MULTI-TeV PROTON SYNCHROTRON APERTURE REQUIREMENTS

N.A. Monoszon and I.A. Shukeilo,
Efremov Research Inst. of Electrical and Physical Apparatus, Leningrad, USSR

V.A. Yarba,
IHEP, Serpukhov, USSR

ABSTRACT

Factors are discussed upon which the aperture of the superconducting multi-TeV synchrotron - Very Big Accelerator (VBA) - depends. The considerations presented are based upon the experience, in the designing and constructing of the biggest proton machines. The estimations are the result of the use of current views on particle dynamics as well as on magnet technology in the field of superhigh energy accelerators. A 20 TeV proton synchrotron with a Nb_3Sn superconducting magnet having a maximum field of 10 T is considered, the magnet lattice being of the FODO type. Such an accelerator was first mentioned at the previous Workshop in Batavia$^{1)}$.

1. INJECTION ENERGY AND BEAM CROSS SECTION

As is known at present the injection energy in a superconducting synchrotron is substantially determined by the field quality of the superconducting magnets. To reduce the effect of residual field on a circulating beam, acceleration should begin in magnetic field high enough. So the injection in the Tevatron and the UNK is 0.66 T and 0.67 T, respectively. The recent experimental data from the FNAL concerning residual fields in NbTi superconducting dipoles show an injection field of 0.1-0.2 T to be adequate to accelerate a beam.

The effective diameter of a superconducting filament from Nb_3Sn is less than that from NbTi alloy, and critical current density is higher. Because of this the VBA injection field appears to be approximately the same as that in the NbTi magnets. Thus the initial energy of a beam in VBA should not be less than several hundreds of GeV, i.e. a machine similar to the FNAL accelerator, SPS or the first UNK ring, should be considered as injectors.

The adiabatic damping of transverse and longitudinal oscillations at acceleration up to an energy of 0.5 TeV turns out to be rather considerable. The modern ion sources have the normalized transverse emittance $\tilde{\varepsilon} = 10\pi$ mm mrad. It in fact increases at acceleration due to a number of factors. Moreover, at the intermediate stage of acceleration, multiturn injection is often used in transverse phase space in order to increase pulse intensity. Owing to this we suppose that in the VBA $\tilde{\varepsilon}_{eff} = 10\tilde{\varepsilon}$. Then one gets the transverse emittance of a 0.5 TeV beam $\varepsilon = \tilde{\varepsilon}_{eff}/\beta\gamma = 0.2$ mm mrad. The corresponding diameter of the beam is quite small. It is 11 mm in the UNK magnet structure$^{2)}$. The momentum spread and amplitude of radial synchrotron oscillations, corresponding to proton energy of 0.5 TeV, are approximately $\pm 5\cdot 10^{-4}$ and 1 mm, respectively. Thus one is able to see that the linear dimension of the beam cross section in the VBA is rather small, less than 15 mm, provided that the length of the lattice period and the wave length of betatron oscillations in the VBA are such as those in the UNK. The number of protons in the beam of the emittance and the momentum spread presented above could amount to 10^{15}.

2. CLOSED ORBIT DISTORTIONS

The reasons of distortions of the closed orbit, around which betatron and synchrotron oscillations take place, are such factors as the random spread of dipole fields in magnet units and the errors in quadrupole alignment. Let us first consider the example based on the following tolerances: the random RMS spread of the dipole field $\langle \Delta B/B \rangle$ in 6m-length units is $1 \cdot 10^{-3}$, the RMS transverse displacement of the quadrupoles $\langle \Delta X \rangle$ is 0.2 mm. In the magnet lattice of the VBA the corresponding RMS closed orbit distortions $\langle Y_{max} \rangle_{\Delta B/B}$ and $\langle Y_{max} \rangle_{\Delta X}$ are 5.0 mm and 17.0 mm, respectively. The distance from the working point to an integer resonance in supposed to be 0.2, and the length of the lattice period and the wave length of betatron oscillations are the same as those in the UNK. The orbit distortions due to the alignment errors of quadrupoles at the tolerances assumed turn out to be dominant. Summing up the orbit distortions $\langle \Delta Y_{max} \rangle_{\Delta B/B}$ and $\langle \Delta Y_{max} \rangle_{\Delta X}$ squarely, one finds the total distortion $\langle \Delta Y_{max} \rangle$ to be 17.8 mm. It is worth noticing that amplitude deviations could be greater at some azimuths than those presented above. In order to eliminate the beam losses the figures mentioned should be doubled.

Owing to the fact that the beam cross section is small as compared to the vacuum chamber cross section one may believe that the β-function be not necessarily minimized at choosing the magnet lattice of the VBA. It is possible, for example, that the amplitude of betatron oscillations be increased to some extent due to the reduction of the optical force of quadrupoles. At this the tolerances upon which the frequency of betatron oscillations depends get less strict, and the orbit distortions due to the alignment errors of quadrupoles get smaller[3)], quadrupole parameters get better.

3. MAGNET LATTICE, TOLERANCES AND DEVIATIONS

The following is the example of a magnet lattice suitable from the viewpoint of engineering as well as of particle dynamics. Long straight sections should be added to this lattice.

a. Magnet Lattice

Number of periods	320
Length of a period	150 m

Quadrupole focal distance	75 m
Phase shift of betatron oscillations per period	60^o
Maximum β-value	260 m
Maximum ψ-value	3.27 m
Chromaticity (without long straight sections) $\varkappa = Q/(\Delta p/p)$	-60

b. Beam and Tolerances

Beam initial emittance	0.2π mm. mrad
Initial momentum spread	$\pm 5 \cdot 10^{-4}$
RMS field spread in dipoles	$1 \cdot 10^{-3}$
RMS spread of quadrupole axes	0.2 mm

c. Transverse Deviations

Betatron oscillation amplitude	7.2 mm
Synchrotron oscillation amplitude	1.6 mm
RMS closed orbit distortions due to $\langle \Delta B/B \rangle$	9.0 mm
RMS closed orbit distortions due to $\langle \Delta X \rangle$	15.4 mm
Total RMS distortion	17.8 mm

4. CONCLUSION

The aperture of the VBA is not determined by the real dimensions of the beam cross section. The factors inducing the closed orbit distortions appear to be more substantial at choosing the aperture.

The estimates presented above are based on rather strict field tolerances. The experience in the development of the biggest machines indicates that these tolerances are on the verge of realization. Some improvements in the magnet system production and the accuracy of geodetic measurements are unlikely to considerably reduce the closed orbit distortions. A substantial advancement is likely to be achieved in orbit correction technique at the stage of starting the accelerator.

It is extremely important in the VBA that the orbit be corrected within the first revolution. In the beam circulating mode orbit distortions may be decreased down to some mm by correcting the orbit according to the data of beam radial position. This procedure is confirmed by the experience with big cyclic accelerators. Thus proceeding from the data quoted in 3c it follows that the aperture of 60-70 mm is sufficient from the point of view of particle dynamics. Betatron oscillations needed for effective slow extraction will be obtained in the vacuum chamber of such an aperture.

However, trying to reduce the aperture by the more strict field tolerances, one should take into account engineering factors natural to superconducting systems. Taking into account the properties of Nb_3Sn superconductors, their production technology, and the protection of coils during quench, one should expect the design current density in the VBA coils to be approximately equal to that in the TeV machines with Nb-Ti magnets. This means that the radial dimension of coils should be increased from 2 cm to 4.5 - 5 cm. The field energy stored outside the magnet bore (in the coil region) will substantially exceed that in the bore. Under these conditions the ultimate reduction of the aperture causes additional troubles in field formation and some minor reductions in stored energy, weight of the superconductor, the dimensions of magnets and their costs.

In accordance with particle dynamics and engineering requirements, one can consider a bore diameter of 80 mm to be adequate.

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REFERENCES

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2) The IHEP Accelerator-Storage Complex Status Report, Ibid., p. 13.

3) I.A.Shukeilo, Journal of Technical Physics. 43, 443 (1973).