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An Efficient Method for Heavy Ion Dose Calculations

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Heavy charged particles deposit much of their kinetic energy at very high rates in small volumes near the end of their range. This characteristic, coupled with the availability of modern particle accelerators, has sparked a revival of interest in the use of ions as a possible treatment tool for certain types of cancers.[1,2] Collisions between projectile ions and atoms in the target medium can result in ion fragments that are different from the original projectile species. The energy deposition characteristics of these fragments differ from those of the projectile in a manner that allows them to travel beyond the range of the original particle. This can result in deposition of doses in healthy tissue beyond the tumor. The loss of projectiles due to the fragmentation process will also affect the dose deposited in the target tumor. An accurate dose calculation requires that these effects be taken into account. Monte Carlo calculations are expensive, time consuming, and can be limited in the number of ion species considered. Linear methods can yield high-order accuracy but can sometimes exhibit the undesirable characteristic of calculating negative fluxes. In order to bypass these difficulties, we have applied the recently developed exponential discontinuous (ED) finite-element method to a calculation of dose deposition by relativistic heavy ion projectiles and fragments.[3] The ED method has been shown to yield strictly positive solutions for positive sources of neutral particles.[4]

DISCLAIMER

The ELDRHIT code described in Reference 3 solves the heavy ion transport equation

$$\frac{\partial \psi_n(x,E)}{\partial x} + \sigma_n(x,E) - \frac{\partial}{\partial E}\left[S_n(E)\psi_n(x,E)\right] = Q_n(x,E) \tag{1}$$

in space and energy in terms of an exponential ansatz of the form

$$\psi_n(x,E) = a_{n,i,g} e^{\lambda_{n,i,g} P_1(x) + \eta_{n,i,g} P_1(E)} \tag{2}$$

where $P_1(x) = \frac{2}{\Delta x_i}(x - x_i)$ and $P_1(E) = \frac{2}{\Delta E_g}(E - E_g)$ and $a_{n,i,g}$, $\lambda_{n,i,g}$, and $\eta_{n,i,g}$ are unknowns. The flux in a phase space cell of dimensions Δx_i by ΔE_g is determined and the dose rate in that cell is then calculated. In general the dose rate at a point x due to an n-type particle with energy E is simply the product of the particle's stopping power and its flux : $\dot{D}_n(x,E) = S_n(E)\psi_n(x,E)$. For tumor irradiation, a spatial distribution of the dose is desired and this is given by integrating $\dot{D}_n(x,E)$ over energy:

$$\dot{D}_n(x) = \int_0^{E_{\max}} S_n(E)\psi_n(x,E)\,dE \tag{3}$$

where $E_{\max}$ is the maximum particle energy. As configured at present, the ELDRHIT code describes the dose distribution for an n-type particle whose energy variable is separated into G groups, as a spatial average of the sum of the doses due to all energy groups in the i^{th} spatial cell or

$$\dot{D}_{n,i} = \frac{1}{\Delta x_i}\sum_{g=1}^{G} S_{n,i,g} \int_{x_{i-1/2}}^{x_{i+1/2}} \int_{E_{g+1/2}}^{E_{g-1/2}} \psi_n(x,E)\,dE\,dx \tag{4}$$

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where the stopping power is treated as a group constant. The total cell dose due to all particles is then determined by summing equation (4) over all particle species.

Using an exact solution of equation (1) for the projectile particle and an ED solution for the fragments, ELDRHIT calculations were compared with the results of Schimmerling *et al.* [5] The ELDRHIT calculations demonstrated excellent agreement with the experiment.[3] The dose distribution of the calculation corresponding to the Schimmerling experimental conditions is given in Figure 1. This calculation indicates that the dose due to all fragments represents approximately 16 percent of the total dose in the region of the neon Bragg peak. The fragments also deposit a noticeable dose beyond that point. A comparison of the ELDRHIT and Schimmerling flux distributions for the nitrogen fragments is given in Figure 2. Similar agreement for the flux was obtained for other particle species.

The agreement of ELDRHIT and Schimmerling linear energy transfer results shown in Reference 3 and the agreement of the particle flux distributions lead us to conclude that this method possesses excellent potential for use as a descriptor of dose distributions for relativistic heavy ion projectiles and their fragments.

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Figure 1. ELDRHIT Cell Average Dose Rate
(Schimmerling Problem)

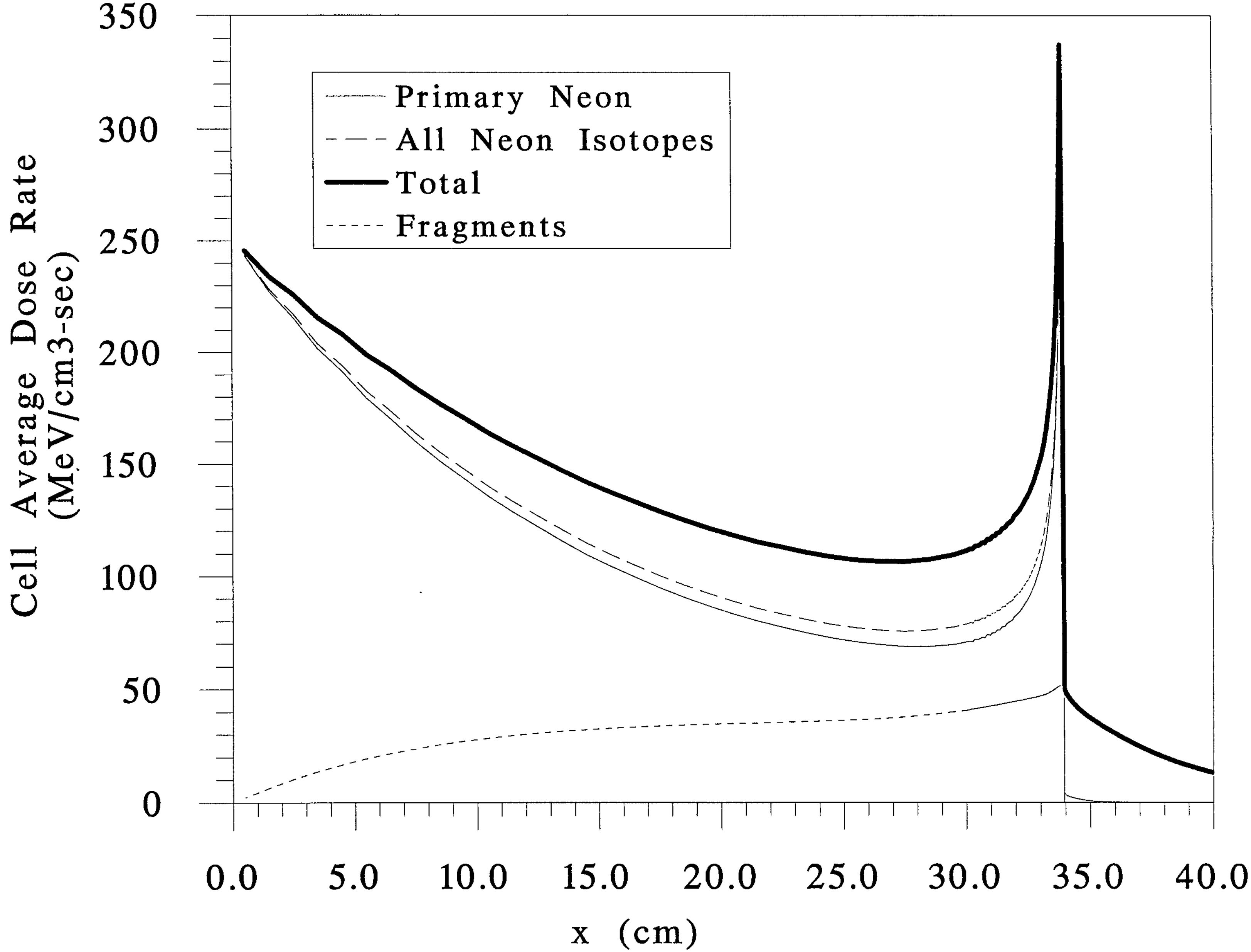
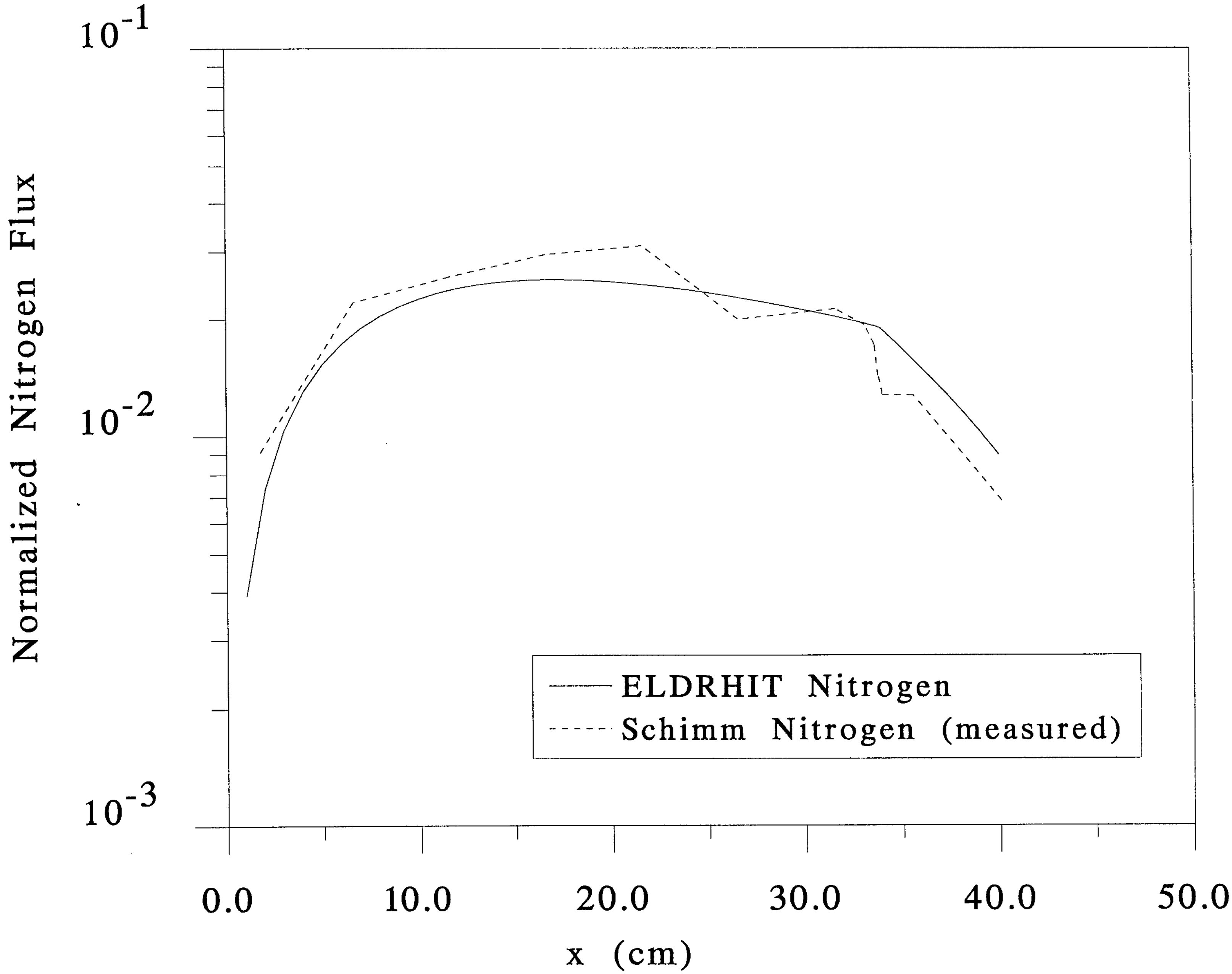


Figure 2. ELDRHIT-Schimmerling Nitrogen Flux Comparison



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