PREPARATIONS FOR UPGRADING THE RF SYSTEMS OF THE PS BOOSTER

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Abstract

The accelerators of the LHC injector chain need to be upgraded to provide the HL-LHC beams. The PS Booster, the first synchrotron in the LHC injection chain, uses three different RF systems (first, second and up to tenth harmonic) in each of its four rings. As part of the LHC Injector Upgrade the current ferrite RF systems will be replaced with broadband Finemet™ cavities, increasing the flexibility of the RF system. A Finemet™ test cavity has been installed in Ring 4 to investigate its effect on machine performance, especially beam stability, during extensive experimental studies. Due to large space charge impedance Landau damping is lost through most of the cycle in single harmonic operation, but is recovered when using the second harmonic and controlled longitudinal emittance blow-up. This paper compares beam parameters during acceleration with and without the Finemet™ test cavity. Comparisons were made using beam measurements and simulations with the BLonD code based on a full PS Booster impedance model. This work, together with simulations of future operation, has provided input for the decision to adopt a fully Finemet™ RF system.

INTRODUCTION

The Proton Synchrotron Booster (PSB) is the first synchrotron in the LHC injection chain, comprised of 4 independent rings, each with 3 RF systems with 1 cavity each for 1st and 2nd harmonics and a cavity for longitudinal emittance blow-up operating at up to 10th harmonic. The PSB currently takes beam from Linac2 injected with relativistic $\beta = 0.3$, and extracts beam for the PS and ISOLDE with $\beta = 0.9$.

As part of the LHC Injector Upgrade (LIU) project [1] the PSB will be upgraded to take beam from Linac4, which will change injection kinetic energy from the current 50 MeV to 160 MeV, and extraction will be at either the current 1.4 GeV for ISOLDE or 2 GeV for the PS, giving $\beta = 0.52$ at injection and $\beta = 0.9$ or 0.95 at extraction.

The large range in relativistic β, and therefore in revolution frequency, requires the RF system(s) to have a large frequency range. Currently the RF cavities use a ferrite core with a tuning loop to change the narrow band resonant frequency. The proposed upgrade to the PSB RF systems for the LIU project is a complete replacement of the current ferrite RF systems with Finemet™ based systems [2]. Finemet™ cores give a very broadband impedance removing the need for a tuning loop, and simplifying the system. The real and imaginary impedances of a single cell are given in Fig. 1.

Across all harmonics it is necessary to supply a minimum of 1 MHz and a maximum of 18 MHz, these frequencies

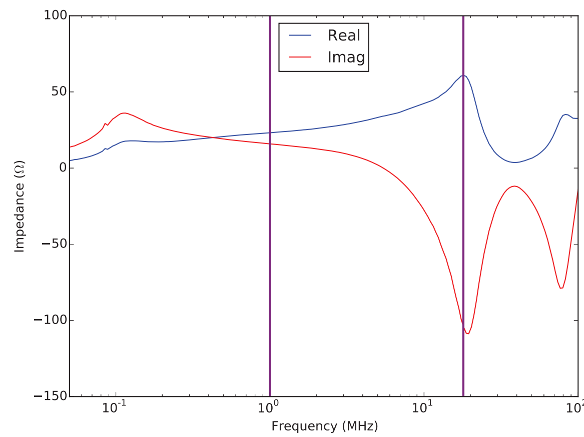

Figure 1: The real and imaginary longitudinal impedances of a single Finemet™ cell [2]. The vertical lines indicate the minimum and maximum RF frequencies required across all harmonics in operation.

are indicated by the vertical lines in Fig. 1. At specified harmonics of the revolution frequency RF feedback loops are used to reduce the Finemet™ cavity impedance.

The Finemet™ cavities are able to operate over the full frequency range required without tuning, this will enable each cavity to operate with any combination of harmonic and voltage, increasing system flexibility. There will be three cavities per ring, each cavity comprised of twelve cells, giving a maximum possible voltage of 24 kV. The specifics of the new RF systems are discussed in detail in [3].

Prior to the decision to replace the current RF systems, an extensive campaign of measurements and simulations was undertaken to determine if the new system would be suitable, in terms of both longitudinal beam dynamics and reliability. As part of this process a ten-cell test cavity was installed in Ring 4 of the PSB, which has been used to experimentally investigate potential negative effects of the new system on beam stability.

In this paper the experimental results are given. Simulations were also performed using the Beam Longitudinal Dynamics (BLonD) code [4] developed at CERN, details of its benchmarking can be found in [5]. The BLonD simulations were also used to predict the effect of an entirely Finemet™ based RF in the PSB, with 36 gaps and increased extraction energy, these results will be presented elsewhere.

MEASUREMENTS

For most production beams double harmonic operation and emittance blow-up are used together with phase and radial loops to provide stable acceleration. Below two sets

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of data are presented, the first obtained from a high intensity production beam for the ISOLDE facility and the second from a non-production test beam developed specifically for these experiments. The test beam was accelerated with single harmonic, no emittance blow-up and had phase and radial loops disabled.

The longitudinal shape of the bunch in the machine was measured with a wall current monitor and the signal was stored for post processing to obtain beam parameters. Depending on how the machine is operated there can be significant shot-to-shot variation in the beam parameters, therefore approximately 20 cycles were used for each measurement to give a statistically meaningfull result for each data point. The measurements given are bunch length at FWHM ($\tau_{0.5}$), phase oscillation amplitude (A_φ) and FWHM length oscillation amplitude (A_τ), where A_φ is the difference between the maximum and mimimum centroid of the FWHM and A_τ is the difference between the maximum and minimum bunch length, all in ns.

During the cycle data were acquired in sections corresponding to between 2 and 5 synchrotron periods to allow high enough resolution for accurate measurements of bunch oscillations. Data points were distributed through the duration of the cycle to allow the complete evolution of the beam to be determined.

RESULTS

ISOLDE Beams

The ISOLDE beams were operated at high intensities ($\approx 8 \times 10^{12}$) to compare the beam parameters between a ring using entirely ferrite cavities (Ring 1) and a ring using a Finemet™ cavity to provide the voltage on *h=2* (Ring 4). For these beams the RF is ussually set to 8 kV on *h=1* and *h=2*, however the test cavity is limited to 7 kV so both rings had voltage at *h=2* set to 7 kV for these measurements. As the cycles measured were in use by the ISOLDE facility the emittance blow-up was not adjusted and was slightly different between the two rings, leading to a slight difference in $\tau_{0.5}$ due to either emittance or bunch shape differences.

The $\tau_{0.5}$, A_φ and A_τ are given in Figs. 2-4. With the exception of $\tau_{0.5}$ there is minimal difference between the two rings, and the points mostly lie within one standard deviation of each other.

Test Beams

The test beam data were taken with all feedback loops disabled, no emittance blow-up and single harmonic acceleration, maximising any intensity effects. Whilst this is not a realistic operating scenario it could demonstrate if there are any negative effects of impedance (with 10 cells and present intensities). Beams were accelerated either with the test cavity short circuited, or open with RF loops disabled (open loop), low intensity beams of $\approx 2 \times 10^{12}$ and high intensity beams of $\approx 7 \times 10^{12}$ were used. The data were taken in the middle of the cycle, from 550 to 650 ms after cycle start.

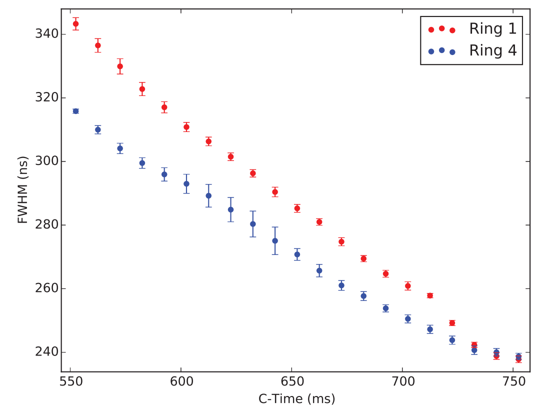

Figure 2: The measured FWHM bunch length ($\tau_{0.5}$) of the ISOLDE beams in Ring 1 (ferrite *h=2*) and Ring 4 (Finemet™ *h=2*).

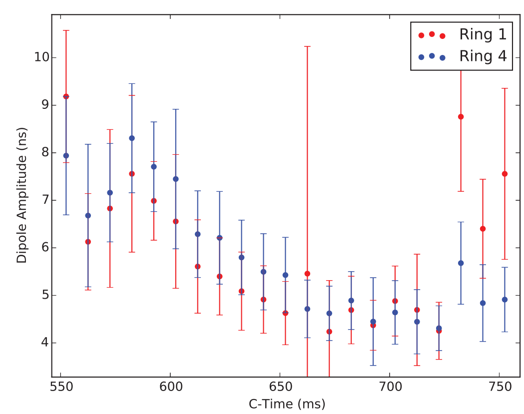

Figure 3: The measured phase oscillation amplitudes (A_φ) of the ISOLDE beams in Ring 1 (ferrite *h=2*) and Ring 4 (Finemet™ *h=2*).

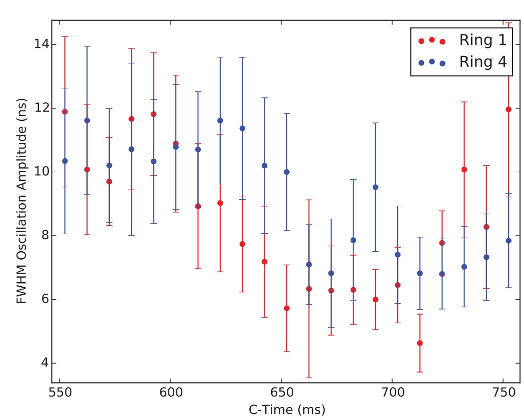

Figure 4: The measured FWHM length oscillation amplitudes (A_τ) of the ISOLDE beams in Ring 1 (ferrite *h=2*) and Ring 4 (Finemet™ *h=2*).

The measured values of $\tau_{0.5}$ are given in Fig. 5, A_φ in Fig. 6 and A_τ in Fig. 7. In most cases there is no significant difference between the 4 cases. The higher intensity beams can be seen to give a slightly increased bunch length in Fig. 5, as would be expected, however the points for open loop and shorted circuit operation are almost indistinguishable. The A_φ again show very little difference, with the low intensity beams taking longer to damp the oscillations that start around 580 ms after injection. There is a noticeable effect in the A_τ when combining high intensities with open loop operation, in this case there are increased bunch length oscillations, for which the Finemet™ would seem to be the most likely explanation. In practice the increased A_τ seen here is not a concern as it is completely suppressed under normal operating conditions as the combination of double harmonic, RF feedbacks in the Finemet™ cavity, and phase and radial loops easily control any excitations.

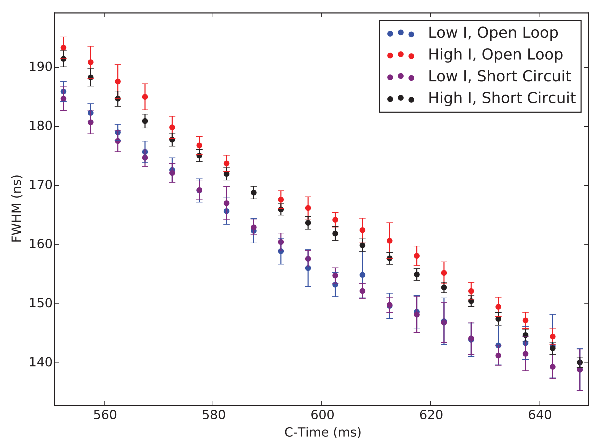

Figure 5: The measured FWHM bunch length ($\tau_{0.5}$) of high (7×10^{12}) and low (2×10^{12}) intensity beams with the Finemet™ test cavity short circuited and with RF feedback loops disabled (open loop) modes.

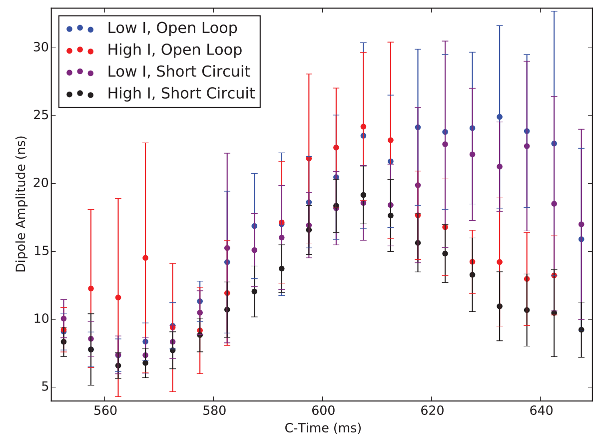

Figure 6: The measured phase oscillation amplitudes (A_φ) of high (7×10^{12}) and low (2×10^{12}) intensity beams with the Finemet™ test cavity short circuited and with RF feedback loops disabled (open loop) modes.

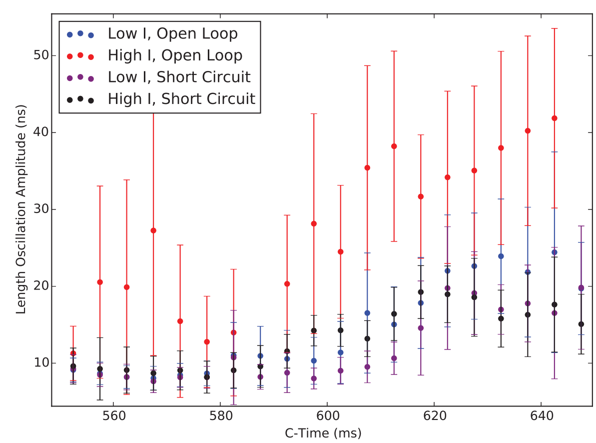

Figure 7: The measured FWHM length oscillation amplitudes (A_τ) of high (7×10^{12}) and low (2×10^{12}) intensity beams with the Finemet™ test cavity short circuited and with RF feedback loops disabled (open loop) modes.

CONCLUSION

The results presented in this paper, along with many more, were part of the decision making process for the Finemet™ upgrade of the PSB RF systems in the LIU project. As has been found the 10 cell test cavity has no significant effect on present beam stability, with the exception of very nontypical operating conditions where an increased beam excitation was observed, but crucially there was still no sign of instability. These measurements were used to validate beam dynamics simulations for after LS2, when the ferrite RF systems will be replaced with Finemet™ RF systems.

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