INVESTIGATIONS OF A NOVEL BUNCH COMPRESSION TECHNIQUE FOR HADRON ACCELERATORS*

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Abstract

Bunch compression is necessary for many accelerator applications, one of which being the creation of muons for the proposed muon collider. The design of a proton driver to deliver a short and very intense proton pulse to a target for the creation of muons is being developed. Some challenges with the proposed baseline design, notably the ambitious requirements for the radiofrequency system, motivate the investigation of alternative compression methods. A series of chirped bunch trains can be compressed in the same compressor ring as in the baseline design, removing the need for an accumulator ring and radiofrequency cavities in the compressor ring. Such a scheme has been investigated using PyORBIT simulations, where the chirp is created by off-frequency cavities at the end of the linac. The impact of space charge was investigated, and was found to be too detrimental for realising the proposed scheme with the current parameters. However, other use cases are foreseen.

INTRODUCTION

The proposed muon collider [1] has stringent requirements on the proton driver, which serve to ensure that the target produces enough muons in a short enough time to be captured and cooled to create useable bunches for the collider stage. An average power of 2 MW at a repetition rate of 5 Hz is required, which at the proton energy of 5 GeV corresponds to bunches with 5×10^{14} protons. The compression should achieve an RMS bunch length of 2 ns, which with the other parameters represents an unprecedented proton density, even though the baseline design divides the bunch in two [1, 2]. The proposed design which delivers this consists of a high intensity 5 GeV linear accelerator (linac), followed by an accumulator ring and a compressor ring, as shown in Fig. 1.

CHIRP CREATION

As the lattice for the compressor ring is designed to maximise the slippage factor for rapid compression, it can in principle fulfil its function even without radiofrequency (RF) cavities providing synchrotron motion in the bucket. A series of short bunches from the linac, which delivers 2 ps bunches, given an appropriate chirp will eventually stack on top of each other in the compressor ring. To create the required chirp, two cavities can be added at the end of the linac, operating at frequencies slightly shifted from the nominal frequency, $f = f_0 \pm \Delta f$.

The bunches will experience the superposition of the field in the two cavities, which has a beating envelope with the same frequency as the frequency shift Δf. As seen in Fig. 2, the bunches receive different energies and a chirp is created over a train of bunches. Chopping the source pulse from the linac appropriately, a series of such bunch trains with varying amplitude are injected directly into the compressor ring. A frequency shift which is an integer fraction of the revolution frequency in the ring ensures overlapping bunch trains. The bunch trains compress during the injection, but must all reach maximum compression simultaneously. Consequently, the final bunch train receives the largest chirp amplitude, and the others follow a $1/t$ dependence over the injection time t.

TOY MODEL

To identify potential parameters for the compression, a toy model was first developed which treated the compression analytically using the slippage factor from the compressor lattice. A frequency shift corresponding to the revolution frequency of the compressor ring was chosen, 0.94 MHz. Bunches are spaced at a frequency of 352.21 MHz from the linac, meaning around 100 bunches can be placed within the linear region of the envelope, and thus only around a quarter of the pulse can be utilised. The current from the linac is 80 mA, determining the total number of bunches to be 3.5×10^5 in order to reach the required intensity of 5×10^{14} protons. Consequently, the injection takes a total of 4122 turns. Based on the high-β cavities in the ESS linac, the energy gain in the off-frequency cavities was conservatively chosen to 10 MeV [3]. For the slippage factor of $\eta = 0.17$, this amplitude compresses the bunches in 248 turns according to

$$\frac{dT_{\text{rev}}}{T_{\text{rev}}} = \eta \frac{dp}{p}. \tag{1}$$

The amplitude was increased from 0.6 MeV to 10 MeV across the injection, and the bunch trains are all simultaneously compressed after 4370 turns. For the baseline design, the compression in the compressor occurs in ~50 turns. In Table 1, the resulting parameters of the toy model are shown, and the compression after 4370 turns is shown in Fig. 3, where each bunch is treated as a single macroparticle.

Improving the Design

While the toy model parameters indeed achieve the required proton driver parameters, it is clear that collective

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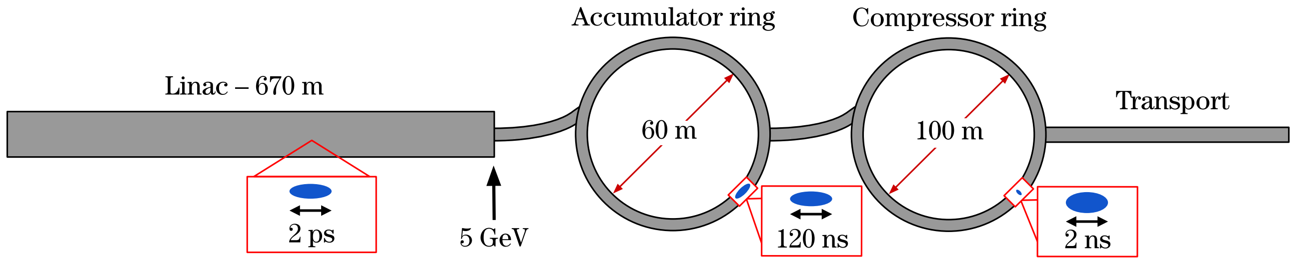

Figure 1: The baseline proton driver design [1, 2].

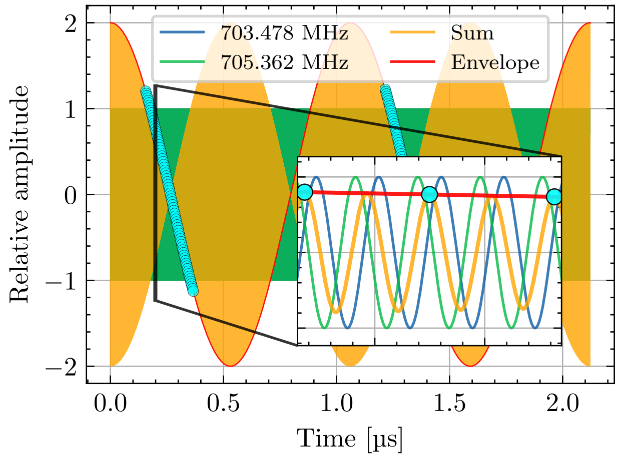

Figure 2: The superposition of the fields from the two off-frequency cavities, with the bunches in a bunch train receiving different energies.

Table 1: Toy Model Parameters

Parameter	**Value**	**Adjusted value**
Amount of pulse kept	24 %	72 %
Pulse length	4.375 ms	1.393 ms
# turns injection	4122	1312
# turns compression	248	248
Amplitude	10 MeV	30 MeV
Final bunch length	1.92 ns	5.63 ns
Average power	2.10 MW	2.01 MW

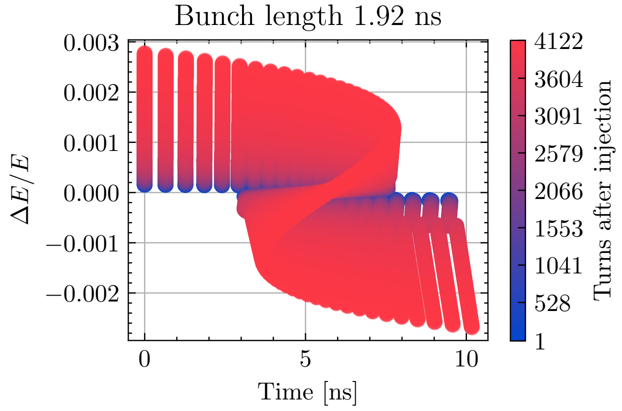

Figure 3: The compression of the 4122 bunch trains after 4370 turns as tracked by the toy model with only the slippage factor taken into account.

effects will severely limit the performance of this compression scheme. As the compression time for the final bunch train can be shortened arbitrarily by adding pairs of cavities, the main limitation is the injection time. To shorten this, the chopped linac pulse can be sent to three separate lines with off-frequency cavities using fast kicker magnets. An ambitious but realistic rise and fall time of 300 ns for the magnets would not limit the number of bunches per bunch train, increasing the pulse usage by a factor three from 24 % to 72 %.The frequency shift can correspondingly be reduced by a factor of three so that one bunch train is still injected every turn, but now from each line. The total length of the bunch train is then also maximised w.r.t. the circumference of the ring, further reducing the strength of collective effects. This also has the consequence of increasing the bunch length in the toy model, as seen in Table 1, due to the increased size of the sinusoidal envelope. However, this effect is negligible compared to the impact from collective effects, as will be seen. The final design for the proposed scheme is shown schematically in Fig. 4.

SIMULATIONS

The compression was studied with particle-in-cell (PIC) simulations with PyORBIT [4]. Simulations were performed first without space charge to confirm the compressive behaviour and parameter choices, demonstrating good agreement with the analytical model. This indicates that nonlinear effects from the lattice are not particularly strong. The non-zero energy spread introduced for a realistic bunch however increased the final bunch length considerably. The impact of energy spread on final bunch length can be given a lower bound using Liouville's theorem, requiring a spread of $\Delta E/E = 3\times10^{-5}$ for achieving the desired bunch length of 2 ns, an order of magnitude below the linac specifications.

This is however not the limiting factor for the final bunch length, as space charge simulations demonstrate. At design intensity, the sequentially injected beam starts experiencing an instability already after ~150 turns, as seen in Fig. 5. This instability then causes microbunching and violent growth in energy spread, leading to bunch deformation and particle loss. While the bunch length does decrease initially, the beam eventually breaks up before the ideal compression would be achieved after 1597 turns.

This behaviour is attributed to the *negative mass instability*, which is characterised by microbunching around local density variations. For a machine operated above transition, the space charge kicks from a region of increased parti-

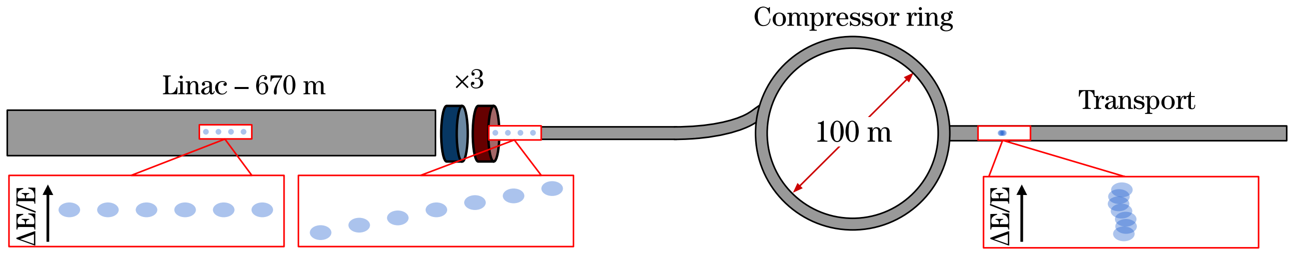

Figure 4: The proposed novel compression scheme, where a 5 GeV linac sends a chopped pulse to one of three lines with cavities shifted in frequency by $\Delta f = 314\,\mathrm{kHz}$ at different phases. The bunch trains are injected on top of each other in the compressor ring with one injection per turn.

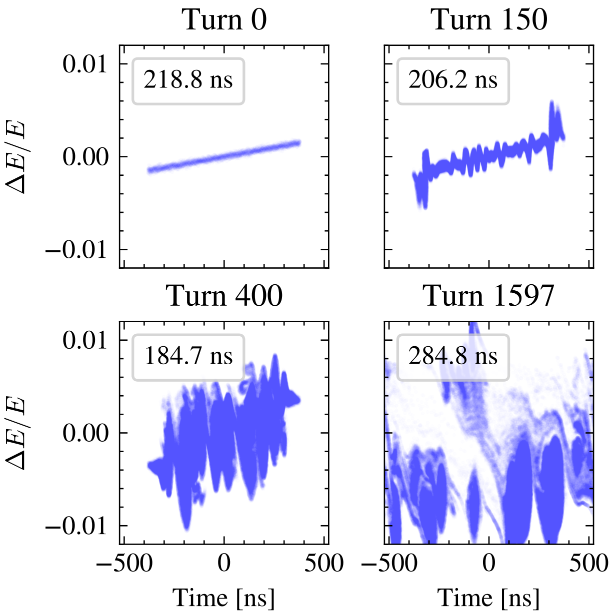

Figure 5: The longitudinal phase space distribution of the beam a certain number of turns after the first bunch train is injected, with the RMS bunch length in the top left.

cle density do not cause repulsion, but rather attraction as follows from Eq. 1 with $\eta > 0$. This increases the particle density and energy spread in these microbunches, with particles deviating enough in energy to be lost due to dispersion effects [5]. At the baseline intensity, only 23 % of the macroparticles are retained by the end of the simulation. Optimising the parameters for maximum retained intensity within realistic constraints, a transverse emittance of 20 mm mrad was chosen, with circular apertures of radius 35 cm placed around the ring. Due to the large energy spread from the chirp and microbunching, the dispersion in the ring contributes considerably to the horizontal beam size, and thus the required aperture. Using elliptical apertures to accommodate this did not help considerably.

Simulations were performed also at lower intensities, showing the same instability. The impact was smaller at reduced intensities, and it was found that with 1×10^{13} protons compression was achievable with more acceptable results. A bunch length of 21.8 ns was achieved with an injection over 26 turns and 297 turns of compression, without particle loss. Doubling the chirp reduced the bunch length to 12.8 ns after 180 turns.

Furthermore, an alternative lattice operating below compression has been cursorily investigated. In this case, η is limited by the particle energy to $\eta < 0.025$, meaning a larger amplitude chirp is required to achieve compression. However, these results, from an unoptimised lattice, show that the space charge repulsion is considerably stronger than the compression even at a 60 MeV chirp amplitude. Given the increased beam size with dispersion at larger amplitudes, such a lattice is not deemed feasible, in line with previous work [6]. A lattice with imaginary transition energy could similarly avoid the negative mass instability, while potentially having $\eta > 0.025$ and is thus an interesting object for future studies.

CONCLUSION

It has been shown that it is indeed possible to compress proton bunches with the proposed scheme based on chirp creation with off-frequency RF cavities outside the compressor ring. Without space charge effects, the simulated procedure follows expectations very well. However, a very small energy spread is required in the bunches to achieve nanosecond bunch lengths, as desired for the muon collider use case. With the introduction of space charge, the desired bunch intensities were shown to be unfeasible due to the strong space charge forces. In the baseline compressor lattice above transition these forces caused strong microbunching and deformation of the beam due to the negative mass instability. An alternative lattice below transition had a slippage factor too small to overcome the space charge repulsion at a reasonable chirp amplitude. The scheme was however demonstrated to achieve compression to 22 ns without particle losses with 1×10^{13} protons, an intensity relevant for other use cases, such as neutrino factories. An increase in repetition rate from the low 5 Hz of the muon collider is also easily achievable, limited only by the linac.

Various potential improvements to the scheme remain to investigate, for example adding weak bunching RF cavities to the compressor ring or using space charge compensation with impedance from Finemet cavities or ferrites.

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