STACKING SIMULATIONS IN THE BETA-BEAM DECAY RING

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Abstract

The so-called beta-beam concept for accelerator-driven neutrino experiments envisages the production of a pure beam of electron neutrinos (or their antiparticles) through the beta-decay of radioactive ions circulating in a high-energy storage ring. An unprecedented number of ions must be collected in the decay ring and maintained in a few short bunches. Stacking is unavoidable to match the available source rates with this demand. A new stacking method makes use of off-momentum injection into the decay ring to approach the circulating beam without requiring ultra-fast injection elements, rotation in the longitudinal plane to bring the fresh bunches onto the central orbit and asymmetric merging to transport these ions into the centre of the large stack. Simulation results are presented for the repetitive stacking process for two candidate ion species of significantly different charge-to-mass ratio.

INTRODUCTION

The beta-beam [1] decay ring is an accumulator for the bunches delivered by an accelerator chain that culminates with the existing CERN PS and SPS machines. Accumulation is possible because the half-life of the highly relativistic (γ=100) stored ions is more than an order of magnitude longer than the cycling time of the injectors. It is proposed to stack the ions using asymmetric bunch pair merging [2], which relies on a dual-harmonic rf system to combine adjacent bunches in longitudinal phase space such that a fresh, dense bunch is embedded in the core of a much larger one with minimal emittance dilution. Each new bunch must be injected into the rf bucket of an existing bunch in the stack, but this is excluded using conventional kickers and septa because of the short rise time that would be required. An alternative injection scheme exploits the fact that the stack is located at only one azimuth in the decay ring and that the revolution period is relatively long. The new bunches arrive off-momentum and are injected in a high dispersion region on a matched dispersion trajectory. This allows almost a full turn for a collapsing injection bump to bring the off-momentum orbit inside the machine at the entry point of the beam. Subsequently, each injected bunch rotates a quarter of a turn in (single-harmonic) longitudinal phase space until the initial conditions for bunch pair merging are met and (dual-harmonic) stacking can proceed. The aim is to collect sufficient ions to ensure that enough neutrinos are localized sufficiently well in time to overcome the background issues at the detector in Fréjus some 130 km away in France. There are two ion species of particular interest: $^{6}He^{2+}$, giving electron anti-neutrinos, and $^{18}Ne^{10+}$ for neutrinos.

DUAL RF SYSTEM

Providing adequate longitudinal acceptance when only a few buckets are populated suggests the use of relatively low rf frequencies. A fundamental at 40 MHz follows naturally from the existing PS rf systems, which produce proton bunches with a 25 ns spacing for the LHC.

The rf voltage requirements are dimensioned by the helium case because of the less advantageous charge-to-mass ratio of this ion species. 20 MV at 40 MHz permits a 1 eVs injected bunch to rotate sufficiently far inside the bucket separatrix to reduce filamentation whilst leaving enough space between this off-momentum bunch and a 15 eVs stack to accommodate not only their betatron sizes plus the septum blade, but also collimation margins and alignment tolerances [3].

The situation is made easier in the neon case because the same relative momentum spread of the stack – as determined by the fixed collimation system [4] – can be achieved at lower 40 MHz voltage without compromising acceptance. Indeed, an increase of the incoming emittance from 1 to 2.2 eVs and of the emittance ratio from 15 to 20 is still consistent with the same off-momentum injection into a 12 MV bucket. Taking more than 20 shots to fill the stack is considered inexpedient because of the tight constraints this would impose on the phase and voltage programmes of the two rf components during merging.

In addition to stacking, the second-harmonic rf system is also required to help shorten the resultant bunches. Consequently, it must provide something of the same order as the 20 MV available at 40 MHz even though much less 80 MHz voltage than this is needed in both the helium and neon cases during the merging itself.

MERGING

RF Programmes

At the start of merging, the 40 MHz voltage is rapidly reduced and an 80 MHz component introduced such that the stack is retained in a large inner bucket that is matched to its momentum spread while a small inner bucket provides just enough acceptance to capture the rotating fresh bunch as it arrives on-momentum. Asymmetric bunch pair merging proceeds by reducing the acceptance of the larger inner bucket while preserving that of the smaller one. The corresponding voltage and phase programmes are shown in Figures 1 and 2, respectively. These are obtained numerically, following the ideas of iso-adiabaticity, by keeping the relative rate of change of synchrotron frequency constant inside the collapsing inner bucket.

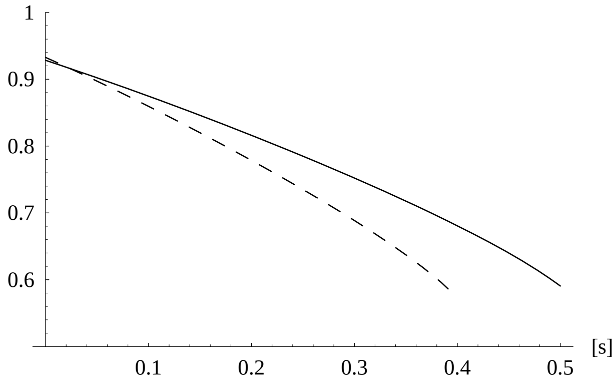

Figure 1: 80 MHz voltage versus time during asymmetric merging expressed as a ratio with respect to constant 40 MHz voltage at 13.5 MV in the helium case (solid line) and 7.9 MV for neon (dashed line).

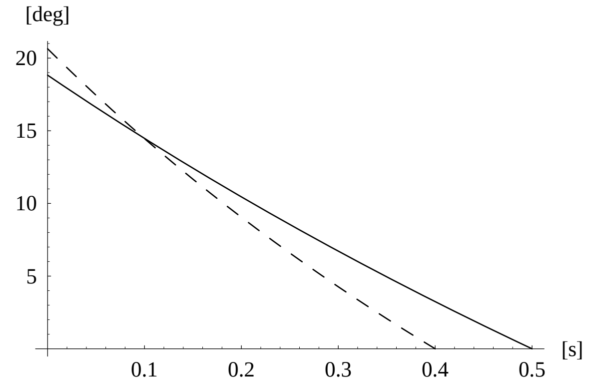

Figure 2: Relative phase (at the fundamental) between 40 and 80 MHz rf components versus time during asymmetric merging for helium (solid line) and neon (dashed line).

Merging is completed in a more conventional [5] symmetric step by further reducing the voltage ratio to a half while maintaining the two rf components in phase opposition (i.e., zero relative phase above transition). This combines the fresh bunch with an equal phase space area at the core of the stack.

Simulations

The rf programmes of the previous section have been validated using the longitudinal tracking code ESME [6]. At the end of asymmetric merging, the 80 MHz component was reduced linearly to zero and concurrently, at the end of symmetric merging, the 40 MHz component was raised linearly back to its injection value. This effectively skipped any bunch shortening and re-established the single-harmonic conditions for another injection step in a minimum tracking time (0.25 s additional simulated machine time in the helium case and 0.2 s for neon). The acceptance of the stack was limited by imposing an aperture restriction to model momentum collimation at 2.5‰, which is the equivalent position of the collimator in the single-harmonic bucket at injection for both ion species.

Within this framework, a single bunch of macroparticles was tracked from the SPS into the core of an empty stack in the decay ring and combined with successive empty shots in order to investigate how ions get pushed outwards from the centre of the stack without having to track an unnecessarily large number of them. Beta-decay was not included in the simulation, so particles were only removed when they reached the edge of the stack as defined by the collimator. Collective effects were also ignored and, obviously, betatron collimation could not be addressed because ESME is not a 6D code.

The results are shown in Figure 3, which reveals that some of the ions are collimated well before the (15th or 20th) shot which fills the stack acceptance and that some even remain long after it. The latter effect is due to the symmetric part of the merging, which mixes particles at the core of the stack. More than 90% of an injected bunch is captured and transported into the stack.

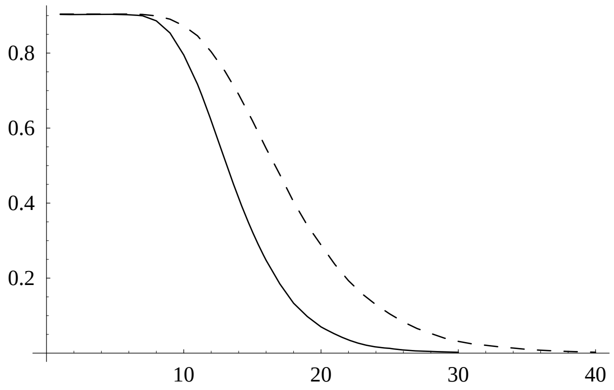

Figure 3: Survival profile of a single injected bunch versus number of stacking steps for helium (solid line) and neon (dashed line).

BETA-DECAY

Before integrating the curves of Figure 3 to obtain the limiting intensity in the stack, it is necessary to correct them for beta-decay. Of course, some particles would have decayed before reaching the collimator, but how they are lost does not matter for the summation. It is sufficient to reduce the number of surviving ions at the end of each step according to the length of time they have spent in the decay ring up to that point.

This yields the effective number of shots accumulated as 8.9 in the helium case and 14.0 for neon. Furthermore, these figures mean that beta-decay between two consecutive shots amounts to 45% of an injected helium bunch, but only 21% of a neon one. The rest must be collimated.

For comparison, if stacking were ideal with a rectangular (collimation) survival profile at 100%, then the number of ions accumulated simplifies to a geometric progression with the number of terms equal to the number of shots that fill the stack. This puts the ultimate stack at 10.7 effective shots for helium and 17.4 for neon and gives an overall figure of merit for the stacking process in excess of 80% in both cases.

Repeating the exercise, starting from an empty stack but with every incoming bunch populated, provides little additional information because the beta-decay-corrected survival profile of the first bunch is the increment in the total number of particles at each step. However, it does show that the energy distribution of the final stack is quasi-parabolic without an undue weighting in the tails.

ACKNOWLEDGEMENTS

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CONCLUSIONS

Repetitive longitudinal stacking in the beta-beam decay ring has been simulated for two different species of radioactive ion, $^{6}He^{2+}$ and $^{18}Ne^{10+}$. Post-processing the results to incorporate beta-decay reveals promisingly high overall efficiencies of more than 80%.

The particular beauty of the method is that it exploits the fact that the beam is radioactive and therefore phase space density is globally decreasing with time. Each fresh bunch is embedded in the core of a stacked one, pushing older less-populated areas of longitudinal phase space to larger amplitudes until, eventually, they are collimated. This ensures that the highest density is maintained at the centre of the bunches and locally gives the process the appearance of cooling.

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