Particle Tracks and LET

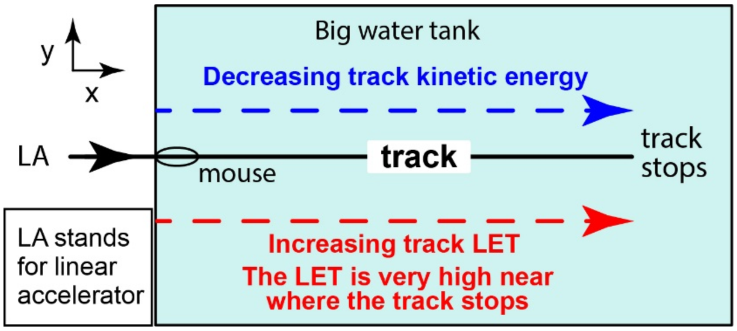
LET, *L*, is a basic attribute of a one-ion HZE beam. It is used in all our URAP models, it is used to help characterize all our data, it is central throughout radiobiology. Here is an attempt to give, for URAP purposes, the main ideas with a minimum of machinery.

HZE Ions

Recall that an HZE ion is, for us, a fully ionized atomic nucleus with given atomic number Z > 3, given atomic mass number u = [Z +(number of neutrons)], and with a given speed β greater than 30% of the speed of light. Its rest mass m is then m=u*(rest mass of a proton), the rest mass of a neutron being, to an approximation more than accurate enough for our purposes, the same as the rest mass of a proton. The relativistic kinetic energy KE is given by a formula that generalizes KE=(1/2)*m*v^2 of Newtonian physics. You can look up the formula but for our purposes we need only the following properties: (a) KE is a monotonic increasing function of β that starts from 0 at β=0 (and approaches infinity as β approaches the speed of light); (b) KE is directly proportional to rest-mass m. Incidentally, KE is usually specified in MeV, a non-SI unit such that 1 MeV = 1.6 * 10^-13 joules = 1.6 * 10^-13 J.

HZE Tracks

A very oversimplified model of an HZE ion track in a linear accelerator beam is a directed straight line segment of finite length, the direction being that of the accelerator beam. The track begins when the linear accelerator has brought the ion speed up to a predetermined value. For present purposes let us suppose the target is an enormous rectangular parallelepiped of water with one face perpendicular to, and centered on, the track (Fig.). As soon as it enters the target the ion starts to slow down because it imparts some of its kinetic energy to the target. To an HZE ion a mouse looks a lot like water, because mouse mass density is pretty close to that of water, so the figure also shows a part of the water tank which might almost as well be a mouse as far as track structure is concerned.



Linear Energy Transfer (LET)

With this oversimplified straight-line model of an HZE ion track, the HZE ion LET is the derivative -d(KE)/dx, where KE is the kinetic energy of the HZE ion and x is distance along the track (Fig.). Since the HZE ion is losing kinetic energy the LET is positive. By the definition as a derivative of an energy with respect to length, the dimensions of LET are energy/length. In radiobiology the units used are usually keV/µm. Here µm is an SI unit (micro-metres) and keV are related to SI units by 1 keV = 1.6 * 10^-16 joules. These are the units used in our scripts.

An aspect that confuses almost everybody at first is that LET increases rather than increases as the HZE ion slows down. The intuitive reason is the following. The main way the HZE ion gives energy to the water is by using its positive charge to yank electrons toward itself (often it yanks them out of their molecule, i.e. ionizes a water molecule). That energy has to come from somewhere and its source is the HZE ion, which loses an equal amount of energy. A highly energetic HZE ion is going so fast the water electrons don't have much time to gain energy before the HZE ion has whizzed right past, so the energy transferred per unit length (the LET) is comparatively small. Once the HZE ion slows down somewhat there is a comparatively long time for the electron yanking process to occur so the LET increases. Overall one gets a snowballing effect which brings the HZE ion to an abrupt halt at what is called the Bragg peak.

To calculate what the LET is for a given speed requires special relativistic quantum mechanics; for more on that look up the Bethe equation or the Bethe-Bloch-Fermi-Barkas equation or some similar name (a lot of people have worked on the equation). But in our projects we only need corresponding results that are available, e.g., by running NASA's GERM code or using the European Union's GEANT2 computational suite.

Stochastic Models

As an aside, a less oversimplified model of an HZE track is an axially symmetric marked stochastic point process, the points representing energy depositions with the amount of energy deposited at a given point given by its mark. In any one sample path of the stochastic process many thousands of pointwise energy deposition typically occur before the track stops. They do not occur on any straight line but for a typical sample path there is a region of very high point density, the track core, which is approximately a right circular cylinder. Examples are shown in the lower right corner of Fig. 1 and in Fig. 2 of the Ballarini .pdf. When using this stochastic model for tracks the corresponding picture of what LET is also becomes stochastic.

Such stochastic track structure models have gradually become ever more sophisticated and more important throughout the last hundred years. During the last half of the 20th century they were the most important physics research for the US and USSR. They now involve intensive ongoing research improvements by many groups world-wide using massive computer suites. They still attract very large funding by the governments of the major world powers and of some minor ones.