MultiLayer Ionization Chambers

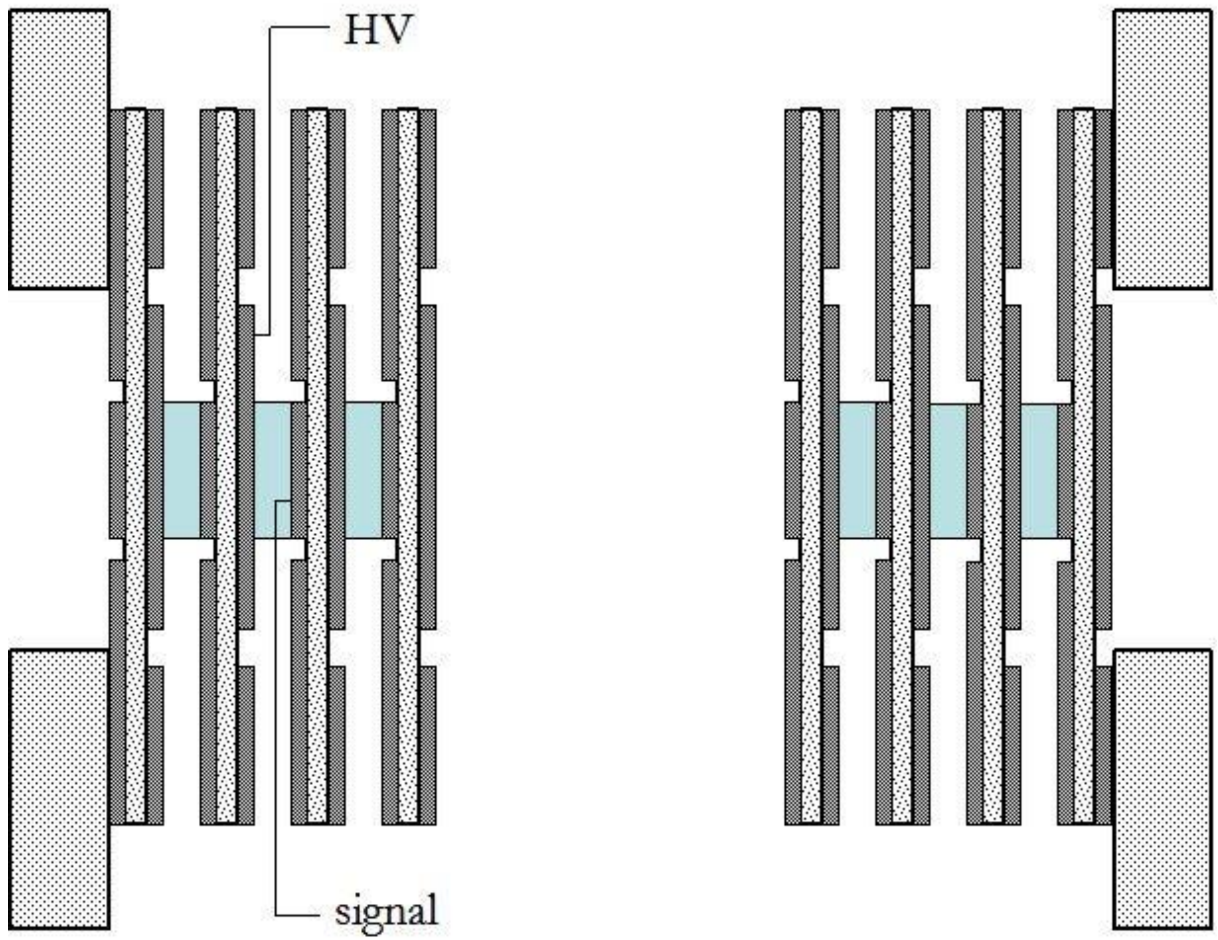
In the 1980's and early 90's a multi-layer ionization chamber (MLIC) was used as a range verifier at HCL. Only the measured range mattered. It is much harder to build an MLIC that measures an entire SOBP *to a clinical level of accuracy*.

In *scattered* beam QA the potential time savings, compared to scans with a single dosimeter in a water tank, are modest: seconds compared to a few minutes. By contrast, in *scanned* or *laminated* beams the time saved is enormous because, otherwise, the entire sequence has to be repeated for each point of a depth scan.

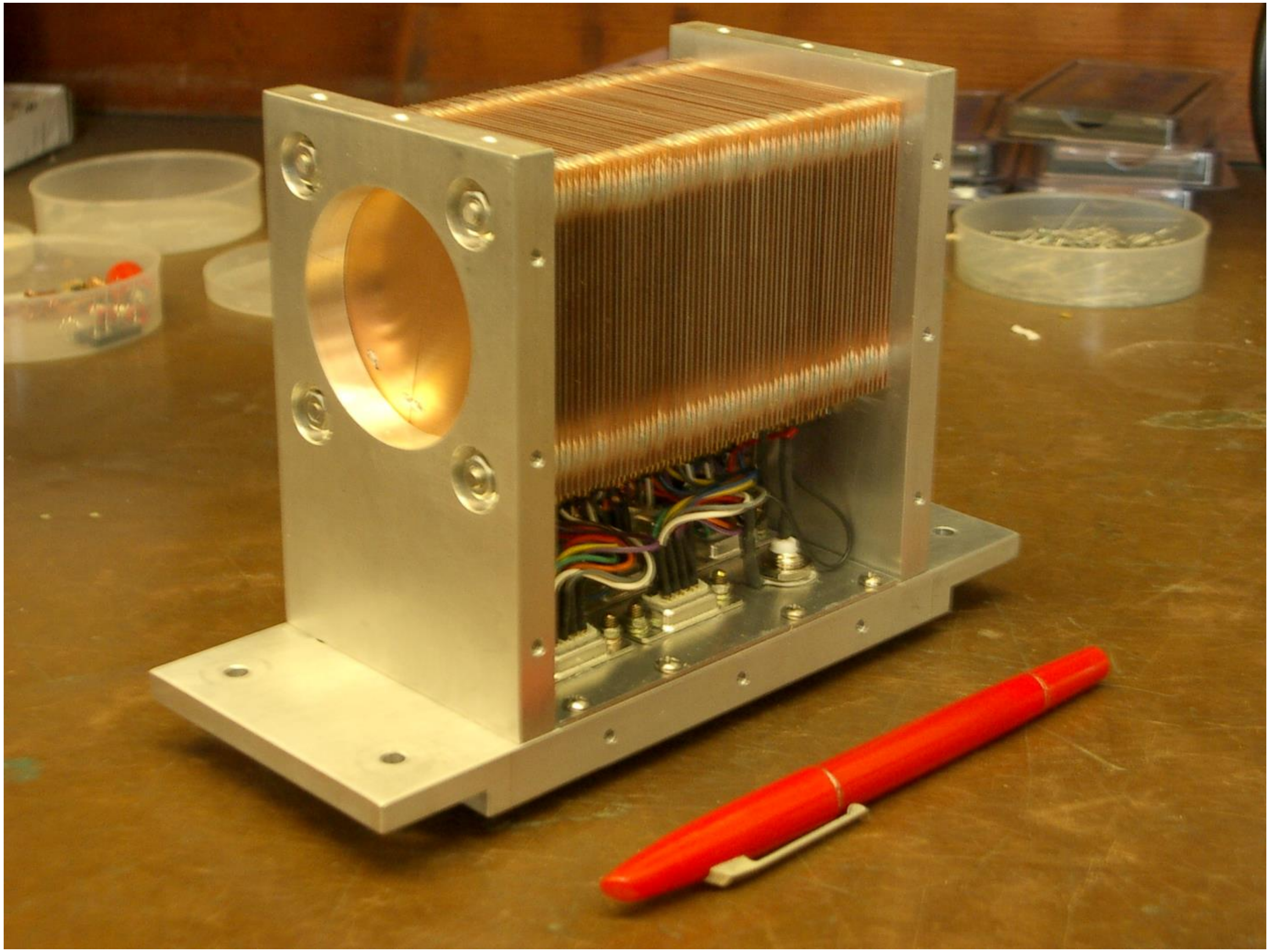
We have constructed and tested an MLIC to replace diode depth-dose scans in the eye treatment line at the Burr Center. Though it is used in daily QA it has not yet replaced the diode scans, mainly because of difficulties associated with the very small fields (sometimes less than 4 mm in diameter). However, it is now used daily in the STAR radiosurgery beam, where fields are larger and the use of lamination gives the MLIC a huge advantage.

We believe there is no fundamental problem in building MLIC's for higher energy beams, and this has now been done at IUCF (see note at end of summary). In this lecture we will describe the small MLIC in detail, then lay down some guidelines which should allow the successful construction of larger devices.

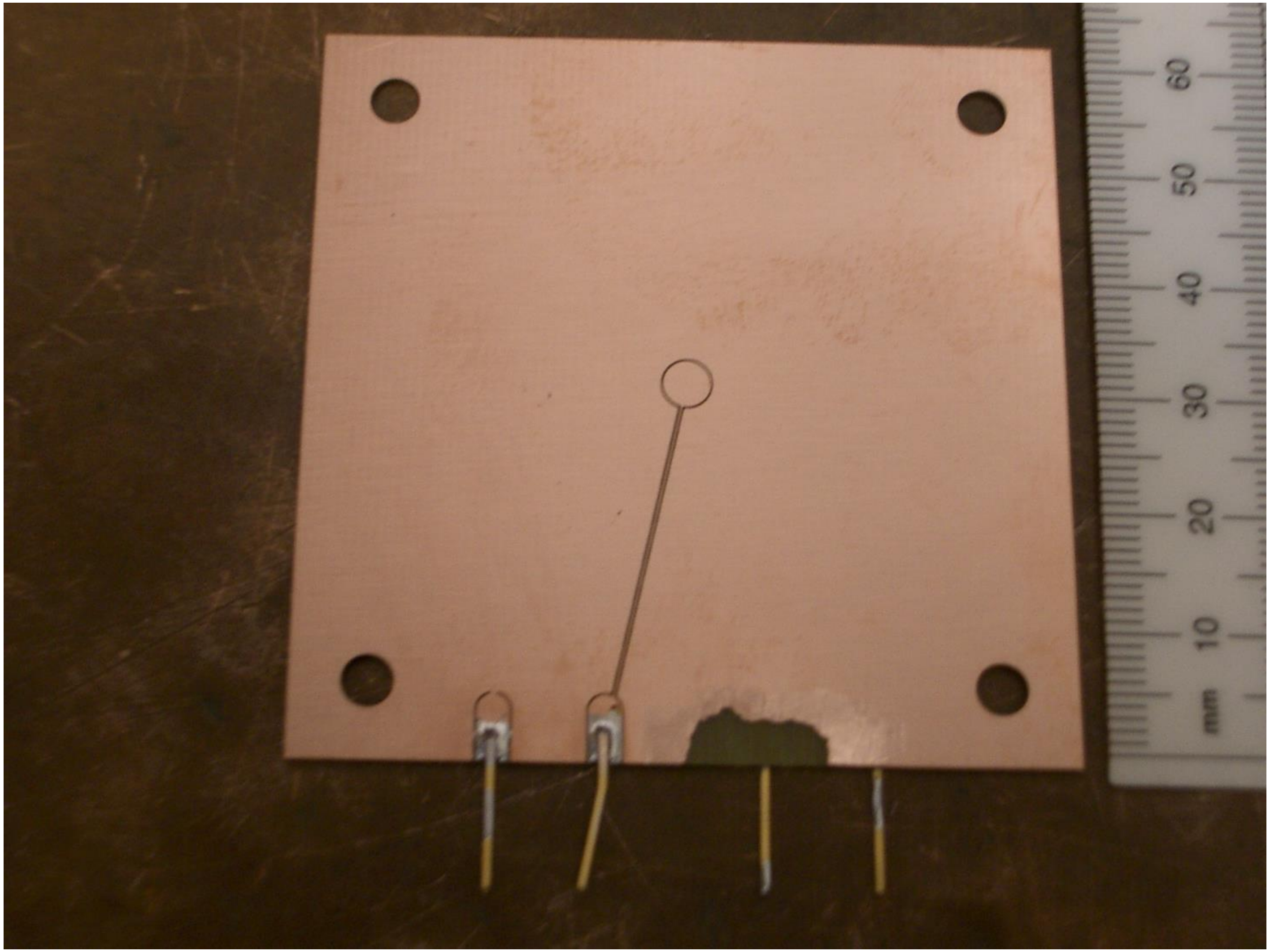
How It Works



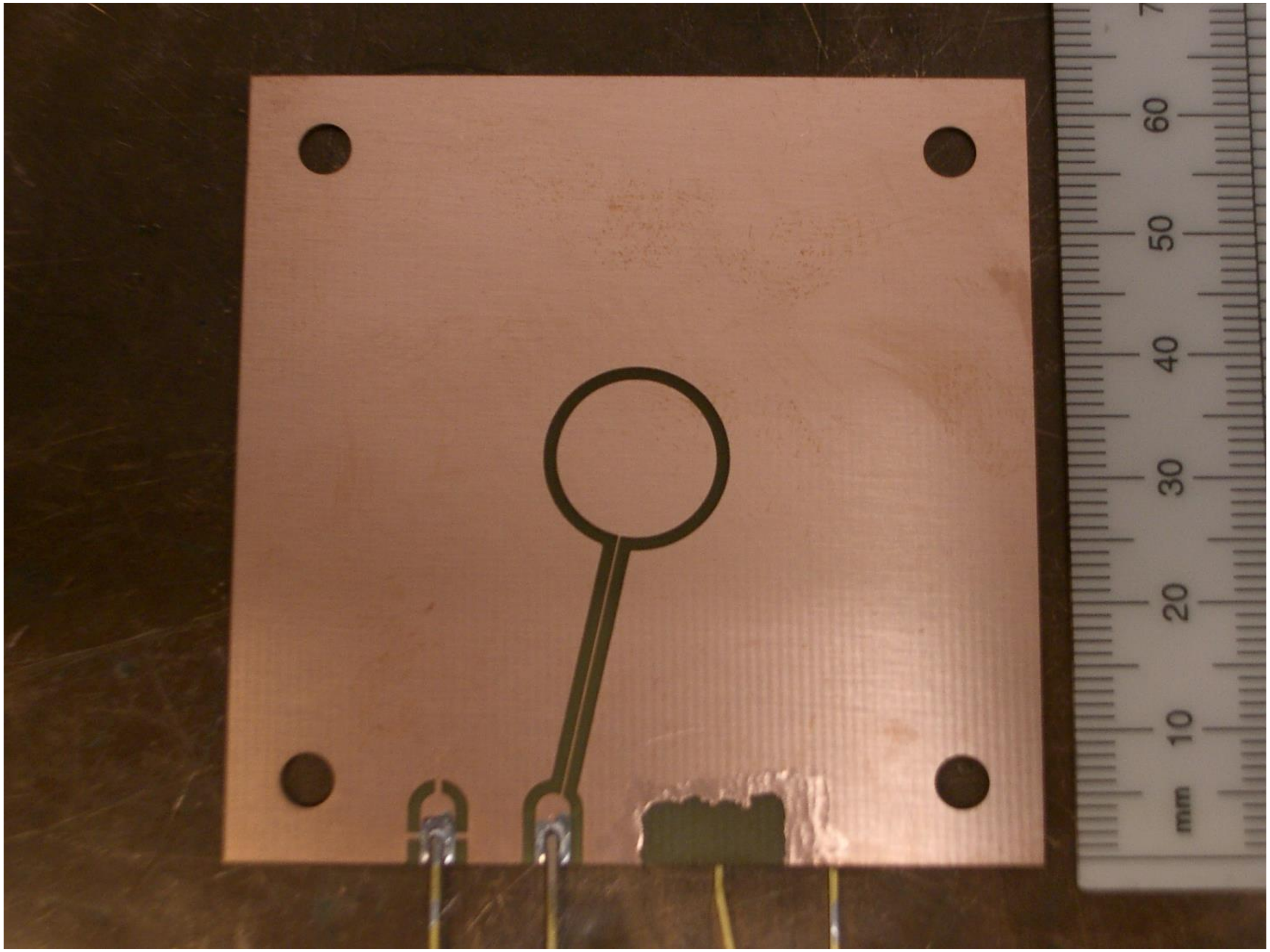
(*Not to scale.*) Identical PC boards with a signal pad on one side, and a (larger) HV pad on the other, form an array of small PPIC's. Grounded guard surfaces make the field uniform in the region of interest. The board and copper provide energy loss, the gap provides active volume, and the whole is proportioned to be roughly water equivalent.



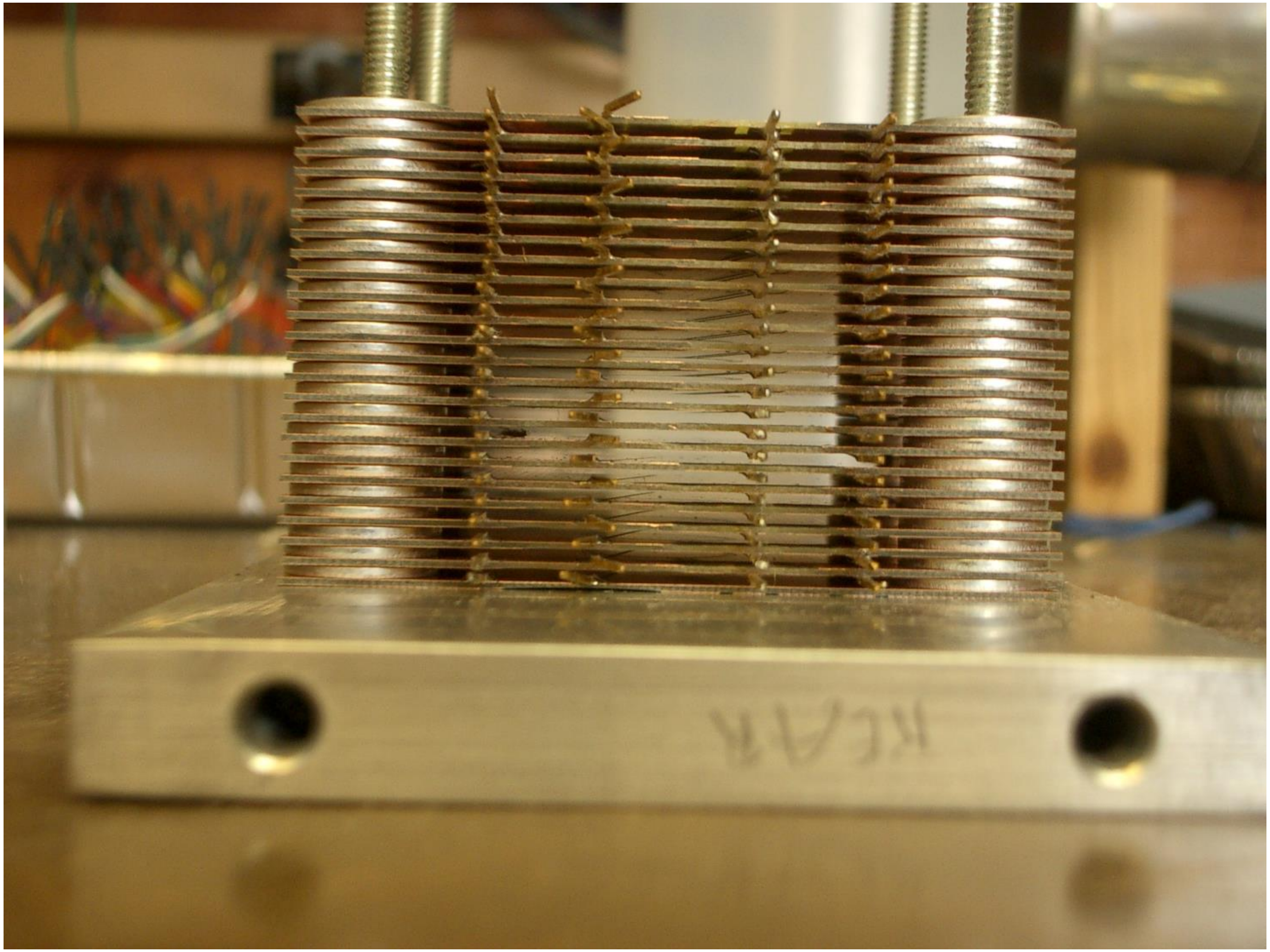
65 identical PC boards, fabricated with standard commercial technology, are mounted 1 mm apart in a rigid frame. Collimation is provided by the eye treatment line. The defining aperture or natural beam size must be much smaller than the hole shown. Otherwise, the connections are bathed in ionized air and contribute garbage signal.



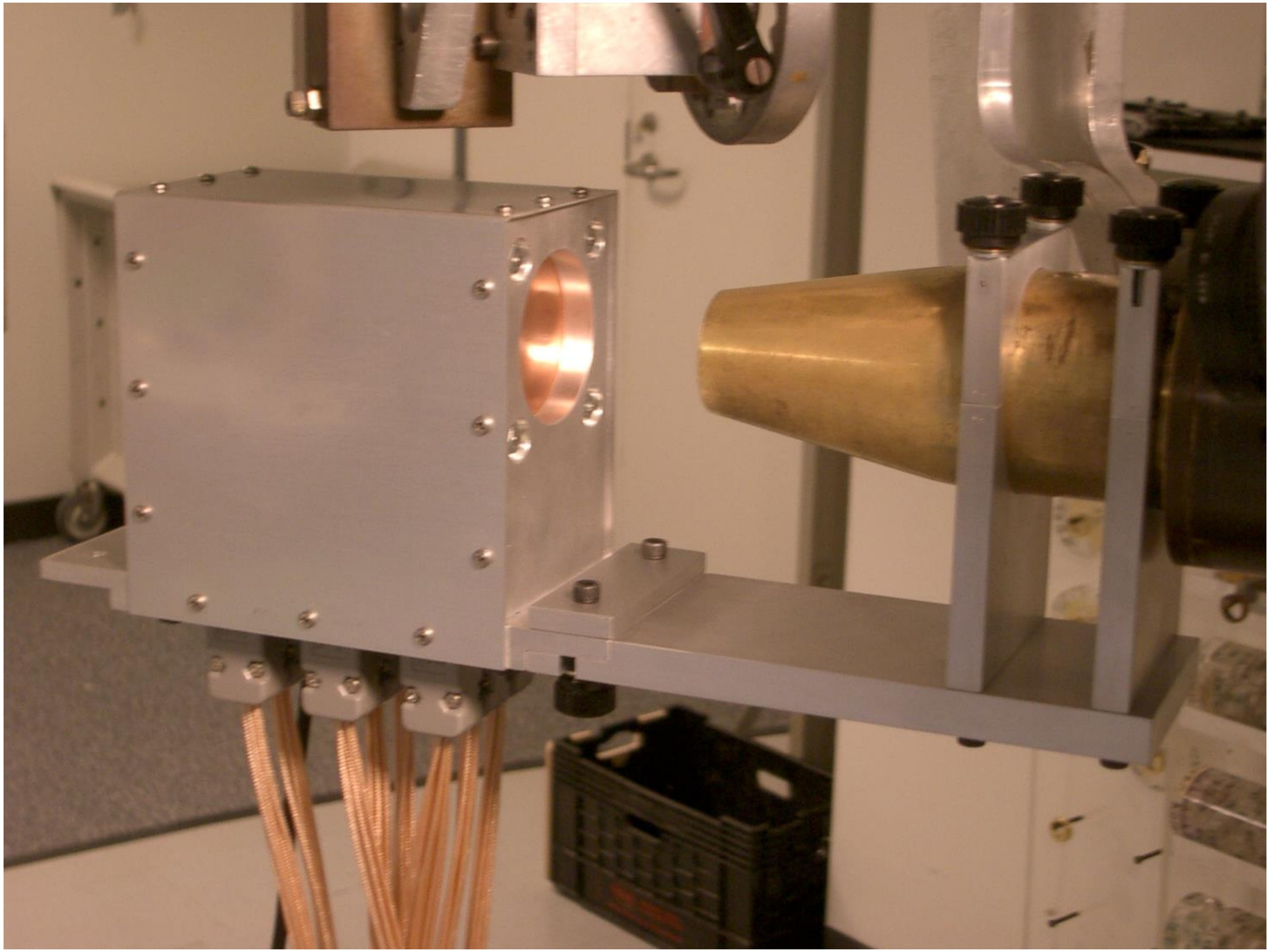
The 4 mm diameter signal pad is surrounded by ground plane. The gap between them is as small (0.006") as can be manufactured reliably, to reduce the number of protons that lose slightly less energy because they go through the gap. Signal and ground are brought out to square pins soldered by hand (note the thermal relief). Copper was removed by hand to avoid having 100 V across the 0.020" board edge.



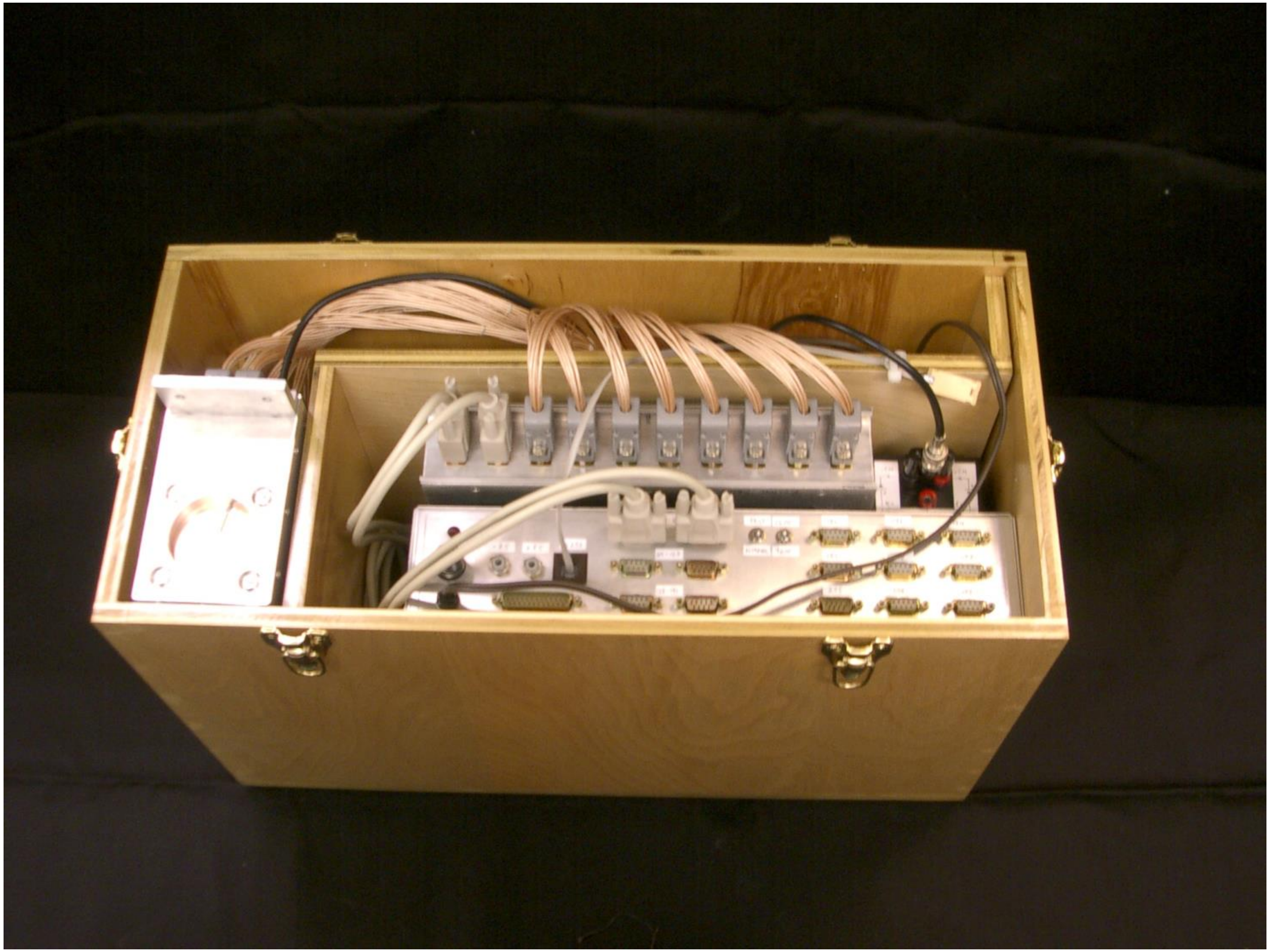
The 0.5" HV pad is also surrounded by ground plane. The copper-free space is larger to accommodate the HV and because it does not matter: protons this far out will never make it to a signal pad. The HV pad, with the ground plane facing it, provides a uniform field over the active volume. The field further out is non-uniform but doesn’t matter. The limited HV pad area reduces superfluous current when the beam is on.



The boards are separated by ordinary flat washers. The square pins just miss the opposing board. Capturing the board with the threaded rods was not a good idea, as it is tedious to fix assembly errors and possible future faults. The assembled stack by itself tends to twist as the screws are tightened. It totally relies on the frame to keep it square!



It takes longer to set up an array device than to take the measurement, so the mechanics should be carefully thought through. The 'eye MLIC' is mechanically compatible with the diode scan device used traditionally. A field light projected onto the (unused) front signal pad facilitates alignment, and sideways motion accommodates eccentric apertures. The MLIC and frame are end-to-end symmetric to pass a high energy beam either way.



Treatment rooms are hostile environments for equipment so thought should be given to storage and ease of setup. The MLIC is kept in a case along with its electronics. Battery-supplied HV is on permanently (BNC cable) for stability of operation. The box is carried to the beam line, the MLIC is removed and mounted, and the power cord and RS-232 modular phone line are plugged in.

```
-----------------------------------------------------------------------
'ZERO '       8  27347.52
     2     -2     -3     -1     -4      1      2     -2
    -2      3      0      1      1      2     -2     -3
     0     -8     -3     -3     -2      1    -10      2
    -4     -3     -4      1      2     -1      0      1
     5     -5     -2     -2     -1     -3      0      0
     0      5      3     -3     -4     -2     -2     -9
     0      2     -4     -6      1     -6      1     -3
     0     -7     -1     -6     -1      3      1      0
-----------------------------------------------------------------------
'BEAM '       9  27357.28
   379    389    397    380    402    402    386    377
   399    387    387    392    398    387    389    383
   412    390    378    397    398    395    390    416
   385    390    407    383    381    359    373    312
   265    193    133     90     46     18     12      3
     6      7      5     -2     -3      1      0     -7
    -1      1     -4     -8      0     -6      1     -3
     1     -8     -1     -7     -2      2      1     -1
-----------------------------------------------------------------------
```

record type, record #, seconds after midnight

64 channels of data (2.44 pC/count)

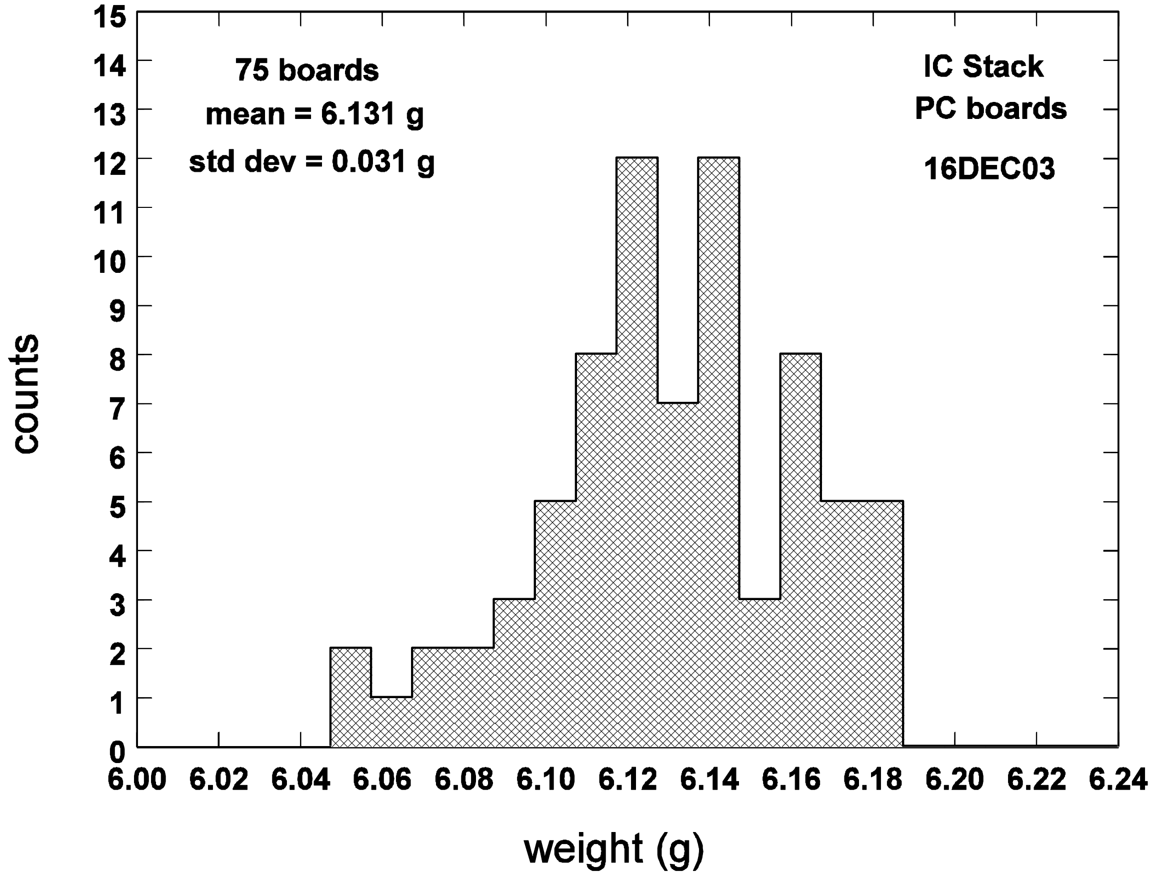
Fragment of 27FEB06.DAT . A data acquisition/data logging/eye calibration program EYECAL was written for a PC in Compaq Visual Fortran. It compiles to a Windows executable. The DAT file records data as they are taken, in the sequence clear, read A, expose to beam, read B. The final number is (B-A), further corrected channel by channel for drift current (measured previously), electronic gain (pC/count) and IC multiplication (gap correction). Other record types have initialization data, patient data and setup data. A PLAYBACK mode allows any run to be played back, either with its original constants or with a new INI file. This is extremely useful during program development.

In retrospect it would have been better to separate data acquisition and logging, which is quite general, from patient-specific aspects, best handled by a separate program.

Issues to be Considered

1. PC board uniformity
2. Current integrator gain
3. IC multiplication (gap correction)
4. Operating voltage (recombination)
5. FR4 stopping power (mm H_2O equivalent per channel)
6. Comparison with single PPIC scans
7. Comparison with diode scans

PC Board Uniformity



Before preparation for assembly the boards, whose area is essentially identical because of the fabrication process, were weighed. The mean weight was 6.131 g with an rms spread of ±0.031 g (0.5%). The outliers were set aside and the rest treated as equal. A ±0.5% difference in the width of individual channels (differential nonlinearity) is insignificant in a depth-dose measurement.

Current Integrator Gain

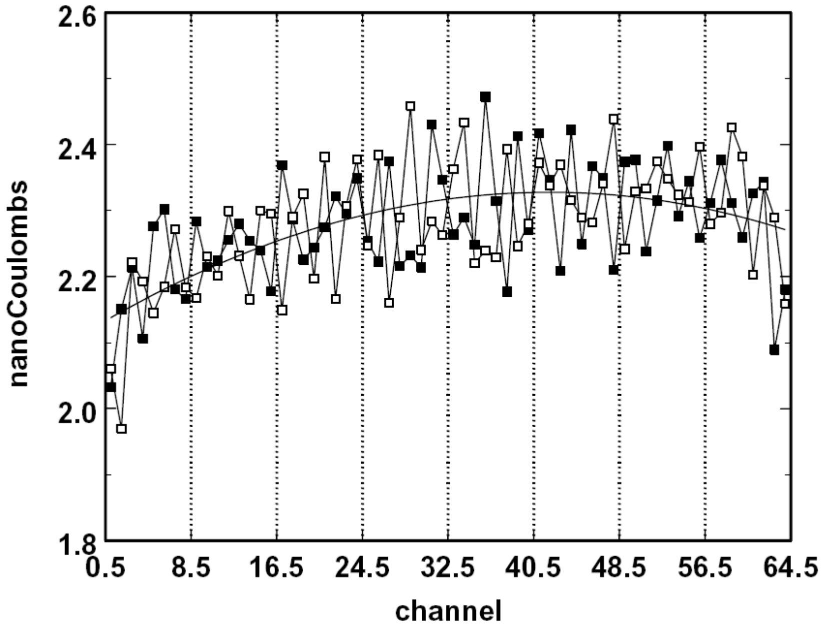
15DEC03.CAL :

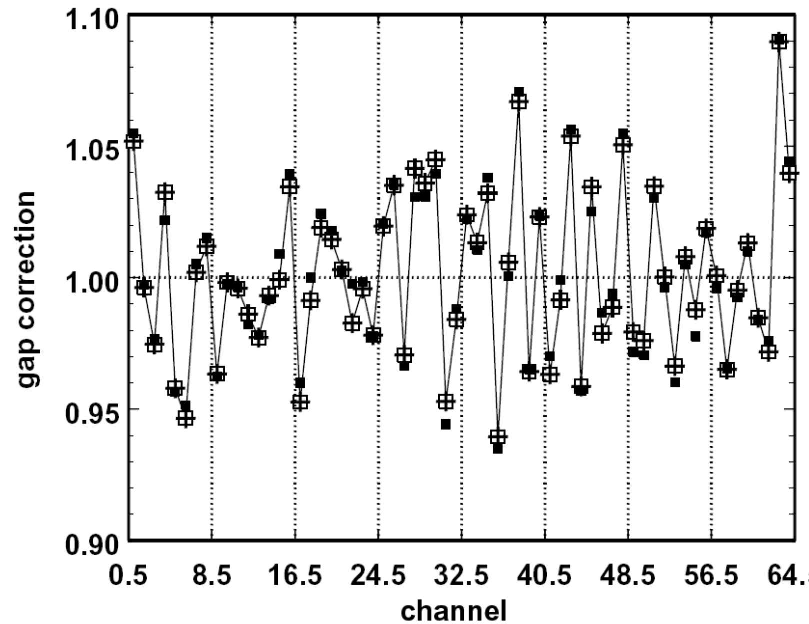
```
2440  pC injected, then counts chans 1-64
1012   996   993  1003   990   991   999   997
 999   988   998   994   992   975  1005  1016
1003  1000   981  1011   992   990   998   997
 982  1012   993   991  1007   983  1006   990
 998   993   980   978   977  1005   985   980
 993   999  1002   976   998  1013  1001  1011
1004   994   981   978   996   988   999  1008
 993  1010   989   988  1003   989   982  1005
```

The 64 channel classical integrators, salvaged from HCL, had been long used and were well understood. They are very stable but have a channel to channel gain variation of a few percent due entirely to the absolute accuracy of the 1000 pF polystyrene integrating capacitors. (Changing opamps, for instance, has no effect on calibration.)

The integrators were calibrated by applying a stable current to each input in turn for an accurate time, using an auxiliary PC program. (Even though PC's have highly accurate clocks, it takes some work to generate time intervals accurate to 0.01 sec because of interrupts.) The file shown is read by the data logging program at initialization time and converted to pC/count for each channel. The advantages of keeping *electronic* calibration separate from the physical 'gap' correction are obvious.

Gap Correction



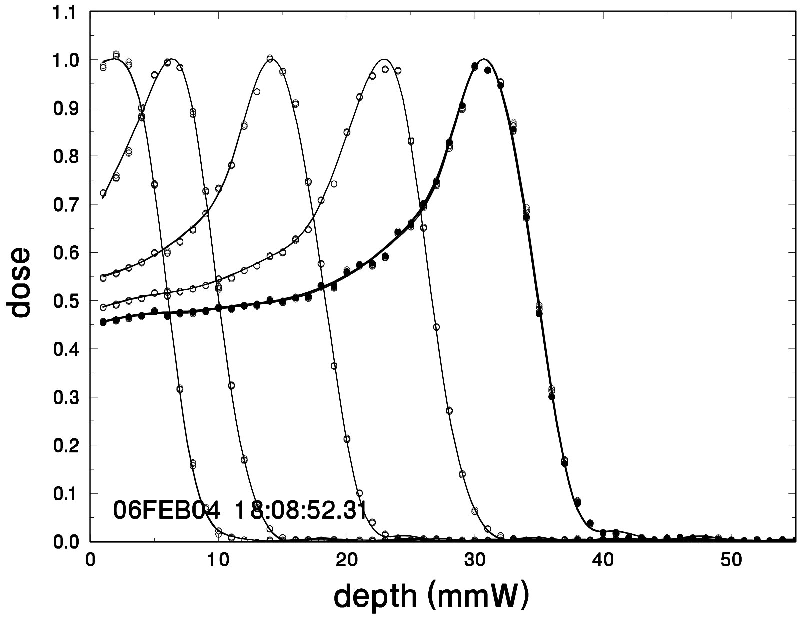


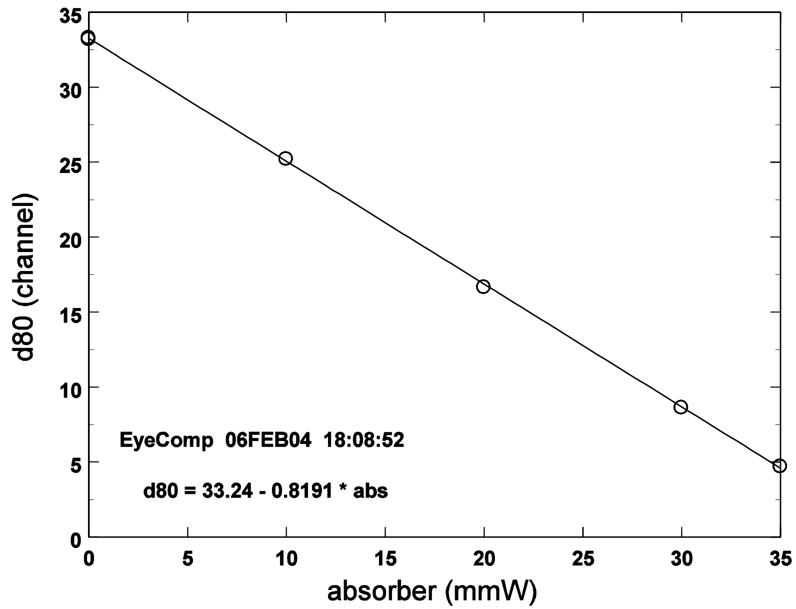
PPIC gain (pC/Gy) depends on active volume. Signal pad *areas* are highly uniform so any variation can be ascribed to the gap. To measure gap variation we expose the MLIC to a high-energy beam (not too large, not too small) from each end so that the role of each gap is reversed (raw data, left side). A fitting program then finds the unknown dose distribution as well as the (overdetermined) 64 gap corrections. The right-hand figure shows gap corrections from two runs and two fits: min/max/rms = 0.94, 1.09, 0.032 . Gap variations can be minimized by making sure connections do not transmit force to the PC board. *Do not use bus wire from board to board.*

Recombination

Under normal operating conditions (i_{IC} = 0.085 nA, d = 0.1 cm, r = 0.2 cm, V = 100 V) we find ξ^2 = 0.004% so recombination should be negligible. This was checked by reducing the nominal 115 V bias by means of a tapped battery pack, and by looking for rate effects.

mm H_2O per Channel; Equivalent Length

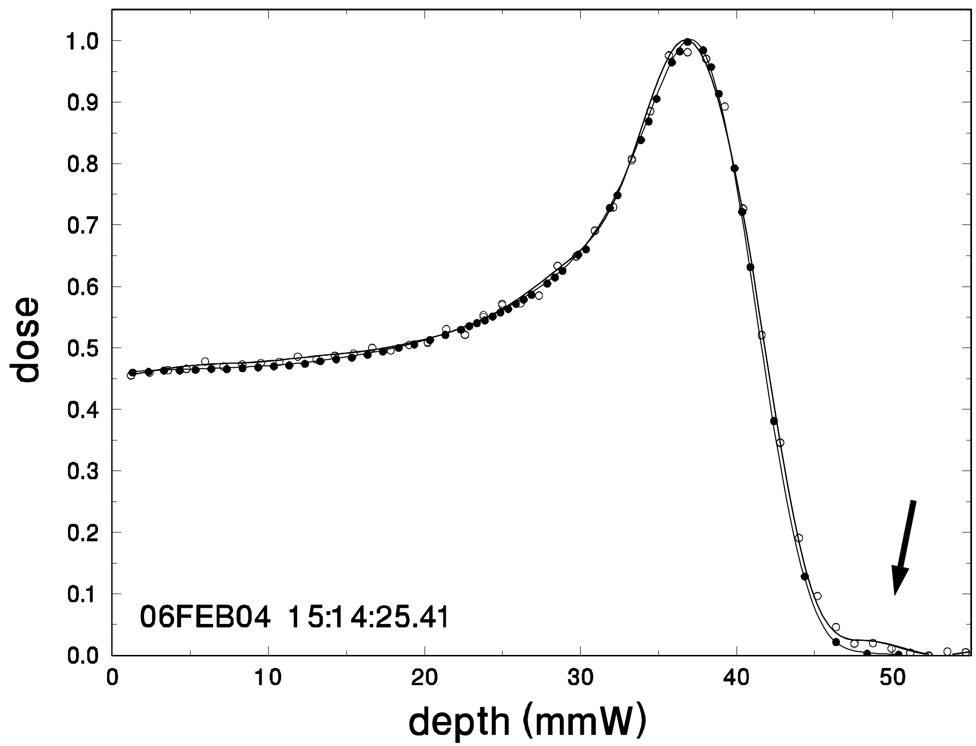




The PC boards are 0.020" FR4 with 0.0014" copper on each side. The expected H_2O equivalent is difficult to work out because of the variable composition of commercial FR4. We were trying for 1.0 mm/channel. Once the MLIC worked we calibrated it against the built-in absorber in the eye treatment line (graphs shown above) as well as a separate wedge absorber/tiny PPIC setup (data courtesy Miles Wagner) and, finally, against scans in a water tank. The final result was 1.22 mm H_2O/channel.

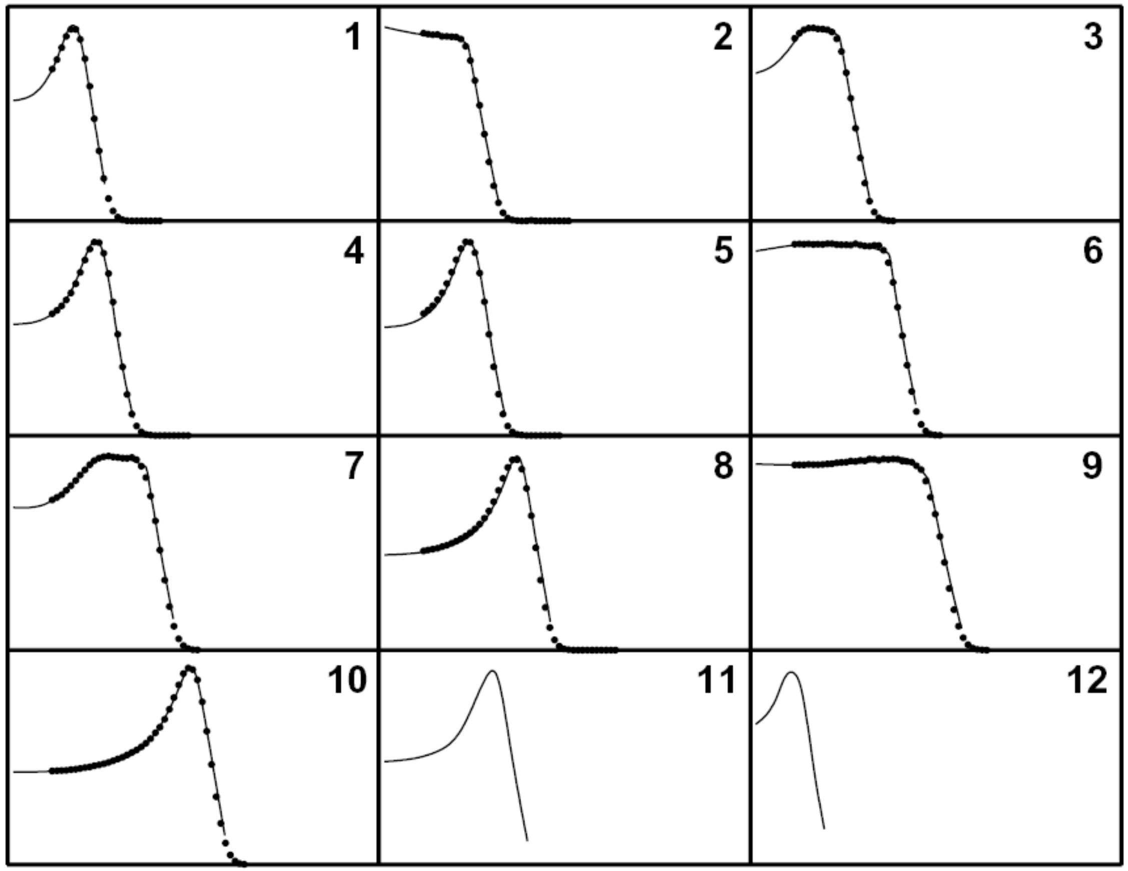
The physical length of the MLIC should be close to that of the equivalent water column in order that *difference* between $1/r^2$ in the MLIC and in a water phantom, for which we correct, be small. This MLIC is 1.363 × longer than the equivalent water column.

Comparison with PPIC Scan



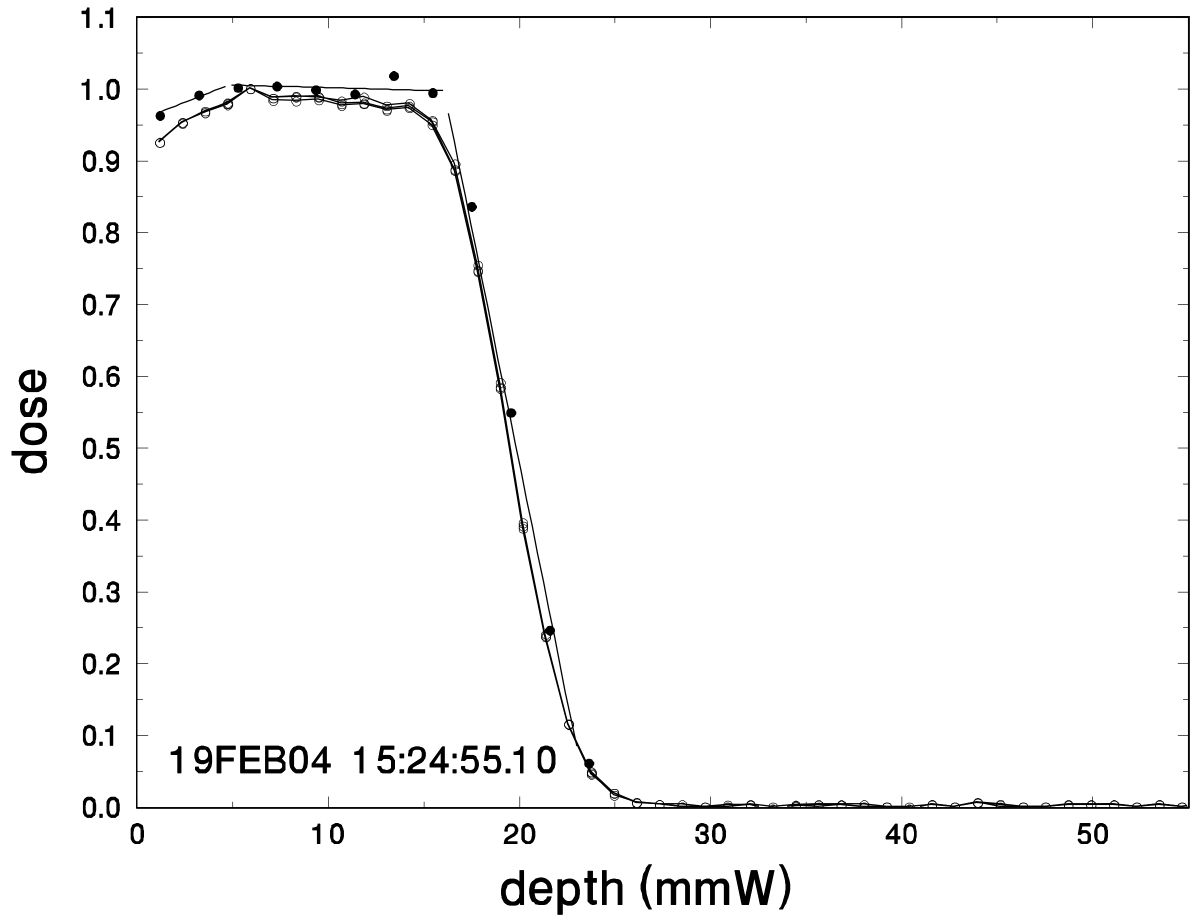
A pristine Bragg peak was measured with the MLIC and with a tiny (3 mm diameter × 2 mm air gap) PPIC riding behind a circular polystyrene wedge (100 × 0.5 mm water equivalent steps) under computer control (data courtesy Miles Wagner). The two scans agree except for a toe beyond the peak from protons that pass through a *succession* of copper-free gaps (each gap $\approx$ 0.2 mm H_2O equivalent). That happens everywhere in the depth-dose but only shows up where the dose would otherwise be zero.

Comparison with PPIC in Water Tank



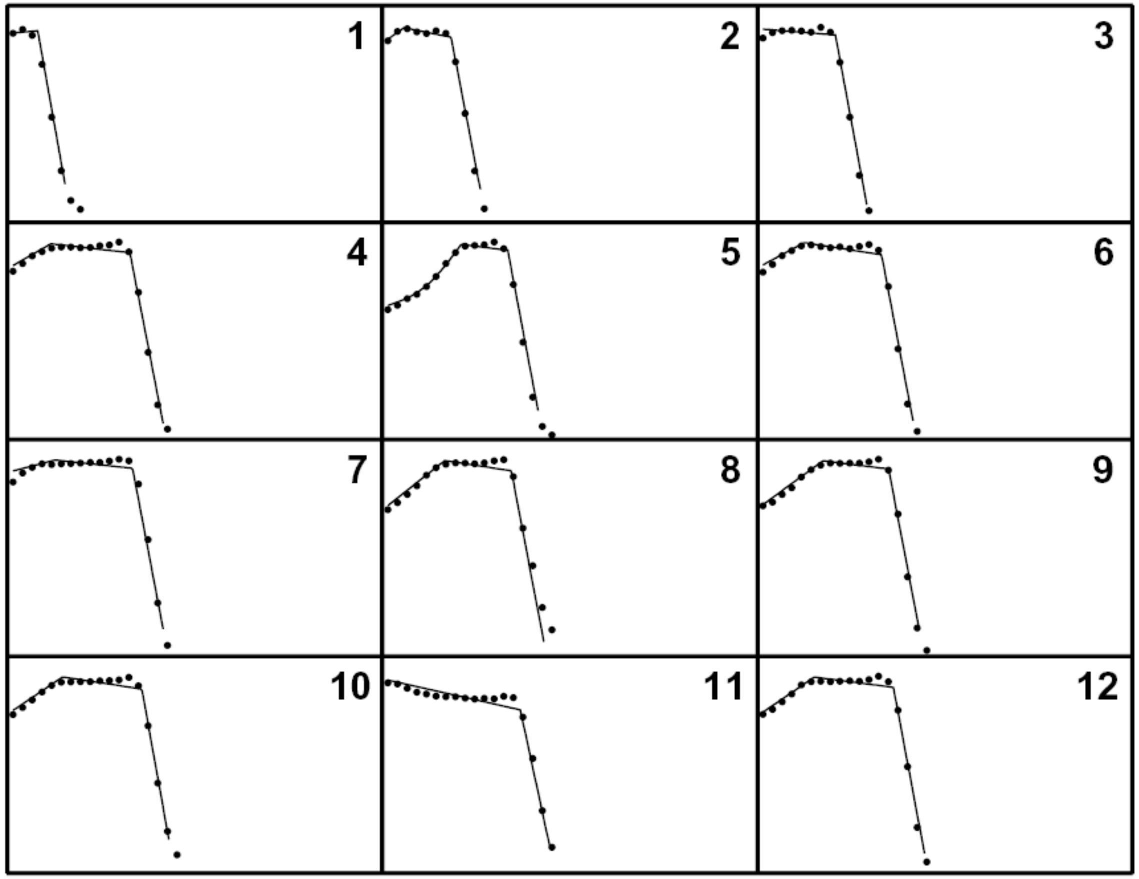
Later, MLIC measurements were compared to identical pristine and SOBP's measured in a water tank using a Markus PPIC (data courtesy Wayne Newhauser and Nick Koch). The graph shows the water tank data (dots) compared to a *fit* to the MLIC data (line). In many cases it almost seems that the water tank data are being fit!

Comparison with Traditional Diode Scan



MLIC measurements on a number of patient eye fields were compared with diode scans using the traditional AMK/diode wheel method, the gold standard at the Burr Center. This is a typical comparison: filled circles = diode scan (about 8 minutes if you get to keep the beam), open circles = several MLIC runs (2 seconds each).

More Comparisons with Traditional Diode Scan



Further comparisons with diode scans. Dots = diode wheel, line = fit to MLIC scan. As did the previous slide, most of these show the slight peakiness expected from the diode's higher response at low energy. That could be handled by looking for a slightly non-flat MLIC result, but problems measuring the output factor for very small fields have so far kept the MLIC from use in patient eye calibrations. It is used for daily QA.

Towards a Bigger MLIC: Electronics

A larger MLIC, say for the Burr Center, should probably go to the maximum range (33.4 cm H_2O at 232 MeV) plus a few cm to display the distal region. 36 cm at 2 mm/channel means 180 channels so it will require a much larger integrator array. No fully satisfactory commercial current integrator array is currently offered. To work for diodes, MLIC's and MLFC's it should meet the following specifications:

1. **Type:** for QA, either classical or recycling is acceptable because some dead time is tolerable. A recycling integrator is only required for the beam monitor.

2. **Polarity:** the integrator should be bipolar to allow leakage current of either sign to be measured.

3. **Input level:** ground, to simplify guarding.

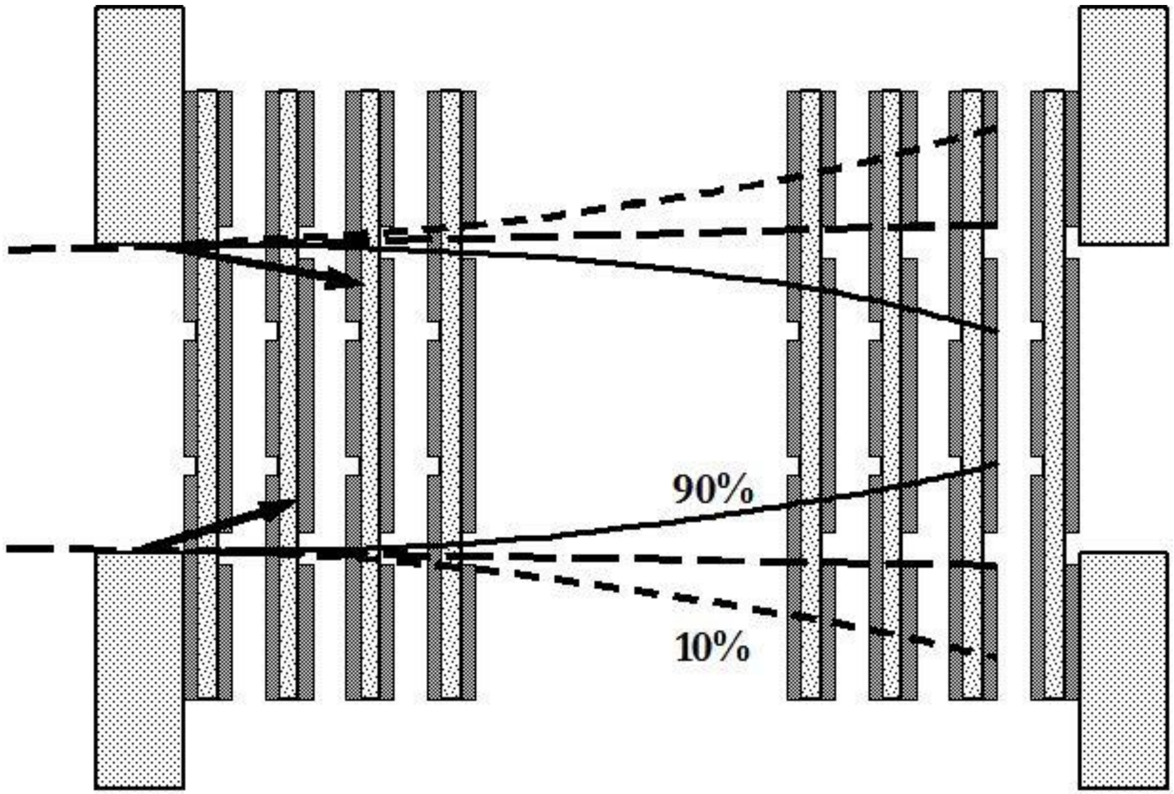
4. **Input voltage burden:** adjustable and stable to roughly 1 μV if array is to be used for diodes.

5. **Sensitivity:** 1 pC/count or better if possible.

6. **Range (if classical):** ±5 nC.

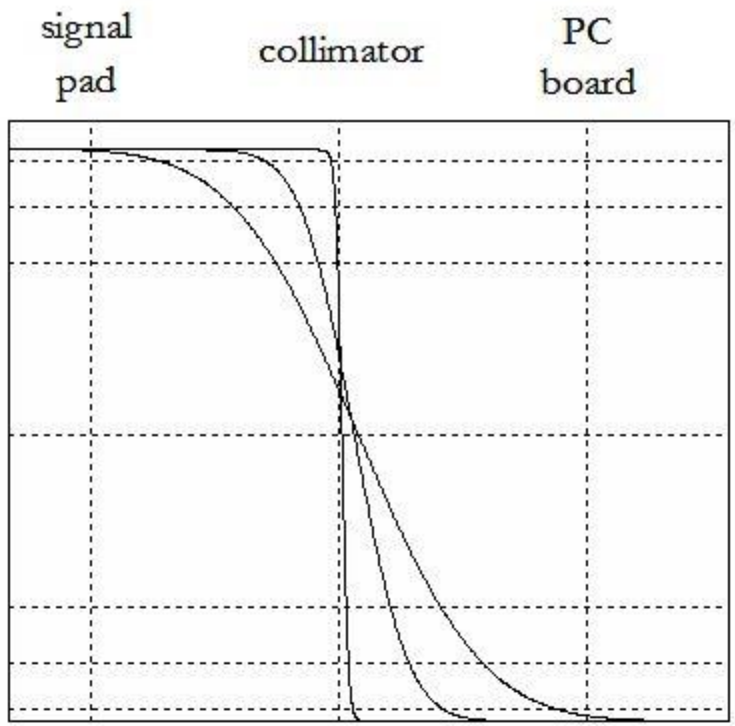
7. **Synchrony:** all integrators serving the same beam should be read at nearly the same time. Data acquisition time of 1 msec (5 μsec/channel) would allow reading 'on the fly' (beam on) in many cases.

Collimator Design



The collimator keeps the hot part of the proton beam confined to the PC board area so outside wiring is not exposed to ionized air. As the beam edge broadens by scattering, the flat part of the dose distribution shrinks. For an accurate measurement the dose should still be substantially flat over the area of the signal pad at end of range. Signal pad, aperture and PC board sizes are therefore related, and a penumbra calculation is needed. *Slit scattered* protons (arrows) normally range out before reaching a signal pad.

Collimator Design (continued)



depth cm	r50 cm	98/02 cm	90/10 cm	80/20 cm
2.000	2.018	0.133	0.080	0.052
12.000	2.094	1.083	0.666	0.435
22.000	2.119	2.420	1.516	0.997

Ideal case, demonstrated using **LOOKUP/PENUMBRA**. *Not a final design* ; the scattering medium is water, not FR4/copper/air. Simulated field with d_{100} = 22 cm, m_{100} = 22 cm, Burr Center option A7, penumbra at 2/12/22 cm depth. With a 2cm radius collimator the dose at 22cm depth is still flat over the signal pad and fully contained in the board.

Step-by-Step Design

1. Choose total ***depth*** and ***number of channels*** → mm H_2O/channel
2. Pick nearest stock thickness of PCB, copper; adjust ***gap*** (1 mm minimum) so total length ≈ length of equivalent water column.
3. Compute ***signal pad radius*** so signal at available dose rate » integrator leakage current ($i_{IC} = 37.6 \times A \times d \times (dD/dt)$ nA)
4. Compute radius of ***hole in collimator*** so dose is still flat over signal pad at max depth.
5. Specify PC ***board size*** so beam is fully contained at max depth.

Miscellaneous Topics

1. Cable: most cables generate spurious current for a while after they are flexed, a problem for any device which we wish to move into place and use as soon as possible. Teflon insulator does not have this problem, and does not generate signal when stray beam passes through it ('stem effect'). We have found RG178B/U miniature Teflon coax (about $0.80/foot) to be very successful even for long cable runs.

2. Spurious currents: when new, devices like the MLIC typically exhibit large currents in a few channels, due to insulators stressed during assembly. These currents may be of either polarity and may be much larger than the expected signal. In our experience, they always decay away in days or (at worst) weeks, but the current *must be given a path in which to flow*. In other words, you should prepare an auxiliary cable or connector which grounds every channel until the offending current goes away.

Spurious currents can interact with the electronics to produce strange effects. For instance, if the integrator is unipolar and the current is the wrong sign, it will charge up the input capacitance (device and cable). When beam comes on, the circuit will appear paralyzed until the signal current has discharged the capacitance and the integrator can start responding.

Miscellaneous (continued)

3. Guarding: remember that you are dealing with very small currents. The need for guarding does not end at the PC board. Any surface path from signal to an electrode not at ground (for instance, a +3.3V power bus) must be intercepted by a guard ring at ground. Inspect the layout carefully. An unguarded path will normally act up worst on humid days (summer).

It is the need for guarding that makes it so undesirable to have the integrator input at a potential other than ground. If the input is at (say) +2V, any surface path to *ground* becomes an enemy in addition to any path to HV or +3.3V. Although it is in principle possible to accommodate this situation by using guard structures at +2V, the net result is that cost savings at the integrator will be offset by the increased cost of every device and cable that uses it.

By default, PC manufacturers usually coat unsoldered surfaces with *solder mask*, an insulating coating. Be sure to specify that all guard rings be left *uncoated* so they can do their job!

Miscellaneous (continued)

4. Bench tests: a great deal can *and should be* learned from bench tests of the MLIC/electronics before any beam tests are done. Start by just resetting, reading and displaying the array. Are there any obvious rogue channels? Do counts change a little indicating that the channel is alive, or not at all indicating that something is saturated? Is the observed drift current reasonable (a fraction of a pA)?

A good global test consists of quickly ramping up the HV during a count. That should induce a more or less equal signal in all channels. Ramping it back down during the next count should get you back to zero if the integrators are bipolar. When interpreting the signal size, remember that it is due to coupling through the PC board (which acts like a capacitor) *and* through the air gap Therefore the end channels will show less signal..

5. Redundancy: we have written down a lot of precautions and you will be tempted to skip some of them. MLIC's *are state-of-the art devices!* Your attitude should be 'How can I provide additional safeguards?', rather than 'What can I get away with?'

Summary

We have reviewed the construction and performance of a small MLIC (7.8 cm H_2O equivalent depth, 64 channels) which has seen daily use at the Burr Center for two years.

There seems to be no fundamental obstacle to building MLIC's to measure the central axis depth-dose for deeper fields. Because net scattering is greater, the collimator aperture will have to be larger to ensure adequate acceptance at the distal end of the SOBP. Still, a radius near 2 cm should work even at the highest energies.

We have pointed out that the collimator is an inseparable part of the design, and we have outlined the design procedure.

The greatest impediment at present is the lack of a satisfactory commercial integrator array. The 128 channel Scanditronix/Wellhöfer emXX device will probably work, although its input resides at +2V and it is unipolar. It is not clear, however, that this integrator is sold separately from the LDA-99 diode array with which it is normally used.

A satisfactory full-depth MLIC would be convenient in scattered beams and indispensable in scanned or laminated beams.

(**Note added in proof**: at the time these lectures were first given, at ProCure Treatment Centers Inc., Bloomington, IN, November 2007, we received a demonstration of a full-depth MLIC recently built at MPRI with input from us, V. Anferov, D. Nichiporov and others. It worked beautifully, measuring the SOBP in a laminated beam at 205 MeV. The current integrator is an in-house design.)