PROTON-BEAM EMITTANCE GROWTH IN SPS COASTS

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Abstract

Proton-beam transverse emittance growth rates were measured during SPS coasts to assess the possibility of using the SPS as a testbed for the LHC prototype crab cavities. The SPS measurements in coasts were performed at different beam energies, for varying RF voltage, beam intensity, and chromaticity. Results from these measurements are presented with potential explanations for the observed emittance growth.

INTRODUCTION

A primary concern for the LHC upgrade with crab cavities is emittance growth driven by phase jitter of the deflecting (or crabbing) mode. Amplitude and phase noise leads to random kicks and dynamic trajectory offsets leading to emittance growth with higher jitter frequencies being more dangerous [1]. Dedicated noise studies were performed in KEKB with phase noise at frequencies close to the betatron tune with different amplitudes in the crab cavities to measure the corresponding beam size blow-up [2]. It is highly desirable to test crab cavities in another hadron machine (for example the SPS) prior to a final implementation. These tests are regarded as a vital step to identify the possible differences between electrons and protons and to quantify the associated emittance growth. They will also address important aspects such as machine protection, cavity operational cycle and required the RF controls. A working group identified several aspects including integration, cryogenics, infrastructure and feasibility of a test in the SPS primarily for use of KEK crab cavities [3]. This study is now extended to test the LHC prototype cavities.

BA4 BYPASS REGION

A special region in the BA4 section of the SPS hosting the present COLDEX experiment was identified as the best location for a test of the KEKB crab cavity which is now abandoned [4]. This region consists of a movable horizontal bypass and essential cryogenic infrastructure for future crab cavity tests. The bypass allows for an easy displacement of the cavities during regular SPS operation (see Fig. 1) and hence remains as the primary choice. Other possible locations in the SPS are also under investigation [4]. Some relevant lattice parameters at the COLDEX bypass region are listed in Table 1. To explore the possibility of resolving the effect crab cavity noise alone, it is important to have a long term natural emittance growth which is sufficiently small. Therefore, tests at higher energies are generally preferred. On the other hand, it is also important to have a measurable effect of the orbit due to crab cavities

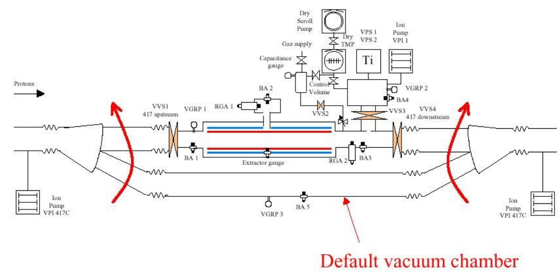

Figure 1: Layout of the present COLDEX experiment in the BA4 region of the SPS ring [5].

Table 1: SPS Parameters at the COLDEX Region

	Unit	Value
Energy	[GeV]	55-270
Long. position	[m]	4020 ± 5
Total length	[m]	10.72
β_x, β_y,D_x	[m]	41.6, 58.6,-0.58
Q_x, Q_y	-	26.12, 26.18

to characterize their effect on the beam, but the orbit effect at higher energies is proportionally smaller for a finite voltage. For example, the peak orbit deviation with crab cavity voltage of 5 MV at 400 MHz of a particle at $1\sigma_z$ with respect to the synchronous particle is is approximately 4.8mm at 55 GeV and only 2.2 mm at 120 GeV. The rms of the closed orbit in the SPS is approximately 3mm which is of the same order of the deviation caused by crab cavities at energies of 150 GeV or higher.

EMITTANCE GROWTH

Before a complete installation of a crab system in the LHC, tests in another hadron collider are highly desired. Crab crossing was successfully demonstrated and made operational at KEKB. Therefore, these experiments primarily focus on the differences between electrons and protons. Several experimental sessions were carried out to measure the natural emittance growth in the SPS to distinguish the effect of crab cavity noise on the long term emittance growth. The relevant parameters for the experiments conducted in the SPS for measuring the natural emittance growth are listed in Table 2. Three different energy ramp cycles with the associated RF voltage programs were used to set up coasts at the respective energies with good transmission of the beam from injection to coast energy.

The first coast was carried out with a single nominal LHC bunch at 55 GeV. Figure 2 shows the evolution of the intensity and transverse emittances as a function of time. A large emittance growth primarily in the horizontal plane

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Table 2: Relevant Parameters for Proton Beams in the SPS

	Unit	Exp I	Exp II	Exp III	Exp IV
Energy	[GeV]	55	120	120	270
P/bunch	[10^{11}]	1.1	0.5	0.2	0.2
Number of bunches	-	1	12	1	1
rms norm $\epsilon_{x/y}$	[μ m]	3.1/2.8	1.5-2.0	2.5	2.5
$Q_{x,y}$	-	26.12, 26.18		26.12, 26.18-26.34	26.12, 26.18
RF Voltage	[MV]	3.0	1.0-4.0	4.6-6.5	4.6-6.5

was observed. A simulation campaign was carried out to explain this emittance growth due to noise sources (for example: dipole current ripple, space charge and other effects like vacuum) but without a clear conclusion [6].

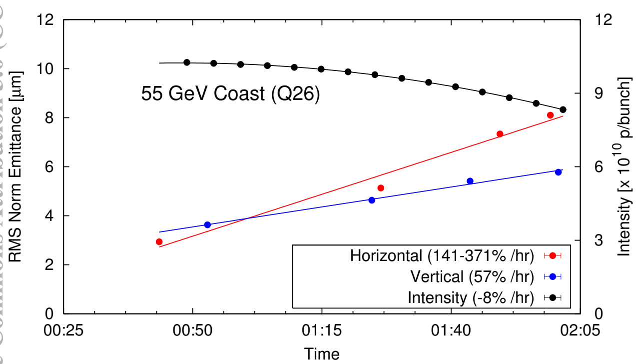

Figure 2: Emittance growth and intensity evolution as a function time at a 55 GeV plateau.

The large natural emittance growth observed at 55 GeV would mask the effect of any additional crab cavity noise at this energy. Therefore, the following experiments were performed at a higher energy (120 GeV). A lower bunch intensity to minimize any emittance growth effects from high bunch charge was used [7]. The first coast was performed with a train of 12 bunches at half the nominal intensity and the nominal voltage of 4 MV. The measurements were split into three parts (see Fig. 3). Data for the bunch intensity were not available. During a first scan a steep emittance

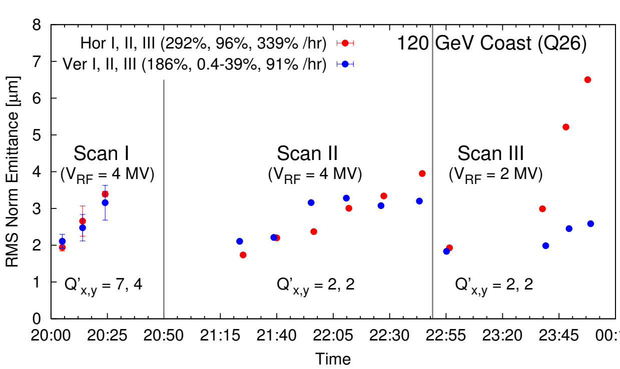

Figure 3: Emittance growth and intensity evolution as a function of time during a 120 GeV plateau with a train of 12 bunches.

growth was observed which could be attributed to the high positive chromaticty of 7 and 4 units in the horizontal and vertical plane. Following the correction of chromaticity to 2 units in both planes, the emittance growth decreased in the 2nd scan by a factor proportional to Q'. No vertical emittance growth was seen in the second scan when a mechanical problem of the wire scanner was fixed. During the 3rd scan, the voltage was lowered to 2 MV and subsequently to 1 MV. A significant increase in the horizontal plane was observed while the vertical plane increase was moderate. Calculations from MADX predict a decrease of the IBS growth rate at lower RF voltage [9] and therefore are in qualitative contradiction to the observed behavior.

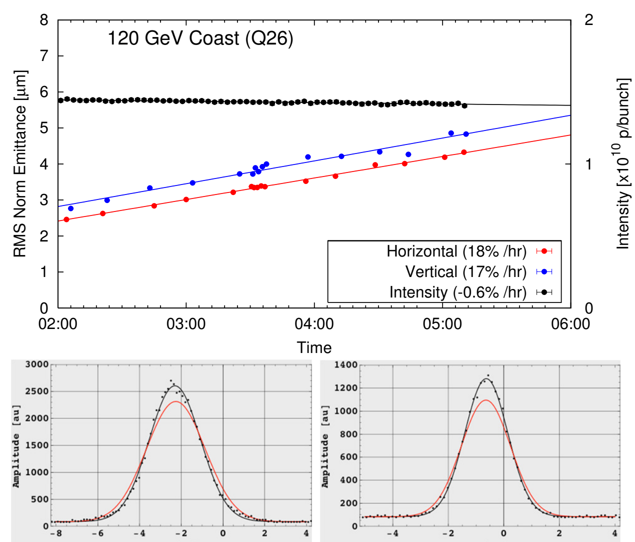

Figure 4: Top: Emittance growth and intensity evolution as a function of time during a 120 GeV plateau for a single low intensity bunch. Bottom: Transverse beam size profiles of the horizontal and vertical planes at the start of the coast (black) and 80 min after (red).

A second experiment at 120 GeV using approximately a factor 5 smaller intensity than the nominal bunch was set up. Figure 4 shows the evolution of the intensity and transverse emittances as a function of time. The smallest emittance growth below 20%/hr was observed with this set up. Consecutive wire scans were performed at 03:40 hours as shown in Fig. 4 revealing negligible or no emittance growth from the measurements themselves. A vertical tune scan from the nominal value of 0.18 to 0.34 in the latter part of experiment resulted in no additional growth. With chromaticity close to zero, sustained dipole oscillations close to

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Table 3: Summary of the Natural Emittance Growth Measurements from the SPS Experiments

Energy GeV	Intensity [x 10^{11}]	$Q_{x,y}$ -	Voltage [MV]	$d\epsilon/dt$ [/hr]	$d\epsilon/dt$ [/hr]
55	1.0	0.13/0.18	2.0	140%	57%
120	0.5 (12b)	0.13/0.18	2.0-4.0	100-300%	40-90%
120	0.1	0.13/0.18-0.34	2.0-4.0	18%	17%
270	0.4	0.13/0.18	1.5-2.0	20-23%	14-24%

the 3rd order resonance were observed but did not lead to any beam loss. The intensity reduction was less than 1%. Figure 4 also shows the transverse beam sizes from two different wire scans separated by 80 min.

For a beam energy of 270 GeV, detailed measurements of emittance growth already exist from 2004 [8]. During these measurements, negligible or no emittance growth was seen in the vertical plane after correction of the growth induced by the wire scanner. The growth from the wire scanner was estimated to be about 0.01 μm per scan and estimated to be about factor 2 worse at 120 GeV. In 2011 measurements were carried out, at 270 GeV to compare the growth rate with that of 120 GeV. The bunch intensity due to injection issues was higher than that of the 120 GeV experiment (Exp III). About 20-25%/hr growth was observed with similar intensity reduction as seen in Fig. 5. Therefore, further experiments at 270 GeV with the lowest possible intensity will be carried out in future. Table 3 summarizes all the emittance growth measurements at the three energies.

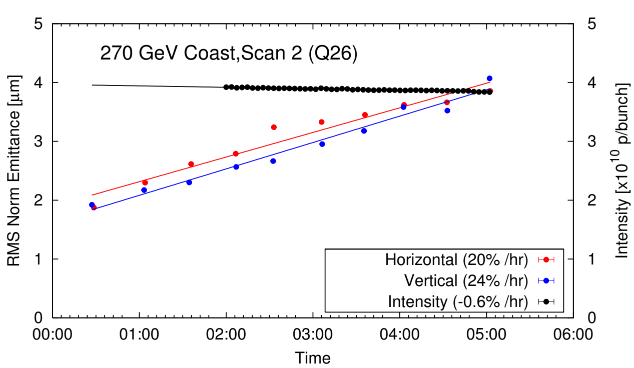

Figure 5: Emittance growth and intensity evolution as a function of time during a 120 GeV.

DISCUSSION

From recent measurements in the SPS the natural emittance growth is substantial at low energies and moderate at higher energies for coasting beams. For all energies, the emittance growth is much higher than in the past when SPS operated in the collider mode.

The emittance growth appears to be primarily a single bunch effect. The effect of the working point is minimal with very low intensity bunches even in the proximity of 3rd resonance. Chromaticity had strong effect and the growth was approximately proportional to Q′. The effect of the RF voltage however is in contradiction with IBS related growth. as predicted by MADX.

Experiments by other groups such as the long-range beam-beam, collimation and crystal collimation have also observed emittance growth of similar magnitude or larger at energies between 55 and 120 GeV [9]. Experiments on wide-band feedback using the SPS beams show slow tune modulation (approx 600-700 Hz) with a magnitude of approximately 2×10^{-3} [10]. Simulations to determine the effect of slow tune modulation are under investigation.

It is hypothesized that an external noise source (for example: dipole or quadrupole power supply ripple) could be a potential source leading to this emittance growth. Other mechanisms such as poor vacuum or space charge were considered, but simulations predict either a too large or too small a growth due to power supply ripple, vacuum or space charge effects at different energies [6]. Use of additional instruments such as the transverse damper pickups and the Schottky monitors are under way to parasitically record the presence of any coherent excitation of the beam from an external source.

ACKNOWLEDGMENTS

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