errors.cm ^{2}) and the LHC particles fluence and energy spectrum are necessaries to calculate the the expected number of errors in our transmission system.
- On the LHC regular arcs the expected flux of hadrons with E > 20 Mev is 3.6 10^{9} h /cm ^{2}.
- By assuming memory refreshment strategies we can expect the following total number of SEU errors per year:
  - **Regular arcs: 0.1 – 0.2 error per node.**
  - **DS: 3 – 60 error per node.**
  - **Betatron Scraper : 100 – 2000 error per node + permanent damage.**

Power supplies



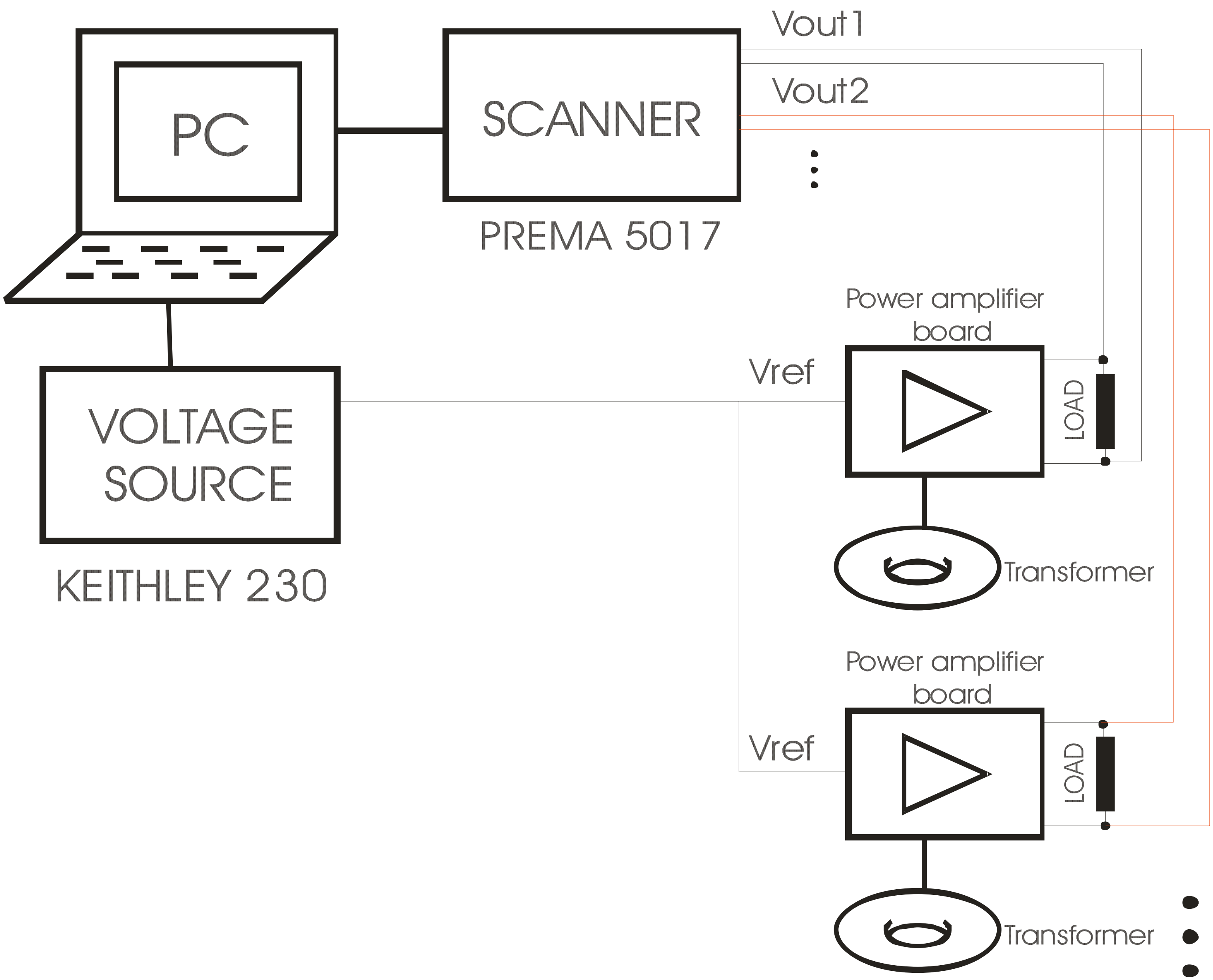
- Analog power supplies (heaters) based on some power amplifiers has been developed by LHC/ACR/IN.

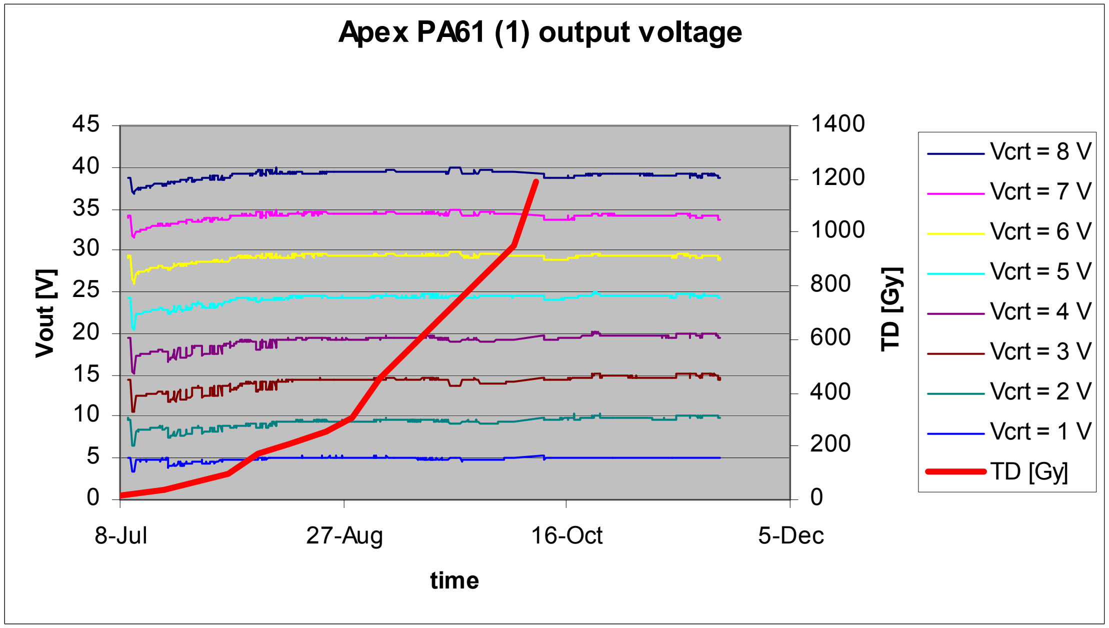
- 15 Power supplies were placed in TCC2 area in order to study the degradation on the power amplifiers (5 families) with the total dose.

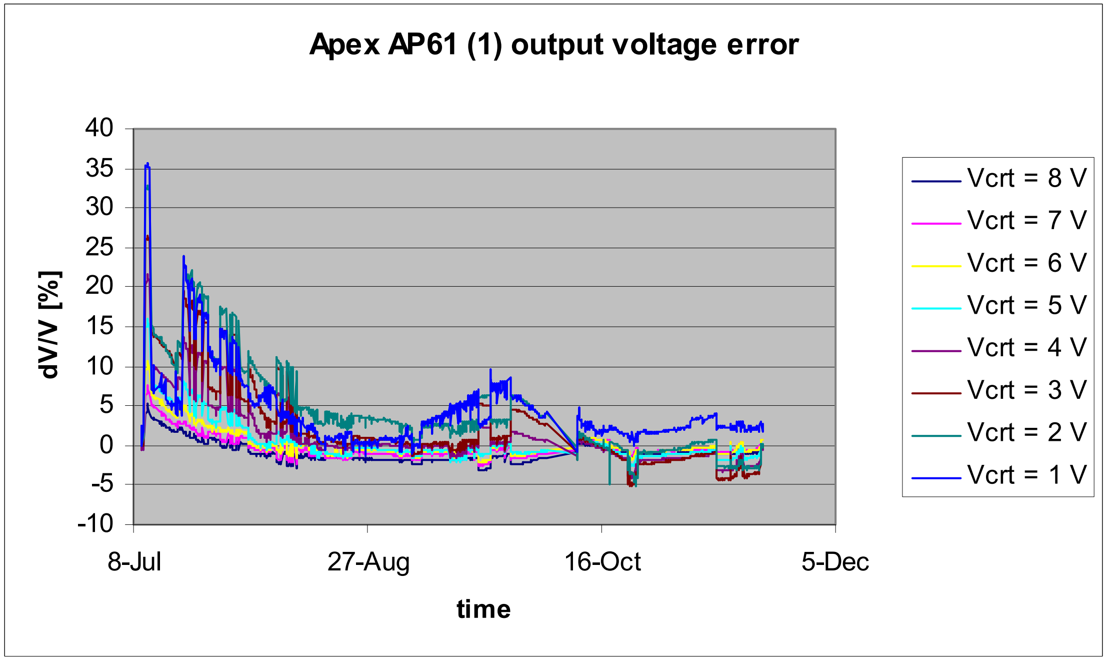
- All power supplies are still running at different degradation levels depending on the Power amplifier used.

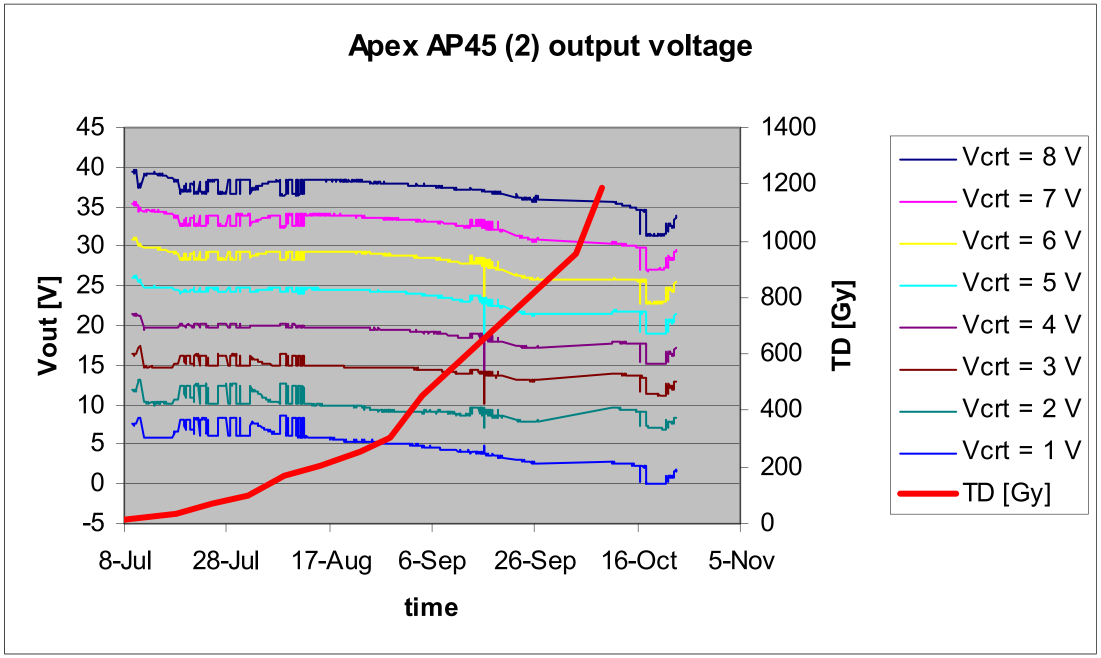
- Unexplained interference effects have been observed.

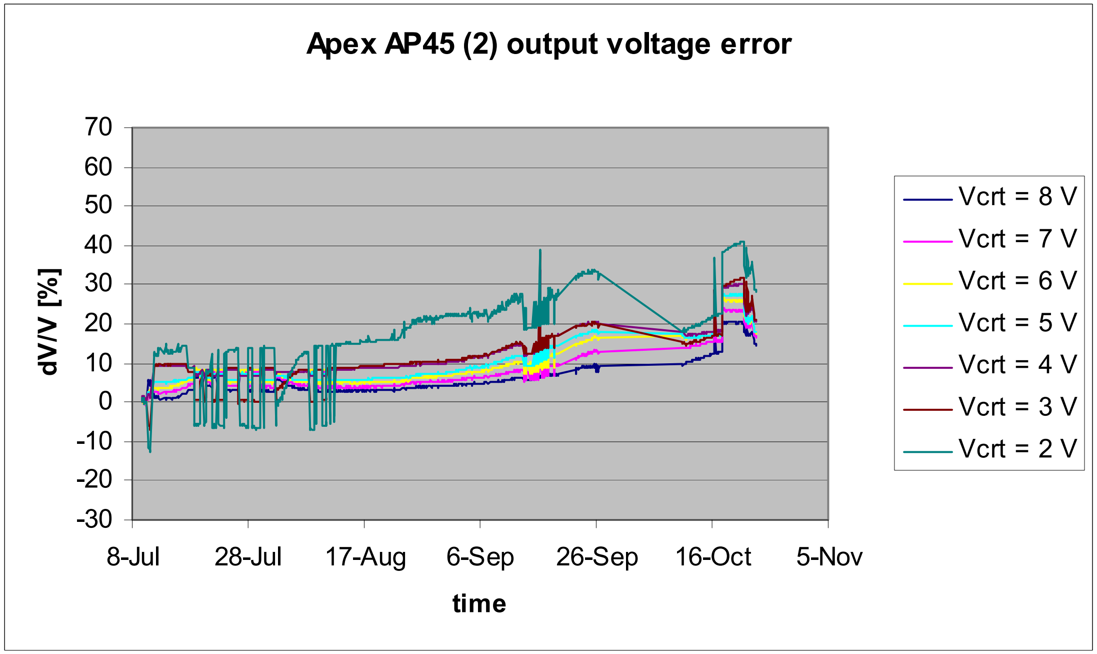
Power supplies experimental set-up




Apex PA61 (1) output voltage
Vout [V]
TD [Gy]
time
45
40
35
30
25
20
15
10
5
0
1400
1200
1000
800
600
400
200
0
8-Jul
27-Aug
16-Oct
5-Dec
Vcrt = 8 V
Vcrt = 7 V
Vcrt = 6 V
Vcrt = 5 V
Vcrt = 4 V
Vcrt = 3 V
Vcrt = 2 V
Vcrt = 1 V
TD [Gy]


Apex AP61 (1) output voltage error
dV/V [%]
time
40
35
30
25
20
15
10
5
0
-5
-10
8-Jul
27-Aug
16-Oct
5-Dec
Vcrt = 8 V
Vcrt = 7 V
Vcrt = 6 V
Vcrt = 5 V
Vcrt = 4 V
Vcrt = 3 V
Vcrt = 2 V
Vcrt = 1 V


Apex AP45 (2) output voltage
Vout [V]
TD [Gy]
45
40
35
30
25
20
15
10
5
0
-5
1400
1200
1000
800
600
400
200
0
8-Jul
28-Jul
17-Aug
6-Sep
26-Sep
16-Oct
5-Nov
time
Vcrt = 8 V
Vcrt = 7 V
Vcrt = 6 V
Vcrt = 5 V
Vcrt = 4 V
Vcrt = 3 V
Vcrt = 2 V
Vcrt = 1 V
TD [Gy]


Apex AP45 (2) output voltage error
dV/V [%]
70
60
50
40
30
20
10
0
-10
-20
-30
8-Jul
28-Jul
17-Aug
6-Sep
26-Sep
16-Oct
5-Nov
time
Vcrt = 8 V
Vcrt = 7 V
Vcrt = 6 V
Vcrt = 5 V
Vcrt = 4 V
Vcrt = 3 V
Vcrt = 2 V