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THE PROTON DIAGNOSTIC ACCELERATOR*

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Summary

The advantage of proton radiography for early cancer detection in soft human tissue has been demonstrated.[1-4] In order for this technique to become a practical medical tool for early detection of cancer, however, a proton source suitable for use in hospitals and clinics is required. An initial concept of such an accelerator has been discussed.[5] It would meet the requirements considerably better than any existing accelerator and be simple, reliable, and economical.

Accelerator Requirements

In the medical application of proton radiography, protons are transmitted through a human being and through an additional absorber to a detector. The energy of the protons must be such that about half stop in the absorber. The remainder are detected to give the very sensitive measure of the amount of material traversed. Since the sensitivity is inversely related to the proton range, the energy must be adjustable to match the average thickness of the part of the body being radiographed. The range of 100 MeV protons in human tissue is about 7.5 g, that of 200 MeV protons about 26 g, and that of 250 MeV protons about 38 g. A proton energy of 200 MeV may be adequate to radiograph most parts of the body.

The range straggling of protons has a standard deviation of about 1.2% of the range. The energy spread of the incident beam must be less than ± 0.25% in order not to broaden the fundamental range straggling curve by more than 10%. An energy spread of 10^{-3} has a negligible effect on the resolution.

Several choices in overall objectives have to be made in order to define in detail the requirements on the accelerator and detection system for proton radiography. Radiographing patients with symptoms, in which a relatively large and well developed tumor may exist, requires only very few protons and simple detection techniques. On the other hand, for screening healthy human beings, in which one strives to detect the smallest possible density anomalies, maximum allowable radiation doses and sophisticated detection systems are required. The latter requirements are much more severe and coincide with our views on the most beneficial use of proton radiography as a practical medical tool. For this purpose, we have adopted the somewhat arbitrary limit of 100 mrad as a safe radiation dose for obtaining proton radiographs of healthy human beings.

A second choice of objectives which might influence the accelerator and detection system requirements is whether one desires projected views of large areas in a single radiograph or scans of small areas or slices from many angles for computerized cross section reconstruction as in x-ray tomography. Here again we have adopted the more severe criteria that for screening healthy human beings one would initially desire the projected view before proceeding to a more detailed examination of potential problems which may have appeared.

With these choices, 100 mrad over an area of 200 cm^2, a total of 10^8 protons is required for an optimum radiograph. It is necessary to know the position (and angle) of the protons entering the subject in order to avoid the degradation of spatial resolution due to multiple coulomb scattering (with a radiograph taken at 180° to observe the second half of the subject with good spatial resolution). Since present detection devices cannot handle an individual data rate of 10^8 per second, then it seems that the proton beam must be a very fine line beam (~ 1 mm diameter) scanned across the subject in the manner of a TV scan with its position known as a function of time. Detection of the ratio of protons transmitted through the back absorber to incident protons would then be done by integrating systems for each position of the proton beam. The technique described places a very strong requirement on the emittance of the extracted beam and on its energy stability during the pulse. These requirements are not met by any existing proton accelerator.

The extreme requirement on the energy stability during a pulse for a scanning beam (including separate pulses from different angles for reconstruction techniques) is not immediately obvious, particularly in view of the tolerable energy spread. It arises from the fact that a simple transmission measurement with good statistics is equivalent to a measurement of the average energy transmitted to high precision, about $\sigma/\sqrt{N}$, where N is the number of protons in a given picture element and σ is the standard deviation due to range straggling. The latter is determined with high precision because range straggling is a result of a very large number of coulomb interactions in traversing a material. Energy spread for a given picture element combines with σ in quadrature, while a variation of average energy for different picture elements causes a shift in the entire range straggling curve. $\delta E/E$ must then be compared with $\sigma/\sqrt{N}$; and, for 100 mrad back surface dose, N is about 5000 protons/mm^2.

For the application of screening healthy human beings for detection of cancer at the earliest possible time, the requirements on the proton source are beginning to be well defined. The accelerator must be simple, reliable, economical, and suitable for use in a hospital or clinical setting. It must deliver 10^8 protons uniformly in time over a period of 1 s in a 1 mm beam with divergence angles of less than 1 mrad, adjustable in energy and with an energy spread ≤ 0.25%.

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The average energy during the 1 s exposure would have to be constant to ± 0.004%.

Accelerator Concept

The initial concept of a proton diagnostic accelerator for hospitals was based on ideas of what a production model, well tested and in use for the purpose intended, would be like. We believe that most of those ideas remain valid, and they are summarized here.

The accelerator would be a synchrotron with a small magnet cross section, a small aperture, and would require low magnet excitation power permitting a ripple-free power supply. Negative hydrogen ions would be injected at 300 kV for one-half turn and accelerated to 200 MeV in 1 s. The vacuum would be 10^{-10} Torr and the RF requirement 100 V. Stripping extraction would be employed to produce very high quality external beams in several locations. The accelerator would be highly reliable and give a good pulse of the desired energy, intensity, and quality on demand from any of the diagnostic stations, although the duty cycle would be rather low. Minimal shielding would be required.

Achieving this kind of operation will take some learning experience, even on the part of experienced accelerator personnel. The criteria for the development model, the first of its kind, are therefore somewhat different. We are beginning to think through the implications of bringing such an accelerator into operation for the first time even though we have not yet begun a detailed design study.

In a development machine, one needs a reasonable duty cycle in order to tune the machine and make it operational. Thus the accelerator should operate continuously at 1 pulse/3 s. One needs much more flexibility to investigate the resonance structure, to make modifications, to develop new diagnostics, and to study all characteristics of the machine in quite some detail. One cannot anticipate that the accelerator will remain under vacuum continuously for very long periods of time as might be possible in an operational diagnostic accelerator. The capability of injection of protons in addition to H^- ions is being considered as an advantageous diagnostic tool. These considerations have led us to turn to a separated function machine with a somewhat larger radius for the development accelerator. The characteristics of this machine are listed in Table I.

Table I

Dimensions	cm	
Circumference	2509.28	
Circumference/2 π	399.36	
Orbit radius	241.92	
Component lengths		
Straight section	8.00	
Defocussing magnet	8.12	
Straight section	8.00	
Focussing magnet	15.42	
Straight section	8.00	
Defocussing magnet	8.12	
Straight section	8.00	
Bending magnet	26.00	
Straight section	60.00	
Bending magnet	164.00	
Injected beam width		
Quadrupoles	2.04	
Bending magnet	1.50	
Injected beam height		
Quadrupoles	0.51	
Bending magnet	0.50	
Orbit Parameters		
Betatron oscillation per revolution		
Radial	2.13	
Vertical	2.19	
Change due to 10^8 H^-	-0.01	
Beam quality at injection		
Radial	3	π mrad cm
Vertical	1	π mrad cm
Beam quality at extraction		
Radial	0.13	
Vertical	0.04	
Magnetic field		
Injection (0.3 MeV)	327	G
Extraction (200 MeV)	8888	G
Gradients (B^{-1} dB/dR)		
Focussing	0.483	per cm
Defocussing	-0.5	per cm
Oscillator frequency (first harmonic)		
Injection	0.3	MHz
Extraction	6.8	MHz

Vacuum Considerations

The injection of low energy H^- ions and the relatively long acceleration cycle of the proton diagnostic accelerator combine to set a severe requirement on the vacuum system, which must be approximately 1 x 10^{-10} Torr. Vacuum chambers which must operate at these extremely low pressures are typically made of stainless steel. Careful measurements by CERN on the stainless steel chosen for their intersecting storage rings showed that this material, even after an in situ bakeout at 300° C, was releasing hydrogen gas at the rate of about 3 x 10^{-12} Torr ℓ/s/cm^2. The measurements also showed that this hydrogen appeared to be diffusing out of the bulk of the material (rather than desorbing from the surface), and the constancy of the rate over long times suggested a virtually infinite reservoir of hydrogen. This was confirmed by chemical analysis which showed the hydrogen impurity to be about 0.001% or 10^{19} molecules/cm^3 of steel.

The required pressure of 1 x 10^{-10} Torr is relatively easy to achieve today. Combined with the high impedance characteristics of the proton diagnostic

accelerator vacuum chamber, however, and the limiting of its baking temperatures (≃ 250° C), makes it a bit more difficult. Also, the most convenient vacuum pump for the job, the sputter ion pump, has very poor pumping speeds for hydrogen at low pressures. Singleton from Westinghouse Research Laboratories has found this to be the most important disadvantage of a sputter ion pump. Attempts to improve this performance by the use of hydrogen-free titanium have not proved successful. Prolonged baking of the pump at 400° C in a vacuum of 10^{-7} Torr was even found to be ineffective in improving low pressure sputter ion pumping performance. These experiments support the suggestion that the lack of pumping is not caused by reemission of hydrogen but simply by the presence of a surface diffusion barrier which inhibits diffusion so that hydrogen cannot be dispersed into the bulk of the cathode.

If the pumping load is primarily reactive gases, such as nitrogen, oxygen, and hydrogen, the ion pump can be combined with a sublimation pump. Now the ion pump plays the secondary role of pumping the residual nonreactive gases while the sublimation pump can provide large pumping speeds for the reactive gases. The sublimation pump evaporates a metal, commonly titanium, either continuously or step-wise onto a surface cooled to room temperature or below. Since each cm^2 of absorbent surface can provide a pumping speed of several ℓ/s for most reactive gases, very high total speeds are achieved in a small unit.

A 1.3 ID stainless steel pipe 19 in long (48.26 cm), chemically cleaned, then baked for 28 h under vacuum at ≃ 250° C reached an ultimate pressure of ~ 1.5 x 10^{-9} Torr. A new 8 ℓ/s ion pump, previously baked at ~ 250° C was mounted at one end of the pipe, and the ionization gauge (Helmer) was mounted at the opposite end. The base pressure achieved agreed quite closely with calculations based on outgassing rates for stainless steel at the above bakeout temperatures (Yale Strausser, Varian Associates, VR-51). Bakeout at higher temperatures (450° C) did not improve the base pressure significantly. A small filament type sublimation pump introduced into the system at the start of the test was subsequently energized for periods of 1/2 min over a period of 10 days (total energized time did not exceed 10 min). The base pressure dropped after each energization of the sublimation pump. After 10 days, the base pressure in the system was 2 x 10^{-11} Torr.

It is conceivable from the above test that a compartmentalized chamber, built as an integral part of and around the outer periphery of the chamber for the circulating beam, could contain the proper combination of ion and sublimation pumping to achieve and maintain the necessary base pressure. Prebaking of the chamber to 400 or 500° C before installation and designing for in-place baking of 200-250° C after installation should assure tolerable contamination if reasonably maintained. Adequate magnetic field for proper operation of the ion pumps might come from the same magnets maintaining the beam in its circulating path.

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