Feeddowns Circuits for Collider Run II

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The sextupole feeddown circuits are used to adjust the tunes and coupling of the protons and antiprotons independently during collider operations. In particular these circuits can adjust the difference in the horizontal tune (or vertical tune or sine or cosine component of the coupling) between the proton helical orbit and the antiproton helical orbit.

The feeddown circuits in Collider Run II consist of the same circuits used in Collider Run I plus two new feeddown families that were selected to improve the differential coupling adjustments. Details of the circuits and magnet locations are given in Appendix A. Four of the seven families are used when the protons and antiprotons are on the injection helix (injection through step 12 of the low beta squeeze) and a different set of four families are used when the protons and antiprotons are on the collision helix (step 12 of the low beta squeeze through collisions.).

The main function of each family is shown in the table below where $\Delta\nu_x, \Delta\nu_y$ are the differential tune adjustments, and ΔC_{sq}, ΔS_{sq} are the differential cosine and sine components of the differential coupling.

Circuit	Injection Helix	Collision Helix
S1	$\Delta\nu_x$	ΔC_{sq}
S2	$\Delta\nu_y$	
S3	ΔC_{sq}	
S4		$\Delta\nu_x$
S5		$\Delta\nu_y$
S6	ΔS_{sq}	
S7		ΔS_{sq}

Ideally each of these circuits would behave independently but in practice each feeddown circuit changes both the tunes and the coupling. Therefore we compute a 4x4 coefficient matrix, M, which relates adjustments in the tune and coupling to the changes in the feeddown circuits,

$$\begin{pmatrix} S1 \\ S2 \\ S3 \\ S6 \end{pmatrix} = \mathbf{M} \begin{pmatrix} \Delta\nu_x \\ \Delta\nu_y \\ \Delta C_{sq} \\ \Delta S_{sq} \end{pmatrix}.$$

In this equations $\Delta\nu_x, \Delta\nu_y$ are the differences in the tunes between the proton helix and antiproton helix, the ΔC_{sq}, ΔS_{sq} are the differences in the coupling tunes between the proton helix and antiproton helix, and the S1, S2, S3, and S6 are the kAmps in the feeddown circuits. To be clear, if $\Delta\nu_x$ is adjusted by 0.002, then the proton tune will increase by 0.001 and the antiproton tune will decrease by 0.001. Also if ΔC_{sq} is changed by 0.002 then the cosine component of the coupling for the proton helix increases by 0.001.

While examining the behavior of the existing feeddown circuits and designing the new feeddown circuits it was hoped that only two sets of coefficients for the M matrix would be needed: one for the injection helix and one for the collision helix. However we found that the coefficients of the 4x4 matrices, M, changed significantly during the different steps of the squeeze making it impractical to use only two sets of matrices. Therefore we use a separate set of coefficients for each step in the squeeze. The coefficients given in this memo are calculated values using the design Tevatron Collider Run II lattice.

Calculation of Coefficients

If particles are traveling about a closed orbit which does not pass through the center of a sextupole magnet then they will experience a quadrupole field which depends on the sextupole strength, the tilt of the sextupole, and the position of the closed orbit. As a result, the tune of the closed orbit will change due to the added quadrupole gradients. In the Tevatron the separate closed orbits of the protons and antiprotons means that each orbit will see a different set of quadrupole gradients. This makes it possible to adjust the tunes and coupling of the protons and antiprotons differentially

Once we know the strengths and feeddown effects of the sextupoles we can calculate the effect they have on the tune and coupling. (The details of the sextupole magnet strengths in the Tevatron and the quadrupole fields for offset closed orbits are given in Appendix B.) The change in horizontal and vertical tune is given by the simple equations

$$\Delta\nu_x = (2)\frac{1}{4\pi}\sum \beta_{\mathrm{x,i}}\ (\mathrm{K_1L})_{\mathrm{no,i}}$$

$$\Delta\nu_y = -(2)\frac{1}{4\pi}\sum \beta_{y,i}\ (\mathrm{K_1L})_{\mathrm{no,i}}$$

where β_x, β_y are the beta function at the locations of the feeddown sextupoles, and $(\mathrm{K_1L})_{\mathrm{no,i}}$ is the normal component of the quadrupole field created by the off-center closed orbit and the sextupole field. The extra factor of 2 in the above equation is because we have defined $\Delta\nu_x, \Delta\nu_x$ as the differential tune shift between the proton helix and the pbar helix. (Without the factor of 2, the tune shift represents the change in tune of the protons between the centered orbit and the helical orbit.)

To quantify the effect that the feeddowns have on the coupling we calculate a sine and cosine term of the coupling as

$$\Delta C_{sq} = (2)\frac{1}{2\pi}\sum (K_1L)_{sq,i}\sqrt{\beta_{x,i}\beta_{y,i}}\cos(\phi_y - \phi_x)$$

$$\Delta S_{sq} = (2)\frac{1}{2\pi}\sum (K_1L)_{sq,i}\sqrt{\beta_{x,i}\beta_{y,i}}\sin(\phi_y - \phi_x)$$

where $(K_1L)_{sq,i}$ is the skew component of the quadrupole field and $(\phi_y - \phi_x)$ is the difference between the vertical and horizontal betatron phase advances. Again the extra factor of 2 in the above equations is because we have defined $\Delta C_{sq}, \Delta S_{sq}$ as the differential coupling between the proton helix and the antiproton helix.

To better understand the coupling constants we express the minimum tune split in terms of $\Delta C_{sq}, \Delta S_{sq}$. If the Tev is tuned up such that there is no coupling on the proton helix then in principle the horizontal and vertical tunes could be set equal to one another. However, if we add a small amount of coupling with the feeddowns then the minimum tune split is

$$\Delta \nu_{min} = \frac{1}{2}\sqrt{\Delta C_{sq}^2 + \Delta S_{sq}^2}$$

This equation can be used to get an idea of the strength of the feeddown circuits.

New Feeddown circuits

For Collider Run II there will be two new feeddown circuits added to improve the coupling adjustments. These feeddown circuits, the S6 and S7 circuits, were chosen to provide a coupling adjustment which was orthogonal to the S3 and S1 circuits. In the expression for $\Delta C_{sq}, \Delta S_{sq}$ there is a term containing the difference in the vertical and horizontal phase advances $(\phi_y - \phi_x)$. Ideally the sextupole elements for the S6 and S7 circuits would be located in the Tevatron where the phase difference is orthogonal to phase difference of the S3 and S1 circuits. However $(\phi_y - \phi_x)$ does not change much in the Tevatron arcs because the horizontal and vertical betatron phase advances are roughly equal. This leaves only a few locations near the B0 and D0 low beta straight sections that are suitable locations for feeddown sextupoles. In addition to having a suitable phase advance the orbit separation at the locations of S6 and S7 magnets must also be suitable.

Within the confines of these constraints the optimum choice for magnets seemed to be the chromaticity sextupoles at locations A46, C46, B14, and D14. Therefore each of these four magnets will be separated from the chromaticity circuits (T:SF and T:SD) and each magnet will be powered individually. The naming convention for these devices is the same as for the other feeddowns and is listed in Appendix A.

Once the choice of magnet locations was narrowed down, the coefficients relating magnet strength to tune and coupling changes were calculated and are shown in Appendix C. As can be seen from the data in Appendix C, the S6 and S7 feeddown circuits are weak compared to the other de-coupling feeddown circuits. In fact, on the injection helix it takes 34 amps of current in the S6 feeddown circuit to de-couple the ΔS_{sq} component by 0.001 units. As the low beta squeeze progresses the S6 circuit does become somewhat stronger, but still remains weak. The S7 circuit, which is used while on the collision helix, is also weaker than the other feeddown circuits, yet stronger than the S6 circuit.

Appendix A: Feeddown circuit locations

Starting with the Run I configuration the following hardware changes were made to the feeddown circuits:

> **Reverse the polarity of the C:S4F2A circuit**.
> This is necessary because the relative polarity of the helix in the long and short arcs has changed.
>
> **Create a "S6" feeddown family.**
> At locations A46 and C46 remove the sextupole magnets from the chromaticity circuit T:SF. Add separate power supplies to these two magnets to create the C:S6A4A circuit at A46 and the C:S6C4A circuit at C46. The C:S6C4A power supply should be connected with the opposite polarity of the C:S6A4A circuit.
>
> **Create a "S7" feeddown family.**
> At locations B14 and D14 remove the sextupole magnets from the chromaticity circuit T:SD. Add separate power supplies to these two magnets to create the C:S7B1A circuit at B14 and the C:S7D1A circuit at D14. Both power supplies should be connected with the same polarity.

A complete listing of the feeddown circuits and the magnet locations is given in the table below

Circuit Name	Polarity	Magnet location	Spool type	Modified for Run II
C:S1B1A	-	B19	E	
C:S1B3A	+	B38	E	
C:S1C2A	+	C24	E	
	-	C32	G	
C:S1E2A	+	E24	E	
	-	E28	E	
C:S1F2A	+	F19	E	
	-	F26	G	
C:S1F3A	+	F34	E	
	-	F38	E	
C:S2A1A	-	A14	D	
C:S2A3A	+	A33	D	
C:S2B4A	-	B43	D	
	+	B47	D	
C:S2C3A	+	C27	D	
	-	C33	D	
C:S2D2A	-	D23	D	
	+	D27	D	
C:S2F1A	+	F12	D	
	-	F16	D	
C:S2F2A	+	F23	D	
C:S2F4A	-	F43	D	

Circuit Name	Polarity	Magnet location	Spool type	Modified for Run II
C:S3A2A	+	A17	C	
	-	A24	C	
C:S3D2A	-	D19	C	
	+	D26	C	
C:S3D4A	+	D38	C	
	-	D46	C	
C:S3E1A	-	E17	C	
	+	E22	C	
C:S3E3A	-	E32	C	
	+	E36	C	
C:S4C2A	+	C19	E	
	-	C26	G	
C:S4C2B	+	C22	G	
	-	C28	E	
C:S4F2A	+	F24	E	Polarity
	-	F28	E	Polarity
C:S5A2A	+	A18	D	
C:S5A3A	-	A37	D	
C:S5D3A	-	D33	D	
	+	D37	D	
C:S5F1A	-	F14	D	
C:S5F3A	+	F33	D	
C:S6A4A	+	A46	T:SF	New
C:S6C4A	-	C46	T:SF	New
C:S7B1A	+	B14	T:SD	New
C:S7D1A	+	D14	T:SD	New

Notes:

The type-C and type-D spools contain skew sextupoles. The type-E, type-G, and the chromaticity spools contain normal sextupoles.

The C:S6xxx and C:S7xxx circuits are new for Run II. Sextupole magnets for these circuits were taken from the chromaticity circuits T:SF and T:SD.

The polarity of C:S4F2A is changed between Run I and Run II.

Appendix B: Sextupole magnet strength and feeddown effect

First we define the sextupole magnetic field as

$$B_x(x, y) = B_2 xy$$
$$B_y(x, y) = \tfrac{1}{2} B_2 (x^2 - y^2)$$

and want to relate this to the magnetic field in a Tevatron sextupole magnet. From "The Tevatron Energy Doubler: A superconducting Accelerator", H. Edwards, (*Ann. Rev. Nucl. Part Sci.* 1985, 35:605-60) we have that the integrated strength of a sextupole magnet is 57 kG-in at 1 inch at 50 Amps. This implies that

$$B_2 L / I = 8.98 \text{ T/m/A}$$

where L is the length of the sextupole and I is the current in the magnet.

If the sextupoles are treated as a thin sextupole magnet, then in the MAD convention the thin sextupole strength is given by

$$\mathrm{K}_2\mathrm{L} = (B_2 L / I) \frac{1}{|B\rho|} I$$

where I is the current in the sextupole, and $|B\rho|$ is the magnetic rigidity.

Next we look at the effective quadrupole field that the sextupole field creates for an off-center closed orbit. If the closed orbit through a thin sextupole has the coordinates x_0 and y_0, then a thin sextupole with strength K_2L and a tilt angle ψ will give a normal quadrupole field with strength

$$(\mathrm{K}_1\mathrm{L})_{\mathrm{no}} = \mathrm{K}_2\mathrm{L}\left(\mathrm{x}_0 \cos 3\psi + \mathrm{y}_0 \sin 3\psi\right)$$

and a skew quadrupole field with strength

$$\left(\mathrm{K}_1\mathrm{L}\right)_{\mathrm{sq}} = \mathrm{K}_2\mathrm{L}\left(\mathrm{x}_0 \sin 3\psi - \mathrm{y}_0 \cos 3\psi\right)$$

Appendix C: Coefficients of Feeddown Circuit matrix

Step	S1/vx	s1/vy	s1/cs	s1/ss	s2/vx	s2/vy	s2/cs	S2/ss	s3/vx	s3/vy	s3/cs	s3/ss	s6/vx	s6/vy	S6/cs	s6/ss
1	-1.576	0.481	1.615	3.843	-0.618	1.843	0.356	0.928	0.058	-0.106	-0.156	3.034	-0.414	0.716	-13.233	-34.525
2	-1.475	0.392	4.091	11.017	-0.592	1.806	0.918	2.539	0.090	-0.216	0.247	4.184	-0.444	0.659	-16.838	-46.560
3	-1.464	0.379	4.681	12.853	-0.578	1.777	1.033	2.886	0.089	-0.251	0.076	3.701	-0.354	0.528	-15.136	-42.256
4	-1.403	0.338	5.061	13.711	-0.570	1.785	1.190	3.321	0.072	-0.295	-0.077	3.238	-0.455	0.566	-12.527	-34.950
5	-1.398	0.296	5.235	14.183	-0.574	1.797	1.271	3.537	0.075	-0.328	-0.186	2.920	-0.427	0.594	-11.243	-31.277
6	-1.394	0.243	5.298	14.311	-0.581	1.811	1.320	3.657	0.078	-0.361	-0.280	2.644	-0.407	0.641	-10.104	-27.981
7	-1.392	0.180	5.257	14.137	-0.590	1.827	1.338	3.686	0.082	-0.394	-0.363	2.402	-0.391	0.699	-9.063	-24.959
8	-1.380	0.104	5.133	13.620	-0.610	1.879	1.347	3.681	0.084	-0.433	-0.418	2.229	-0.400	0.797	-8.192	-22.373
9	-1.381	0.065	4.999	13.159	-0.620	1.897	1.315	3.570	0.086	-0.450	-0.444	2.147	-0.398	0.850	-7.820	-21.209
10	-1.381	0.023	4.880	12.768	-0.630	1.917	1.296	3.499	0.089	-0.468	-0.480	2.041	-0.391	0.888	-7.339	-19.799
11	-1.394	0.003	4.462	11.319	-0.651	1.955	1.120	2.945	0.088	-0.473	-0.433	2.118	-0.409	1.042	-7.616	-20.008
12	-1.424	0.033	3.865	9.226	-0.682	2.019	0.816	2.037	0.081	-0.461	-0.297	2.365	-0.437	1.302	-8.749	-21.822

Coefficients for Injection Helix

Step	S4/vx	s4/vy	s4/cs	s4/ss	s5/vx	s5/vy	s5/cs	S5/ss	s1/vx	s1/vy	s1/cs	s1/ss	s7/vx	s7/vy	S7/cs	s7/ss
12	2.223	-0.755	0.007	-0.131	-0.637	1.880	-0.027	-0.063	-0.191	0.246	-0.063	3.782	0.104	-0.177	-3.260	-7.665
13	2.142	-0.727	0.008	-0.097	-0.598	1.765	-0.032	-0.070	-0.200	0.291	-0.088	3.313	0.121	-0.218	-3.077	-6.783
14	2.049	-0.693	0.007	-0.041	-0.560	1.648	-0.031	-0.065	-0.195	0.295	-0.161	2.802	0.122	-0.224	-2.744	-5.723
15	1.987	-0.691	0.026	-0.189	-0.555	1.631	-0.023	-0.047	-0.175	0.324	-0.274	2.371	0.110	-0.218	-2.322	-4.663
15*	1.877	-0.610	-0.042	0.184	-0.513	1.548	-0.010	-0.063	-0.130	0.340	-0.792	3.191	0.299	-0.478	-1.056	-6.987
15**	1.876	-0.611	-0.040	0.174	-0.514	1.549	-0.010	-0.059	-0.135	0.343	-0.792	3.193	0.302	-0.480	-1.056	-6.990

Coefficients for Collision Helix

Coefficients are changes in kAmps in the feeddown circuits for changes in $\Delta\nu_x$, $\Delta\nu_y$, ΔC_{sq}, and ΔS_{sq}. Step 15 is 35 cm β^* with separator bumps across B0 and D0. Step 15* is 35 cm β^* with separator bumps across B0 and D0 and with has as the phase bumps for the collimators in place. Step 15** is 35 cm β^* with the phase bumps for the collimators and beams colliding at B0 and D0. See text for definition of $\Delta\nu_x$, $\Delta\nu_y$, ΔC_{sq}, and ΔS_{sq}. For the record, the coefficients for ΔC_{sq} and ΔS_{sq} were calculated using the betatron phase advances from the Tevatron E0 location.