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Sensitivity of SLS tunes on lengths and fringing fields of quadrupoles

Gurnam Singh
Andreas Streun

Paul Scherrer Institut
CH-5232 Villigen PSI
Switzerland

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The tune point for the D2R optics presently used for the operation of the SLS is (20.38,8.16). In order to achieve this tune point practically, the strengths of quadrupoles have to be 1.15% higher than theoretical strengths. The objective of these studies is to establish whether the tune point is significantly influenced by the effective lengths of the quadrupoles and fringing fields. Effect of the errors in edge angles of the bending magnets is also taken into consideration in these studies.

In the SLS, three types of quadrupoles have been used. For calculation of lattice parameters, the lengths of the quadrupoles are taken as 200mm, 320mm and 440mm. The currents of quadrupoles for operation of the SLS are calculated as per the theoretical values of G.L(product of gradient and quadrupole length).

For the following studies, it is important to know the effective lengths of quadrupoles at their operating strengths. In the following table, we list the effective lengths (L_{eff}) of quadrupoles at the required operating strengths using the available magnetic field measurement data[1].

Table 1 : Quadrupole Parameters in D2R Optics

Name	L(mm)	K(m^{-2})	G(T/m)	G.L(Gauss)	I(A)	L_{eff}(mm)
QAL	200	1.4478	11.5821	23164.1	59.2	230.6, 230.9, 230.8, 230.6
QAM	200	1.3763	11.0108	22021.6	56.0	230.6, 230.9, 230.8, 230.7
QAS	200	1.6439	13.1509	26301.8	62.0	230.6, 230.9, 230.8, 230.6
QBL	320	1.1046	08.8370	28278.4	47.6	350.8
QBM	320	0.9652	07.7213	24708.1	41.3	350.9
QBS	320	1.1399	09.1190	29180.8	49.2	350.8
QCL	440	1.8824	15.0593	66261.0	82.2	469.6
QCM	440	1.9797	15.8378	69686.5	86.6	469.5
QCS	440	1.8916	15.1330	66585.2	82.6	469.6
QDL	320	1.8529	14.8232	47434.2	79.0	350.4
QDM	320	2.0429	16.3430	52297.7	87.7	350.7
QDS	320	1.9784	15.8271	50646.7	84.7	350.5
QL1	200	0.1000	00.8000	01600.0	02.3	230.9, 231.2, 231.0, 230.9
QL2	440	1.8479	14.7829	65044.8	80.6	469.6
QL3	440	1.8581	14.8647	65404.8	81.1	469.6
QL4	200	2.1949	17.5591	35118.3	88.4	229.4, 229.9, 230.0, 229.8
QM1	200	0.6629	05.3035	10607.1	26.5	230.9, 231.2, 231.0, 230.9
QM2	440	2.2165	17.7324	78022.4	97.3	468.6
QM3	320	1.6544	13.2352	42352.8	69.9	350.7
QS!	200	0.9142	07.3133	14626.5	37.8	230.8, 231.1, 231.0, 230.8
QS2	440	2.5541	20.4330	89905.2	112.0	468.0
QS3	440	1.9220	15.3760	67654.2	84.0	469.5

QA00, QA01, QA02, QA03 data for 200mm long quadrupoles
QB27 data for 320mm long qadrupoles
QCW01 data for 440mm long quadrupoles

On the basis of the above data, We, now, assume the lengths of the quadrupoles to be 230mm, 350mm and 469mm and calculate their strengths according to their G.Ls as given by D2R optics. For these strengths(Appendix), the tune point turns out to be (19.98,7.92). When this lattice is tuned to the required tune point (20.38,8.16) using the program OPA, the new strengths of the quadrupoles obviously higher are given in Table 2

Table 2

	$K_1(m^{-2})$	$K_2(m^{-2})$	δK	%Change
QAL	1.258920	1.270595	0.011675	0.927
QAM	1.196824	1.207923	0.011099	0.927
QAS	1.429443	1.442699	0.013256	0.927
QBL	1.009941	1.016870	0.006929	0.686
QBM	0.882432	0.888486	0.006054	0.686
QBS	1.042173	1.049323	0.007150	0.686
QCL	1.765260	1.777371	0.012111	0.686
QCM	1.856530	1.869267	0.012737	0.686
QCS	1.773900	1.786070	0.012170	0.686
QDL	1.694080	1.709790	0.015710	0.927
QDM	1.867775	1.885096	0.017321	0.927
QDS	1.808813	1.825587	0.016774	0.927
QL1	0.086956	0.087762	0.000806	0.927
QL2	1.732860	1.744749	0.011889	0.686
QL3	1.742246	1.758403	0.016157	0.927
QL4	1.908558	1.921652	0.013094	0.686
QM1	0.576472	0.581818	0.005346	0.927
QM2	2.078600	2.092861	0.014261	0.686
QM3	1.512100	1.526123	0.014023	0.927
QS1	0.794919	0.802291	0.007372	0.927
QS2	2.395170	2.411603	0.016433	0.686
QS3	1.802380	1.819095	0.016715	0.927

Though the strengths of quadrupoles have to be increased either by 0.927% or 0.686% but the magnitudes of increase in strengths are smaller than the actual increase of 1.15% However, there is a clear indication that the reason for the higher strengths is the higher lengths of quadrupoles.

It has been reported [2] that as per the field measurements performed on the SLS bending magnets, the edge angle of each 14^0 magnet is 6.4^0 as against the specified value of 7^0 and that of 8^0 magnet is 3.4^0 ,whereas the specified value was 4^0. The edge angle errors are not currently included in D2R optics calculations.

When we take into account the edge angle errors, the tune point shifts from (19.98,7.92) to (19.99, 7.77). Starting with this tune point, if we try to reach the tune point (20.38, 8.16) using the program OPA, the quadrupole strengths have to be increased as given in the Table 3

Table 3

	$K_1(m^{-2})$	$K_2(m^{-2})$	δK	%Change
QAL	1.258920	1.274784	0.011675	1.26
QAM	1.196824	1.211906	0.011099	1.26
QAS	1.429443	1.447456	0.013256	1.26
QBL	1.009941	1.017260	0.006929	0.72
QBM	0.882432	0.888827	0.006054	0.72
QBS	1.042173	1.049726	0.007150	0.72
QCL	1.765260	1.778053	0.012111	0.72
QCM	1.856530	1.869984	0.012737	0.72
QCS	1.773900	1.786755	0.012170	0.72
QDL	1.694080	1.715428	0.015710	1.26
QDM	1.867775	1.891312	0.017321	1.26
QDS	1.808813	1.831607	0.016774	1.26
QL1	0.086956	0.088052	0.000806	1.26
QL2	1.732860	1.745418	0.011889	0.72
QL3	1.742246	1.764201	0.016157	1.26
QL4	1.908558	1.922389	0.013094	0.72
QM1	0.576472	0.583736	0.005346	1.26
QM2	2.078600	2.093664	0.014261	0.72
QM3	1.512100	1.531155	0.014023	1.26
QS1	0.794919	0.804936	0.007372	1.26
QS2	2.395170	2.412528	0.016433	0.72
QS3	1.802380	1.825093	0.016715	1.26

Here the strengths of the quadrupoles have been increased either by 1.26% or by 0.72% and this situation seems to be close to the reality. Now, if we increase the strengths of all quadrupoles by 1.15%, the tune point shifts from(19.99,7.77)to (20.74,8.00) The horizontal tune becomes much higher than the required tune, whereas it is vice versa for the vertical tune. If the edge angle errors are excluded, the tune point is 20.73/8.15 Though these results suggest that the higher required strengths of the quadrupoles could be due to their longer effective lengths but quantitatively it is not fully explained by the lengths assumed . One of the reasons for the additional error may be that in reality, quadrupoles do not follow the hard-edge model, therefore, the correct tune values can not be obtained by simply considering the higher effective lengths of quadrupoles.

Effect of fringe fields:

In order to calculate the tune value accurately, it is essential to take into consideration the actual longitudinal distribution of gradient of each quadrupole. Unfortunately, the data for longitudinal distribution of gradients at various currents is not available. Here, to calculate the distribution along the beam path at all currents, we use the plots of longitudinal distribution at 120A as shown in Figs. 1&2 which represent the longitudinal distribution of gradient in a 200mm long quadrupole (QA00.05) and a 440mm quadrupole(QCW01.05) respectively. Since, no plot for longitudinal distribution is available for the 320mm long quadrupoles, their longitudinal distribution was derived using the profiles for 200mm quadrupoles (QA00.05) and 440mm quadrupoles (QCW01.05). For these studies, the quadrupoles are broken up into small segments of different lengths. A 200mm quadrupole is divided into 34 parts and 440mm quadrupole into 22 parts. As regards the 320mm quadrupoles, each one of them is divided into 36 parts (additional two parts defines central peak field) when the profile of QA00.05 is used and into 22 parts when the profile of QCW01.05 is used. The tunes calculated following this procedure for finding out longitudinal distribution can have some error because the information on gradient is derived from the plots, the number of parts in which each quadrupole is divided is limited and the longitudinal gradient distribution at 120 A does not truly represent the distributions at the all operating currents which are normally much lower.

With the division of quadrupoles into many parts, the number of elements becomes much higher than what can be handled by the program OPA, therefore the program TRACY was used for these studies. Due to limitations of TRACY, the edge angle errors could not be included. The tune points are found out for the two cases as discussed above considering the same G.L as given by D2R optics. The tune point turns out to be (19.86,7.85) when the profile of QA00.05 is adopted for 320mm quadrupoles and it is (19.85,7.84) when the profile of QCW01.05 is used for them. The fact that the two tune points are so close to each other indicates that the effect of fringing field is well accounted for in these studies. Besides, any of the above tune points can be considered as a reference for further studies. It is also evident here that these tune points are not far from the (19.98, 7.92) obtained with higher lengths of quadrupoles. The difference between the theretical and experimental tune values can be narrowed down by increasing the lengths of quadrupoles further. However, in keeping with usual convention of taking the lengths of quadrupoles equal to their effective lengths, the quadrupole lengths are not increased further.Now, when we consider the first case of the fringing field with the tune point (19.86, 7.85) and increase the strength of all quadrupoles by 1.15%, the tune point shifts to (20.60,8.10) which is again not far from (20.73,8.15) obtained earlier by taking the lengths of quadrupoles to be 230mm, 350mm and 469mm. Taking these lengths of quadrupoles and horizontal tune to be 19.86 as predicted by the fringing field calculations, it is estimated that to achieve the required horizontal tune of 20.38, the strengths of quadrupoles will have to be increased by 1.00 %.The corresponding vertical tune, in the absence of edge angle errors will be 8.13. If there is no edge angle error, the tunes obtained after increasing the strengths by 1% are nearly the same as practically achieved..So, the major part of the increase in strengths is taken care of by assuming the lengths of quadrupoles to be 230mm, 350mm and 469mm.

An additional advantage of using these lengths for quadrupoles for theoretical calculations is that the since starting optics will be more close to the real optics, the spurious dispersion produced to the mismatch between dipole and quadrupole fields will be much less than the present case.

Conclusions :

The difference between the practical and theoretical strengths of quadrupoles is grossly well explained by considering longer lengths and fringing field of quadrupoles

References:

1. BINP Inspection Reports for QB27, QA00 QA01, QA02, QA03, QCW00

2 V Vrankovic's e-mail on 15.05.2001 to A Streun

Acknowledgements :

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Appendix :

OPA INPUT FILE FOR QUADRUPOLE LENGHTS OF 0.23m, 0.35m and 0.469m

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{----- C:\OPA\GS\D2LE.OPA---.........................................-}

{----- Global parameters (units: GeV, m, rad) ------------------------------}

Title = SIMILAR TO REAL OPERATING MACHINE;

Energy =   2.400000; NPeriod = 3;
Meth   = 0; Nbend = 1; Nquad = 1;

    BetaX   =    4.5620231; AlphaX  =   -0.0000000;
    EtaX    =    0.0000010; EtaXP   =   -0.0000000;
    BetaY   =    3.7291978; AlphaY  =   -0.0000000;
    EtaY    =    0.0000000; EtaYP   =    0.0000000;
    OrbitX  = 0.0000000000; OrbitXP = 0.0000000000;
    OrbitY  = 0.0000000000; OrbitYP = 0.0000000000;
    OrbitDPP= 0.0000000000;

{----- Table of elements (units: m, m^-2, deg, T; mm, mrad) --------------- }
{      Conventions: Quadrupole: k>0 horizontally focusing                  }
{                   Sextupole : k=m*l, m:=Bpoletip/r^2/(B*rho)             }

AAA           : Drift, L = 0.000000, Nslice =  1, Ax = 32.50, Ay = 16.00;
D050          : Drift, L = 0.500000, Nslice =  1, Ax = 32.50, Ay = 16.00;
D51           : Drift, L = 0.485000, Nslice =  1, Ax = 32.50, Ay = 16.00;
D52           : Drift, L = 0.485500, Nslice =  1, Ax = 32.50, Ay = 16.00;
D1            : Drift, L = 0.385000, Nslice =  1, Ax = 32.50, Ay = 16.00;
D2            : Drift, L = 0.525000, Nslice =  1, Ax = 32.50, Ay = 16.00;
D3            : Drift, L = 0.345500, Nslice =  1, Ax = 32.50, Ay = 16.00;
D4            : Drift, L = 0.385000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DL1           : Drift, L = 0.540000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DL2           : Drift, L = 0.330500, Nslice =  1, Ax = 32.50, Ay = 16.00;
DL3           : Drift, L = 0.525500, Nslice =  1, Ax = 32.50, Ay = 16.00;
DL4           : Drift, L = 0.330500, Nslice =  1, Ax = 32.50, Ay = 16.00;
DLPLUS        : Drift, L = 0.880000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DM1           : Drift, L = 0.580000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DM2           : Drift, L = 0.450500, Nslice =  1, Ax = 32.50, Ay = 16.00;
DM3           : Drift, L = 0.345000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DS1           : Drift, L = 0.580000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DS2           : Drift, L = 0.450500, Nslice =  1, Ax = 32.50, Ay = 16.00;
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DS3           : Drift, L = 0.345500, Nslice =  1, Ax = 32.50, Ay = 16.00;
DSX           : Drift, L = 0.245000, Nslice =  1, Ax = 32.50, Ay = 16.00;
DSX1          : Drift, L = 0.245500, Nslice =  1, Ax = 32.50, Ay = 16.00;
MGP           : Drift, L = 0.500000, Nslice =  1, Ax = 32.50, Ay = 16.00;
QAL           : Quadrupole, L = 0.230000, K = -1.258920,  Ax = 32.50, Ay = 16.00;
QAM           : Quadrupole, L = 0.230000, K = -1.196824,  Ax = 32.50, Ay = 16.00;
QAS           : Quadrupole, L = 0.230000, K = -1.429993,  Ax = 32.50, Ay = 16.00;
QBL           : Quadrupole, L = 0.350000, K =  1.009941,  Ax = 32.50, Ay = 16.00;
QBM           : Quadrupole, L = 0.350000, K =  0.882432,  Ax = 32.50, Ay = 16.00;
QBS           : Quadrupole, L = 0.350000, K =  1.042173,  Ax = 32.50, Ay = 16.00;
QCLH          : Quadrupole, L = 0.234500, K =  1.766013,  Ax = 32.50, Ay = 16.00;
QCMH          : Quadrupole, L = 0.234500, K =  1.857322,  Ax = 32.50, Ay = 16.00;
QCSH          : Quadrupole, L = 0.234500, K =  1.774656,  Ax = 32.50, Ay = 16.00;
QDL           : Quadrupole, L = 0.350000, K = -1.694080,  Ax = 32.50, Ay = 16.00;
QDM           : Quadrupole, L = 0.350000, K = -1.867775,  Ax = 32.50, Ay = 16.00;
QDS           : Quadrupole, L = 0.350000, K = -1.808813,  Ax = 32.50, Ay = 16.00;
QL1           : Quadrupole, L = 0.230000, K = -0.086956,  Ax = 32.50, Ay = 16.00;
QL2H          : Quadrupole, L = 0.234500, K =  1.733599,  Ax = 32.50, Ay = 16.00;
QL3H          : Quadrupole, L = 0.234500, K = -1.742989,  Ax = 32.50, Ay = 16.00;
QL4           : Quadrupole, L = 0.230000, K =  1.908558,  Ax = 32.50, Ay = 16.00;
QM1           : Quadrupole, L = 0.230000, K = -0.576472,  Ax = 32.50, Ay = 16.00;
QM2H          : Quadrupole, L = 0.234500, K =  2.079486,  Ax = 32.50, Ay = 16.00;
QM3           : Quadrupole, L = 0.350000, K = -1.512100,  Ax = 32.50, Ay = 16.00;
QS1           : Quadrupole, L = 0.230000, K = -0.794919,  Ax = 32.50, Ay = 16.00;
QS2H           : Quadrupole, L = 0.234500, K =  2.396191,  Ax = 32.50, Ay = 16.00;
QS3H          : Quadrupole, L = 0.234500, K = -1.803149,  Ax = 32.50, Ay = 16.00;
BHE           :      Bending, L = 0.400000, T =  4.00000, K =  0.000000,
              T1 =  4.00000, T2 =  0.00000, Gap =  0.00,
              K1 = 0.0000, K2 = 0.0000, Ax = 32.50, Ay = 16.00;
BM0           : Bending, L = 0.350000, T =  3.50000, K =  0.000000,
              T1 =  0.00000, T2 =  0.00000, Gap =  0.00,
              K1 = 0.0000, K2 = 0.0000, Ax = 32.50, Ay = 16.00;
BM1           : Bending, L = 0.350000, T =  3.50000, K =  0.000000,
              T1 =  7.00000, T2 =  0.00000, Gap =  0.00,
              K1 = 0.0000, K2 = 0.0000, Ax = 32.50, Ay = 16.00;
SD            : Sextupole, K = -3.949799, Ax = 32.50, Ay = 16.00;
SE            : Sextupole, K = -2.033546, Ax = 32.50, Ay = 16.00;
SF            : Sextupole, K =  4.247511, Ax = 32.50, Ay = 16.00;
SL1           : Sextupole, K = -7.420078, Ax = 32.50, Ay = 16.00;
SL2           : Sextupole, K =  2.898742, Ax = 32.50, Ay = 16.00;
SM1           : Sextupole, K = -3.857892, Ax = 32.50, Ay = 16.00;
SM2           : Sextupole, K =  3.400525, Ax = 32.50, Ay = 16.00;
SS1           : Sextupole, K = -7.244432, Ax = 32.50, Ay = 16.00;
SS2           : Sextupole, K =  4.186648, Ax = 32.50, Ay = 16.00;
OMB           : OpticsMarker, Ax = 32.50, Ay = 16.00,
           BetaX =   0.449999, AlphaX =  -0.000002,
           BetaY =  14.800162, AlphaY =   0.000026,
           EtaX  =   0.030001, EtaXP  =  -0.000001,
           EtaY  =   0.000000, EtaYP  =   0.000000,
           OrbitX  =    0.000, OrbitXP =    0.000,
           OrbitY  =    0.000, OrbitYP =    0.000,
           OrbitDPP =    0.000;
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{----- Table of segments ----------------------------------------------------}

QCS           :2*QCSH;
QCM           :2*QCMH;
QCL           :2*QCLH;
QM2           :2*QM2H;
QS2           :2*QS2H;
QS3           :2*QS3H;
QL3           :2*QL3H;
QL2           :2*QL2H;
B             :BHE, -BHE;
BHM            :BM1, BM0;
TL1           :-BHM, D1, QAL, DSX, SD, D2, QBL, DSX;
TL2           :SF, DSX1, QCL, D3, SE, DSX, QDL, D4, B;
PLOT          :D1, BHM, OMB, -BHM, D1, QAL, DSX, SD, D2, QBL, DSX, SF, DSX1,
              QCL, D3, SE, DSX, QDL, D4, B, D4;
TL            :-BHM, D1, QAL, DSX, SD, D2, QBL, DSX, SF, DSX1, QCL, D3, SE,
                     DSX, QDL, D4, B;
TM            :-BHM, D1, QAM, DSX, SD, D2, QBM, DSX, SF, DSX1, QCM, D3, SE,
                     DSX, QDM, D4, B;
TS            :-BHM, D1, QAS, DSX, SD, D2, QBS, DSX, SF, DSX1, QCS, D3, SE,
              DSX, QDS, D4, B;
DM            :D51, 6*D050;
DS            :D52, D050, 2*MGP;
DL            :D51, 9*D050, DLPLUS;
ML            :DL1, SL1, DSX, QL1, DL2, QL2, AAA, DSX1, SL2, DL3, QL3, DL4,
              QL4, DL;
MM            :DM1, SM1, DSX, QM1, DM2, QM2, DSX1, SM2, DM3, QM3, DM;
MS            :DS1, SS1, DSX, QS1, DS2, QS2, DSX1, SS2, DS3, QS3, DS;
TML           :OMB, TL, ML;
TMM           :OMB, TM, MM;
TMS           :OMB, TS, MS;
SIX           :-TML, TMS, -TMS, TMM;
PER           :SIX, -SIX;
PERL           :TL2, ML, -TML, TMS, -TMS, TMM, -TMM, TMS, -TMS, TL1;
PERLE         :ML, SIX, -TMM, TMS, -TMS, TL;
RING          :3*PER;
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