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An Empirical Model for Controlling Beam-Beam Effects in ISABELLE*

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I. Introduction

The beam-beam interaction may limit the beam intensity in ISABELLE. Although considerable progress has been made in understanding the beam-beam interaction, there appears to be no reliable method at present for computing the effects of the beam-beam interaction. The steps taken at ISABELLE to limit beam-beam effects are based largely on the experience accumulated at the ISR. At the ISR, the beam-beam effects do not appear to be large, and the beam intensity at the ISR does not appear to be limited by beam-beam effects. The beam-beam effects may be much stronger in ISABELLE because of factors like higher intensity and stronger non-linearities.

An empirical model for controlling beam-beam effects in ISABELLE can be arrived at based partly on the experiences at the ISR and based partly on conjecture. Establishing an empirical model may be thought of as consisting of the following steps:

1. Assume a model for the mechanism for beam growth.
2. Establish the critical parameters that lead to beam growth.
3. Establish working tolerances for the critical parameters.

The working tolerances are somewhat different from what one usually means by tolerances. They are based partly on experience, partly on theory, partly on conjecture, and partly on what is doable. They represent a compromise, and provide a useful guide for designing the different components of the accelerator. The working tolerances may change as more information is acquired.

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DISCLAIMER

II. Model of Beam Growth

The model for beam growth assumed is

Non-Linearities + "Something" → beam growth

where the "Something" may be

"Something" → noise

ripple

tune modulation

randomizing perturbation

The phrase "randomizing perturbation" indicates some perturbation which in some sense makes the particle forget its history so that it is crossing the non-linear resonances in an almost random way. It is known that multiple crossing of a non-linear resonance will often cause only a limited growth, while random crossing of a non-linear resonance will cause a steady, and often much larger, growth. In the ISR, there is some evidence[1,6] that the randomizing perturbation may be intra-beam scattering.

In the light of the above model, the steps required to limit beam growth due to the beam-beam interactions are

1. Limit the strength of the non-linearities.
2. Limit the "Something"--noise, ripple, tune modulation or randomizing perturbation.

III. Magnet Non-Linearities

Superconducting magnets are likely to have stronger[2] non-linear error fields than conventional warm magnets. Recent measurements of the error fields in ISABELLE magnets indicate that the non-linear field errors in ISABELLE magnets may be a factor 10 larger than those found in the ISR magnets.[3] At the ISR, magnet non-linearities do not appear to play an important role in causing beam growth. Because of the larger non-linear fields in ISABELLE, it may not be wise to assume that this will also be the case for ISABELLE. Certainly, one should strive to keep the non-linear fields in ISABELLE magnets as low as possible.

The working tolerances for the non-linear error fields are given in terms of the multipole coefficients Δb_n, and Δa_n which are defined by expanding the error field in the median plane as

$$\Delta B_y = B_o(\Delta b_o + \Delta b_1 x + \Delta b_2 x^2 + \ldots .)$$
$$\Delta B_x = B_o(\Delta a_o + \Delta a_1 x + \Delta a_2 x^2 + \ldots .)$$

The working tolerance for ISABELLE can be roughly and simply stated as

$$R^n \Delta b_n \lesssim (n + 1)\ 2 \times 10^{-4}$$
$$R^n \Delta a_n \lesssim (n + 1)\ 2 \times 10^{-4}$$

where R is the radius of the main coil in the magnets; R = 6.5 cm for ISABELLE. This working tolerance is the expected[2] rms error multipoles caused by a random rms .005 cm (2 mil.) error in the location of the current blocks of the main coil. In this sense, these tolerances appear to be simply what seems to be achievable. However, it will be seen below that for several known effects they are indeed the tolerances. In this connection, it may be worthwhile recalling what was said about working tolerances in Section I, that they are a useful guide based partly on experience, partly on theory, partly on conjecture, and partly on what is doable.

There are about four known effects which indicate that the above working tolerances are indeed tolerances. These are:

1. Uncorrectable closed orbit error error. The random dipole error field will vary across the aperture[4] because of the presence of the higher order error multipole fields. Thus, when the closed orbit is corrected at the center using the system of dipole correctors, it will not be corrected at the edges of the aperture. For ISABELLE, this leads to a possible 5 mm orbit error at both edges of the aperture.

2. Vertical dispersion error. The field errors, particularly Δa_1, generate a vertical dispersion which can change the beam size at the crossing points by about 25% at 30 GeV and about 12% at 400 GeV. This may cause a possible 25% variation in $\Delta\nu$, the beam-beam ν-shift, increasing the strength of the beam-beam resonances. Also, the luminosity may be reduced by 25%.

3. Random error in β_y or the crossing points. The field errors cause β_y to vary around the ring by about $\Delta\beta_y/\beta_y = 10\%$. This will cause a beam-beam $\Delta\nu$ variation of 5%, and a 5% reduction in luminosity. The random $\Delta\beta_y/\beta_y$ also helps to excite the 1/3 resonances by interacting with the large sextupole required for chromaticity correction.

4. Width of the 1/3 resonance. The field errors excite non-linear resonances. In particular, the 1/3 resonance may have a width of $\Delta\nu = 1 \times 10^{-3}$.

The above four effects show that if the error fields exceed the working tolerances by very much, some large damaging effects may result.

It is interesting to compare the stop bands of the non-linear resonances generated by the magnet error fields with those generated by the beam-beam interaction. This is done in Table I. The beam-beam resonances listed in Table I are the imperfection resonances generated by orbit errors and random errors in β_y at the crossing points.[5] One sees that for ISABELLE, the magnet resonances and the beam-beam resonances are comparable for the lower order resonances.

Table I

N Resonance Order	Magnetic Field Error Resonances	Beam-Beam Resonances
2	6.5 E-3	1.6 E-4
3	4.3 E-4	7.6 E-4
4	3.4 E-5	9.1 E-5
5	3.8 E-6	1.2 E-4
6	4.5 E-7	1.3 E-5
7	5.4 E-8	2.0 E-5
8	6.5 E-9	1.3 E-6
9	---	2.5 E-6
10	---	1.5 E-7

IV. Beam-Beam Non-Linearities

In this section, we specify the working tolerances which are intended to limit the strength of the beam-beam non-linearities. These are

1. Beam-beam $\Delta\nu \leq .005$.
2. Vertical orbit error at crossing points $\lesssim$ .05 mm (about 10% of beam size).
3. Vertical dispersion at crossing points

$$Y_p \frac{\Delta p}{p} \lesssim 1\% \text{ of beam size}$$

4. Random $\Delta\beta_y/\beta_y$ at crossing points $\lesssim$ 1%.
5. Periodicity of six is maintained.
6. Control of the working line so as to be able to avoid resonances.

For day one operation of ISABELLE, the periodicity of six is to be maintained. Operation with a lower periodicity may be considered afterward. There is some experience at the ISR that operation with lower periodicities, even a periodicity of 1, is possible. However, it appears to this writer, that it is quite a different matter to suggest operation with a lower periodicity for a machine that is already working, than to suggest it for ISABELLE which will have much stronger non-linearities and whose operation has not been studied.

Present plans for first day operation of ISABELLE will probably not allow the correction of the errors in the vertical dispersion and of β_y at the crossing points to the above tolerance. However, the capability to do so at a later date has been provided.

V. Tune Modulations

According to our model for beam growth, any modulation of the ν-value, ν_x, ν_y with time is of concern. Sources of this modulation include intra-beam scattering,[6] drift in the power supplies, and ripple in the power supplies.[7]

Drift in the power supplies of the various correction coils and in the main power supply can cause the ν-value to drift. The working tolerance in the amount the ν-value can drift is assumed to be

$$\Delta\nu \leq .001$$

This appears to be the tolerance assumed at the ISR.[8] The working line in ν-space is constrained to be between the resonances 22.60 and 22.67 and about .01 from the coupling resonance. Part of the beam is usually about .01 from some resonance. Thus, a drift of about .001 can move the beam appreciably closer to some resonance.

There are about 103 correction coil power supplies in each ring of ISABELLE. Power supply errors for each correction coil can cause the ν-value to drift, and one has to chose the power suply accuracies of all these 103 power supplies so that the total ν-drifts due to all of them, plus that due to the main power supply, does not exceed the working tolerance $\Delta\nu \leq .001$. Table II lists all the correction coil power supplies, the full scale accuracy of each power suply, and the peak ν-drift caused by each power supply, and the total ν-drift due to all the power supplies.

Ripple in the main power supply can cause a ν modulation with time. Experiments done at the ISR indicate[9] that a ripple in ν-value of $\Delta\nu \geq 1 \times 10^{-6}$ can cause appreciable increases in the background rate. The working tolerance assumed for the ν-ripple is

$$\Delta\nu \leq 1 \times 10^{-6}$$

This leads to a required ripple for the main power supply of 1×10^{-7}.

The requirements on the ripple of the correction coil power supplies is almost as severe as it is for the main power supply, primarily because there are many correction coil power supplies. The required ripple for each correction coil power supply is also listed in Table II.

Table II. Accuracy requirements for the correction coil power supplies in order to limit ν-drift and ripple.

	Correction Coil	Capacity Required At 400 GeV (cm^{-n})	Current Required At 400 GeV (A)	Power Supply Accuracy At Full Scale	$\Delta\nu_x/10^{-3}$ (peak)	$\Delta\nu_y/10^{-3}$ (peak)	Ripple Factor Required (peak)
Quadrupole	$b_{1,H}$	3.0 E-3	129	50 E-6	0.265	0.041	.6 E-6
Quadrupole	$b_{1,V}$	3.0 E-3	129	50 E-6	0.047	0.262	.6 E-6
Sextupole	$b_{2,H}$	6.0 E-4	170	10 E-6	0.262	0.086	.1 E-6
Sextupole	$b_{2,V}$	6.0 E-4	170	10 E-6	0.176	0.286	.1 E-6
Octupole	$b_{3,H}$	8.0 E-5	154	25 E-6	0.294	0.097	.3 E-6
Octupole	$b_{3,V}$	8.0 E-5	154	25 E-6	0.147	0.225	.3 E-6
Decapole	$b_{4,H}$	5.0 E-6	81	50 E-6	0.110	0.036	.6 E-6
Decapole	$b_{4,V}$	5.0 E-6	81	50 E-6	0.041	0.059	.6 E-6
Duodecapole	$b_{5,H}$	1.5 E-6	99	125 E-6	0.092	0.016	1.0 E-6
Duodecapole	$b_{5,V}$	1.5 E-6	99	125 E-6	0.001	0.005	1.0 E-6
Quadrupole	$b_{1(\text{bypass I})}$	9.0 E-3	300	15 E-6	0.326	0.353	.1 E-6
Quadrupole	$b_{1(\text{bypass II})}$	9.0 E-3	300	50 E-6	0.320	0.236	.6 E-6
Insertion Quad.	b_1(Q9)	4.8 E-3	206	200 E-6	0.140	0.024	2.0 E-6
Insertion Quad.	b_1(Q8)	4.8 E-3	206	200 E-6	0.024	0.139	2.0 E-6
Insertion Quad.	b_1(Q7)	4.8 E-3	206	200 E-6	0.137	0.025	2.0 E-6
Insertion Quad.	b_1(Q6)	4.8 E-3	206	200 E-6	0.026	0.149	2.0 E-6
Insertion Quad.	b_1(Q5)	4.8 E-3	206	200 E-6	0.155	0.017	2.0 E-6
Insertion Quad.	b_1(Q4)	4.8 E-3	206	200 E-6	0.011	0.107	2.0 E-6
Insertion Quad.	b_1(Q2)	4.8 E-3	206	200 E-6	0.446	0.321	2.0 E-6
Insertion Quad.	b_1(Q1)	4.8 E-3	206	200 E-6	0.184	0.618	2.0 E-6
Skew Quad.	a_1(Q1)	2.4 E-3	103(?)	200 E-6	—	—	—
Dipole	a_o, b_o	800 G	100	200 E-6	—	—	—
Dipole	a_o, b_o	400 G	50	200 E-6	--	--	---

Total $\Delta\nu_x$(peak) = 0.88 E-3

Total $\Delta\nu_y$(peak) = 0.95 E-3

VI. Experimental Devices for First Day Operation

An important question is what should be the requirments for experimental devices, such as a spectrometer magnet at a crossing point, that is expected to be in place when the accelerator is first turned on. This problem is still being worked on at present.[10] The following requirements are tentatively suggested.

1. Preserve periodicity. The beam-beam $\Delta\nu$ at the crossing point, where the experimental device is located, should be relatively unchanged. The periodicity is actually destroyed by random orbit errors and random β-variations which change the beam-beam $\Delta\nu$. The experimental device should change $\Delta\nu$ by an amount which is less than that due to the random errors which are not correctable; in ISABELLE, this is about 2% of the unperturbed $\Delta\nu$.

2. Beam-beam non-linear stop bands introduced by the experimental device should be less than those due to random errors, such as orbit errors, after the random errors have been corrected as well as possible.

3. Magnetic field non-linear stop bands introduced by the experimental device should be less than those due to random magnetic field errors in the accelerator magnets.

After the accelerator has been operating and studied, a more severe perturbation by the experimental device may be considered.

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