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MEASUREMENT OF INCOHERENT LASLETT TUNE SHIFTS IN THE FERMILAB MAIN RING

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Summary

The incoherent radial and vertical tune shifts have been measured in the Fermilab Main Ring via the resonance scan technique, and the results are compared to the Laslett predictions.

Introduction

In 1963 Laslett(1) calculated the effects on the particle tune in a synchrotron caused by the beam itself. In 1973 and 1974 Stiening attempted to measure these effects(2,3) in the Fermilab Main Ring. He was not completely successful in reconciling theory with experiment. Recently the Main Ring Group noticed a large intensity dependent coherent tune shift which seems to be describable as a Laslett tune shift.(4)

In light of the interest caused by the rediscovery of the coherent tune shift, we decided to try to measure the incoherent shift again. Several factors contributed to this decision. First, both previous experiments reported discrepancies between theory and observed values. Second, the Booster is now capable of greater intensities per bunch than for the previous experiments, presumably yielding larger tune shifts. Finally, new hardware[5,6,7] and software[8] has been developed, making measurement of transverse emittance and longitudinal bunch length extremely easy. The technique used to measure the tune shift is identical to that reported in Reference 3. At two different intensities resonance scans were done by varying quadrupole currents (see Fig. 1). As the tunes shifted, the resonance dips at $3\nu=58$ and $2\nu=39$ should be observed at different quadrupole current settings.

In addition to these measurements, the emittance at each intensity was obtained by measuring the transverse width of the beam on its first turn pass through the MR multiwires and fitting the emittance to this data[8]. The longitudinal bunch length was measured using the new Beam Quality Meter electronics which measures the bunch length in nanoseconds(6) for each Booster bunch on its first pass through FØ. Only one Booster batch was injected in each MR cycle, and the intensity was varied by changing the number of turns injected into the Booster. Table I shows the experimental results.

Sho Ohnuma has recently supplied the Main Ring Group with a compilation of formulas[9] obtained by Laslett and Resegotti[10] regarding intensity dependent tune shifts. He has folded-in all the Main Ring parameters leaving us free to plug in the following numbers:

1. The number of particles in each bunch
2. The number of rf bunches in the ring
3. Total charge in the ring (1&2)
4. $2r_z$, the full longitudinal length (meters) of each bunch
5. ϵ_x and ϵ_y, the transverse emittances

Formulas have been provided for these effects:

A. Incoherent Shifts

1. Self field
2. Image field, electric
3. Image field, magnetic, DC
4. Image field, magnetic, AC

B. Coherent Shifts

1. Image field, electric
2. Image field, magnetic, DC
3. Image field, magnetic, AC
4. Image field, magnetic

Table II indicates the change in tune shifts predicted by these formulas for our experimental conditions. It is interesting to note that the transverse emittance and longitudinal bunch length affected not only the magnitude of the change in tune shift but also the sign. The self field tune shift may be the best example of this.

The self field tune shift is a relatively strong tune shift as compared to the others listed above, and is negative in both planes; the space charge effect in this case lowers the tune compared to the tune of a single particle.

However, when the formula is applied to our experimental conditions, we find that the tune shift downward is smaller in the case of 2×10^{12} protons per batch than for $.8\times10^{12}$ protons per batch. This is because of the large increase in the emittance and longitudinal bunch length, both of which appear in the denominator of the equation. Hence theory predicts a positive tune shift for the self field effect as the intensity is increased; in this experiment +.015 in the horizontal plane and +.008 in the vertical plane.

As evidenced by the table, the sum of all these predicted tune shifts ends up being +.026 for the horizontal plane and -.001 for the vertical plane.

The results of the experiment indicate that in the horizontal plane the tune did increase with intensity $\Delta\nu = .013 \pm .005$, and in the vertical plane went down slightly, $\overline{\Delta}\nu = -.009 \pm .005$.

Conclusion

The primary observation made by this experiment is that as the intensity is increased by putting more turns into Booster the emittance and longitudinal bunch length into MR increase enough to make the theoretical tune shift much different from what is assumed by considering only the increase in intensity.

Several assumptions are still being made in the calculations. The bunches are assumed to be identical elliptical cylinders with a uniform charge distribution. Also the geometries of the vacuum chamber and magnet pole have been simplified and the value of ϵ_2 used is

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the same as that of reference 4 (these results are not very sensitive to the value of ε_2 used). In calculating the image effects, it is assumed that there is no effect due to the beam size, and also the a.c. magnetic field is assumed not to penetrate the vacuum chamber wall. With these caveats, the agreement between the calculated and measured tune shifts is encouraging in that the magnitude of the difference between the horizontal and vertical is adequately reproduced and the sign is proper:

$$\Delta\nu_H^{meas} - \Delta\nu_V^{meas} = +.027$$

$$\Delta\nu_H^{calc} - \Delta\nu_V^{calc} = +.022$$

We now realize that the Booster is saving us from large tune shifts by giving us fat bunches. Should the Booster be able to produce high intensities in small bunches, the Main Ring may experience real problems from the incoherent tune shifts.

References

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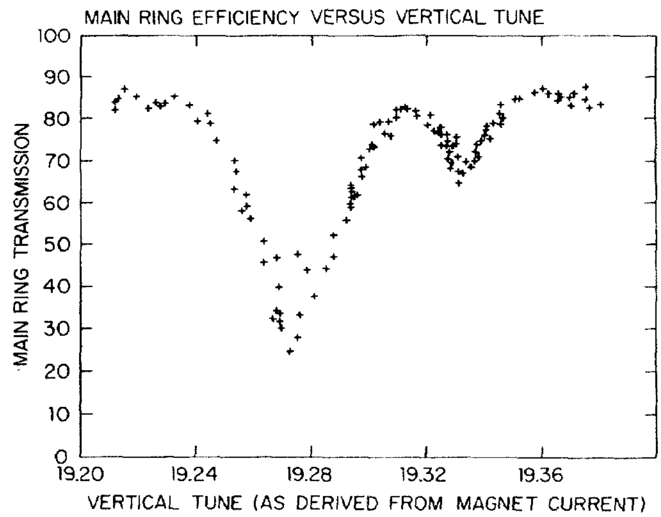

Figure 1

TABLE I

Vertical Data

	Low Intensity	High Intensity
	$.8\times10^{12}$	2×10^{12}
Observation of $3\nu_y=58$	$.332\pm.005$	$.341\pm.005$
ε_y (πmm-mr)	.287	.53
longitudinal bunch length FWHM (meters)	.63	1.04

Horizontal Data

Observation of $3\nu_x=58$	$.346\pm.005$	$.333\pm.005$
ε_h (πmm-mr)	.315	.74
longitudinal bunch length FWHM (meters)	.63	1.04

TABLE II

HORIZONTAL TUNE SHIFTS

Incoherent Tune Shifts

	High Intensity	Low Intensity	Difference (High-Low)
1. Self field	-.02775	-.04295	.0152
2. Image field, electric	+.1075	.0781	.0294
3. Image field, magnetic DC	+.00444	.001776	.00266
4. Image field, magnetic AC	-.1034	-.06902	.0344
Sum of Incoherent	-.01921	-.03939	.0202

Coherent Tune Shifts

	High Intensity	Low Intensity	Difference (High-Low)
1. Image field, electric	.3219	.2121	.1098
2. Image field, DC magnetic	.00444	.001776	.0027
3. Image field, AC magnetic	-.3096	-.2007	-.1089
4. Image field, magnetic	-.005899	-.00236	-.0035
Sum of Coherent	.01082	.00477	.006
Incoherent + Coherent			.026

VERTICAL TUNE SHIFTS

Incoherent Tune Shifts

	High Intensity	Low Intensity	Difference (High-Low)
1. Self field	-.03874	-.04714	.0084
2. Image field, electric	-.09365	-.06171	-.0032
3. Image field, magnetic DC	-.003933	-.001573	-.0024
4. Image field, magnetic AC	+.09008	.06015	.0299
Sum of Incoherent	-.04624	-.05027	.004

Coherent Tune Shifts

	High Intensity	Low Intensity	Difference (High-Low)
1. Image field, electric	-.2805	-.1848	-.0957
2. Image field, DC magnetic	-.003933	-.001573	-.00236
3. Image field, AC magnetic	.2698	.1802	.0896
4. Image field, magnetic	.00514	+.002056	.00308
Sum of Coherent	-.009489	-.004182	-.005
Incoherent + Coherent			-.001