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SYNCHROTRONS FOR HEAVY IONS - BEVALAC EXPERIENCE

H.A. Grunder, R.A. Gough, and J.R. Alonso

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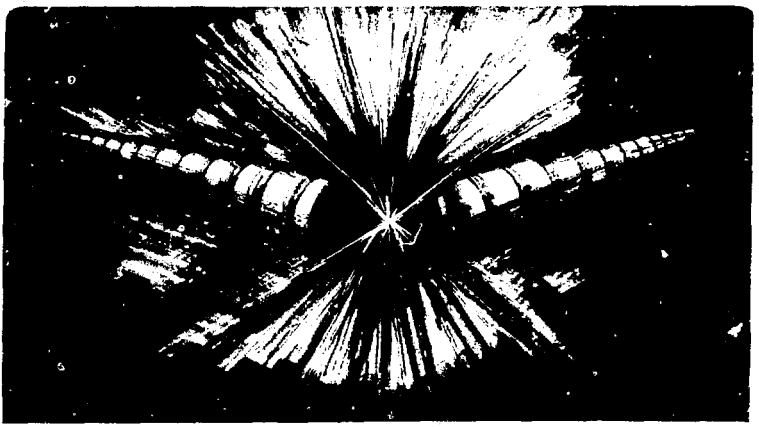

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Synchrotrons for Heavy Ions - Bevalac Experience[1]

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Introduction

The Bevalac is a remarkable machine, an excellent example of the adaptability of accelerator hardware to perform tasks its original designers never dreamed of. From the earliest days of GeV proton beams, on through to our present relativistic heavy ion capability the Bevatron/Bevalac has been a pioneering enterprise. We are now embarking on a new adventure, upgrading to a high intensity uranium capability, opening up yet another new field of physics.

Impressive as are its achievements though, perhaps the most valuable lessons to be learned today from the Bevalac as a heavy ion facility relate to new operational modes imposed by the requirements of our vigorous medical and nuclear science research groups. The Bevalac, then, should be viewed not as a model of accelerator hardware--a modern heavy ion complex will look quite different, but as a model for an operating versatile multifaceted, multiuser heavy ion facility. Of value to the planning of a new accelerator such as MARIA is the knowledge of operating modes peculiar to heavy ions and specific hardware requirements to carry out its mission with the mandated flexibility and reliability.

We shall address these questions in this paper, starting with a discussion of parameters and machine characteristics most suitable for medical and nuclear science applications.

Then we shall talk about our experience in interleaving these two research programs, and finally, we will concentrate on accelerator configuration questions; injectors, repetition rate, vacuum systems and cost criteria which will be relevant to the design of MARIA.

Specifications

Before discussing any specific details of accelerator design or technological options, let us first review the requirements of the research communities which will be using MARIA.

1. Biomedical Specifications

For biomedical research directed toward a clinical cancer therapy program, the mass and the range in tissue constitute the two primary specifications. Figure 1 shows the range-energy relationships for a variety of ion species. Since a penetration of 30 cm is sufficient to treat most human tumors, we see that an energy of about 825 MeV/amu is sufficient for ions up through and including argon, the heaviest particle for which any clinical experience exists. If we assume a 20% energy allowance for beam shaping and dosimetric devices, this energy is increased to approximately 1 GeV/amu. This estimate might be a bit conservative but this is a situation where extra reliability can be realized at little

additional cost. Note that the highest mass for a particular range has the highest rigidity, thus it will determine the accelerator size.

The intensities needed for biomedical applications are determined by the radiotherapeutic requirements for the treatment of large tumors. Table 1 shows the beam intensities required for a dose rate of 600 rad-liters/min in 1 liter volumes of different thicknesses. Based on clinical experience at Berkeley, this dose rate has proven adequate for the treatment of large tumors. Increasing these intensity specifications by a factor of two or three would seem prudent to ensure a high degree of operational reliability.

Table 1: Beam Intensities for 600 Rad-ℓ/Minute in 1000 cm^3 Volumes of Different Depths

	DESIRED BEAM INTENSITIES (Particles/Second)		
Particle	Area = 400 cm^2 Depth = 2.5 cm	Area = 200 cm^2 Depth = 5 cm	Area = 50 cm^2 Depth = 20 cm
π^-	2.0×10^{10}	1.44×10^{10}	7.0×10^{9}
Protons	1.35×10^{10}	9.5×10^{9}	4.5×10^{9}
Alphas	3.4×10^{9}	2.4×10^{9}	1.1×10^{9}
Carbon	6.7×10^{8}	4.5×10^{8}	2.2×10^{8}
Neon	3.0×10^{8}	2.25×10^{8}	1.0×10^{8}
Argon	1.1×10^{8}	7.8×10^{7}	3.8×10^{7}

Beam specifications to satisfy the biomedical requirements are summarized in Table 2 for charged particle beams of protons through argon. Here, the extracted flux has been increased to allow for some losses in the beam delivery system. It is to be noted that these fluxes do not exceed those typically observed in the Bevalac. Neither the transverse emittance requirements nor the acceptable momentum spread exceed values considered routine in any modern accelerator. Large duty factors are desirable for many of the beam delivery options.

Table 2: Summary of Beam Specifications for Medical Ion Accelerators

Particle	Extracted Flux (s^{-1})	T_{max} (MeV/amu)	ε (m Radians)	$\Delta P/P$	η
P	8×10^{10}	220	$\leq 2 \times 10^{-5}$	2.0×10^{-3}	>0.25
α	2×10^{10}	220	$\leq 2 \times 10^{-5}$	2.0×10^{-2}	>0.25
C	4×10^{9}	430	$\leq 2 \times 10^{-5}$	1.0×10^{-3}	>0.25
Ne	2×10^{9}	600	$\leq 2 \times 10^{-5}$	1.0×10^{-3}	>0.25
Si	10^{9}	750	$\leq 2 \times 10^{-5}$	1.0×10^{-3}	>0.25
Ar	10^{9}	825	$\leq 2 \times 10^{-5}$	1.0×10^{-3}	>0.25

Let us now digress momentarily to examine the choice of accelerator options to meet these specifications. We can quickly eliminate the cyclotron as a viable option for the main accelerator as follows. Even if we compromise the argon specification and require only a 20 cm range, a rigidity of approximately 9 T-m is needed. For a normal conducting

conventional cyclotron, this implies a pole tip diameter of over 9 meters. A superconducting cyclotron could reduce this diameter to perhaps 4 meters, but even this is more than twice the diameter (four times the size) of any facility either planned or under construction. A normal conducting, separated-sector machine, such as the massive GANIL cyclotrons would still fall markedly short of meeting even the 20 cm argon beam specification. From this example, it is clear that either a linac or a synchrotron will be the only realistic alternatives for MARIA.

2. Physics Specifications

To establish the specifications for an accelerator capable of providing useful beams to the physics community, it is interesting to review briefly some of the major physics facilities in operation or being planned around the world. Figure 2 shows the mass-energy performance curves of selected accelerators. The two synchrotrons, the Bevalac and Saturne II, are the only existing accelerators which can meet the specifications that were established above for biomedicine. In the lower energy portion of this figure, some interesting comparisons can be made regarding the choices for an injector. The linac is seen as providing the broadest range of ion species when compared to either established cyclotron technology or state of the art electrostatic machines.

It is also interesting to examine the areas now being explored by the world physics community as to the directions where exciting heavy ion physics will be found. Figure 3 shows a heavy ion reaction "phase diagram" which summarizes some of the characteristic features of various nuclear reaction mechanisms. The major reaction processes are shown in relation to incident energy and impact parameter, which form the coordinates of the phase diagram. The upper boundary is determined by the constraint $\pi (R_1+R_2)^2(1-V/E)$, where V is the Coulomb barrier in the incident channel. Central collisions leading to fusion are found in the lower left portion of the diagram. Deeply-inelastic scattering processes and ultimately simple transfer reactions resulting from grazing collisions occur at higher impact parameters. As we look to higher incident energies, these processes evolve into a peripheral, spectator-participant mechanism and the violent total explosions which occur in central collisions of relativistic heavy ions. The exact location of the boundaries which delineate these various mechanisms is not well known and is an interesting area for future research.

The basic parameters given before for MARIA, designed to satisfy radiotherapy needs will provide a machine suitable for exploring not only these most interesting areas of nuclear physics, but also a myriad of other disciplines, from atomic physics and production of exotic new isotopes to cosmic ray

physics, from biophysics to tomographic imaging and heavy ion radiography. All that is needed is to plan for sufficient versatility in particle species, energy and beam quality, and an adequate control system to provide the required flexibility without sacrifice of the reliability mandated by the therapy program.

Operational Considerations

Experience at the Bevalac in running just such a multifaceted program as described above has yielded some interesting insights.

1. Scheduling. Conflicts must be resolved between nuclear science experiments, where large uninterrupted blocks of beam time are most desirable, and radiotherapy, which demands fixed time slots each day.

2. Flexibility versus efficiency. Radiotherapy has required the same beam and energy each day, while other users' needs most always call for different conditions. Thus to make use of the hours between therapy runs, at least two machine retunes must be performed. Demands for such frequent changes led initially to increased maintenance problems and an unacceptably high fraction of total tuning time. Operational experience and control system upgrades have been a key to overcoming these problems in our present operation.

3. Multiplicity. The concept of multiplicity, delivering beams simultaneously to more than one experimenter takes on a new dimension in a heavy ion facility because seldom will one find two users desiring identical ions and energies. Beam splitting under these circumstances has been used mainly for parasitic running; beam line tuning, equipment testing, and experimental setup. The prime consideration in Bevalac operations has been to reduce time delay between experiments, concentrating on fast switching between different accelerator configurations. Our most notable success in this area occurred this summer, when in a period of 3 days we ran six different ion species to 3 different experimental setups: nitrogen-15, helium, carbon, argon and iron for nuclear science, and silicon for radiobiology; the last four switches occurring during a 12 hour period. The integrated switching and tuning time for all these modes was around two hours.

The key concept, then, for running a successful program at a heavy ion facility is flexibility. The ability to call up beam sharing modes, by either spatial or time splits (Figure 4), underneath prime users, or to accelerate different ions on different pulses (Figure 5) is of paramount importance for good utilization of the available resources. One mode used very successfully at the Bevalac arises from the pattern of beam use in therapy. Treatments take from one to two minutes of beam time, while patient setup and alignment requires typically half

an hour. Rapid switching of beam lines allows us almost uninterrupted radiobiology running, with only an occasional loss of beam during actual treatments. Switching recuires about one minute each way. All magnets are cycled to high currents then allowed to settle slowly to their tuned values. Our experience has been that beam alignment reproducibility is better than 1 mm, so bringing the switched beam directly into the pre-positioned patient is no problem.

This mode of operation is possible even for as large a facility as MARIA, servicing four or five treatment rooms, since substantial time will still be available for the continuous user. With a suitable control system and accelerator configuration the switch need not be restricted to the same particle-same energy, so that the continuing experiment can be totally independent of the ongoing therapy treatments, and each program is almost transparent to the other. This is the ideal that a modern heavy ion facility should strive for, and what is most important, it is within the realm of present-day technology to achieve it.

Keys to meeting this goal are;

1. Control system, with sufficient capacity and speed to switch the hundreds of machine parameters that must be changed for different modes. (At the SuperHILAC this switching occurs in a few milliseconds, with time sharing capability between four different modes.)

2. Precise control of magnets and other sensitive parameters to ensure precise reset'ability to the tuned values. This may require magnet control through magnetic field values (NMR, for example) rather than magnet currents.

3. Operator-control system interface, to ensure operational smoothness, keep tuning time to a minimum, and reduce chances for operator error.

4. Beam monitoring. An extensive monitoring system is needed to ensure beam integrity at all experimenter sites.

5. Reliability-diagnostics. Monitoring and control of every free parameter is of utmost importance. Experience indicates that a lack of reproducibility in an operating mode can generally be traced to inadequate or incomplete monitoring. Such thorough monitoring allows also for rapid pinpointing of equipment failure, saving valuable time in tracing faults.

6. Careful experimental area layout, to allow for maximum utilization of shared beams.

7. Dual injectors allow for redundancy, hence increased reliability for critical operations, but also allow, when tuned with different ions, for very rapid switching between ion species in the accelerator.

Accelerator Technology Relevant to Heavy Ion Synchrotrons

Selecting an optimal parameter set for a heavy ion synchrotron requires careful examination of a number of very different factors.

1. Vacuum Requirements

The biomedical specifications for MARIA by themselves require beam intensities and energies which will compete internationally with the most advanced heavy ion facilities now under construction. Consequently, it would be inadvisable to limit the synchrotron in any way which would make future retrofitting for higher masses (A greater than 40) difficult. In this regard, the vacuum system needs to be carefully specified. Assuming an injection energy of 5 MeV/amu and a $d/dt(B\rho) = 150$ T-m/sec, a vacuum in the 10^{-8} to 10^{-9} Torr range will be adequate to accelerate $^{238}U^{50+}$ with minimal losses. The interrelationship of injection energy, tank pressure and mass can be seen in Figure 6(a), (b) and (c). These figures have been prepared from calculations based on charge exchange cross section data which are not always well known, but which give a reasonably accurate quantitative picture of vacuum requirements. By 1981, experimental data from the Bevalac will be available permitting more accurate information for future planning. At that time, with the completion of the Uranium Beams Project, charge exchange losses down to pressures of 10^{-10} Torr can be determined. In any event, the qualitative trends from these figures is certainly clear, it is entirely reasonable to plan for the acceleration of partially stripped heavier ions.

Note that for the acceleration in the synchrotron of any given mass the charge state, and hence the final maximum energy, is implicit in the choice of injection energy, since the number of electrons which can be stripped from an ion passing through a foil depends on the ion's velocity. Thus for 3 MeV/amu uranium ions one might have 40+ as the mean charge emerging from the stripper, while at 8 MeV/amu the mean charge would be 65+. The lower charge-to-mass ratio at the lower injection energy leads to a more rigid beam, hence to a lower energy at the highest accelerator field.

A point which emerges from these considerations is that once a high vacuum system (10^{-8} to 10^{-9} Torr) has been specified, it becomes possible to accelerate partially stripped lighter ions (A less than 40) with minimal intensity losses. Then the user requirement for a slow, uniform spill might be met using a stripping extraction scheme.

2. Beam Intensities, Repetition Rate and Cost

Another consideration which is not specifically a subject of this paper, but which should be a key issue in these deliberations, is the injector. The versatility and reliability of the overall facility will depend crucially on the design choices that will have to be made. The design team should be aware that the injector will be one of the toughest problems.

In our specifications we concluded that a beam intensity of around 10^9 particles per second was satisfactory if obtained in a reliable fashion. The available injectors for heavy ions do not have an adequate brightness to allow single turn injection. However, injection over 25 to 50 turns can be realistically studied in a synchrotron designed for this purpose. Allowing for the usual losses in stacking (0.5 - 0.8), RF capture (0.5 - 0.7) and extraction (around 0.5), it is possible to calculate the number of extracted particles per pulse per particle microampere (pμA) injected. From the above numbers, we get an extracted flux of roughly 2×10^8 particles per pulse per pμA injected. Let us assume for now a repetition rate of 2 Hz, so that our injector has to deliver 2.5 pμA to achieve an extracted flux of 10^9 particles/second.

The intensities presently available at the SuperHILAC are shown in Figure 7. Also indicated are the intensities expected when the third injector comes on line. It should be noted, however, that this performance is not indicative of the full potential of a Wideroe/Alvarez linac system. This is because through historical constraints at the SuperHILAC the beam is stripped twice leading to an intensity loss for the high masses of about a factor of seven. The upper curve in Figure 7 shows what could be achieved with only one intermediate stage of stripping. It can be seen that very substantial fluxes can be obtained up to mass 150. Beyond mass 200, however, attaining very high beam intensities becomes more challenging.

In the above example, a repetition rate of 2 Hz was assumed. Synchrotron technology is well developed, and any choice of repetition rate up to 60 Hz is technically achievable. Usually, a high rep rate is chosen in situations where high beam intensity is at a premium. The choice of rep rate for MARIA will be governed in large measure by cost considerations. Figure 8 gives an example of cost optimization for synchrotron components assuming a fixed injection energy, injector current and brightness. This example does not take full account of all the MARIA specifications, nor does it consider the impact of the injector. It does, however, serve to illustrate the elements which must be evaluated in considerable detail as the design process evolves.

Figure Captions

1. Range-energy curves for ions to mass 40. The horizontal line indicates the energy necessary for each ion to penetrate to a depth of 30 cm in tissue. Note that an accelerator built for 30 cm argon (825 MeV/amu) will deliver lighter beams with substantially longer ranges.

2. Machine parameters for various heavy ion facilities, existing and planned. The relevant areas for MARIA are presently accessed only by the two synchrotrons, Saturne II and the Bevalac.

3. A heavy ion reaction phase diagram which depicts the characteristic processes occurring in different regions of impact parameters and incident energy space. The boundaries between the regions are not well known experimentally. The transition from low energy equilibration processes to high energy fast abrasion processes is illustrated schematically.

4. Beam sharing concepts for heavy ions. Spatial splitting by means of a septum magnet conserves duty cycle but restricts both users to the same ion at the same energy. Time

splitting sacrifices duty cycle, but allows for energy independence by extracting the beam at different field values for different experimenters (2b).

5. The most desirable beam sharing concept for heavy ion accelerators, delivering different particles at independent energies to each user. This mode provides for the greatest freedom between experimental programs, at the cost of some loss in duty cycle.

6. Survival curves for heavy ions for different injection energies at synchrotron pressures of a) 5×10^{-8} Torr, b) 1×10^{-8} Torr and c) 5×10^{-9} Torr. At 5×10^{-8} Torr even argon capability is not possible without a very high injection energy, but at 1×10^{-8} Torr a more modest 5 MeV/amu injector ensures adequate survival of even the highest mass ions. For a reasonable margin of safety, pressures of the order of 5×10^{-9} Torr should be planned for.

7. Beam intensities available from the SuperHILAC at present, and with the Third Injector. This injector, designed for much lower charge to mass ratio ions, will substantially boost heavier ion outputs. A principal source of loss with very heavy ions is stripping, since only one charge state

of the very many produced can be accepted for further acceleration. Presently two stripping stages exist at the SuperHILAC. The uppermost curve shows the beam intensities to be expected if the SuperHILAC were redesigned to produce the same final energy with only one stripping stage.

8. Cost optimization for synchrotron components with respect to repetition rate. Such analyses of the interrelationships of accelerator design variables are used to optimize the design specifications of a new facility.

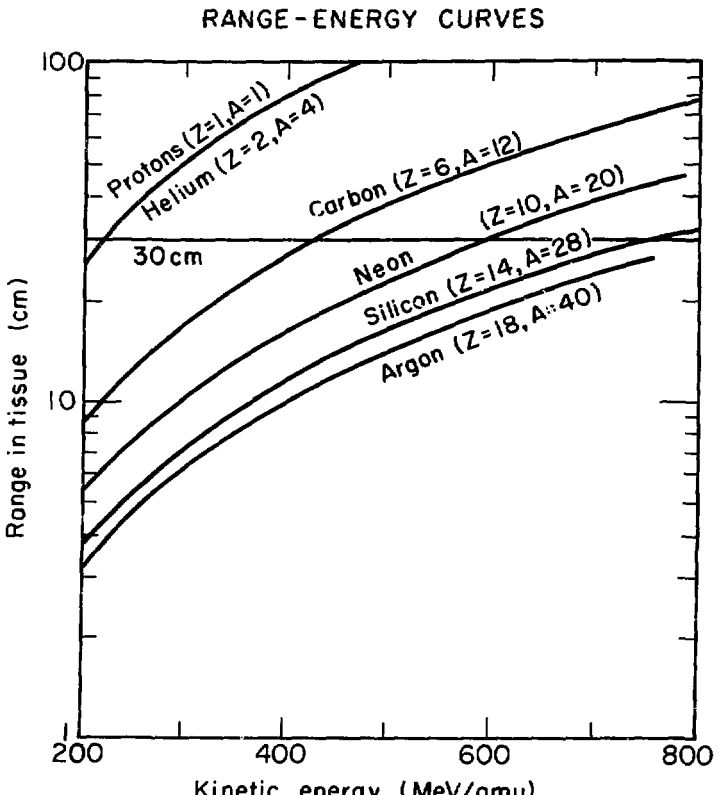

Figure 1

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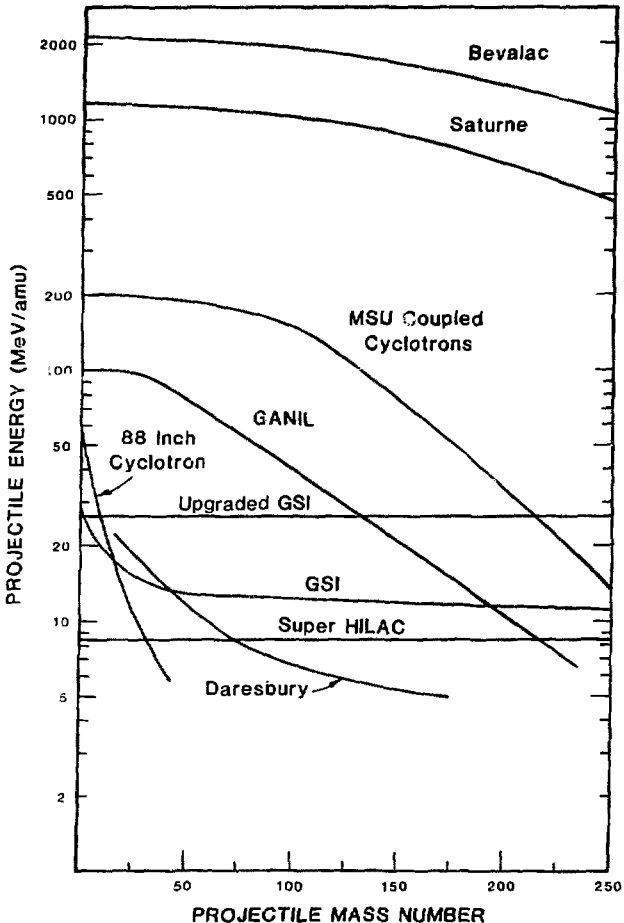

Figure 2

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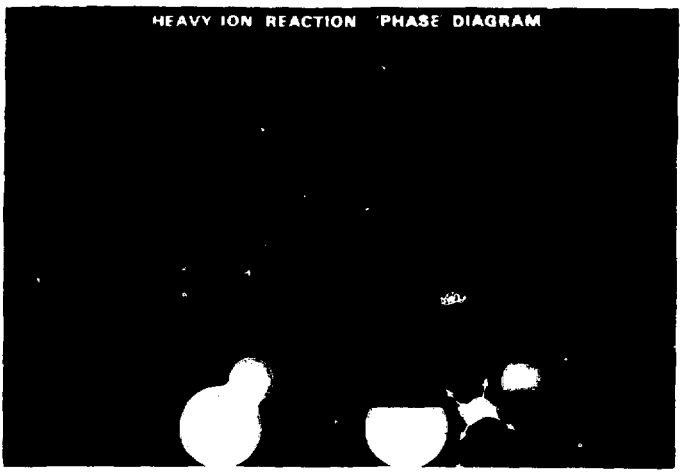

Figure 3

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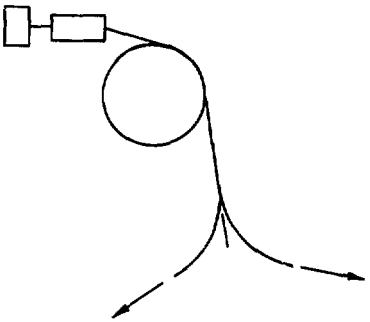
1. SPLITTING IN SPACE

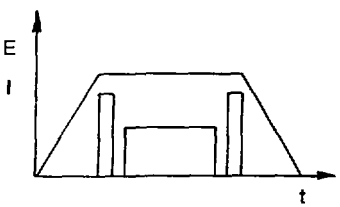
SAME PARTICLE
SAME ENERGY
SAME DUTY CYCLE



2. SPLITTING IN TIME

a { SAME PARTICLE
SAME ENERGY
SHARED DUTY CYCLE

b { SAME PARTICLE
DIFFERENT ENERGY
SHARED DUTY CYCLE



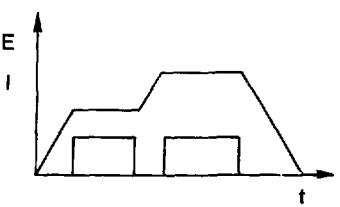


Figure 4

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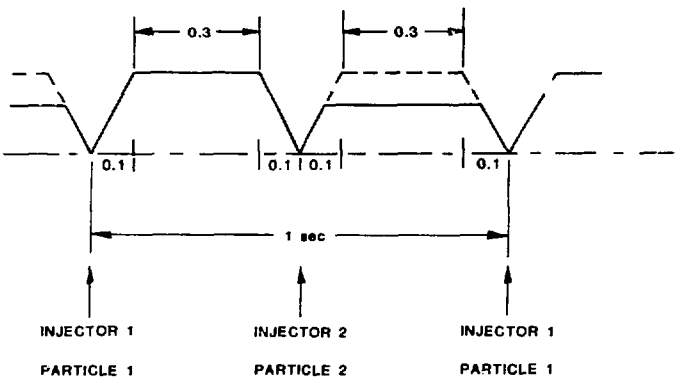

Figure 5

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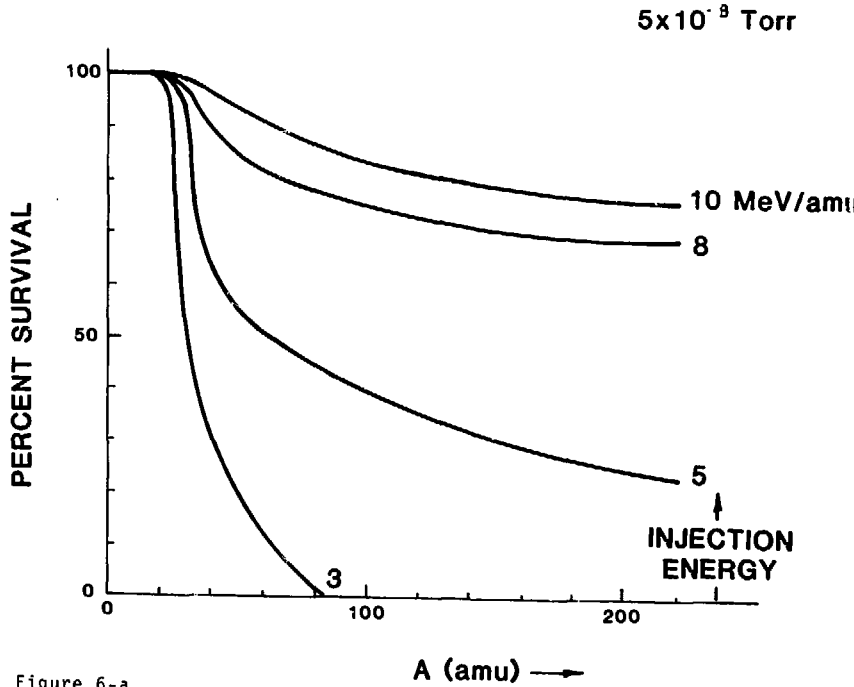

Figure 6-a

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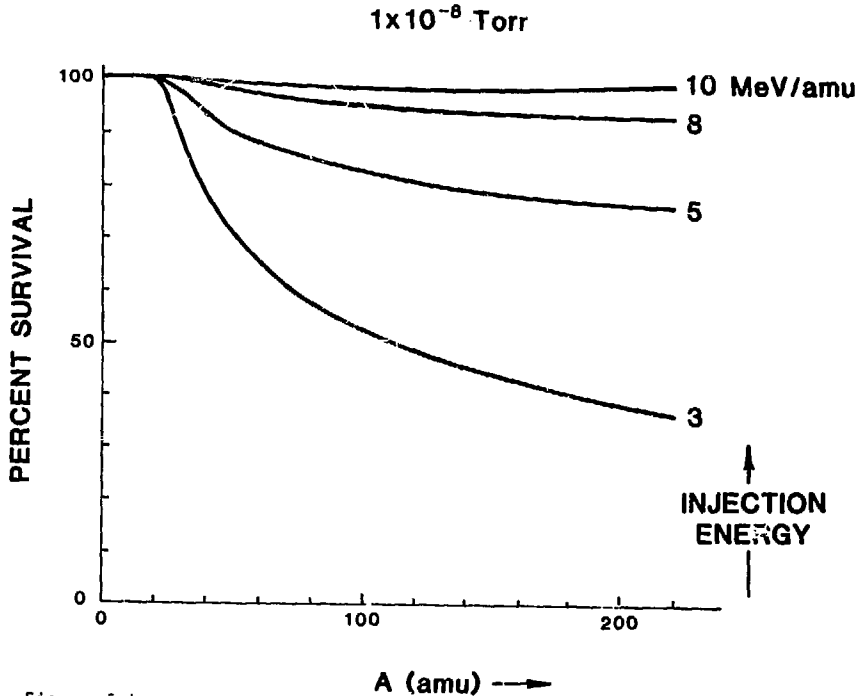

Figure 6-b

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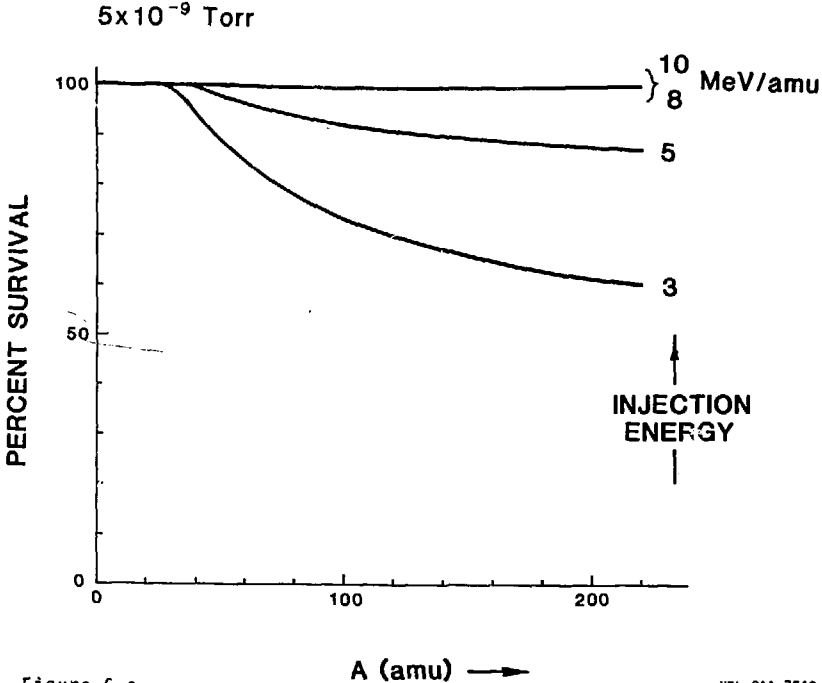

Figure 6-c

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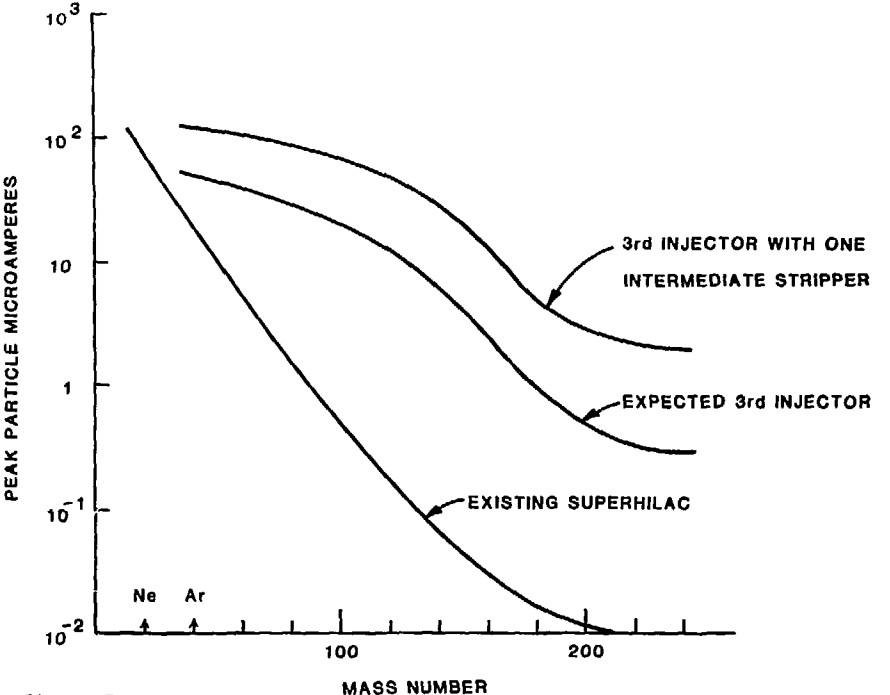

Figure 7

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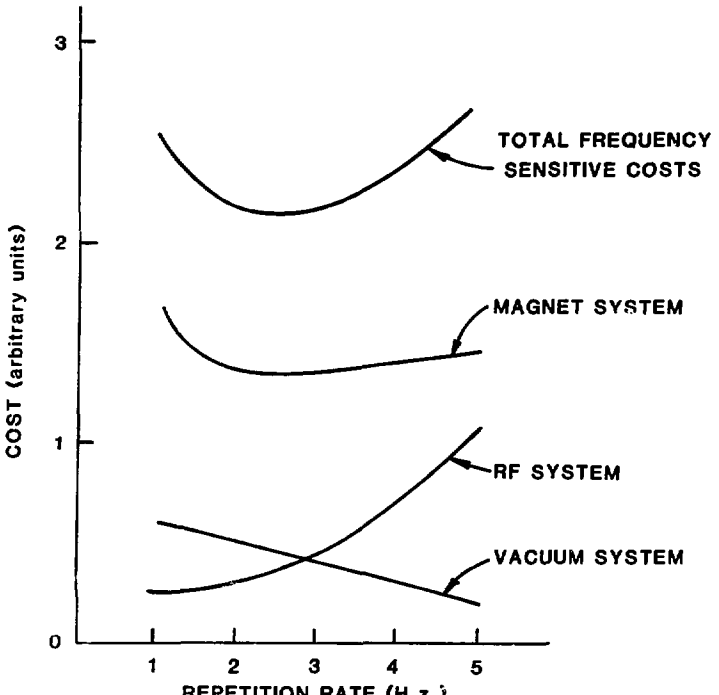

Figure 8

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