

# Diode Dosimeters

Semiconductor diodes are inexpensive, yield high output, and do not require bias, making possible simple detector arrays to measure transverse dose distributions.

Some diodes are extremely small and therefore well suited to measuring high dose gradients, as in eye treatment or neurosurgery fields. A.M. Koehler ('Dosimetry of proton beams using small silicon diodes,' Rad. Res. Suppl. **7** (1967) 53) carefully measured diode characteristics looking towards that application, and diodes are still the gold standard for eye beam calibrations at the Burr Center despite several attempts to come up with something better.

However, diodes suffer radiation damage so they need occasional recalibration. They have a significant temperature coefficient, and over-respond to low energy protons by comparison with PPIC's. Also, they require a current integrator that keeps the voltage across the diode as near zero as possible. The effective resistance of a well used diode at zero applied volts can be as low as 10 M $\Omega$ , so a voltage burden of even 1  $\mu$ V causes 0.1 pA of 'drift'. Therefore integrators to be used with diodes must hold a voltage burden in the  $\mu$ V range. For ion chambers and Faraday cups that is not a concern.

Energy response and radiation damage depend greatly on the fabrication technology. Scanditronix sells diodes whose response is the same as that of a PPIC. Google G. Rikner or E. Grusell to bring up articles on these diodes, which are fairly expensive.

# Dose Response vs. Rate

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KOEHLER

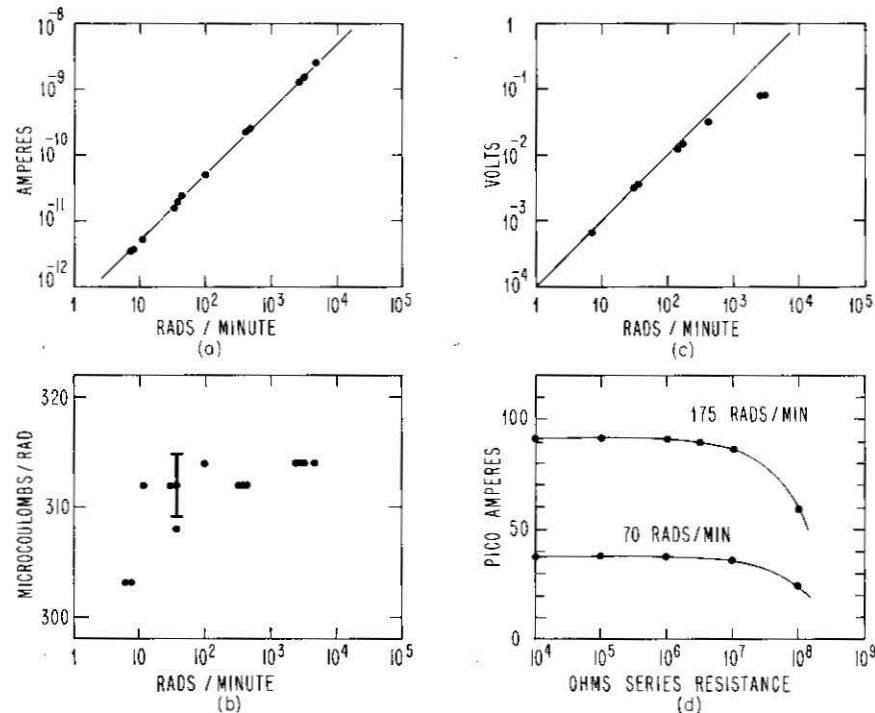


FIG. 3. Output from silicon diode due to radiation. Short-circuit output current is shown in (a), open-circuit voltages in (c). Linearity of short-circuit current is illustrated on an expanded scale in (b). Effect of varying circuit resistance is shown in (d).

The diode is a linear dosimeter if and only if the output current flows into a short circuit. Either a classical or recycling integrator will accomplish that. However, as explained earlier, the voltage at the input must be adjusted to zero *within a few  $\mu$ V*. That only lasts if the opamp's offset voltage tempco and long-term drift are correspondingly small. The Texas Instruments TLC27L2 has appropriate specs.

# Radiation Damage, Tempco, and Energy Response

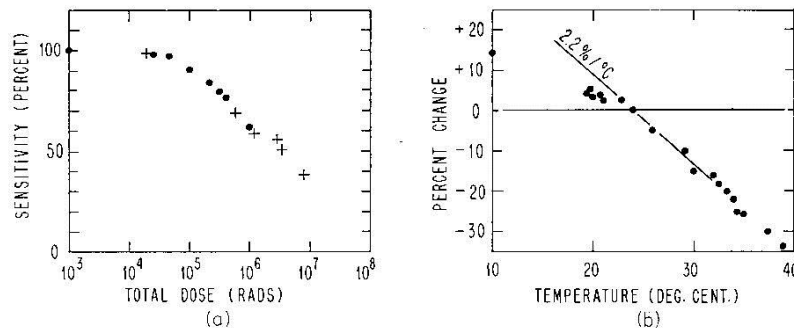


FIG. 4. Radiation damage and temperature effect. Degradation of short-circuit current sensitivity of dosimeter after large cumulative exposure is shown in (a); variation of output with ambient temperature in (b).

The diode Koehler tested over-responds (relative to a PPIC) by  $\approx 8.5\%$  in the Bragg peak. Nonetheless this diode was and still is used to measure the depth-dose in the very successful eye treatment program. Other diodes behave differently!

(left) Radiation damage kicks in at about 10 Krad. Sometimes it pays to pre-irradiate diodes when they are to be used as dosimeters.

(right) The diode Koehler tested had a large tempco,  $-2.2\%/^{\circ}\text{C}$ .

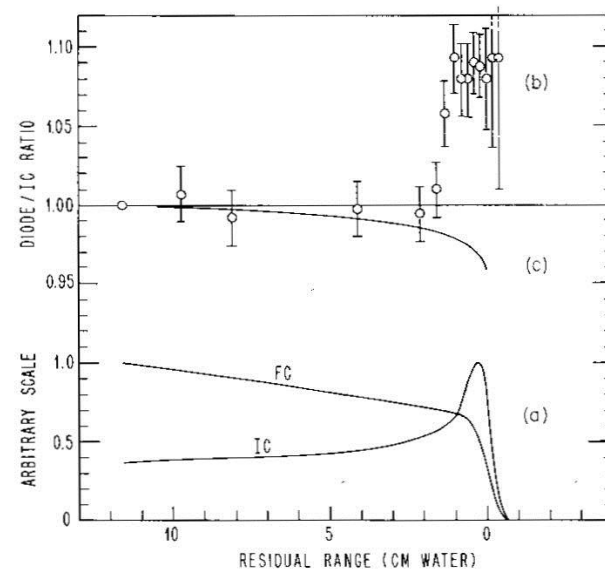
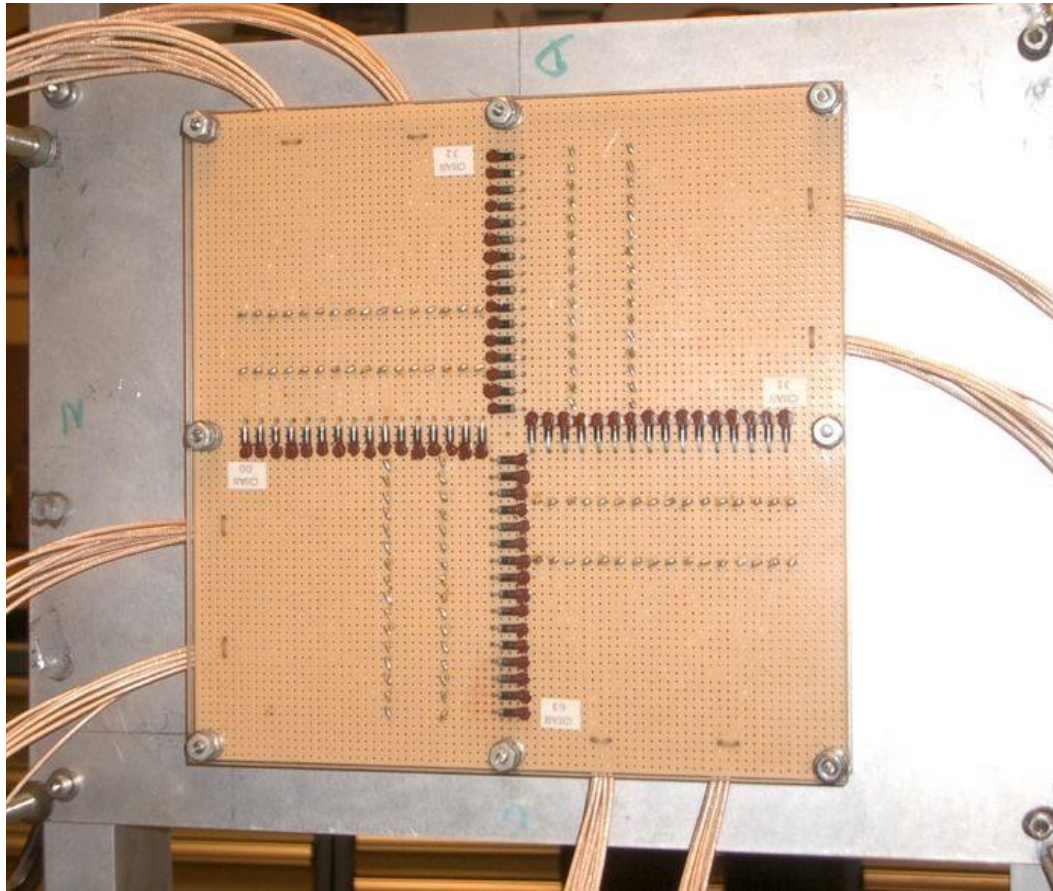


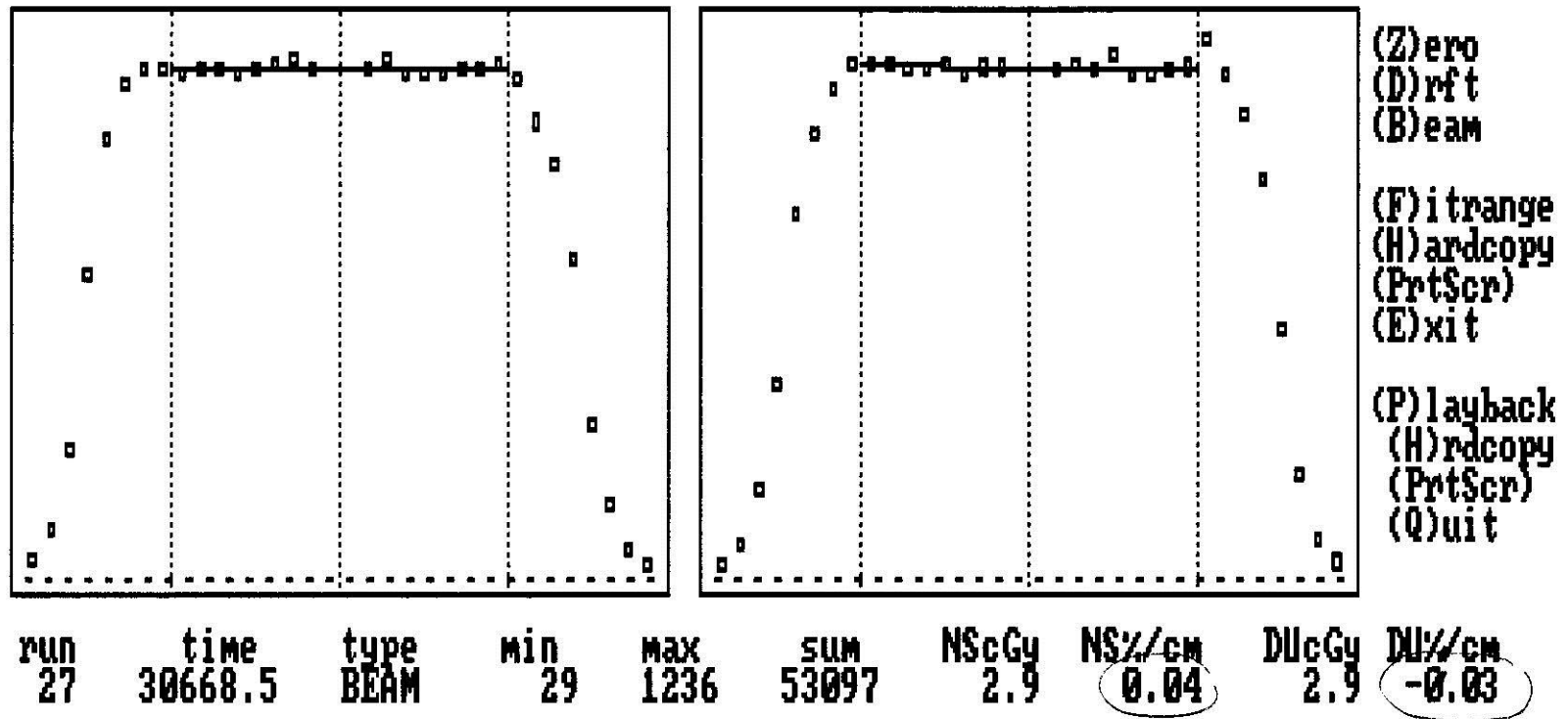
FIG. 5. Comparison of silicon dosimeter to nitrogen ion chamber. In (a) the integrated dose measured by the ion chamber (IC) and the proton current measured by the Faraday cup (FC) are shown. Points at (b) show the ratio of integrated dose measured by the silicon diode to that measured by IC. Curve (c) is the calculated ratio of  $dE/dx$ , normalized at 11.5 cm residual range.

# A 2D Diode Array



The  $32 \times 32$  'CROSS' diode array built for QA in the HCL radiosurgery beam and now used for general purposes at the Burr Center. 1N4004 diodes are mounted on perfboard at 0.2" pitch. Leads not at ground are covered with insulating paint to discourage ions. The diodes put out so much signal (130 pC/rad) that they will not reach the 10 Krad damage threshold in the lifetime of the device, so they are *not* pre-irradiated.

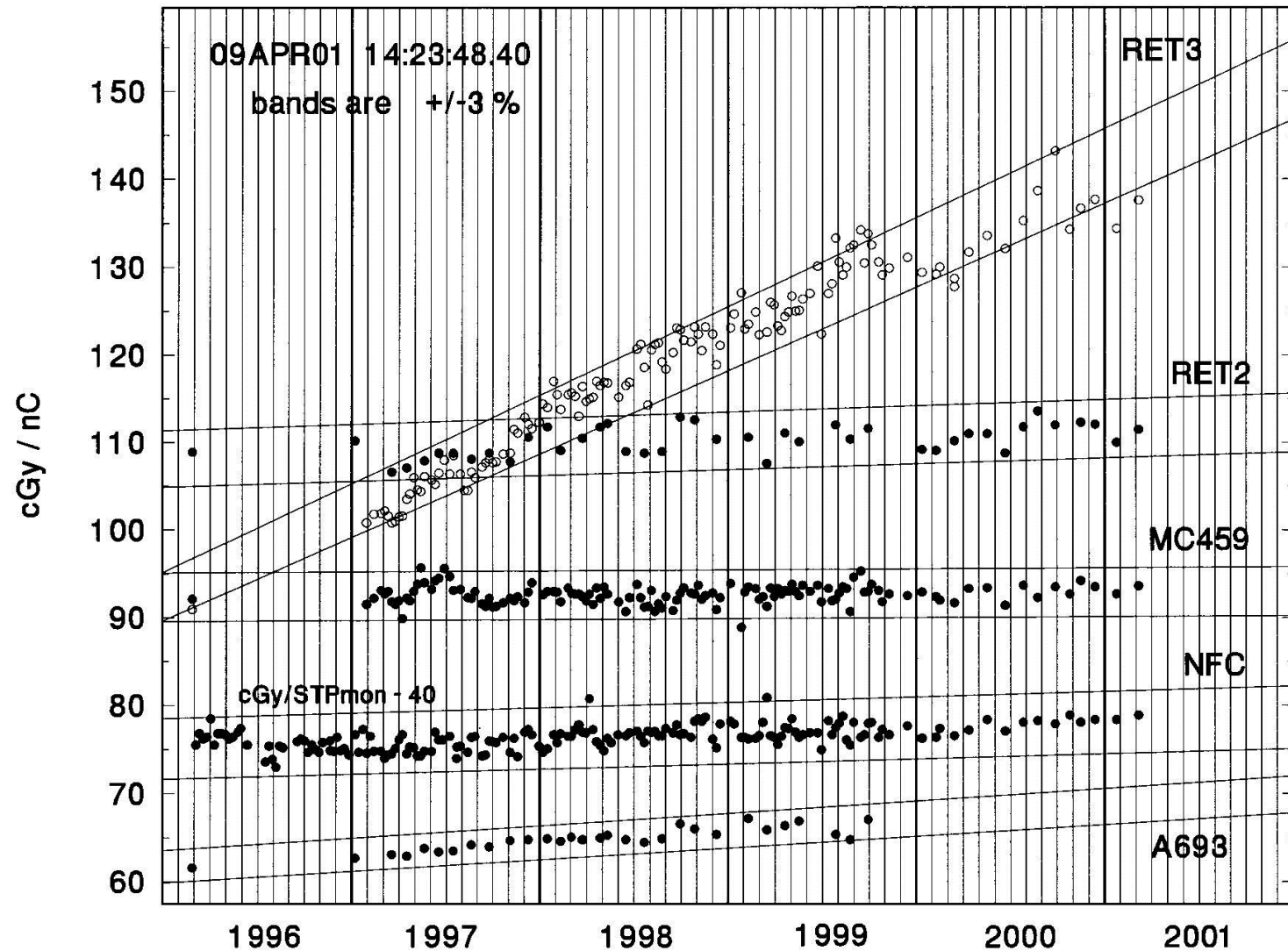
## ... and its Output



Real-time displays on the PC running the CROSS array. The measurement shown took 2 *seconds*. Array devices usually take much longer to set up than to use, so ease of setup and robustness should guide the mechanical design. Data log files should be generated and named automatically e.g. 29FEB08.DAT, without operator choice or intervention.

Diodes are recalibrated annually by exposing CROSS to a Gaussian dose distribution at several preset positions. The 64 diode constants and a few parameters for the unknown dose distribution are thus overdetermined, and found by a least-squares fit.

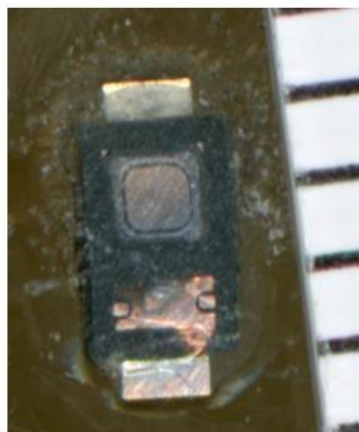
# Radiation Damage Over a Span of Years



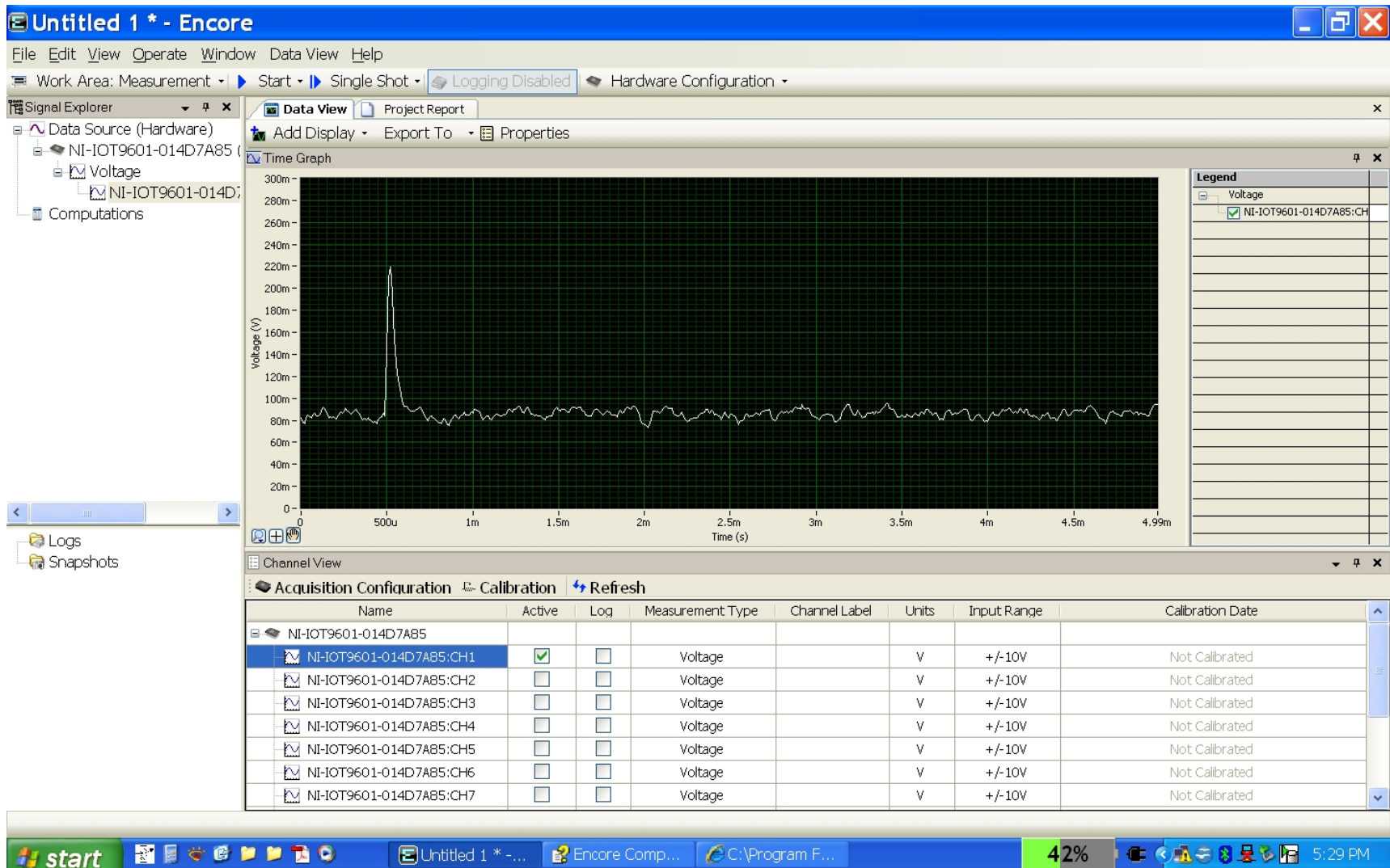
History of weekly diode calibrations at HCL showing radiation damage over 5 years, greatest for the diode (RET3) used daily in the eye treatment line.



The DFLR1600 is a surface-mount 1A 600V rectifier costing \$0.10 in 1000's. With a suitable preamp and a 10  $\mu$ Ci source one can see pulses at a few per second on the bench. The internal geometry is plane-parallel, perfect for dosimetry.

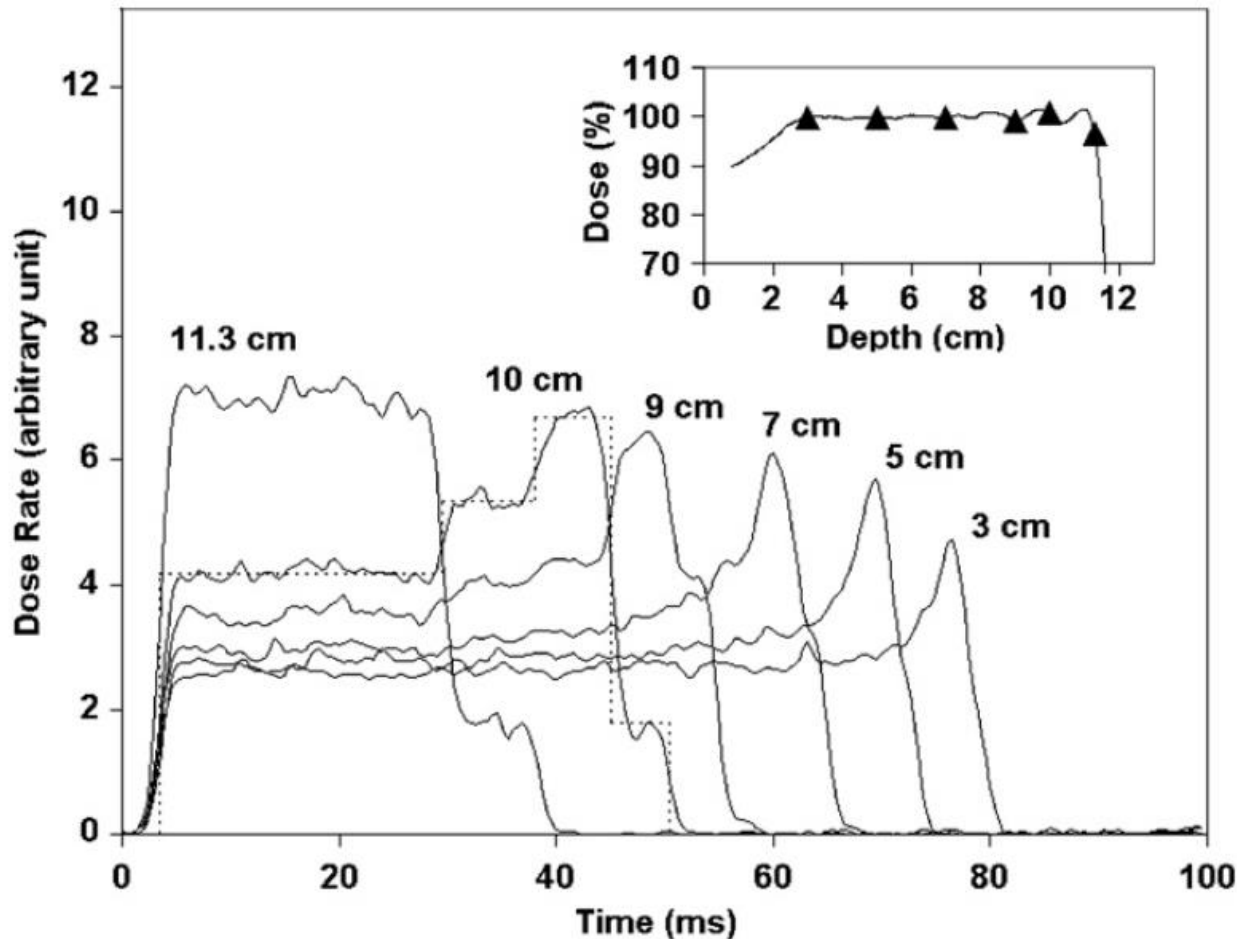
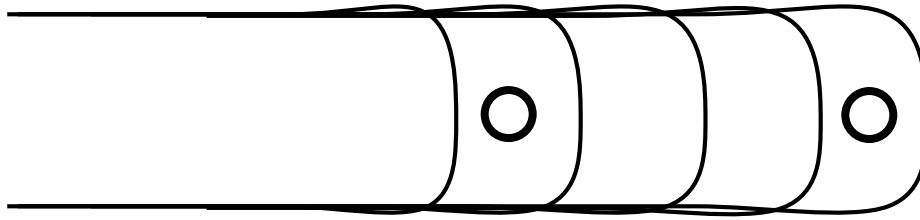




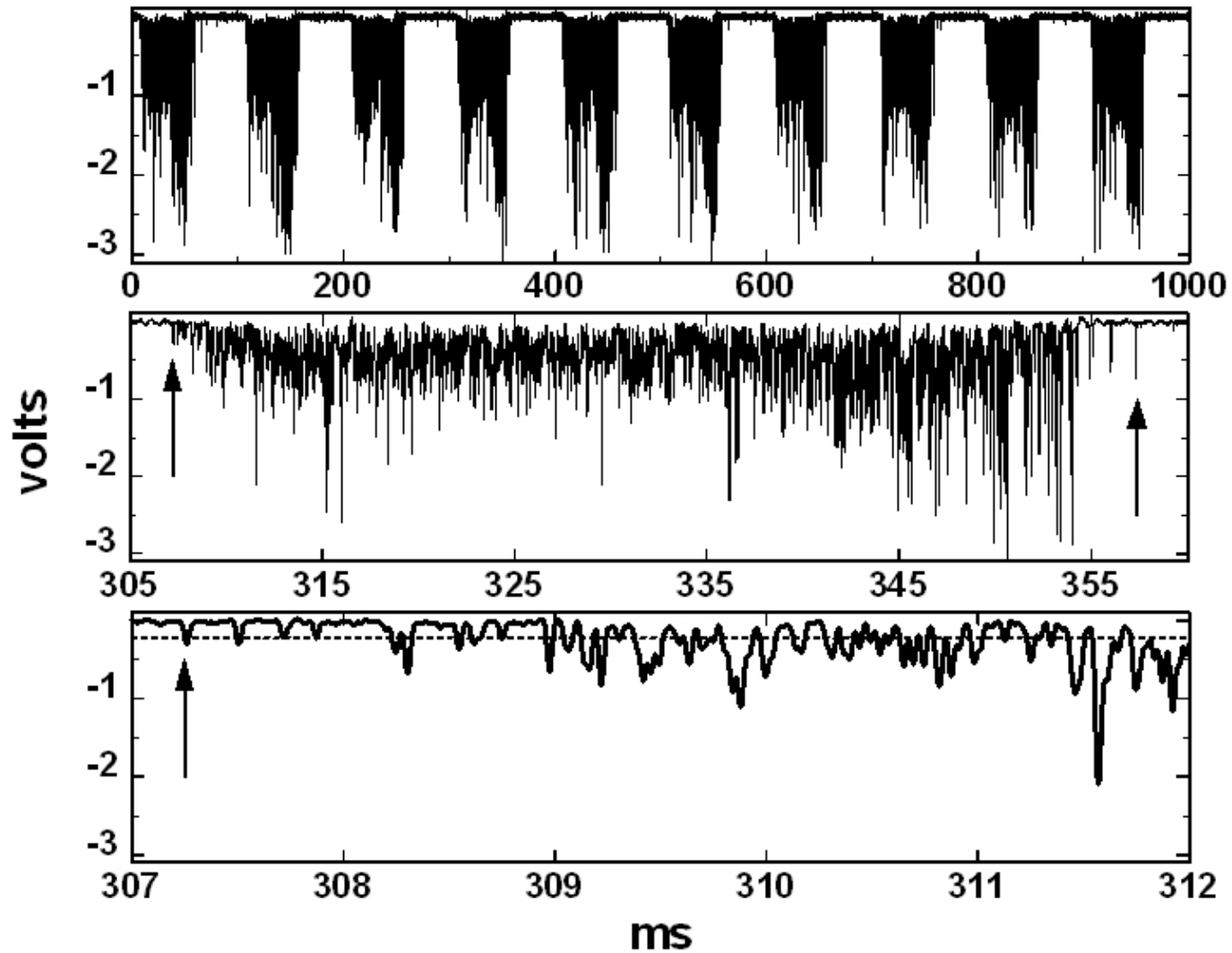


Single pulse recorded with an IOtech 6220 data logger (16 bits, 100K samples/sec, 10  $\mu$ s/sample). The 6220 (\$3000 including software) can sample up to 12 channels simultaneously at that rate. Data are stored in files for off-line analysis.

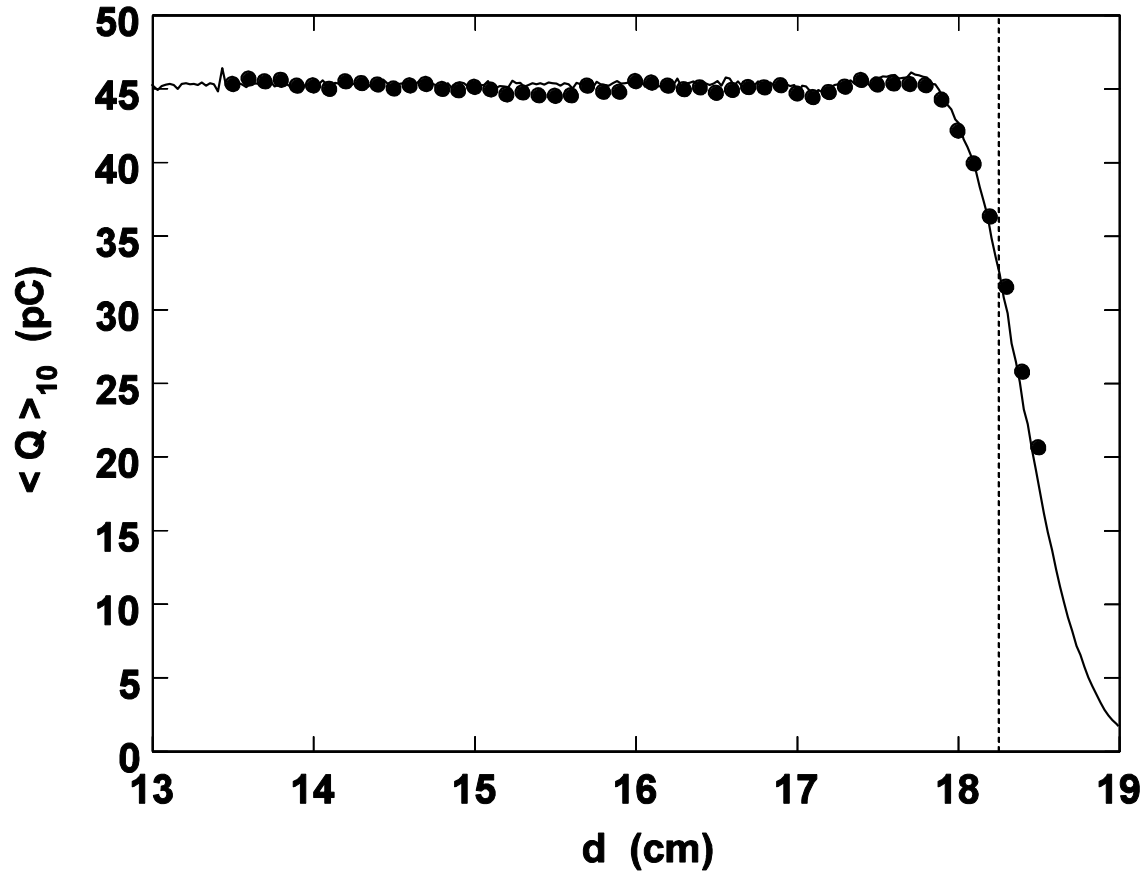




A dosimeter in a passive range modulated beam puts out a signal whose duration depends on its depth in the beam. The abrupt steps are smeared by the finite distal falloff of the Bragg peak and because the beam usually passes through several mod steps. The figure shows data from a small IC with the amplifier time constant deconvolved (H-M Lu, Phys. Med. Biol. **53** (2008) 1413 – 1424)



With a small diode driving a moderately fast amplifier the signal at one depth looks like this. Top: ten modulator cycles. Middle: fourth cycle. Bottom: start of fourth cycle. We see pulses from one or a few protons even at radiotherapy dose rates because the diode is so small.



As a reality check we can sample the waveform, integrate (sum) over each burst, average over ten bursts and apply the known amplifier V/nA to find the charge  $\langle Q \rangle_{10}$ . Doing this at many depths we obtain the diode's version of the SOBP. The line represents data from a Markus (small plane-parallel IC) chamber (arbitrary normalization).

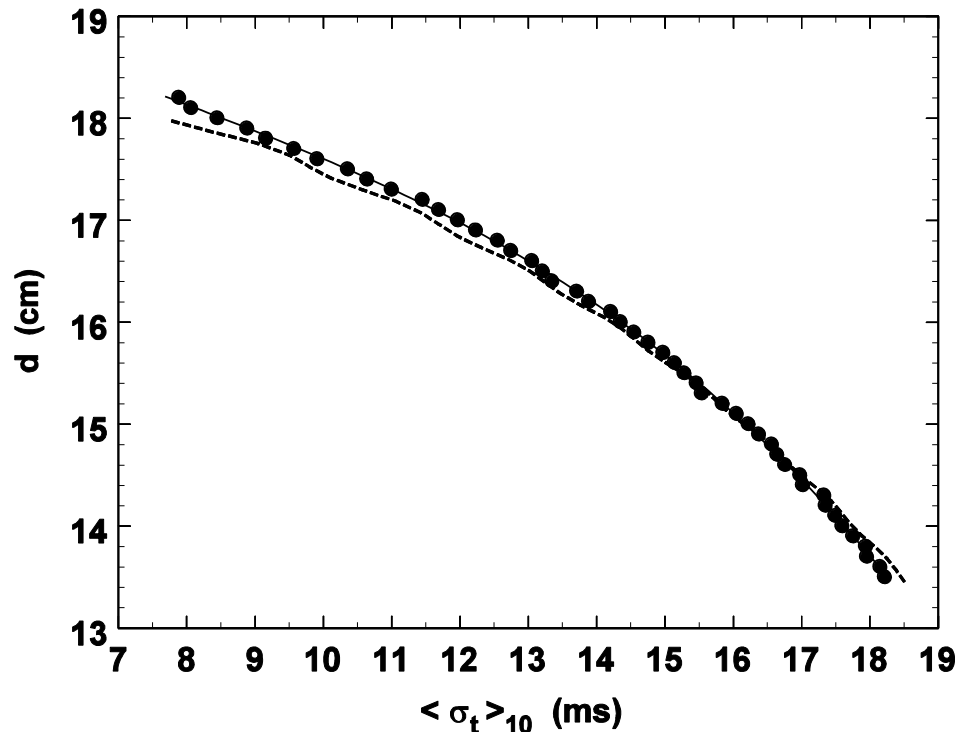
How best to characterize the width of the burst, which should correlate with depth? A simple and efficient measure is the rms value  $\langle \sigma_t \rangle_{10}$  computed by the procedure shown to the right. This works as well for stochastic distributions as for smooth ones. Straightforward arithmetic: no smoothing or curve fitting!

$$S \equiv \sum_{i=i_1}^{i_N} v_i \quad (\text{V})$$

$$m \equiv \frac{1}{S} \sum_{i=i_1}^{i_N} v_i t_i \quad (\text{ms})$$

$$\sigma_t \equiv \left( \frac{1}{S} \sum_{i=i_1}^{i_N} v_i (t_i - m)^2 \right)^{1/2} \quad (\text{ms})$$

$$s \equiv \frac{1}{S \sigma_t^3} \sum_{i=i_1}^{i_N} v_i (t_i - m)^3 \quad (\text{dimensionless})$$



Diode depth in a water tank as a function of  $\langle \sigma_t \rangle_{10}$  is well fit by a cubic (four term) polynomial, which can serve as a calibration function. The rms deviation of measured points from the fit is 0.29 mm! This precision was confirmed with test data not used in the fit.

These measurements, using a single diode in a water tank, have been written up and accepted for publication. The diode was a PTW dosimetry diode, but we have now done similar measurements with an array of DFLR1600's. The calibration and depth resolution are similar: Gottschalk et al., 'Water equivalent path length measurement in proton radiotherapy using time resolved diode dosimetry,' Med. Phys. **38** (2011) 2282 - 2288

Bottom line: if you calibrate a diode in a passively scattered, range modulated calibration beam and subsequently place the diode at an unknown depth in the water tank, a simple measurement using  $\approx 0.2\%$  of a typical single fraction dose will tell you the WEPL (water equivalent path length) to that point to  $\approx 0.3\text{mm}$  ( $1\sigma$ ).

We are now doing measurements with an array of diodes and an anthropomorphic prostate phantom. The goal, using diodes mounted on a rectal balloon, is to measure WEPL to the rectal wall with a test beam on treatment day. If we compare that with WEPL from the treatment planning program, we can adjust the energy of the treatment beam.

Small diodes are unique in that, properly used, they can measure fluence rate (by counting pulses) and dose rate (by integrating the area) simultaneously. Both need to be calibrated (equivalent to measuring effective area and effective mass).

# Summary

Diodes are inexpensive, rugged and easy to use as they require no bias. Though small ion chambers are preferred nowadays for clinical dosimetry, diodes still have their place.

When used in arrays to measure transverse dose, over-response at low energies does not matter if the distribution of energies is independent of transverse position. Diode arrays are simple, inexpensive and rugged, but depend on the availability of a suitable current integrator array.

The current integrator input must present a low impedance and a small, stable voltage burden  $\approx 1\mu\text{V}$ . If diodes are used for precise dosimetry their temperature coefficient must be measured and taken into account. They must also be recalibrated occasionally because of radiation damage.

In a passive range modulated beam the time dependence of diode response contains precise information about the water equivalent path length (WEPL) to the diode. With the availability of fast multi-channel data loggers, this opens up the possibility of using end-of-range to discriminate between the target volume and the volume to be spared, if a diode or diode array can be placed in a body cavity (oesophagus, oral, or rectal) distal to the target volume.