2. Beam Transport and Interaction with Matter

Chairmen: G. Bida (Los Angeles) and S.J. Heselius (Turku)

The topics to be discussed in the first part of the session on Beam Transport and Interaction with Matter are listed below in Table 1. In reviewing the available literature on some of these topics, it became apparent that the extent to which they are relevant to target design and performance was poorly understood. This is especially true of beam quality and beam transport. Thus, the purpose of this workshop will be best served by discussing some terms and concepts important to beam quality and transport and then to identify what parameters common to these topics are the most useful in the regard of target design. Similarly for beam diagnostics, suggestions will be proposed as to what are the most useful "probes" from a target design/production point of view. Finally, how beam extraction and hot atom chemistry are factored into our thinking on target design will be discussed.

Table 1.

Beam Transport and Interaction with Matter

- beam extraction
- beam transport/optics
- beam diagnostics
- beam quality
- hot atom chemistry

Figure 1 schematically represents the typical history of a particle beam as it is "messaged" upon exit from an accelerator and "probed" prior to impingement on a target. Normally, in designing a target for external use, the details of beam extraction are not an issue. This is usually left to the accelerator designer and our concern is that we have sample extracted beam with which to work. However, the emergence of small, negative ion machines may change our thinking in this regard.

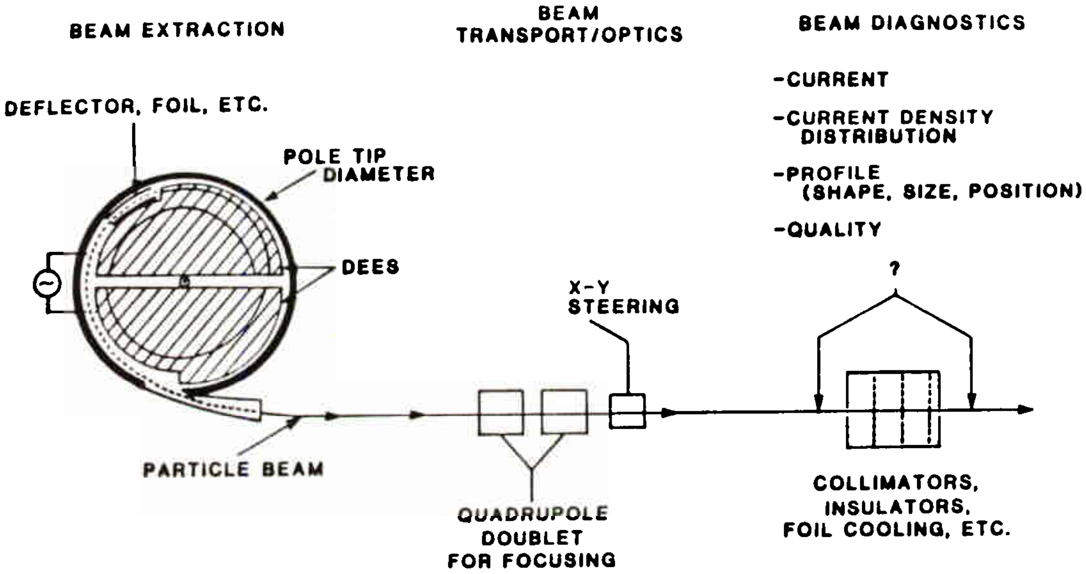


Figure 1.
Simplified schematic representation of typical beam preparation and diagnostic methods used in radionuclide production.

Beam extraction presents the most formidable challenge for cyclotron designers, especially for high energy positive ion machines. Useful high beam currents are strongly dependent on the success of beam extraction, known as the extraction efficiency. The methods in common use are summarized in Figure 2. These methods are amply detailed in the bibliography provided for this topic.

Some qualifying remarks concerning an earlier statement about negative ion machines are in order. From an extraction viewpoint, negative ion machines possess several advantages:

- minimum of extraction hardware, easier to tune and control
- normally 100% extraction efficiency
- easy energy variation.

More to the point of this discussion, the forces tending to disrupt beam quality are minimized for negative ion machines. In terms of optimizing radionuclide production, the point of beam diagnosis moves closer to the point of extraction. In turn, some of the considerations that go into beam transport and target design need to be re-evaluated and the heretofore avoidable area of beam extraction should be factored into optimizing target design.

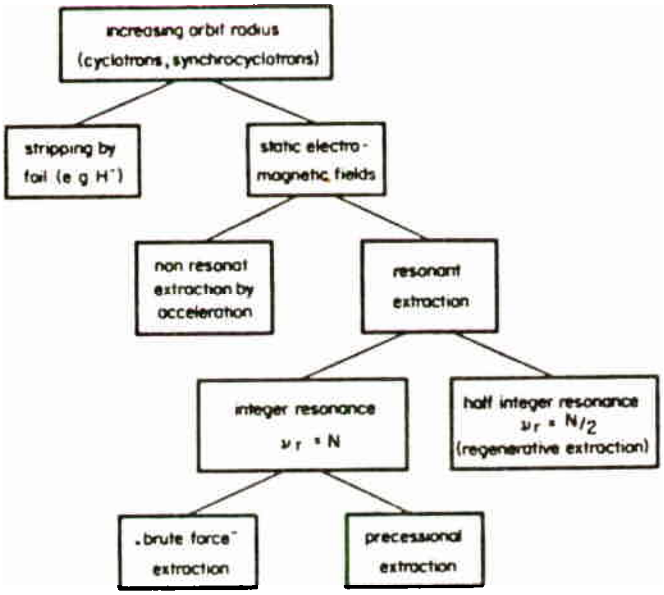


Figure 2.
Beam Extraction Methods (W. Joho <1>)

The topics of beam quality and beam transport are both rather involved and also intimately related. For the nuclear physics user of the cyclotron whose interest may involve the study of closely spaced nuclear quantum states, the issues of beam transport and quality are of great importance. Indeed, a knowledge of beam emittance is essential to the mathematical formalism used in designing and choosing beam preparation and transport systems. The treatment that follows has largely been adapted from Banford<2> and Livingood<3>.

A particle moving in a three-dimensional cartesian coordinate system is completely specified if we know the three coordinates x,y, and z and the three momentum components p(x),p(y), and p(z). This six-dimensional space is known as phase space. A beam is represented by a group of points in phase space, all of which lie within a six-dimensional hypervolume in phase space. Subject to certain restrictions, properties of this hypervolume are related to certain observable quantities. The restrictions are that:

- forces acting on the beam are conservative (work done by force on moving particles depends only on particles' initial and final states, not on the path taken)
- the three components of motion are mutually independent.

Under these assumptions, we state (without proof) that the volume enclosing the representative points of the beam in this phase space remains constant. Some further simplications can be made:

- axial (z motion) momentum remains constant in a beam line with no degraders
- here, the angular divergence of a particle relative to the beam axis is equal to the ratio of transverse to axial momenta.

Hence, we can replace p(x) by the angular divergence– x' (=d(x)/d(z)); similarly, for p(y). Thus, we now need only work in four–dimensional phase space in which the coordinates are x, x', y and y', i.e., displacement and divergence. We can now provide two important definitons:

- The volume enclosing the representative points of the beam in 4–D space divided by π^2 defines the emittance of the beam. The density of particles is called the brightness. Together, these parameters constitute what is known as beam quality.
- Beam transport is essentially the manipulation of phase space regions into shapes which represent the desired beam.

The emittance of a beam emerging from a circular accelerator is limited by the space available for axial and transverse oscillation during acceleration and by the extraction mechanism. A beam traveling between two obstacles under the action of a linear restoring force proportional to the displacement, x, from the equilibrium path is described by simple harmonic motion (see eq. 1 and Figure 3). Particles 1, 2, and 3 all have the same amplitude. If we trace out the various particles' motions in (x,x') space, the contour that results is an ellipse (see eq. 2–4).

$$\frac{d^2X}{dZ^2} = - X\,(2\pi/\lambda)^2 \qquad (1)$$

$$X = a\,\sin\,[(2\pi Z/\lambda)+\phi] \qquad (2)$$

$$X' = \frac{dX}{dZ} = (2\pi/\lambda)a\,\cos\,[(2\pi Z/\lambda)+\phi] \qquad (3)$$

$$(X/a)^2 + (X'\lambda/2\pi a)^2 = 1 \qquad (4)$$

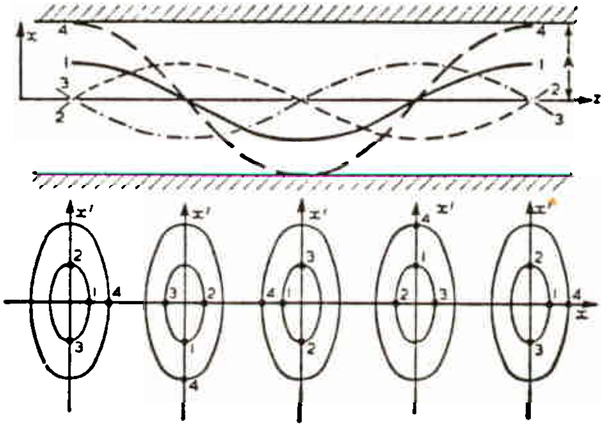
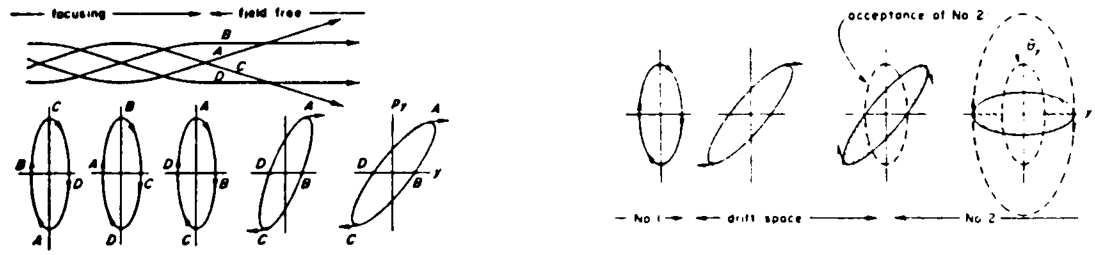


Figure 3.
Emittance from Cyclic Accelerators
(adapted from Fig. 2.5 of reference 2)

The concepts of acceptance and matching are illustrated in Figure 4. When a beam leaves a focusing region and enters a field-free region, known as drift space, each point in the phase space maintains a constant momentum (p_x) but moves parallel to the x-axis. The effect is a tilted ellipse resulting from shearing the upright ellipse horizontally. The area of the ellipse, however, remains constant. The term acceptance is complementary to emittance and refers to a piece of equipment rather than a beam. In order to achieve 100 % transmission of a beam, the emittance must be less than or equal to the acceptance of the apparatus in question. If such is the case, then the emittance of the beam is said to be matched to the acceptance of the device.



A) BEAM PROFILE IN DRIFT SPACE

B) DEVICE ACCEPTANCE & MATCHING

C) BEAM TRANSPORT VIA LENSES & DRIFT SPACE

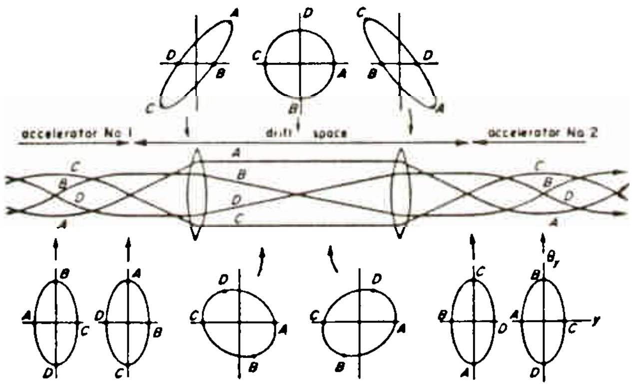


Figure 4.
Relationship between Emittance and Acceptance
(adapted from Figs. 15-13, 15-16, and 15-17 of reference 3)

When a particle beam moves from a field-free region back into a focusing region, the particles resume their sinusoidal motion and the limiting sheared ellipse appears to rotate as seen in the figure. Without appropriate optics, mismatch can result. In the bottom half of the figure, an example is given of how optics are used to transport a beam from one acclerator to another through field-free regions.

Emittance measuring methods usually consist of a pair of slits to define a displacement coordinate (x or y) followed by a means of detecting the range of angular divergences present at the chosen displacement. The quantity usually measured is the beam current. Phase space contours are then obtained by plotting data points of the same current intensity, such as shown in Figure 5. Equidensity contours of beam current for different fractions of the maximum current density are given for measurements in the horizontal and vertical planes. Typical emittance data are given in units of mm x mrad at a particular energy. Some thoughts on the utility of measuring the beam emittance are as follows:

- A quoted beam emittance, e.g. 30 mm x mrad typical for an AVF machine, is, at best, only qualitatively useful since it says little about the shape of the area (horizontal vs. vertical plane aside) having this dimension.
- Emittance is not a routinely measured or quoted parameter used in target design.
- Beam quality is sacrificed both axially (due to straggling) and transversely (due to multiple scattering) upon passage through degraders (or isolation foils).
- Energy changes associated with beam passage through degraders are not conservative. Hence, the beam emittance increases due to scatter.
- Sufficiently useful information can be obtained from current density distribution and divergence data without translating it into phase space plots.

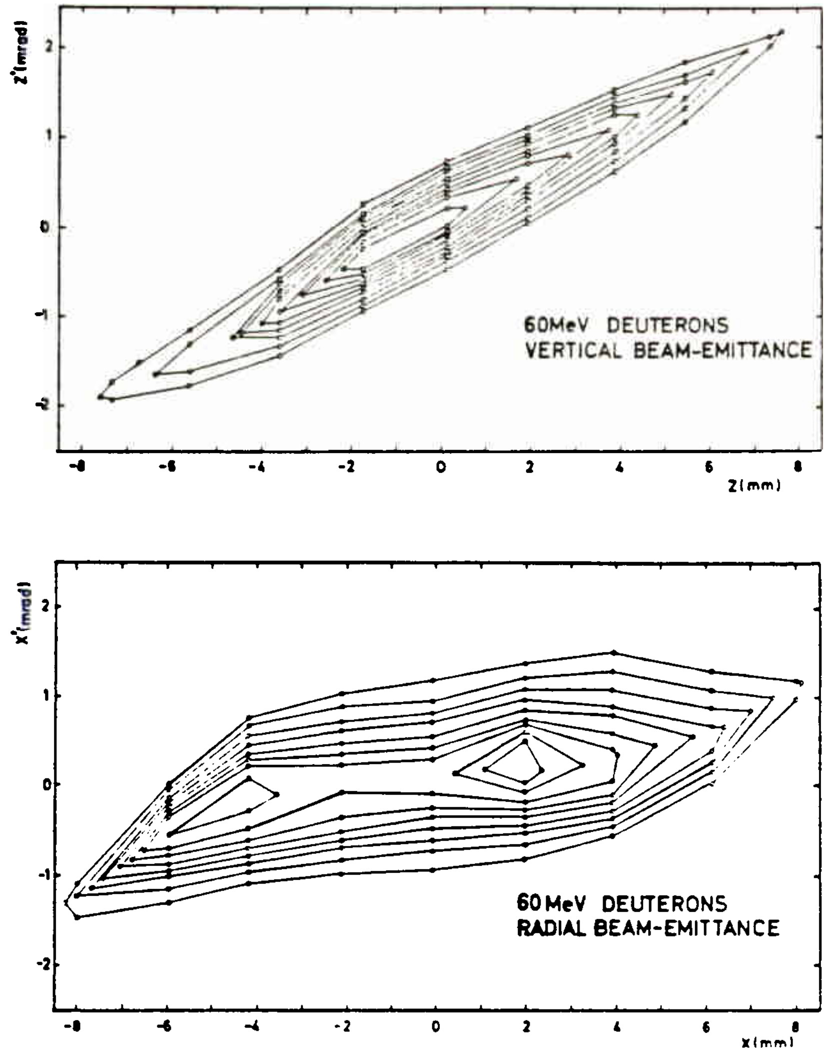


Figure 5.
Vertical and horizontal beam emittance patterns
(this is Fig. 5 of reference 4).

Beam diagnostics is also a diverse topic. For our purposes, diagnostics external to the acclerator are the main focus. In Figure 1 are listed the most useful parameters one might want to measure for aid in target design. Beam quality is included for those who might find it useful but, at the least, the beam's angular divergence should be measured. Some of these parameters may be useful in deciding collimator size, beam sweeping or steering conditions, etc. and certainly after introduction of degrader/isolation foils to determine what effect these may have on beam profile.

Now that the particle beam has been appropriately defined, we are ready to use it. Because of the energies involved subsequent to radionuclide production, an investigation of the product(s) resulting from the species generated in nuclear reactions are essential in determining if a desired final product or precursor has been made, and if so, how much and under what conditions. The field of hot atom chemistry, now 50 years old, has been thoroughly reviewed and detailed in the bibliography provided. However, the generation and reaction of hot atoms is not the whole story in radionuclide production. Some factors previously identified<5> are listed in Figure 6. One point that should be kept in mind is the dose delivered to a given system in a radionuclide production scenario. The result is in-target radiolysis that can sometimes lead to decomposition or unwanted secondary reaction of the primary adducts formed via recoil processes. A classical example of what can happen is the production of ^{11}CO and $^{11}CO_2$ in the $^{14}N(p,\alpha)^{11}C$ system<6>. For N_2 mixtures containing >5 % O_2, ^{11}CO is the major product with some % $^{11}CO2$ increasing with an increased total dose due to the radiation-induced oxidation of ^{11}CO. For these reasons, the scope of our experiments has to extend beyond the initial investigation of hot vs thermal (scavenger vs moderator) product distribution.

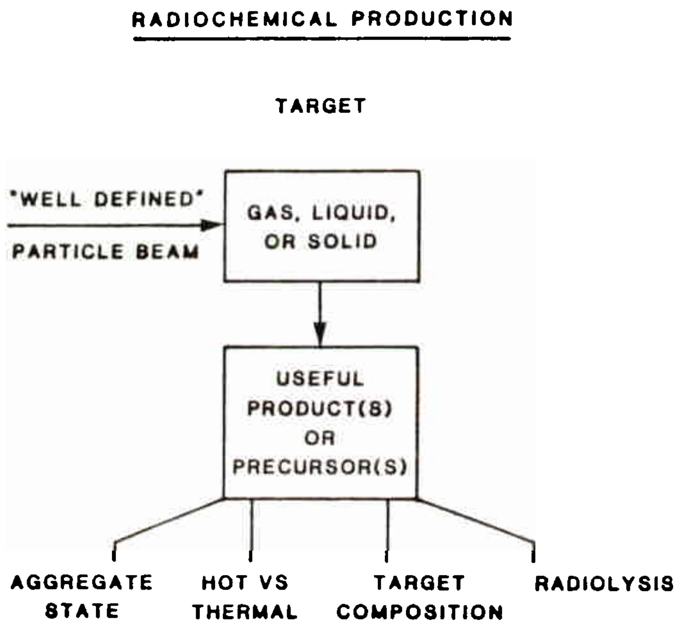


Figure 6.
Factors that can affect product distribution
during radiochemical production

References

1. Joho W., Extraction from Medium and High Energy Cyclotrons. Proceedings of the Fifth Int. Cyclotron Conference, McIlroy RW (Ed.), Butterworth & Co., London, 1971, pp. 159-179
2. Banford A.P., The Transport of Charged Particle Beams. E. & F.N. Spon Ltd., London, 1966, Chapter 2.
3. Livingood, J.J., Principles of Cyclic Particle Accelerators. D. van Nostrand Co., Inc., Princeton, N.J., 1961, Chapter 15.
4. Kuhlmann W., Bojowald J., Mayer-Boricke C. et al, An Automatic Beam-Emittance-Measuring Device for the Julich Isochronous Cyclotron (JULIC). Nucl. Inst. Methods, 80, 89-94 (1970).
5. Brinkman G.A., In-Beam Production of Labeled Compounds. Int. J. Appl. Radiat. Isot., 33, 525-532 (1982).
6. Ache H.J., Wolf A.P., The Effect of Radiation on the Reactions of Recoil Carbon-11 in the Nitrogen-Oxygen System. J. Phys. Chem., 72, 1988-1993 (1968).

Additional References

A. Beam Extraction

I. General

1. Harvey, B.G., The Cyclotron. Chapter I.B in Nuclear Spectroscopy and Reactions (Part A), Academic Press, New York, 1974, pp. 45-49.
2. Livingood, J.J., Principles of Cyclic Particle Accelerators. D. Van Nostrand Co., Princeton, N.J., 1961.
3. Joho, W., Extraction from Medium and High Energy Cyclotrons. Proceedings of the Fifth Int. Cyclotron Conference, McIlroy, R.W. (Ed.), Butterworth & Co., London, 1971, pp. 159-179.
4. Paul, A.C., Wright, B.T., Variable Energy Extraction from Negative Ion Cyclotrons. IEEE, NS-13, 74-83 (1966).
5. Martin, J.A., Beam Extraction from Sector-Focused Cyclotrons. Proceedings of the Int. Conference on Sector-Focused Cyclotrons and Meson Factories, Howard, F.T. and Vogt-Nilsen, N. (Eds.), CERN, Geneva, 1963, pp. 48-51.