Modulators

We have seen how to flatten the dose transversely by single or double scattering. We now flatten the dose longitudinally (in depth) by using a 'rotating wheel of variable thickness' (R.R. Wilson, 'Radiological use of fast protons,' Radiology 47 (1947) 487-491).

Design is complicated because, for several reasons, we want to put the range modulator (as it is now called) upstream where it will also serve as the first scatterer. This seems impossible. The modulator scatters more where it is thick, presenting a varying Gaussian to the second scatterer. But by compensating the modulator, given that the last few steps (hard to compensate) don't contribute much to the dose, a satisfactory engineering compromise can be struck.

At this point, assume we have already designed the double scattering system, so we know how much scattering is required of the modulator.

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refining scattering-angle compensation

useful energy range of a modulator

beam gating and beam current modulation

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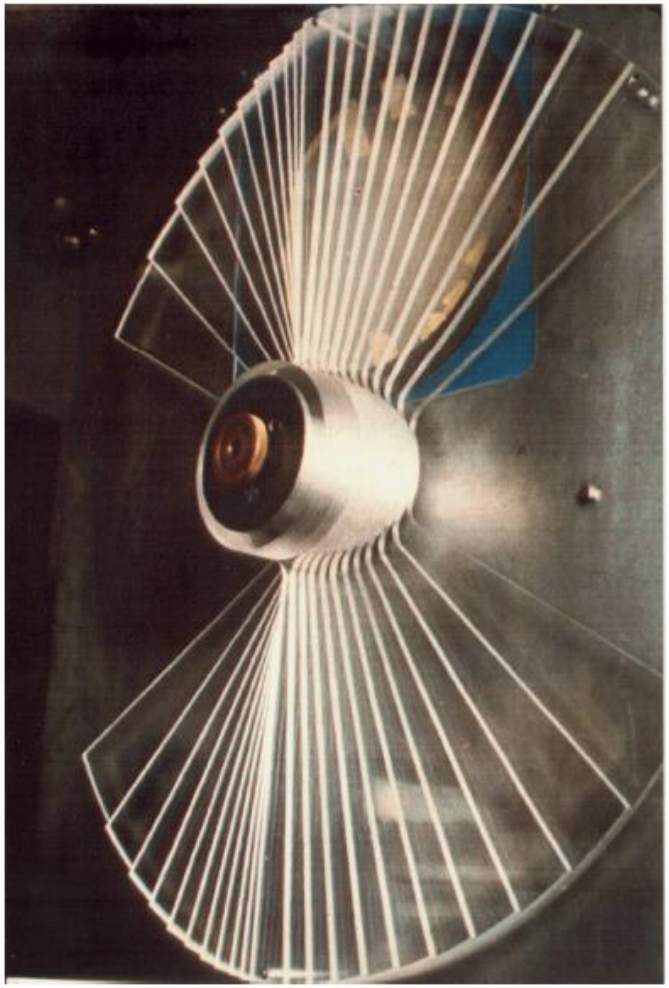
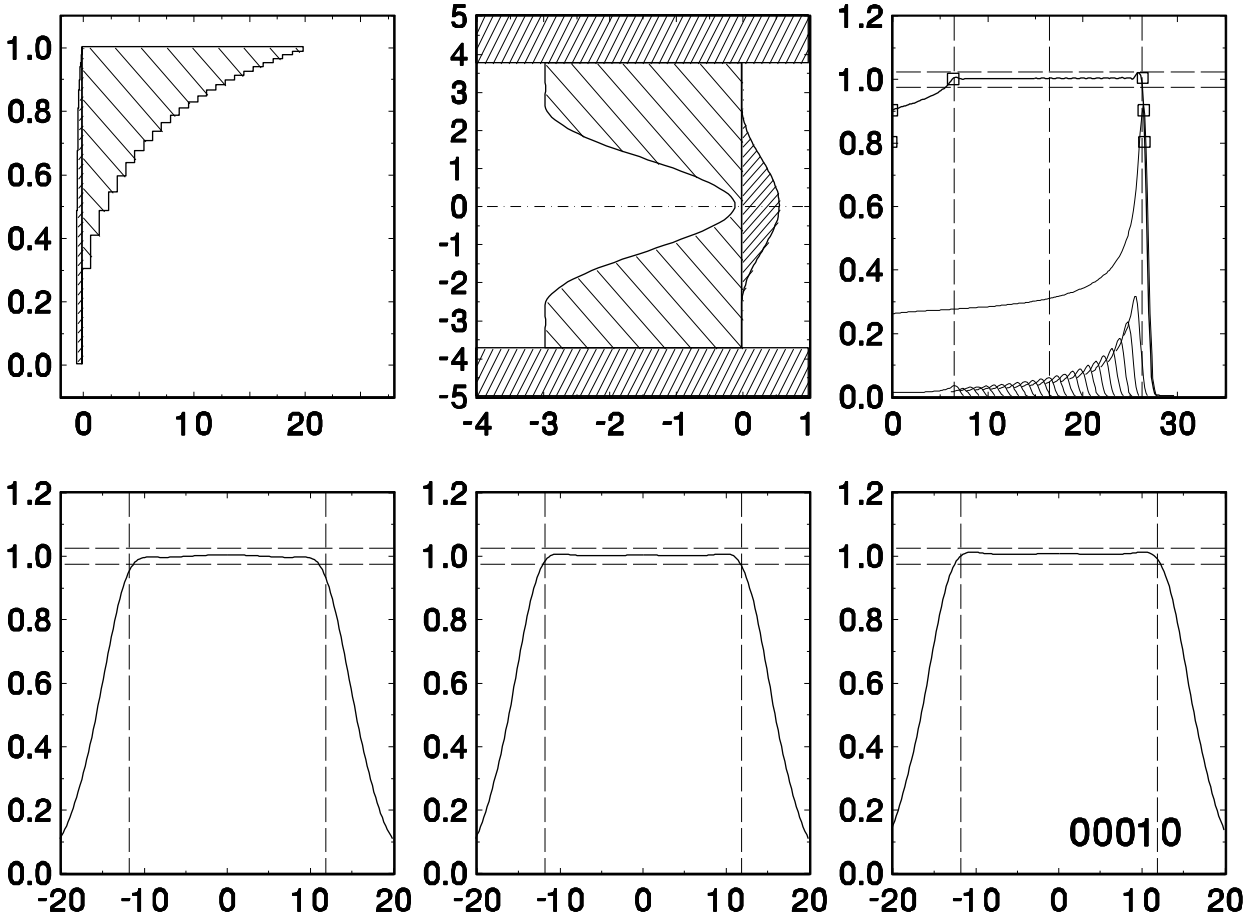
modulators in single scattering

Downstream Modulator



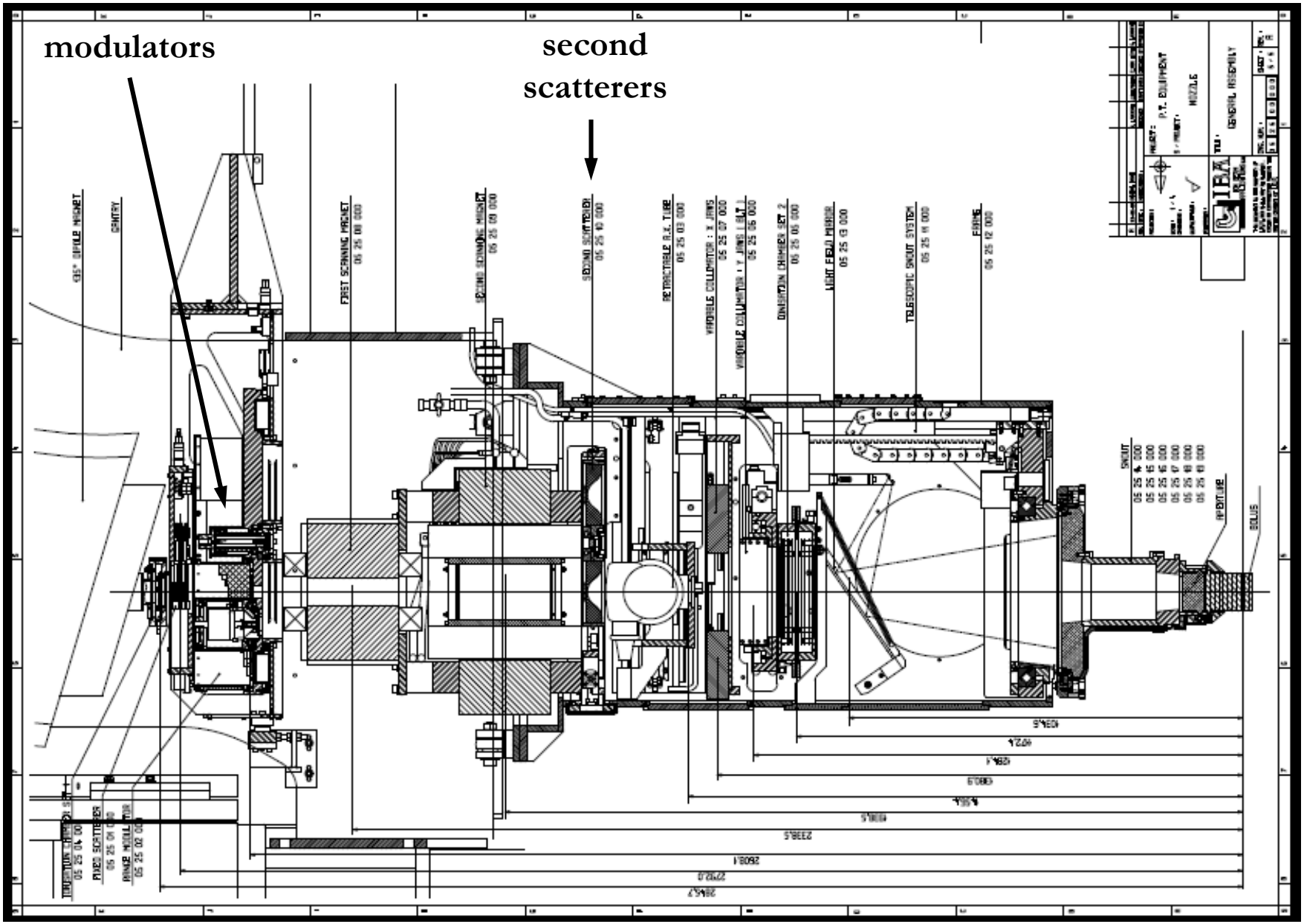
See Koehler et al., Nucl. Instr. Meth. 131 (1975) 437-440. A downstream mod is near the patient so it has to be large (diam. = 82 cm). Because of its short throw, scattering in the modulator doesn't matter much so it works with *any* double scattering system.

Elements of a Modern Double Scattering System

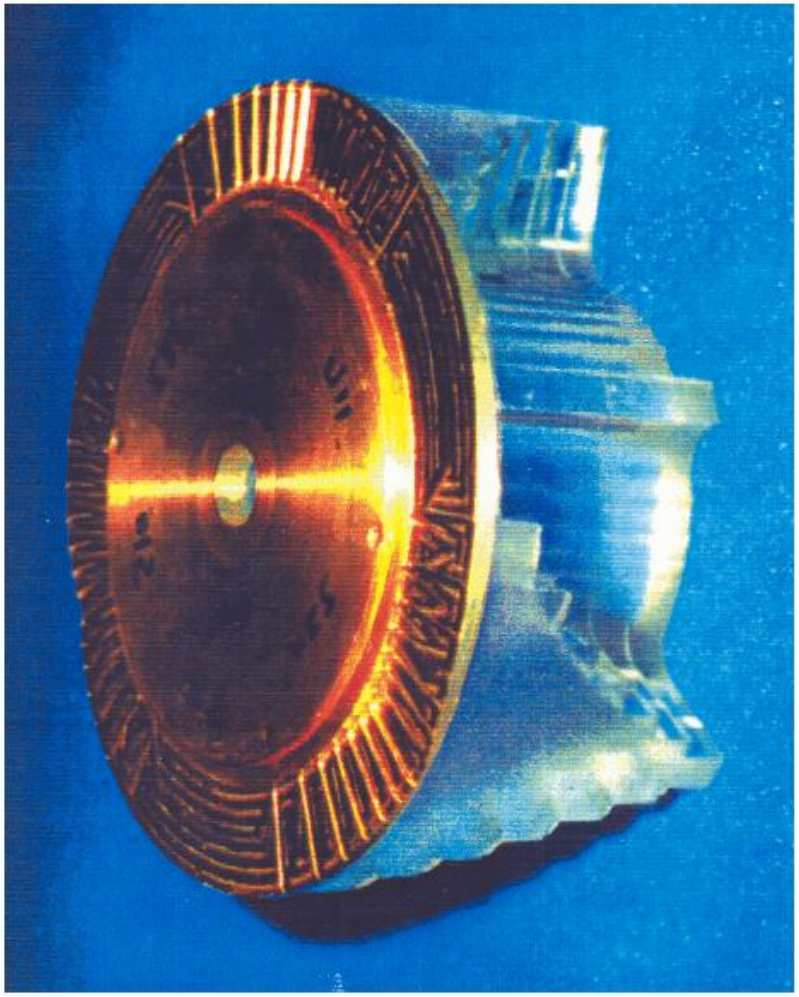


This ouput from the beamline design program NEU shows (L-R top row) an angle compensated range modulator, an energy compensated contoured scatterer, the predicted depth-dose distribution, and (bottom row) predicted transverse scans at the three depths marked in the depth-dose. This talk concerns the modulator.

IBA Nozzle (Burr Center Gantry)

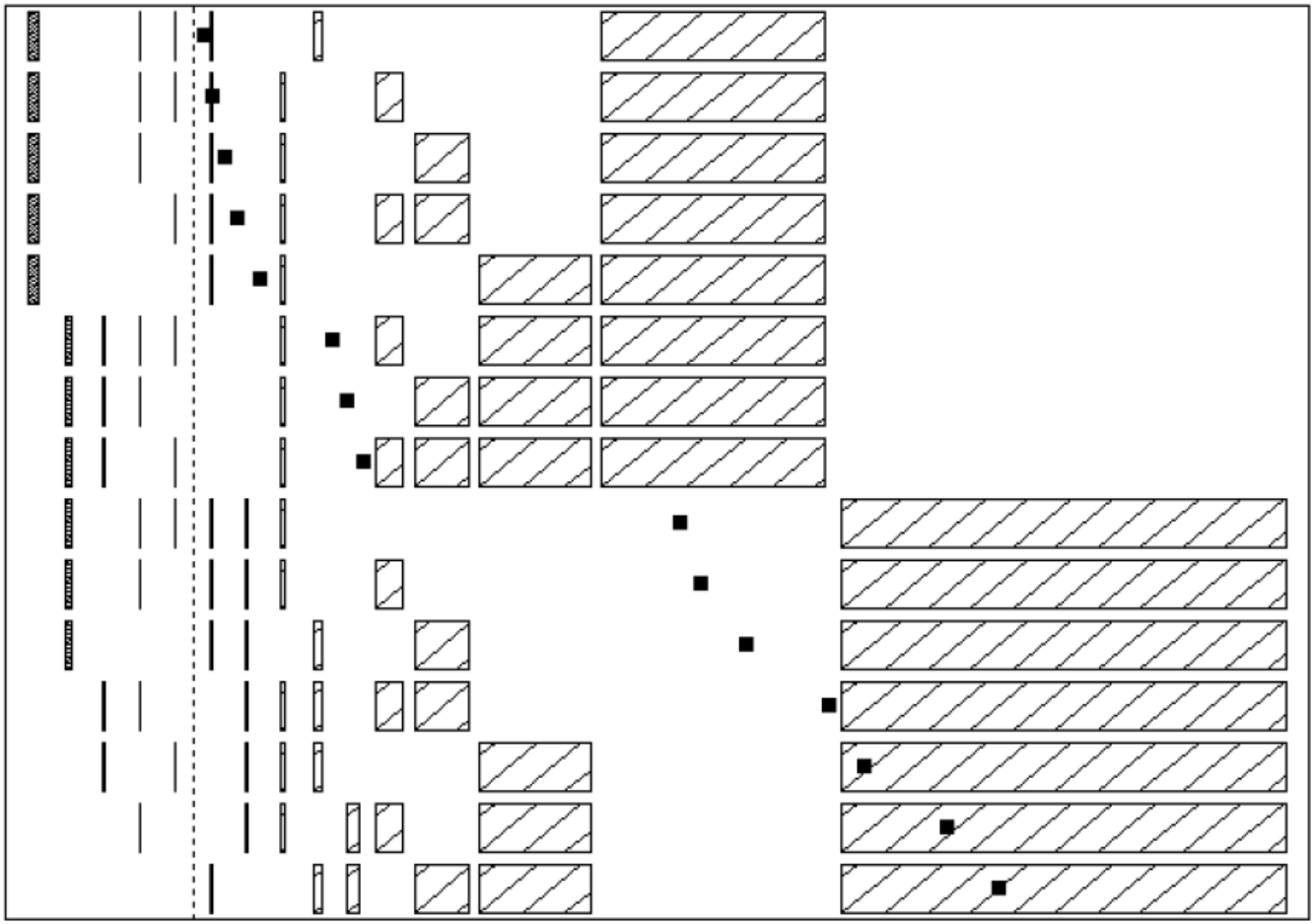


Upstream Modulator



A compensated 'upstream' modulator, diameter ~12 cm. This acts as S1 in a double scattering system so it has to produce a constant scattering angle insofar as possible. It only works in double scattering systems designed for that particular angle.

Lamination



Scattering, modulation and range shifting with binary degraders instead of a wheel. A 15-combination sequence of lead and plastic degraders produces a desired SOBP and, at the same time, the amount of scattering needed for S1 in a single scattering system.

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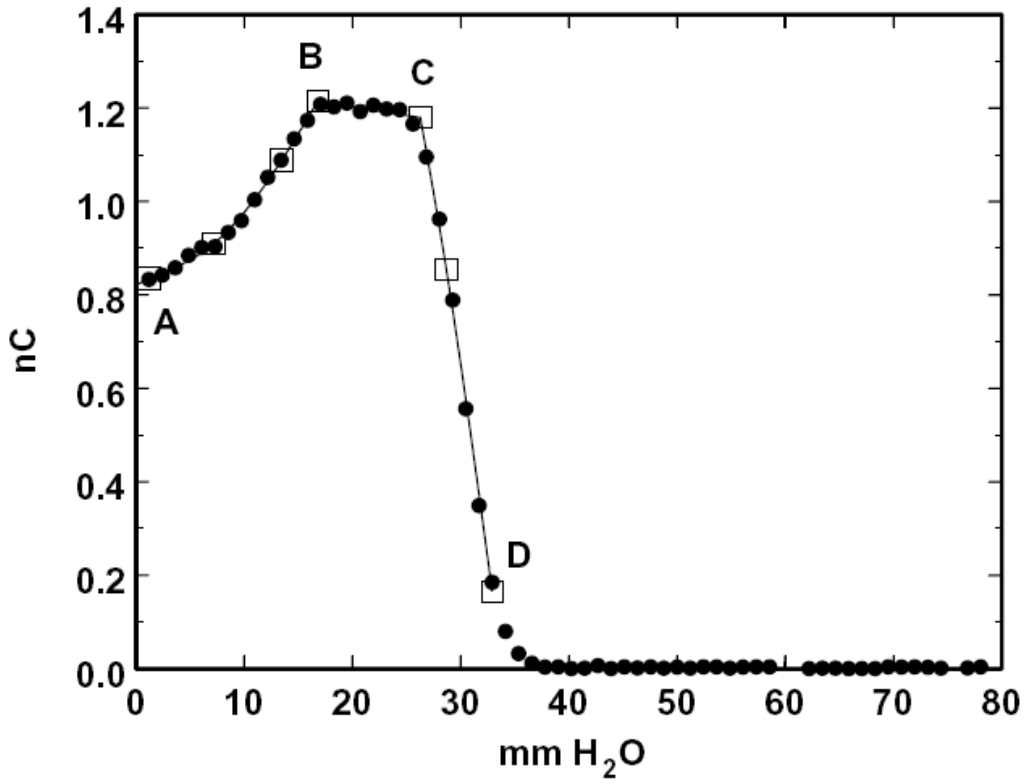
Defining 'Modulation'



Corners B and C are determined by a *broken spline* fit. (C_x – B_x) is defined as m_{100}, the modulation at full dose. The average dose between B and C is defined as the 100% level. Other measures of modulation, for instance m_{90} , can also be defined but only as long as A remains below 90% . Our programs provide a specified m_{100} (the only easy thing to do) but also compute and print m_{90} , a widely used clinical definition of 'modulation'.

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Designing a Range Modulator

A range modulator, made let us say from brass and Lexan, is completely specified by the *number of steps* and, for each step, the *thickness of brass*, the *thickness of Lexan*, and the *weight* of that step (absolute or relative time spent in the beam). To find those quantities:

1. Compute the H_2O equivalent step size , a compromise between ripples in the SOBP and sharpness of the distal falloff. The width of the Bragg peak at the 80% level is a good starting value. You may want to adjust it slightly later on.

2. Compute the number of steps to obtain the desired m_{100}. If necessary, back up and adjust the step size slightly to meet tolerance on m_{100}.

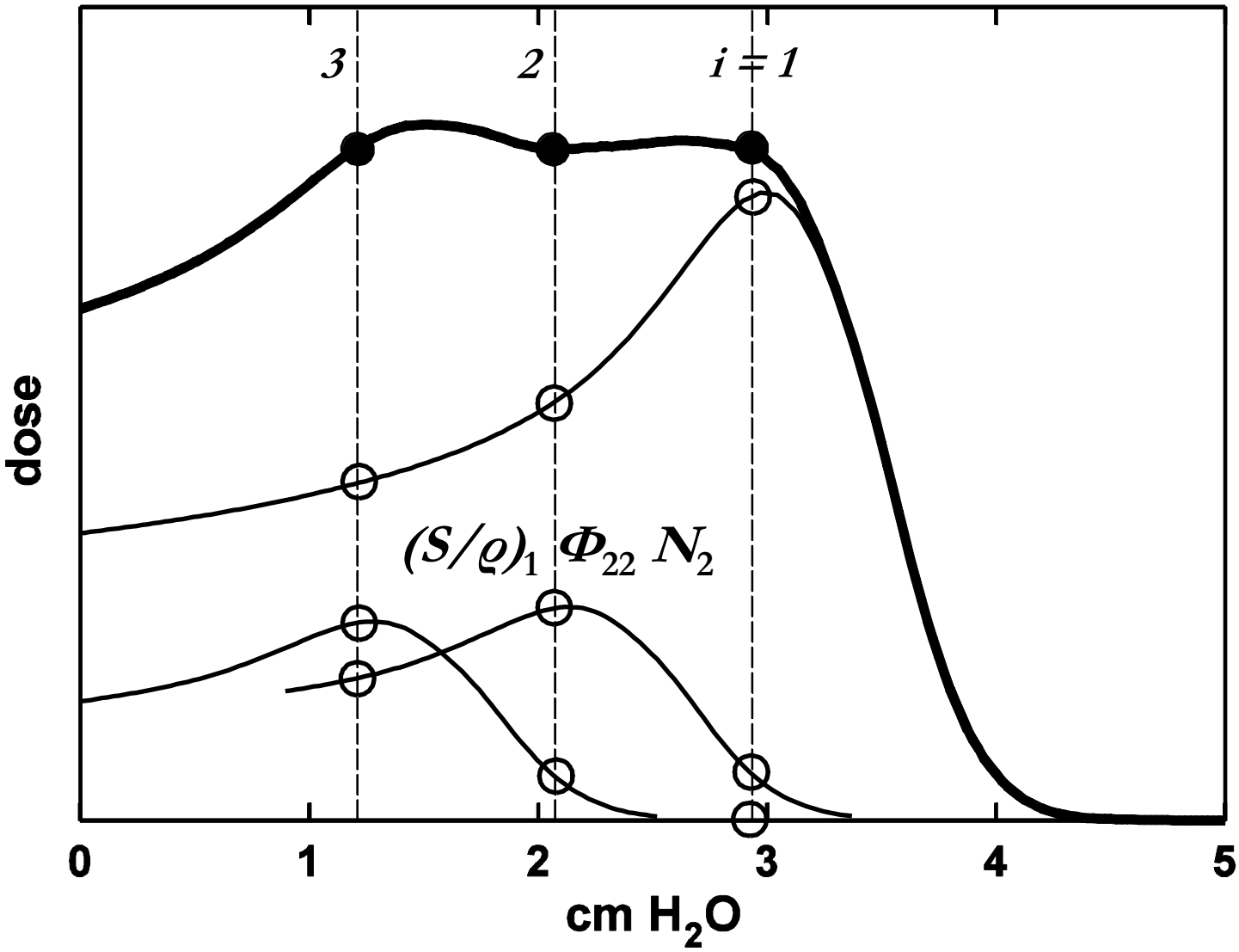
3. You now know the required pullback (H_2O equivalent) for each mod step. You also need to know the ideal scattering for each step. That comes from a previous computation of the double scattering system. You can now compute the thicknesses of brass and Lexan for each step (a binary degrader problem).

4. Knowing the *actual* scattering for each modulator step (it may not exactly equal the ideal) you can now compute the fluence at an arbitrary position in the water tank (from the double scattering integral) and, from the normalized measured Bragg peak, the effective stopping power at the relevant pullback. That leads to equations (next four slides) that determine the absolute weights N_j (gigaprotons) of the steps, completing the design.

Computing Weights: Index Definitions

M	# modulator steps = # z positions
$i = 1 \ldots M$	position index
$j = 1 \ldots M$	modulator step index (1 is deepest step)
z_i	a measuring plane position along beam axis
$(S/\rho)_k$	effective stopping power (Gy/(gp/cm^2)) at water equivalent depth k
Φ_{ij}	fluence per proton on axis. Depends on i via location of measuring plane and on j via scattering effects (modulator composition)
d_i	desired dose at position z_i
N_j	# gp (gigaprotons) required for step j

Computing Weights: Sample Equation



$$d_2 = (S/\rho)_2\,\Phi_{21}\,N_1 + (S/\rho)_1\,\Phi_{22}\,N_2 + (S/\rho)_0\,\Phi_{23}\,N_3$$

Computing Weights: Linear Algebra

Writing the sum for each of the M dose positions we obtain M linear equations for the M weights N_j. The coefficients are known.

$$d_i \;=\; \sum_{j=1}^{M} (S/\rho)_{i-j+1}\, \Phi_{ij}\, N_j \quad , \quad i = 1 \ldots M$$

This is a standard problem in linear algebra, usually written

$$\vec{d} \;=\; \mathbf{G}\; \vec{N}$$

where **G** is a known matrix, d a known (desired) vector and N an unknown vector. The solution, formally written

$$\vec{N} \;=\; \mathbf{G}^{-1}\; \vec{d}$$

is obtained by Gauss-Jordan elimination or LU decomposition (see Numerical Recipes).

Computing Weights: Notes

1. The specified doses d_i need not be equal. They can be any given values. We might, for instance, actually want a sloped SOBP.
2. The method only guarantees that the dose will equal d_i at the given points. In between it will vary, especially if the number of modulator steps is small.
3. The reference position on the Bragg peak need not be the peak value. In the example it is midway between the lower and upper 80% points, which seems to work a bit better.
4. Modulation 'gap': as we widen the desired SOBP we reach a point where the dose is flat to skin even though we have not yet specified full modulation! That happens sooner for high energy or short throw systems, and going beyond that point yields negative weights. This is a basic limitation on range modulation, having to do with the shape of the pristine Bragg peak. It is more pronounced at high energy because the entrance region is flatter (nuclear reactions).

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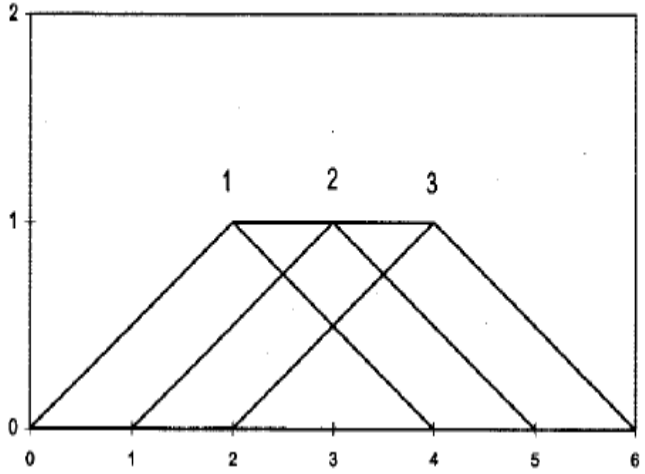
Can We Improve on the M × M Method ?

The short answer is 'no'. Damien Prieels ('A new technique for the optimization of a range modulator,' IBA technical note 1997) asked two related questions: Is a continuous wedge better than a stepped wedge? Is there a better optimization technique for the weights?

He found that a continuous wedge (that is, very small steps) either yields negative (non physical) weights or, if applied carefully, can yield a realizable design which, however, is no smoother than one obtained with a finite step size and coupled linear equations.



His plausibility argument: if we try to form a flat top by superimposing triangles, the middle triangle will be rejected by the optimization process! Something of the same kind goes on with Bragg peaks.

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Refining Compensation

Recall that each step of the modulator is compensated so that, as far as possible, it presents the best Gaussian to the second scatterer. For many years, we compensated each step to the same angle as the first step. Because of the systematics of scattering, that causes the modulator to overscatter slightly as j increases, yielding a slightly dished tranverse distribution.

D. Prieels (IBA) noted that the design could be improved if each step were compensated to a slightly different (decreasing) angle. He implements that by re-optimizing the transverse flatness at each j. However, that is time consuming, and yields designs whose lead/Lexan ration is not smooth as a function of j. We get around those problems by letting the target angle for each step be a linear function of j. We have found the best slope for that line empirically; it changes very little from one design to the next.

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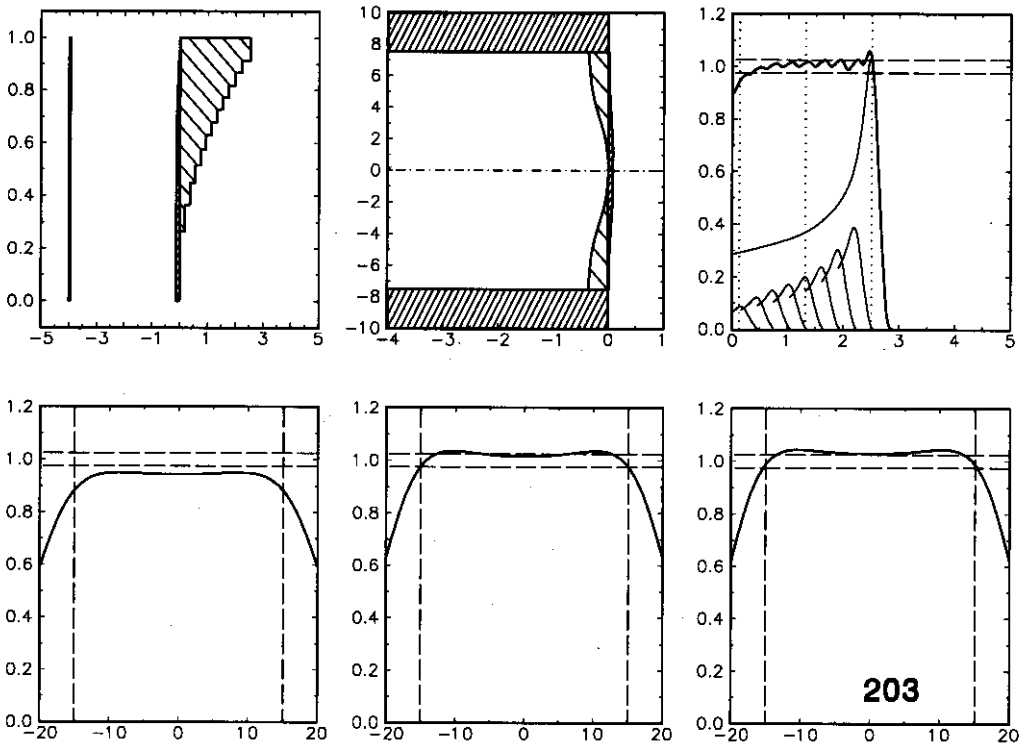
Useful Energy Range of a Modulator



Performance of a 70-82 MeV system at 70 MeV. The SOBP has two problems: tilt due to relatively greater scattering at the thick end (which also causes the 'dished' appearance of the transverse scan) and excess ripple because the Bragg peak is too narrow. That could be avoided with a slightly smaller step, but the tilt would remain. The small useful energy span would appear to mandate a large library of modulators to cover the range of clinical requirements.

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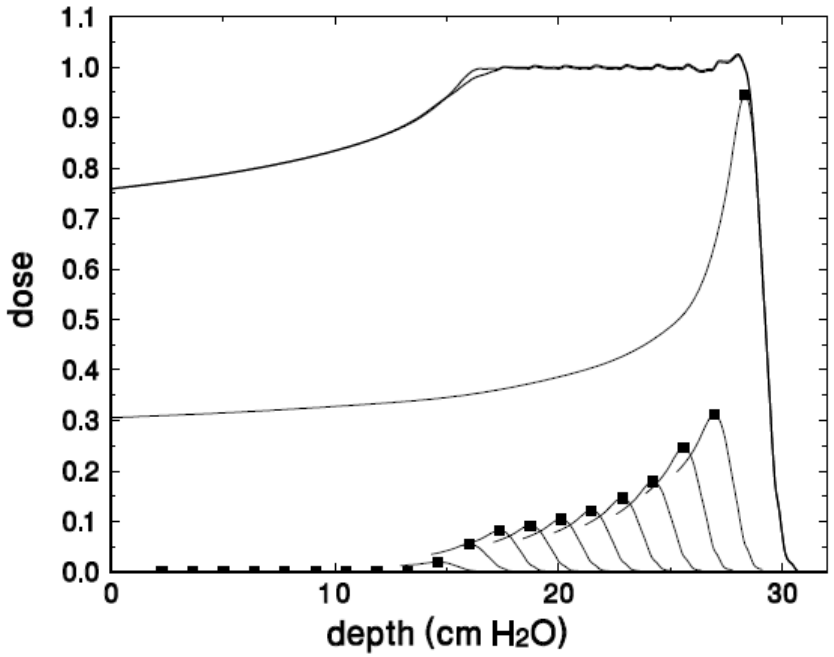
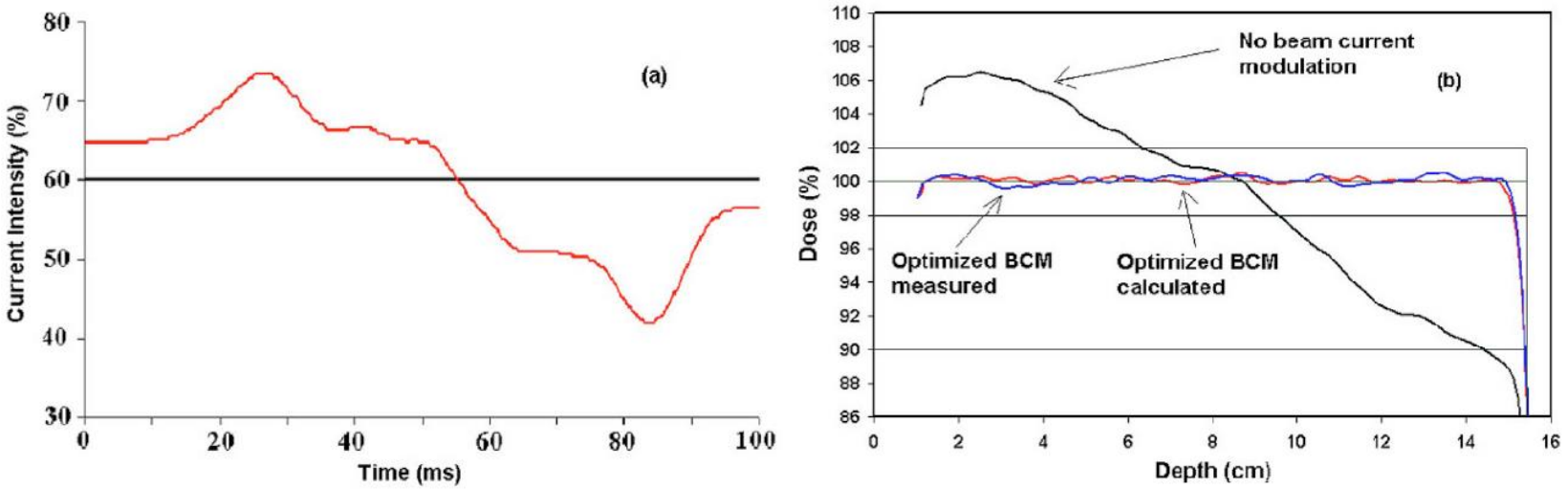
Beam Gating



The required library can be reduced drastically by designing all modulators for full modulation, then cutting the beam off during proximal steps. There must be a *beam-spot block* between the shallowest and deepest steps. Otherwise, gating will cause a large error in the SOBP at the distal edge.

Though extremely useful, beam gating costs some average dose rate because the beam is off part of the time. It also rounds the proximal corner slightly because the beam inevitably covers several steps at the instant it is cut off. (In simple modulators, the beam can cover arbitrarily many steps with no ill effect.) It also necessitates additional QA because there is more to go wrong.

Beam Current Modulation



The SOBP can be corrected for energy and other effects by means of beam current modulation (BCM). The angular position of the modulator wheel must be known to the control system at each instant of time, and cyclotron output current must be controlled accurately. BCM files can be computed from first principles (difficult) or from time-resolved dose measurements according to a method described by H.M. Lu and H. Kooy (Med. Phys. 33 (2006) 1281-1287). Beam gating (previous slide) is a limiting case of BCM: the BCM file calls for zero beam during the appropriate angular interval.

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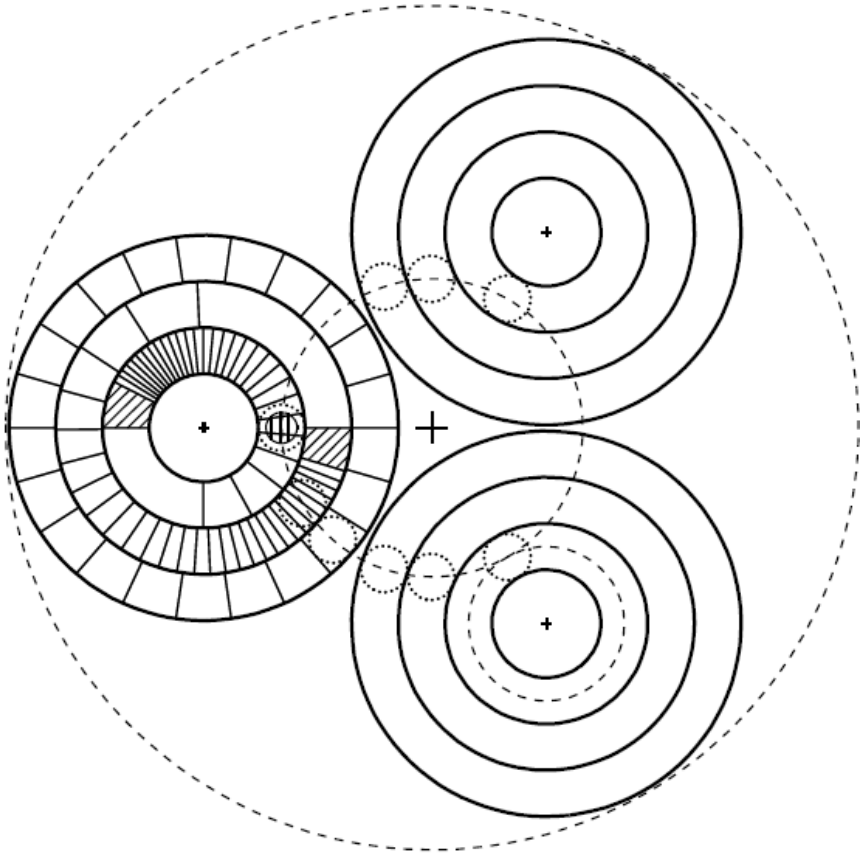
The 3 × 3 Arrangement



Using all available tricks, we still need several modulator tracks to cover the requirements. It is very desirable that they be *remotely selectable* at any gantry position, for operational efficiency and to minimize radiation exposure to staff.

Miles Wagner invented the ingenious 3×3 arrangement shown at left. Each of the 9 tracks can be positioned in the beam by merely turning the large wheel. With BCM, that is more than enough tracks to cover all clinical requirements.

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Modulators for Single Scattering

Designing a modulator when it is the only scatterer (S1) is the same as designing one for double scattering. We just substitute the single scattering fluence for the double scattering fluence.

There is, however, one big difference. We may add lead to get the desired field radius, but we never *need* to compensate the modulator unless we want to. Overscattering by thick steps always gives *too wide* a Gaussian, that is, a flatter dose than required, which is fine. To retain a flat SOBP we merely need to make the corresponding weights larger, as is done automatically by the matrix procedure we described earlier.

That said, we might want to go to the extra trouble of a binary modulator even in single scattering. The output of a real time monitor (MLFC or MLIC) surrounding the beam can be harder to interpret if the beam 'breathes' with modulator angle.

Summary

We have learned how to design a stepped compensated modulator by solving coupled linear equations in which the on-axis fluence and the effective stopping power appear as known coefficients. Nothing is gained with continuous modulation or other solution methods.

To change the modulation we can use beam gating. That slightly degrades the proximal corner and requires additional QA.

A given modulator only meets specifications over a finite range e.g. ±2.5% from 200-235 MeV. To improve on this we can use beam current modulation, which requires good control over the cyclotron output and still more QA. Beam gating can be included in BCM.

IBA proton nozzles use all of these techniques, with remotely changed modulator tracks arranged in a 3×3 configuration.