

## EULIMA BEAM DELIVERY

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Abstract

The stopping light ion beam must be scanned through the tumour in three dimensions, laterally and in range. Range changing with a fixed energy cyclotron implies a degrader. The optimum beam condition at the degrader is calculated, and it is shown that the increase in phase space by multiple scattering is acceptable. Range straggling and projectible fragmentation are also tolerable.

In contrast to conventional radiotherapy (x-rays, cobalt) the light ion beam from EULIMA and similar machines can be exactly localized, laterally to  $\pm 1.5$  mm, and in range to 5 mm. This allows the tumour to be treated precisely by scanning in three dimensions over a designated volume of arbitrary shape. The beam delivery system must accomplish this reliably and safely at reasonable cost.

- This requires lateral (x-y) deflection by a fast magnet
- Variable range
- Variable exposure time to achieve a uniform biologically effective dose, see Fig 1.
- Position sensitive monitors
- Rapid switch off in case of malfunction

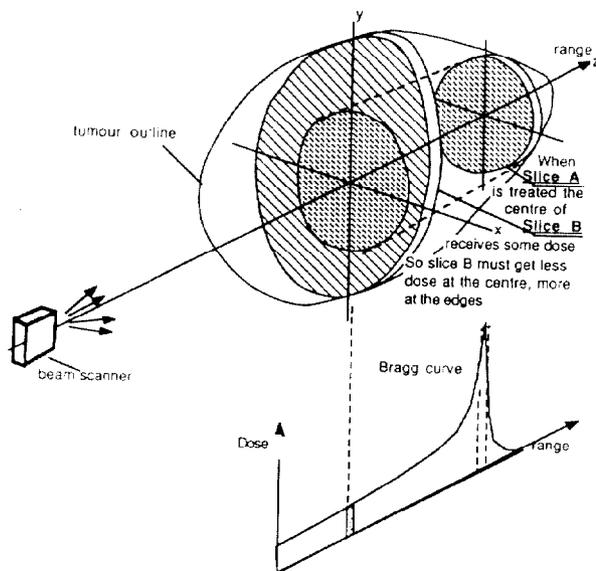


Fig. 1 3 D Conformal Therapy

Fig 1 shows a typical treatment plan. By adjusting the range, the Bragg curve is placed successively at various depths. Each depth slice is scanned in the x-y plane over the tumour cross-section at that depth; Note that when distal slice A is treated, the centre of central slice B will receive some dose. This must be compensated when slice B is treated, by giving more dose at the edges than at the centre. Therefore in general each slice requires a carefully computed non-uniform dose.

In any scanning system tissue movement is a problem. An unfortunate correlation between movement and scanning period could cause part of the system to be overdosed while other parts receive nothing. Internal organs move cyclically in synchronisation with breathing and heart beat. Synchronizing the beam with respiration is one possibility [1], and the pulse could also be included, implying an accelerator with plenty of intensity to spare and good on/off control. The alternative is to repeat the scan many times and hope that unforeseen correlations will cancel out. Hope is a virtue, but we prefer not to depend

upon it when lives are at stake.

Lateral scanning

The scanning across the x-y plane may be either continuous (called "raster scan") or intermittent (called "pixel scan").

Pixel scan

The target plane is treated at a triangular mesh of points, Fig 2, with spacing  $p$ , and a Gaussian beam spot of standard deviation  $\sigma$ .

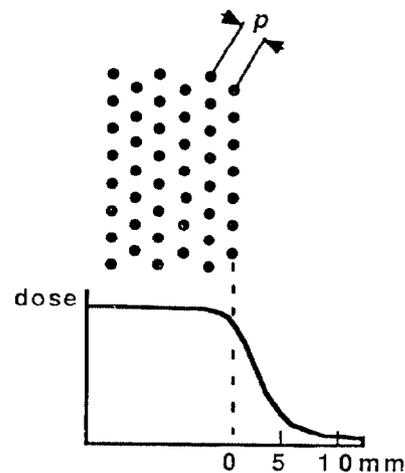


Fig. 2 Pixel Scanning

If  $\sigma \geq 0.5 p$  the dose is uniform to 1.2 %. The edge definition depends on  $\sigma$  and is shown in Fig 2 for  $\sigma = 2.5$  mm,  $p = 5$  mm. This is good enough to delineate a cross-section of arbitrary shape by choosing which pixels to treat. The procedure would be as follows: beam off - move spot to pixel - beam on until desired dose is reached - repeat for next pixel.

We see the following advantages for the pixel scan

- flexible shape in each plane
- each pixel is dosed separately giving flexible dose distribution
- no collimators
- no beam when spot is moving
- no error from magnet rise time or transient oscillations
- no error from beam intensity fluctuations
- conceptually simple computer control
- good security

An essential technical prerequisite is a means of switching the beam on and off. With a cyclotron this can be done at low energy in the injection line, because the particles only spend  $60 \mu\text{s}$  inside the machine and the beam loading is negligible. However with a synchrotron using resonant ejection to get a long burst it takes several milliseconds to cut the beam; therefore a fast beam switch needs to be included in the transport system, and this is expensive.

The time available per pixel is determined by the desired maximum treatment time (5 mn), the number of pixels ( $10^4$  for a one litre tumour), and the number of times one scans the tumour in each session (say 10). This gives 3 ms per pixel, to include spot settling time, on/off switching and treatment.

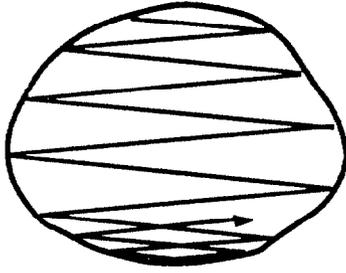


Fig. 3 Raster Scanning

Raster scanning

With equally spaced parallel lines, spacing  $p$ , a Gaussian spot of standard deviation  $\sigma$  gives a dose uniform to 2.83 % if  $\sigma \geq 0.5 p$ . In principle a cross-section of any shape can be delineated (Fig 3), but it requires the horizontal turning points to be correlated with vertical position and there will be some overdose at the turning points where the spot velocity is less. In general the intensity can be modulated by varying the spot velocity. Note that at Berkeley the raster scan gives a rectangular field and collimators are used to define the exact tumour shape, so the turning points are screened.

The main advantage of the raster scan is that no on/off switch is needed in the beam. It requires :

- a steady beam
- precise control of scan velocity
- fast magnet response with no undesirable transients

Disadvantages are :

- probable overdose at turning points or collimator needed
- rapid beam fluctuations cannot be compensated
- faster magnet response will be needed and this means more power.

Scanning in range

Typically the depth required in tissue is 5 cm (min) to 20 cm (max). (Shallower tumours could be treated by low energy proton machines). The corresponding particle energies for carbon are 140-340, and for oxygen 170-420 MeV/nucleon. With a synchrotron there is no problem in varying the extraction energy. A cyclotron however has a fixed extraction energy, so it will be necessary to reduce the energy by passing the beam through a slab of matter (called the degrader) of variable thickness. However the degrader has several undesirable effects which must be analysed :

- a) increase of the beam phase space by multiple scattering
- b) increase of the momentum spread by energy straggling
- c) fragmentation of the incoming particle, giving lighter ions of roughly the same velocity with a longer range in the patient.

Multiple scattering

At any point along the beam axis we assume that in the horizontal phase space defined by

$$\mathbf{X} = \begin{pmatrix} x \\ p \end{pmatrix}$$

the distribution of particles is Gaussian, with the one standard deviation contour defined by the ellipse

$$\bar{\mathbf{X}} \boldsymbol{\sigma}^{-1} \mathbf{X} = 1 \tag{1}$$

The symmetric matrix

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} \tag{2}$$

Then specifies the beam shape and area, and is transformed according to

$$\boldsymbol{\sigma}' = \mathbf{R} \boldsymbol{\sigma} \bar{\mathbf{R}} \tag{3}$$

where  $\mathbf{R}$  is the usual transport matrix (3). The overall variance of the distribution in the  $\theta$ -direction is  $V_{\theta} = \sigma_{22}$ .

We consider how the matrix  $\boldsymbol{\sigma}$  is changed by a degrader of finite thickness  $t$ , adding the effects of multiple scattering in each larger  $dt$  to the effect to the drift distance  $dt$ . For drift alone

$$\mathbf{R} = \begin{pmatrix} 1 & dt \\ 0 & 1 \end{pmatrix}$$

so applying (3)

$$d\boldsymbol{\sigma}/dt = \begin{pmatrix} 2\sigma_{12} & \sigma_{22} \\ \sigma_{22} & 0 \end{pmatrix} \tag{4}$$

For scattering alone

$$d\sigma_{22}/dt = d\theta_{\text{rms}}^2 = \mathbf{K}(t) \tag{5}$$

with  $\mathbf{K}(t) = 200 Z^2/A^2 p^2 \beta^2 X_0$  (6)

for a projectile of charge  $Z$ , mass  $A$  velocity  $\beta c$ , and momentum  $p$  in MeV/c, in a degrader of radiation length  $X_0$ .  $\mathbf{K}$  varies with  $t$  because  $p$  and  $\beta$  are changing. Adding (4) and (5) gives the total change in  $\boldsymbol{\sigma}$ ,

$$d\boldsymbol{\sigma}/dt = \begin{pmatrix} 2\sigma_{12} & \sigma_{22} \\ \sigma_{22} & \mathbf{K} \end{pmatrix} \tag{7}$$

For a degrader of total thickness  $t$ , (7) can be integrated term by term to give at the output

$$\boldsymbol{\sigma}_{\text{out}} = \boldsymbol{\sigma}_{\text{d0}} + \boldsymbol{\sigma}_{\text{s}} \tag{8}$$

where  $\boldsymbol{\sigma}_{\text{d0}}$  is the matrix expected at the end of the degrader due to the drift distance only and the effect of the scattering is entirely included in

$$\boldsymbol{\sigma}_{\text{s}} = \begin{pmatrix} \mathbf{C} & \mathbf{B} \\ \mathbf{B} & \mathbf{A} \end{pmatrix} \tag{9}$$

with

$$\mathbf{A}(t) = \int_0^t \mathbf{K} dt, \quad \mathbf{B} = \int_0^t \mathbf{A} dt, \quad \text{and} \quad \mathbf{C} = 2 \int_0^t \mathbf{B} dt \tag{10}$$

Note that  $\boldsymbol{\sigma}_{\text{s}}$  is independent of the phase space of the incoming beam, and depends only on the properties of the degrader, plus the beam momentum. In general the beam emittance, that is the area of the ellipse in phase space is

$$\pi \epsilon = \pi \sqrt{\det(\boldsymbol{\sigma})}$$

The emittance is not changed by drift distance only so the input beam emittance is given by

$$\epsilon_{\text{in}}^2 = \det(\boldsymbol{\sigma}_{\text{in}})$$

In (8) we now vary the components of  $\boldsymbol{\sigma}_{\text{d0}}$  keeping the emittance fixed, to find the condition for minimum emittance  $\epsilon_{\text{out}}$  at the output with scattering included. One finds for the optimum beam,

$$\boldsymbol{\sigma}_{\text{d0}} = (\epsilon_{\text{in}}/\epsilon_{\text{s}}) \boldsymbol{\sigma}_{\text{s}} \tag{11}$$

where

$$\epsilon_{\text{s}}^2 = \mathbf{A} \mathbf{C} - \mathbf{B}^2 \tag{12}$$

That is the components of the unscattered beam must be proportional to the components of  $\boldsymbol{\sigma}_{\text{s}}$ , with magnitudes adjusted to give the correct determinant. Substituting in (8), one finds in this case, for the output emittance including scattering

$$\epsilon_{\text{out}} = \epsilon_{\text{in}} + \epsilon_{\text{s}} \tag{13}$$

In summary, if the shape of the input beam is optimized the increase in emittance due to the degrader is  $\epsilon_{\text{s}}$ ; this is only a function of the degrader characteristics and adds linearly to the input emittance.

The integrals in equation (10) have been evaluated for various materials, slowing down a beam from 20 cm range in water to 5 cm range. The results are given in Table 1 for beams of fully stripped carbon.

Table 1  
 Degradar parameters for C<sup>12</sup> beam slowing down from 20 cm range-in-tissue to 5 cm

Material	$\rho$	Xo cm	thickness cm	$E_s$ mm.mrad
Li	0.53	155	34.5	6.25
H <sub>2</sub> O	1.00	36.1	15.0	5.10
Be	1.85	35.3	10.0	2.23
B <sub>4</sub> C	2.52	20.7	7.1	2.06
graphite	2.26	18.8	7.5	2.42
Cu	8.96	1.4	2.5	3.55

The density of the degrader is significant, as well as the thickness in radiation lengths, and for this reason boron carbide turns out to be the best material. (Diamond would be even better, but is not available in the required thickness). The output emittance of 2.06 mm.mrad (one standard deviation) for B<sub>4</sub>C is encouraging. However the one standard deviation ellipses, in horizontal and vertical planes together, only contain 16 % of the particles. To pass 40% of the particles we must double the emittance in both planes to 4 mm.mrad, which is comparable to synchrotron output beams with no degrader. As the cyclotron has plenty of intensity to spare we can sacrifice the rest of the beam and still have more particles.

One concludes that multiple scattering in the degrader is not an impediment for a light ion cyclotron.

Energy straggling

For a thin layer with a projectile of charge Z, velocity  $\beta c$ , in a target of charge Z<sub>T</sub>, the variance V in energy increases as

$$dV/dt = 4\pi n e^4 Z^2 Z_T (1 - \beta^2/2)/(1 - \beta^2) \quad (14)$$

where n is the number of target atoms per cm<sup>3</sup>. Projecting to the end of the degrader and integrating, the final variance is

$$V = \int_{E_{out}}^E \left\{ \frac{dE}{dX} \langle E_{out} \rangle \right\}^2 \frac{dV}{dt} dt \quad (15)$$

Degrading a carbon ion beam from 20 cm range in water to 5 cm range gives  $dp/p = 0.5\%$ . If non-dispersive bends are used this should not be a problem for the beam optics.

Fragmentation

It is intended to place the degrader close to the cyclotron, so that fragments with the wrong magnetic rigidity will be lost in the bending magnets. As fragments in general have the same velocity as the incoming projectile, only those with the same Z/A as the projectile need be considered. Light fragments of the same Z/A have much smaller  $dE/dx$  and longer range. Therefore only the fragments produced in the final layers of the degrader will have the same rigidity as the main beam.

Partial cross-sections for carbon and oxygen beams of 2.1 GeV/n in a beryllium target for deuteron production are 329 and 417 nb respectively ; for helium production 383 and 501 nb. At 400 MeV/n the cross-sections will be smaller. Other fragments are much less probable. For oxygen penetrating 10 cm of beryllium one finds that  $d^2 + He^4$  together are 10 % of the beam ; but allowing for the different  $dE/dx$  we expect only about 1% of the beam to have the correct rigidity.

Therefore fragmentation does not seem to be a serious problem provided that a momentum selection is made after the degrader.

Beam layout

A preliminary drawing of the EULIMA beam delivery system is given in Fig 4. Initially there will be one vertical and one horizontal beam, both with scanners. Further beams can be added as indicated.

References

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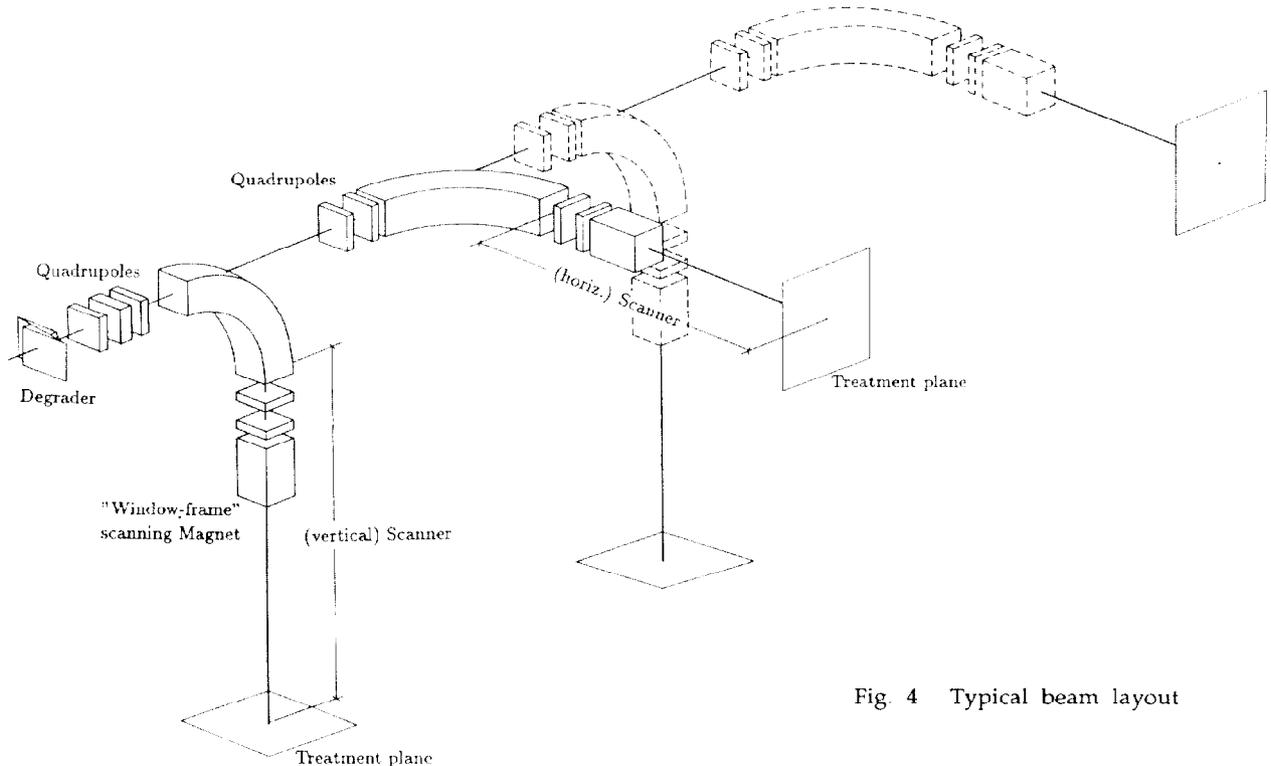


Fig. 4 Typical beam layout