Report on Running Channels in iseg 32-Ch HV Power Supplies

DRAFT, 15 November 2006

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We report a study and solution of the so-called "running channel" (**RC**) phenomenon observed in the iseg[d] 32-channel HV power supplies for the ATLAS Liquid Argon Calorimetry.

Description of the RC phenomenon

In the iseg PS's in question, each group of 16 channels is supplied with a single bulk high voltage supply, which is regulated at about 50 V above the highest voltage requested, with a minimum of 900 V (for 2 kV PS's) or 1500 V (for 2500 V units). In each individual channel this bulk voltage is regulated down to the required value by a per-channel series regulator, hereafter called "voltage regulator" (**VR**).

Per channel actually *two* voltage regulators *in series* are used, to insure that the maximum voltage drop $\mathbf{V_{drop}}$ across a single unit doesn't exceed the rated value of 1500 V per regulator. The VR goes into a “controlled avalanche”, exhibiting a “knee” in the reverse bias current versus V_{drop}, for voltages above 1600 V. The VR has a low-voltage control side; the rated “isolation voltage” $\mathbf{V_{iso}}$ between control and high voltage sides is 5 kV.

The VR devices are specified to have a maximum leakage current (off-state current) of 10 μA at 1500 V. This *maximum* leakage current by itself is much larger than is acceptable to us, as it would develop about 500 V across the 50 MΩ voltage divider in the channel output (and 350 V/μA leakage over the 350 MΩ dividers!). However, the *typical* leakage currents, as measured by iseg, are of order 1-10 nA, and are thus quite acceptable.

The RC phenomenon is a substantial increase, after hours to weeks of operation, of the leakage current in channels of a HV power supply module. This was observed initially for many of the 256 HV-channels being tested at CERN.

Those leakage currents cause a potentially dangerous increase in voltage output on such a channel if it is either "off" or at a significantly lower voltage than the bulk high voltage value. The voltage build-up occurs when the HV PS's are used to supply a capacitive device like our calorimeter, which sinks zero current in a low-luminosity situation (compare Figure 1).

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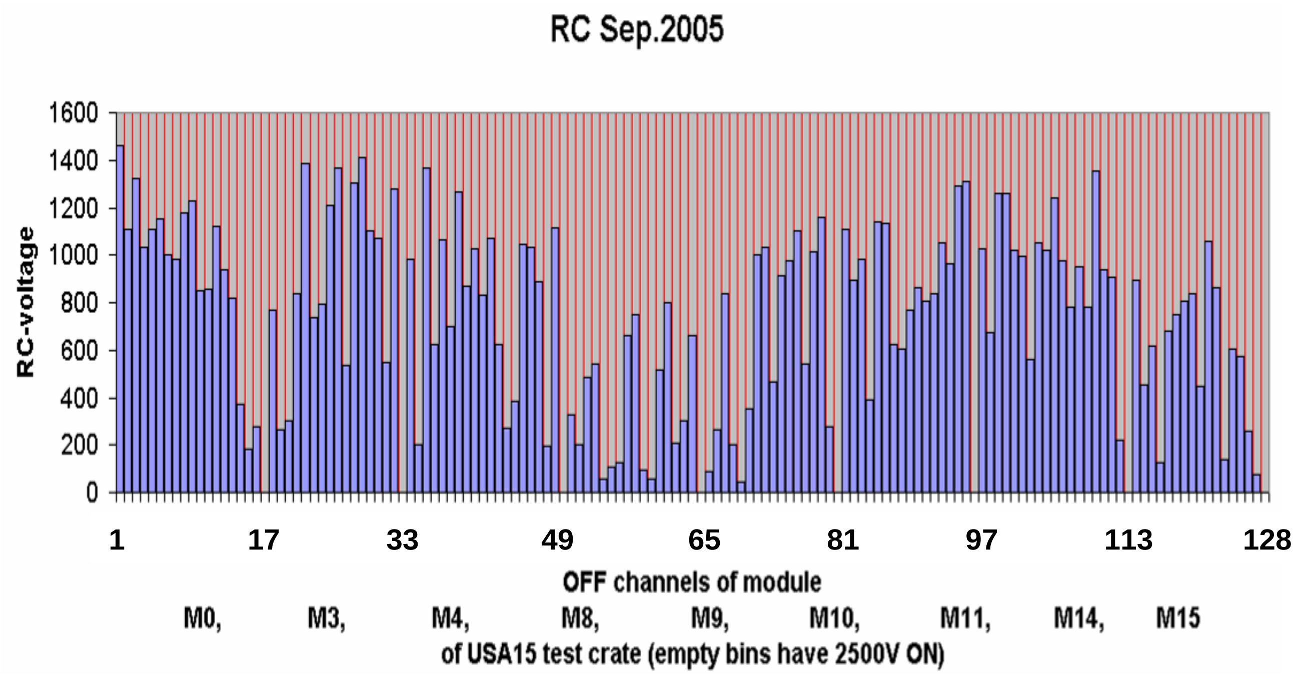

Figure 1. Distribution of voltages in channels switched "OFF" when V_{bulk}=2550 V. These 200 µA high-current HV modules have 350 MΩ divider resistors, and are more prone to exhibiting RCs.

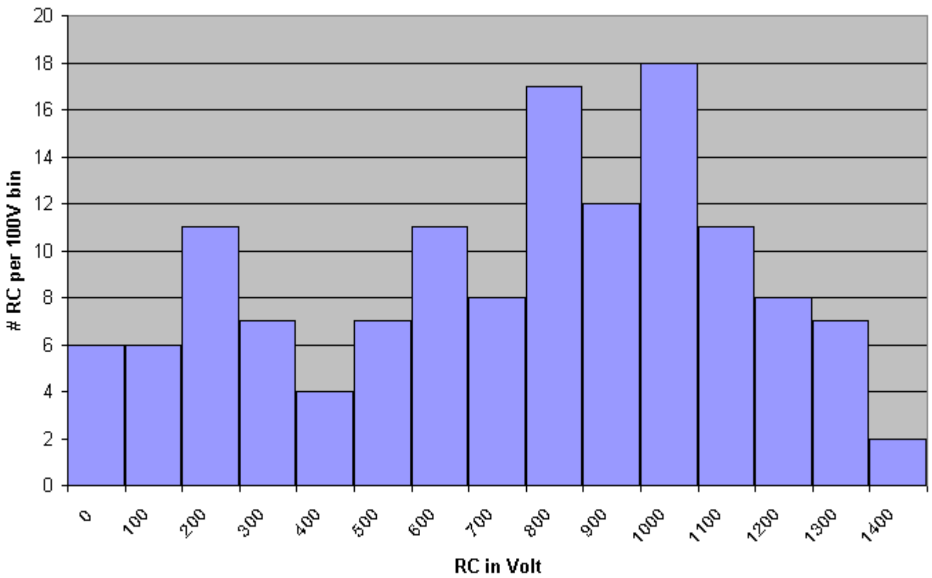

Figure 2. Voltage distribution of the "OFF" channels above.

Figure 1 and Figure 2 show, for modules with 350 MΩ dividers (which are most sensitive to leakage currents), the distribution of RC's when a single HV output is raised to 2500 V (ensuring the bulk supply is at 2550 V), while all other channels are set to "OFF". The RC voltage distribution appears in almost all channels and peaks at about 1000 V.

Subsequently, systematic leakage current measurements were made on VR's in situ (HV-PS) and also of single VR's by iseg (compare Fig. 3) and the TU-Dresden. The results of TU-Dresden confirm the iseg measurements.
The phenomenon of excessive leakage currents appears if the output of the VR is put at **positive** potential with respect to the regulation input. In doing so the 'knee' voltage of the output avalanche characteristics is reducing as a function of time.

The following conditions have an impact on that time dependant reduction:

1. The potential difference between the output middle contact and the regulation input: The higher this difference is the faster the effect appears.
2. The temperature of the chip: At temperatures about 70 ^{0}C and higher the decrease of the knee voltage is magnitudes of order faster as is the case at normal temperature (20^{0}C).
3. The environmental humidity: rel. humidity of less than 20% slows down the effect by a factor of 2 to 3 as compared to rel. humidity values of > 80%.

Negative potential difference at the output or tempering without any potential difference at temperatures of 30 to 85 ^{0}C reverse the effect completely, at least temporarily, for up to several weeks, and even storing a module (partially) cures pre-existing RC's.

As shown in Figure 3, the leakage current measurements done at iseg on 15 factory-new samples (VR pairs) show, apart from the 'knee'-lowering effect as function of the insulation voltage, a change in the avalanche slope, which becomes smoother as the applied insulation voltage is higher.

The avalanche curve was measured after driving the samples for 22 hrs at 70^0 C and 80% rel. humidity. To be noted is the fact that, already at isolation voltages above ~250 V, the VR's run out of specification i.e. the leakage current is above 100 uA for output voltages of 1500 V.

The preparation time of 22 hrs for those test samples was chosen arbitrarily. For longer times, the lowering of the 'knee' continues, however at a slower rate.

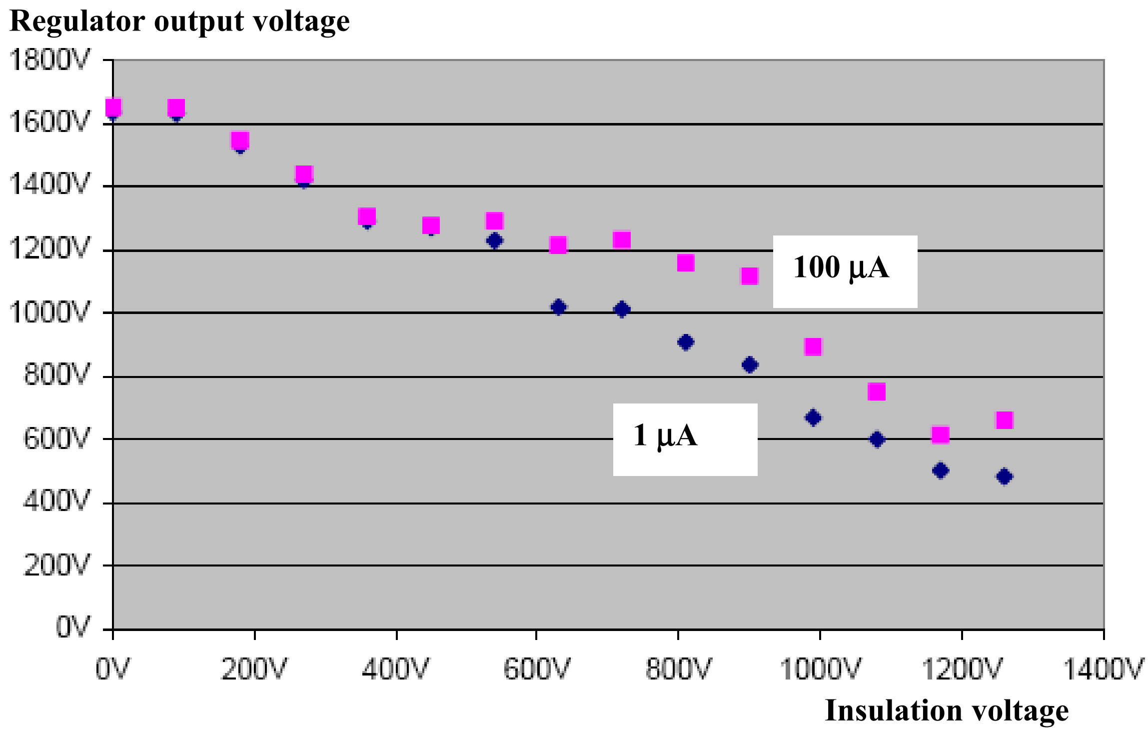

Figure 3. Leakage currents as measured for different insulation voltages and different output voltages.

Effect of RC's on Calorimeter Operation

The RC phenomenon becomes visible and potentially dangerous for channels which have to be at a (much) lower voltage than the bulk voltage. In this section, we would like to discuss the effect of RC's on LAr operation. In the Liquid Argon calorimeters several types of channels exist that must operate, either intentionally or after mishaps, at voltages that are much lower than the bulk voltage. We distinguish three classes, and discuss the effect of RC's for each:

1. Channels that are not connected, e.g. in principle every 8^{th} channel is non-connected (NC) in the EM Barrel, although in practice most such channels are connected to weak channels. It is estimated[h] that about 64 (57 in the Barrel) out of a total of 312 16-channel EM half-modules (21%) have one or two such NC channels. It is quite possible that NC channels can be put under high voltage, but not necessarily the full voltage of surrounding cells, without affecting operation or breakdown on the ATI connectors inside the calorimeter. In this way RC's for such channels could be avoided. Alternatively, disconnecting/disabling the particular wire or contact pin inside the HV cable connector may be a semi-permanent solution.
2. Channels that are shorted inside the cryostat, i.e. have a resistance of ~1 MΩ or smaller, which trips the HVPS at voltages of 50 V or less. Such “shorted” channels present no problem of running because already 1 MΩ is sufficient to drain a 10 μA leakage current down to 10 V levels. At such currents, power dissipation inside the filters is no problem either. If, however, one doesn’t want to allow such currents to flow through “bad” calorimeter channels, then a RC will possibly present a problem. In the EM Barrel, about 11 half-modules have one or more channels with a short.
3. Channels that must operate at less than nominal voltage (i.e. at 15%-99% of nominal voltage) to prevent HV breakdown. These are so-called “weak” calorimeter cells. It is noted[i] that the signal response of our calorimeter cells with fast readout depends on the high voltage V as $V^{0.3}$. Thus, typically, for a calorimeter cell to be useful for energy measurement, it must be placed at 15% or more of the nominal voltage value, i.e. above a voltage in the range 150-300 V. However, the resolution of the cells deteriorates greatly below about 25% of nominal, i.e. about 400 V. According to Figure 2, RC's are observed when the output voltage of a channel is 1500 V or less. Potentially this condition occurs in a significant fraction of the weak calorimeter channels. If a weak channel must be placed at a lower than nominal voltage level, e.g. 300 V in case of a 2000 V bulk HV, the channel may see a slow increase in voltage and consequently experience a breakdown. Such a condition will also depend on the standing (luminosity driven) current in the calorimeter cell(s): a high standing current will at least delay but possibly not deter the onset of the RC phenomenon. In the EM Barrel, about 25 half-modules have one or more weak channels.

Finding Summary 1:

We conclude that the occurrence of “Running Channels” in the HV Power Supplies is potentially harmful to the calorimeter, and is therefore unacceptable.

Origin of the RC phenomenon

We are fully confident that the observed leakage current is occurring inside the VR's, and not on the PCB or in the coating. First, the observed currents are too high for surface currents, with typical PCB surfaces and coatings having a resistance in the order of 10-100 GΩ/□. Second, RC's have

[h] Francesco Tartarelli, private communication, 22 February 2006.
[i] L. di Ciaccio, D. Fournier, F Hubaut, note ATL-COM-LARG-2005-003 (2005).

been observed in modules with a wide variety of use and repair-histories: modules that are factory-new, modules recently cleaned, etc.. Finally, tests in CERN and TU-Dresden of RC VR's, mounted outside the iseg PS have conclusively shown that these VR chips demonstrate an increased leakage current at the level of several to many µA's:

1. Grounding the control side of the VR's did not change the RC phenomenon (CERN, TU-Dresden).
2. With either of the series VR's lifted off the PCB the RC phenomenon disappeared (CERN, TU-Dresden).
3. Leakage currents of the same magnitude were reproduced with the leaky VR's mounted on a test PCB (TU-Dresden), whereas fresh new devices exhibit currents in the order of nA's.
4. A pair of new VR's put in series on a test bench exhibited dramatic running after several days at 2.5kV combined voltage.[j]

It is notable, that although "fresh" VR's exhibit leakage currents of a few nA, the manufacturer's specification for VR devices is 10 µA.

We have measured the "voltage balance" of the two VR's in series in each channel of a particular module, and found that (within statistics) there is no evidence that the VR's operate at voltages exceeding their specification, see Figure 4. Indeed, it seems the devices work in well-balanced pairs as intended.

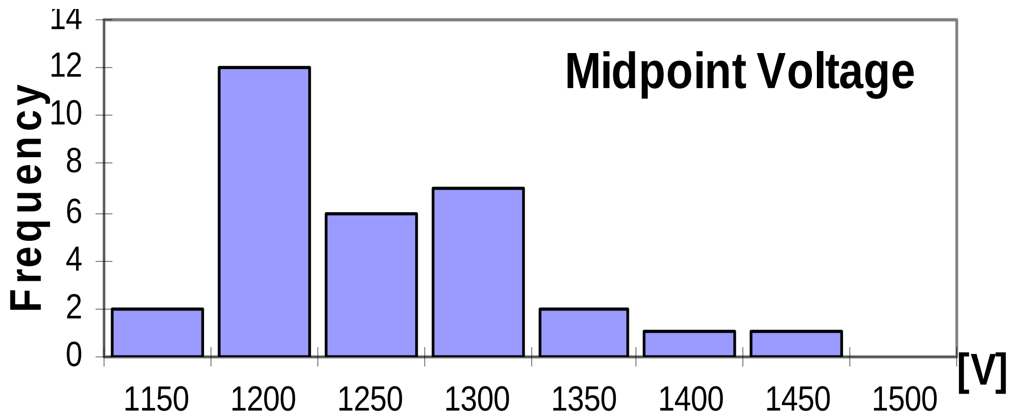

Figure 4. Voltage at point between the series connected VRs; 31 channels. V_{mid} for RCs: 1198V (Ch7; V_{out}=602V), 1445V (Ch30; V_{out}=19V), 1481V (Ch31; V_{out}=125V). V_{bulk}=2550V.

Both "fresh" (i.e. new) VR's were tested, as well as de-soldered VR';s from RC's (channel 28, 30; "up" is the VR at the side of the bulk HV and "down" indicates the VR near the channel output) at TU-Dresden, and the leakage currents were measured as function of voltage drop across the individual regulators, see Figure 5.

Also in this Figure, the leakage current through two VR's in series is plotted versus the total voltage across the series, and is in good agreement with the individual device measurements.

Additional measurements on individual VRs have been performed at TU-Dresden, see Figure 6, and show that the RC phenomenon is universal for the VR devices, i.e. given time all devices will "run". Over time, the "knee" becomes softer and the 1 µA voltage point moves down to as low as 200 V!

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[j] P. Eckstein, H. Futterschneider, test d.d. 3 March 2006, TU-Dresden. Several pairs of new VRs were put under tension, one pair became a RC.

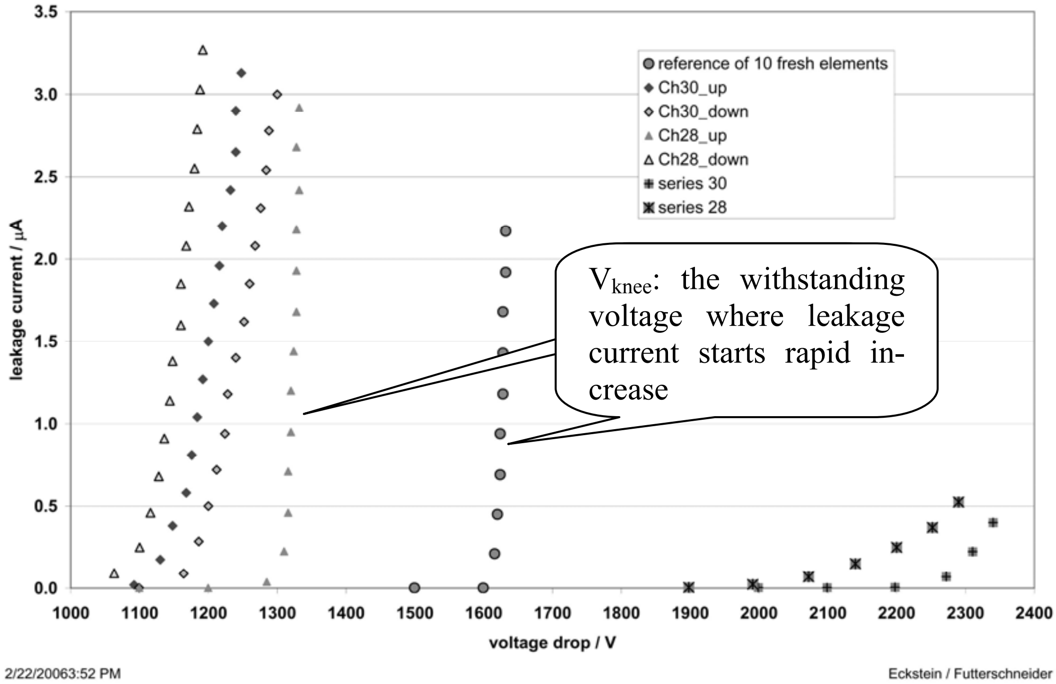

Figure 5. Leakage currents vs. applied voltage across Voltage Regulator devices.

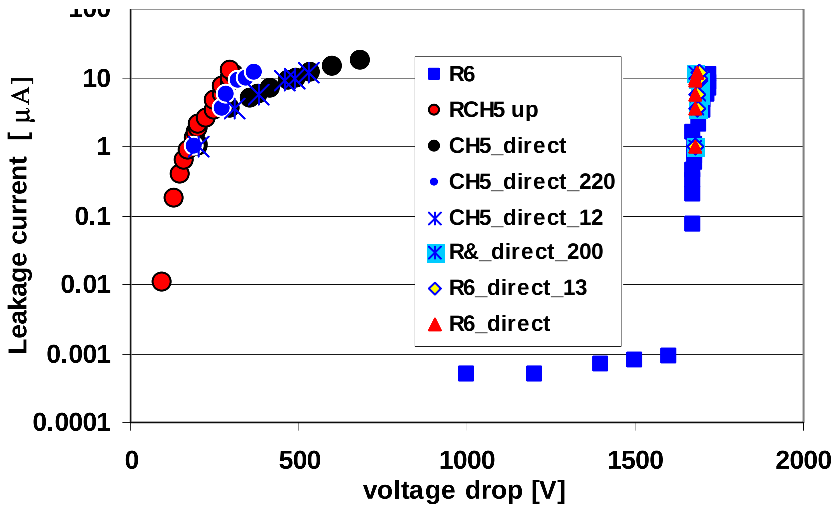

Figure 6. Leakage current vs. applied voltage across single VR devices.

It is worth noting that applying heat to individual VR's (by solder iron) regenerates them, i.e. reduces the leakage from order µA to a few nA.

Cause of Deterioration of Voltage Regulators

We developed several hypotheses for deterioration of the VR and the appearance of a RC. Initially we thought that running a VR at V_{drop} near or in slight excess of the maximum (1500 V) would cause deterioration.

However, extensive tests performed at iseg and TU-Dresden unequivocally showed that the increase is uniquely related to the ***isolation voltage difference***, $\mathbf{V_{iso}}$, between the control side and the HV regulation side of the VR. A DC potential difference of +3 kV between HV and control sides (all HV-side contacts to +HV, and all control-side contacts to ground) causes the leakage current to increase substantially when the VR is subsequently used as a regulator (and lowers the “knee” in the leakage current-vs.-V_{drop}). This effect appears after several days under high V_{iso}, and is more rapid (a few hours) when the VR is heated to 70° C while V_{iso} is applied. The same tests also show that the phenomenon is *absent* for a *negative* voltage difference between HV side and control side.

Removing the HV and heating the VR's does temporarily cure or reset the problem. Remarkably, reversing V_{iso} reverses the deterioration: putting a “running” VR under reverse V_{iso} gradually improves the characteristics, i.e. decreases leakage current and increases V_{knee} back to typical values!

Additional confirmation of this precise cause comes from tests at TU-Dresden, where several chips were operated at V_{drop} equal to V_{knee}, such that the leakage current was kept around 1 μA, but with the control side left floating. These VR's did not deteriorate after more than 3 weeks under tension.

The manufacturer of the VR's was contacted, duplicated the tests done by iseg, and has confirmed the effect. Clearly, the VR is deteriorating although it is operating well within its specifications. We speculate that a prolonged DC V_{iso} produces an slow accumulation of electrons by leakage from the control side towards a critical part of the HV-side regulator elements.

Detector-Discharge Bypass Diodes

There is evidence that the bypass diodes, which protect the VR's in case of emergency crow-bar from the detector discharge, also contribute to the RC problem, in particular when their maximum operating voltage is exceeded. According to their specifications, these diodes go into soft, controlled avalanche at 1500 V (i.e. very close to the maximum rated voltage across the VR), and are rated to have a maximum leakage current (reverse bias current) of 5 μA at 1400 V reverse bias. This maximum leakage current is highly temperature dependent: 8 μA at 100°C. We removed the diodes in the three RC's in a particular module and found a small decrease in overall leakage currents.

In other modules that were repaired (i.e. where the VRs were replaced by non-leaking VRs; see below), some channels still exhibited output voltages of 10-20 V (with Vset=0), which was caused entirely by higher-than-average current through the bypass diodes.

Finding Summary 2:

The RC phenomenon is caused by slow deterioration of the VR's, even though the devices are operated well within specs. The deterioration occurs when the devices are used for regulation of positive DC HV. The device manufacturer admits to the faulty behavior of the VR's.

The bypass diodes may contribute to the problem (in some cases significantly).

Current Measurement

The iseg HV module has a current measurement circuitry for each channel. It consists of circuitry for each individual channel, which sits between the bulk supply and the VRs. The current to the channel is mirrored and transmitted by optocoupler to the current measuring circuitry sitting at ground potential. There, the current flowing through the resistive divider is subtracted electronically, and the net current compared with the preset current limit. The MOSFET in the optocoupler is protected by a parallel avalanche diode, which goes in conduction around 1700V. The MOSFET is put in series with a reverse-biased avalanche diode (“DIODE”) which is rated at around 1300 V. The leakage currents through the MOSFET-DIODE series may be substantial when either of the devices is much worse than typical (but often still within specs), see Figure 7. This phenomenon is very similar to the RC phenomenon discussed above, although the optocoupler is used with the OPPOSITE voltage bias between control and output as the VRs, i.e. the control is at HV and the

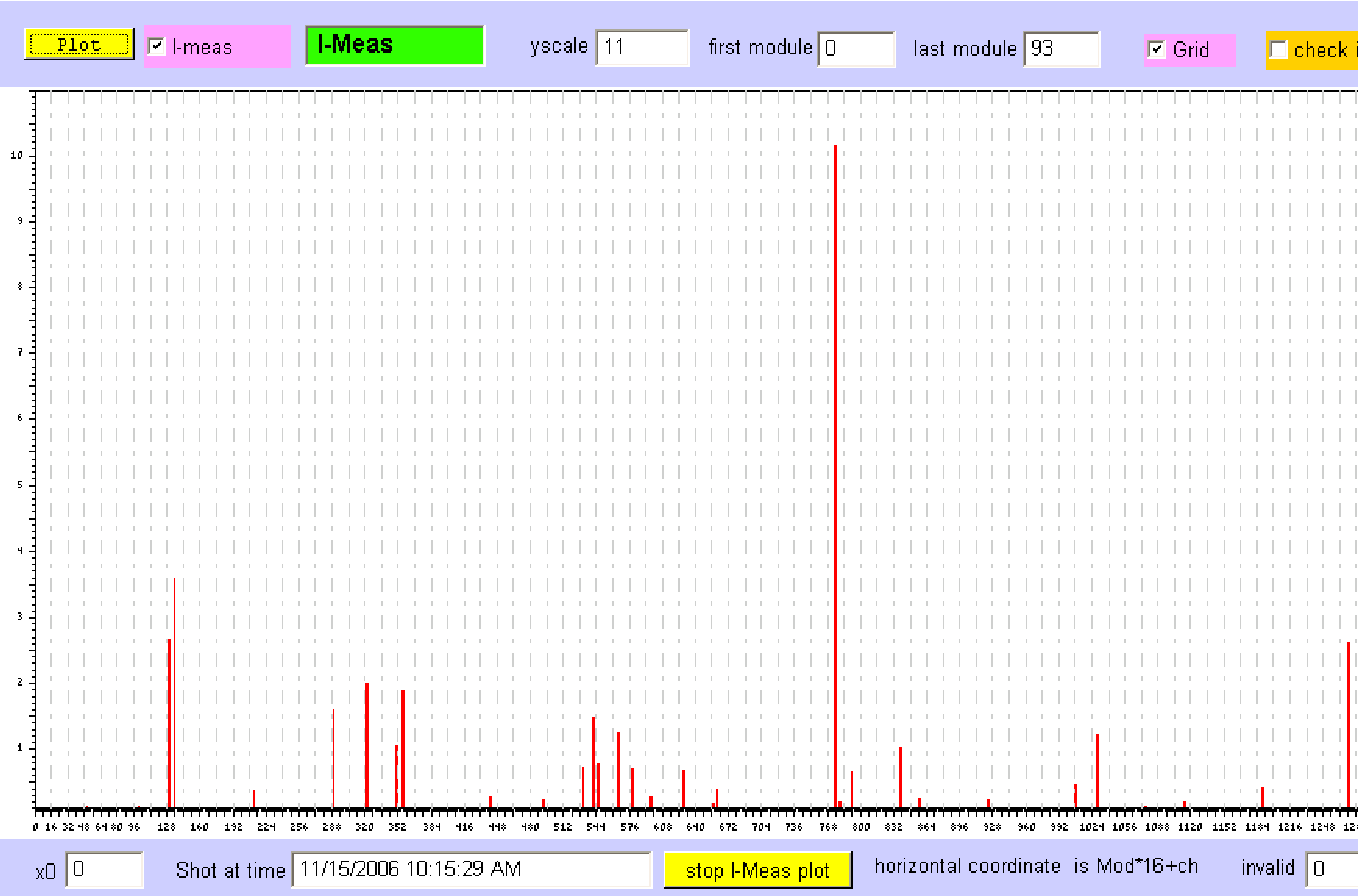

Figure 7. Currents (µA) in 1120 HV channels (i.e. 70 HV boards). 27 channels that are "OFF" show currents in excess of 200 µA; 12 channels are above 1 µA.

output near ground. For POSITIVE HV between control and output, the device has never shown deterioration.

For NEGATIVE iseg supplies however, we expect deterioration is bound to occur, and curative measures should be taken in that case!

> ***Finding Summary 3:***
>
> *Diodes and/or optocouplers used in the current measurement circuitry may show leakage currents that are substantial and unacceptable. Although they provide false information, they pose no risk to the calorimeter.*
>
> *Current-optocouplers in NEGATIVE iseg modules may fail in the same way as the VRs in POSITIVE iseg modules.*

Curing the RC Problem

Improvements are discussed to the components and PCB layout. We believe that the solution proposed provides a cure for the RC problem, even though we do not understand in detail the solid state physics mechanism that leads to deterioration of the VR devices.

Recommended Modifications to HV Components

It is difficult to suggest improvements which will completely guarantee that RC's will not occur in the future. This is inherent in the fundamental design idea implemented in the supply, which is a common bulk supply followed by 16 individual down-regulators. It also stems from the fact that we do not know the detailed physics mechanism of the deterioration of the VR's.

iseg has identified a 600 V VR device, with 5 kV V_{iso}. This device, presumably of a different internal design, does **not** display the RC phenomenon when operated under the extreme condition of 70 °C and 3kV insulation voltage, which deteriorated the original devices within a few hours. Two samples of those new devices where tested for two weeks each under those conditions, without failure.

iseg has built a small daughter board carrying 5 such 600 V devices in series for a prototype solution. 4 × sixteen such boards mounted in iseg HV PS's have been tested for more then three weeks successfully.

We recommend the proposal by iseg, i.e. the **replacement of the present VRs** by a different type of regulator which does not exhibit the RC phenomenon, as the main cure.

Action Summary 1:

iseg has tested the replacement of the current two VR's in series by a special-purpose daughterboard containing VR's of a different type (and presumably of different internal design), which have been shown to be stable over long periods under high temperature operation. We propose this as the best replacement solution for the defective VR's.

We recommend that iseg changes the by-pass diodes which exhibit a too large leakage current with **pre-selected diodes** of low leakage, such that **no channel exhibits more than 5 V** due to leakage currents when the V_{set} = 0V and the bulk voltage is at maximum.

Action Summary 2:

We recommend that iseg change the bypass diode(s) in case the leakage current through the by-pass diode(s) leads to more than 5 V at the output of a channel with V_{set}=0 and V_{bulk} at maximum. This is best achieved by pre-selecting low-leakages bypass diodes

Similar recommendations are made regarding the HV components in the current measurement circuitry, for the exact same reasons. The optocoupler and HV diode used there may be marginal, or deteriorate (in NEGAIVE HV modules). A large leakage in these components, while not posing a risk to the calorimeter, presents a false current reading in the circumstance where the bulk voltage is highest and the current through voltage divider is small (i.e. low V_{set}).

Action Summary 3:

We recommend that iseg replace diodes and/or optocouplers used in the current measurement circuitry in each channel that shows more than 200 nA of leakage current. This is best achieved by pre-selecting these components for low leakage current.

We recommend that iseg replace the current-optocouplers in all NEGATIVE iseg modules.

Recommended Modifications to the Printed Circuit Board

Regarding the printed circuit board (PCB), a number of improvements, especially for the repair of PCB, were suggested at the February meeting at iseg. However note, that according to us, the RC phenomenon is *not* related to the PCB production procedures, although surface leakage could upset the voltage sharing between VR's and thereby precipitate the RC phenomenon.

Acknowledgements

We thank Dr. Rainer Richter (MPI Munich) for helpful discussions. MR thanks CERN and LAPP, Annecy for financial support.

Summary

We conclude that the “Running Channel” problem is a serious hazard to LAr calorimeter operation, and is due to faulty Voltage Regulators (VR), which deteriorate over time even though they are operated within the manufacturer’s specified limits. Tests done at iseg trace the problem to deterioration caused by the (positive) DC high voltage difference between the HV side of the regulators and the low-voltage control side of the devices in positive H modules. We propose to accept the solution suggested by iseg and to replace all current VR devices by devices of a different design shown to be free from the defect., which would be mounted on a small daughter board to fit the current VR footprint. A similar problem has been found in the current measurement of negative HV modules.