A HOSPITAL-BASED PROTON MEDICAL ACCELERATOR*

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My goal in the design of a medical accelerator is to focus on one that would be suitable for general use in a hospital or clinical setting rather than one that might be more appropriate for large dedicated medical centers. This choice is based on the belief that if protons were generally available in hospitals, and as convenient to use as any other method of radiation treatment of cancer, then protons would prove effective for treatment of many more cancer sites than is the case today. I am under no illusion about the amount of R&D and length of time required to demonstrate that protons are at least as good as present methods for treatment of tumor sites for which they have not yet been used. In the long run, however, I think protons will take their place in hospitals along with electron beams to give the physician a wider choice in the treatment of cancer.

To achieve this goal, minimizing the construction and operating cost of the accelerator and its transport and beam delivery system is very important, simplicity and reliability are essential, and the flexibility and ease of use of the entire system are very important. The latter places a strong emphasis on being able to safely and inexpensively transport 250 MeV proton beams in order to provide for several different treatment rooms, each of which might have different characteristics, including at least one with beams from more than one direction.

It would be highly desirable to be able to scan the proton beam across the two transverse dimensions of the treatment volume, and to scan in depth by varying the proton energy from the accelerator on a pulse-pulse basis. This procedure would not only allow 3-D contouring of the volume treated but could, theoretically, make use of 100% of the accelerated beam for treatment. If so, it would reduce the cost of the accelerator, and also reduce the amount of shielding required around the accelerator, the

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transport lines, and the treatment areas. It would, however, require slow extracted beams with uniform and precisely-controlled current. I believevthe latter can be achieved in a reliable way by accelerating H^- ions and extracting protons by stripping the electrons from the proton in a very thin foil. This charge-exchange extraction technique will be explained later.

Another very significant advantage of a slow extracted beam relates to the resulting high beam quality. The required aperture and number of focusing elements in the transport system are reduced. In addition, the low average beam current leads to reduced shielding requirements on the transport line. These points will be discussed further in a later section.

Simplicity and reliability of the accelerator system are enhanced by the following choices:

1. Single turn injection.
2. Slow acceleration of H^- ions to 250 MeV.
3. Low space charge tune shifts.
4. Currents considerably below instability thresholds.
5. Utilizing charge-exchange extraction.
6. Conservative design of all components.
7. Avoiding technology unsuited for hospital operation.
8. Good diagnostics, control, and alignment procedures and equipment.

The process of transmitting H^- beams through very thin foils to remove the 2 electrons and change the ions into protons is quite common in the worldwide accelerator community today. The technique is in daily use (when the accelerators are operating) at Argonne, Fermilab, Brookhaven, KEK (Japan), and Rutherford (England). At all of these laboratories charge-exchange is used at injection into a circular machine in order to overcome, in a simple way, a fundamental injection limitation. It seems essential in order to achieve high circulating currents in small accelerators (the practical development of this technique was undertaken to accomplish this with the Argonne Rapid-Cycling Synchrotron, a 500 MeV, 30 Hz, proton accelerator with an average current of 12 µA, operating with the Intense Pulsed Neutron Source). However, the performance of larger accelerators has sometimes been improved by this technique, resulting in increased beam currents and greater reproduceability on a pulse-pulse basis.

For the proton accelerator concept presented here, however, injection is very straightforward and simple. On the other hand, achieving an extracted beam of uniform current over a long period of time (the ions circulate about 2 million times around the ring in 0.4 second) is more difficult. Here I propose that H^- charge-exchange extraction will simplify achieving this goal, and perhaps lead to the equivalent in improved performance already seen with charge-exchange injection.

The acceleration of H^- ions, which appears highly advantageous for the extraction process, introduces two technical requirements that are quite different than if protons were accelerated. The first of these is a much higher vacuum requirement (estimated at 10^{-10} torr) in order that the ions not lose their electrons in collisions with residual gas atoms. I believe that this vacuum requirement can be met in a reliable and straightforward way by the use of newly-developed Zr-Al getters. The vacuum system will be discussed in more detail later.

The second technical requirement related to the choice of H^- ions is the limitation to a maximum magnetic field in the accelerator of 6 kG or less. At higher fields, at the full proton energy of 250 MeV, the magnetic field would be sufficient to separate the electrons, and the ions would be lost. The relatively low peak field implies a diameter of approximately 40' for the main accelerator. This size could appear to be a serious drawback to the proposal of retrofitting proton therapy facilities into existing hospital space. However, if one can achieve transport of the proton beam as simply and inexpensively as appears possible, then locating the accelerator in any available space, such as in a basement or under a parking lot, would be feasible. Such transport systems are simplified by high beam quality (to minimize both the number and aperture of transport elements) and the low peak currents of slow extracted beams (to minimize shielding requirements). Both of these beam characteristics can be achieved in a simple manner by charge-exchange extraction of circulating H^- ions.

This method of extraction is so simple, requiring only a properly-placed foil and a pair of orbit-controlling magnets, that extraction from many points around the ring is feasible. In my design, I propose to provide for extraction from all 8 straight-sections of the ring, and to utilize extraction at any desired energy, including the injection energy, as a diagnostic tool to measure the properties of the circulating beam. These individual extracted beams can terminate in a shielded beam dump, or they can be transported for treatment or other use. Figure 1 shows a possible layout of several extracted beams. The beams at the top and bottom of the sketch might be bent upward (e.g., if the accelerator were in the basement) for directing the beam into one of any number of treatment rooms. The number of treatment rooms is only limited by the number that can be efficiently utilized, which might most strongly depend on how much setup time is required for a given treatment. If this time can be reduced by improved beam characteristics, then more efficient use of the accelerator might result in lower cost treatment. The 3 beams (from 2 extraction points) in the lower left of the sketch are intended to illustrate a possible layout to provide 3 radiation fields, at least 1 of which should be vertical, in a single treatment room. The desirability of the latter was pointed out to me by John Archambeau of Loma Linda Univ. The 3 beams in the upper right would be provided for a number of purposes. One important use would be to have the accelerator operating continually, even when not delivering beam for treatment. Thus the operational status of the accelerator would be known at all times. Other uses of these test beams might be to develop new techniques, improved characteristics, or other development of the medical capability. In addition, there could be other important physics uses of the beams, such as proton-induced x-ray studies.

Also shown in Figure 1 are a few of the parameters of the accelerator design. Note the low requirements on the H^- source, 1 mA for 1 μsec, the small space charge tune shift at injection, and the low RF voltage requirements. These low values might indicate that the design is not optimized; no attempt has been made to optimize the parameters, or to produce an engineering design. The maximum beam amplitude (the beam diameter is twice this value) decreases from about 1 cm at injection to 3 mm at the full energy of 250 MeV.

As an injector for the accelerator I would choose one on which the performance and reliability have already been demonstrated, and the cost is known and reasonable for the purpose. One such accelerator is the Model 5SDH Pelletron Accelerator produced by the National Electrostatics Corp. It is a small tandem accelerator with 1.6 MeV on the terminal. It is a proven machine, having been used industrially for a few years, and the price of the accelerator without source was quoted in August, 1984, as \$100K. While it is normally run with much lower currents on a DC basis, there seems little doubt that it could handle the short duration beam currents suggested here. The H^- ion source would have to be mounted in the terminal, but I do not believe there would be any problem with source reliability at the low duty cycles required.

Protons could also be provided by this injector system (and at higher injection energy) for direct proton acceleration. An H^- source at the input end of the Pelletron, with stripping in the terminal, would produce proton beams of 3 MeV. The accelerated current with this injection energy could be 2 times higher, but a different technique for extraction would be required.

Initial ideas of the magnet cross-section are shown in Figure 2. I have chosen a large number of short magnets (8 per octant, or 64 total for the ring) in order that they can be straight magnets for ease of fabrication, and because only a short magnet length can be tolerated after the stripping foil. Other choices could be made and might be better for different reasons. The low required magnet power and cooling for this magnet at 1 Hz means that the magnet could easily be designed to operate at 10 Hz.

A sketch of the vacuum chamber design is shown in Figure 3. Here the octant chamber would be curved to avoid a large number of welds, which seems prudent since the required vacuum is high. The 8 straight magnets would fit over this curved vacuum chamber with a sagitta of about 1/2 cm, quite adequate in view of the large horizontal dimensions of the chamber. The circulating beam does not use a very large part of the horizontal aperture. The proton beam after the foil, however, moves outward by 4 cm in the final magnet before the straight section. The key to attaining a very high vacuum in a reliable way are the Zr-Al getter strips shown here on the inside radius of the vacuum chamber, out of the way of the circulating beam. Properly conditioned, a 2 cm wide strip will have a pumping speed of 200 liters/sec/meter of length. This should be adequate to hold the pressure of the chamber shown (baked before installation) below 10^{-10} torr with sufficient margin of safety. The system needs ion pumps at the straight sections to pump methane and the noble gases. The eddy current fields and heating in the 1/8" stainless steel chamber will not be a problem at the 1 Hz repetition rate. At higher repetition rates such questions will have to be examined more carefully.

As an exercise, because the vacuum system is one of the more expensive parts of this accelerator concept, an initial estimate of the cost of the vacuum system equipment is also shown in Figure 3. This estimate does not include contingency or EDIA (engineering, design, installation, and administration).

Figure 4 shows the variation of the horizontal (x) and vertical (y) amplitude around the ring at injection (1.5 MeV). Also shown is the horizontal displacement for a momentum error of 10^{-3}. The abscissa goes from the center of one octant at the left, through 4 bending magnets, a straight section containing a horizontally-focusing quadrupole followed by a defocusing quadrupole, and 4 bending magnets to the center of the next octant. This arrangement is shown schematically at the bottom of the Figure.

A schematic of the stripping extraction is shown in Figure 5. The foil, of thickness of perhaps 100 $\mu g/cm^2$ (Argonne uses foils of 50 $\mu g/cm^2$ for injection at 50 MeV; Fermilab uses thicker foils for injection at 200 MeV.), is located between the last two bending magnets of the octant. The horizontal position of the beam at this position is precisely controlled by two weak magnets, located in straight sections before and after the extraction straight section, with feedback from extracted beam current monitors. Only the extreme outer edge of the circulating H^- beam is brought onto the foil. Ions which penetrate the foil lose their 2 electrons (with very high efficiency, approaching 100%). The protons then bend the opposite direction from the ions in the following magnet and come out of the machine in the straight section. They receive an additional angular kick from the quadrupole, which was horizontally focusing for the H^- ions, but is horizontally defocusing for the oppositely-charged protons. The effect from the quadrupole is relatively small, however. The foil need not be very high in the vertical direction if it can support itself. Here I have shown it with 1 mm height that would have a probability of 1/4 of intercepting the ions vertically if they were at the right horizontal position. The differences in the two planes are shown in the phase space plots, where the cross-hatched area is the foil and the primes refer to angles in the x and y direction.

The table of Figure 5 shows a comparison of the rms coulomb scattering angle introduced by the foil and the maximum beam divergences of the circulating beam for different beam energies. Used as a diagnostic technique, it is clear that a correction is required to determine the characteristics of the circulating beam from measurements on the extracted beam at the lower energies, but that multiple coulomb scattering is negligible at 70 MeV and above. One conclusion from these calculations is that considerably thicker foils could be utilized for the extracted beams for therapy, so there should be no problems with foil lifetime or reliability.

One possible advantage of the low-current, long beam duration of the slow extraction might be in minimizing the shielding required in the transport of this beam. For example, if the total beam pulse containing 6×10^9 protons were extracted uniformly in 0.4 sec, then the peak current would only be 2.5 nA. If an accident occurred such that protons were striking the beam pipe or transport magnets, then strategically placed neutron detectors could turn the beam off in perhaps 1 µsec. In this case only 1.5×10^4 protons would have been unintentionally lost, and this would not present a difficult shielding problem for the transport line.

The simplicity of the transport line can be understood by considering the emittances of the extracted beam. These might be 0.3 mm-mrad in the vertical plane and extremely small in the horizontal plane. Dealing with the vertical plane, it would be possible to maintain the beam diameter below 1 cm with a quadrupole pair every 30 m. These might then be permanent magnet quadrupoles with a 1 cm bore placed inside the vacuum pipe. They would require no power, cooling, or maintenance. What is not so well known is that such a transport system could be arranged to efficiently transport any proton energy from 50 to 250 MeV by simply adjusting the matching conditions at each end of the transport line, however long, for the energy to be transported.

The bending magnets in the transport line are no longer restricted to low fields, so it is proposed that they would be the ring magnets (for cost effectiveness) with pole face inserts to reduce the vertical gap to 1 cm and increase the field to 20 kG. At this field, the radius of curvature of 250 MeV protons would be 1.2 m. The bending magnet field, as well as that in the matching quadrupoles, the switching magnets, and the scanning magnets would have to track the beam energy on a pulse-pulse basis.

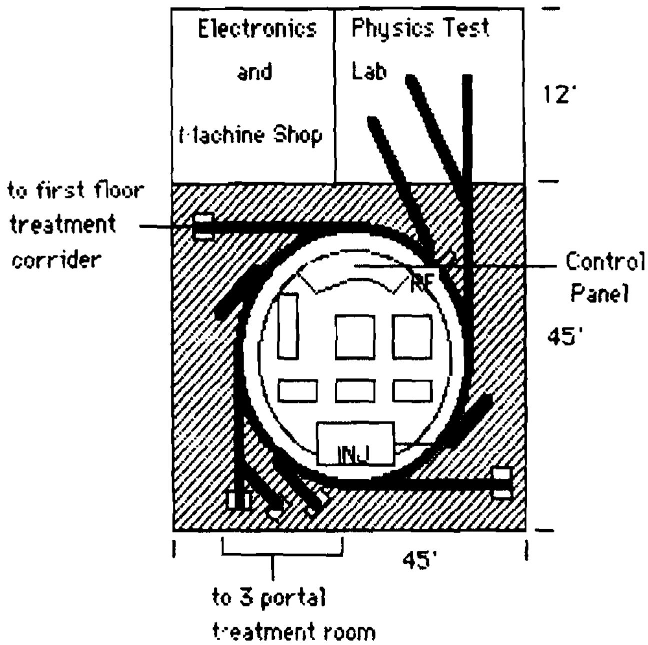
I consider the possibility of scanning beams to be one of the most attractive features of the design concept presented here. To deliver a uniform dose with scanning requires beams of high quality, long duration, and precisely-controlled current. The latter requires active feedback from beam current monitors. I don't believe beams with suitable characteristics exist in any facility today, but they can be produced with the stripping extraction of H^- ions. This is partly due to the fast and very direct relationship between the extracted beam current and the currents in a pair of bump magnets in the ring that control the beam position at the stripping foil.

One possible scenario for scanning beams is shown in Figure 6. If the goal is to scan an area of 30 x 30 cm with horizontal and vertical deflecting magnets 3 m away, the deflecting magnets must have an integrated field strength of $\pm$0.12 Tm for 250 MeV protons. A possible choice would be 20 cm long magnets excited with AC currents to fields of $\pm$ 6 kG. Each horizontal scan could cover the same width, and the beam turned on and off to cover only the desired contour for that position (with perhaps a small current left on outside this contour to monitor the beam position when it is nominally off). When the beam is at the extreme position it would be moved 1mm vertically and scanning resumed on the opposite swing of the sine wave. The total scan at one depth would then take 300 horizontal sweeps (for 30 cm vertical height), and, in a beam time of 0.4 sec, the required magnet AC excitation would be about 400 Hz. The power supply might be a well-controlled AC generator. For smaller fields, say 10 x 10 cm, one might want a slower scanning rate. A generator that could be connected to produce current at either 125 or 375 Hz might be suitable. This area scan would be repeated at a different penetration depth (proton energy) on each pulse until the desired volume was covered. As an example, with 1 mm difference in penetration/pulse (implying considerable overlap due to range straggling, which can be adjusted to any value desired to produce uniformity), a 10 cm depth could be irradiated in less than 2 min. Greater overlap, hence longer irradiation times for a given volume, would result in higher delivered dose.

At the fastest scanning rate, the beam is moving horizontally only 1 mm in 4.4 µsec. This time is more than that of 20 revolutions of the beam around the ring. Therefore there is no need to turn off the RF accelerating voltage and debunch the circulating beam. Retaining the RF fields can be useful for beam control in the ring, and the bunch structure on the extracted beam (about 5 MHz) can be of advantage to monitor the precise energy of the beam.

The beam size incident on the patient should be optimally adjusted, taking into account the unavoidable coulomb scattering of the protons in the patient. To scan with a "pencil" beam would produce an unnecessarily high skin dose. Fortunately, this type of matching is easy to do, and the optimum size depends upon the depth of penetration. A table of the rms beam spread due to multiple coulomb scattering as a function of the energy (or range) of the protons is shown in Figure 6. The effect can be quite significant for very deep-seated tumors, and must be included in the treatment planning.

In conclusion, I believe that achieving uniform radiation doses utilizing scanning beams is possible, and that this technique should increase the efficiency of treatment. It would result in a higher efficiency in the use of the accelerated beam, thereby requiring less accelerator intensity, less shielding around the accelerator, transport lines, and treatment rooms, and simplifying the problem of beam transport and delivery. The latter factor appears to make it possible to locate the accelerator in nearly any available space and safely transport the protons to any desired area. While one can clearly build medical accelerators with any desired current (at a cost that may be proportional to the cube root of the current), may accelerate protons rather than H^- ions, and may utilize conventional beam delivery techniques, the advantages I have outlined of accelerating H^- ions and using charge-exchange extraction and scanning beams seem to outweigh the disadvantage of the larger radius required.

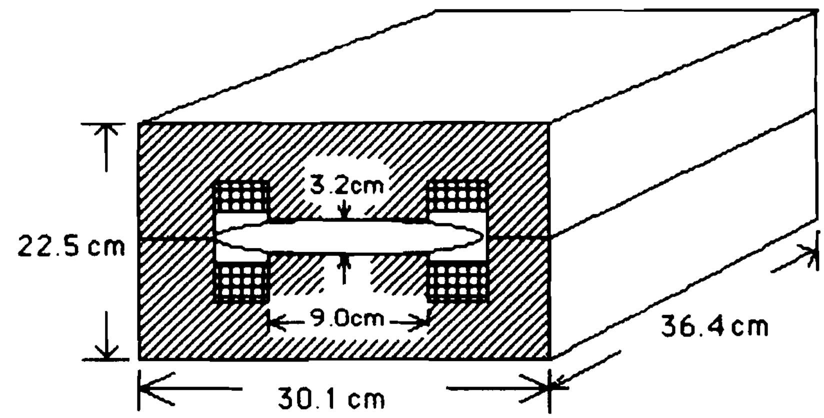


POSSIBLE BASEMENT FLOOR PLAN

PARAMETERS

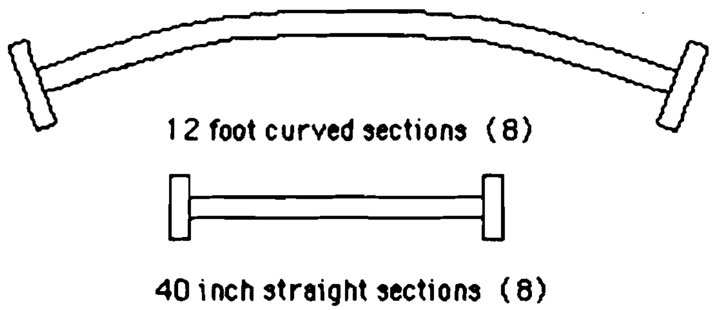
Injection	Acceleration	Extraction
1.5 MeV	f_i = 500 kHz	250 MeV
440 G	f_f = 5.4 MHz	6000 G
1 mA-1 µs	ΔE = 280 V/turn	t ~ 100 nsec
c = A/π = 1.9 cm-mr	V_{RF} =560 V	c = 1.36 mm-mr
x_{max} = 1.10 cm	Rep. Rate = 1 Hz	x_{max} = 3.0 mm
y_{max} = 1.02 cm	Field Rise = 0.3 sec	y_{max} =2.75 mm
N = 6 x 10^9 ions	Constant Field = 0.4 sec	
ΔQ = 0.1	Field Fall = 0.3 sec	

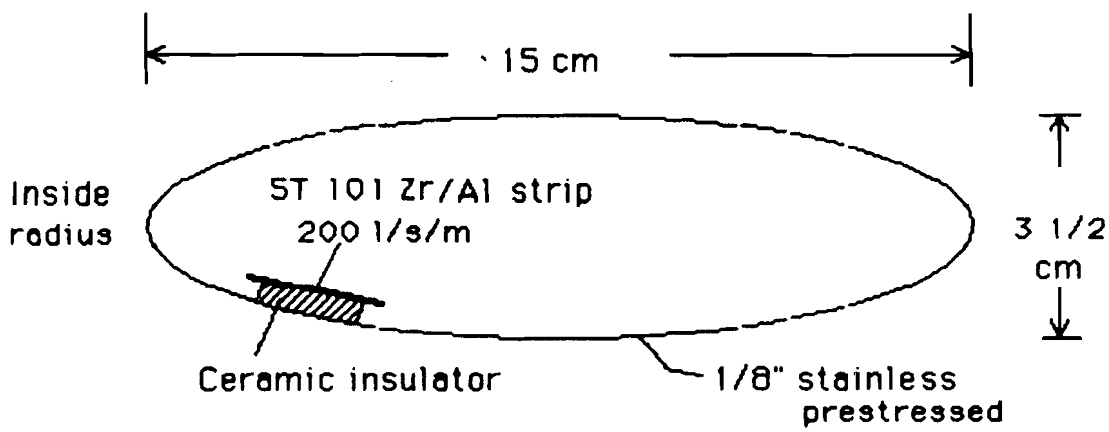
FIGURE 1. POSSIBLE LAYOUT AND PARAMETERS



0.231" sq. Cu conductor - 1/8" dia. hole
5 turns/layer x 4 layers/pole
424 A at 1.22 V =476 watts (DC)
x 64 magnets = 30.5 kW
185 kg/magnet (96.5 kg w/12 kG in yoke)

FIGURE 2. Magnet Cross Section





VACUUM CHAMBER CROSS SECTION

Preliminary Estimate of Vacuum System Cost

1.	38 m of ST101 Zr/Al strip	$75/m	$ 2,850
2.	12 -11 l/s ion pumps	$2500 ea.	30,000
3.	1 - 280 l/s turbo pump pack	$7725 ea.	7,725
4.	4 - 6" metal isolation valves	$10,000 ea.	40,000
5.	4 - 4" metal isolation valves	$6500 ea.	26,000
6.	4 - ion guages and controls	$1000 ea.	4, 000
7.	Chamber (design, fab, clean, inst)	$500/ft.	60,000
		Total	$170,575

Figure 3. Vacuum System

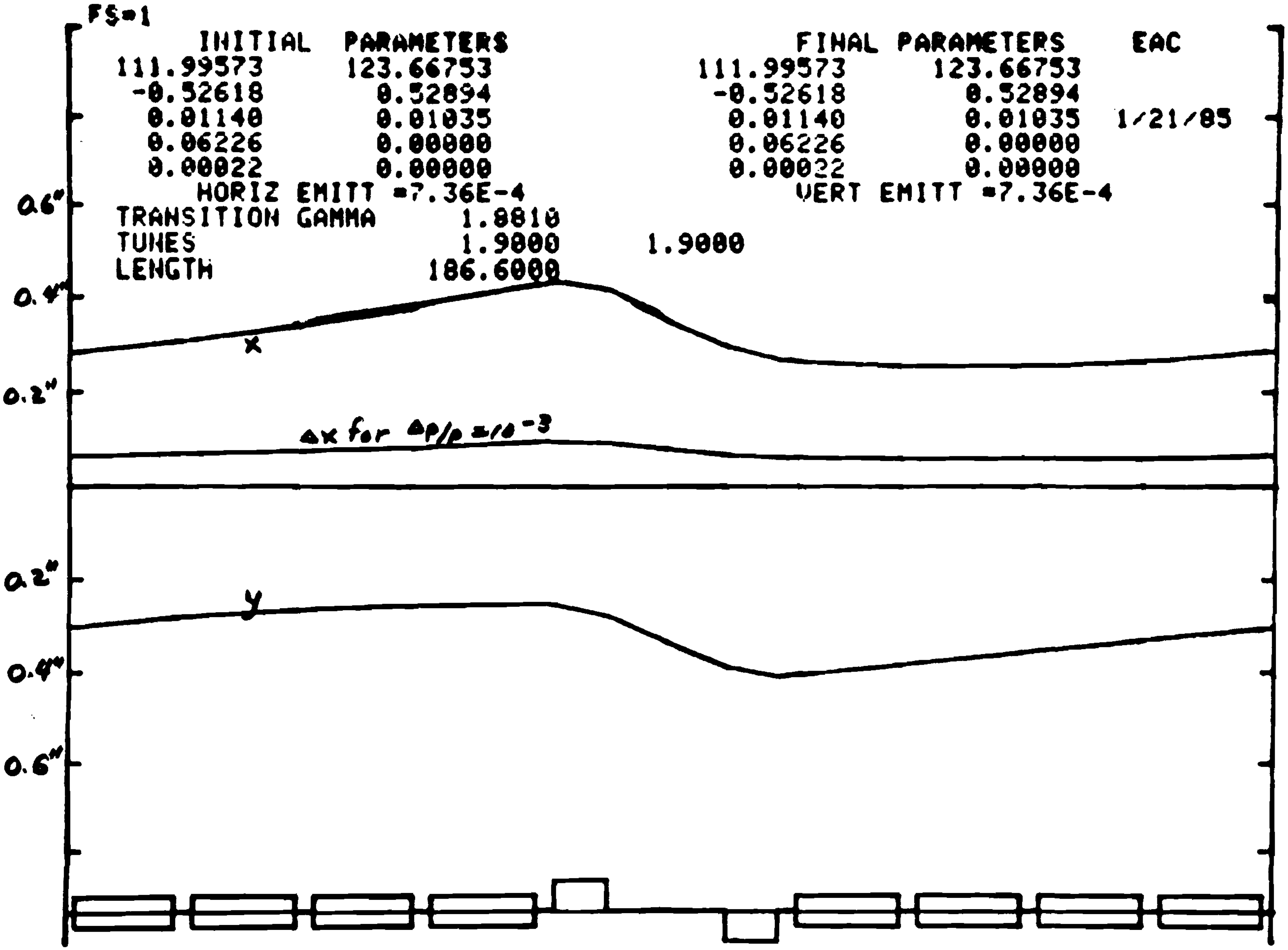
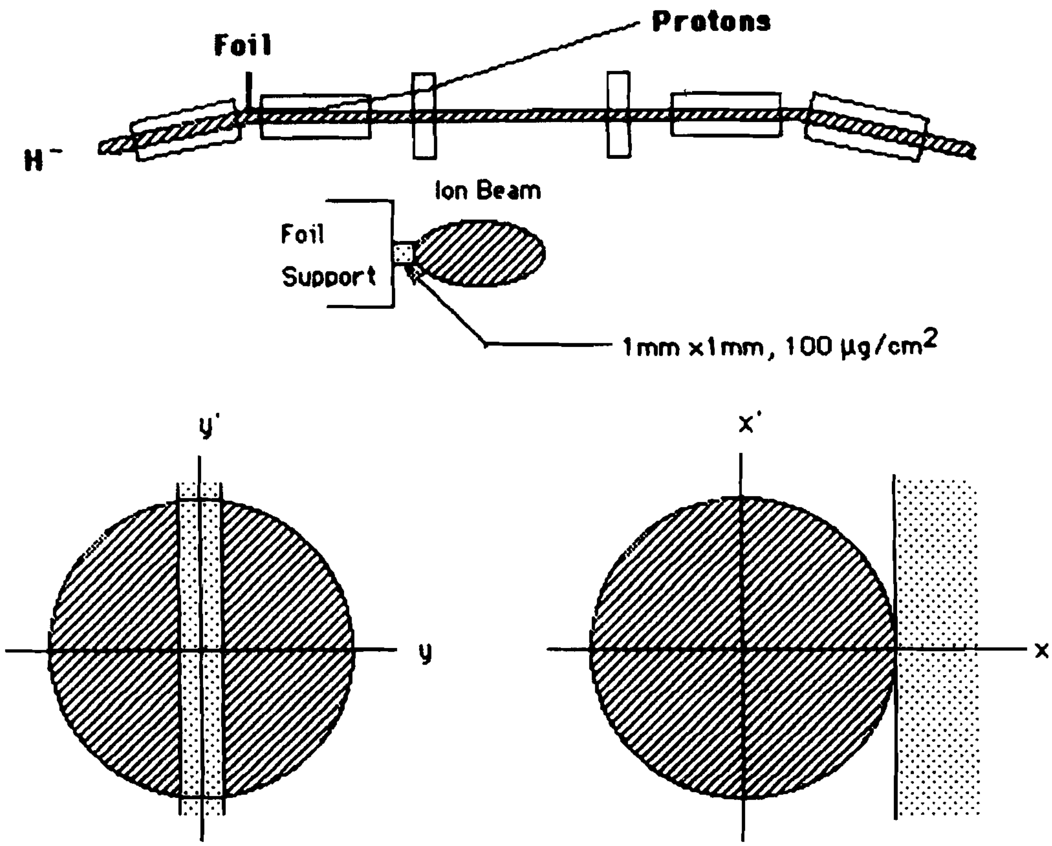


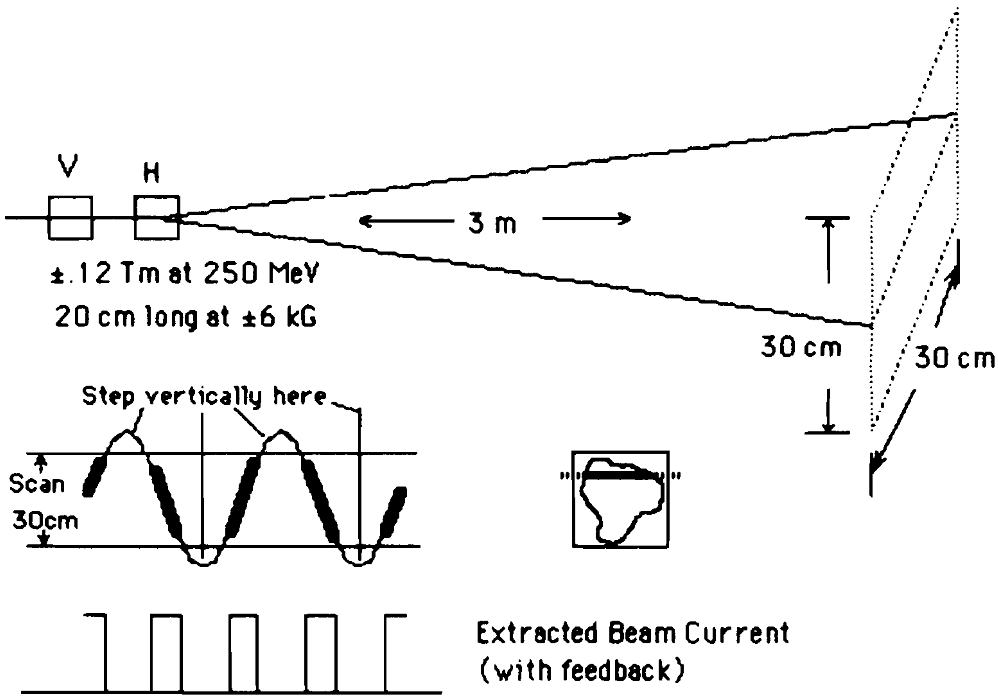
FIGURE 4. BEAM AMPLITUDES



Foil Scattering

E(MeV)	ø (circ-mr)	ø (foil-mr)
1.5	1.63	0.80
3.0	1.37	0.40
10.	1.01	0.12
70	0.62	0.02
200	0.47	0.007
250	0.44	0.005

Figure 5. Stripping Extraction



Multiple Scattering of Protons in Tissue

Energy (MeV)	Range (g/cm^2)	Y (rms-mm)
100	7.5	1.9
137	13	3.15
153	16	3.85
201	26	6.05
226	32	7.4

Figure 6. Scanning Beams