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MEASUREMENTS OF BEAM-BEAM INTERACTIONS IN GEAR-CHANGING COLLISIONS IN DESIREE*

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Abstract

In this work we perform measurements on the interactions of colliding beams in a gear-changing system. Gear-changing was first demonstrated in DESIREE in May of 2020, and showed several promising avenues to measure beam-beam effects. DESIREE has a unique collision scheme where the beams are moving in the same direction, which provides for unique interactions. This experiment used a 4 on 3 gear changing system with one bucket in each ring left empty. This allows us to see the bunch profile while it is undergoing collisions. We then measured the bunch length over time and used a Fourier transform to extract longitudinal evolution data and compared it to baseline data of uncollided beams.

INTRODUCTION

Gear-changing is a collider synchronization method that stores different harmonic numbers of bunches in each ring of a collider. These are collided by changing either the pathlength of one of the rings, or by changing the velocity of one of the bunches. For example, in a 4 on 3 gear-changing system the beam with 3 bunches would move at 4/3 the velocity of the 4 bunch beam. This has some advantages. In medium to low energy ion colliders. It can allow the machine to collide certain combinations of energies, where the velocity is not significantly close to c, without altering the pathlength of one of the collider rings. It can also reduce systematic errors in some types of experiments, as an example, ones where spin polarization is important [1].

Gear changing also has drawbacks. Since each bunch interacts with each other bunch, reaching equilibrium can take significantly longer than in a normally synchronized machine. Furthermore, if one bunch has a significant offset it will equilibrate with all of the other bunches in the ring, spreading that offset to all of them. There has also been theoretical work showing a potential resonance condition that is driven by a gear-changing system [2].

The Double ElectroStatic Ion Ring ExpEriment (DESIREE) is a small ion collider at Stockholm University in Sweden. It collides singly charged ions of up to 25 keV on those of up to 100 keV. DESIREE is a collider that, as designed, has zero energy collisions. Both beams move in the same direction, and their velocities are normally matched to study mutual neutralization interactions like those that are found in the interstellar medium [3]. The energy range is such that we can "dial-in" desired ion velocities, which is an excellent platform for gear-changing interactions. Because the bunches are moving at different velocities, collisions occur in a moving reference frame. A schematic diagram of DESIREE is shown in Fig. 1.

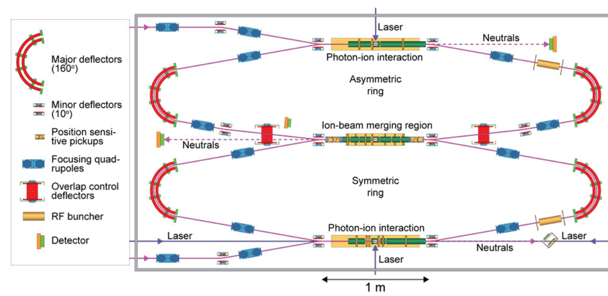

Figure 1: A schematic Diagram of DESIREE.

The work presented here is a part of a larger program to study gear-changing using DESIREE, the program is referred to as Direct Observations in DESIREE of Gear-changing Events (DODGE). This program has made measurements in DESIREE on three occasions, in October 2019 to test beam properties, May of 2020 where we first demonstrated a gear changing system, and February of 2021 which is reported here [4].

EXPERIMENT DESIGN

The experiments performed in 2019 and 2020 provided the background for the experiments shown here. We use a 4 on 3 gear changing system using 7 keV carbon on 14.3 keV nitrogen, similar to one of the systems tested in May 2020. They showed that the evolution of the bunch length over time, a measure of synchrotron motion, is very sensitive. We tested two collision configurations, one that filled all buckets and one that left the last bucket of each ring empty. This creates a repeating pattern which shows gear changing at a glance, it also periodically lets us see each bunch without a collision, to help us measure the evolution of the beams' parameters. An example of the missing bunch pattern is shown in Fig. 2.

A simple two particle model of the interactions showed that there would be a longitudinal kick during each interaction. This means that using oscilloscope settings with a higher level of sensitivity, as well as more slices should give us a measurable effect. The experiment consisted of two sets of beam parameters. One we refer to as the "low current" system, it is equivalent to the 4 on 3 parameters we used in May of 2020. The second we call the "high current" system, where the bunch population was doubled by

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increasing the carbon source, and doubling the nitrogen bunch length. These parameters are seen in Table 1.

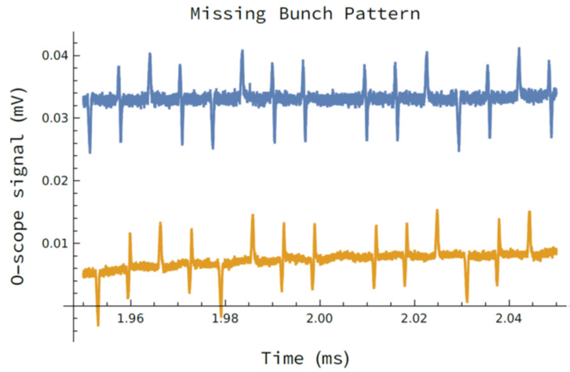

Figure 2: An example of the missing bunch pattern.

Table 1: Parameters Used in this Experiment

	Low Current		High Current	
	C	**N**	**C**	**N**
Beam Energy	7.04 keV	14.3 keV	7.04 keV	14.3 keV
Avg Bunch Length	174 ns	167 ns	194 ns	325 ns
Bunch Population	4.4×10^4	3.7×10^4	9.7×10^4	6.9×10^4

EXPERIMENTAL RESULTS

During this experiment we took turn-by-turn data for 30 ms of store time, which is a bit over 1100 carbon turns. In order to extract the information that we needed, we used a skip code to only zoom in on the uncollided bunches. Once we had zoomed in on them, we fitted the curve to a gaussian which gave us the bunch length, the centroid position, and the signal magnitude. An example of the high current bunch length evolution is shown in Fig. 3.

Since the information is extracted from a fitted curve, there will be some noise due to the fitting process. The longer bunch length used in the high current nitrogen parameters means that it gives a much cleaner signal. Future experiments will use longer bunch lengths to help get this level of data cleanliness.

The next step in this experiment is to find the Fourier spectra of the collided beams and their baselines, and compare them. For a Fourier spectrum the points must have an equal time step between them, since only two thirds of the nitrogen turns have uncollided bunches, we organize both beams into 78 μs superperiods, equivalent to 3 carbon turns and 4 nitrogen turns. The spectra of the high current system are shown in Fig. 4. If we look at the difference between the two spectra, we see what might be a shift in the carbon, though the noise level of the signal obscures this.

The nitrogen signal, on the other hand, shows a definite frequency shift. The signal is stronger in this system due to the reduced noise. We want to look further into this system to find more evidence of the longitudinal beam-beam effect.

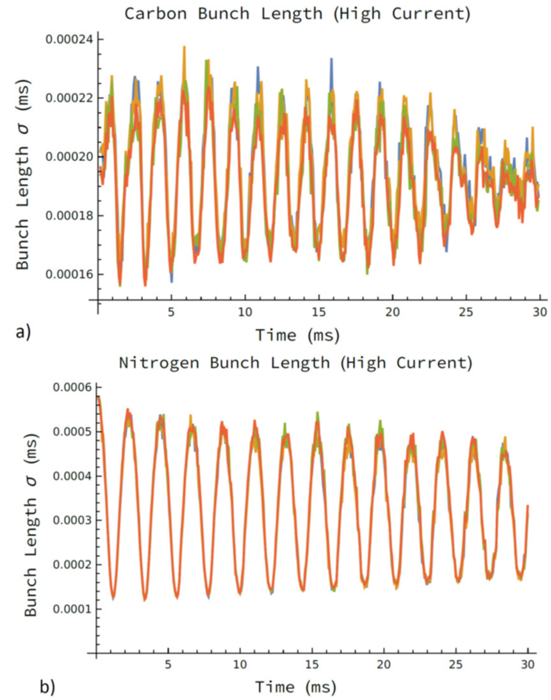

Figure 3: This is the evolution of the bunch length in the high current parameter set for a) carbon and b) nitrogen.

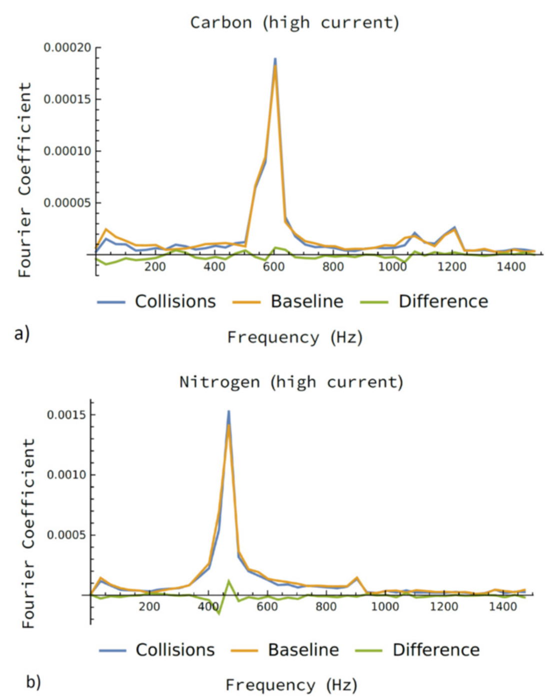

Figure 4: These plots show the average of the spectra for the collided beam, the baseline beam, and the difference between them for the high current a) carbon and b) nitrogen systems.

The next thing we looked at is the relative motion between the centroids of the bunches undergoing collisions, as well as their baselines. We divided the data into buckets with the uncollided bunches in them, in this experiment we take the centroid position of the beam under collision and the centroid position of the baseline beam in the same bucket and subtract the two. The results for the high current parameter set are shown in Fig. 5.

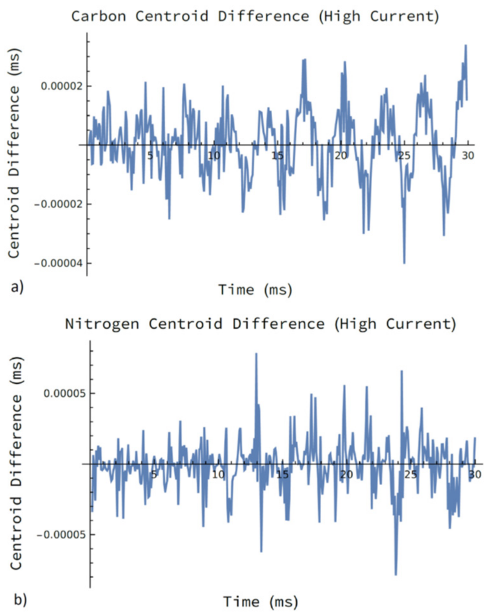

Figure 5: This shows the relative centroid motion between the collided and baseline beams in the high current a) carbon and b) nitrogen beams.

As can be seen in these results, there is some level of structure on the nitrogen beam, but a definite structure, and an increasing magnitude on the structure as time progresses. When we take the Fourier spectrum of the relative centroid motion, we get the results shown in Fig. 6. The results show a peak in the carbon that is weaker in the low current and stronger in the high current. The nitrogen data doesn't show much in the low current system, but shows a pair of peaks in the high current system. It should be noted that the signals for the nitrogen are usually much stronger due to the lower noise level.

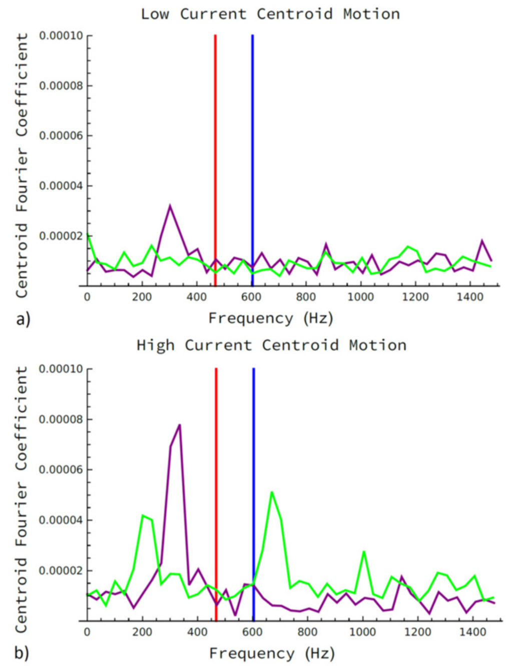

Figure 6: These show the spectra of the centroid motion of the a) low current and b) high current relative centroid motion. The blue and red lines show the location of the carbon and nitrogen peak bunch length frequencies respectively. The purple line is the average carbon centroid difference spectrum, and green is the average nitrogen centroid difference spectrum.

FUTURE WORK

From this data we can conclude that there is a measurable beam-beam interaction that occurs in a gear-changing system in DESIREE. It also appears that the carbon beam might be approaching a resonance. Future work will explore the parameter space of this phenomenon, and can hopefully lead to a new understanding of low energy beam-beam interactions.

The next round of experiments will utilize longer bunch lengths to get cleaner signals, and will be structured to get more data points at different currents. We also intend to vary the RF voltage, which will alter the relative positions of the peaks for the nitrogen and carbon, and will use different ion species. We are currently looking at trying the same system with hydrogen and helium, whose higher charge to mass ratio should give us a stronger interaction.

On a longer term, we intend to look at longitudinal phase space tomography, which could be done by simply kicking one beam out earlier than the other. This would allow us to track the beam-beam effect with gear changing in a detailed manner. We also need to develop a theoretical framework for this type of low energy, comoving, longitudinal beam-beam interaction. The assumptions underpinning the normal incoherent beam-beam tune shift formula don't fully apply in this system, and a good theoretical framework combined with simulations will help to get the most out of future experiments in DESIREE.

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