

Outline

This talk covers some of the more common proton and neutron detectors used in proton radiotherapy. It concentrates on real-time detectors that require instrumentation. We'll not cover film, Gafchromic film, TLD's, gels or MOSfets .

Detectors we'll discuss either measure

fluence \equiv **protons/cm²** ('fluence meter') or

dose \equiv **J/Kg** ('dosimeter')

though we'll see that diodes, properly instrumented, can measure both simultaneously, at clinical dose rates!

Fluence meters we'll discuss are Faraday cups, single and multi-layer. They are used for beam current measurement, range measurement and range verification.

Dosimeters are diodes (when used conventionally) and ionization chambers (IC's). Large plane-parallel IC's may be used as 'integral' beam monitors or to measure the axial depth-dose (Bragg peak) in a pencil beam. Large segmented IC's are used to measure the transverse dose distribution of a beam. Small IC's (either plane-parallel or 'thimble' are used to map the dose field in a water tank, and for absolute dosimetry. (There is no real reason the two functions need to be separate.) Multi layer IC's may be used for a quick depth-dose measurement.

Current Integrators

In proton radiotherapy, dosimeters are used in two distinct ways: as beam monitors, to end the treatment at the prescribed dose, and for QA, usually in *arrays*, to measure the lateral or depth dose distribution.

In either case, considerable thought should be given to the electronics that processes the output. Some commercial systems sample the output *current*, which varies of course with the time structure of the beam. To eliminate very fast variations, the current may be filtered, or data may be smoothed in software, or both. Beam intensity variations during the scan may be canceled by measuring the instantaneous ratio of the ‘field chamber’ current to a ‘reference chamber’ current.

We prefer to *integrate* the current, measuring the total output charge. That extracts the maximum possible information from the signal and makes filtering, with its somewhat complicated time response, unnecessary. The integration time can be very short if desired. If information about the *absolute* charge is preserved, a transverse or depth scan using **N** beam monitor units per point simultaneously measures the monitor’s output factor. Most commercial hardware/software, however, does not work that way.

An array of dosimeters (IC’s or diodes) requires an array of integrators, and that can be more challenging and expensive than the detector itself. There are two kinds of integrators: *classical* and *recycling*. Both can be used either singly or in arrays, using either discrete integrated circuits or ASIC’s (Application Specific Integrated Circuit).

Classical and Recycling Integrators

FIG. 1. Basic integrator circuit.

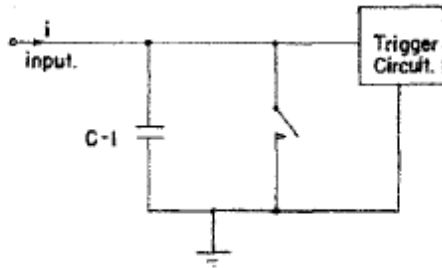
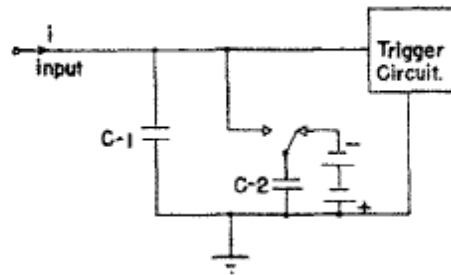


FIG. 2. Modified integrator circuit.



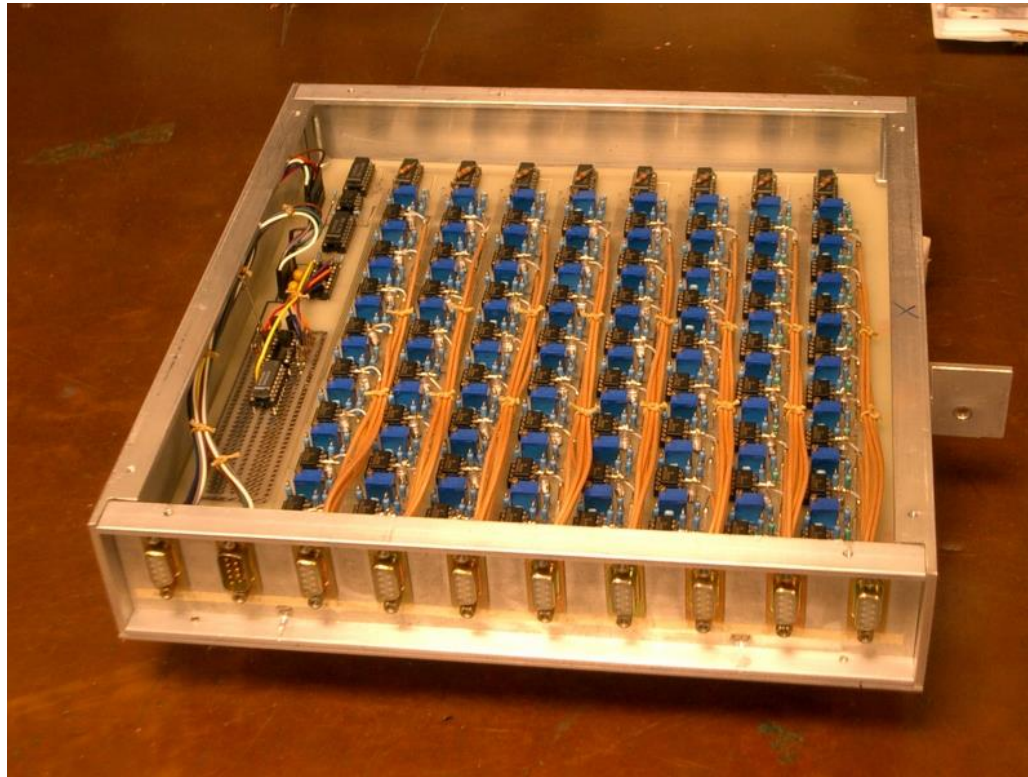
Classical integrator. When the voltage across C_1 reaches some level, discharge C_1 by closing the switch. During this time, current is lost. Accuracy depends on the stability of C_1 (no problem) and the stability of the threshold level. Residual charge at the end of measurement may be significant.

Recycling or 'charge-balancing' integrator or 'current to frequency converter.' Subtracts a charge quantum ΔQ and issues an output pulse whenever the voltage on C_1 reaches threshold. Accuracy depends only on the stability of ΔQ . No deadtime. Good fit to control system.

Drawings from Lewis and Collinge, 'A precision current integrator of medium sensitivity,' Rev. Sci. Instr. **24** (1953) 1113.

Analogy: measuring flow rate from a faucet with a bucket. **Classical**: when water reaches a certain level, empty the bucket and increment a counter. You lose water while you empty the bucket. **Recycling**: when water reaches the level, remove an accurate dipper full of water and increment a counter. You lose no water, and in a long measurement (many counts) only the accuracy of the dipper matters, not exactly when you dip it into the bucket.

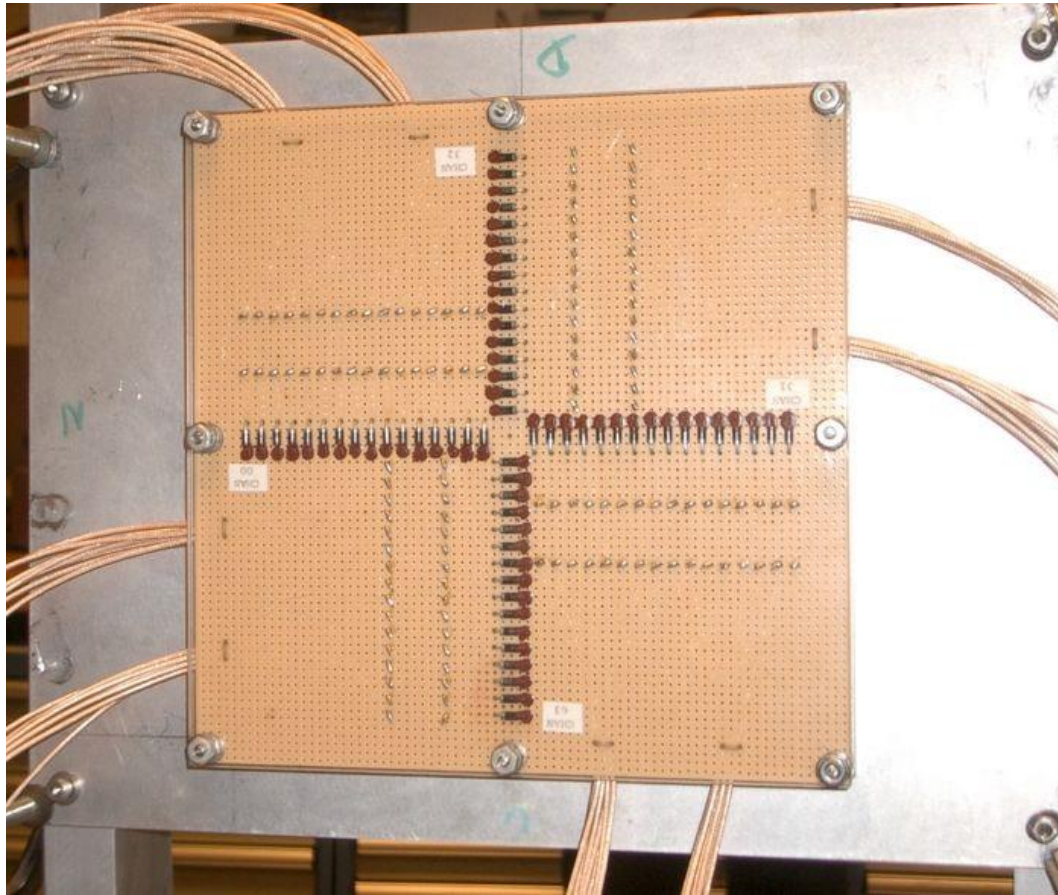
64 Channel Classical Integrator Array



This array built ca. 1995 is still used at the Burr Center for CROSS and MLIC. A second unit houses a scanning ADC to read the integrators and transmit data to a host computer via RS-232.

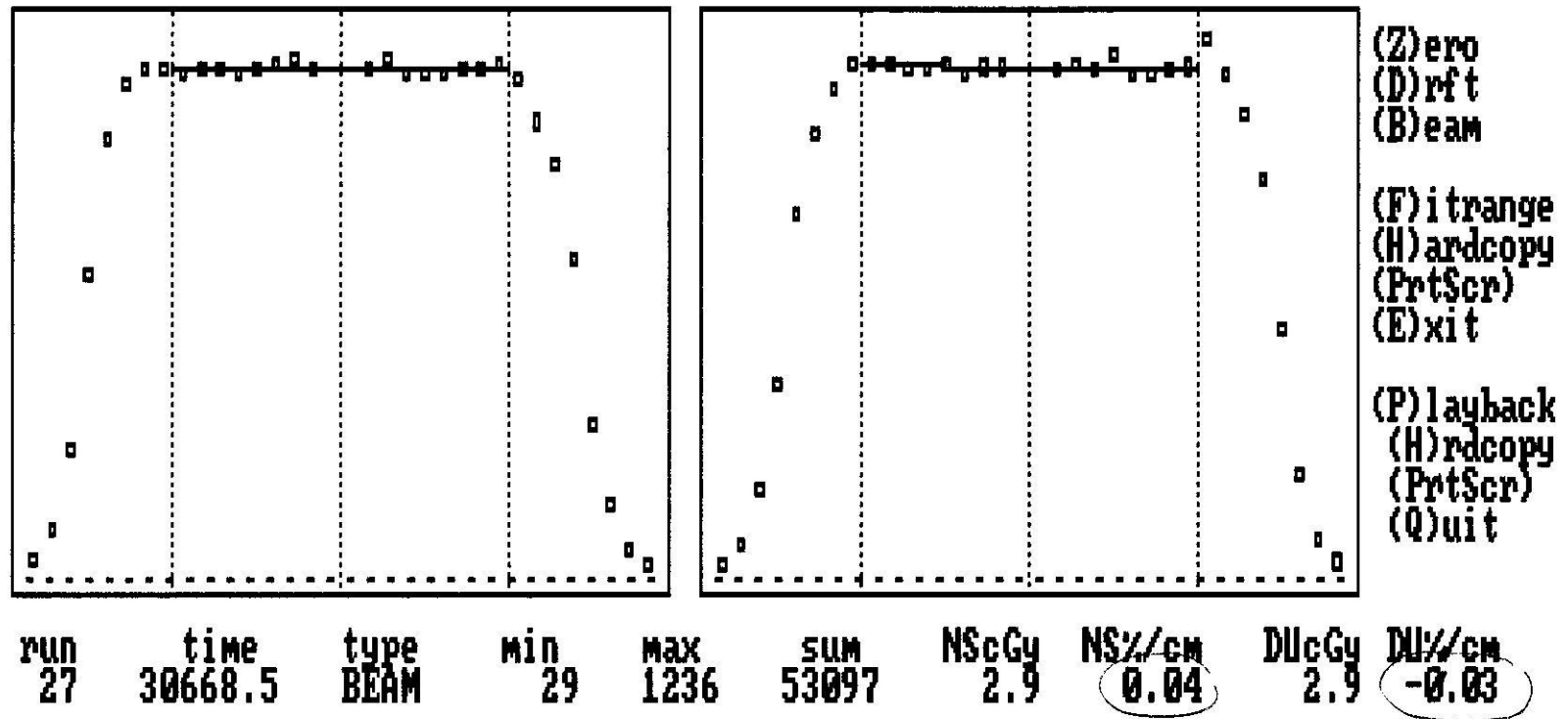
No all-purpose integrator array is commercially available at present, though it is easy enough to write the specs for one. At present, integrator arrays are sold as packages with array detectors and software by various manufacturers, but not separately.

A Diode Array



The 32×32 '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 ion collection. 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.

Real-Time Output



On-line displays on the PC running the CROSS array. The measurement shown took *two seconds*. Array devices take longer to set up than to use so ease of setup should guide the mechanical design. Data should be recorded in a compact and automatically named *log file* with no operator response needed.

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.

General-Purpose Integrator Array: Specs

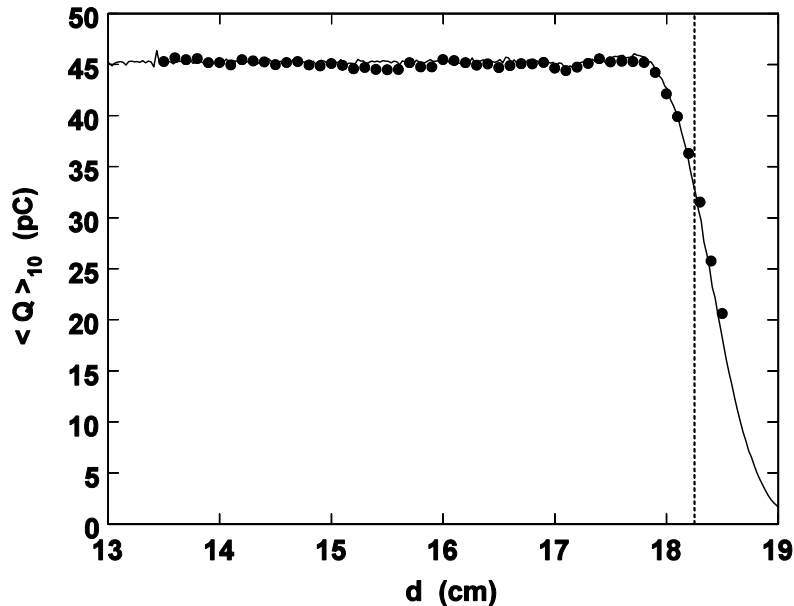
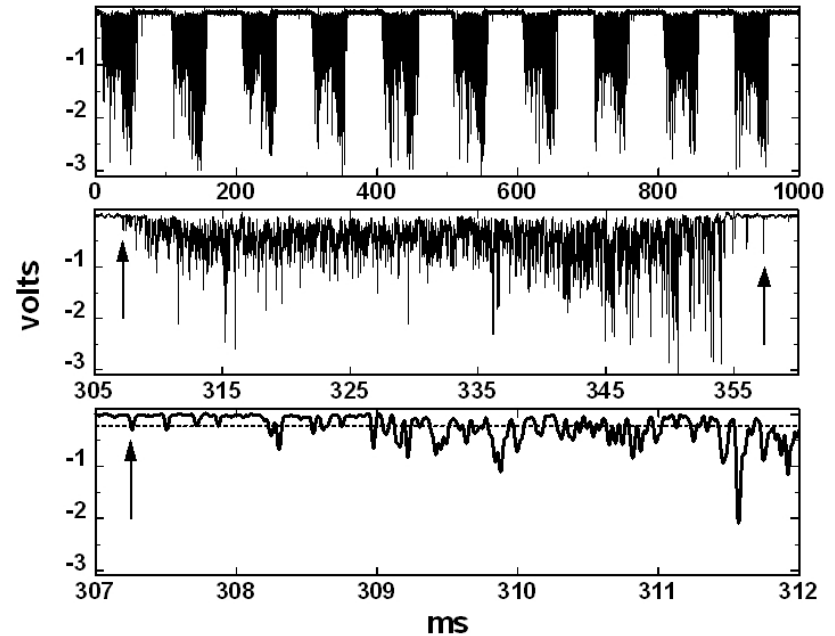
The future, especially as beam scanning becomes more common, will see greater use of detector arrays: multi-layer IC's, diode arrays and multi-layer Faraday cups. Frequently the detector itself will be home-built for a specific application, but all such detectors will require current integrator arrays. At present (2008) no fully satisfactory integrator array is commercially available. A general purpose integrator should meet the following specs:

1. **Type:** for QA, either classical or recycling is acceptable because some dead time is tolerable. For the beam dosimetry monitor, a recycling integrator is required.
2. **Polarity:** the integrator should be bipolar to allow leakage current of either sign to be measured. If it must be unipolar, it should *sink* current to work with Faraday cups.
3. **Input level:** the input should be at ground to simplify guarding of the detector.
4. **Input voltage burden:** should be adjustable and stable to $\approx 1\mu\text{V}$ if integrator is to be used for diode arrays. Other detectors don't care.
5. **Sensitivity:** 1 pC/count or better if possible.
6. **Range (if classical):** $\pm 5\text{ nC}$.
7. **Synchrony:** integrators serving the same beam line should be strobed at nearly the same time. Total scan time $\approx 1\text{ msec}$ ($\approx 5\text{ }\mu\text{sec/channel}$) would allow reading 'on the fly' (beam on) in many cases.

Digital Sampling Plus Software

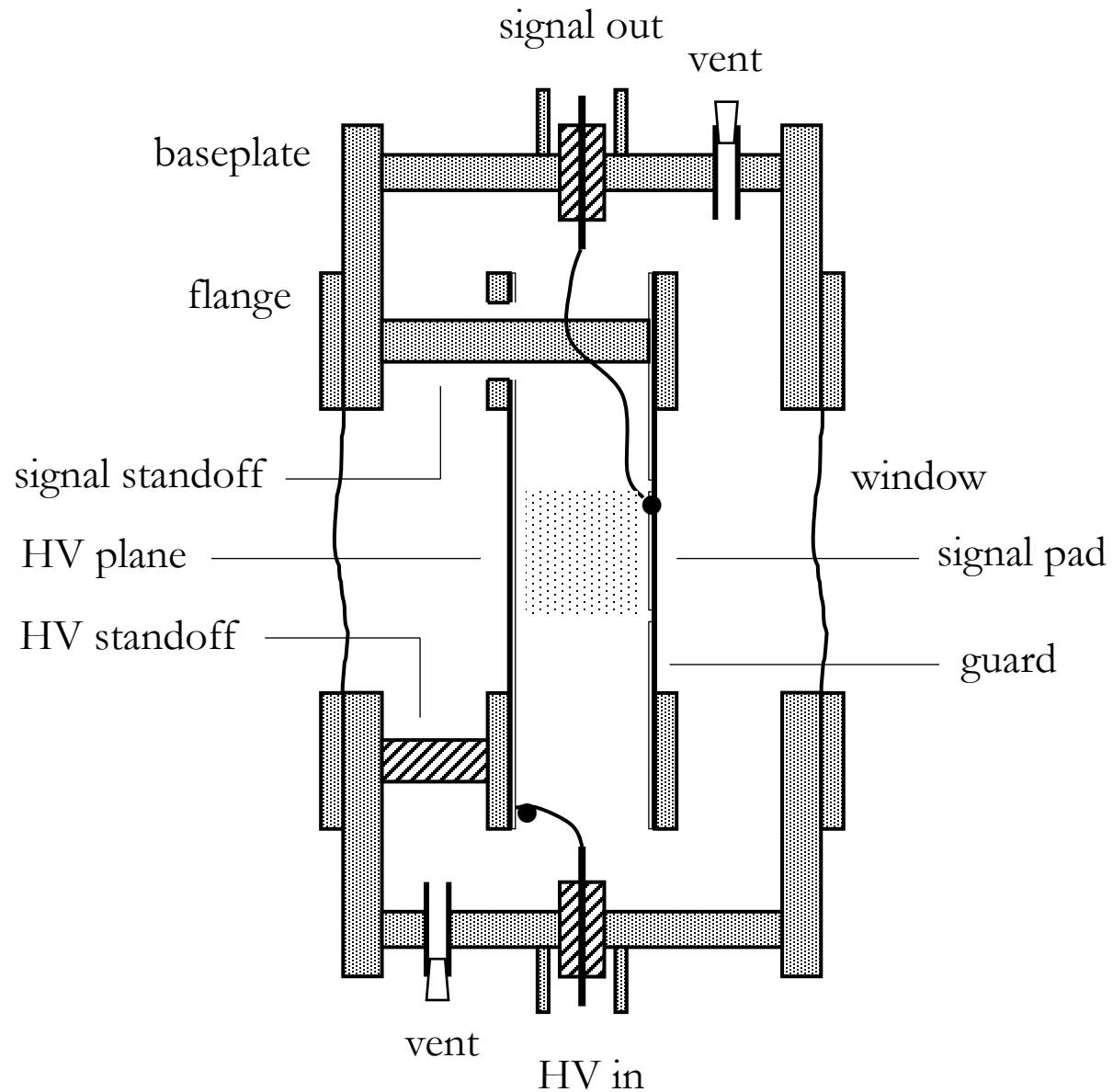


IOtech 6220, 16 bits,
12 channels, 100 Ks/s,
Ethernet, \$3000



Left: SOBP measured with a PTW diode > fast amplifier > Lecroy oscilloscope. Above: ten modulator cycles : 10^6 numbers! Adding these we get total charge or dose. The line (left) is from a Markus IC using conventional electronics.

Plane-Parallel IC (Beam Monitor)



IC Output Current

$$i_{IC} = 37.6 A d \dot{D} \text{ nA}$$

if Ad is in cm^3 and dose rate is in Gy/sec . This form is useful if the dose rate is essentially constant over A (a small PPIC in a big beam). If on the other hand we assume a beam that is uniform over A and zero elsewhere we obtain

$$\frac{i_{IC}}{i_p} = 37.6 d \frac{S}{\rho}$$

for the current *multiplication* of the PPIC, with d in cm and S/ρ in $\text{MeV}/(\text{g}/\text{cm}^2)$. Absent recombination, this holds *whatever* the shape of the beam as long as it is fully contained in A . If there *is* recombination it will be worse, the smaller the beam.

The neurosurgery beam monitor chambers at HCL had two gaps adding up to $d = 0.25''$ which gives a multiplication of 110 at 160 Mev (S/ρ (air) = $4.608 \text{ MeV}/(\text{g}/\text{cm}^2)$). The measured value was 104. Probably d was slightly less than its nominal value.

It is good design practice to observe one or the other limit: A much smaller than the beam, in which case the IC can be regarded as sampling the local value of the dose, or much larger ('integral chamber') in which case it measures total beam current. Intermediate cases are more difficult to interpret, and do not tell us anything simple.

Recombination

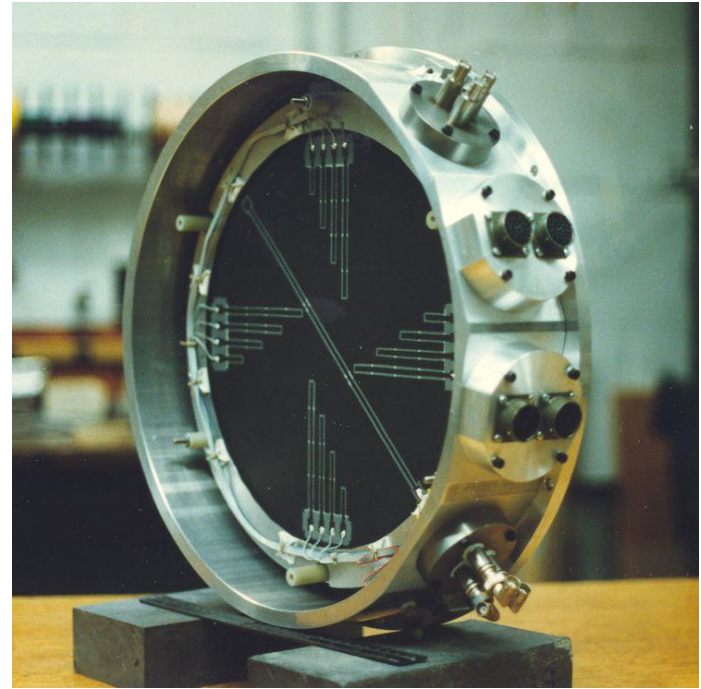
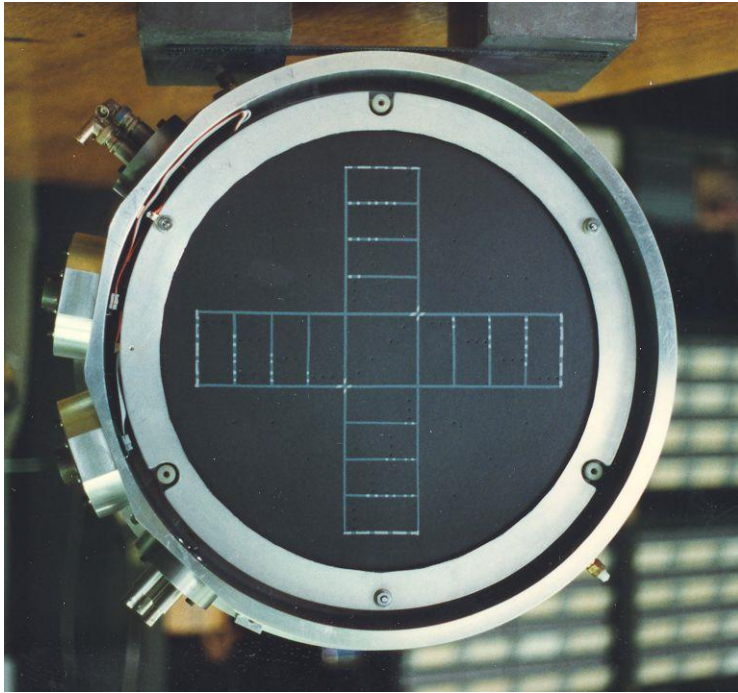
IC's are prey to recombination, which results in an output current less than that given above. More important, recombination, if it is significant, depends on many factors and is therefore likely to vary with time.

Current in IC's is usually carried by positive ions going one way and negative ions going the other way. (In some cases electrons may play a role.) When two oppositely charged ions collide they may recombine, effectively removing a quantum of charge from the output current. Fortunately this is not as common as might be thought, because conservation of energy and momentum must hold in the collision. However, it does happen.

Recombination is worse a) the greater the gap, b) the lower the bias voltage, c) the greater the current density and d) the lower the duty factor (fractional 'on' time) of the beam. Thus it tends to be worst at the IC that monitors cyclotron output (very large current density) and we try to make the gap as small as possible. We may use another kind of transmission monitor (secondary emission monitor) or use an IC gas other than air (helium).

Recombination in the other air-filled IC's of a proton radiotherapy center is usually negligible.

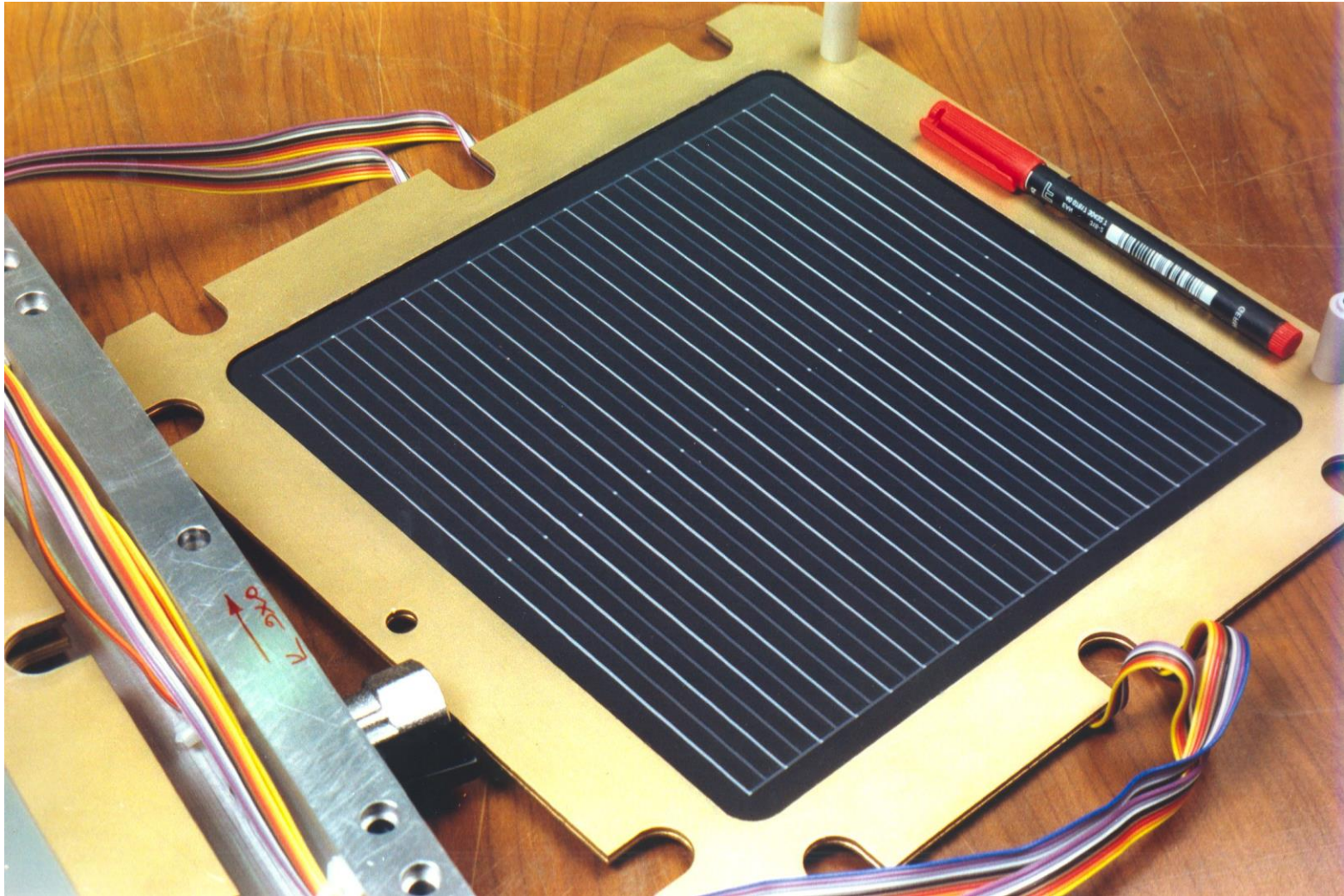
Case Study: Combined Dose and Flatness Monitor



At HCL in 1995 we decided to replace the Room 2 (large field) beam monitor IC with one that would sample the center of the beam as a dose monitor *and* provide dose flatness data for a closed-loop beam centering system. The left-hand photo shows the central ‘dose’ pad flanked by ‘flatness’ pads, 8 in each direction. Two complete planes existed providing a redundant dose measurement and spare flatness pads. The patterns were created by spraying a conductive coating onto masked 0.003" stretched matte artist’s Mylar.

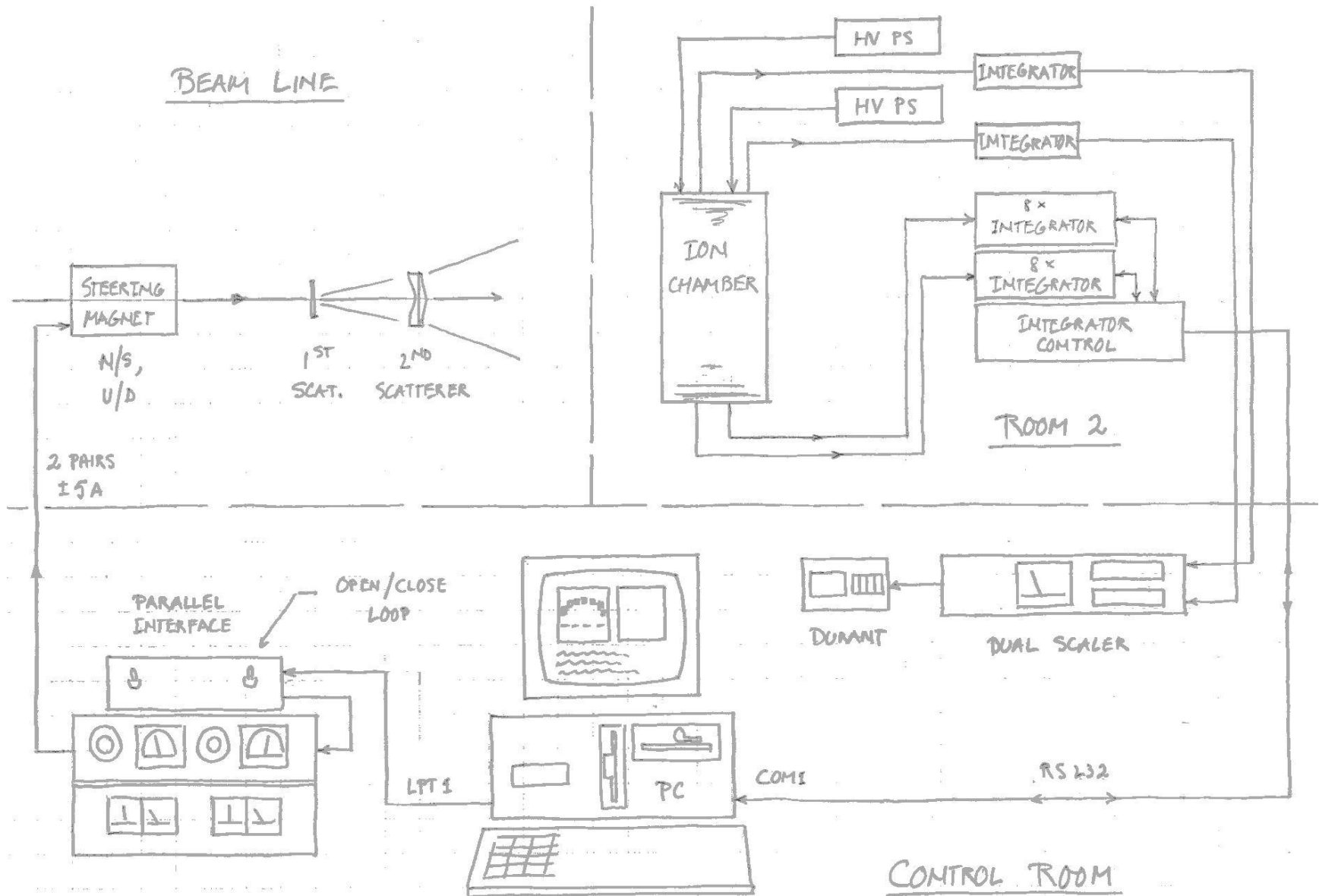
The right-hand photo shows the lead-out traces on the field-free side of the assembly, connected by pin-pricks filled with conductor. The assembly was hermetic to exclude humidity. Sealed multi-pin connectors were made by hand from commercial components.

An Alternative: Strips



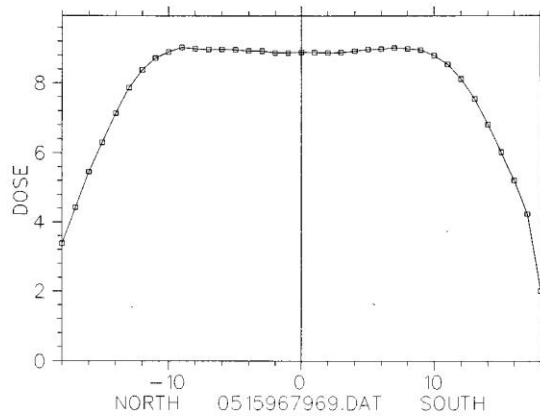
The segmented IC in the standard IBA nozzle uses 32 *strips* instead of pads, with another 32 orthogonal. The dosimetry pad has to be on a separate plane. A Monte Carlo study showed this would also work, and it cuts down on the electronics.

Block Diagram of Beam Monitor and Steering System

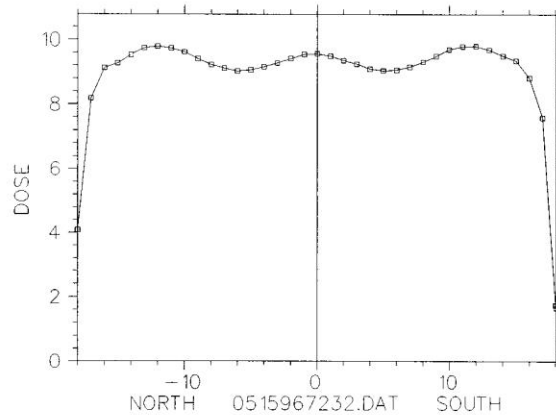


The Bottom Line

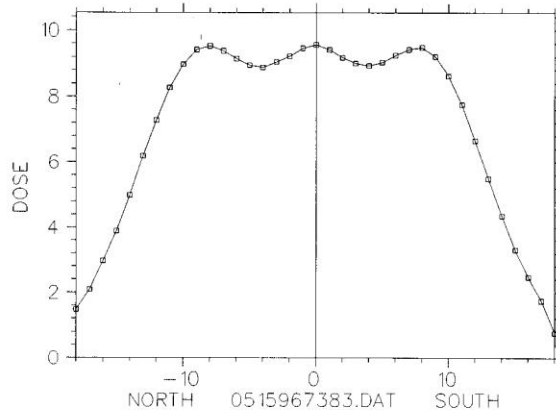
CONTOURED



LARGE

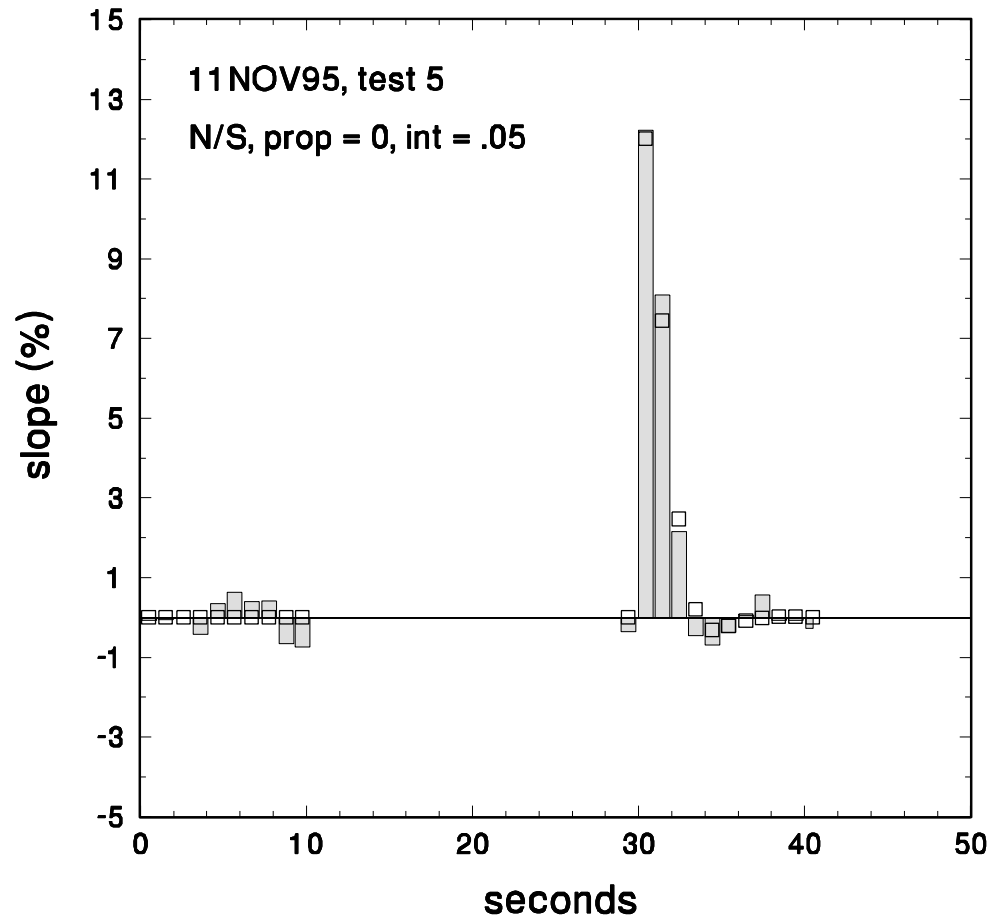


SMALL



N/S dose scans taken with the 'Oilcan' dosimeter while the steering system held the dose flat.

Settling Time



An auxiliary program analyzes the fitted slope history. This shows system response to a deliberate 12% step perturbation, far greater than anything normal. Even then, the system settles in 3 sec, 1/20 of a normal treatment. Bars = measured data, squares = predicted response. (Digital feedback systems lend themselves to exact analysis.)

THIMBLE ION CHAMBERS

Click on an image below to learn more



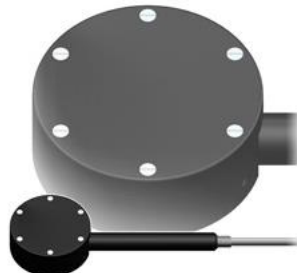
We have been discussing IC's which are larger than the useful beam. For mapping the dose field, in air or in a water tank, we need an IC which is much smaller than the beam. The 'thimble' chamber has a cylindrical geometry and isotropic response, making it useful for photon dosimetry. However, in proton dosimetry the effective thickness depends on where the proton passes through. A pristine Bragg peak measured with a thimble chamber will appear wider than one measured with a plane-parallel chamber.

PARALLEL PLATE CHAMBERS

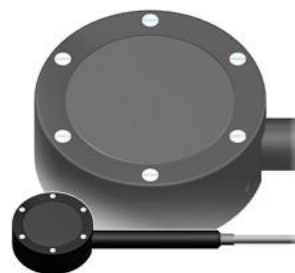
Click on an image below to learn more



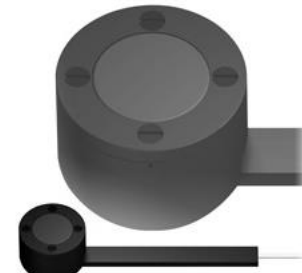
EXRADIN A10 ION CHAMBER



EXRADIN A11 ION CHAMBER



EXRADIN A11TW ION CHAMBER



EXRADIN MAGNA A600 ION CHAMBER

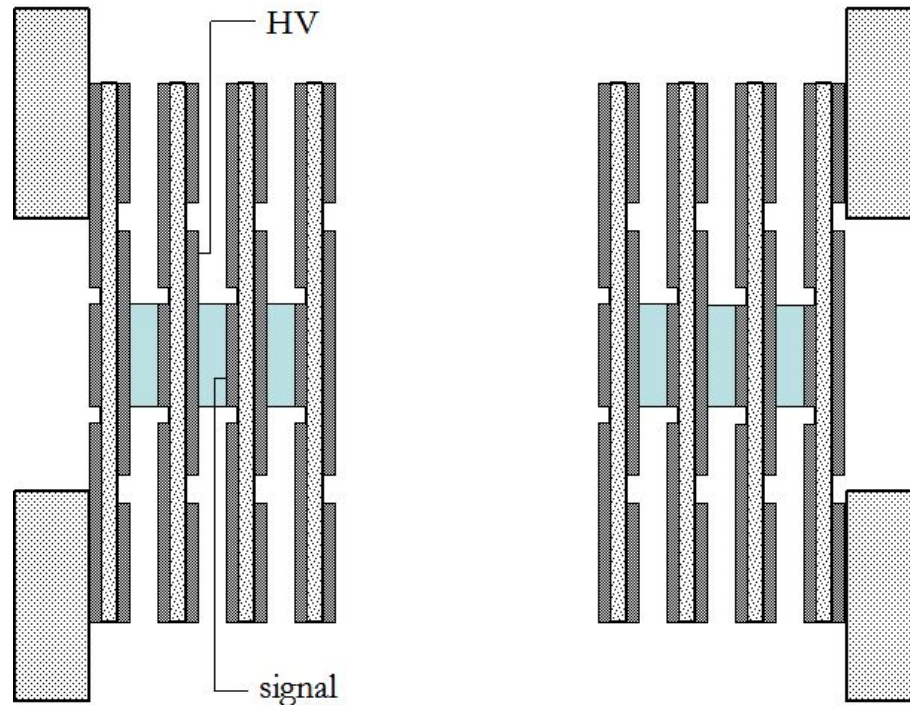


EXRADIN MAGNA A650 ION CHAMBER

Small plane-parallel chambers (PPIC) are available commercially. They are frequently called ‘Markus’ chambers though technically that refers to a PPIC of very specific dimensions and construction. The effective thickness of a PPIC is independent of where the proton goes through, so a truer picture of the Bragg peak is obtained.

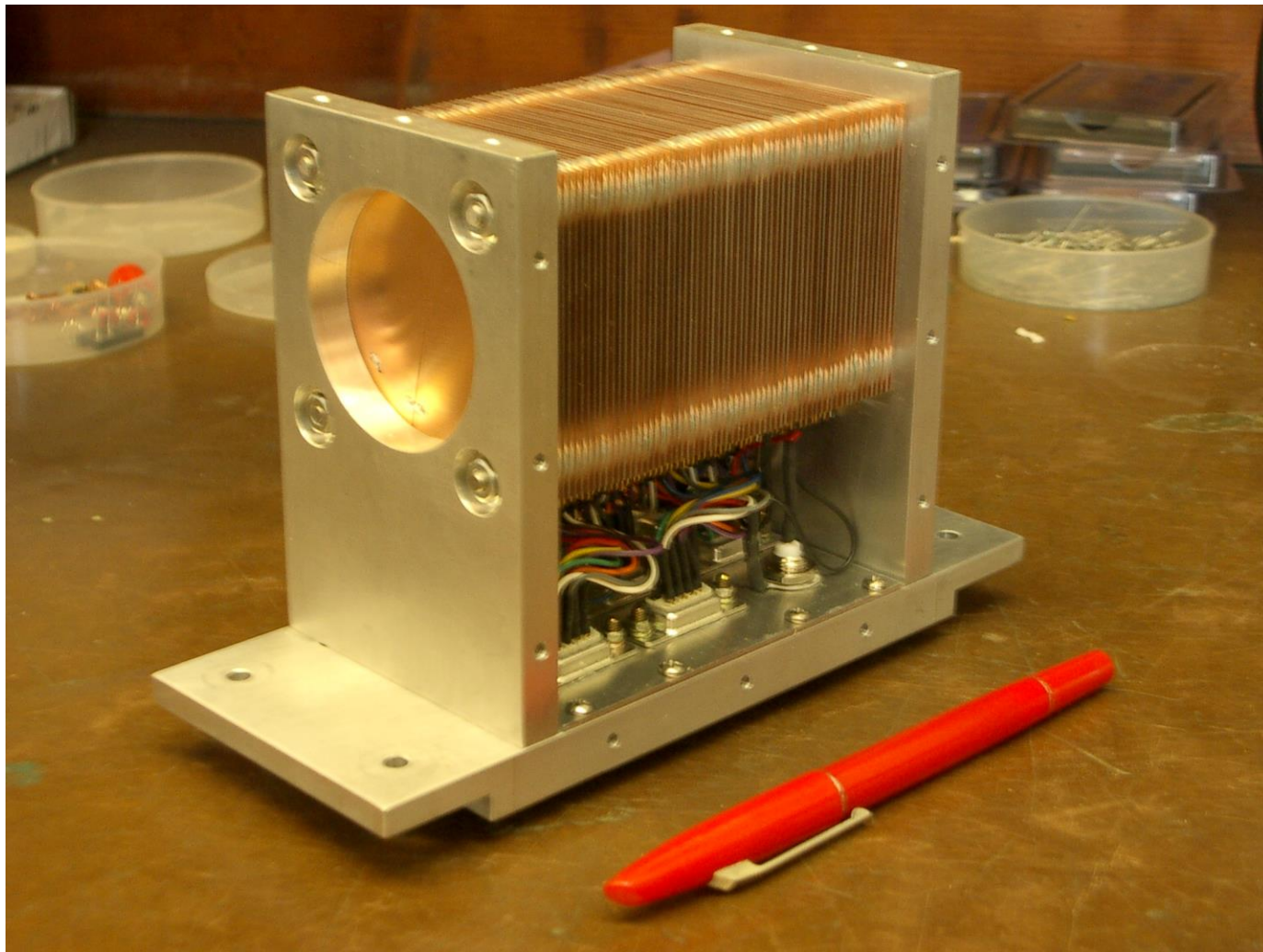
Sometimes small PPIC’s are used to measure the Bragg peak and the SOBP while thimble chambers are used for absolute dosimetry. That facilitates comparison with well established γ -ray dosimetry techniques.

Multi-Layer Ionization Chamber (MLIC)

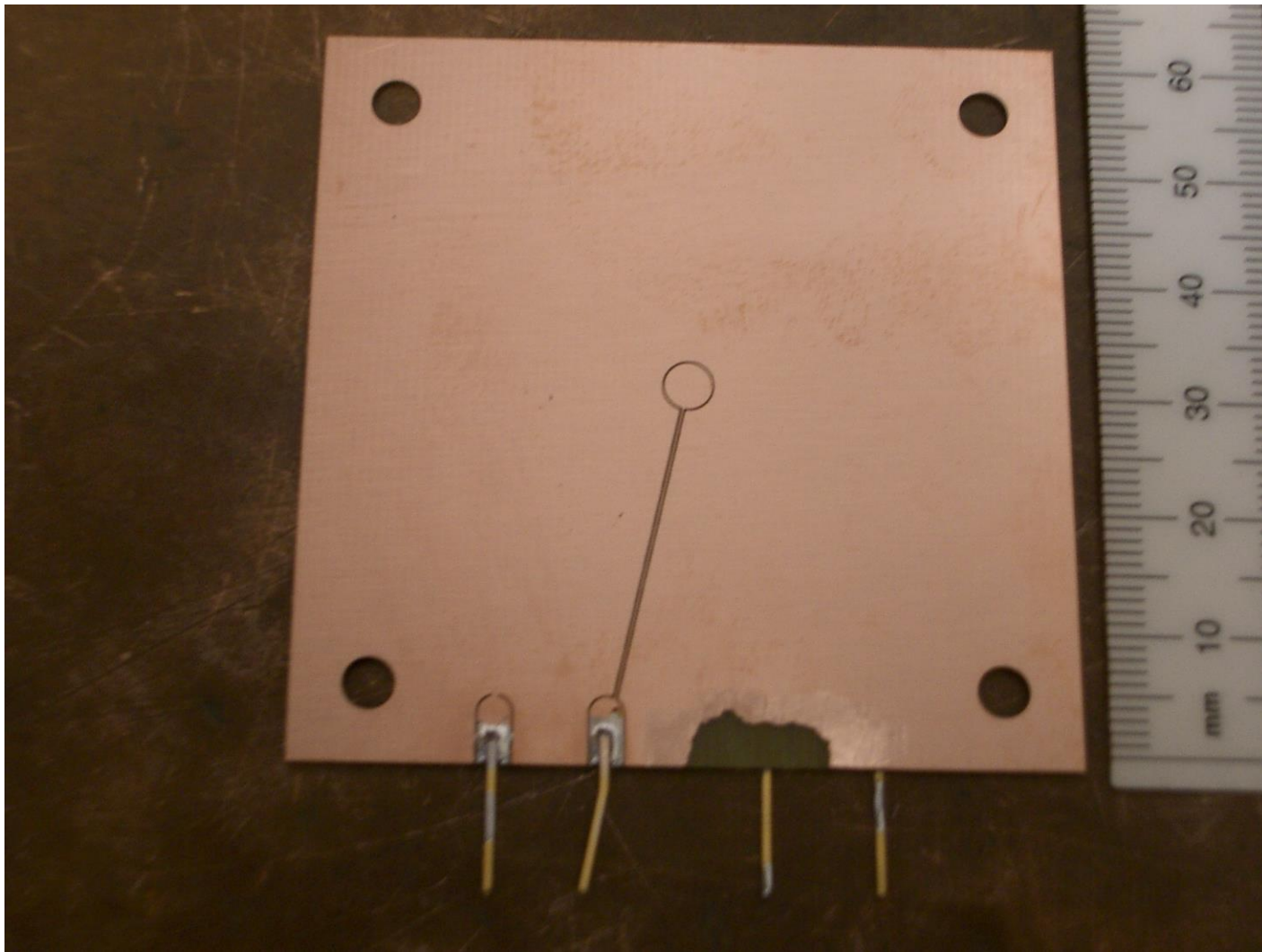


We have described segmented IC's used to measure the transverse dose distribution. An array of IC's can also be used to measure the depth-dose distribution, but the conceptual design is considerably harder because upstream IC's affect the signal in following IC's. The stack must, in some sense, resemble a uniform water tank.

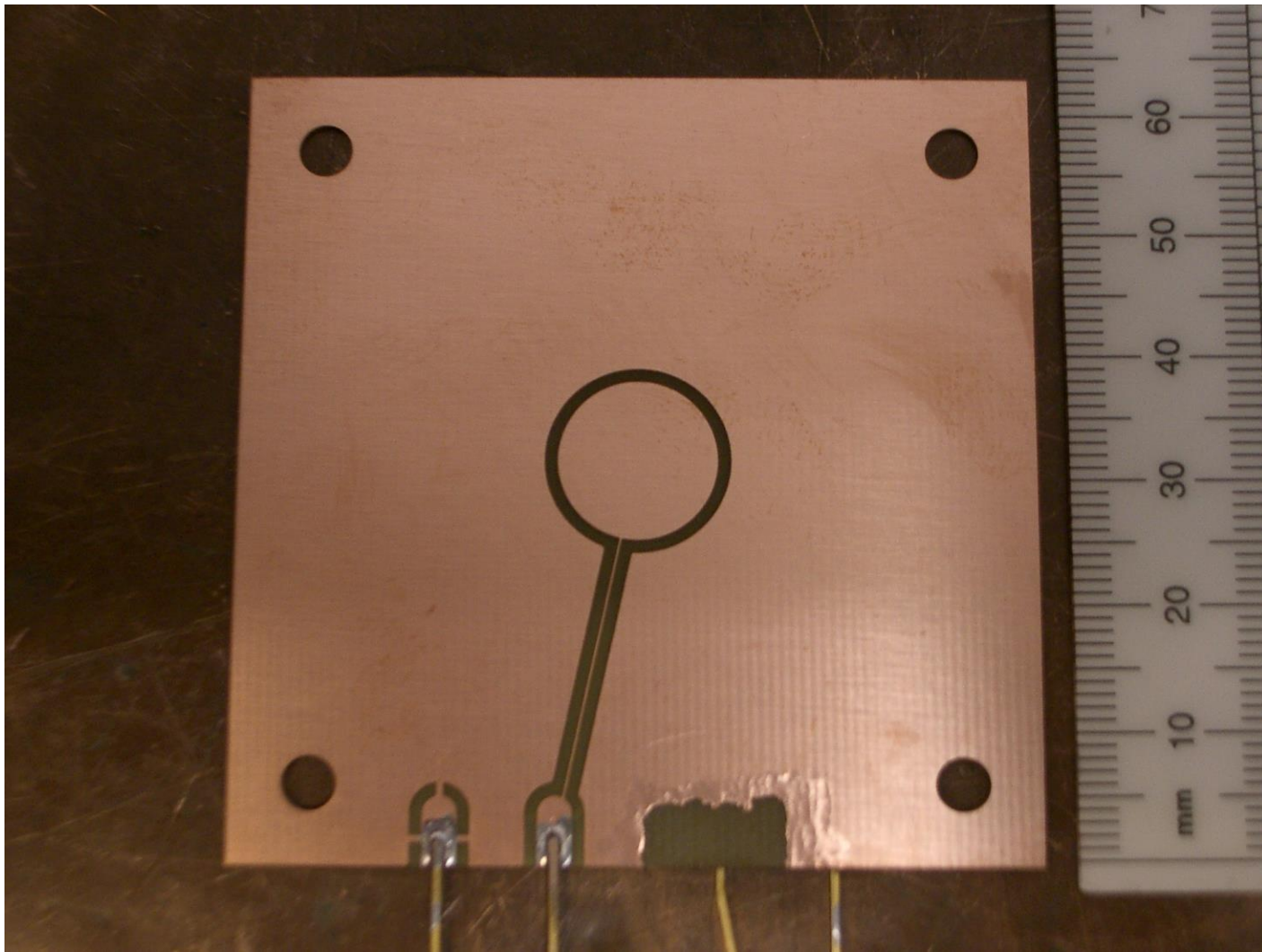
Identical PC boards with a signal pad on one side, and a (larger) HV pad on the other, form an array of small PPIC's. Grounded guard surfaces make the field uniform in the region of interest. The board and copper provide energy loss, the gap provides active volume, and the whole is proportioned to be roughly water equivalent.



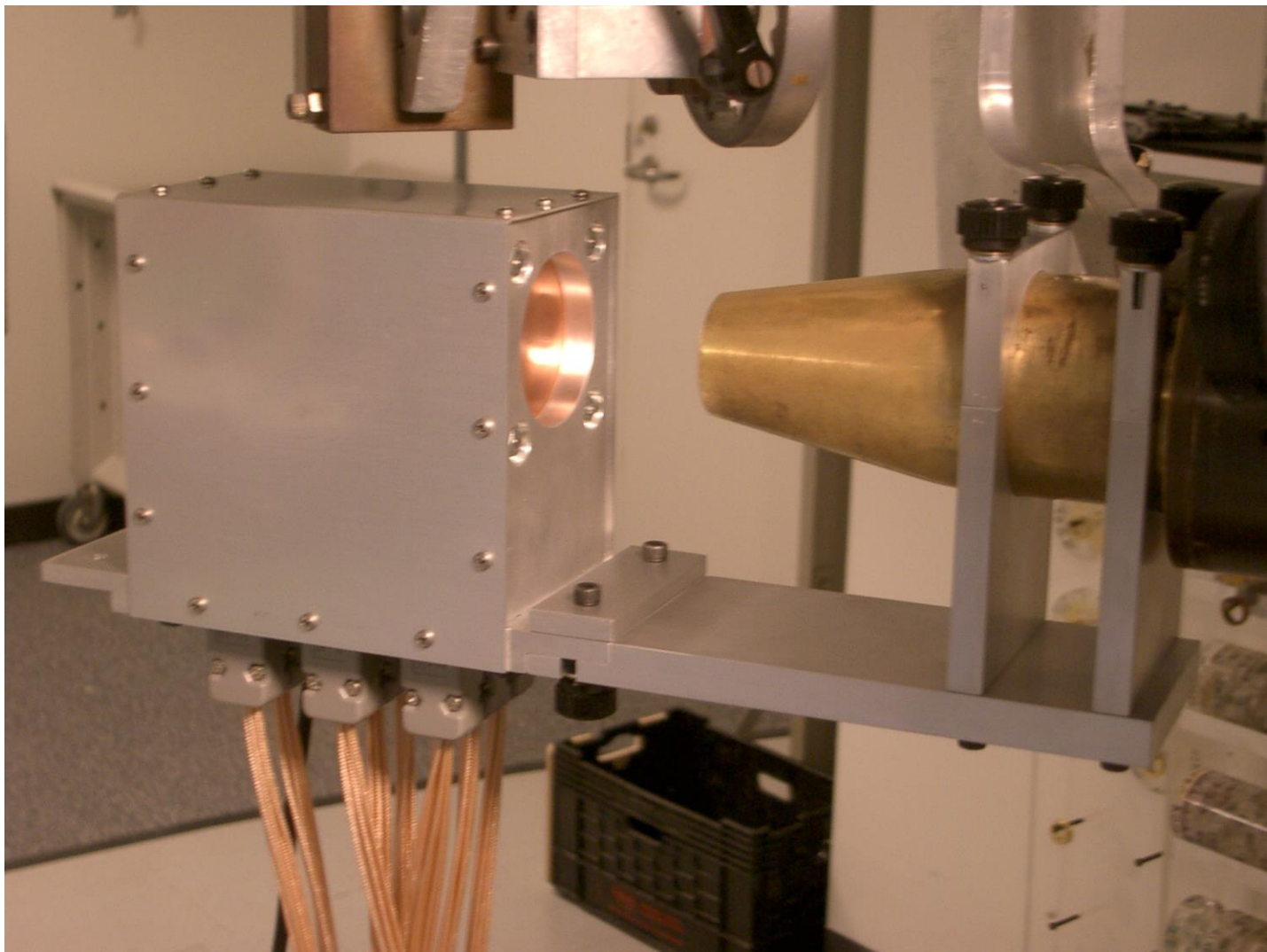
65 identical PC boards, fabricated with standard commercial technology, are mounted 1 mm apart in a rigid frame. Collimation is provided by the eye treatment line. The defining aperture or natural beam size must be much smaller than the hole shown. Otherwise, the connections are bathed in ionized air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

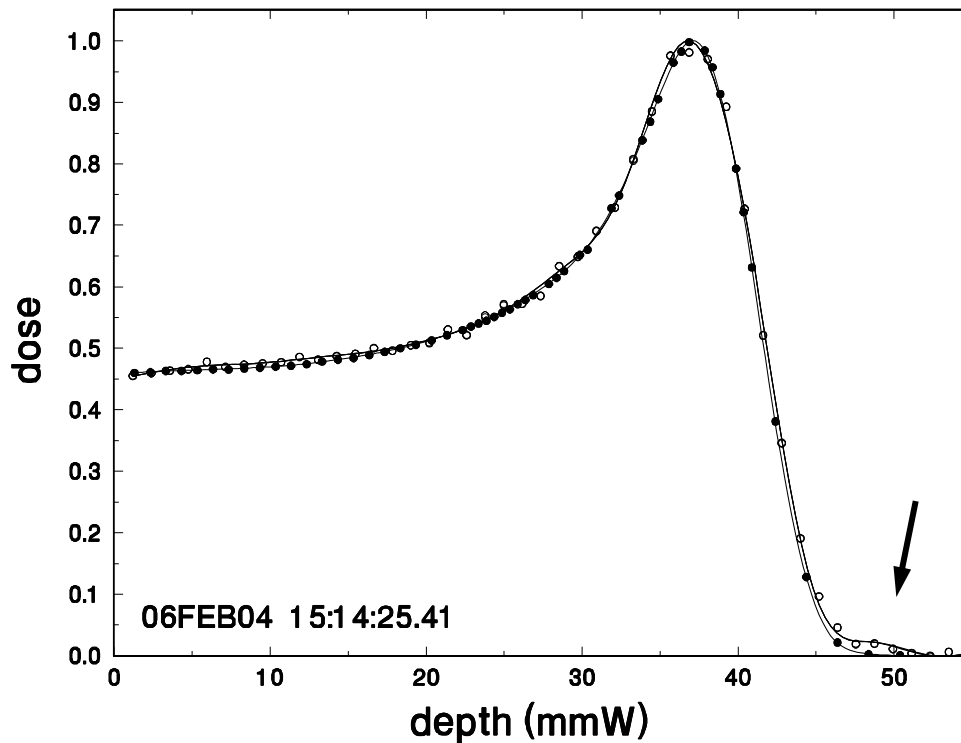


The 0.5" HV pad is also surrounded by ground plane. The copper-free space is larger to accommodate the HV and because it does not matter: protons this far out will never make it to a signal pad. The HV pad, with the ground plane facing it, provides a uniform field over the active volume. The field further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



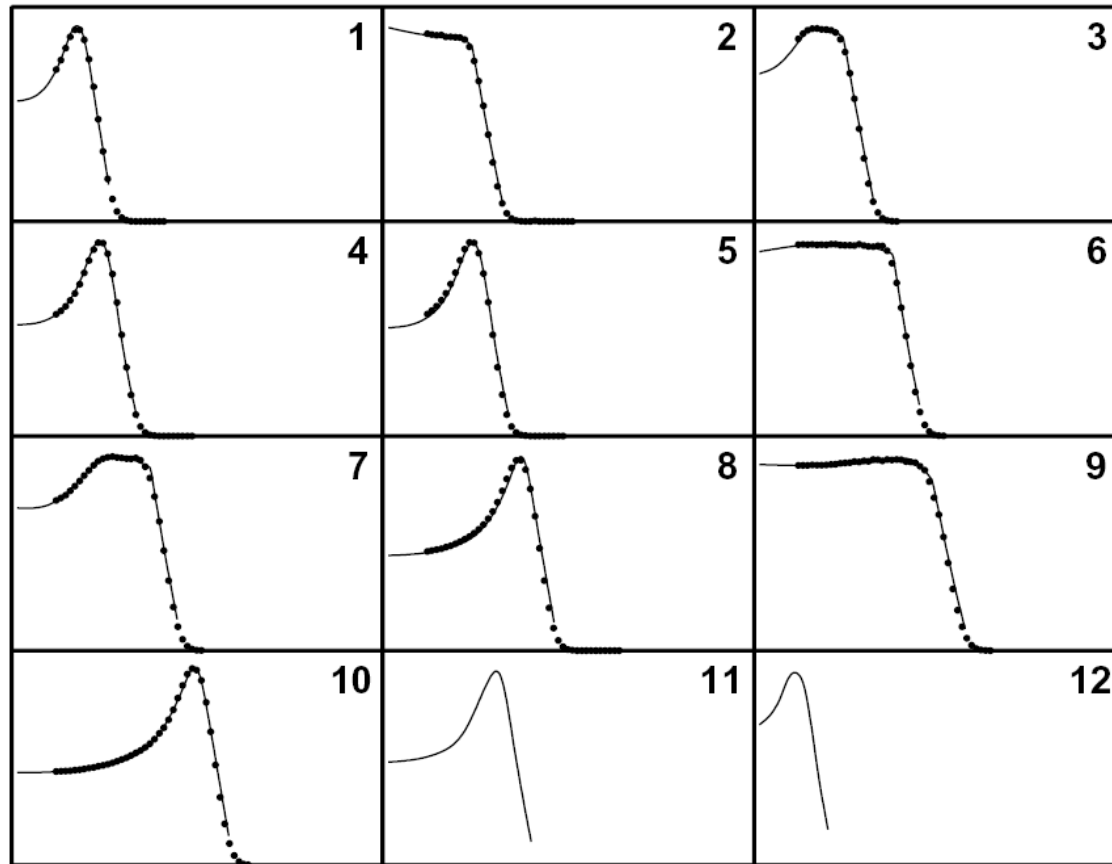
It takes longer to set up an array device than to take the measurement, so the mechanics should be carefully thought through. The ‘eye MLIC’ is mechanically compatible with the diode scan device used traditionally. A field light projected onto the (unused) front signal pad facilitates alignment, and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

Comparison with PPIC Scan



A pristine Bragg peak was measured with the MLIC and with a tiny (3 mm diameter \times 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 ≈ 0.2 mm H₂O equivalent). That happens everywhere in the depth-dose but only shows up where the dose would otherwise be zero.

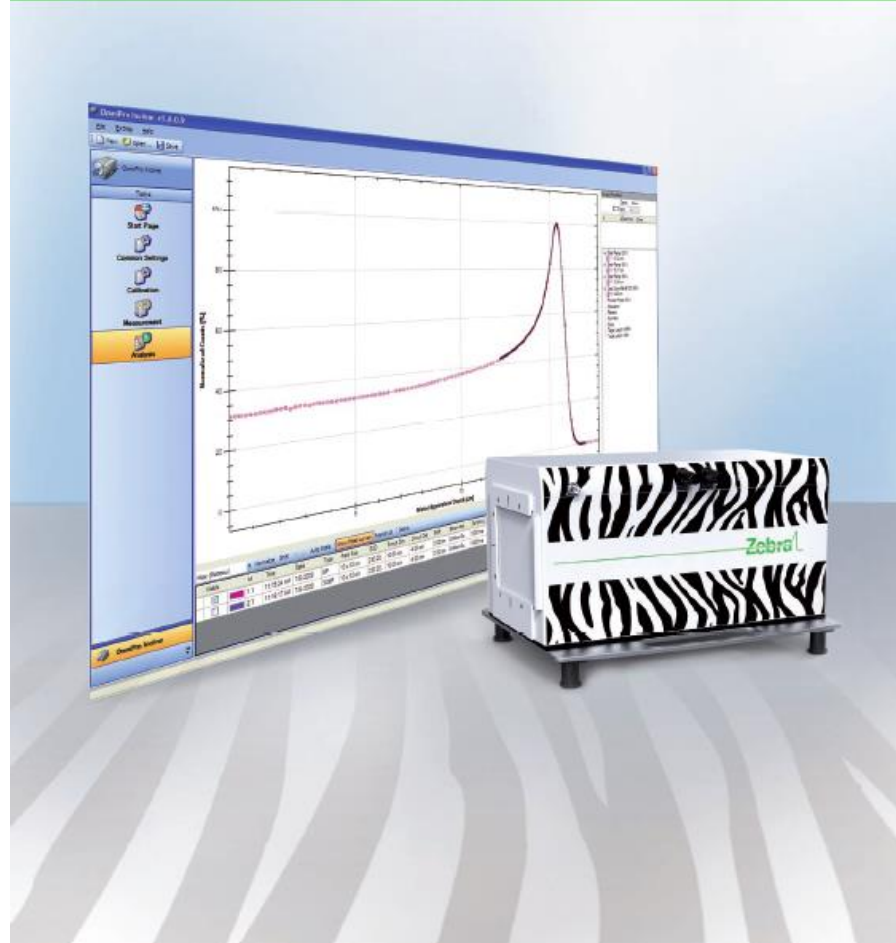
Comparison with PPIC in Water Tank



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!

Zebra with OmniPro-Incline

High precision Particle Therapy Dosimetry



Faraday Cups

A Faraday cup (FC) is a shielded insulated block thick enough to stop the beam. We measure the charge accumulated on the block. Since the proton's charge is very well known ($+1.602 \times 10^{-19}$ C) we are effectively counting protons. Therefore the FC is a *fluence meter* (protons/area) if the cross sectional area of the incident beam is known.

The art of designing FC's consists of making sure that *all* the charge is counted and that *no spurious charge* is picked up, either by the FC itself or in the charge measuring device (current integrator).

The FC is *not* a dose meter. However, **dose = fluence \times mass stopping power**, so the FC can be used to determine the dose at a point in a beam line if the mass stopping power of the protons is also known. This is the basis of the 'Faraday cup method' of dosimeter calibration (Verhey et al., Rad. Res. **79** (1979) 34).

To look up the mass stopping power we need to know the beam *energy*. Happily, the FC can also be used to measure that or, strictly speaking, the *mean proton range* in some well characterized material such as aluminum.

Traditional FC's, which we will discuss first, are somewhat elaborate devices because of the various safeguards against spurious charge gain or loss. For one thing, they require a vacuum system, albeit a fairly crude one. However, it turns out that a much simpler 'vacuumless' device, which we have dubbed a 'Poor Man's Faraday Cup' (PMFC) also works very well. We'll spend most of the lecture on those.

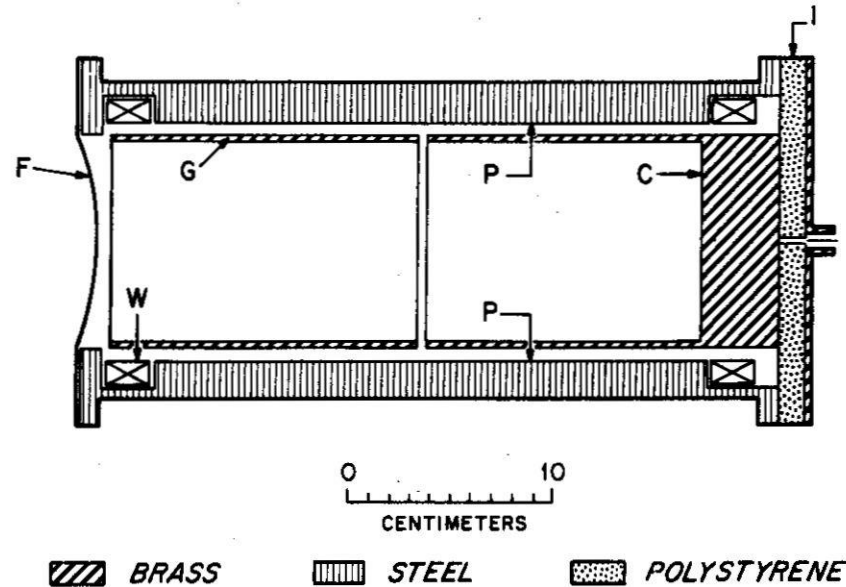


FIG. 2. Schematic of Faraday cup. C is the collecting cup, F is the entrance window, G is a guard ring for electric field application, W are windings for magnetic field application, P is the steel casing, I is a polystyrene insulator.

A traditional FC. The interior is evacuated to eliminate spurious charge from ionized air. A decent mechanical pump is good enough. However, that leaves us open to secondary electrons emitted from the window **F** and/or secondary electrons escaping the beam stop **C**. To turn those back, we can provide an electric field (**G**) or a magnetic field (**W**). Mechanical stress on the insulator **I** can also cause spurious current, but that decays eventually if the output is grounded. Everything (FC, pump, power supplies) is mounted on a cart which holds the FC at beam height. This is an unwieldy arrangement in cramped quarters. The pump must be powered continuously.

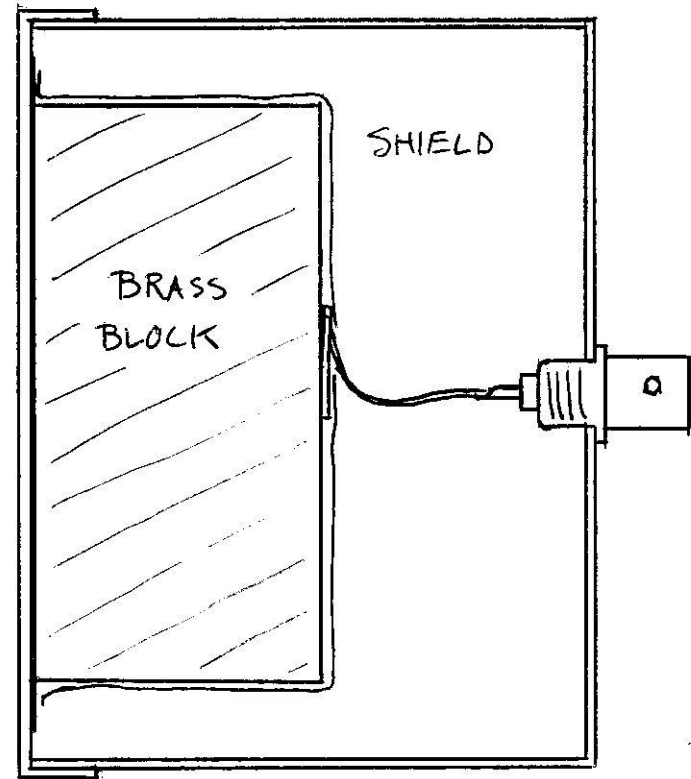
A Poor Man's Faraday Cup

This can be built in one day for a few dollars. You can hold it in your hand and put it in just about any beam line.

The brass block is separated from the front wall by a thin sheet of Kapton, Mylar or polyethylene. Some arrangement keeps it pressed, but not too tightly, against the front. An interior insulator and shield keep ionized air away from the block.

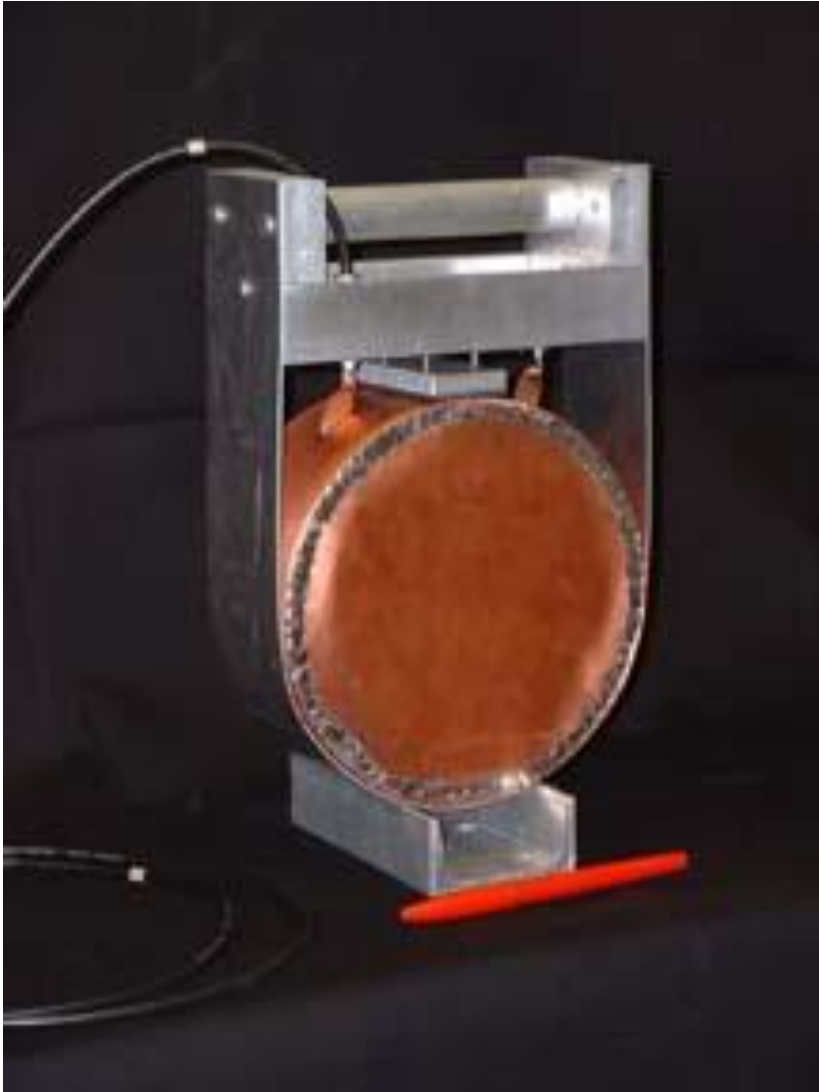
We were feeling pretty good about this and had given a talk at PTCOG when we got a letter from David Bewley, an old protoneer. Turns out he had used such beam stops years earlier in electron beams (and he was not the first), and had then used a similar device for protons to measure range.

Our main contribution, in the end, was to show that these devices have good efficiency.



ALUMINUM
BOX

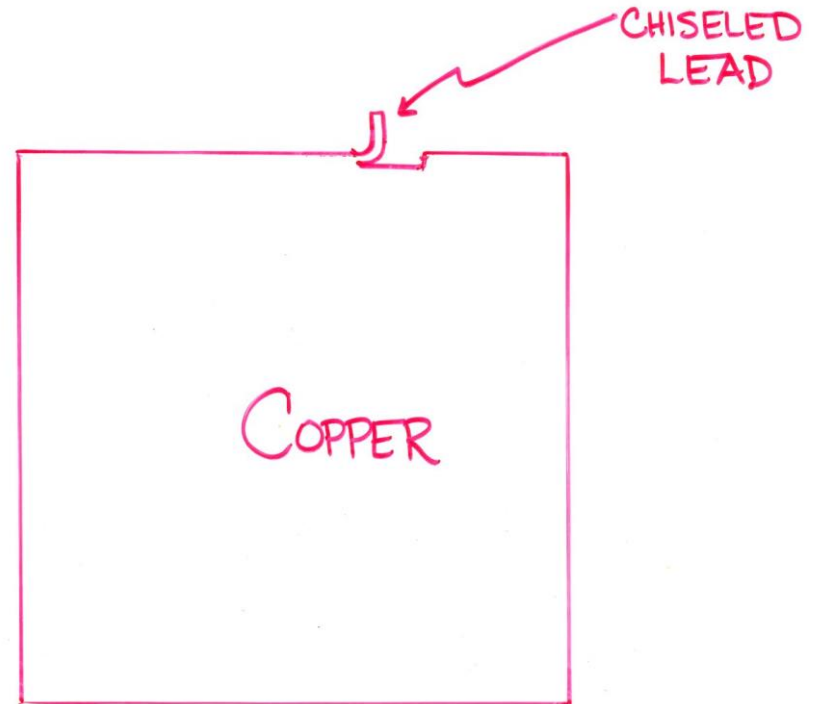
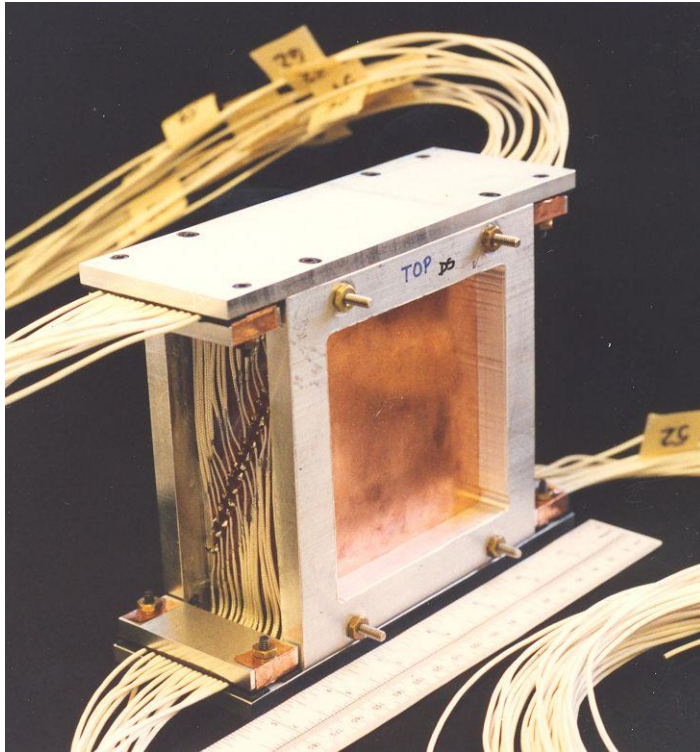
PMFC for 230 MeV



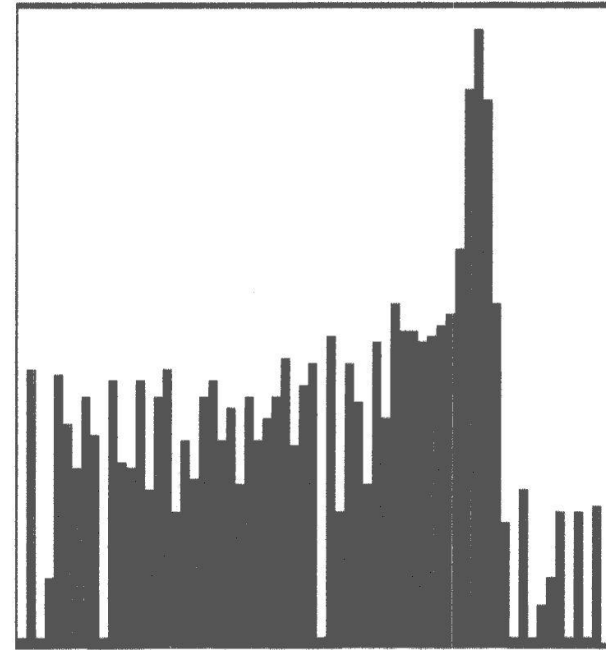
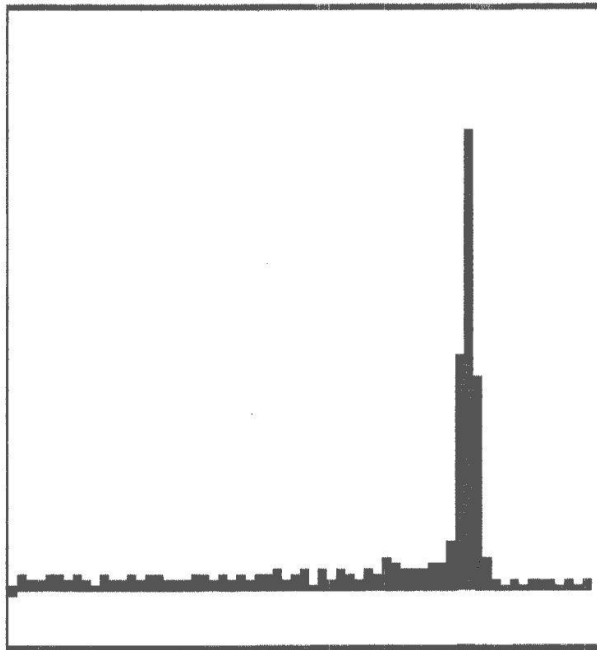
In 2003 we built this PMFC, for use at the Burr Center, using two brass aperture blanks (total 25 lb.). The brass is covered by two layers of 0.003" Kapton, then a copper-clad Mylar shield, copper side out.

At first, such a device is extremely unstable on the bench because trapped static charge on the insulator induces output charge by capacitive coupling whenever the front or back shield moves. It can be improved by a 'girdle' that presses the front and back shields firmly in. With time and a bit of radiation the problem goes away and the girdle can be removed. The device is now extremely stable and has a charge defect on the order of 1% relative to the NFC (Ethan Cascio, priv. comm.).

The First MLFC



was skillfully constructed at HCL in 1995 by Rachel Platais, a cyclotron operator on 'research time', under our direction. $66 \times 0.476 \text{ g/cm}^2$ copper plates (2 shields and 64 active) were each separated by $2 \times 0.0005''$ Kapton sheets: about 2% of the energy loss was in Kapton. Readout was by our standard 64 channel integrator and scanning ADC interfaced to a laptop via RS-232. The MLFC worked immediately and *too well*. Total charge corresponded to 96% of the beam current even though it was well known that there would be copious secondary electron emission by the Kapton.

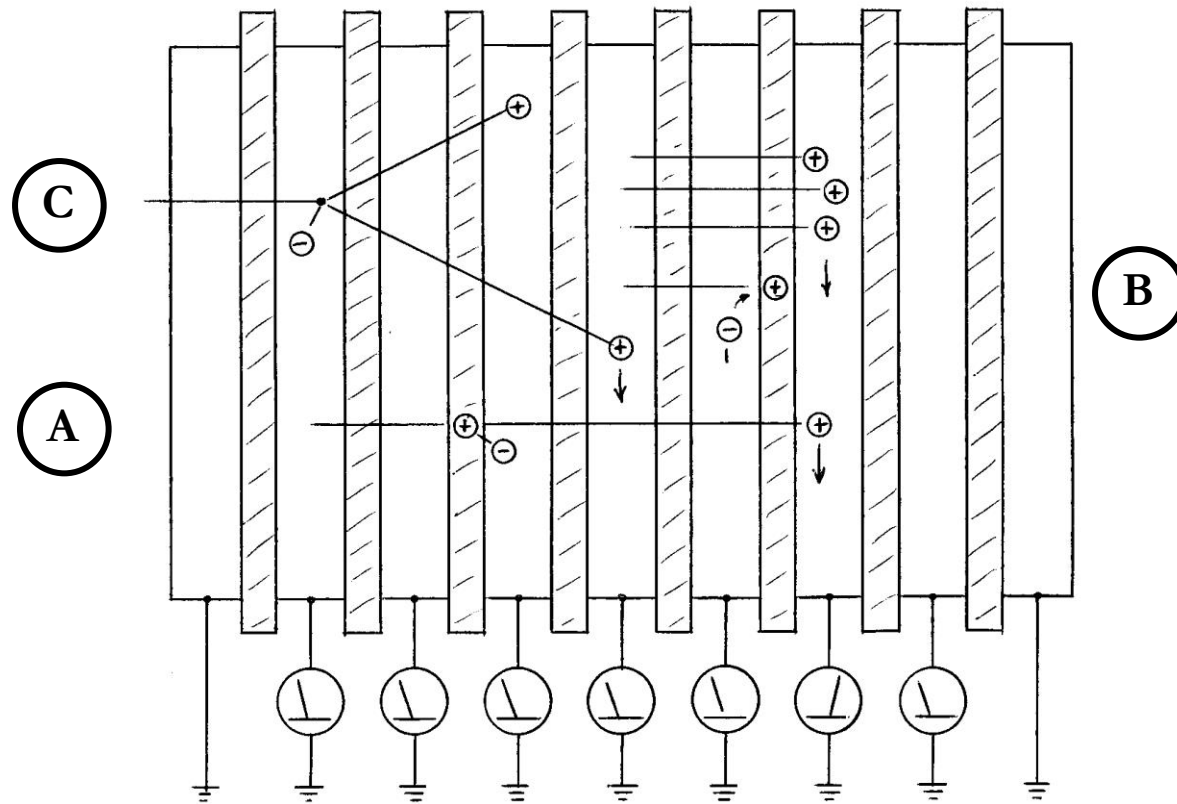


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Press any key to end trial.
Trial 25 ended; please wait ...
RS-232 final read finished ...
-60.00 1592.00 11.69 min, max, total nCoul
saving 26NOV94.013 trial 25 ...
next (T)rial, new (F)ile or (O)ptions :
(B)egin, (C)hange constants, (P)layback or e(X)it :
  
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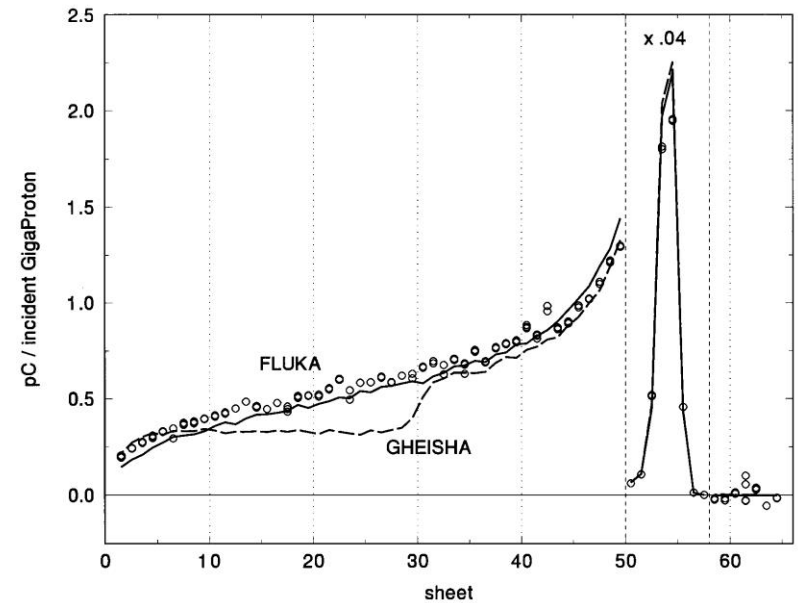
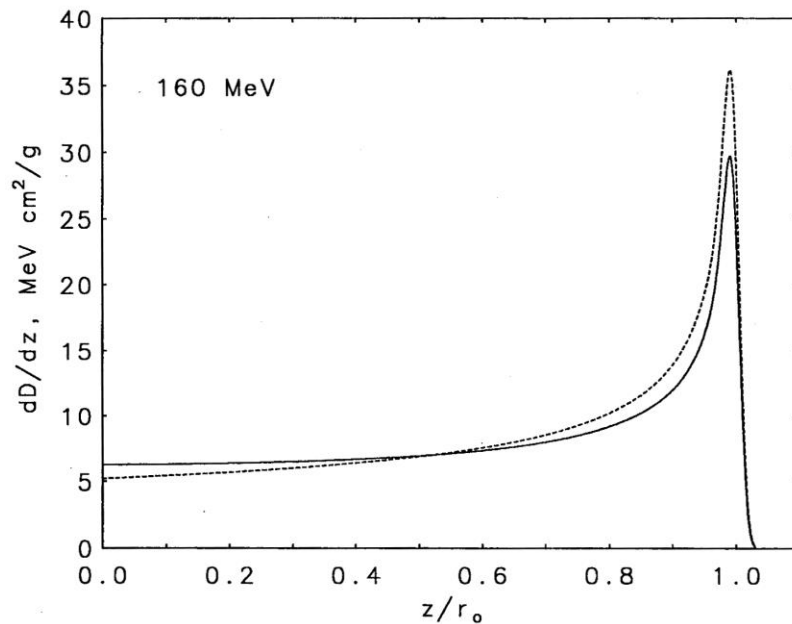
Online end-of-run display of a very early MLFC trial by the Bondwell laptop computer (2 floppies, no hard drive, QuickBasic running under early DOS). Left = linear, right = logarithmic.

Why It Works 'Too Well'

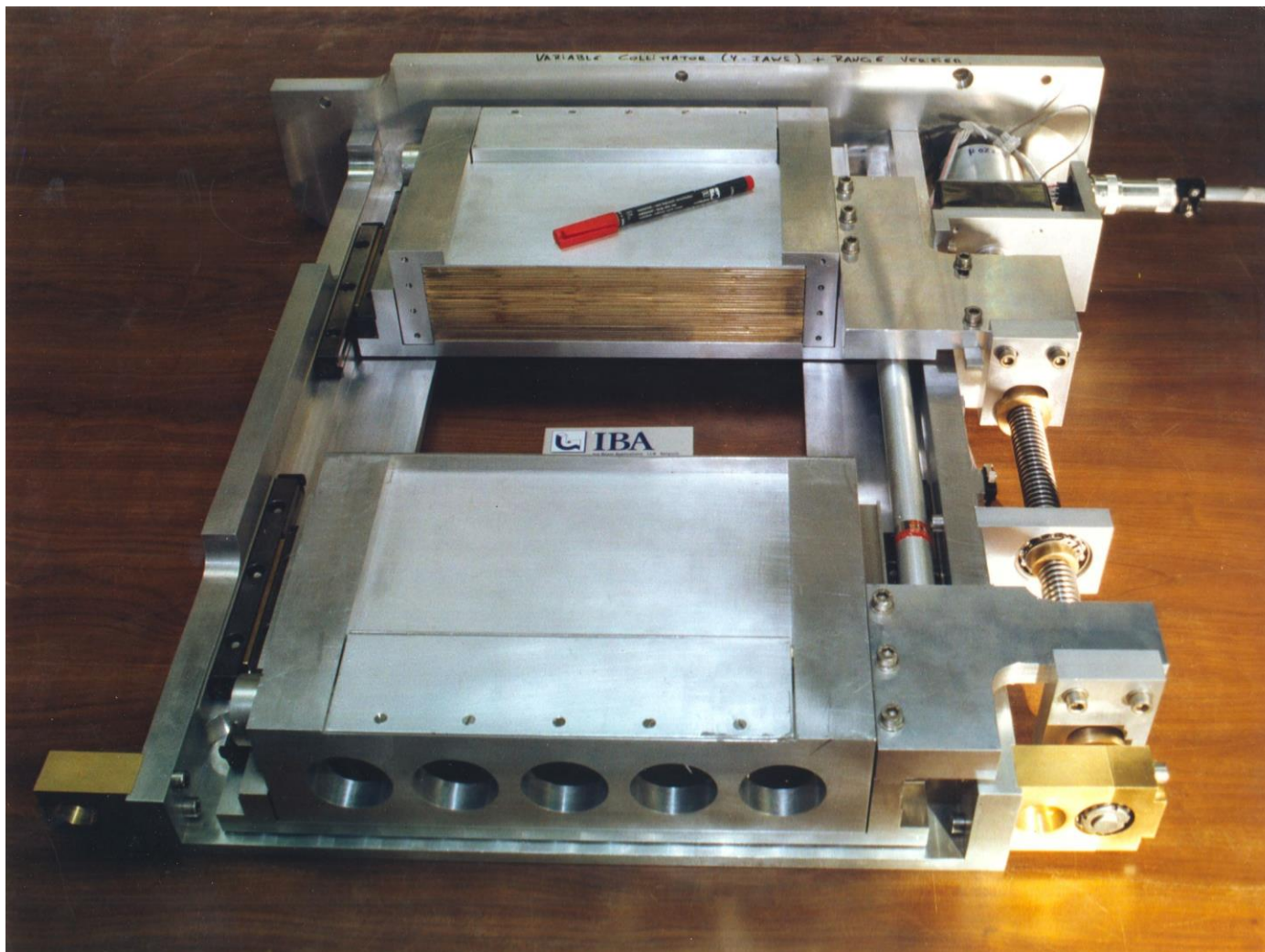


Why the device works so well is explained by simple electrostatics. A) Proton knocks an electron out of Kapton before stopping. Electron is essentially 'bound' to the positive vacancy left behind, so does not contribute to measured current. B) Proton stops in Kapton. It induces a mirror charge in the facing conductor, so it is counted anyway. C) Proton has a nuclear reaction. Net charge in MLFC still $+e$. Therefore the MLFC counts *all* the charge entering and *only* the charge entering. 'Internal' processes in insulator and conductors have no effect.

Using the MLFC to Test Monte Carlo Models

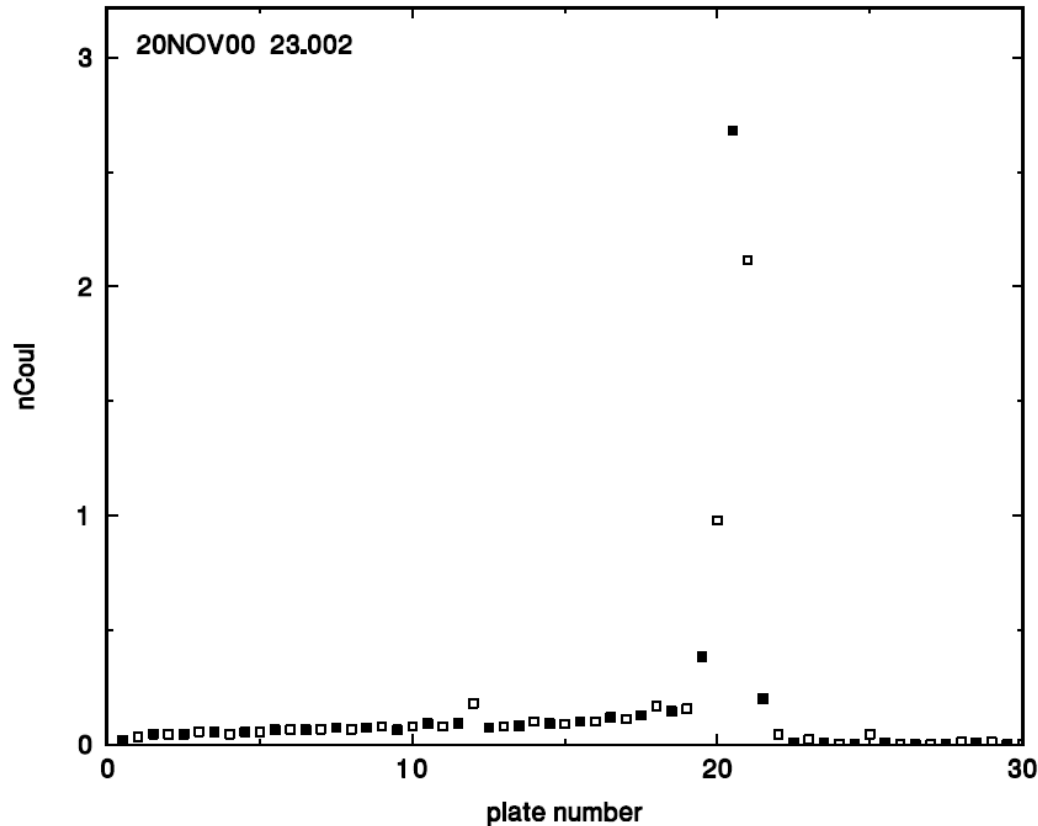


Monte Carlos are often used in proton radiotherapy but many MC's are not well tested at proton therapy energies. The Bragg peak (left, Berger NISTIR 5226 (1993)) is relatively insensitive to nuclear reactions: the difference shown is from turning them off *entirely*. In a MLFC, by contrast, the signal before the EM peak is *entirely* from nuclear secondaries (right, Gottschalk, Platais and Paganetti, Med. Phys. **26** (1999) 2597). The first hint is that the integral of that part is 20% of the total, just as predicted from the non-elastic reaction cross section. 100% acceptance, and the fact that we measure *charge* not *dose* make this an unambiguous test of whether a MC predicts the number and range distribution of nuclear secondaries correctly. For instance, the graph shows that the (default) Gheisha model of Geant3 is poor. The comparison of MC with experiment is *absolute*: no normalization.



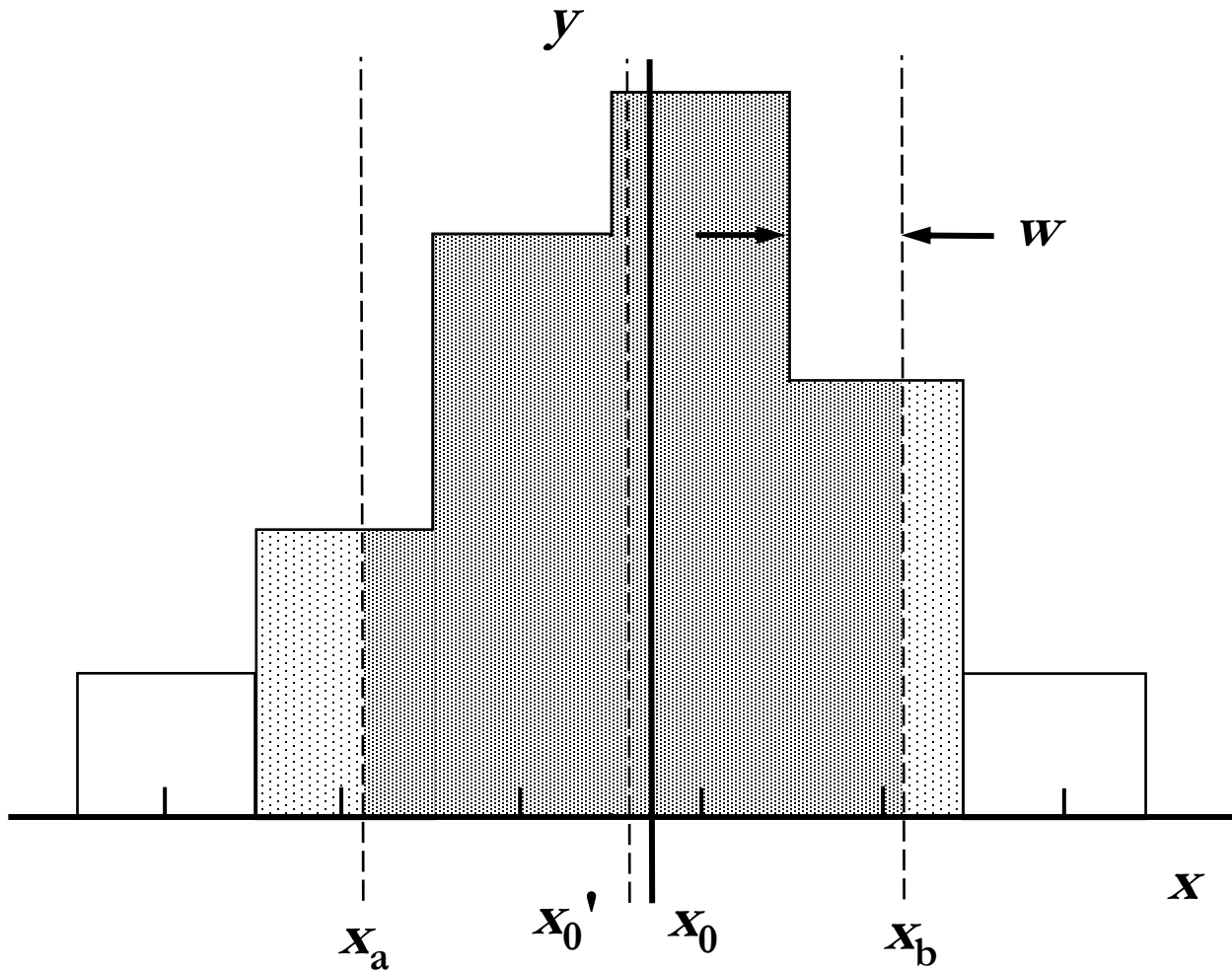
A MLFC range verifier (RV) is built into two opposing jaws of the 4-jaw collimator of the IBA proton nozzle. It consists of 2mm brass plates. The opposite jaw has an additional 1mm for depth offset to improve total resolution. The next few slides will give some results for this RV. For details see B. Gottschalk, 'Calibration of the NPTC Range Verifier,' IBA technical note (2001), RVcal.pdf on our Web directory.

Preliminary Analysis



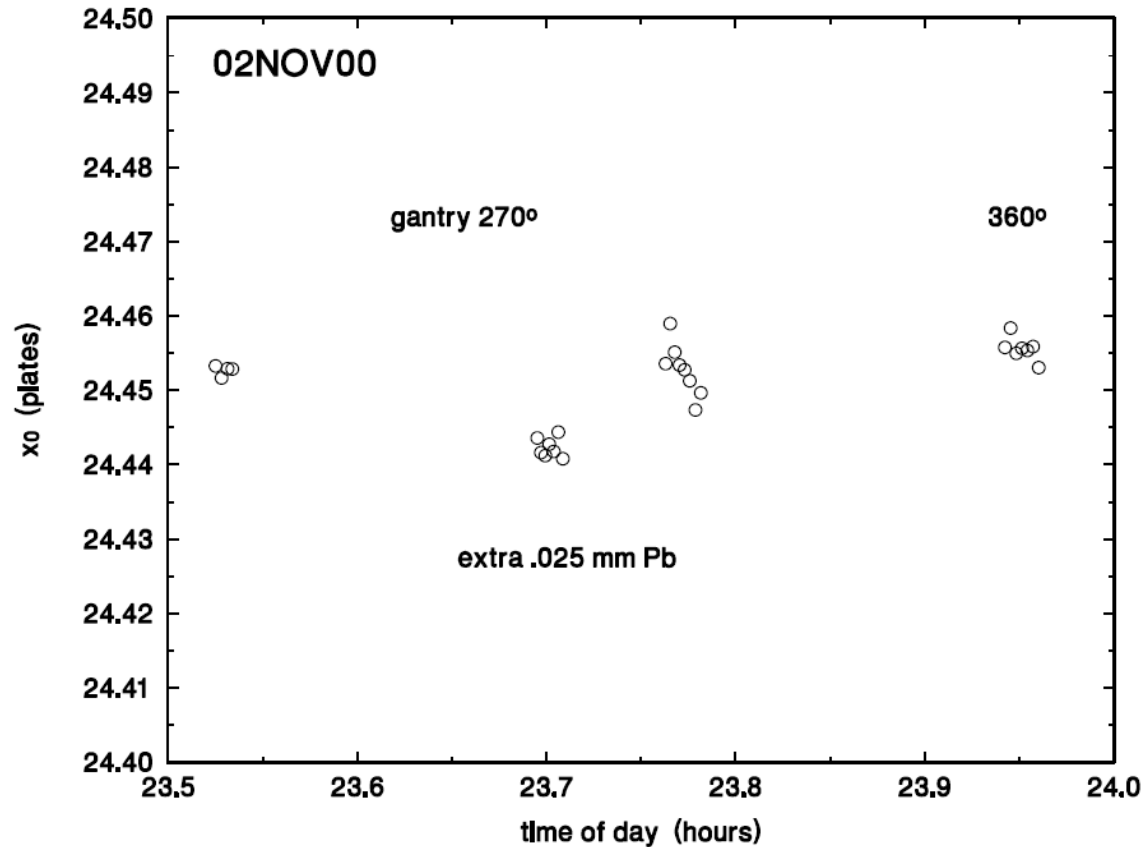
Measurements in the next few slides were taken around 2000 with the help of Yves Jongen and other IBA staff. Most data were taken with the RV jaws closed. First, data from the two jaws are merged and corrected for beam imbalance between the jaws. The mean of the peak is then computed by a straightforward 2-stage process based directly on the counts. (Fitting with a binned Gaussian takes much longer and is *less* accurate.)

Finding the Centroid (Graphical)



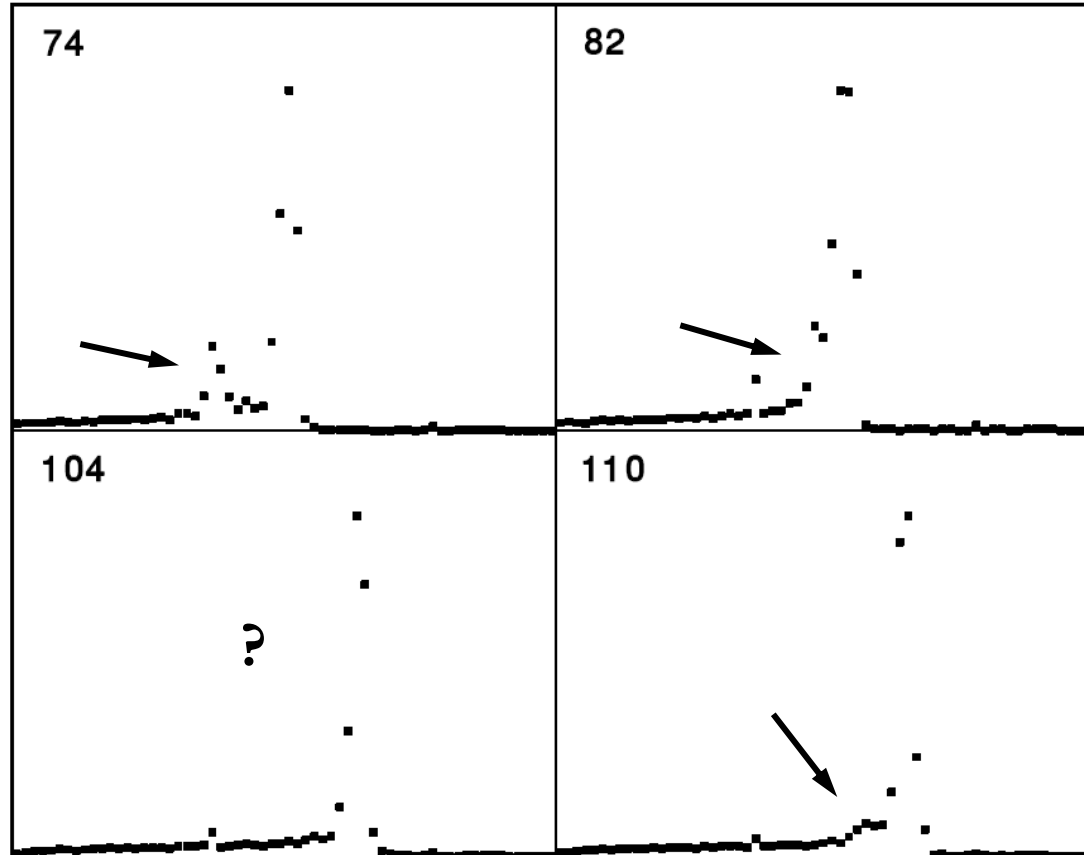
If the beam is polyenergetic (e.g. range modulated) things are much more complicated. We have not been able to develop a good automatic algorithm, nor have we been able to use such MLFC data for more than a rough check on the modulation.

MLFC Resolution



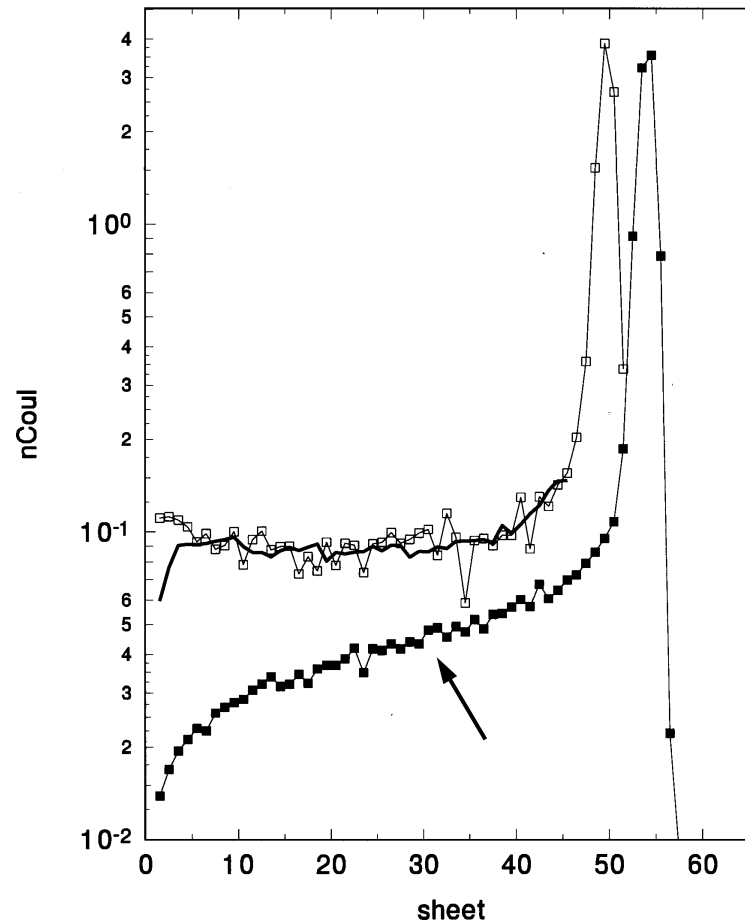
Now that we have a well-defined analysis method, what is the range resolution of the system? The RV was exposed several times to a single scattered beam. Then a 0.025mm Pb foil (0.12mm H₂O equivalent) was added; then removed; then the gantry angle changed by 90° to see if that matters. The RV resolution, with the aid of the 1mm brass plate offset, is about 1% of the thickness (11mm H₂O equivalent) of its brass plates!

Beam Scraping



Most of the outlier runs showed evidence of beam scraping: some protons were losing energy in things they weren't supposed to hit. Much of this was eventually traced to the lollipop frames and fixed by opening them up. A MLFC is a good diagnostic device particularly in the early commissioning phase. The long tail to the left is *not* scraping but nuclear reactions in the MLFC.

Other Beam Contamination



Besides scraping, another source of beam contamination is slit scattering. Details of this MLFC experiment were given in the lecture on slit scattering. Note that the signal from nuclear reactions (arrow) is always present. The Monte Carlo (bold line) computes the *additional* signal from slit scattering.

Neutron Detectors

fluence meters:

moderated detector (Bonner sphere, Snoopy, REM Meter)

(detour: radiation protection basics)

bubble counter

gross physical dose meter:

ionization chamber

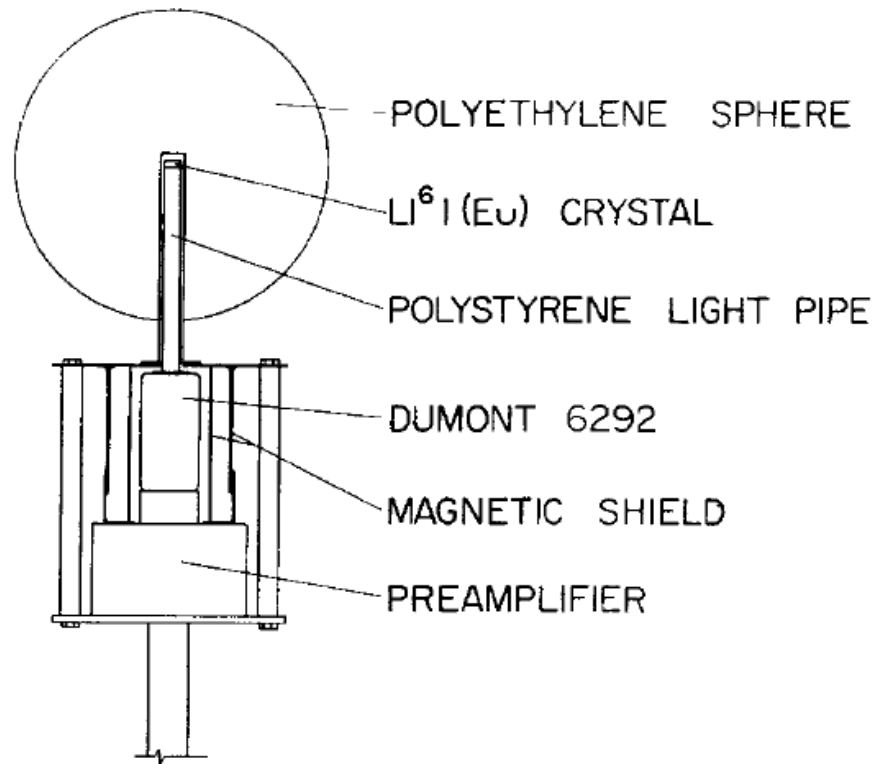
microdosimeters:

track-etch plate (CR-39)

tissue-equivalent proportional chamber (Rossi counter)

solid-state array

Moderated Detector



From Bramblett et al., 'A new type of neutron spectrometer,' Nucl. Instr. Meth. **9** (1960) 1-12 . They first noted that a series of 'Bonner spheres' of different sizes exposed at the same point could measure (crudely) the neutron energy distribution at that point, and that a 12" diameter sphere had a relative response at each neutron energy proportional (within a factor 2) to the neutron effective dose at that energy (total counts = total eff. dose to a person standing there).

Moderated Detector (cont.)

This is your basic area monitor. A neutron *moderator* which slows neutrons to thermal energy (0.025 eV, 2 km/s) surrounds a small *detecting element* which has a very high cross section for thermal neutrons. The simplest moderator is a polyethylene (CH₂) sphere. Three possible detecting reactions are:

${}_3\text{Li}^6 (\text{n},\alpha) {}_1\text{H}^3$ (4.787 MeV) Li^6 I(Eu) scintillator (somewhat obsolete)

${}_5\text{B}^{10}(\text{n},\alpha){}_3\text{Li}^7$ (2.78 MeV) BF_3 gas proportional counter

${}_2\text{He}^3(\text{n},\text{p}){}_1\text{H}^3$ (0.764 MeV) He^3 gas proportional counter

High efficiency and good γ rejection are desirable. Basically this detector is a neutron *fluence* meter but if the moderator is properly designed the detector's response can approximate the biologically equivalent dose to the human body. In that case the detector is called a REM (Roentgen Equivalent Man) meter.

In general, moderated detectors are quite sensitive. A typical 10" Bonner sphere yields 14,000 counts/mrem as calibrated with a moderated Am-Be source (4.86×10^{-5} mrem/sec at 1 m). A 'Snoopy' BF_3 detector (Andersson-Braun moderator, somewhat directional) is only slightly less sensitive (9,000 cts/mrem). Indeed, when moderated detectors are used to measure neutron dose to the patient the beam intensity must be reduced well below the therapy value.

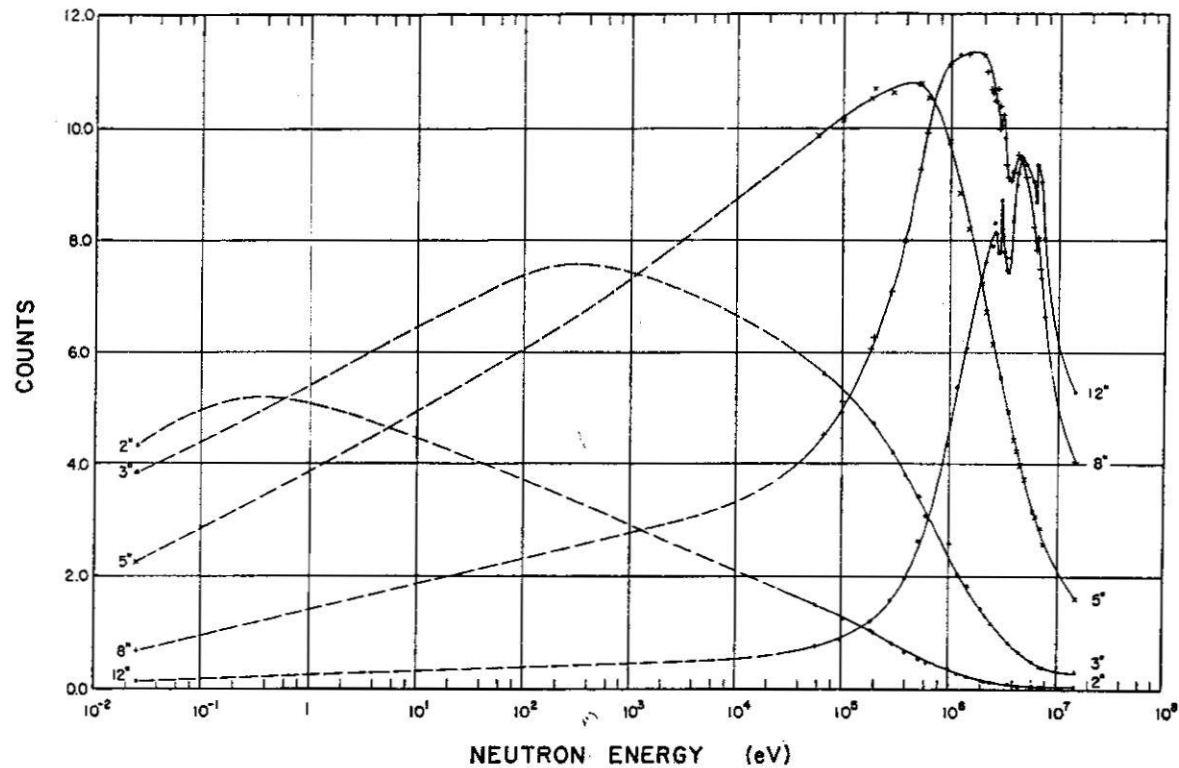


Fig. 8. Results with all counters giving the counts per 10^6 neutrons emitted from an isotropic point source 40 cm away.

From Bramblett et al. : measured response of Bonner spheres of various diameters to monoenergetic neutrons of different energies. The smaller spheres slow the neutrons down less so their response peaks at lower energy. In the large spheres, low energy neutrons are apt to be captured by H before reaching the detector, accounting for the low response. Since this paper, more accurate response curves have been computed with the aid of Monte-Carlo programs.



A modern neutron survey meter (Ludlum Model 12-4). The moderator is a 9" diameter cadmium-loaded polyethylene sphere and the detector is a He^3 gas proportional counter.

In a modern proton therapy center a number of such meters are mounted at various locations, feeding data to a central point where it is recorded, to monitor neutron dose to staff and the general public.

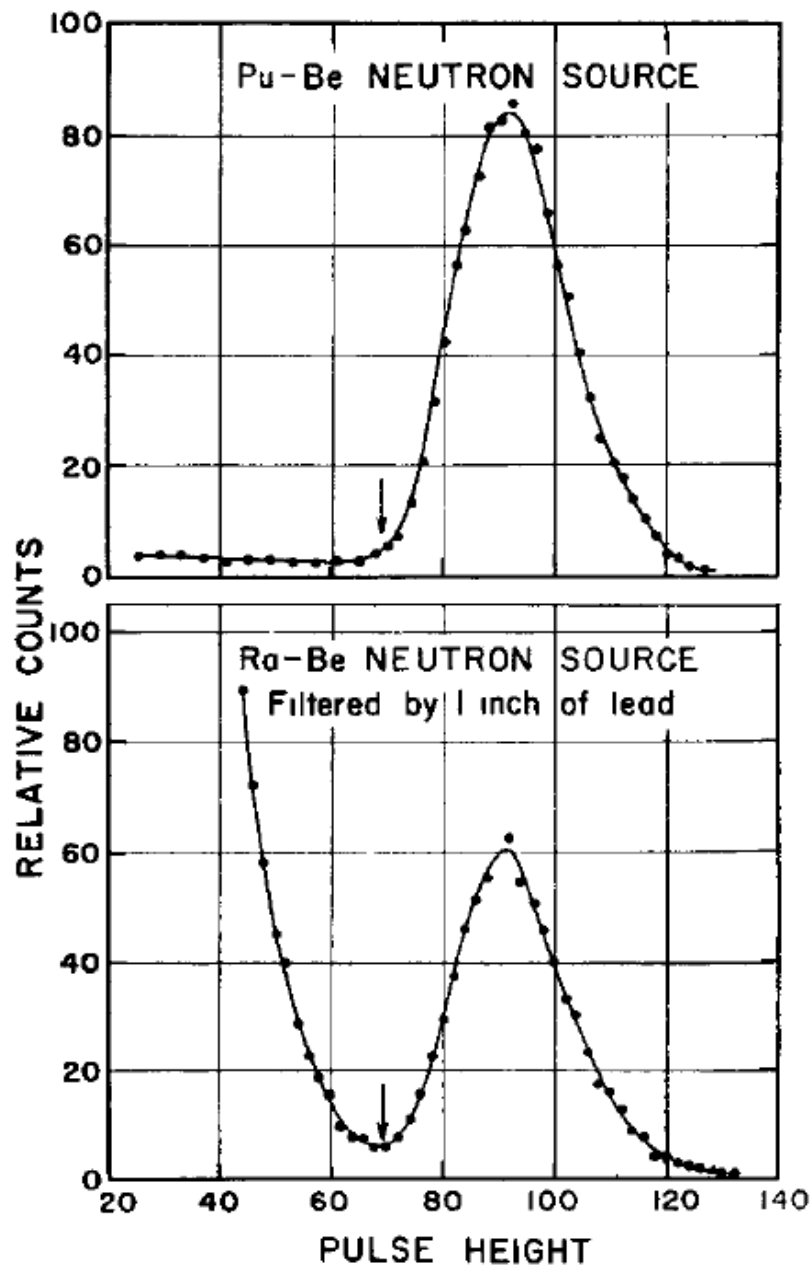


Fig. 2. Pulse spectra obtained with 8 inch counter showing the effect of a large number of γ rays

From Bramblett et al. This pulse-height spectrum tells us nothing about the neutron energy spectrum! It is merely the scintillator response to the monoenergetic capture of a thermal neutron. Pu-Be puts out very few γ rays, so there is almost no background.

Ra-Be has far more γ rays giving the rising background. This would be nearly absent if a BF_3 or He^3 gas counter were used instead of the Li^6I scintillator. Even so, a pulse-height discriminator set at the arrow will eliminate most of the γ -ray counts.

Ionization Chamber

Neutrons ultimately produce ionizing radiation which can be detected with something as simple as a large plane-parallel ion chamber (PPIC). Of course this will detect total ionization from protons, neutrons, γ 's and ions, but if one is reasonably certain (say from a Monte Carlo) that the radiation is mostly neutrons (for instance, on the beam axis just downstream of the Bragg peak) this is a simple technique.

A PPIC measures physical dose (D , not H) to the extent that W (energy per ion pair) is independent of energy. One needs a large PPIC because the physical dose rate is $\sim 10^4$ smaller than the proton dose rate. Thus, one might use an active volume $\sim 30 \text{ cm}^3$ (e.g. PTW 233612) rather than the 0.02 cm^3 (Markus chamber) that might be used to scan the Bragg peak itself.

Some calibration uncertainty results from the variation of W in air for various particle species that might be produced but $W = 34 \text{ eV/ion pair} = 34 \text{ J/C}$ (protons) is a reasonable compromise. The water/air stopping power ratio also varies with particle species and energy but overall, the calibration error is about $\pm 5\%$, very good for neutron work, and the calibration is *absolute* because the active volume of a large PPIC is well determined by its dimensions.

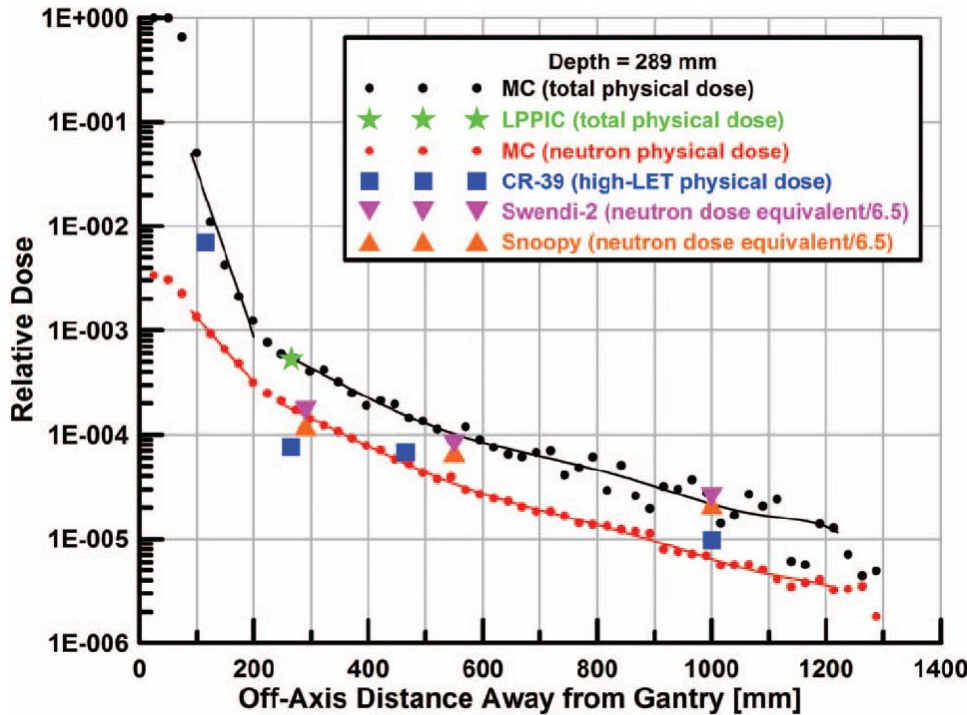


FIG. 7. Dose relative to the prescribed dose at a depth of 289 mm in the phantom patient. Black circles represent the total physical dose calculated by MCNPX. Between 90 and 200 mm off-axis the values were fit with an exponential curve. Between 200 and 1400 mm off-axis the data were fit with a fifth-order polynomial. The green star represents the total dose measured with the LPPIC. Red circles represent the neutron only physical dose calculated by MCNPX. Blue squares represent the high-LET physical dose measured with CR-39. Inverted magenta triangles represent the neutron only physical dose derived from the SWENDI-2 dose equivalent measurements by dividing by an average quality factor of 6.5. Orange triangles represent the neutron only physical dose derived from the Snoopy dose equivalent measurements by dividing by an average quality factor of 6.5.

Moyers et al. 'Leakage and scatter radiation from a double-scattering based proton beamline,' Med. Phys. 35 (2008) 128-144. This figure compares *physical* neutron and total doses measured and inferred from various detectors to Monte Carlo calculations. The ion chamber point (LPPIC, green) agrees well with the MC prediction of total dose.



- Accurate, sensitive, real-time neutron dosimeters
- Immediate visible response to neutron radiation
- Ideal for ALARA programs and rapid measurements of neutron radiation fields
- Tissue-equivalent, energy-independent, neutron dose measurements
- Zero sensitivity to gamma radiation, providing accurate neutron dosimetry in mixed fields
- Lightweight, rugged, and compact
- Low cost and reusable hundreds of times
- Simple to use, maintenance-free, no power required
- Fully temperature-compensated
- Proven, patented, reliable technology
- Meets ICRP-60 sensitivity requirements

Bubble Detectors are the most sensitive, accurate, neutron dosimeters available. Used for over 15 years by nuclear facilities, research institutes, military personnel, and the medical community, Bubble Detectors provide instant visible detection and measurement of neutron dose. Inside the detector, tiny droplets of superheated liquid are dispersed throughout a clear polymer. When a neutron strikes a droplet, the droplet immediately vaporizes, forming a visible gas bubble trapped in the gel. The number of droplets provides a direct measurement of the tissue-equivalent neutron dose.

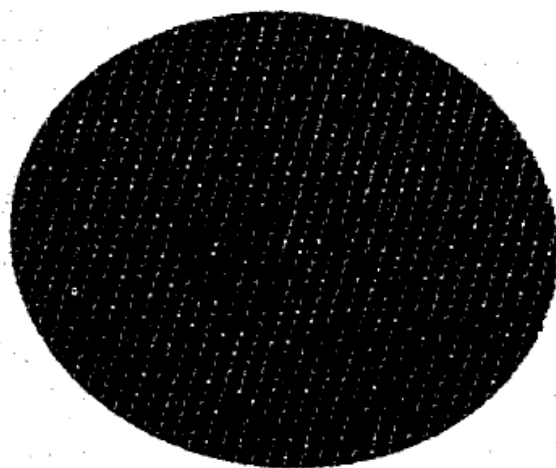
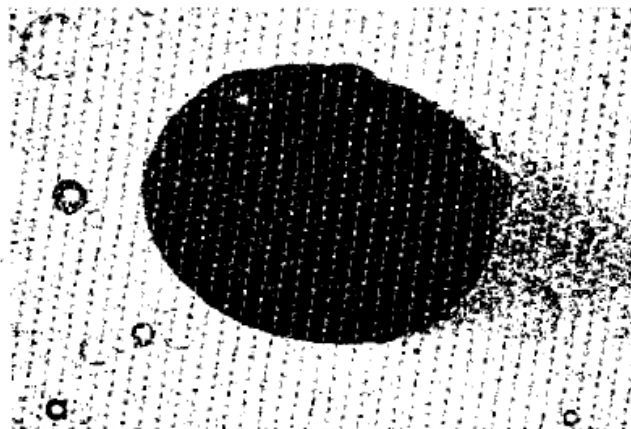
The Bubble Detector is the only neutron dosimeter where the response is independent of dose rate and energy, with zero sensitivity to gamma radiation. Bubble Detectors are so compact, lightweight, and rugged, that they can be clipped to a coat or shirt pocket, placed in areas with limited access, or used in close proximity to a neutron source for a quick assessment. With an isotropic angular response, neutron dose can be accurately measured regardless of the direction of neutrons relative to the detector. Bubble Detectors are ideal for ALARA programs, providing the user with an immediate measurement of neutron hazards.

CR-39 Track Etch Detectors

(description courtesy George Coutrakon, LLUMC)

CR-39 is a near tissue-equivalent thermosetting polymer sensitive to charged particles of $\text{LET} \geq 5 \text{ keV}/\mu\text{m}$ (50 MeV/cm, corresponding to a $\sim 10 \text{ MeV}$ proton in water). An ion traversing the CR-39 breaks chemical bonds in the polymer, producing latent damage along the trajectory. After exposure, the detector is etched in 6.25 *N* NaOH at 50°C, converting the damage trails to conical pits which can be measured with an optical microscope. The size of the elliptical opening of each track is proportional to the LET of the charged particle that produced it. By measuring many tracks one can infer an LET spectrum and therefore, dose and dose equivalent.

CR-39 is used in commercial dosimetry systems or, sometimes, by experts in in-house experiments. Commercial dosimeters use a polyethylene converter to produce proton recoils from fast neutrons and/or a borated converter to produce α 's from thermal neutrons.



b

Fig. 1. Comparison of surfaces of (a) Lexan and (b) CR-39 etched in NaOH solution. The thickness of material removed by etching was $25\text{ }\mu\text{m}$ for Lexan and $45\text{ }\mu\text{m}$ for CR-39. The elliptical holes are the mouths of track etch pits that intersected the surface at an angle. For CR-39 the particle that produced the track was ^{40}Ar ; for Lexan it was an ultraheavy cosmic ray with $Z > 75$. The minor axis of the ellipse for CR-39 is $80\text{ }\mu\text{m}$. The greater homogeneity of CR-39 than of Lexan results in a far smoother etched surface, far more uniform etched track lengths and diameters, and less variability of response to particles of a given ionization rate.

From Cartwright et al. 'A nuclear track recording polymer of unique sensitivity and resolution,' Nucl. Instr. Meth. 153 (1978) 457-460, evidently the first paper to tout CR-39.

Track-etch techniques *per se* had been used for some time, but the uniform response, high sensitivity and 'superb optical quality' made CR-39 superior.

Track-etch techniques are widely used outside neutron detection: cosmic ray studies, free quark searches, monopole searches ... There is an extensive literature.

Neutrak® Dosimeter for Neutron Radiation

Neutrak dosimetry service provides neutron radiation monitoring with CR-39® and Track Etch technology. The Neutrak detector is a CR-39 (allyl diglycol carbonate) based, solid-state nuclear track detector that is not sensitive to x, beta or gamma radiation, and can be packaged specifically for neutron detection only, or as a component of another dosimeter such as Luxel®+ or InLight® to include x, gamma and beta radiation monitoring. The CR-39 is laser engraved for permanent identification, and wrapped with a 2-D bar code to assure efficient chain-of-custody.

Landauer's comprehensive full service includes automatic exchange out of dosimeters for each wear period, processing and analysis, data management, reporting of exposure results, direct computer access via the Internet to Landauer's database for shipment tracking, and customer service and technical support programs.



Design

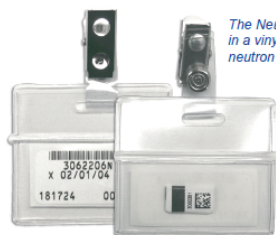
Neutrak dosimeters span the full spectrum of energies found in neutron environments. Landauer offers two neutron dosimeters, a fast neutron dosimeter and a combination fast, intermediate, thermal neutron dosimeter. Neutrak's fast neutron dosimeter uses a polyethylene radiator for fast neutrons that records recoil protons resulting from neutron interactions in the dosimeter. Neutrak's thermal/intermediate neutron dosimeter has a design intended for fast, intermediate, and thermal neutrons. The left area of the chip uses a polyethylene radiator for fast neutrons while the right area uses a boron loaded Teflon® radiator for fast, intermediate, and thermal neutrons that records alpha particles resulting from neutron interactions in the dosimeter.

Track Etch Technology

The CR-39 is processed with Track Etch technology. During analysis in our laboratory, the CR-39 is etched for 15 hours in a chemical bath to enlarge exposure tracks. The fast neutron dose is measured by counting the tracks generated as a result of the proton recoil with the polyethylene radiator, while the thermal/intermediate dose is measured by counting the alpha tracks generated with the boron radiator.

Neutrak Dosimeter Selection Guide

	Fast Neutron	Fast, Intermediate, and Thermal Neutron
Typical Applications	Monitoring personnel working with unmoderated or moderately shielded fast neutron sources such as Californium-252 and Americium-241 Beryllium.	Monitoring radiation near graphite-moderated neutron sources or monitoring requirements that involve exposure to low, high or varying mixtures of neutron energies such as those occurring in nuclear power plants, shielded high-energy accelerators, etc.
Technical Specifications	Energy range: 40 keV to 40 MeV Dose Measurement Range: 20 mrem to 25 rem (200 µSv to 250 mSv)	Energy range: 0.25 eV to 40 MeV Dose Measurement Range: 10 mrem to 25 rem (100 µSv to 250 mSv)
Accreditations Approvals Licenses	NVLAP (National Voluntary Laboratory Accreditation Program) accredited (NVLAP Lab Code 100518-0) in category VIA when combined with Luxel+ or InLight. HSE (Health and Safety Executive) United Kingdom, External: Whole Body Neutrons. DOELAP (Department of Energy Laboratory Accreditation Program) accredited. CNSC (Canadian Nuclear Safety Commission) authorized for use.	



The Neutrak dosimeter packaged in a vinyl pouch specifically for neutron detection only.



The Neutrak dosimeter can be sealed inside the Luxel+ plastic blister pack.



The Neutrak dosimeter can be enclosed inside the InLight holder.

LET Counters (Rossi counters)

The pattern of energy (dose) deposition by a particle, not just the total energy deposited, is very important in determining the biological effect. Low LET particles (γ 's, protons) produce single hits in many cells. Neutrons (via low energy protons from glancing collisions) produce multiple hits in fewer cells. These are difficult for the cell to repair, leading to a larger biological effect.

Microdosimetry is the art of measuring not just average dose but the pattern of dose deposition at the cellular scale. Macroscopic counters mimic the cellular scale by using tissue-equivalent gas as the detection medium. One detects single events (beam intensity must be reduced) and logs the energy deposited in each event using a pulse-height analyzer.

Unlike moderated counters and ionization chambers, which are relatively easy to use, LET counters and their associated data logging and analysis require considerable care and are best left to experts. If you are seriously interested in microdosimetry, ICRU Report 36 is required reading. Our description is very abridged and meant only to allow one to read the literature on unwanted neutron dose with some understanding.

2.54 CM DIAMETER PROPORTIONAL COUNTER

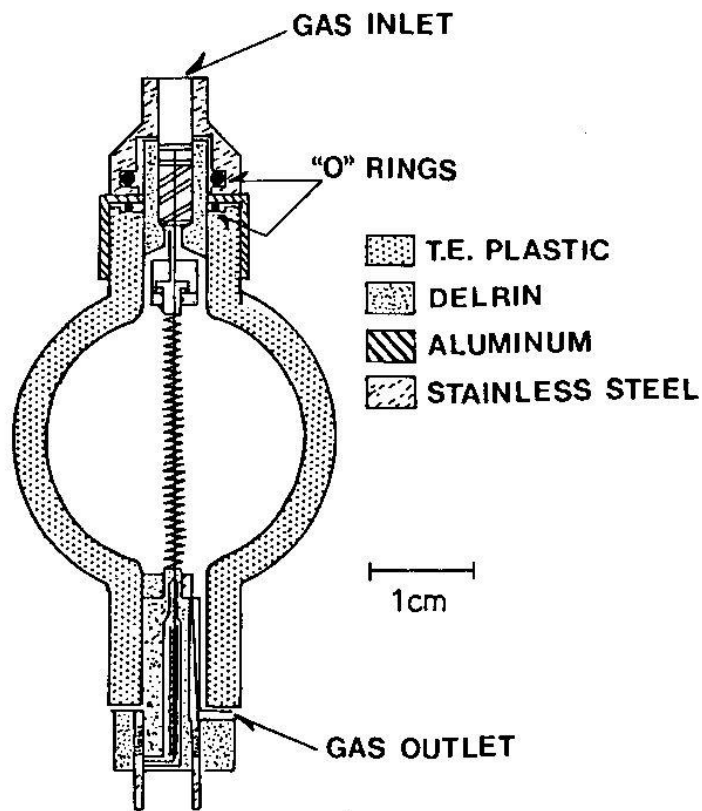
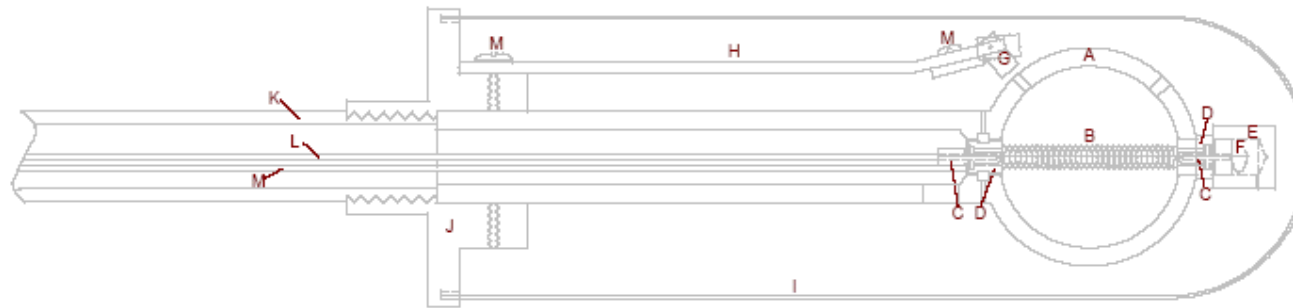



Fig. D.1. This solid-wall counter is an example of the type most frequently used in microdosimetry. The helix is maintained at positive potential with respect to the outer shell, so electrons are collected throughout the spherical region. The center wire is, of course, positive with respect to the helix. Tension is maintained in the center wire by means of a spring at the top. A gas inlet and outlet are provided for a gas-flow system.

'Rossi' counter, from ICRU 36. Both the spherical shell and the fill gas are tissue equivalent. A track crosses the sphere, secondary electrons (the final product of any ionizing particle) drift towards the helix/wire assembly, and are multiplied by the avalanche process between the helix and the wire. The resulting charge pulse, further amplified and filtered, has a height proportional to the charge (therefore energy) deposited by that single event.

Many such pulses are accumulated in a pulse-height analyzer. Because of the large dynamic range, data are taken at several overlapping electronic gain settings and those spectra need to be matched (combined) into a single one, with checks to make sure the gas gain was constant throughout.



- A. Sphere, 0.050" thick A-150 TE Plactic wall
 B. Central Electrode, 0.0018" dia. SS wire,
 Helix, 0.0018" dia. SS wire, 0.031" ID x 20 truns (in sphere dia)
 C. Insulator, Electrode, Polycarbonate
 D. Insulator, Helix, Teflon
 E. Spring Cover, Lucite
 F. Spring, SS, 0.002" thick, 0.020" wide x 0.125" long
 G. Source Rod, 0.062" dia x 0.115" long, points up when off
 H. Source Support, Aluminum, 0.032" thick x 0.175" wide x 1.45" long
 I. Cover, Aluminum, 0.007" thick wall, 0.76" ID
 J. Header, Aluminum
 K. Stem, Aluminum, 0.035" wall
 L. Signal Wire, Copper, 0.016" dia
 M. Helix Wire, Copper, 0.016" dia
 N. Screw & Lock Washer, Steel, 2-56 x 3/16

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Commercial Rossi counter, drawing courtesy Far West Technology Inc., www.fwt.com This counter, which costs \$3800 (2007), has a built-in calibration source which can be aimed at or away from the active volume.

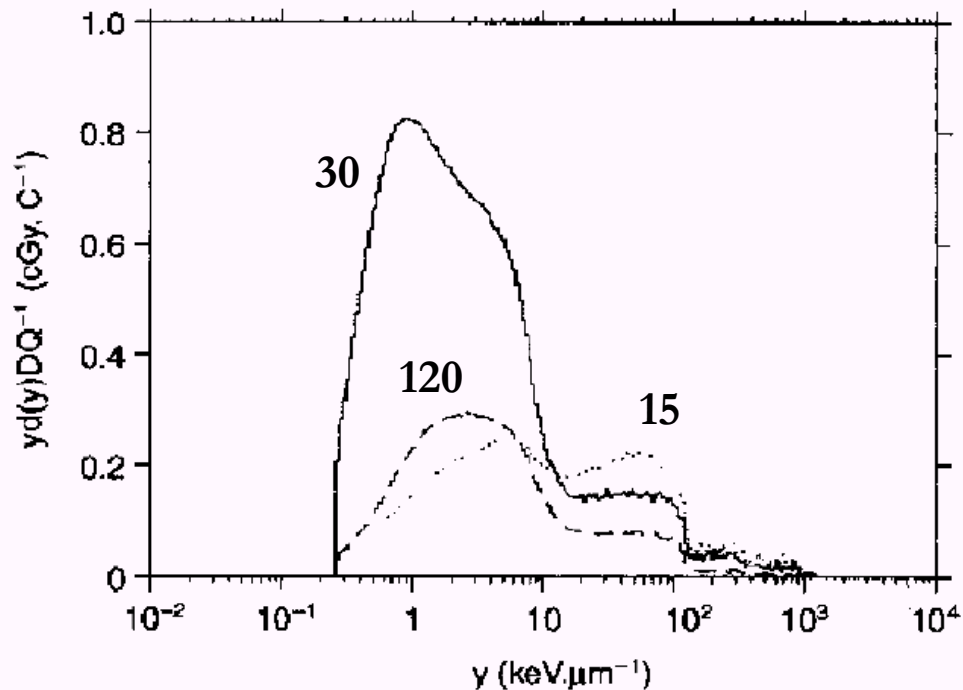
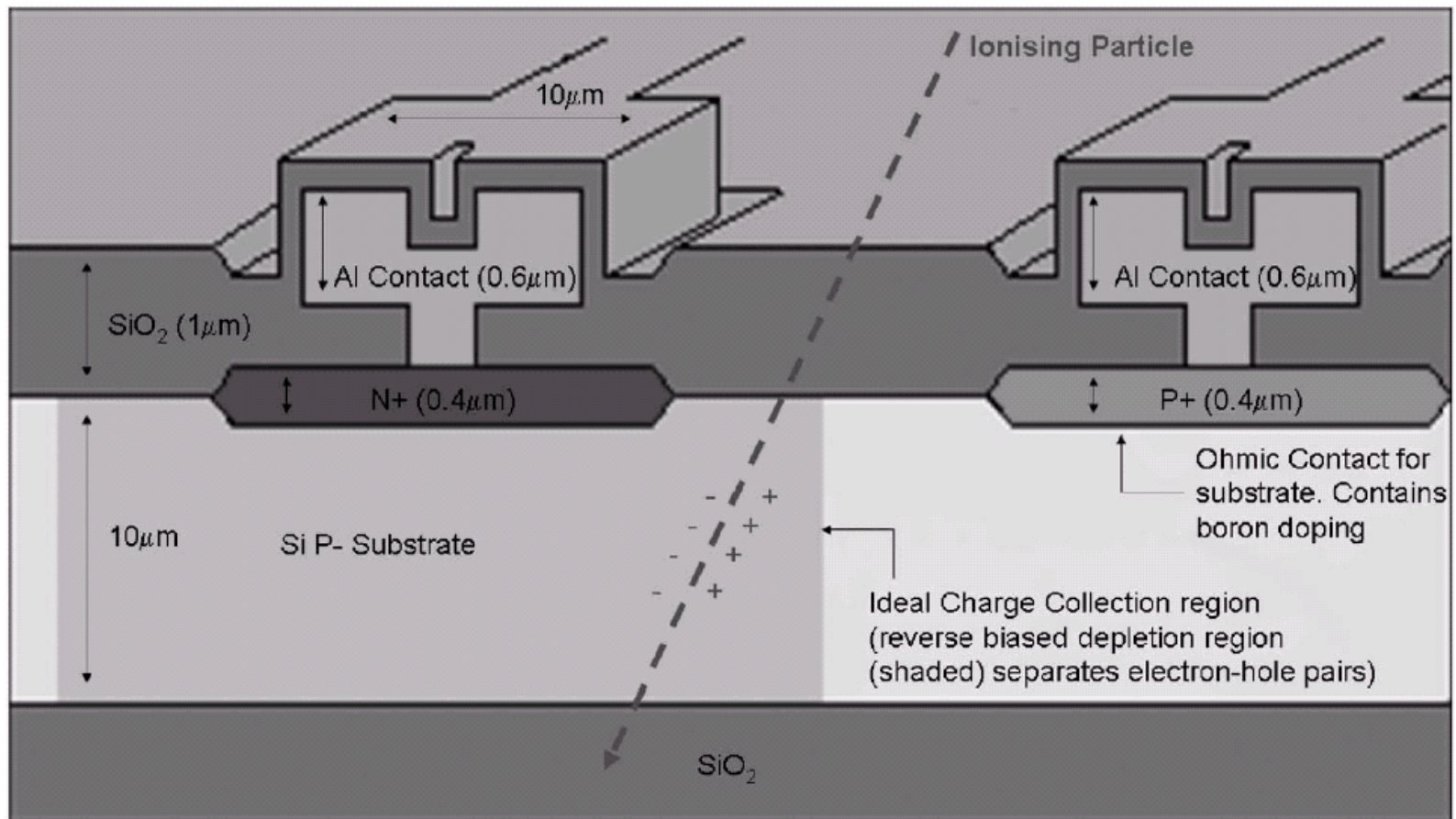
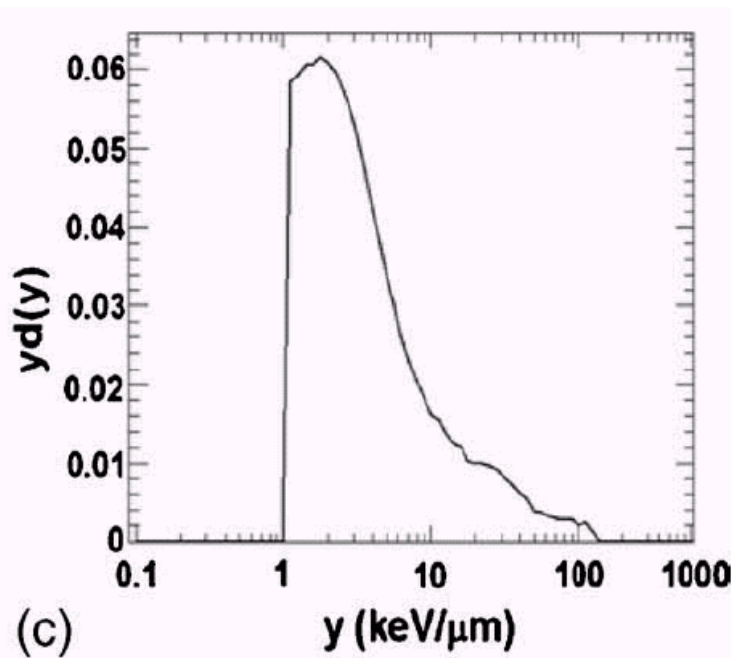


Figure 4. Single-event spectra measured in air 15 cm behind the patient collimator (No 4 in Figure 1) and at lateral displacements of 15 (···), 30 (—) and 120 cm (---) from the central axis of a circular treatment field 4 cm in diameter. Spectra are normalised per treatment gray at the isocentre.

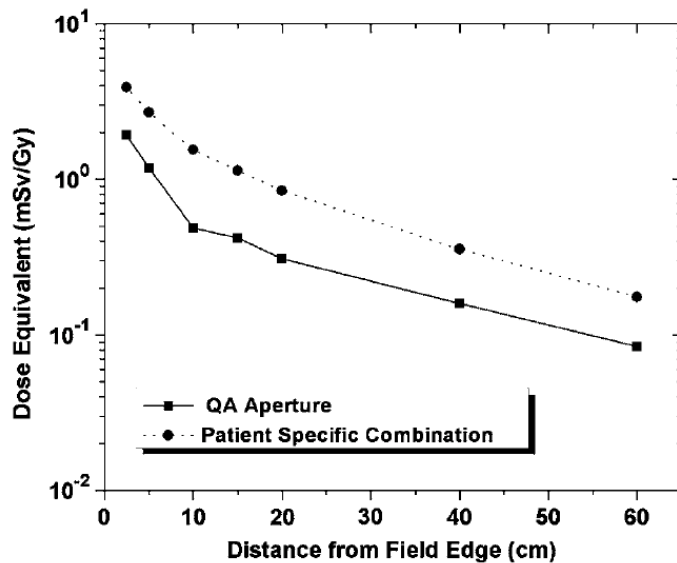
This figure from Binns and Hough (Rad. Prot. Dosim. 70 (1997) 441) illustrates the full power of microdosimetry. The neutron component (10-100 keV/ μm) falls steadily with increasing distance (15, 30, 120 cm) from the beam axis. The low LET component has a strong flare at 30 cm, just outside the shadow of the patient collimator, attributed to unblocked protons from the beam window and scattering system. Because of their low LET this has relatively little effect on the *equivalent* dose (mSv) to the patient. Nevertheless, this proton leakage was blocked later by additional shielding.



The SOI (Silicon-On-Insulator) microdosimeter is a relatively new, not yet commercial technique (Wroe et al., Med. Phys. 34 (2007) 3449 and references therein). Here the fiducial volume actually *is* of μm dimensions. A large array (4800 $30 \times 30 \times 10 \mu\text{m}$ cells) is used to get enough signal. Even so, the whole detector is small enough to be embedded in a phantom. A $\frac{1}{2}$ mm polyethylene converter in front of the array converts neutrons to recoil protons.



$y d(y)$ spectrum measured in a proton radiotherapy beam with the SOI detector. The analysis follows standard microdosimetry practice. The edge at 1 keV/ μm is non-physical and comes from the electronic cutoff of sensitivity. The radiation is almost all protons with just a hint of neutrons and the ‘proton edge’.



Neutron dose measured just outside the proton field with the SOI detector. As usual, the dose near the field edge is of order mSv/Gy. This graph shows that, as the patient collimator is closed down, the neutron dose goes up. Fewer protons stop in the patient but more stop in the collimator and these are more spread out by the time they reach the patient.

Neutron Detector Summary

Moderated neutron counters are easy to use, sensitive, and measure dose equivalent (H) with reasonable accuracy. However, they are bulky and difficult to incorporate into a patient phantom. They are generally used to measure H near the target volume or to monitor the low dose in radiation-worker or public areas.

Bubble counters are small, inexpensive, reusable and real-time. They can be inserted into a phantom and measure H reasonably well. They are sensitive enough to measure dose to the patient and radiation workers.

Large plane-parallel ion chambers can be used to measure D if it is known *a priori* that it is mostly from neutrons. In that case, they are simple and absolute.

Track-etch detectors are the most common commercial monitor for radiation protection. They are not very sensitive, but can give some information on RBE.

Tissue-equivalent proportional counters (TEPC's) used with microdosimetry techniques give by far the most information about the radiation field. The equipment is commercially available. However, data collection and interpretation are relatively complicated and best left to the experts. Silicon-on-insulator (SOI) microdosimetry arrays are compact but not yet commercially available. The relatively high charge threshold should not be a problem for neutrons.