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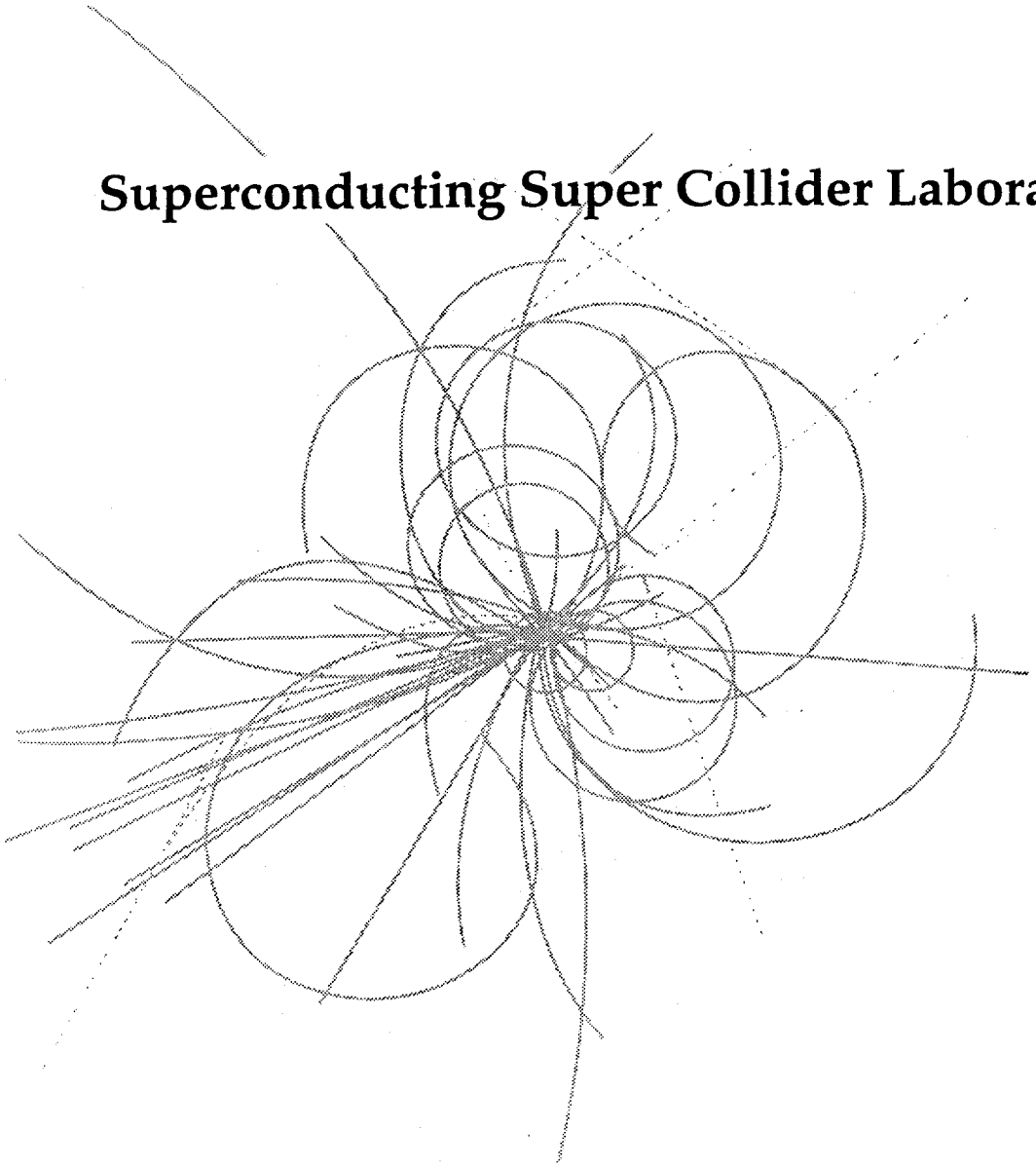
Superconducting Super Collider Laboratory



Ripple Distribution in Magnet Strings of the SSC Collider

K. Smedley

September 1992

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Ripple Distribution in Magnet Strings of the SSC Collider

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1.0 INTRODUCTION

With a circumference of 87 km, the Superconducting Super Collider (SSC) main collider ring will have a revolution frequency of 3.4 kHz. The fractional part of the betatron oscillation will be near the power supply ripple frequencies (720 Hz and its sub/super-harmonics), assuming 12-pulse Silicon-Controlled Rectifier (SCR) power supplies are used.* The Collider is powered by ten power supply units in ten sections along the ring. Each section will have an average length of about 8.7 km. The voltage ripple in the power supply generates ripple current in the magnet coil that, in turn, generates ripple in the magnetic field of dipoles and quadrupoles. The ripple in the magnetic field will be a function of time and space due to the transmission line effect. The work reported in this paper gives a thorough analysis of the differential mode ripple distribution in the magnet string of the collider standard arc.

2.0 SCR POWER SUPPLY RIPPLE

There will be ten power supply units distributed along the ring;[1] each of them covers a sector that averages one-tenth of the circumference, as shown in Figure 1. Each power supply unit (see Figure 2) includes a ramping power supply and a holding power supply in series. In the collider mode and injection mode, the ramping power supply is bypassed. In the ramping mode, both power supplies will be on. In this paper only the collider mode and the injection mode are discussed. The power supplies are configured with two 6-phase stars in parallel.[2] The typical voltage waveforms of the power supply are studied. Assumptions include: the utility power has 1% of amplitude imbalance and 1% of phase imbalance, transformers have 2% imbalance, the current sharing inductance has 10% imbalance, and the thyristors have a 0.5-V on-state voltage distribution band. The power supply voltage waveforms and spectrum are shown in Figure 3 and Figure 4, respectively, for the collider mode. The power supply voltage waveforms and spectrum are shown in Figure 5 and Figure 6, respectively, for the injection mode. The voltage function is

$$v_{ps} = |v_{ps_0}| + \sum_{n=1}^{\infty} |v_{ps_n}| \cos\Big(n\omega t + \arg(v_{ps_n})\Big) \ . \tag{1}$$

where $\omega = 2\pi 60$ rad.

The power supply ripple has a very wide frequency spectrum. The dominant frequency is 720 Hz and its super harmonics. The subharmonics presented in this paper are estimated according to random unbalance of the power supply parameters. In case there is a systematic distribution of the power supply parameter unbalance, certain subharmonics will be greater.

* It is possible that we will use SCR and switching mode hybrid power supplies.

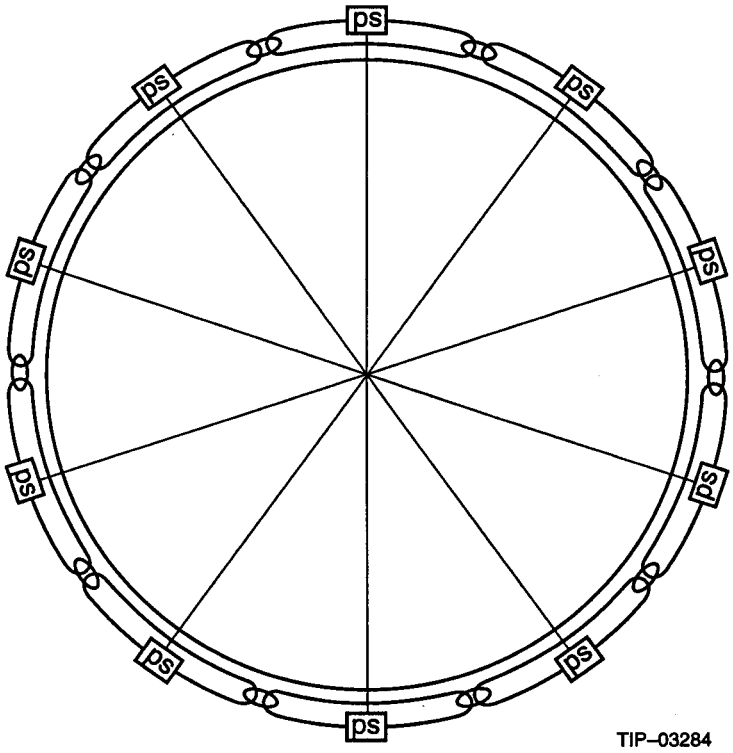

Figure 1. Collider Power Supply Location.

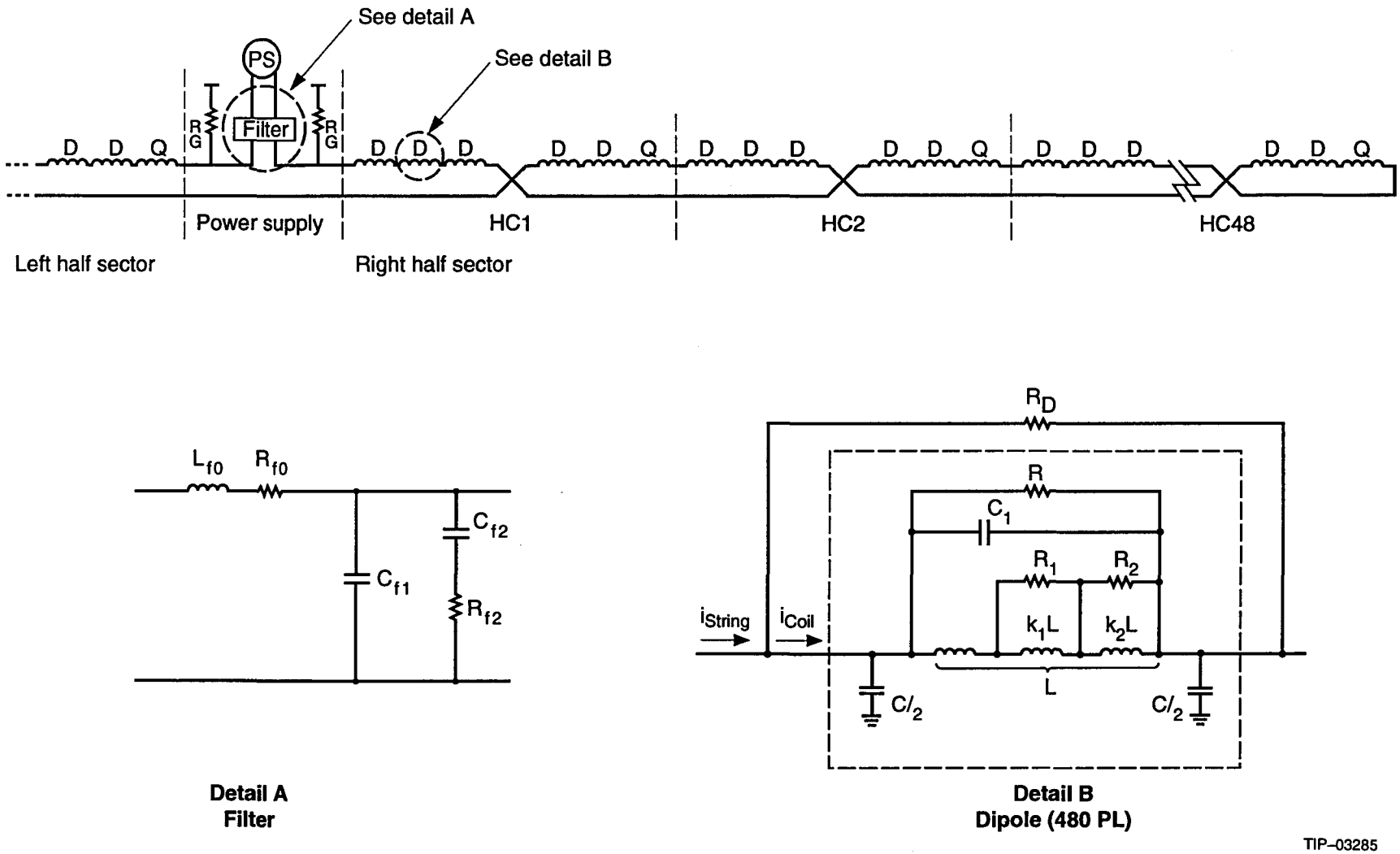

Figure 2. Electrical Circuit of a Standard Sector.

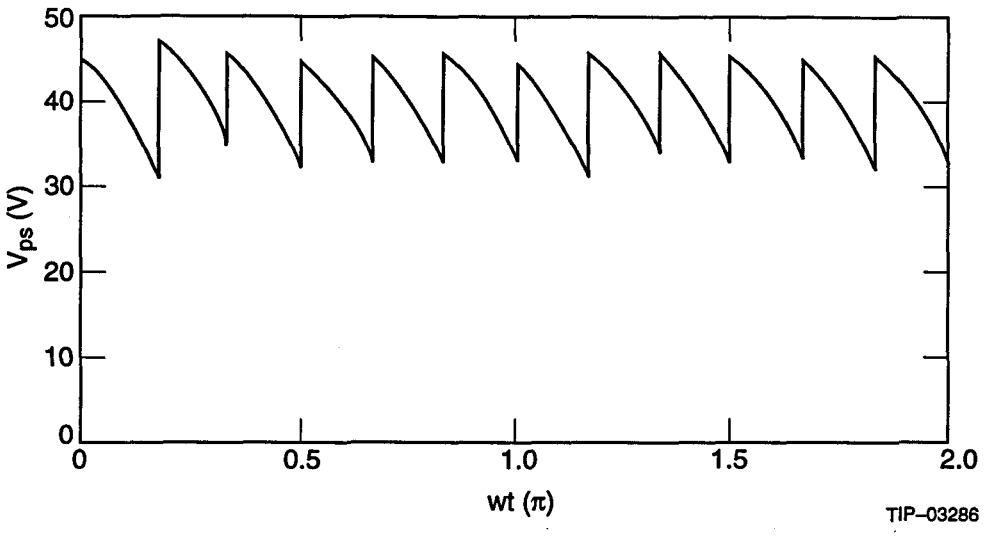

Figure 3. Typical Power Supply Voltage Waveform at Collider Mode.

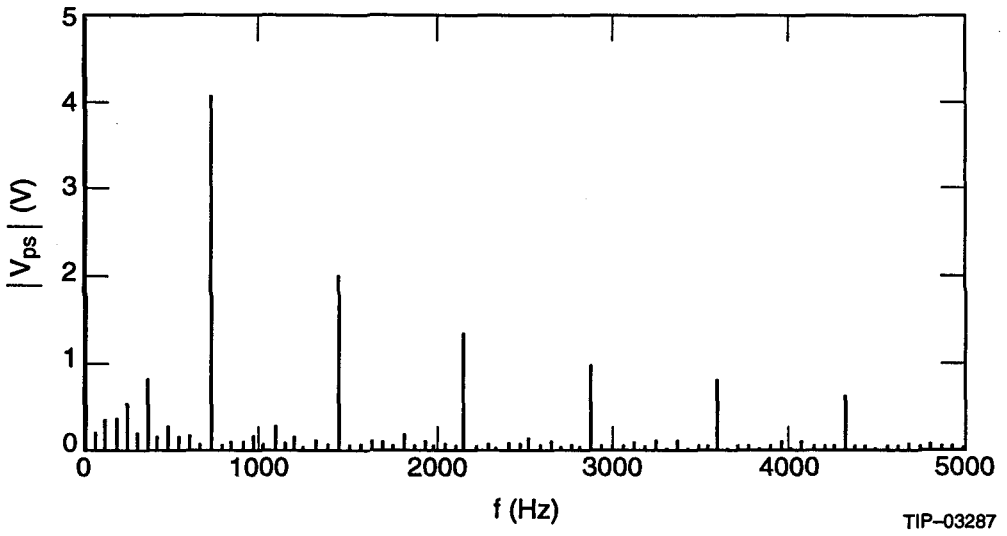

Figure 4. Typical Power Supply Voltage Spectrum at Collider Mode.

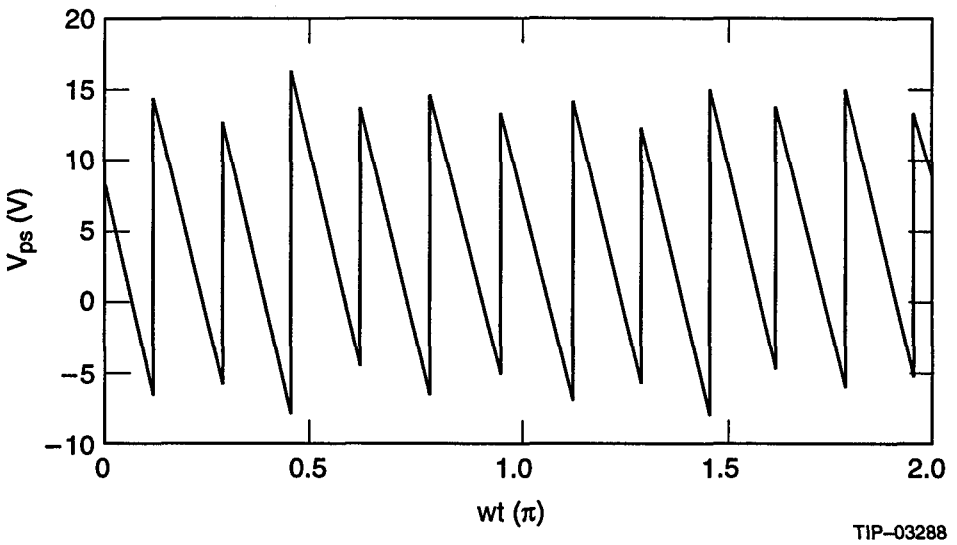

Figure 5. Typical Power Supply Voltage Waveform at Injection Mode.

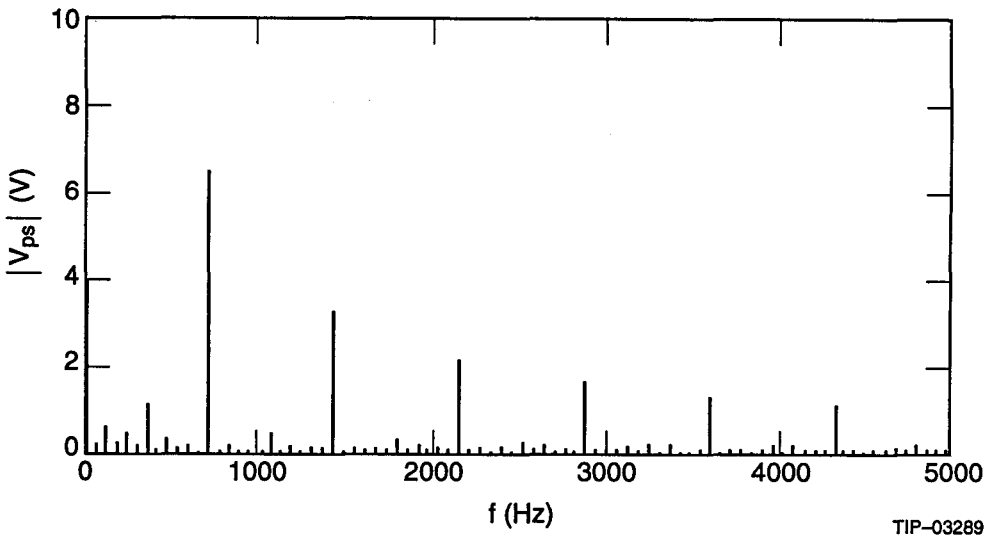

Figure 6. Typical Power Supply Voltage Spectrum at Injection Mode.

3.0 CURRENT RIPPLE AT DRIVE-POINT

The collider magnet string circuit is shown in Figure 2. The magnet string contains 96 half cells. Each half cell has five dipoles and one quadrupole. Altogether there are 480 dipoles and 96 quadrupoles in each magnet string.

The magnet string is connected to the power supply through a low pass filter as shown in Figure 2. The circuit parameters of the low pass filter are $L_{fo} = 2$ mH, $R_{fo} = 2$ mΩ, $C_{f1} = 2$ mF, $C_{f2} = 30$ mF, and $R_{f2} = 0.37\ \Omega$ (see Reference 3).

The ac electrical model[4] is shown in Figure 7. The parameters calculated from the transfer function are $L = 65.6$ mH, $R = 273.5\ \Omega$, $k_1 = 0.207$, $R_1 = 3.3\ \Omega$, $k_2 = 0.317$, $R_2 = 45.6\ \Omega$, $C1 = 74$ nF, and $C = 280$ nF.

A damping resistor R_d will be connected across the magnet in parallel with the series impedance. The damping resistor influences the drive-point current ripple amplitude and the attenuation length along the magnet string. Figure 8 shows the magnet coil current per volt of the power supply ripple for a range of damping resistors; the effect of the power supply filter is included. The coil current is a fraction of the magnet string current. The lower damping resistance value leads to lower ripple current amplitude; however, the attenuation length will be longer. On the other hand, if the damping resistance is too small, the magnet current ramping rate may be reduced. A damping resistor of 12.5 Ω is used in this analysis.

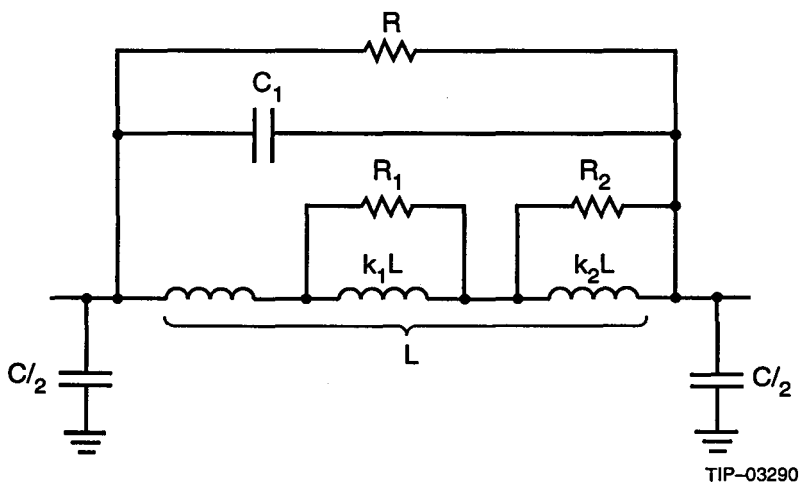

Figure 7. Ac Circuit Model of Dipole Magnet.

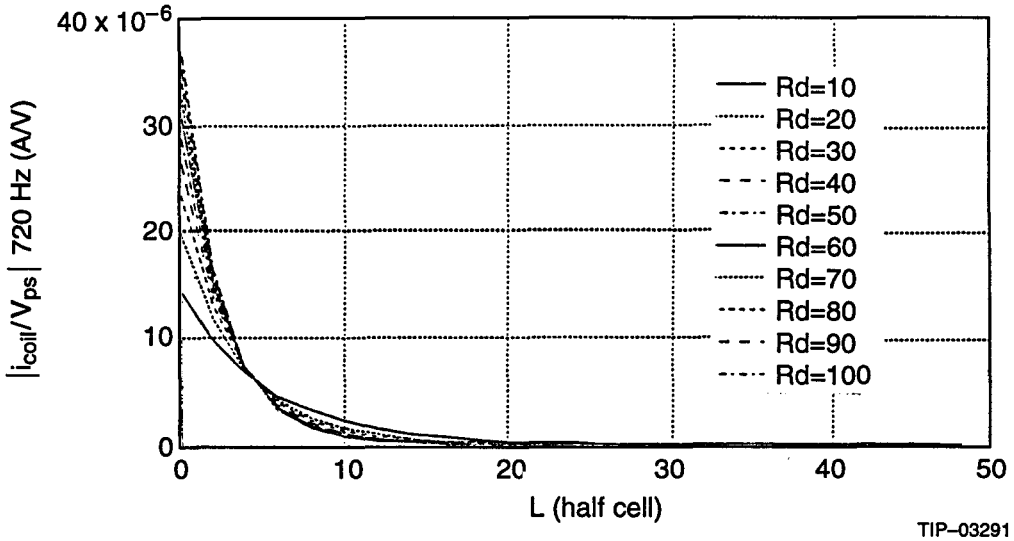

Figure 8. Damping Resistance Influence for 720-Hz Ripple Component.

The power supply voltage to the drive-point string current transfer function $T_{dp} = \frac{I_{string}}{V_{ps}}$ is shown in Figure 9, where $|T_{dp}|$ is the amplitude and T_{dp} is the phase.

The transfer functions $\frac{I_{string}}{V_{ps}}$ and $\frac{I_{coil}}{V_{ps}}$ are listed in the Appendix. The drive-point string current and coil current can be obtained by

$$i_{string} = v_{ps} \times \frac{I_{string}}{V_{ps}} \tag{2}$$

$$i_{coil} = v_{ps} \times \frac{I_{coil}}{V_{ps}} \ . \tag{3}$$

As an example, the 60-Hz component of the coil current at the drive-point for the collider mode can be obtained as follows:

$$\begin{aligned} |I_{coil}|_{60\text{Hz}} &= |V_{ps}|_{60\text{Hz}} \times \left|\frac{I_{coil}}{V_{ps}}\right|_{60\text{Hz}} \\ &= 0.185(V) \times 0.000893\left(\frac{A}{V}\right) = 1.653 \times 10^{-4}(A) \end{aligned} \tag{4}$$

$$\begin{aligned} \arg(I_{coil})_{60\text{Hz}} &= \arg(V_{ps})_{60\text{Hz}} + \arg\left(\frac{I_{coil}}{V_{ps}}\right)_{60\text{Hz}} \\ &= -11.99^\circ + (-65.06^\circ) = -77.05^\circ \ . \end{aligned} \tag{5}$$

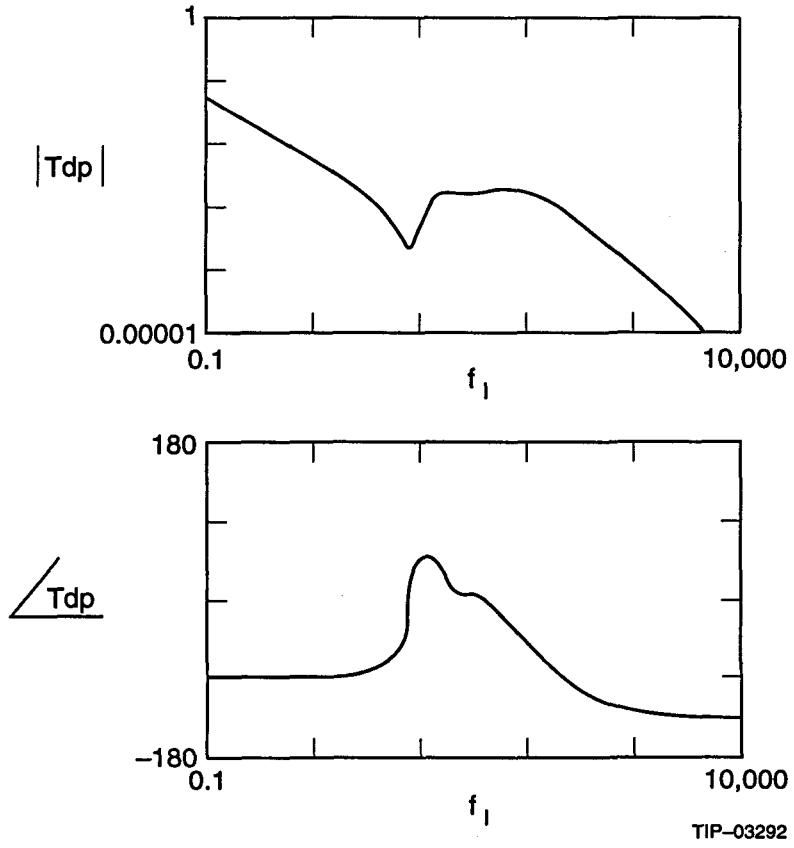

Figure 9. Power Supply Voltage to Drive-Point Current Transfer Function.

4.0 CURRENT RIPPLE SPATIAL DISTRIBUTION

The current ripple at the drive-point propagates along the magnet string. The attenuation coefficient α_n and the phase shift coefficient β_n are listed in the Appendix for each ripple frequency component. The string current and coil current along the magnet string will be

$$i_{string}(l) = \sum_{n=1}^{\infty} |i_{string_n}| e^{-\alpha l} \cos\left(n\omega t + \arg(I_{string_n}) - \beta_n l\right) \tag{6}$$

$$i_{coil}(l) = \sum_{n=1}^{\infty} |i_{coil_n}| e^{-\alpha l} \cos\left(n\omega t + \arg(I_{coil})_n - \beta_n l\right) . \tag{7}$$

As an example, the 60-Hz component of the coil current distribution along the magnet string for the collider mode can be obtained as follows:

$$i_{coil}(l)_{60\mathrm{Hz}} = 1.653 \times 10^{-4} e^{-0.0839l} \cos(377t - 77.05^\circ - 7.82^\circ l)\ (A) . \tag{8}$$

The 60-Hz coil current distribution is plotted in Figure 10. Notice that the coil current at even- and odd-number half cells is not continuous, because the magnets alternate between the top bus and bottom bus as shown in Figure 2. Since the left- and right-side strings are symmetrical, only the ripple distribution of the right-side string is plotted.

The coil current and the string current have the same attenuation coefficient and phase propagation rate along the magnet string. The higher frequency current components attenuate faster and have larger phase shifts along the magnet string.

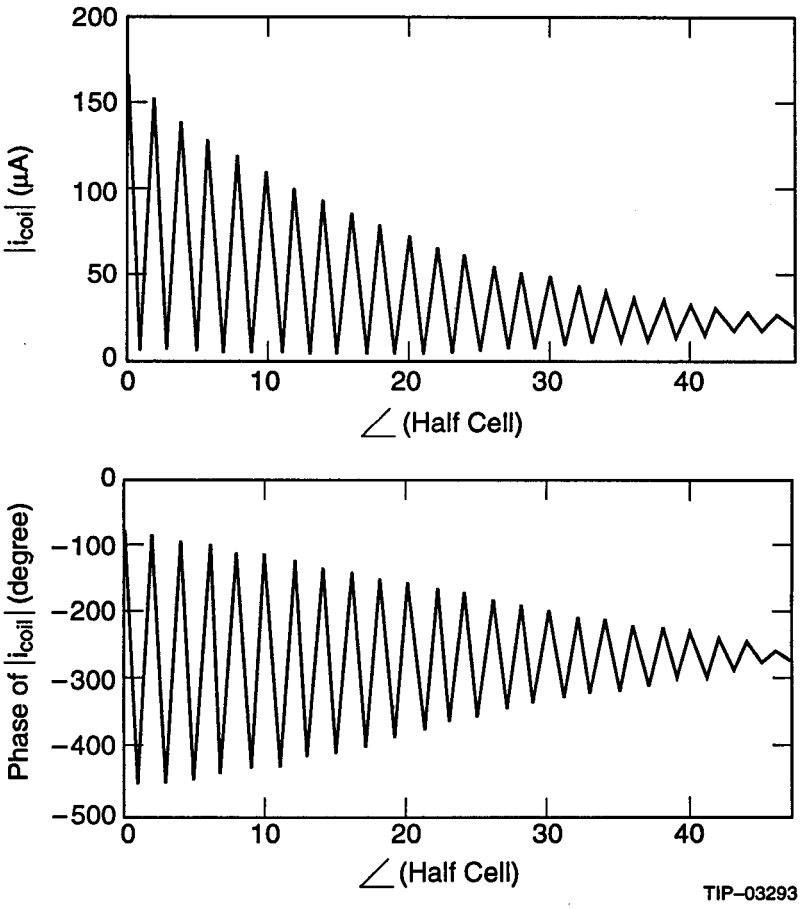

Figure 10. 60-Hz Coil Current Spatial Distribution.

5.0 MAGNETIC FIELD RIPPLE PATTERN

The current in the magnet coil is further transferred into the magnetic field in the beam tube. The measured coil current to the magnetic field in the beam tube transfer function $\frac{B}{i}$ is shown in Figure 11.

The beam tube attenuation is very small when the frequency is lower than 1 kHz. The magnetic field ripple of a particular magnet can be obtained by transferring the coil current of that magnet into the magnetic field using the preceding transfer function.

This transfer function was measured in a warm magnet without copper liner. The resistivity of stainless steel does not change significantly between room and cryogenic temperature. A cryogenic copper liner is expected to further attenuate the magnetic field.

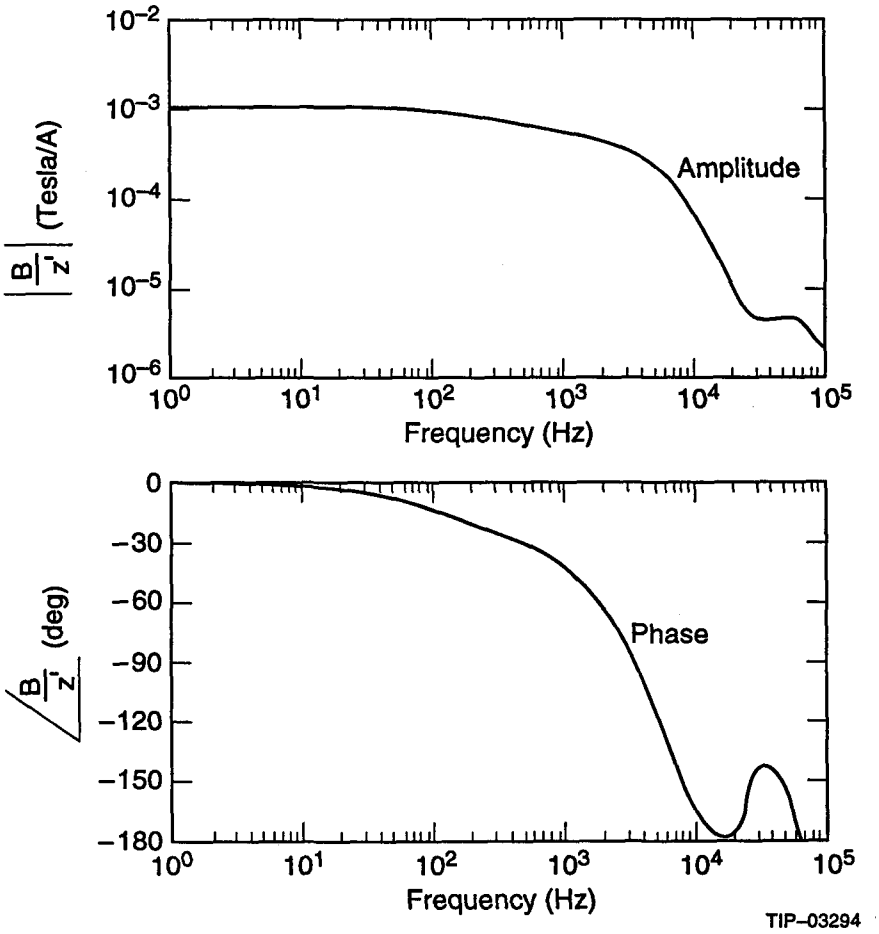

Figure 11. Coil Current to Magnetic Field Transfer Function.

6.0 SUMMARY

The power supply noise with frequency lower than a few Hz is rejected by the voltage and current regulation loop. However, the rejection from the current regulation loop is not very significant to the 720-Hz ripple components and their super/sub-harmonics.

The differential mode ripple distribution is studied in this paper. In reality, there are combined effects from differential mode ripple and common mode ripple. Research is required to find the common mode ripple source and its distribution in order to design a proper grounding circuit and an effective common mode filter such that the common mode ripple effect on the beam is minimal.

Analytical analysis[5] and SPICE simulation[6,7] are used in this paper.

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1. J. Sanford and D. Matthews, "Site-Specific Conceptual Design of the Superconducting Super Collider," SSC Lab., 1990.
2. K. Smedley, "Technical Requirement for Thyristor Assemblies," SSC Lab., 1991.
3. C. Jach, Private communication.
4. K. Smedley and R. Shafer, "Measurement of the AC Electrical Characteristics of the SSC Superconducting Dipole Magnets," Heacc'1992, Hamburg.
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6. A. Jayasuriya, "SPICE Simulation of the Standard ARC of the SSC Collider," SSC Summer Student Report, 1992.
7. A. Sreeniva, "Magnet Current Regulation and Magnet Modelling," Summary/Progress Report, 1991.

APPENDIX

Collider Standard Arc Ripple Distribution

Appendix: Collider Standard Arc Ripple Distribution

condition: Power supply: 2 six-phase stars in parallel
Damping resistor: 12.5 ohm

Frequency	V_{ps} (collider mode)		V_{ps} (injection mode)		I_{string}/V_{ps} (drive point)		I_{coil}/V_{ps} (drive point)		α	β
f (Hz)	amp (V)	phs(°)	amp(v)	phs(°)	amp (A/V)	phs(°)	amp (A/V)	phs(°)	(1/half cell)	(° /half cell)
60	0.18542	-11.987	0.067305	50.27	0.0019169	-16.106	0.00089287	-65.06	0.08388937	7.81933525
120	0.33267	-134.78	0.57427	-94.786	0.0015893	-54.445	0.00045464	-109.48	0.1446023	10.9277953
180	0.35389	-138.49	0.13624	-97.375	0.0011285	-76.721	0.00023902	-131.53	0.188975	13.1708627
240	0.53306	129.56	0.40235	55.748	0.00081602	-90.003	0.00014136	-143.18	0.22511982	15.0476406
300	0.14839	105.65	0.11721	120.67	0.00061502	-98.578	9.22E-05	-150	0.25636627	16.7086853
360	0.80573	72.168	1.1518	-137.11	0.00048133	-104.51	6.45E-05	-154.38	0.28433877	18.2196985
420	0.11782	97.025	0.061858	-41.974	0.00038845	-108.82	4.75E-05	-157.38	0.30994123	19.6163766
480	0.24714	24.636	0.25675	48.83	0.00032133	-112.1	3.63E-05	-159.51	0.33372573	20.9210191
540	0.11216	-53.676	0.037903	134.54	0.00027118	-114.65	2.86E-05	-161.03	0.35605382	22.148965
600	0.16194	-53.727	0.12949	-172.88	0.00023265	-116.71	2.31E-05	-162.11	0.37717599	23.3115113
660	0.042901	160.21	0.014501	-36.272	0.00020233	-118.38	1.89E-05	-162.84	0.39727415	24.4173873
720	4.0987	-97.571	6.4741	-5.6467	0.000178	-119.78	1.58E-05	-163.29	0.41648581	25.4735679
780	0.031866	-105.59	0.0099308	24.535	0.00015815	-120.96	1.34E-05	-163.5	0.43491849	26.4857574
840	0.070382	-81.374	0.089874	169.04	0.0001417	-121.97	1.15E-05	-163.53	0.45265861	27.4586999
900	0.073141	-166.37	0.021608	-164.92	0.0001279	-122.84	9.92E-06	-163.39	0.46977722	28.3963898
960	0.11766	113.21	0.085369	11.288	0.00011619	-123.59	8.66E-06	-163.11	0.48633382	29.3022242
1020	0.031634	143.95	0.029793	27.512	0.00010615	-124.26	7.63E-06	-162.72	0.50237896	30.1791155
1080	0.25832	74.875	0.37439	126.18	9.75E-05	-124.85	6.77E-06	-162.23	0.51795612	31.0295779
1140	0.063644	106.73	0.024493	-136.11	8.99E-05	-125.38	6.04E-06	-161.66	0.53310304	31.8557974
1200	0.11912	13.671	0.15138	-34.192	8.33E-05	-125.85	5.43E-06	-161.02	0.54785279	32.6596835
1260	0.055902	-74.321	0.016086	46.038	7.74E-05	-126.27	4.91E-06	-160.32	0.56223452	33.4429157
1320	0.088393	-40.374	0.054539	95.544	7.22E-05	-126.66	4.46E-06	-159.57	0.5762741	34.2069772
1380	0.036323	147.28	0.0068553	-130.12	6.76E-05	-127.01	4.07E-06	-158.79	0.58999458	34.9531852
1440	2.0233	-92.921	3.2202	-102.28	6.34E-05	-127.32	3.73E-06	-157.96	0.60341665	35.682714
1500	0.031357	-118.48	0.0051416	-69.296	5.97E-05	-127.62	3.44E-06	-157.11	0.61655892	36.3966162
1560	0.045924	-55.232	0.051529	76.269	5.63E-05	-127.89	3.18E-06	-156.24	0.6294382	37.0958385
1620	0.049322	177.7	0.011776	102.95	5.32E-05	-128.13	2.95E-06	-155.35	0.64206975	37.7812352
1680	0.074854	95.756	0.074067	-53.461	5.03E-05	-128.36	2.74E-06	-154.45	0.65446743	38.4535811
1740	0.023753	179.77	0.017034	-67.662	4.78E-05	-128.58	2.56E-06	-153.54	0.66664393	39.113581
1800	0.15863	70.313	0.2242	29.973	4.54E-05	-128.77	2.39E-06	-152.61	0.67861084	39.7618773
1860	0.05119	112.28	0.015323	128.63	4.32E-05	-128.96	2.25E-06	-151.69	0.69037881	40.3990588
1920	0.089244	5.4285	0.12633	-124.1	4.12E-05	-129.13	2.11E-06	-150.76	0.70195762	41.0256652

1980	0.043585	-87.884	0.010348	-47.483	3.94E-05	-129.29	1.99E-06	-149.83	0.71335634	41.6421941
2040	0.070192	-32.38	0.033885	4.3855	3.76E-05	-129.44	1.89E-06	-148.91	0.72458332	42.249104
2100	0.034777	142.56	0.004591	135.45	3.60E-05	-129.58	1.79E-06	-147.98	0.7356463	42.8468195
2160	1.3457	-90.967	2.145	161.31	3.46E-05	-129.71	1.70E-06	-147.06	0.74655248	43.4357342
2220	0.031561	-123.2	0.0033942	-163.39	3.32E-05	-129.84	1.61E-06	-146.15	0.75730857	44.0162141
2280	0.040785	-38.326	0.037175	-16.775	3.19E-05	-129.96	1.54E-06	-145.24	0.7679208	44.5885998
2340	0.041833	167.3	0.0080338	8.8292	3.06E-05	-130.07	1.47E-06	-144.33	0.778395	45.1532093
2400	0.062502	82.704	0.076857	-136.35	2.95E-05	-130.17	1.40E-06	-143.44	0.78873664	45.7103397
2460	0.024203	-162.26	0.011909	-163.08	2.84E-05	-130.27	1.34E-06	-142.55	0.79895081	46.2602695
2520	0.11763	65.059	0.16006	-66.166	2.74E-05	-130.37	1.29E-06	-141.67	0.80904233	46.8032601
2580	0.0458	115.76	0.011178	33.189	2.65E-05	-130.46	1.23E-06	-140.8	0.81901569	47.3395567
2640	0.07664	-0.25218	0.1152	143.34	2.56E-05	-130.54	1.19E-06	-139.94	0.82887515	47.8693902
2700	0.038993	-96.819	0.007689	-142.03	2.47E-05	-130.62	1.14E-06	-139.09	0.8386247	48.3929785
2760	0.062356	-27.19	0.024374	-86.42	2.39E-05	-130.7	1.10E-06	-138.24	0.84826812	48.9105273
2820	0.034114	140.14	0.0035067	40.843	2.32E-05	-130.77	1.06E-06	-137.41	0.85780898	49.4222304
2880	1.0085	-89.694	1.6084	64.957	2.24E-05	-130.84	1.02E-06	-136.59	0.86725066	49.9282719
2940	0.031753	-125.62	0.0024888	102.44	2.18E-05	-130.91	9.90E-07	-135.77	0.87659634	50.4288259
3000	0.039702	-28.084	0.029705	-110.11	2.11E-05	-130.97	9.58E-07	-134.97	0.88584907	50.9240577
3060	0.03855	160.32	0.0060599	-85.894	2.05E-05	-131.03	9.28E-07	-134.18	0.89501172	51.414124
3120	0.05809	73.775	0.080259	134.03	1.99E-05	-131.09	9.00E-07	-133.4	0.90408702	51.899174
3180	0.025394	-153.31	0.0091456	101.44	1.94E-05	-131.14	8.73E-07	-132.62	0.91307758	52.3793499
3240	0.095866	59.937	0.12448	-162.28	1.88E-05	-131.2	8.47E-07	-131.86	0.92198587	52.8547862
3300	0.042825	118.13	0.0088163	-62.319	1.83E-05	-131.25	8.24E-07	-131.11	0.93081425	53.3256126
3360	0.069862	-4.1933	0.10884	49.483	1.78E-05	-131.29	8.01E-07	-130.36	0.93956498	53.7919518
3420	0.036835	-102.91	0.0061564	123.04	1.74E-05	-131.34	7.79E-07	-129.63	0.94824019	54.2539214
3480	0.058106	-23.604	0.019025	-176.95	1.69E-05	-131.38	7.59E-07	-128.91	0.95684195	54.7116336
3540	0.033748	138.68	0.0028722	-53.865	1.65E-05	-131.43	7.40E-07	-128.19	0.96537222	55.1651958
3600	0.8066	-88.694	1.2868	-31.378	1.61E-05	-131.47	7.21E-07	-127.49	0.97383287	55.6147116
3660	0.031899	-127.09	0.0019371	8.3476	1.57E-05	-131.51	7.04E-07	-126.79	0.98222571	56.0602791
3720	0.039674	-21.603	0.025146	156.28	1.53E-05	-131.54	6.87E-07	-126.11	0.99055244	56.5019932
3780	0.036829	155.44	0.0048405	179.14	1.49E-05	-131.58	6.72E-07	-125.43	0.99881474	56.9399444
3840	0.056469	67.728	0.083171	41.624	1.46E-05	-131.61	6.56E-07	-124.76	1.00701418	57.37422
3900	0.026436	-148.19	0.0074181	5.9183	1.43E-05	-131.65	6.42E-07	-124.1	1.01515229	57.8049038
3960	0.082718	55.184	0.10185	101.62	1.39E-05	-131.68	6.28E-07	-123.46	1.02323053	58.2320765
4020	0.040948	119.83	0.0072927	-157.86	1.36E-05	-131.71	6.15E-07	-122.82	1.0312503	58.6558154
4080	0.065661	-6.9711	0.10465	-45.101	1.33E-05	-131.74	6.02E-07	-122.18	1.03921297	59.0761954
4140	0.035668	-107.23	0.0051599	27.927	1.30E-05	-131.77	5.90E-07	-121.56	1.04711982	59.4932884
4200	0.055477	-21.006	0.015688	92.704	1.28E-05	-131.79	5.79E-07	-120.94	1.05497212	59.9071636
4260	0.033516	137.69	0.0024566	-148.64	1.25E-05	-131.82	5.68E-07	-120.34	1.06277108	60.3178875
4320	0.67212	-87.83	1.0725	-127.7	1.22E-05	-131.85	5.57E-07	-119.74	1.07051785	60.7255252
4380	0.032013	-128.08	0.0015647	-85.678	1.20E-05	-131.87	5.47E-07	-119.15	1.07821357	61.1301386

4440	0.039939	-17.241	0.022087	62.429	1.17E-05	-131.89	5.37E-07	-118.57	1.08585931	61.5317877
4500	0.035815	151.87	0.0040137	84.046	1.15E-05	-131.92	5.27E-07	-117.99	1.09345614	61.9305311
4560	0.056002	63.563	0.085625	-52.147	1.13E-05	-131.94	5.18E-07	-117.42	1.10100505	62.3264246
4620	0.027266	-144.95	0.0062366	-89.616	1.11E-05	-131.96	5.10E-07	-116.86	1.10850702	62.7195226
4680	0.074114	50.873	0.086185	5.5232	1.08E-05	-131.98	5.01E-07	-116.31	1.11596301	63.1098776
4740	0.03966	121.1	0.0062285	106.59	1.06E-05	-132	4.93E-07	-115.77	1.12337393	63.4975409
4800	0.0628	-8.9539	0.10164	-140.13	1.04E-05	-132.02	4.85E-07	-115.23	1.13074066	63.8825613
4860	0.034975	-110.44	0.004461	-67.29	1.02E-05	-132.03	4.78E-07	-114.7	1.13806405	64.2649872
4920	0.053708	-19.05	0.013481	2.4098	1.01E-05	-132.05	4.70E-07	-114.18	1.14534495	64.6448642
4980	0.033354	136.99	0.0021638	116.54	9.87E-06	-132.07	4.63E-07	-113.66	1.15258415	65.0222377
5040	0.57612	-87.045	0.91951	135.98	9.70E-06	-132.08	4.56E-07	-113.15	1.15978243	65.3971512
5100	0.032101	-128.79	0.0013	-179.54	9.53E-06	-132.1	4.50E-07	-112.65	1.16694055	65.7696471
5160	0.040271	-14.144	0.019901	-31.646	9.36E-06	-132.11	4.43E-07	-112.15	1.17405924	66.1397658
5220	0.035168	149.17	0.0034145	-11.095	9.20E-06	-132.13	4.37E-07	-111.66	1.18113922	66.507548
5280	0.056074	60.638	0.087742	-146.68	9.04E-06	-132.14	4.31E-07	-111.18	1.18818117	66.8730318
5340	0.027925	-142.72	0.0053787	174.84	8.89E-06	-132.15	4.26E-07	-110.7	1.19518577	67.2362552
5400	0.068168	47.009	0.074702	-90.568	8.75E-06	-132.17	4.20E-07	-110.23	1.20215366	67.5972544
5460	0.038722	122.09	0.0054443	11.022	8.60E-06	-132.18	4.14E-07	-109.76	1.20908549	67.9560655
5520	0.06071	-10.377	0.099335	124.54	8.46E-06	-132.19	4.09E-07	-109.3	1.21598186	68.3127226
5580	0.034534	-112.89	0.0039443	-162.58	8.33E-06	-132.2	4.04E-07	-108.85	1.22284337	68.6672597
5640	0.052443	-17.536	0.01197	-87.948	8.19E-06	-132.21	3.99E-07	-108.4	1.22967062	69.0197095
5700	0.033234	136.45	0.0019471	21.666	8.06E-06	-132.22	3.94E-07	-107.96	1.23646415	69.3701039
5760	0.50416	-86.309	0.80482	39.668	7.94E-06	-132.23	3.90E-07	-107.52	1.24322452	69.7184737
5820	0.032173	-129.34	0.0011002	86.699	7.82E-06	-132.24	3.85E-07	-107.09	1.24995228	70.0648496
5880	0.040597	-11.848	0.018264	-125.92	7.70E-06	-132.25	3.81E-07	-106.67	1.25664794	70.4092608
5940	0.034727	147.06	0.002962	-106.29	7.58E-06	-132.26	3.76E-07	-106.25	1.26331201	70.7517363
6000	0.05642	58.55	0.089625	118.32	7.47E-06	-132.27	3.72E-07	-105.83	1.26994498	71.0923038