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THE DESIGN OF THE ZERO GRADIENT SYNCHROTRON BOOSTER-II LATTICE*

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Introduction

A 500 MeV booster has been designed at the Argonne National Laboratory to increase the beam intensity from the Zero Gradient Synchrotron (ZGS). Many turns of H^- ions from the 50 MeV linac will be injected into the booster and stripped to H^+ so that the ring will contain the maximum useful charge in each booster pulse. Several booster pulses will be injected into the ZGS to form one ZGS pulse. This machine is now under construction.

Booster Requirements

Some of the features required in Booster II are:

1. Multiturn injection of 50 MeV H^- ions onto a stripper is used to get an intense beam in the booster. The beam will be injected through a hole in the thin outer yoke of a focussing magnet. The H^- beam will leave this magnet traveling in a booster orbit and will be stripped to H^+ in the following straight section. The only effect that this has on the lattice is that there must be enough space in the straight section for the stripper.

2. The space charge limit must be well over 10^{12} protons per booster pulse. This is achieved by making the area of the useful magnetic field in the ring magnets large enough. The space charge limit is maximized by adjusting the magnet lengths so that the beam makes effective use of the available space.

3. Straight sections are required for many purposes: the stripper, extraction magnets, RF cavities and so forth. To minimize the number of space wasting straight section ends, the booster is designed with 6 periods. A peak magnetic field of about 10,000 G is required to realize adequate straight section length in the circumference.

4. The transition energy must be well outside of the range of beam energies in the booster, 50-500 MeV. A transistion gamma, E/E_0, of two is satisfactory and easily obtained in a machine with 6 periods.

5. The external beam must have high quality for injection into the ZGS and must be extracted from the booster in a single turn. The beam is extracted by kicker magnets. The beam is given a large deflection angle while it is still in the good field region of the ring magnets. This is done by passing the beam through a short defocussing magnet after the final kicker. The radial beta function in the straight section following the defocussing magnet is quite small. This permits a septum magnet to be placed between the space used by the injected beam and the extracted beam.

Design Calculations

The betatron frequencies, beta functions, transition energy, magnetic field strength, space charge limits, extraction orbits, and so forth were calculated by a computer program written in SPEAKEASY.[1] SPEAKEASY is a high level computer language which, for example, manipulates arrays and matrices in response to simple commands. Tabular and graphic output are also part of the language.

Equations such as those found in ref. 2. A Selection of Formulae . . . from CERN, were used for most calculations. However, the maximum change in the betatron frequency of a particle due to space charge is computed by

$$\Delta Q = -\frac{NrR}{\pi \beta^2 \gamma^3 Q B} \ \text{average}\left[\frac{1}{b(a+b)}\right] F$$

where N = number of protons
r = classical proton radius
R = synchrotron circumference/2π
Q = betatron frequency
B = bunching factor
b = half height of beam
a = half width of beam, including momentum oscillation
F = a factor assumed to be 1.

Description of Booster II

A plan of Booster II is shown in Fig. 1 and the lengths of the elements are given in Table I. The circumference of the booster is 1/4 of the ZGS circumference.

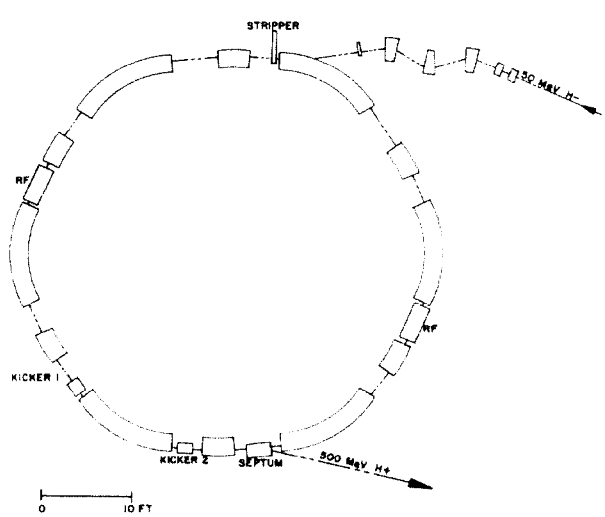

Fig. 1

Booster II Plan View

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Table I

Booster II Dimensions

Circumference (length of central orbit)	1691.064 in
Circumference/2 π	269.141 in
Orbit radius in magnets	145.000 in
Length of short straight section	54.000 in
Length of defocussing singlet magnet	26.151 in
Length of long straight section	76.000 in
Length of FDF triplet magnet	125.693 in
First focussing section	34.458 in
Central defocussing section	54.724 in
Second focussing section	36.522 in
Width of useful field at injection	4.000 in
Height of gap at center line (145 in radius)	2.460 in
The magnet is used as the vacuum chamber	
Vacuum chamber height at center line	2.460 in
Vacuum chamber width	16.48 in

Table II gives other characteristics. The betatron oscillation frequencies were chosen to avoid recognized resonances. The number of vertical oscillations per revolution is slightly less than ν_y=7/3. ν_x is between the $2\nu_x - \nu_y = 2$ line and the $\nu_x = \nu_y$ line.

Table II

Booster Characteristics

Betatron oscillations per revolution		
radial	2.20	
vertical	2.32	
change due to 10^{13} protons	-0.1	
Transition gamma (E_T/E_o)	2.0	
Maximum radial beta function	277.	in
Maximum vertical beta function	211.	in
Maximum orbit displacement per dp/p	83.	in
Beam quality for filled chamber		
radial	8.	π mr in
vertical	5.	π mr in
Magnetic field		
at 50 MeV	2.8 kG	
at 500 MeV	9.9 kG	
Normalized gradient (B^{-1} dB/dR)		
focussing magnets	0.0811 per in	
defocussing magnets	-0.0811 per in	
Oscillator frequency (first harmonic)		
at 50 MeV	2.2 MHz	
at 500 MeV	5.3 MHz	

Figs. 2, 3, and 4 illustrate features of Booster II. In all three figures the synchrotron elements are identified by the initials:

S	short straight section
D_1	singlet defocussing magnet
L	long straight section
F_1	first focussing element of the triplet
D_2	defocussing element of the triplet
F_2	second focussing element of the triplet
K_1	first extraction kicker
K_2	second extraction kicker
S_1	first septum magnet
S_2	second septum magnet

Fig. 2 shows the beta functions and the off momentum orbit. Note that both the amplitude of the off momentum orbit and the radial beta function are small near the singlet defocussing magnet. This is important for extraction of the beam.

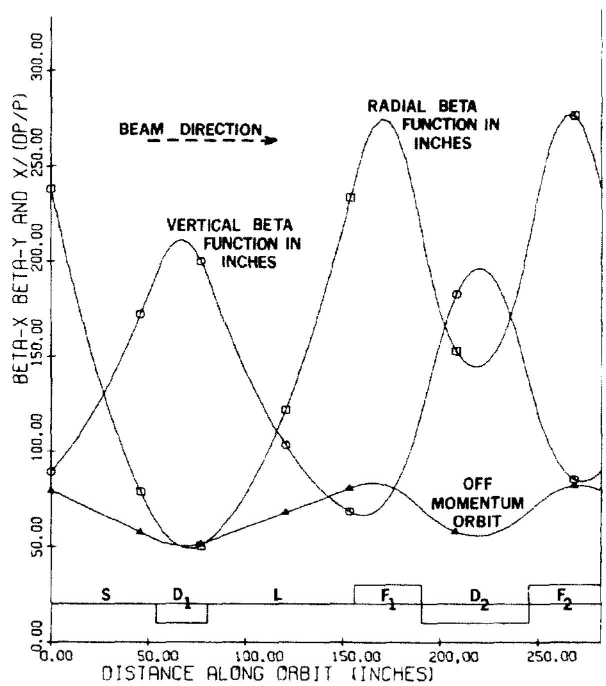

Figure 2

Beta Functions and Off Momentum Orbit
The off momentum orbit is
in inches per dp/p.

Fig. 3 shows the space used by the beam at injection as a function of position in the lattice. The elements of the booster lattice are separated by x's. The curve labeled with the beam direction arrow is the maximum absolute x versus the maximum absolute y for the beam envelope as a function of position through one period of the booster. The radial amplitude includes contributions due to momentum spread and betatron oscillations. The line labeled pole tip gives min. abs. y vs. min. abs. x for a pole tip with a central gap of 2.22 in. The lengths of the focussing and defocussing magnets and the absolute field gradient were adjusted to get the desired betatron frequencies and to make the envelope of the beam use the space enclosed by the pole tip and x = 2. As would be expected the beam does not go to maximum x in the defocussing magnets nor to maximum y in the focussing magnets. The corner at large y and x is not used in either type of magnet. These facts were used to guide the detailed magnet design.

Extraction

The beam bucket is extracted in a single turn by using fast kicker magnets. The positions of the kicker magnets, in relation to the ring magnets, are shown in Fig. 1. Fig. 4 shows the relationship between the envelope of the extracted beam, the aperature of the magnets, and the space required by the injected beam. The first kicker, K_1, bends the beam 10 mr. The second kicker, K_2, bends the beam 15 mr. After the beam leaves K_2 and goes through the ring magnet D_1 it passes outside of the septum of septum magnet S_1. S_1 operates at 5000 G and bends the beam 52 mr in its 10 in length. S_2 operates at 10,000 G and bends the beam 210 mr in its 30 in length. The beam then passes outside of the thin outer yoke of the next ring magnet.

References

1 - The SPEAKEASY -3 Reference Manual, May, 1973, Stanley Cohen, Argonne National Laboratory, ANL-8000.

2 - A Selection of Formulai and Data Useful for the Design of A. G. Synchrotrons, C. Bovet, R. Jouiran, I. Gumowski, K. H. Reich, CERN/MPS-SI/Int. DL/70/7, April 23, 1970.

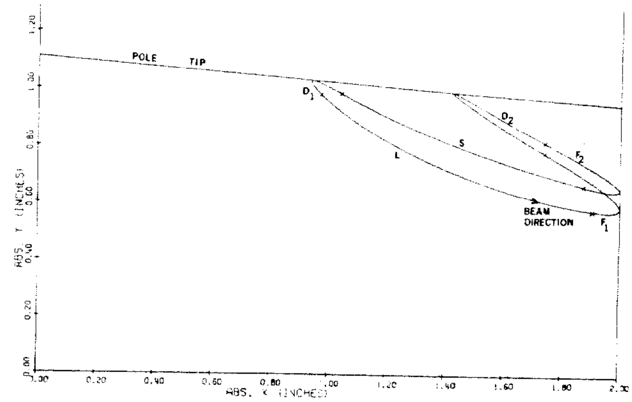

Fig. 3
Maximum Beam Dimensions vs. Position Through One Period of the Booster.

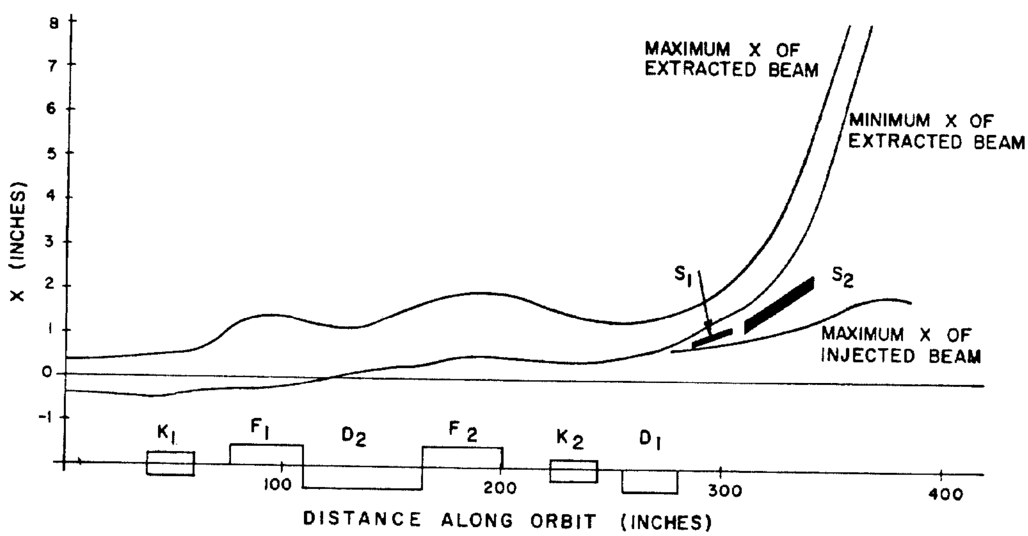

Fig. 4

Extracted Beam