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INVESTIGATION OF THE $Q_H + 2Q_V = 19$ RESONANCE IN THE CPS

C.J. Gardner* and J.P. Potier

Introduction

During the Summer of 1986 and again in early December of that year, careful studies of the $Q_x + 2Q_y = 19$ resonance at low energy in the CPS were carried out by van Asselt, Potier and Hancock [1-2]. In these studies, the tunes were placed at several points along the $Q_x + 2Q_y = 19$ resonance line, and the amount of sextupole correction required to eliminate beam losses due to excitation of the resonance was determined. It was found in the earlier study and reconfirmed by the latter that the amount of sextupole correction required varied as the tunes were moved along the resonance line. Since the resonance is excited by a 19th harmonic in the azimuthal variation of the sextupole fields around the machine, one does not expect changes in tune, which are introduced by the low-field quadrupoles, to alter the sextupole fields present in the machine or to change the required sextupole correction.

Shortly after the December study, the PS was shutdown and underwent a number of upgrades which included (among other things) the installation of new vacuum chambers, modification of the passive networks connected to the pole-face windings, and the installation of new figure-of-eight loops which are now placed around the poles of the main magnets.

It was the purpose of the present investigation to determine the mechanism for the curious dependence of the required sextupole correction on the position along the resonance line and to compensate for this effect. However, when the resonance was studied in August (1987), after the shutdown and completion of the upgrade, it was found that with the tunes on the resonance and with the correction sextupoles turned off, no beam loss occurred, indicating that the sextupole fields which had excited the resonance in the previous studies had disappeared.

In the following report, the details of this most recent study are given and calculations pertaining to a possible mechanism for the previously observed effect are presented.

* Visitor from Brookhaven National Laboratory, who spent 3 months at CERN (from 1.7.1987 until 30.9.1987)

Excitation of the resonance

In the papers of G. Guignard [3-4-5] on the theory of sum and difference resonances, it is shown that if the tunes are near a particular resonance, then this resonance will be excited whenever the excitation coefficien, κ, is nonzero.

For the case of the $Q_x + 2Q_y = 19$ resonance, κ may be written

$$\kappa = C \int_0^L ds\, b_{12}(s)\, \Gamma(s) \tag{1}$$

where C is a constant inversely proportional to the momentum, $L = 2\pi R$ is the length of the equilibrium orbit, s is the distance along the orbit measured from a fixed reference point,

$$b_{12}(s) = \left(\frac{\partial^2 B_y}{\partial x^2}\right)_{\substack{x=0\\y=0}} \tag{2}$$

$$\Gamma(s) = \beta_x^{1/2}(s)\, B_y(s)\, e^{i\psi(s)}$$

$$\psi(s) = [\mu_x(s) - Q_x\, s/R] + 2\,[\mu_y(s) - Q_y\, s/R] + 19\, s/R \tag{3}$$

$$\mu_x(s) = \int_0^s \frac{ds'}{\beta_x(s')} \quad ; \quad \mu_y(s) = \int_0^s \frac{ds'}{\beta_y(s')}$$

The constant C, appearing in (1) is given by

$$C = \frac{1}{4\sqrt{2}} \quad \frac{1}{2\pi R}\, \frac{e}{cp} = 5.6 \times 10^{-5}\ T^{-1}\ m^{-2} \tag{4}$$

in which we have used $R = 100$ m and $cp/e = 5.0$ Tm. (Note that the value of κ given by (1-4) is a factor of $1/\sqrt{R}$ smaller than that given by G. Guignard [5]. This is due to a different normalization of coordinates and momenta used here. To obtain Guignard's κ, equation (1) must be multiplied by $\sqrt{R}$).

Since the phase differences $\mu_x(s) - Q_x\, s/R$ and $\mu_y(s) - Q_y\, s/R$ are relatively small and since the beta functions β_x and β_y oscillate relatively rapidly, we see from equations (1-4) that κ is essentially proportional to the 19th harmonic in the azimuthal variation of $b_{12}(s)$ around the machine. The real and imaginary parts of κ, which we denote by $\mathrm{Re}\kappa$ and $\mathrm{Im}\kappa$, are then essentially the cos and sin components of this harmonic.

The resonance can only produce unlimited growth in the amplitudes of the betatron oscillations if the tunes are such that

$$-\frac{W}{2} < Q_x + 2Q_y - 19 < \frac{W}{2} \tag{5}$$

where W is the stopband width of the resonance.

For the $Q_x + 2Q_y = 19$ resonance, this stopband width is [3-4-5]

$$W = (2/\pi)^{1/2} \; R \; |\kappa| \; \frac{1}{\sqrt{\varepsilon_{10}}} \; (\varepsilon_{20} + 4\varepsilon_{10}) \tag{6}$$

where ε_{10} and ε_{20} are the initial horizontal and vertical emittances. (Note that the value of $|\kappa|$ used in (6) must be taken from equations (1-4) since the definition of κ given here is slightly different than Guignard's - see comment after equation (4)).

Correction schemes

Any naturally occuring sextupole fields in the machine which produce a nonzero value of κ can excite the resonance resulting in beam loss. We denote this value of κ by κ_o and call it the intrinsic κ of the machine. To cancel κ_o, so that the resonance cannot be excited, correction sextupoles located at various positions, s_j, in the ring are excited with currents I_j in such a way that they produce a value of κ equal to $-\kappa_o$

Assuming the sextupoles are point sextupoles each having an integrated strength of S T/m per Amp, we find, using equations (1-4), that they introduce a κ given by

$$\kappa_{corr} = C\,S \sum_j I_j \Gamma_j \quad ; \quad \Gamma_j = \Gamma(s_j) \tag{7}$$

Two different schemes (labelled A and B) of sextupoles have been used in the PS to produce κ_{corr}. Tables I and II list the sextupoles and excitation currents used for each scheme.

Table I - Scheme A

Sextupole	S_j (meters)	Cos excitation I_j (Amps)	SIN excitation I_j (Amps)
XDN02	8.403	.307	.908
XDN14	82.641	-.996	.249
XDN40	246.324	-.884	.590
XDN44	270.937	.424	.849
XDN52	322.562	-.307	-.908
XDN64	396.601	.996	-.249
XDN90	560.283	.884	-.590
XDN94	585.896	-.424	-.849

Table II - Scheme B

Sextupole	S_j (meters)	Cos excitation I_j (Amps)	SIN excitation I_j (Amps)
XDN02	8.403	0	-1
XDN14	82.641	-1	0
XDN52	322.562	0	1
XDN64	396.601	1	0

In each scheme, the currents I_j are controlled by a cos knob and a sin knob, and the columns labelled cos and sin excitation give the amounts by which the currents change when these knobs are incremented by 1 Amp.

The sum

$$I\Gamma = \sum_j I_j \Gamma_j \qquad (8)$$

which appears in equation (7) is proportional to κ_{corr} and can be calculated using the parameters contained in the TWISS file generated by the MAD code [6]. A table of these parameters is given in Appendix A. Tables III and IV give the real and imaginary parts of $I\Gamma$ for schemes A and B respectively. In each table, $I\Gamma$ has been calculated for four positions along the line $Q_x + 2Q_y = 19$ and the columns labelled cos and sin excitation give the values of $I\Gamma$ obtained with the currents given in the corresponding columns of tables I and II.

Table III (Scheme A)

Tunes		Cos excitation		Sin excitation	
Q_x	Q_y	ReIΓ	ImIΓ	ReIΓ	ImIΓ
6.1	6.45	294.2	52.1	-99.3	299.4
6.2	6.4	297.0	55.9	-96.0	297.4
6.3	6.35	297.9	56.1	-94.5	297.3
6.4	6.3	297.4	55.1	-94.2	297.9

Table IV (Scheme B)

Tunes		Cos excitation		Sin excitation	
Q_x	Q_y	ReIΓ	ImIΓ	ReIΓ	ImIΓ
6.1	6.45	155.5	-9.0	13.6	-151.9
6.2	6.4	155.6	-7.9	11.9	-152.7
6.3	6.35	155.8	-8.3	11.4	-153.1
6.4	6.3	155.5	-8.9	11.4	-153.1

In both tables, we see that IΓ depends only very weakly on the tunes, which is expected since the quadrupoles used to vary the tunes do not significantly distort the beta functions at the positions of the sextupoles. The values of κ_{corr} produced by each scheme may therefore be written as follows :

$$\kappa_{corr} = CS\ [(297+55i)I_c + (-96+298i)I_s] \qquad \text{(Scheme A)} \qquad (9)$$

$$\kappa_{corr} = CS\ [(156-9i)I_c + (12-153i)I_s] \qquad \text{(Scheme B)} \qquad (10)$$

where I_c and I_s are the currents (in Amps) requested by the cos and sin knobs respectively.

In principle, both schemes work perfectly well for producing the desired κ_{corr} and scheme A was in fact used in the first study carried out by van Asselt and Potier. However, because of the rather complicated distribution of excitation currents required in this scheme (which makes it susceptible to various systematic errors), it was decided to go to the simpler scheme B which has been used in all subsequent studies. A schematic diagram showing the way the currents are delivered to the sextupoles in scheme B is given in Appendix B.

Discussion of the August (1987) study

The technique used to observe the $Q_x + 2Q_y = 19$ resonance in this most recent study was similar to that used in the previous studies [1-2]. The tunes were programmed, using the QFUNC program, so that they satisfied the resonance condition for a period of time during the 20 ms long, 1.5 GeV/c injection flat of a magnetic "C" cycle. Specifically, the function generator (GFA) for the low-field quadrupoles was started at 160 ms (C-train time) and the tunes were programmed to arrive at a point with the vertical tune .05 below the resonance line at the beginning of the injection flat (215 ms). Then during the first 5 ms of the injection-flat, the vertical tune was increased so that it arrived on the resonance line at 220 ms. This position on the resonance line was then maintained for the remaining 15 ms of the injection flat and for an additional 25 ms giving a total of 40 ms in which to observe the resonance. The function generator for the correction sextupoles was also started at 160 ms and was programmed so that the sextupole correction remained at a constant value for the entire time the tunes were on resonance. An example of the tune program, and the function control values for the correction sextupoles are given in Appendix C.

To ensure a negligible space-charge tune spread, the intensity in the PS was reduced to 2-4 x 10^{11} ppp (1-2 x 10^{10} protons per bunch). This was achieved by inserting the sieve (passoire) between the linac and the booster. The emittances of the beam extraced from the booster were then found to be

$$\begin{aligned} \varepsilon_x &= 10\ \pi\ \text{mm.mrad} \\ \varepsilon_y &= 6\ \pi\ \text{mm.mrad} \end{aligned} \qquad (11)$$

The tune spread due to chromaticity and momentum spread was approximately .007 [1].

Under these conditions, the beam intensity was monitored with current transformer TRA78 during the injection flat. With the correction sextupoles turned off, no beam loss was discernible when the tunes were on the resonance line, indicating that the intrinsic excitation coefficient, κ_o, observed in the previous studies was no longer present. To test the validity of this measurement - i.e. to show that a nonzero value of κ would have produced beam loss - the correction sextupoles were excited with currents $I_c = I_s = 2$ Amps in correction scheme B. Beam loss was then seen to occur during the time the tunes were on resonance. The four photographs of Figure 1 show the TRA78 signals observed when the tunes were moved onto the resonance at four different points (Q_x = 6.1, 6.2, 6.3, 6.4) along the line $Q_x + 2Q_y = 19$. In each photo, the top and middle traces show the TRA78 signal observed with the sextupoles turned OFF and ON respectively. (With no beam loss, the amplitude of the TRA78 signal was approximately 800 mV with 2×10^{11} ppp in the PS. In the photos, the zero level has been offset so that the total amplitude is not seen.) The bottom trace in each photo shows dB/dt, which is zero during the 20 ms injection flat and then becomes positive for the acceleration to the 3.5 GeV/c flat. The photos clearly show that a nonzero value of κ can produce observable beam loss when the tunes are on resonance.

To determine the smallest value of $|\kappa|$ that can be detected by observing beam loss with TRA78, the tunes were carefully measured with the tune meter and adjusted so that they both were within .001 of satisfying the relation $Q_x + 2Q_y = 19$. Beam losses were then just barely discernible with either I_c or I_s equal to 0.2 A (correction scheme B). The value of $|\kappa|$ corresponding to either of these currents is (using equations 10)

$$|\kappa| = CS\ (31), \tag{12}$$

where [7]

$$S = .108\ \text{T/m per Amp} \tag{13}$$

is the integrated strengh per Amp of each correction sextupole and C is given by (4). The stopband width for this value of $|\kappa|$, obtained by using (4) and (11-13) in (6), is

$$w = 2.1\ |\kappa| = .0004\ . \tag{14}$$

Equation (12) gives an upper limit on the magnitude, $|\kappa_o|$, of the intrinsic excitation coefficient present in the machine during this study and, upon comparison with the data of the previous studies (see Table V), shows that the sextupole fields which excited the resonance in these studies have apparently disappeared. One is forced to conclude that some defect in the machine was responsible for these fields and that somehow this defect was removed during the shutdown and upgrade period.

An attempt fo explain the curious effects seen in the first two studies

The following table summarizes the results obtained in the two studies [1-2] carried out before the shutdown and upgrade of the PS. The correction currents, I_c and I_s required on the injection flat at various points along the resonance line are given with the corresponding values of κ_{corr} obtained from equations (9) and (10).

Table V

		Study (1) (Scheme A)			Study (2) (Scheme B)		
Q_x	Q_y	I_c (Amps)	I_s	κ_{corr}	I_c (Amps)	I_s	κ_{corr}
6.1	6.45	-0.1	-1.0	CS (66-304i)	0.2	0.7	CS (40-109i)
6.2	6.4	0.4	-1.0	CS (215-276i)	0.47	0.29	CS (77- 49i)
6.3	6.35	1.0	-1.0	CS (393-243i)	0.9	0.2	CS (143-39i)
6.4	6.3	1.5	-1.0	CS (542-216i)	-	-	-

In both studies, the correction, κ_{corr}, required depends on the position along the resonance line, but the values of κ_{corr} are rather different.

Prior to the study carried out in August (1987), it was thought that the dependence of κ_{corr} on the position along the resonance line might be due to sextupole fields introduced by the low-field quadrupoles. These quadrupoles are each located inside the upstream end of a main ring magnet very close to the magnet iron. It is thought that because the iron is so near, the quadrupole field is enhanced as one moves radially outwards in the focusing quadrupols and as one moves radially inwards in the defocusing quadrupoles, thereby producing sextupole fields. (Measurements to determine if there is in fact such an enhancement will be carried out in the near future). If we let κ_f and κ_d be the excitation coefficients produced by the sextupole fields of the focusing and defocusing quadrupoles, then the correction, κ_{corr}, must be such that

$$\kappa_o + \kappa_f + \kappa_d + \kappa_{corr} = 0 \qquad (15)$$

where κ_o is the intrinsic excitation coefficient due to sextupole fields other than those produced by the quadrupoles.

In the following discussion, expressions for κ_f and κ_d are developed and used in equation (15) along with the values of κ_{corr} from table V to determine the strengths of the sextupole fields introduced by the quadrupoles.

If we let S_{fj} and S_{dj} be the integrated sextupole strengths per Amp introduced by the focusing and defocusing (f and d) quadrupoles at positions s_{fj} and s_{dj}, then using (1-3) we find

$$\kappa_f = C\, I_f \sum_{fj} S_{fj}\, \Gamma_{fj} \quad ; \quad \Gamma_{fj} = \Gamma\,(s_{fj})$$

$$\kappa_d = C\, I_d \sum_{dj} S_{dj}\, \Gamma_{dj} \quad ; \quad \Gamma_{dj} = \Gamma\,(s_{dj}) \qquad (16)$$

where I_f and I_d are the currents in the f and d quadrupoles. Although the quadrupoles are all positioned inside the main magnets in the same way, the sextupole strengths they introduce are not all the same because some quadrupoles are enlarged to accommodate a larger straight-section. If we let S_f and S_d be the sextupole strengths introduced by the normal f and d quadrupoles, and let $(1 + \varepsilon_f)S_f$ and $(1 + \varepsilon_d)S_d$ be the corresponding strengths introduced by the enlarged quadrupoles, then equations (16) become

$$\kappa_f = C\, I_f\, S_f \left[\sum_{fj} \Gamma_{fj} + \varepsilon_f \sum_{Lfj} \Gamma_{Lfj}\right]$$

$$\kappa_d = C\, I_d\, S_d \left[\sum_{dj} \Gamma_{dj} + \varepsilon_d \sum_{Ldj} \Gamma_{Ldj}\right] \qquad (17)$$

where

$\sum_{fj}$ denotes summation over all f quadrupoles,

$\sum_{Lfj}$ denotes summation over the enlarged f quadrupoles,

$\sum_{dj}$ denotes summation over all d quadrupoles,

$\sum_{Ldj}$ denotes summation over the enlarged d quadrupoles.

The sums appearing in (17) are easily calculated using the parameters contained in the TWISS file generated by the MAD code [6]. A table of the values of these parameters is given in Appendix D. It is found that

$$\sum_{fj} \Gamma_{fj} = 0 \quad ; \quad \sum_{dj} \Gamma_{dj} = 0 \qquad (18)$$

$$\Gamma_{Lf} = \sum_{Lfj} \Gamma_{Lfj} = (215 + 9i)$$

$$\Gamma_{Ld} = \sum_{Lfd} \Gamma_{Lfd} = (0.3 + 76i) \qquad (19)$$

These sums were evaluated for several different tunes along the resonance line and were found to depend only very weakly on the tunes. It should be noted that the null values of the sums in (18) are not accidental but are due to the fact that the quadrupoles are placed in the ring so that each quadrupole is 180° away from another quadrupole. With this kind of symmetry, no odd harmonics can be produced and hence the sums, which are essentially 19th harmoniccs, are zero. The enlarged quadrupoles do not possess this symmetry and hence the sums in (19) are nonzero. Using equations (18-19) in (17) we find

$$\kappa_f = C\ I_f\ \varepsilon_f S_f\ (215+9i)$$
$$\kappa_d = C\ I_d\ \varepsilon_d S_d\ (0.3+76i) \tag{20}$$

When the tunes are moved along the resonance line by changing I_f and I_d by amounts ΔI_f and ΔI_d, κ_f and κ_d change by amounts

$$\Delta\kappa_f = C\ \varepsilon_f S_f (215+9i)\Delta I_f$$
$$\Delta\kappa_d = C\ \varepsilon_d S_d (0.3+76i)\Delta I_d \tag{21}$$

and from (15) we see that κ_{corr} must change by amount

$$\Delta\kappa_{corr} = -\ \Delta\kappa_f - \Delta\kappa_d. \tag{22}$$

Putting in values for ΔI_f, ΔI_d and $\Delta\kappa_{corr}$ corresponding to the tune changes in table V, these equations may then be solved for $\varepsilon_f S_f$ and $\varepsilon_d S_d$. For the data of study (1), we obtain

$$\varepsilon_f S_f = -\ 0.3\ S \quad , \quad \varepsilon_d S_d = -1.6\ S \tag{23}$$

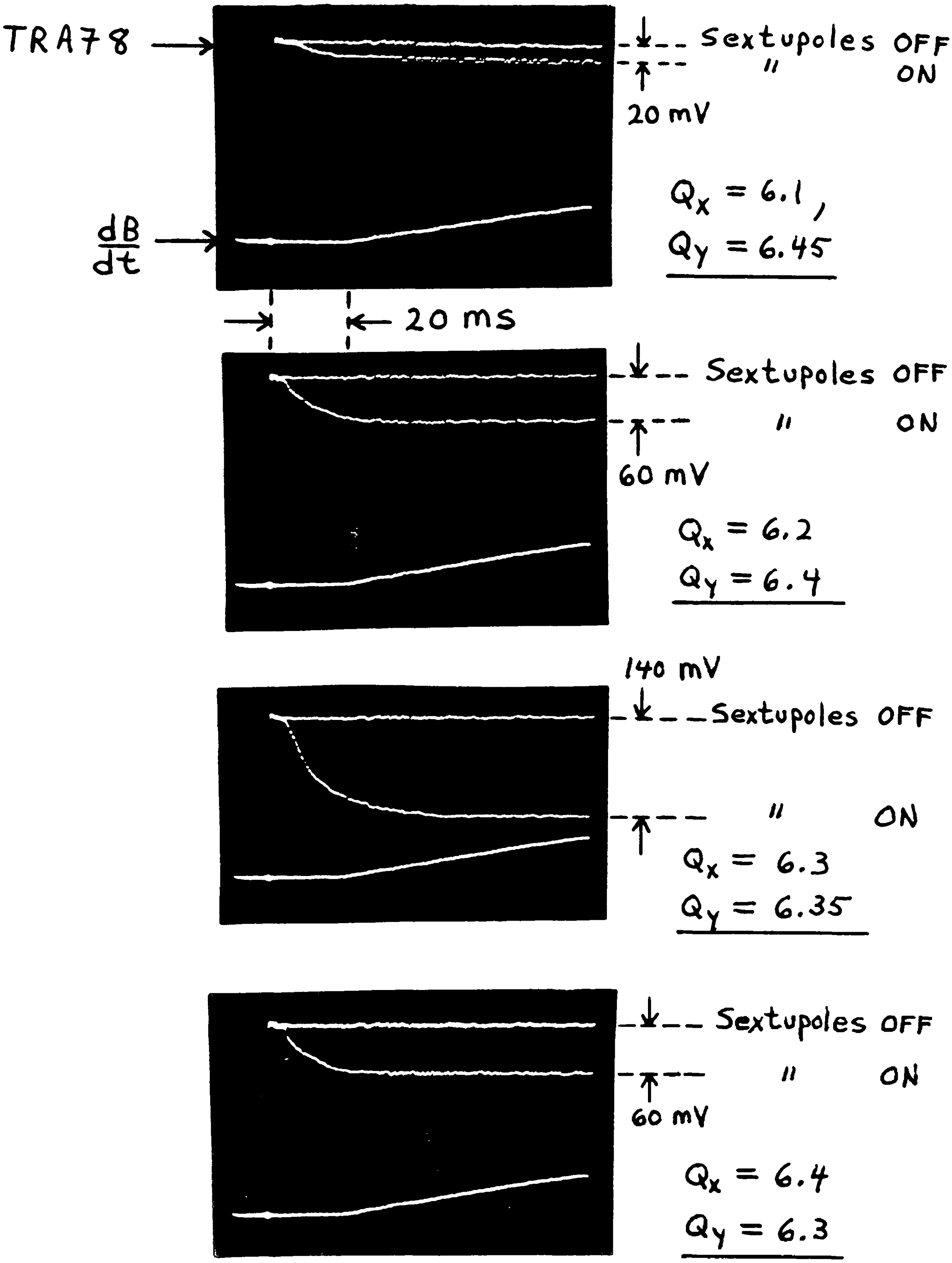
and for that of study (2), we obtain

$$\varepsilon_f S_f = -\ 0.1\ S \quad , \quad \varepsilon_d S_d = -2.5\ S \tag{24}$$

where S is the integrated strength (per Amp) of a single correction sextupole (see equation 13). (Note that to obtain (23-24), the following quadrupole calibration was used: when $\Delta Q_x = 0.2$ and $\Delta Q_y = -0.1$, then then $\Delta I_f = 5.13$ A and $\Delta I_d = 0.34$ A).

The results (23-24) indicate that the quadrupoles must introduce rather large sextupole fields (of the same order as those produced by the correction sextupoles) to account for the observed dependence of κ_{corr} on the position along the resonance line. This does not seem plausible, but a measurement of the sextupole fields introduced by the quadrupoles (if, in fact, they exist) would still be useful and interesting.

Figure 1


TRA78
dB/dt
Sextupoles OFF
" ON
20 mV
Qx = 6.1,
Qy = 6.45
20 ms
Sextupoles OFF
" ON
60 mV
Qx = 6.2
Qy = 6.4
140 mV
Sextupoles OFF
" ON
Qx = 6.3
Qy = 6.35
Sextupoles OFF
" ON
60 mV
Qx = 6.4
Qy = 6.3

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APPENDIX A

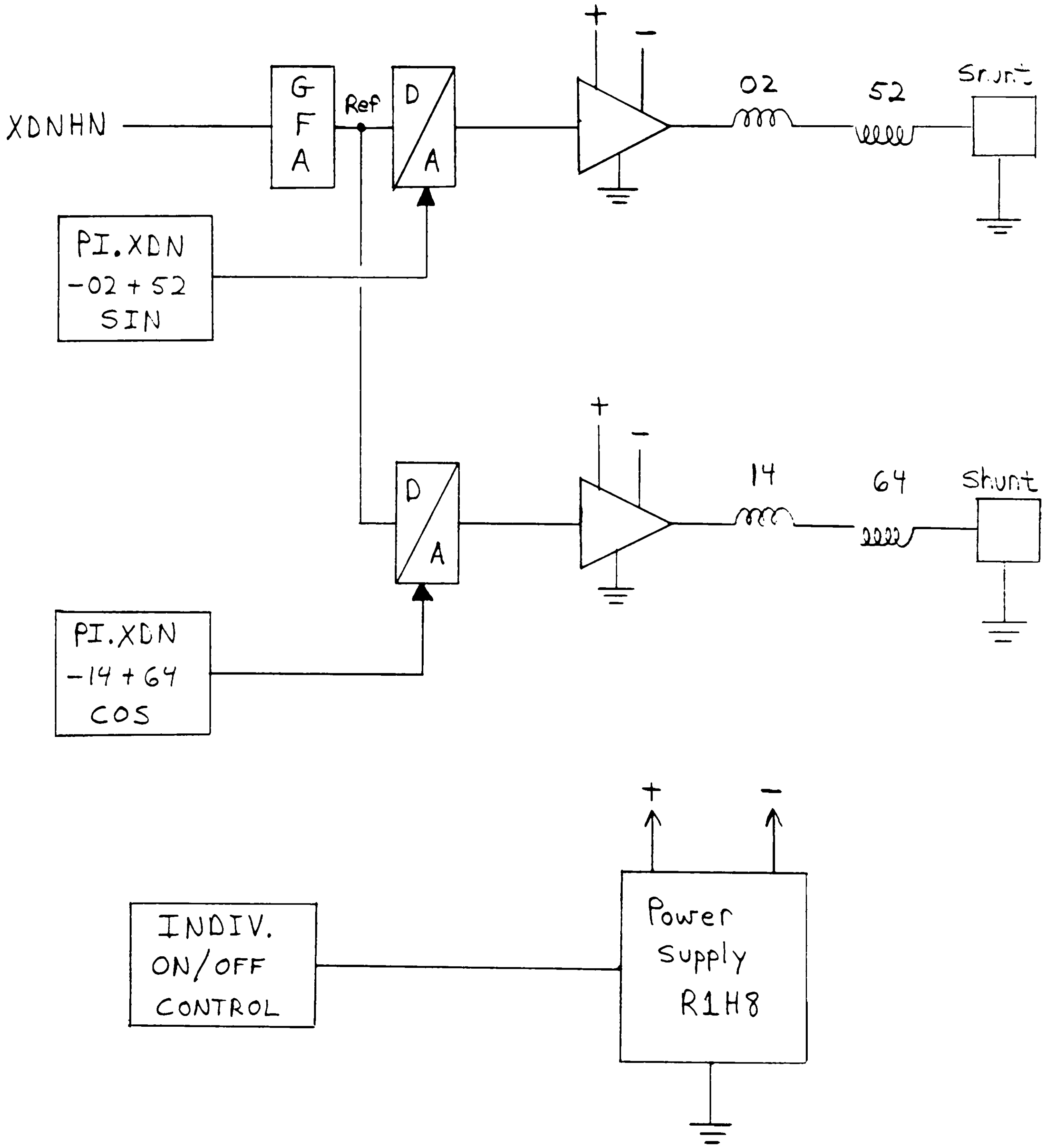
The MAD code produces a file called TWISS which contains the values of all parameters needed to calculate κ_{corr} given in equation (7). The values of these parameters at the location of each sextupole are as follows:

Sextupole	s_j (m)	β_x (m)	$\mu_x/(2\pi)$	β_y (m)	$\mu_y/(2\pi)$	ψ
XDN02	8.403	11.857	0.085	22.294	0.088	94.714
XDN14	82.641	12.609	0.820	21.894	0.830	180.310
XDN40	246.324	11.739	2.447	22.229	2.470	161.345
XDN44	270.937	12.609	2.691	21.918	2.718	70.335
XDN52	322.562	11.857	3.208	22.294	3.237	274.712
XDN64	396.601	12.609	3.941	21.918	3.978	358.336
XDN90	560.283	11.749	5.568	22.235	5.618	339.320
XDN94	585.896	12.644	6.825	21.845	5.873	258.229

Here s_j is the distance along the equilibrium orbit measured from straight section zero, and ψ is expressed as an angle between 0° and 360°. This table was obtained with tunes $Q_x = 6.247$ and $Q_y = 6.298$ which are the bare tunes calculated by the MAD code.

APPENDIX B

Schematic diagram for sextupole correction - Scheme B



APPENDIX C

Sample tune program used to put the tunes on the $Q_x + 2Q_y = 19$ resonance line at $Q_x = 6.1$, $Q_y = 6.45$.

```
PLS OPTION MD    *Q-FUNCT.USER=C /LELOW* SETTING:FILE MD/NR10
 NB    C      B      QHZ     QVZ     QH     QV     1987-09-20-11:26:47
  1   215    703   6.256   6.285   6.1    6.4
  2   220    703   6.256   6.285   6.1    6.45
  3   225    703   6.256   6.285   6.1    6.45
  4   230    703   6.256   6.285   6.1    6.45
  5   235    707   6.256   6.285   6.1    6.45
  6   240    705   6.256   6.285   6.1    6.45
  7   245    717   6.256   6.285   6.1    6.45
  8   250    734   6.256   6.285   6.1    6.45
  9   255    761   6.25    6.285   6.1    6.45
 10   260    795   6.256   6.285   6.1    6.45
```

Function control values for the correction sextupoles.

```
                      ----FUNCTION CONTROL VALUES---
N        A-0      A-1      V-2      V-3      V-4      V-5      A-6       7
DX       0        1        2000     10000    10000    2000     1
Y        C        C        1001     1001     1001     C        C
CLOCK 10US        - -      - -      - -      - -      - -      - -
N          8        9        10       11       12       13       14       15
DX
Y
CLOCK
N         16       17       18       19       20       21       22       23
DX
Y
CLOCK
N         24    FUNCTION = XDNHN          TERMINAL = PIAFGXDNHN
DX              LINE = 37      NMAX = 24       NCRT = 6
Y               SCALING FACTOR :  2047 BITS FOR 10000  MA
CLOCK           TIMING =  36   IN PTIM /PLS-DECODER =  7
ALL OK - INTERACTION CAN START
```

APPENDIX D

The MAD code produces a file called TWISS which contains the values of all parameters needed to calculate the sums appearing in (17). The values of these parameters at the location of each quadrupole are as follows:

SS	NAME	DIST	BETAX	MUX	BETAY	MUY	PSI
5	QNF	26.413	22.431	0.257	11.645	0.269	288.482
6	QLD	33.816	12.182	0.338	20.181	0.340	9.597
9	QNF	51.825	22.004	0.509	12.540	0.525	206.196
10	QND	57.829	11.739	0.572	22.229	0.581	269.345
17	QLF	102.651	22.492	1.018	11.764	1.036	41.919
18	QND	108.654	12.617	1.078	21.945	1.094	105.591
21	QNF	128.064	20.344	1.268	12.055	1.291	317.957
22	QND	134.067	11.857	1.334	22.294	1.348	22.713
27	QLF	165.483	22.492	1.643	11.764	1.666	5.918
28	QND	171.486	12.617	1.703	21.945	1.724	69.591
31	QLF	190.896	20.344	1.893	12.055	1.921	281.956
32	QLD	196.899	11.857	1.959	22.294	1.978	346.712
35	QNF	214.908	22.431	2.131	11.645	2.158	180.481
36	QND	222.311	12.182	2.212	20.181	2.230	261.597
39	QNF	240.321	22.004	2.383	12.540	2.415	98.195
40	QND	246.324	11.739	2.447	22.229	2.470	161.345
45	QNF	277.740	22.431	2.756	11.645	2.788	144.482
46	QND	285.143	12.182	2.836	20.181	2.860	225.596
49	QNF	303.153	22.004	3.008	12.540	3.045	62.194
50	QND	309.156	11.739	3.071	22.229	3.100	125.343
55	QNF	340.572	22.431	3.381	11.645	3.418	108.480
56	QLD	347.975	12.182	3.461	20.181	3.489	189.595
59	QLF	365.985	22.004	3.633	12.540	3.674	26.193
60	QLD	371.988	11.739	3.696	22.229	3.730	89.343
67	QNF	416.810	22.492	4.142	11.764	4.185	221.917
68	QND	422.813	12.617	4.202	21.945	4.243	285.590
71	QNF	442.223	20.344	4.392	12.055	4.440	137.957
72	QND	448.226	11.857	4.458	22.294	4.497	202.711
77	QNF	479.642	22.492	4.766	11.764	4.815	185.916
78	QND	485.645	12.617	4.827	21.945	4.873	249.590
81	QNF	505.055	20.344	5.017	12.055	5.070	101.955
82	QLD	511.058	11.857	5.082	22.294	5.127	166.713
85	QLF	529.068	22.431	5.255	11.645	5.307	360.480
86	QND	536.471	12.182	5.335	20.181	5.379	81.595
89	QNF	554.480	22.004	5.507	12.540	5.564	278.193
90	QND	560.483	11.739	5.570	22.229	5.619	341.343
95	QNF	591.899	22.431	5.880	11.645	5.937	324.480
96	QND	599.302	12.182	5.960	20.181	6.008	45.595
99	QNF	617.312	22.004	6.132	12.540	6.194	242.193
100	QND	623.315	11.739	6.195	22.229	6.249	305.341

Here N, L, f and D denote normal, enlarged, focusing, and defocusing quadrupoles respectively. "DIST" is the distance along the equilibrium orbit measured from straight section (s.s.) zero and PSI is expressed as an angle between 0° and 360°. MUX and MUY are given in units of 2π. The table was obtained with tunes Q_x =+ 6.247 and Q_y = 6.298 which are the bare tunes calculated by the MAD code.

PSS

J. Boillot
R. Cappi
S. Hancock
L. Henny
J.P. Potier
T. Risselada
J.P. Riunaud
Ch. Steinbach
+ E. Brouzet

AAS

V. Chohan
E. Jones
M. Martini
S. Maury
C. Metzger
F. Pedersen
L. Rinolfi

BS

L. Magnani
E. Malandain
N. Rasmussen
K. Schindl
H. Schonauer

LPS

J.P. Delahaye
B. Frammery
H. Kugler
J.P. Potier (PSS)
J. Riche

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Chefs de Groupes PS

B. Allardyce
R. Billinge
Y. Baconnier
O. Barbalat
M. Boutheon
L. Coull
D.C. Fiander
H. Haseroth
E. Jones
P. Lefèvre
J.H.B. Madsen
G. Nassibian
F. Perriollat
P.L. Riboni
K. Schindl
D.J. Simon

c.c. D. Dekkers

LEAS

S. Baird
R. Ley
D. Manglunki
G. Tranquille

J. Gareyte/SPS

M. Chanel/PS
D. Mohl/PS

Distribution (of abstract)

PS Scientific Staff