HOSPITAL - BASED ACCELERATOR FOR PROTON RADIOTHERAPY

B. Gottschalk, A.M. Koehler and M.S. Wagner
Harvard Cyclotron Laboratory
44 Oxford St., Cambridge, MA 02138

Abstract

The rationale for designing a dedicated hospital-based proton accelerator for therapy is reviewed and the specifications for such a machine are given. The main parameters of a suitable conventional proton synchrotron are listed, and certain aspects (main magnet, choice of lattice, choice of proton source and RF system) are discussed in somewhat more detail. Important areas of the design, such as the extraction system, remain to be finished, but there is reason to hope that such a machine could be designed to sell for a few million dollars. This would make protons available to complement photons in radiotherapy.

1. Introduction

Protons, which exhibit biological effects similar to photons, are nevertheless advantageous in radiotherapy because of the sharp dose distributions which can be obtained. Considerable clinical experience has accumulated: some 5000 persons have been treated world wide with protons or other heavy charged particle beams, with excellent results in many cases. As of May 1 our lab alone had treated 3029 patients for such disorders as benign tumors of the pituitary gland, arteriovenous malformations (AVM's) of the brain, ocular melanoma, cancer of the prostate, tumors abutting the central nervous system and other tumors lying near critical and/or radiosensitive structures. We now treat over 450 patients per year. For most procedures our costs are comparable with conventional radiotherapy or surgery; two-thirds of our patients are treated on a fee-for-service basis without Federal support.

A recent workshop[1] at Fermilab discussed the possibility of a commercial hospital-based machine to make proton radiotherapy more generally available. In addition to stimulating further research, such machines would provide protons to complement photons in the everyday operation of large radiotherapy departments. To make this realistic, the cost of the machine would have to be in the low millions of dollars. High reliability, safety, maintainability and a minimum of operating staff (preferably one person) are also important. The energy should be selectable at a few values up to 250 MeV, and an average internal current of some 20 nAmps is required for reasonable doserates if large volumes are to be treated with existing beam-spreading and delivery techniques. Active spreading and/or scanning systems could lower the current requirement considerably. Several machine types were discussed; the chief proponent of each is given in parentheses. They are: superconducting FM cyclotron (H. Blosser); superconducting synchrotron (R.R. Wilson) room-temperature H^- synchrotron (R. Martin) and conventional proton synchrotron (B. Gottschalk).

It is still unclear how or where the first such machine will be built. Perhaps it will be a strictly private venture, or perhaps a collaboration of industry with existing therapy centers and national labs can be arranged. In any event, we have done some thinking about the conventional proton synchrotron option and we report the current status here. Important gaps remain in the design, such as the specification of a specific proton source and an extraction system. Nevertheless, the gross parameters of the machine - size, weight, power consumption - are probably fairly well established.

2. Overview of Machine Parameters

energy: injection at 300 KeV, maximum 250 MeV
internal average current: 20 nanoAmperes
ramp: .08 sec up, .04 flattop, .08 down
magnetic field: .049 T injection, 1.5 T maximum
magnet: 4 x 90^o, ρ = 1.6 m, const. gradient, n = .5
straight sections: 4 x 1 m, R/ρ = 1.4

tunes: $\nu_h \cong \nu_v \cong \gamma_{tr} \cong .8$
lattice functions: $\hat{\beta}_h = \hat{\beta}_v = 2.9$ m; $\alpha_p = 3.2$ m
magnet aperture: 4 cm high x 12 cm wide
vertical admittance: 140 π mm mrad
incoherent tuneshift at injection: - .13
peak injector current: 4 mA

coil: 4 x 10 turns .46" OD hollow copper conductor
average power 120 KW, peak stored energy 55 KJ
I R = 200 volts, L dI/dt = 1100 volts (full series)
effective current density: 5.4 KA / in^2 copper
cooling @ 8 ckts/quadrant: $\Delta T = 30\ ^oC$ at $\Delta P = 12$ PSI

RF frequency swing (h = 10): 5 to 130 MHz
average energy gain/turn: 420 eV
RF power (50 Ω broadband system): 3.5 KW

machine O.D.: 16 feet
weight: 8 tons steel, 1 ton copper + support frame

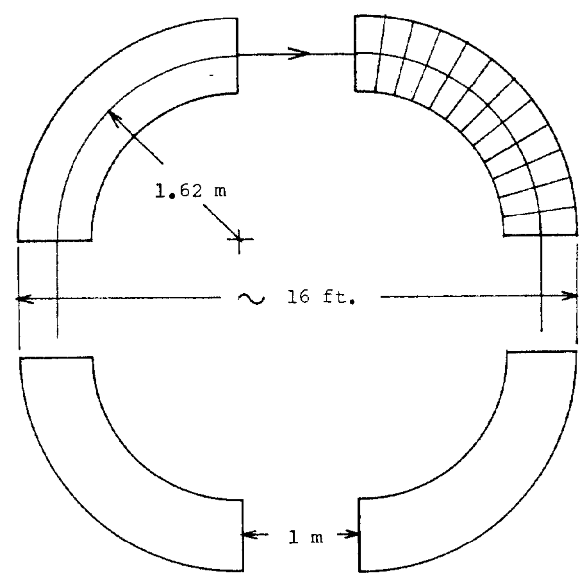

Fig. 1: Main magnet plan view, approx. to scale.

3. Main Magnet

Fig. 1 is a plan view of the magnet and Fig. 2, a cross section. Each quadrant comprises twelve 7.5^o wedge-shaped lamination stacks. The approximation of radial symmetry by rectilinear segments has been studied[2] and seems to be adequate. Each quadrant is excited by a single 40-turn coil of hollow copper conductor. Cooling is conservative if 8 water circuits are used per quadrant. Eddy-current heating of the coil has been estimated at about 5% of the ohmic heat. Eddy-current distortion of the field near the coils is a potentially serious problem and is under study.

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We plan to put the entire magnet structure under vacuum, avoiding fabrication problems and aperture loss associated with a beam pipe. The vacuum jacket for each quadrant will also serve as the mechanical frame.

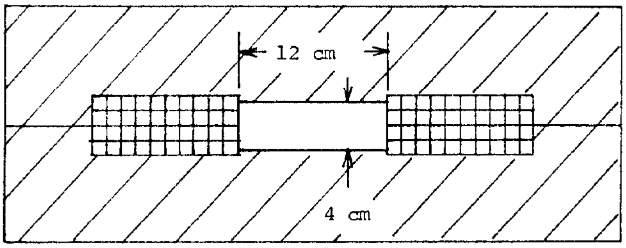

Fig. 2: Main Magnet Cross Section

4. Lattice

Since simplicity is a prime requirement, it would be desirable to have the transition energy of the machine either above or below the working range $\gamma = 1$ to 1.266 . Very general rules dictate vertical and horizontal tunes of the order of 1. We have looked into both alternating-gradient (AG) and constant-gradient (CG) guide fields. They are contrasted in Fig. 3. Using AG, one can keep γ_{tr} above the working range for a circumference factor R/ρ greater than ~ 2; however, rather asymmetric tunes and large beta functions result. With CG, γ_{tr} can be below the working range for R/ρ less than ~ 1.5 . Disadvantages of this choice are greater dispersion and less room for extraction devices, RF cavity etc. By the same token, the machine will be smaller if one can get away with it; also, the CG magnet should be easier to fabricate. For these reasons we have provisionally settled on a CG machine with $R/\rho = 1.4$ and both tunes around .8, well positioned for third-integer resonant extraction (heavy arrows). The final decision hinges on the design of a practical extraction system.

5. Proton Source

The simplest scheme is single-turn injection with the protons debunching before their adiabatic capture by the main RF. Assuming half a turn is available, we require $\sim$ 4 mA peak for about 1 microsecond, five times per second: a very low duty factor. A duoplasmatron source easily meets this requirement; it should be pulsed to extend filament life.

The lower the injection energy, the cheaper the proton source will be. The usual problems with too low an injection energy are field distortion due to remanent fields, excessive frequency swing and spacecharge defocusing. At 300 KeV the field is already 490 Gauss so field errors should be manageable. With the proposed broadband RF system, frequency swing is not a problem. The spacecharge limitation can best be appreciated by working out the incoherent transverse tuneshift. At the relevant current and proton speed, beam-wall effects should be negligible[3]. For nonrelativistic protons

$$\Delta Q = -\frac{r_o N}{2\beta^2 B}\frac{R}{Q_o S}$$

gives the tuneshift[4] averaged over the vertical and horizontal motions provided[5] the beam is not too asymmetric in cross section (aspect ratio 2 or less). The symbols along with their values in the present case are r_o = classical proton radius = 1.53×10^{-18} m, N = # of protons in the ring = 2.5×10^{10}, $\beta = v/c = .0253$, B = RF bunching factor = .2, R = gross radius of machine = 2.27 m, Q_o = unperturbed tune = .84 and

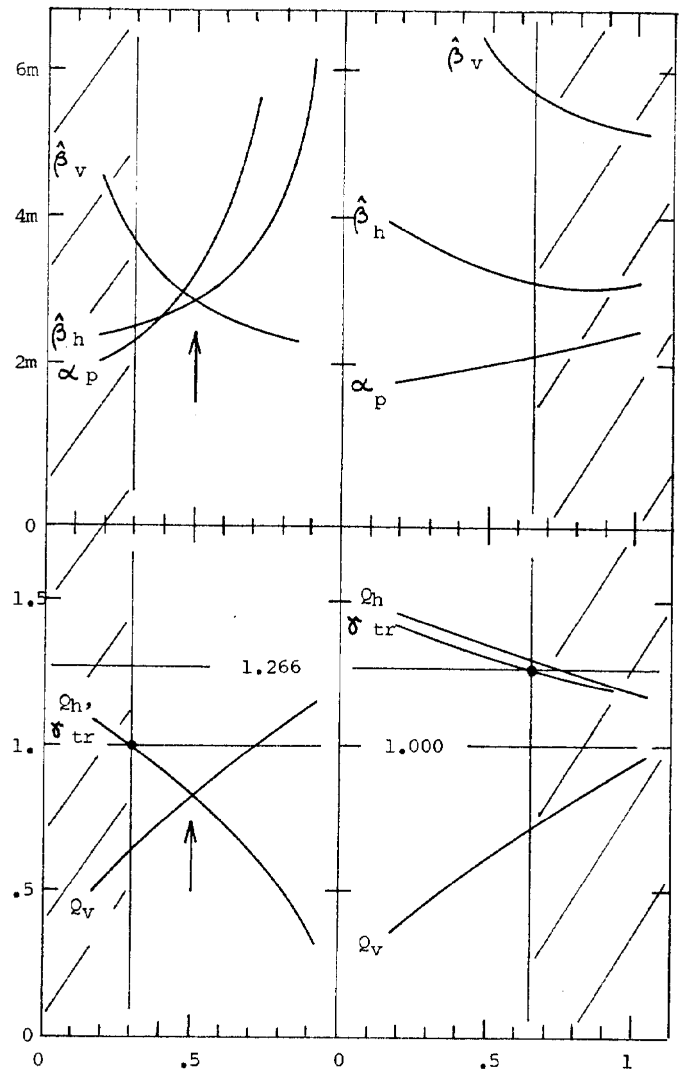

Fig. 3: Lattice functions and tunes vs. field index. Left panel: CG machine with $R/\rho = 1.4$; right panel, AG machine with $R/\rho = 2$. The cross-hatched regions are not useable if transition is to be avoided.

S = cross sectional area of beam = $\pi \times .02$ m $\times .04$ m = 2.5×10^{-3} m^2. We assume the beam fills the aperture vertically and 2/3 of the aperture horizontally with an elliptical cross section. All this gives $\Delta Q = -.16$; the beam is space-charge limited, as it probably should be for an efficient design. Reducing the energy below 300 KeV would call for an increase in aperture. There may be a safety factor in B; with a linear power supply it should be possible to accelerate with less tight bunching for the first few MeV.

Clearly there is no fundamental difficulty in finding a 300 KeV proton source. However, some ingenuity here might well reduce the overall cost. The design should take advantage of the extremely low duty cycle. Very possibly the injector for the first model will be chosen for expediency to be followed by more research and development if the machine goes commercial. The following possibilities come to mind:

DC accelerating column: an off-the-shelf choice. At 300 KeV it must be pressurized. DC capability is orders-of-magnitude greater than actually required.

Pulsed accelerating column: a conventional column could be pulsed using a thyratron and pulse-forming network with a step-up transformer of the sort used for klystron modulation. Because of the short pulse the column could be smaller and air-insulated. Pulse-to-pulse stability and adequate flattop are possible technical problems.

Pulsed matched RFQ: We have made a preliminary design of a short 300 KeV proton RFQ matched to DC parallel beams at both ends; this is done without additional hardware by flaring the vanes and tapering the modulation depth (that is, adiabatically turning off the transverse focusing and acceleration). Length is only about half the free-space wavelength; thus the structure is electrically short which makes it easier to achieve a flat longitudinal voltage distribution. Operating frequency may be chosen for convenience which also eases the design. By now, many RFQ's are operating well but they tend to be mechanically fussy to build and are by no means cheap. In the long run this could be an efficient choice but it also seems to require more R&D than the others.

Pelletron or Dynamitron: these are commercial few-MeV accelerators sold for ion implantation, chemical analysis, carbon dating etc. They are fairly large and one would be buying much more DC capability than needed. One would have to check that the pulsed current requirement of a few mA could be met with adequate stability. Such a machine can be viewed as a fallback in case of unforseen problems with low injection energy.

6. RF System

The protons will be accelerated by a drift tube filling one of the straight sections; this calls for operation at the tenth harmonic with a frequency swing from 5 to 130 MHz. However the energy gain per turn is only 420 eV. On estimating the drift tube capacitance one finds that its frequency response should be adequate if it is shunted by a 50Ω dummy load, perhaps with some peaking inductance. Therefore the simplest scheme appears to be a broadband RF amplifier driving the drift tube; about 3.5 KW are required if one assumes the factor of two gained in the drift tube approximately cancels the synchronous phase angle factor. The signal waveform will have to be carefully shaped since (except at the high end) there will be no smoothing from resonance. The feedback system will be a conventional one using a beam sum signal for phase lock and a radial position signal for frequency control.

7. Miscellaneous

The overall design is still far from complete. The most important part still to be specified is the extraction system. It should provide a reasonable duty cycle (of the order of 10%) less for clinical reasons than to permit the use of various diagnostic detectors. (For beam scanning, an even better duty cycle would be necessary.) High extraction efficiency is not required; even at 50% efficiency, activation of the machine would not be a serious problem. Trouble-prone devices such as electrostatic septa should be avoided if possible. At present, vertical third-integer resonant extraction seems the most attractive.

The control system must permit safe operation of the machine by a single operator, and provide sufficient diagnostic information to pinpoint problems rapidly. It will be computer-based, using dedicated circuits preset by the computer for aspects (such as injector timing and RF feedback system) requiring fast response.

The main power supply should be linear if possible to permit flexible operation of the machine. With available components it seems just possible to build a switching supply with the main filtering done by the magnet inductance itself. In principle the flyback time could be considerably shorter than the ramp-up time to the extent that one can tolerate a larger voltage across the coil and supply components. This would ease other areas of the design such as the RF, but we have not assumed it at present.

The vacuum system is straightforward. The RF system, working at low voltage and already heavily loaded externally, should be virtually immune from sparking and multipacting. Ample pumping capacity should be installed to deal with outgassing from epoxy and to assure quick recovery after shutdown for repair or maintenance. Failsafe valves should be provided to secure the system against power outages.

Shielding requirements should be modest compared to the 1200 tons of concrete provided at the cyclotron, because far less beam will be lost internally. Unextracted beam should be stopped in well-defined locations which can be shielded locally. A shielded beam dump should be available for tune-up and diagnostic running. The main shielding problems will arise from beam stopped in the patient and in the beam-conditioning hardware required for treatments, and these problems are already dealt with at existing facilities.

8. Conclusion

We have sketched a design for a conventional proton synchrotron to be used for therapy. To us, a synchrotron seems the best match to the requirements, allowing one to capitalize on low current while keeping energy selectability. The present parameters may well change in detail as the design, particularly the extraction system, is filled in, but the qualitative picture of a modular machine of modest size and weight seems pretty firm. We are currently estimating the cost of such a machine and are hopeful that, after about a decade of discussions and proposals of similar machines, the next few years will actually see the construction of one.

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