Effect of Opening Helix on Flying Wire Emittance Measurements

Stan Pruss

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It has been noted for some time that after the protons are injected, when the helix is opened the proton normalized vertical emittance (as measured by the flying wires) increases by about two π mm-mr. The horizontal emittance decreases by about the same amount. This has been recognized as a false result, but there has been uncertainty as to whether it was due to the flying wires not measuring the beam sigma correctly when the beam center moved at the wires or whether the effective beta at the wires changed when the helix was opened and the orbit changed all around the machine. This study attempts to answer that question. The study took place Sunday, Feb. 25, 1996, from 18:30 to 22:30. The study consisted of injecting P1, P2 and P3 as normal, coalesced bunches and P4 and P5 as uncoalesced bunch trains of nominally 11 bunches. The purpose in using more than a single bunch was to increase statistical sampling and to investigate whether there was any significant difference between coalesced and uncoalesced bunches. Because the injection kicker had a long flat-top for 36 bunch studies, P6 could not be injected and when P5 was injected, P1 emittance increased by about two π mm-mr. The flying wires were flown several times, the helix was turned on, the wires flown several times, the helix turned off, and the wires flown several times. The helix cycling was performed by knobbing the power supplies to avoid any possible emittance dilution from a non-adiabatic change. Note that during the helix off state during helix cycling, one of the power supplies for the horizontal separators was inadvertently not turned down to zero, leaving the horizontal part of the helix at ~16% of normal. After three cycles of helix on-off, a local horizontal three bump was made to duplicate the horizontal orbit change at the E11 wires and the wires were flown several times. The local bump was removed and the wires flown several times. Finally, the protons were put onto the pbar helix, then back to the proton helix, then back to the pbar helix, while the wires continued to be flown.

Figure 1 - Beam center at E11 Flying Wires during this experiment. The next figure shows the bunch intensity for the five bunches during this period.

Figure 2 - Bunch intensities during this experiment

Note that the uncoalesced bunches 4 and 5 lost intensity the first time the helix was turned on, while the coalesced bunches 1,2, and 3 had very poor lifetime when the vertical helix was turned off while leaving the horizontal helix on. Also note that all the bunches had poor lifetime when we returned to the proton helix after having been on the pbar helix. We have no good understanding of these effects, since the tune spectra were never observed to go coherent or cross known resonant problem regions. These effects certainly made this analysis more difficult, but we believe the effects reported below

were not caused by these losses. The next figure shows the emittance of P1 during this experiment.

Figure 3 - P1 emittance during this experiment

There were 176 wire flies during this four hour experiment. The most obvious effect is that the emittance is growing rapidly with time. After extracting this data from the lumberjack datalogger and using a statistical analysis program, Data Desk, I get the following results:

1) If I consider only the data from 18:30 to 18:54 and from 21:08 to 21:21 with all separators off and fit to a linear growth with time, I get the first set of numbers in the table below. If I fit only the data during helix cycling with the helix on, I get the second set of numbers which are in parentheses.

Bunch #	growth rate (π mm mr/hour)	error	residual
P1 V	4.01(4.04)	0.12(0.31)	0.56(0.81)
P2 V	4.46(4.95)	0.10(0.23)	0.45(0.58)
P3 V	4.34(4.78)	0.11(0.27)	0.48(0.71)
P4 V	5.13(5.87)	0.08(0.24)	0.37(0.63)
P5 V	4.57(5.15)	0.08(0.23)	0.37(0.59)
average	4.50(4.96)	0.41(0.66)	
P1 H	3.67(2.49)	0.51(0.70)	2.34(1.81)
P2 H	4.45(3.03)	0.54(0.89)	2.49(2.30)
P3 H	4.31(3.68)	0.58(0.81)	2.62(1.99)
P4 H	4.85(3.69)	0.35(0.40)	1.55(0.99)
P5 H	3.46(2.93)	0.49(0.51)	2.19(1.24)
average	4.15(3.17)	0.57(0.52)	

Note that the "error" entry on the "average" line is the rms of the 5 bunch values. The residual may be considered a measure either of the flying wire measurement error, and/or of the inadequacy of the parameterization. Here it is consistent with the prejudice that the flying wire system doesn't measure the horizontal emittance very well. This analysis indicates that the vertical emittance grows faster with the helix open, while the horizontal emittance grows more slowly. I suspect the experiment hasn't adequately controlled all the other possible variables. I don't believe this invalidates the next analysis.

2) Next I fit the data from 18:54 to 20:30 when the helix was being cycled and exclude the data with only one plane of separators on. This data is shown in the next figure. FWHPCE is the beam center at the E11 horizontal wire showing the helix cycling. T:FWVEMI is the vertical emittance of P1. I try to fit to a linear growth with time and a step change in emittance with the helix cycle. The two slanting lines are to guide the eye and have about the fitted growth rate with time and are separated by about the fitted proton-helix-on emittance step.

Figure 4 - P1 vertical emittance and horizontal position during helix cycling

I get the following fits:

bunch	time	slope	error	helix	step	error	residual
P1 V	3.88		0.26	2.43		0.25	0.86
P2 V	4.53		0.20	2.07		0.19	0.67
P3 V	4.45		0.23	2.13		0.22	0.76
P4 V	5.22		0.21	2.18		0.21	0.72
P5 V	4.65		0.20	2.11		0.19	0.66
average	4.55		0.48	2.19		0.14	
bunch	time	slope	error	helix	step	error	residual
P1 H	1.88		0.63	-4.23		0.61	2.03
P2 H	2.64		0.72	-3.25		0.70	2.31
P3 H	2.25		0.71	-3.59		0.70	2.31
P4 H	3.31		0.53	-3.14		0.53	1.73
P5 H	2.39		0.56	-3.54		0.57	1.83
average	2.49		0.53	-3.55		0.43	

After looking at all of the data, I believe the data suggest/are consistent with the hypothesis that the growth with time has a non-linear component. However, it is clear that there is a reversible change in the calculated emittance when the proton helix is turned on or off. The vertical increases by about 2.2 and the horizontal decreases by about 3 1/2. The vertical is measured better than the horizontal again. I tried to distinguish the separate effects of only the horizontal separators on or only the vertical separators on and found all the effect seemed to come from the horizontal separators.

3) Next I fit the data from 20:20 to 21:08 during which time a local horizontal three bump was used to move the beam at the E11 wires from the nominal helix off position to the nominal helix on position. I get the following fits:

Bunch #	time	slope	error	3-bump	step	error	residual
P1 V	3.41		0.36	-0.72		0.42	1.00
P2 V	3.74		0.25	-0.54		0.29	0.69
P3 V	3.67		0.29	-0.65		0.34	0.80
P4 V	3.95		0.24	-0.85		0.28	0.67
P5 V	3.67		0.23	-0.59		0.28	0.64
average	3.69			-0.67		0.12	
P1 H	3.33		0.45	0.42		0.74	2.61
P2 H	4.30		0.48	0.13		0.76	2.26
P3 H	3.80		0.48	1.18		0.75	2.23
P4 H	4.66		0.46	0.22		0.70	1.98
P5 H	3.41		0.44	1.15		0.65	1.86
average	3.9			0.62		0.51	

The change in calculated emittance due to the three bump appears to be a factor of three smaller than the change from opening the helix

and is the opposite sign. The data is fit almost as well with only the growth with time and would be consistent with no effect from the three bump. Because the three bump was not cycled on and off as the helix was, the individual bunch fit errors are somewhat larger.

4) Finally, I fit the data during helix off/pbar helix/proton helix /pbar helix cycling from 21:10 to 22:30.

bunch	time	slope	error	helix	step	error	residual
P1 V	0.53		0.38	2.09		0.15	0.97
P2 V	1.36		0.39	1.98		0.16	0.97
P3 V	1.13		0.40	1.97		0.16	1.02
P4 V	1.77		0.35	2.22		0.14	0.89
P5 V	1.83		0.42	2.18		0.16	1.02
average	1.32		0.53	2.09		0.11	

bunch	time	slope	error	helix	step	error	residual
P1 H	0.66		1.05	-4.16		0.43	2.65
P2 H	1.52		1.00	-3.92		0.41	2.53
P3 H	2.18		1.37	-4.26		0.57	3.47
P4 H	0.84		0.76	-3.80		0.32	1.94
P5 H	1.15		0.92	-3.73		0.39	2.32
average	1.27		0.60	-3.98		0.23	

The "helix step" column is scaled to a "helix off" to "proton helix on" step to be easily comparable with 2) above. The growth rate with time is smaller, but the "helix step" numbers are remarkable consistent, especially considering that the two data sets have no overlap.

Conclusion: There is an effect on the calculated emittance from opening the helix, but it is not an instrumental effect due to the flying wire measuring a different sigma if the beam center is moved at the wire location. This experiment raises the very interesting question of why the emittance was growing so fast with time during the experiment. An intrabeam scattering calculation gives a growth rate slightly below 1π mm mr/hour, far below the 4π mm mr/hour measured here. Jerry Annala reports that previous measurements of emittance growth rates at 150 GeV gave a result of about 1π mm mr/hour.