SOME THOUGHTS ABOUT A 20-TEV PROTON SYNCHROTRON

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This proposal will discuss a 20-TeV proton synchrotron with an average beam intensity of 10^{13} protons/second. The design cycle would include 20 seconds of filling, 40 seconds of acceleration and 40 seconds of magnet recovery. Since it is anticipated that 10T superconducting magnets will be available at the start of construction, full advantage will be taken of the reduction in cost that the magnet technology offers. The design intensity corresponds to an average power output of the synchrotron in the form of beam of 50 mW. Since superconducting magnets do generate heat at helium temperature when they are pulsed, a large fraction of the refrigerator capacity is devoted to absorbing this load. If the average intensity could be reduced by a factor of two by lengthening the cycle time to 200 seconds, the cost of the refrigerator and rf system would be greatly reduced. The cost of the machine would be reduced by 25% by such a strategy. It is, however, of interest to consider a maximum performance machine at this time.

The machine as it is described here does not include an injector, or any provision for experimental use. These factors must be added to the cost. Long straight sections are provided with the normal quadrupole lattice for transporting the beam. Special magnets must be installed for experimental use of these areas.

A number of features unique to a large superconducting synchrotron require departures from the usual scaling laws for such machines. A high tune is chosen to minimize the effect of gradient errors in the magnets. Since the size of the magnet is directly linked with the field accuracy that can be achieved, this consideration is of great economic importance. Regions of normal iron-copper dipole magnets will be placed downstream of regions where there are to be extraction devices or beam scrapers to protect the superconducting magnets from the beam. An automatic, dynamic, orbit correction scheme will be incorporated to cancel the effects of surveying errors, foundation movement, and magnet errors. Since such systems have been demonstrated (at least in principle) on existing machines, it can be assumed that the requirements on the choice of site can be eased and that construction costs can be reduced.

Lattice

Present experience with the two 400-GeV synchrotrons shows that large machines are very sensitive to magnetic field imperfections even if the magnets are made very carefully. Since it appears at present that the quality of superconducting magnets may be inferior to that of iron-copper magnets, the design of the 20-TeV machine must be such that the influence of the field imperfections is minimized. This is accomplished by making the momentum dispersion and β-functions as small as possible by increasing the fraction of the circumference occupied by quadrupoles, from the 10% value characteristic of present machines to about 25%. The benefit of such a choice of quadrupole strength has already been demonstrated. The CERN 400-GeV machine with a tune of 27 is considerably less sensitive to dispersion related errors than is the Fermilab machine which operates at a tune of 19. The extreme sensitivity of betatron oscillation instability to the amplitude of the oscillations in the presence of field imperfections requires that the magnification of the transverse dimensions of the beam in the transfer from the injection be minimized. This is accomplished by choosing a small β value in the lattice.

The usual FODO lattice has been chosen for the usual reasons. This lattice is characterized by a cell length 2L and a quadrupole focal length F. The ratio $L/F = \sqrt{2}$ is chosen to give a 90° phase advance in the cell. The maximum value of the betatron function is then $\beta = (2 + \sqrt{2})\ L = \sqrt{2}(2 + \sqrt{2})F$. A beam-pipe diameter of 8 cm is assumed and the quadrupole gradient is $(dB/d_x) = (B_d/a)$ where B_d is the dipole field and a is the pipe radius. At the peak energy $(dB/dx) = 250$ T/M. The size of the beam pipe is determined by a consideration of the manner in which conductor placement errors distort the guide field. The 8 cm value at this moment is something of a guess.

A 10 meter long quadrupole will have a focal length of 27 meters. From the above consideration the cell length 2L = 76.4 meters. In this cell 50 meters will be occupied by dipole and 6.4 meters will be free space for correction elements and magnet connections. At 20 TeV, $B\rho = 6.67\times 10^4$ Tm. Therefore 41900 meters of 10T bending magnet length is required. Thus 840 cells with dipoles are needed. In addition the machine will have 120 cells without bending magnets. The Q value will therefore be 240. Although this value is 10 times larger than that of present machines, there should be no difficulty in achieving the required power supply accuracy at a reasonable cost. Table I summarizes the geometrical specifications.

Table I.

Quadrupole length/cell	20.0 meters
Dipole length/cell	50.0 meters
Free space/cell	6.4 meters
Total cell length	76.4 meters
Cells with dipoles	840 (65.17 km)
Cells without dipoles	120 (9.17 km)
Total number of cells	960 (73.34 km)

Beam Intensity

It is assumed that the 20-TeV ring will be "box car" loaded from a smaller injector. Existing 400-GeV machines (with $\beta_{max} \simeq 120$ m) demonstrated that a particle density of 5×10^{12} protons/km can be achieved. Since the β-max value of the lattice described above is only 130 meters there will be only a very small beam since magnification in the transfer from an injector like the Tevatron will be negligible and there should be no difficulty in accepting the particle density given above. The total intensity is then $5 \times 10^{12} \times 73.3 = 3.6 \times 10^{14}$ protons. We shall adopt 10^{15} as the peak intensity in anticipation of improvements that will be incorporated in the design of the injector. It is interesting to note that the stored energy in this beam at 20 TeV will be 3.2×10^{9} joules.

Cycles

To achieve 10^{13} protons/second on the average, a cycle time of 100 seconds is required. It will be assumed that this cycle will be 20 seconds of filling time, 40 seconds of acceleration, and 40 seconds of flat-top and magnet de-excitation.

RF Requirements

A 40 second acceleration time with 10^{15} particles in the beam implies a power input to the beam of 80 MW. Taking into account the losses in copper cavities, the final rf power requirement is 160 MW during acceleration. If superconducting cavities are developed, an 80 MW saving can be achieved. Since the revolution frequency is 4090 Hz, the required rf voltage (assuming a synchronous phase angle of 60 °) is 141 MV. An rf frequency of 300 MHz has been chosen so that efficient klystrons can be used as the power source. The harmonic number at this frequency will be 73,340. The synchrotron frequency corresponding to the above parameters is 2.85 Hz at the peak energy.

Magnet Power Supply

The magnetic field volume is approximately 211 m^3. At 10T the energy density in magnetic field is 39.8 MJ/m^3 so the total stored energy will be 8.4×10^9 joules. The peak power flow during a cycle with a constant acceleration of 500 GeV/second will be 420 MW. This could be reduced to 300 MW without greatly increasing the cycle time by reducing the rate of acceleration near the top energy. This pulsed power requirement is within the capabilities of existing power grids.

Refrigeration

The two main sources of heat load at low temperature are the static radiation load, and the losses in the superconductor when the magnets are excited in a pulsed mode. In a high-field machine with a short cycle the latter load will dominate. A static radiation load of 1 W/meter is assumed. The pulsed load is more difficult to predict because it is dependent on superconductor technology. A guess at this number is 400 J/machine cycle-meter. For the proposed machine the static heat load will be 73 kW at low temperature. In addition another 10 kW must be reserved for power leads and cold-warm transitions. The pulsed load will be 22 MJ/cycle at low temperature or 220 kW on the average. These results are summarized in Table II.

Table II. Average Heat Load at Helium Temperature

Static (radiation)	73 kW
Power leads	10 kW
AC loss	220 kW
Total	303 kW

To estimate the room temperature power consumption of the refrigerator a multiplication factor of 600 is assumed. With that conversion the power grid average load will be 182 MW.

Table III. Power Requirements

	Peak	Average
RF System[a]	246 MW	98 MW
Magnet Power	± 420 MW	10 MW
Refrigerator	300 MW	180 MW
Total	946 MW	288 MW

[a] 65 % efficiency is assumed for the klystrons.

Cost

A summary of the basic machine cost is summarized in the following table:

Table IV. Cost of the Basic Machine

Tunnel at $1000/m	73 × 10^6	$
RF at $1/watt input	246 × 10^6	$
Magnets at $2000/foot	332 × 10^6	$
Refrigerator	200 × 10^6	$
Controls and corrections	10 × 10^6	$
Magnet power supply	25 × 10^6	$
Total	$ 886 × 10^6	$

Conclusion

There does not appear to be any fundamental technical obstacle to the construction of a 20-TeV machine. Energy costs and availability may limit the repetition rate to a value lower than that given in this proposal