

## Summary of April 10, 2017 Lattice

J. S. Berg

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**Brookhaven National Laboratory**

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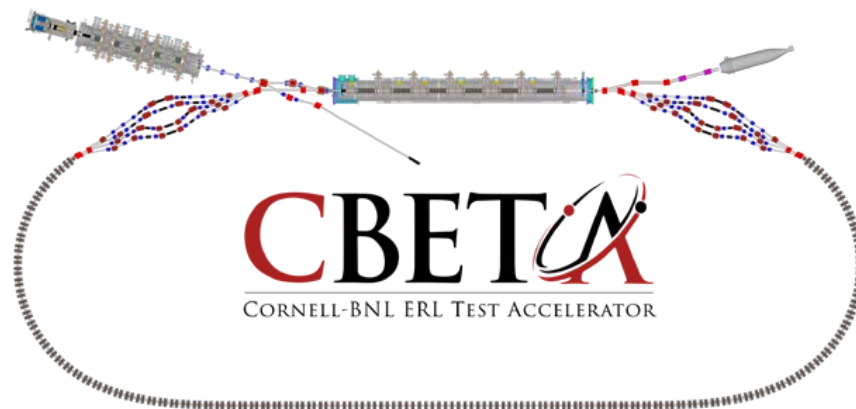
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Collider-Accelerator Department, Brookhaven National Laboratory, Upton NY 11973  
U.S. Department of Energy  
Office of Science, Office of Nuclear Physics

Cornell Laboratory for Accelerator-Based Sciences and Education, Ithaca, NY 14850

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# Summary of April 10, 2017 Lattice

J. Scott Berg<sup>1</sup>

Brookhaven National Laboratory; P. O. Box 5000; Upton, NY, 11973-5000; USA

## Abstract

We present a summary of the April 17, 2017 CBETA Lattice.

Table 1: Machine parameters.

Total energy, injection (MeV)	6
Total energy, pass 1 (MeV)	42
Total energy, pass 2 (MeV)	78
Total energy, pass 3 (MeV)	114
Total energy, pass 4 (MeV)	150
RF frequency (GHz)	1.29994000 GHz
Harmonic number, normal pass	343

## 1. Introduction

Table 1 gives important high-level parameters for the machine. A drawing of the CBETA lattice is shown in Fig. 1. The machine consists of a number of sections:

**Injector (IN)** Production of the beam, acceleration to 6 MeV, and transport to the beginning of the linac. This is already in place and operating, and little more detail will be provided here.

**Linac (LA)** A 1.3 GHz superconducting linac, accelerating electrons nominally by 36 MeV. This is already in place and operating, and little more detail will be provided here, other than the fact that the precise operating frequency will be 1.29994000 GHz.

**Beam Stop (BS)** A transport line for the final 6 MeV decelerated beam.

**Spreaders (SX/RX)** SX will capture the beams from the linac at the four nominal design energies, match the betatron functions, and steer the orbits so that after the beams are recombined, they arrive on the periodic orbits in the FFAG arc. RX reverses this process, taking the beams from the FFAG arc back to the linac.

**Arc (FA/FB)** The FFAG arc returning the beams coming out of and going back into the the spreaders.

**Straight (ZA/ZB)** A straight beamline similar to the FFAG arc, returning the beam across the distance parallel to the linac.

**Transition (TA/TB)** An adiabatic transition between the FFAG arc and the straight, bringing the full energy range of beams from the arcs onto the axis of the straight.

The arc, straight, and transition sections are detailed in a separate document, with the exception that I will detail some modifications of individual magnets near the spreader.

## 2. Spreaders

There are four SX lines and four corresponding RX lines, corresponding to the four design energies. They are numbered 1 through 4, from lowest to highest energies, and designated S1, S2, etc. A detailed view of the SX lines is shown in Fig. 2. The first three lines have two different configurations, depending on whether the energy recovery linac is run with that pass at its maximum energy or not. Each spreader line has one configuration when it is used for the highest energy (recovery mode), and a different configuration when it is lower than the highest energy (non-recovery mode). This reconfiguration requires moving the magnets and beam pipe. The current lattice files have configurations for 1 pass and 4 pass energy recovery. Configurations for 2 and 3 pass recovery still need to be designed.

Just before the SX lines, there is a dipole (LA.DEMER.BEN01) to bend the 6 MeV beam to the beam stop line that all beams will pass through. When running in the fractional arc test (FAT) configuration, this magnet will not be present. A study of the lattice in this configuration has yet to be done.

Each spreader line has 8 quadrupoles for betatron and dispersion matching plus  $R_{56}$  control. All quadrupoles are 20 cm long.

*Email address:* jsberg@bnl.gov (J. Scott Berg)

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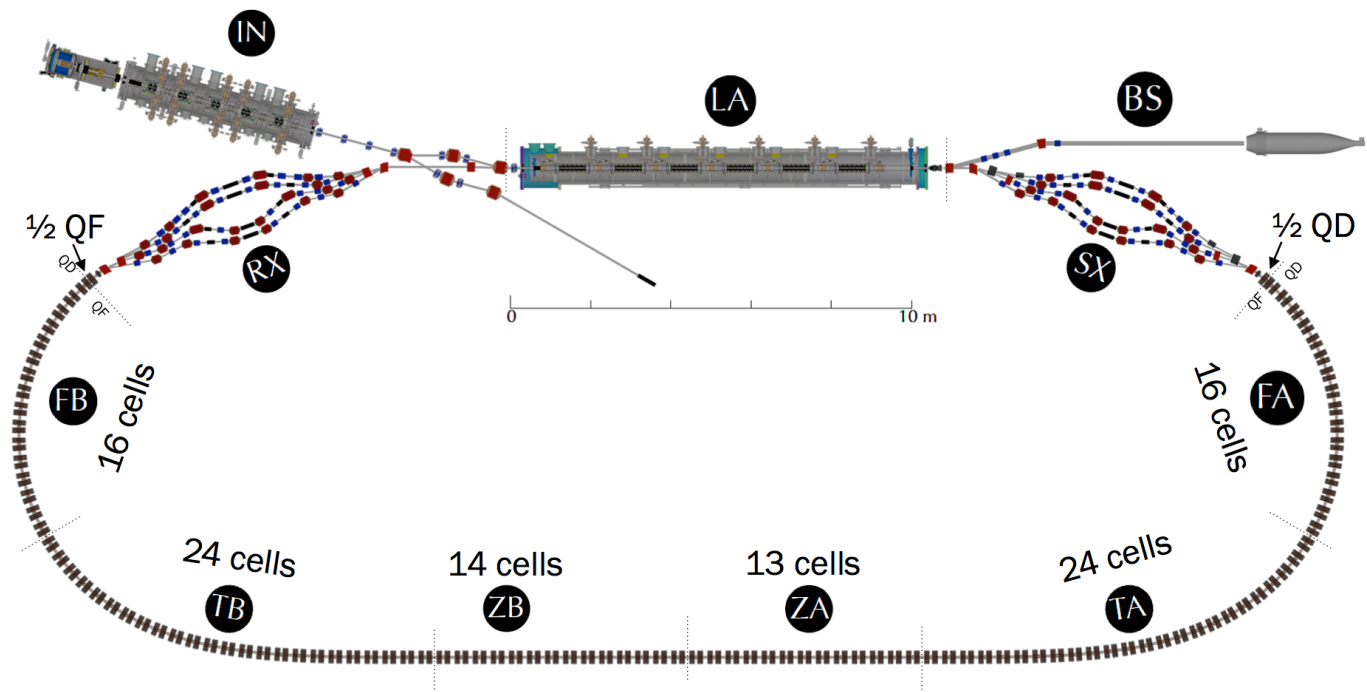


Figure 1: Overview of the CBETA lattice.

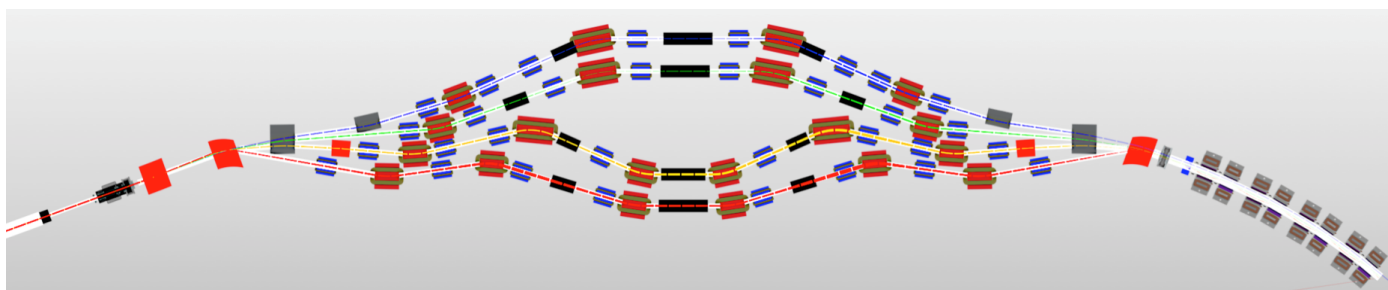


Figure 2: Detail view of the SX spreader line.

Table 2: Common dipole parameters.

	Energies (MeV)	Length (m)	Field (T)
IN.MERGE.BEN03	6–150	0.32	+0.0160
LA.DEMER.BEN01	6–150	0.20	+0.0258
S1.BEN01	42–150	0.20	-0.3760
S1.BEN08	42–150	0.20	-0.3502
R1.BEN01	42–150	0.20	-0.3502
R1.BEN08	42–150	0.20	-0.3502
R1.BEN99	42–150	0.20	-0.0258
S2.BEN01	78–150	0.20	-0.1676
S2.BEN10	78–150	0.20	-0.1676
R2.BEN01	78–150	0.20	-0.1676
R2.BEN10	78–150	0.20	-0.1676

Numbering of elements in spreaders starts with smaller numbers at the linac end unless otherwise indicated.

From the design report, we intend to have four vertical correctors per spreader line. They are not currently in the lattice.

The beam pipes between the central four dipoles of each line are connected by sliding joints to allow for small path length adjustments.

### 2.1. Common Dipoles

Several dipoles are shared by multiple beams. IN.MERGE.BEN03 merges the injected beam at the linac, while LA.DEMER.BEN01 serves to send the low energy beam to the dump after the linac. IN.MERGE.BEN03 is currently in place on the floor. LA.DEMER.BEN01 will not be in place for the fractional arc test. S1.BEN01 separates the beams at the entrance to the spreader into multipole lines, and S1.BEN08 recombines them before entering the FFAG section. Since the diagnostic beam line for the injector requires a greater space between R1.BEN01 and IN.MERGE.BEN03 than there is between LA.DEMER.BEN01 and S1.BEN01, an extra dipole, R1.BEN99, is inserted between R1.BEN01 and IN.MERGE.BEN03 assist with steering while allowing the Rn lines to be nearly symmetric to the Sn lines. S2.BEN01, S2.BEN10, R2.BEN01, and R2.BEN10 are septa that bend the three highest energies. Table 2 gives the fields and lengths of these dipoles. The common dipoles nominally create a 30 degree bend angle for the 42 MeV beam at each end of the spreaders. Similarly, the common dipoles nominally create a 23 degree bend angle for the 78 MeV beam at each end of the spreaders.

### 2.2. Individual Lines

S1 and R1 each have 6 dipoles that are not shared with other lines. When doing energy recovery for more than one pass (non-recovery mode), these dipoles are set to bend by specific angles, and no additional tuning is applied to them in the design. Table 3 gives the dipole parameters in non-recovery mode for these lines, and Table 4 gives the

Table 3: S1/R1 non-common dipole parameters, non-recovery.

	Length (m)	Angle (deg.)	Field (T)
S1.BEN02	0.20	-18	+0.2200
S1.BEN03	0.20	+25	-0.3056
S1.BEN04	0.20	-17	+0.2078
S1.BEN05	0.20	-17	+0.2078
S1.BEN06	0.20	+25	-0.3056
S1.BEN07	0.20	-18	+0.2200
R1.BEN02	0.20	-18	+0.2200
R1.BEN03	0.20	+25	-0.3056
R1.BEN04	0.20	-17	+0.2078
R1.BEN05	0.20	-17	+0.2078
R1.BEN06	0.20	+25	-0.3056
R1.BEN07	0.20	-18	+0.2200

Table 4: S1/R1 quadrupole gradients, non-recovery.

	Gradient (T/m)		Gradient (T/m)
S1.QUA01	-0.2953	R1.QUA01	-0.4413
S1.QUA02	+0.8173	R1.QUA02	+0.9319
S1.QUA03	-1.1328	R1.QUA03	-0.9613
S1.QUA04	+0.6881	R1.QUA04	+0.3480
S1.QUA05	+2.0911	R1.QUA05	+1.8964
S1.QUA06	-1.4607	R1.QUA06	-1.3669
S1.QUA07	+1.2341	R1.QUA07	+0.8416
S1.QUA08	-0.5383	R1.QUA08	-0.0955

Table 5: S1/R1 dipoles changed for recovery mode. BEN61 replaces BEN03, BEN62 replaces BEN04, etc. BEN02 and BEN07 are unchanged.

	Length (m)	Angle (deg.)	Field (T)
R1.BEN61	0.20	+19.03	-0.2326
R1.BEN62	0.20	-11.03	+0.1348
R1.BEN63	0.20	-11.03	+0.1348
R1.BEN64	0.20	+19.03	-0.2326
S1.BEN61	0.20	+19.03	-0.2326
S1.BEN62	0.20	-11.03	+0.1348
S1.BEN63	0.20	-11.03	+0.1348
S1.BEN64	0.20	+19.03	-0.2326

Table 6: S1/R1 quadrupole gradients, recovery.

	Gradient (T/m)		Gradient (T/m)
S1.QUA01	-0.6245	R1.QUA01	-0.5864
S1.QUA02	+1.1663	R1.QUA02	+1.2760
S1.QUA03	-0.6935	R1.QUA03	-0.7145
S1.QUA04	+0.4160	R1.QUA04	+0.5310
S1.QUA05	+2.0362	R1.QUA05	+1.8314
S1.QUA06	-1.1840	R1.QUA06	-1.1044
S1.QUA07	+1.3461	R1.QUA07	+0.9622
S1.QUA08	-0.4832	R1.QUA08	+0.1230

Table 7: S2/R2 non-common dipole parameters, non-recovery.

	Length (m)	Angle (deg.)	Field (T)
S2.BEN02	0.15	+2.00	-0.0605
S2.BEN03	0.20	-18.00	+0.4087
S2.BEN04	0.30	+37.00	-0.5600
S2.BEN05	0.20	-24.00	+0.5449
S2.BEN06	0.20	-24.00	+0.5449
S2.BEN07	0.30	+36.77	-0.5565
S2.BEN08	0.20	-17.63	+0.4002
S2.BEN09	0.15	+2.00	-0.0605
R2.BEN02	0.15	+2.00	-0.0605
R2.BEN03	0.20	-18.00	+0.4086
R2.BEN04	0.30	+37.00	-0.5600
R2.BEN05	0.20	-24.00	+0.5449
R2.BEN06	0.20	-24.00	+0.5449
R2.BEN07	0.30	+35.53	-0.5378
R2.BEN08	0.20	-15.90	+0.3610
R2.BEN09	0.15	+2.00	-0.0605

Table 8: S2/R2 quadrupole gradients, non-recovery.

	Gradient (T/m)		Gradient (T/m)
S2.QUA01	-0.5638	R2.QUA01	-0.5665
S2.QUA02	+0.6729	R2.QUA02	+0.6433
S2.QUA03	-1.4963	R2.QUA03	-1.2778
S2.QUA04	+0.8750	R2.QUA04	+0.5591
S2.QUA05	+0.3653	R2.QUA05	+0.7014
S2.QUA06	-2.1499	R2.QUA06	-2.3046
S2.QUA07	+1.6422	R2.QUA07	+1.6184
S2.QUA08	+0.1734	R2.QUA08	+0.6334

quadrupole gradients. Tables 5 and 6 give the corresponding parameters in recovery mode. Note that only some dipoles change in recovery mode.

S2 and R2 each have 8 dipoles that are not shared with other lines. The dipoles are set to specific angles, then BEN07 and BEN08 are adjusted make slight steering corrections. Their dipole parameters are given in Table 7, and their quadrupole gradients are given in Table 8.

S3 and R3 each have 4 dipoles that are not shared with other lines. BEN02 and BEN03 have defined angles, the remaining dipoles are adjusted to give the desired total

Table 9: S3/R3 non-common dipole parameters, non-recovery.

	Length (m)	Angle (deg.)	Field (T)
S3.BEN01	0.20	-15.66	+0.5196
S3.BEN02	0.30	+20.00	-0.4425
S3.BEN03	0.30	+20.00	-0.4425
S3.BEN04	0.20	-15.66	+0.5195
R3.BEN01	0.20	-15.73	+0.5218
R3.BEN02	0.30	+20.00	-0.4425
R3.BEN03	0.30	+20.00	-0.4425
R3.BEN04	0.20	-15.50	+0.5142

Table 10: S3/R3 quadrupole gradients.

	Gradient (T/m)		Gradient (T/m)
S3.QUA01	-1.4116	R3.QUA01	-1.5254
S3.QUA02	+0.2650	R3.QUA02	+0.5056
S3.QUA03	+0.4364	R3.QUA03	+0.6096
S3.QUA04	-1.6250	R3.QUA04	-1.8527
S3.QUA05	+1.1217	R3.QUA05	+0.2872
S3.QUA06	-0.7900	R3.QUA06	-0.0612
S3.QUA07	-1.6307	R3.QUA07	-2.1204
S3.QUA08	+0.7756	R3.QUA08	+1.2333

Table 11: S4/R4 non-common dipole parameters.

	Length (m)	Angle (deg.)	Field (T)
S4.BEN01	0.20	-9.00	+0.3930
S4.BEN02	0.20	-6.89	+0.3011
S4.BEN03	0.30	+24.00	-0.6986
S4.BEN04	0.30	+24.00	-0.6986
S4.BEN05	0.20	-6.85	+0.2992
S4.BEN06	0.20	-9.00	+0.3930
R4.BEN01	0.20	-9.00	+0.3930
R4.BEN02	0.20	-6.97	+0.3045
R4.BEN03	0.30	+24.00	-0.6986
R4.BEN04	0.30	+24.00	-0.6986
R4.BEN05	0.20	-7.13	+0.3113
R4.BEN06	0.20	-9.00	+0.3930

bend angle including common magnets, and also to provide some steering of the beam. The dipole parameters are given in Table 9, and their quadrupole gradients are given in Table 10.

S4 and R4 each have 6 dipoles that are not shared with other lines. BEN01 and BEN06 are septa. BEN01, BEN03, BEN04, and BEN06 have defined angles, while the remaining dipoles are adjusted to give the desired total bend angle including common magnets, and also to provide some steering of the beam. The dipole parameters are given in Table 11, and their quadrupole gradients are given in Table 12.

Table 12: S4/R4 quadrupole gradients.

	Gradient (T/m)		Gradient (T/m)
S4.QUA01	+0.3990	R4.QUA01	+0.0072
S4.QUA02	-2.7819	R4.QUA02	-2.5713
S4.QUA03	+2.6538	R4.QUA03	+2.9938
S4.QUA04	-3.4843	R4.QUA04	-3.9228
S4.QUA05	+1.4835	R4.QUA05	+0.0902
S4.QUA06	-3.3893	R4.QUA06	-3.8358
S4.QUA07	-0.3454	R4.QUA07	+0.4393
S4.QUA08	+2.3217	R4.QUA08	+2.0596



Table 13: Beam stop quadrupole gradients.

	Gradient (T/m)
DU.QUA01	-0.6652
DU.QUA02	+0.6297
DU.QUA03	-0.6749
DU.QUA04	-0.1340

### 3. FFAG Arcs (FA/FB)

At the beginning of FA, there is one special half-length BD, centered on the beam pipe. It is 12 mm from a standard 42 mm BPM block. 16 mm downstream from that BPM block, there is the first QF in a standard FFAG cell, offset an additional 3 mm to the outside. The longitudinal spacing then continues as usual in the arc. The first standard BD (FA.QUA02) is offset inward by 3.2 mm, the second BD (FA.QUA04) is offset outward by 0.5 mm, and the remaining quadrupoles are in their standard positions.

Similarly, at the end of FB, there is a half-length QF, 12 mm downstream from a standard BPM block, then 16 mm to a standard BD (FB.QUA32) offset inward by 4.3 mm, then a standard longitudinal geometry upstream from there. There are additional offsets upstream in the next QF (2.4 mm outward). The lattice file has smaller offsets in the for most of the remaining upstream BDs in FB.

### 4. Beam Stop (BS)

The beam stop line has four 0.15 m quadrupoles and one 0.2 m dipole. The dipole bends by 15 degrees and has an field of 0.0261 T. Quadrupole gradients are given in Table 13.

### 5. Performance

Figure 3 shows the emittance through four passes of energy recovery. Figure 4 shows the normalized emittance through four passes of energy recovery. Emittance growth is negligible.

### Appendix A. Items Remaining

- Recovery mode design for S2/R2
- Recovery mode design for S3/R3
- Move S2.QUA02/QUA07 (and similarly for R2) to resolve physical conflict with S3.BEN01/BEN04
- Add vertical correctors to spreaders



Figure 3: Beam size and bunch length through 4-pass energy recovery.



Figure 4: Normalized beam emittance and energy spread through 4-pass energy recovery.