BNL-104757-2014-TECH

AGS/AD/Tech Note No. 341;BNL-104757-2014-IR

Modeling Backleg Winding Bumps with the BEAM Program

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August 1990

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

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Accelerator Division
Technical Note

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Windings around the backlegs of the AGS ring magnets are used to manipulate the equilibrium orbit at various locations in the ring during injection and extraction. The windings are excited with currents in configurations which produce lambda and three-halves lambda bumps. Following are results obtained by modeling these bumps with the BEAM code [1].

1 Additions to the BEAM Code

The version of the BEAM code used here contains the nuquads, which are used to adjust the tunes of the machine at low field, and the beta quads, which are used to eliminate the beta function distortion due to remanent fields. In the BEAM code the horizontal and vertical nuquads [2] are excited with currents determined by settings of NUQH and NUQV. A command of N counts issued to NUQH or NUQV results in a current of $N/80$ amps in the corresponding nuquad string. A command of N counts issued to BTQD results in a current of $N/500$ amps in the beta quads according to the scheme of reference [2]. A setting of BTQD = 2800 is required to eliminate the beta function distortion.

2 The Three-Halves Lambda Bump at A20

The three-halves lambda bump at A20 is produced by backleg windings on the L18, L19, A12, A13, B6, B7, B20, and C1 magents. These windings are connected in series to a single power supply so that each winding is excited with the same current. The number of turns around each of the backlegs depends on the length of the magnet. Five and six turns are wound around the backlegs of the 'long' (90 inch) and 'short' (75 inch) magnets respectively. This insures that the dipole kicks produced by magnets of different lengths will be equal if the backleg windings are excited with equal currents.

To simulate the effect of the backleg windings in the BEAM code, the particle momentum is incremented by an amount δp just before it enters a magnet with a backleg winding, and is decremented by the same amount as it exits the magnet. Table I lists $\delta p/p$ for each of the eight magnets used to produce the three-halves lambda bump at A20. (Here p is the particle momentum on the reference orbit.)

Table I: A20 3/2 λ Bump

Backleg	Type	Length	$\delta p/p$
L18	F	long	$-a$
L19	D	short	$-1.2a$
A12	D	short	$1.2a$
A13	F	long	a
B6	F	long	a
B7	D	long	a
B20	D	short	$-1.2a$
C1	F	short	$-1.2a$

Note that the set of eight magnets consists of four pairs of adjacent magnets. Each pair consists of an F (focusing) and a D (defocusing) type magnet so that adjacent magnets produce no net shift in the machine tunes. The sign of $\delta p/p$ indicated in the table is such that the first and fourth pairs produce horizontal kicks to the inside (for $a > 0$) and the second and third pairs produce kicks to the outside. Since the four pairs are spaced approximately one-half betatron wavelength apart, a 3/2 λ bump with it's center between the second and third pairs is produced. The deviation of this bump from the unperturbed equilibrium orbit is approximately twice as large at the center as it is at the other two maxima of the bump. Outside the bump region the equilibrium orbit is not appreciably distorted. Although each pair of backlegs produces no net shift in the machine tunes, the bumped orbit does pass through sextupole fields produced by the main magnets and the beam therefore sees quadrupole fields which can shift the machine tunes and open up the half-integer resonance stopbands. The tune shifts, stopband widths, and bump amplitudes obtained from the BEAM code for various values of a are given in the following tables.

With BTQD = 2800 (to eliminate the beta function distortion at injection) the BEAM code was run with the 250 gauss (injection field) field map option for various values of a. (The momentum on the reference orbit for this field map is 0.650 GeV/c.) The results obtained with NUQH = NUQV = 0 are summarized in Table II. Columns 2 and 3 list the horizontal and vertical tunes, and columns 4 and 5 list the position and angle (in the BEAM code coordinate system) of the equilibrium orbit at the center of the A20 straight section.

Table II: A20 $3/2\,\lambda$ Bump

a	Q_H	Q_V	y (in)	y' (mrad)
−0.025	8.7444	8.7733	−1.81	−2.84
−0.020	8.7443	8.7735	−1.47	−2.25
−0.015	8.7442	8.7740	−1.13	−1.66
−0.010	8.7437	8.7746	−0.79	−1.07
−0.005	8.7427	8.7759	−0.45	−0.48
0.000	8.7430	8.7759	−0.10	0.12
0.005	8.7433	8.7762	0.24	0.71
0.010	8.7445	8.7757	0.59	1.30
0.015	8.7455	8.7756	0.94	1.90
0.020	8.7451	8.7763	1.29	2.50
0.025	8.7454	8.7769	1.65	3.10

The half-integer ($2Q_H = 17$) stopband width, W, for various values of a was obtained in two different ways. The results are given in tables III and IV. To obtain the widths listed in table III, NUQV was fixed at −654 and the range of settings of NUQH was found for which the particle was inside the stopband. (The particle is inside the stopband whenever the trace of the transfer matrix for one turn around the machine is qreater than 2 or less than −2.) This range is indicated in column 2. The stopband width is the width of the corresponding range of horizontal tunes (listed in column 3) obtained with no bump ($a = 0$).

Table III: A20 3/2 λ Bump

a	Nuquad Stopband		W
-0.025	$1291 < \mathrm{NUQH} < 1336$	$8.5045 > Q_H > 8.4934$	0.0111
-0.020	$1292 < \mathrm{NUQH} < 1327$	$8.5042 > Q_H > 8.4956$	0.0086
-0.015	$1295 < \mathrm{NUQH} < 1322$	$8.5035 > Q_H > 8.4969$	0.0066
-0.010	$1298 < \mathrm{NUQH} < 1319$	$8.5027 > Q_H > 8.4976$	0.0051
-0.005	$1301 < \mathrm{NUQH} < 1316$	$8.5020 > Q_H > 8.4983$	0.0037
0.005	$1306 < \mathrm{NUQH} < 1317$	$8.5008 > Q_H > 8.4981$	0.0027
0.010	$1304 < \mathrm{NUQH} < 1323$	$8.5013 > Q_H > 8.4966$	0.0047
0.015	$1302 < \mathrm{NUQH} < 1330$	$8.5018 > Q_H > 8.4949$	0.0069
0.020	$1297 < \mathrm{NUQH} < 1337$	$8.5030 > Q_H > 8.4932$	0.0098
0.025	$1295 < \mathrm{NUQH} < 1345$	$8.5035 > Q_H > 8.4912$	0.0123

To obtain the widths listed in table IV, NUQV and NUQH were set to zero and the range of momentum was found for which the particle was inside the stopband. This range is listed in column 2. The stopband width is the width of the corresponding range of horizontal tunes (listed in column 3) obtained with no bump ($a = 0$).

Table IV: A20 3/2 λ Bump

a	Momentum Stopband		W
-0.025	$0.01152 < \Delta P/P < 0.01188$	$8.5082 > Q_H > 8.5012$	0.0070
-0.020	$0.01158 < \Delta P/P < 0.01189$	$8.5068 > Q_H > 8.5009$	0.0059
-0.015	$0.01166 < \Delta P/P < 0.01186$	$8.5053 > Q_H > 8.5014$	0.0039
-0.010	$0.01176 < \Delta P/P < 0.01191$	$8.5032 > Q_H > 8.5006$	0.0026
-0.005	$0.01187 < \Delta P/P < 0.01193$	$8.5013 > Q_H > 8.5002$	0.0011
0.005	$0.01183 < \Delta P/P < 0.01196$	$8.5019 > Q_H > 8.4996$	0.0023
0.010	$0.01179 < \Delta P/P < 0.01196$	$8.5026 > Q_H > 8.4996$	0.0030
0.015	$0.01176 < \Delta P/P < 0.01199$	$8.5032 > Q_H > 8.4991$	0.0041
0.020	$0.01174 < \Delta P/P < 0.01205$	$8.5036 > Q_H > 8.4980$	0.0056
0.025	$0.01169 < \Delta P/P < 0.01207$	$8.5046 > Q_H > 8.4976$	0.0070

The tune shifts and stopband widths seen in tables II–IV can be understood qualitatively in the following way. The central maximum of the A20 bump is to the outside (for $a > 0$) and is in the A19 straight section which is between two D magnets. The other two maxima of the bump are to the inside and are in the A5 and B13 straight sections which are both between F magnets. At these maxima the bumped orbit passes through sextupole fields produced by the main magnets and the beam therefore sees a quadrupole field which is proportional to the displacement of the bumped orbit form the nominal equilibrium orbit. This quadrupole field is twice as large at central maximum as it is at the other two maxima, and it has the opposite sign. The integrated strength of these quadrupole fields over the region of the bump is therefore approximately zero. However, the contribution of a quadrupole field at some point along the bumped orbit to the tune shift and the stopband width is proportional to both the quadrupole strength and the beta function at that point. Since the central maximum of the bump is at a beta minimum, and the other two maxima of the bump are at beta maximums, the contribution of the central maximum is not canceled by the contributions of the other maxima. The result is a net contribution to the tune and stopband width which depends on the amplitude of the bump.

3 The Three-Halves Lambda Bump at L20

The three-halves lambda bump at L20 is produced by backleg windings on the K19, K20, L13, L14, A7, A8, B1, and B2 magnets. As with the A20 bump, the windings are connected in series to a single power supply and five and six turns are wound around the backlegs of the 'long' and 'short' magnets respectively. Table V lists the amounts by which the momentum is incremented in each magnet to simulate the effect of the backleg windings in the beam program.

Table V: L20 3/2 λ Bump

Backleg	Type	Length	$\delta p/p$
K19	D	short	$-1.2a$
K20	D	short	$-1.2a$
L13	F	long	a
L14	F	long	a
A7	D	long	a
A8	D	long	a
B1	F	short	$-1.2a$
B2	F	short	$-1.2a$

As with the A20 bump, the set of eight magnets consists of four pairs of adjacent magnets which produce a 3/2 λ bump centered between the second and third pairs. However for the L20 bump, the adjacent magnets in each pair are either both F or both D magnets. This means that the quadrupole perturbations due to the backleg windings do not cancel locally as they do with the A20 bump. Instead, the contribution of the K19 and K20 backlegs to the tune shift and stopband width is canceled by the contribution of the A7 and A8 backlegs which are approximately one betatron wavelength away and are excited with the opposite current. Similarly, the contribution of the L13 and L14 backlegs is canceled by that of the B1 and B2 backlegs. Although the backlegs produce no net shift in the machine tunes, the bumped orbit does pass through sextupole fields produced by the main magnets and the beam therefore sees quadrupole fields which can shift the machine tunes and open up the half-integer resonance stopbands. The tune shifts, stopband widths, and bump amplitudes obtained from the BEAM code for various values of a are given in the following tables.

With BTQD = 2800 the BEAM code was run with the 250 gauss (injection field) field map option for various values of a. The results obtained with NUQH = NUQV = 0 are summarized in Table VI. Columns 2 and 3 list the horizontal and vertical tunes, and columns 4 and 5 list the position and angle (in the BEAM code coordinate system) of the equilibrium orbit at the center of the L20 straight section.

Table VI: L20 3/2 λ Bump

a	Q_H	Q_V	y (in)	y' (mrad)
0.000	8.7430	8.7759	−0.10	0.12
0.005	8.7431	8.7760	0.26	0.88
0.010	8.7445	8.7755	0.63	1.65
0.015	8.7449	8.7757	1.01	2.41
0.020	8.7445	8.7767	1.38	3.18
0.025	8.7447	8.7775	1.75	3.94

The half-integer ($2Q_H = 17$) stopband width, W, obtained for various values of a is given in tables VII and VIII. To obtain the widths listed in table VII, NUQV was fixed at −654 and the range of settings of NUQH was found for which the particle was inside the stopband. This range is indicated in column 2. The stopband width is the width of the corresponding range of horizontal tunes (listed in column 3) obtained with no bump ($a = 0$).

Table VII: L20 3/2 λ Bump			
a	Nuquad Stopband		W
0.005	$1305 < \text{NUQH} < 1314$	$8.5010 > Q_H > 8.4988$	0.0022
0.010	$1305 < \text{NUQH} < 1316$	$8.5010 > Q_H > 8.4983$	0.0027
0.015	$1303 < \text{NUQH} < 1321$	$8.5015 > Q_H > 8.4971$	0.0044
0.020	$1300 < \text{NUQH} < 1325$	$8.5022 > Q_H > 8.4961$	0.0061
0.025	$1299 < \text{NUQH} < 1329$	$8.5025 > Q_H > 8.4952$	0.0073

To obtain the widths listed in table VIII, NUQV and NUQH were set to zero and the range of momentum was found for which the particle was inside the stopband. This range is listed in column 2. The stopband width is the width of the corresponding range of horizontal tunes (listed in column 3) obtained with no bump ($a = 0$).

Table VIII: L20 3/2 λ Bump			
a	Momentum Stopband		W
0.005	$0.01185 < \Delta P/P < 0.01195$	$8.5016 > Q_H > 8.4999$	0.0017
0.010	$0.01178 < \Delta P/P < 0.01192$	$8.5027 > Q_H > 8.5004$	0.0023
0.015	$0.01178 < \Delta P/P < 0.01193$	$8.5027 > Q_H > 8.5002$	0.0025
0.020	$0.01177 < \Delta P/P < 0.01195$	$8.5030 > Q_H > 8.4999$	0.0031

The tune shifts and stopband widths for the L20 bump are smaller than those for the A20 bump. This can be understood qualitatively in the following way. The values of the beta function at the maxima of the L20 bump (in straight sections L6, L20, and A14) are approximately equal. Using the arguments given in the preceeding section, one then finds that the contributions to the tune and stopband width due to the orbit displacement in the sextupole fields approximately cancel, resulting in smaller tune shifts and stopband widths.

4 The Lambda Bump at L20

The lambda bump at L20 is produced by backleg windings on the L6, L7, A14, and A15 magnets. The windings are connected in series to a single power supply and seven turns are wound around each backleg. Table IX lists the amounts by which the momentum is incremented in each magnet to simulate the effect of the backleg windings in the beam program.

Table IX: L20 λ Bump			
Backleg	Type	Length	$\delta p/p$
L6	F	long	$-7a/5$
L7	D	long	$-7a/5$
A14	F	long	$7a/5$
A15	D	long	$7a/5$

The set of four magnets consists of two pairs of adjacent magnets which produce a lambda bump centered between the two pairs. Since each pair consists of an F and a D magnet, adjacent magnets produce no net shift in the machine tunes. However, the beam on the bumped orbit sees quadrupole fields (due to the displacement of the bumped orbit in the sextupole fields of the main magnets) which can shift the machine tunes and open up the half-integer resonance stopbands. The tune shifts, stopband widths, and bump amplitudes obtained from the BEAM code for various values of a are given in the following tables.

With BTQD = 2800 the BEAM code was run with the 250 gauss (injection field) field map option for various values of a. The results obtained with NUQH = NUQV = 0 are summarized in Table X. Columns 2 and 3 list the horizontal and vertical tunes, and columns 4 and 5 list the position and angle (in the BEAM code coordinate system) of the equilibrium orbit at the center of the L20 straight section.

Table X: L20 λ Bump				
a	Q_H	Q_V	y (in)	y' (mrad)
0.000	8.7430	8.7759	−0.10	0.12
0.005	8.7422	8.7759	−0.07	0.59
0.010	8.7421	8.7752	−0.04	1.07
0.015	8.7424	8.7745	−0.01	1.54
0.020	8.7431	8.7740	0.02	2.02
0.025	8.7423	8.7745	0.05	2.50

The half-integer ($2Q_H = 17$) stopband width, W, obtained for various values of a is given in tables XI and XII. To obtain the widths listed in table XI, NUQV was fixed at −654 and the range of settings of NUQH was found for which the particle was inside the stopband. This range is indicated in column 2. The stopband width is the width of the corresponding range of horizontal tunes (listed in column 3) obtained with no bump ($a = 0$).

Table XI: L20 λ Bump

a	Nuquad Stopband		W
0.005	$1303 < \mathrm{NUQH} < 1310$	$8.5015 > Q_H > 8.4998$	0.0017
0.010	$1298 < \mathrm{NUQH} < 1314$	$8.5027 > Q_H > 8.4988$	0.0039
0.015	$1296 < \mathrm{NUQH} < 1315$	$8.5032 > Q_H > 8.4986$	0.0046
0.020	$1299 < \mathrm{NUQH} < 1317$	$8.5025 > Q_H > 8.4981$	0.0044
0.025	$1297 < \mathrm{NUQH} < 1318$	$8.5030 > Q_H > 8.4978$	0.0052

To obtain the widths listed in table XII, NUQV and NUQH were set to zero and the range of momentum was found for which the particle was inside the stopband. This range is listed in column 2. The stopband width is the width of the corresponding range of horizontal tunes (listed in column 3) obtained with no bump ($a = 0$).

Table XII: L20 λ Bump

a	Momentum Stopband		W
0.005	$0.01187 < \Delta P/P < 0.01192$	$8.5013 > Q_H > 8.5004$	0.0009
0.010	$0.01177 < \Delta P/P < 0.01190$	$8.5030 > Q_H > 8.5008$	0.0022
0.015	$0.01173 < \Delta P/P < 0.01186$	$8.5039 > Q_H > 8.5014$	0.0025
0.020	$0.01167 < \Delta P/P < 0.01184$	$8.5050 > Q_H > 8.5018$	0.0032
0.025	$0.01160 < \Delta P/P < 0.01184$	$8.5066 > Q_H > 8.5018$	0.0048

In addition to the set of magnets listed in Table IX, two other sets of magnets were modeled with the BEAM code. Both sets produced a lambda bump centered near L20. The first set consisted of magnets L5, L6, A13, and A14, and produced larger angles at L20 than those listed in Table X; however it also opened up larger half-integer stopbands. The second set consisted of magnets L7, L8, A15, and A16. This set opened up smaller half-integer stopbands but the angles produced at L20 were also smaller.

5 References

1. G. H. Morgan, 'Fortran IV Revision of BEAM, the AGS Orbit Computing Program', Accelerator Department Internal Report No. GHM–1, June 1, 1966. C. J. Gardner, Memorandum—New BEAM Program Note, January 24, 1986.

2. C. J. Gardner, 'A Review of the Low-Field Correction System Presently Employed in the AGS', AGS/AD/Op. Note No. 17, February 4, 1988.