250 MeV SYNCHROTRON FOR PROTON THERAPY

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I. SPECIFICATIONS

These were discussed yesterday by Michael. Let's review them:

In principle, alpha particles can give a sharper dose distribution than protons. However, for equal penetration an alpha beam must have four times the energy and twice the magnetic rigidity; therefore the machine is twice as large as the already-large p machine. Other items such as the main power supply scale accordingly. One has to show that the advantage gained in practice is worth this substantial additional effort, for a significant number of patients. Of course one can design for protons and then use that machine for alphas as far as it will go; for instance the 250 MeV proton machine could be used to treat eyes with alphas, and this might be very sensible. For now, let's confine ourselves to protons.

An energy of 250 MeV penetrates 37.6 cm of water; this is more than adequate. Degrading from here down to 60 MeV would produce a rather sloppy Bragg peak, so the energy ought to be variable, even if it is held fixed for any given treatment.

An accelerated current of about 20 nAmp is indicated to meet the goal of 1 Gray/minute for large fields with some safety margin. Assume for instance that we wish to treat a 30 cm diameter field to a depth of 15 cm (a fairly extreme example):

$$i = \frac{1\,\cancel{\text{Gray}}}{\cancel{\text{min}}} \times \frac{1.2\times10^{9}\,\cancel{\text{proton}}}{\cancel{\text{Gray}}\,\cancel{\text{cm}^2}} \times 707\,\cancel{\text{cm}^2} \times \frac{\cancel{\text{min}}}{60\,\text{sec}} \times \frac{1.6\times10^{-19}\,\text{coul}}{\cancel{\text{proton}}} = 2.3\ \mu\text{Amp}$$

However, if we use the passive double-scattering technique to get a flat field, we lose a factor of five, and the extraction/beam transport process could cost us another factor of two, so 20 nAmps seems about right.

This unfortunately exhausts the list of absolute requirements. Michael quite properly pointed out that the clinician is interested in a complete facility, not a machine. But this does not mean that the designer has to consider the entire facility ab initio, and I shall not do so, except to try to arrive at a machine which will not be incompatible with any reasonable clinical goals. Hospital based is the overriding requirement. This means reasonable size and weight; however, we are talking about a pretty large facility so there is no point in taking heroic measures to make the machine extra small. Compatibility with an isocentric gantry mainly means keeping the emittances under control, and scanned beams demand a reasonable duty factor, say 50% or better. The most serious shielding problems will arise in connection with the gantry.

Another class of requirements: reliability, maintainability and ease of operation will get no arguments from anyone; of course the question is how to achieve them. The LBL/Arizona study appears to assume that the very first machine will have to meet all these requirements within a short time after construction, and concludes that this can only be done by a combination of the obvious techniques (i.e. conservative design choices, use of proven commercial components where possible ...) with an intensive application of reliability analysis. I could not disagree more strongly here. In the long run, reliability can only be guaranteed by gradual progress through a series of prototypes.

Finally, cost is obviously an important factor. Although I have been foolish enough to fling cost estimates about from time to time, our design is not really complete enough yet, nor are its less conventional aspects sufficiently well tested, to allow an accurate estimate. The numbers that have been quoted perhaps reflect our hopes more than a true assessment of what can be done. A study done by Andy and Kris Johnson a few years ago indicates that a machine costing under $2,000,000 ought to break even on a fee-for-service basis. This goal does not seem impossible.

II. TYPE OF MACHINE

A 250 MeV proton linac is a very large machine. Proton linacs are not easily tunable, and perhaps most important, one is unable to trade off the low current requirement for cost savings.

The FM cyclotron is well-proven technology and features a simple control system and no injector. However, we are talking about a 400-ton object which would certainly have to be built in situ. Output energy is fixed and extraction efficiency is good only with extremely careful engineering of the central region.

An alternating-gradient synchrotron seems the best choice by far. The current requirement can be met and money can be saved by keeping the aperture just large enough to meet it. Output energy is easily variable. The machine weighs a few tons. It should be relatively easy to shield since extraction efficiency is high and it is possible to control where the beam losses occur. Construction is intrinsically modular and (if the machine is ever commercialized) it is reasonable to envision building and testing a machine at the factory and then shipping it out to be reassembled and commissioned in a matter of weeks. The control system is more complicated but this is precisely where technology has made its greatest strides. Finding a reliable and economical injector may be the greatest problem.

III. PTA250 REFERENCE DESIGN

I have attached a reference design. Please don't take it too literally. For instance, it wasn't really made with the 50% duty factor in mind. This will increase the cycle time, reducing the beam, but with scanned beams one ought at least to recoup the factor of five lost in generating a flat field by passive means. The reference design is only meant to convey the general scale of the machine we are discussing. Let me go into just a few of the design decisions and tradeoffs.

The overall size of about 7.5 meters is determined by how much field one can get in the laminated magnets plus the length of straight sections one needs to fit in the RF, extraction gear, internal beam monitors etc. I started off with a quadrant design; one could go to more superperiods but there does not seem to be any special advantage to this. 1.2 Tesla max field is certainly a conservative assumption; one may be able to go to 1.5 with a corresponding reduction in size.

The next choice is the lattice. By the basic rules (90^o betatron phase shift per superperiod) any reasonable machine in this energy range will have a tune near 1, making it a weak-focusing machine in some sense even though it is alternating gradient. The lattice should achieve this with minimal gradients; also, the beta functions should be reasonably flat. The 4 x (OFDFO) lattice, which is a variant of the quadrupole triplet idea, seems to meet these goals. Perhaps the most important goal is that, if possible, the machine stay below transition. This appears to be just possible at 250 MeV.

The next major choice is the aperture. This will impact not only the magnet weight but also the size of the power supply, since the gap height determines the current and the volume determines the inductance. First, we had to pick a repetition rate to determine how many protons need to be packed into a pulse. There is no sharp optimum, but 10/sec seems clinically convenient and is not far from the figures suggested by the LBL/Arizona study. Given the number of protons per pulse, the aperture size is determined either by the size of the matched beam at injection or by the tune shift at injection. Assuming injection at 300 KeV (which choice is justified later), the two criteria are comparable for the aperture (about 1 x 3 inches) we have chosen.

Having picked the aperture, one has a number of choices revolving around fabrication. Putting the entire magnet under vacuum has been done at a number of synchrotrons, and takes advantage of the rather modest vacuum requirement. It allows one to utilize the aperture more efficiently, and circumvents the need for a beam pipe with its eddy-current problems. A more debatable (but also less far-reaching) decision is to try foil-wound coil construction rather than the more conventional hollow-conductor. This would permit a slightly smaller magnet (since the packing factor is higher) and eliminate the water manifold which, given the proportions of the coil, would have to be extensive. The foil-wound design cools well enough on paper, but thermal resistance at interfaces tends to be greater under vacuum; this will have to be tested.

The last decision I shall have time to cover is the choice of RF system. The frequency swing is prodigious (24/1). However, the energy gain/turn is a modest 1.2 KV, and it looks as though we can get by with a drift tube (filling one of the straight sections) loaded with 50 ohms. This solution is brute-force (14 KW of RF) but exceedingly simple, and should make for reliability.

IV. THE INJECTOR

The choice of injector may take the longest to settle down. One school of thought seems to revolve around injecting at a few MeV using one of a variety of off-the shelf machines (Dynamitron, Pelletron...). If we are thinking of single-turn injection (for simplicity) we require some tens of mA for about a microsecond, ten times per second - a very low duty factor. The standard machines are greatly overqualified for average current, somewhat underqualified for peak current, and all quite large.

If the aperture estimates are right, and if we can indeed get away with a broad-band RF system, injection at a few hundred KeV looks OK. This makes it possible to use one of a number of smaller machines: small pulsed RFQ, DC accelerating column powered by a Cockroft-Walton supply, pulsed accelerating column powered by a high-voltage pulse transformer. The last takes advantage of klystron modulating technology. The voltage is certainly no problem; the main question is whether the pulse-to-pulse repeatability and the flattop accuracy are adequate. We have started looking into this only recently.

We have studied the RFQ option (certainly the trendiest choice if nothing else) in some detail. Proton RFQ's have been operated to 3 MeV, but these are very large machines and produce monstrous peak currents which we do not need. A pulsed 700 KeV RFQ has been working well at Brookhaven for some time now, and some of the technology could be taken over. What distinguishes a 300 KeV RFQ qualitatively from a much larger one is that, even with full matching at both ends, the device need only be about half a wavelength long which makes it far easier to obtain the desired longitudinal voltage distribution.

V. THE HCL MACHINE DEVELOPMENT PROGRAM

Let me close with some remarks on where we stand. In the near term we plan to concentrate on two things: a) Fill in some gaping holes in the conceptual design (extraction mechanism, control system ...) to produce a well-rounded design which we can try to sell; b) Begin constructing and testing a short magnet section to investigate durability, field accuracy, fringe fields, behavior under vacuum etc. The second project is appropriate at this time because the magnet requirements are sufficiently well defined, because the magnet is by far the single largest component, and because the cycle time for specifying, procuring and testing a magnet prototype is fairly long.

Our longer range plans are also two-pronged: a) Prepare a proposal for a full facility. This will include all the ancillary items listed by Michael. Of course the prime movers in such a proposal will have to be the clinicians at some major center, but it would certainly help if we had a better idea of the machine by then. b) At the same time, construct a 70 MeV "eye machine" at HCL. This makes sense in our particular situation: it fits into real estate we control, it would be very useful in the treatment program, and it would serve as a test bed for the larger machine.

Let us hope that, after nearly a decade of dedicated-machine proposals, something will actually happen this time.

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REFERENCES

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PTA250 REFERENCE DESIGN A

I. INPUT PARAMETERS

particle	protons
energy range (main ring)	.3 - 250 MeV
average accelerated current	20 nanoamperes
pulse spacing	.1 second
max field	1.2 Tesla
coil type	foil wound, edge cooled
copper packing fraction	.8
coil window (HxW)	3.46 x 6.92 cm
# turns in coil	40
aperture (HxW)	2.6 x 7.8 cm (1 x 3 in)
lattice	4 x (OFDFO)
field index	approx. .8
circumference factor	2

II. LATTICE CHARACTERISTICS

bend radius	2.02 meter
tune (H,V)	1.2, .8 (approx.)
transition energy	250 MeV (approx.)
max beta functions (H,V)	3.9, 6.8 meter
max dispersion function	2.8 meter

III. ELECTRICAL

field range	.039 - 1.2 Tesla
current range	20 - 620 Amperes
coil resistance	.42 Ohms
coil inductance	77 milliHenry
I*R max	260 Volts
L*dI/dT max	920 Volts
average power	56 KiloWatt
stored energy	15 KiloJoule

IV. MISCELLANEOUS

tuneshift at injection	-.2 (bunch fact. = 5)
H x W of matched beam at 300 KeV	2.2 x 1.6 cm (LASL ion source)
weight (steel, copper)	3.8, .5 tons
operating temp. (steel, copper)	40, 50 degr. C
side of circumscribed square	7.5 meter (25 feet)
energy gain/turn	1.2 KiloVolts
RF power (50 ohm broadband system)	14 KiloWatts
time per turn	3.4 - .14 microsecond