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Energy Matching Between Linac4 and the PSB

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Summary

Until 2018, before Long Shutdown 2, injection to the PSB was done with a coasting proton beam from Linac2, which was then captured by the RF system. With the new Linac4, this has been replaced with bunch-to-bucket injection, which requires the energy of the two machines to be well matched. This note describes the procedure applied for the energy matching.

Contents

1 Introduction

There are three parameters of interest for the energy matching. These are the synchronisation frequency, the energy of the beam extracted from Linac4, and the magnetic field in the PSB. In this case, the synchronisation frequency is fixed, and the Linac4 energy and PSB magnetic field are adapted. Fixing the synchronisation frequency is preferred as changes to it are not automatically propagated to all Linac4 systems, which requires expert intervention. Therefore, it is operationally more complex than energy and field changes.

The nominal beam energy and magnetic field for a 994 kHz revolution frequency are 160.7 MeV and 2320.5 G respectively. In practice, there is likely to be an error on the calibration of the magnetic field and the energy of the injected beam, which can be corrected using the protocol described in this note. The procedure is repeated after any change to Linac4 or the PSB that could affect the injected beam energy or the magnetic field.

Similar methods are used for energy matching between the PSB and the PS [1], and between LEIR and the PS [2]. However, these are not directly applicable to the Linac4-PSB energy matching as matching a linac to a synchrotron has different constraints, therefore a slightly different method is employed.

2 Field and Energy Offset Calculation

To compute the error in magnetic field and momentum, the beam is injected into the PSB with the RF switched off. Then, two of the standard differential relations [3] are applied

$$\frac{dp}{p} = \gamma^2 \frac{df}{f} + \gamma^2 \frac{dR}{R}, \tag{1}$$

$$\frac{dB}{B} = \gamma^2 \frac{df}{f} + \left(\gamma^2 - \gamma_{\mathrm{tr}}^2\right) \frac{dR}{R}, \tag{2}$$

where p, B, f and R are the design momentum, magnetic field, revolution frequency and mean radius respectively, γ is the relativistic factor at the design energy and γ_{tr} is the relativistic factor at transition crossing.

The frequency offset between the coasting beam and the design revolution frequency, df, cannot be directly measured. However, with design revolution frequency, f_d, and coasting beam revolution frequency, f_b, the beam will slip with time, with the change in beam position as a function of time, $d\tau/t$, given by

$$\frac{d\tau}{t} = \frac{f_d - f_b}{f_d}. \tag{3}$$

As $d\tau$ can be measured (see Section 3.2) and f_d is known, df/f is given by

$$\frac{df}{f} = \frac{-d\tau}{t}. \tag{4}$$

Then, Eq. (4) is inserted into Eqs. (1) and (2). Here, the differential form is replaced with the discrete difference form to reflect the discrete measurements used. The momentum error, Δp_{PSB}, and magnetic field error, ΔB_{PSB}, can therefore be calculated as

$$\Delta p_{\mathrm{PSB}} = p\left(\gamma^2 \frac{-\Delta\tau}{t} + \gamma^2 \frac{\Delta R}{R}\right), \tag{5}$$

$$\Delta B_{\mathrm{PSB}} = B\left(\gamma^2 \frac{-\Delta\tau}{t} + \left(\gamma^2 - \gamma_{tr}^2\right) \frac{\Delta R}{R}\right). \tag{6}$$

After inserting measurements of ΔR and $\Delta\tau$ into Eqs. (5) and (6), the error in injected beam momentum and PSB magnetic field can be determined. The field error, ΔB_{PSB}, can be directly compensated by the calibration of the magnetic field. However, Linac4 requires an energy correction, so the measured momentum error with respect to the PSB, Δp_{PSB}, must be converted to an energy offset at the exit of Linac4, $\Delta E_{\mathrm{Linac4}}$). The momentum of the incoming beam is calculated as

$$p_{\mathrm{Linac4}} = \Delta p_{\mathrm{PSB}} + p_d, \tag{7}$$

then the energy error is given by

$$\Delta E_{\mathrm{Linac4}} = \left(p_{\mathrm{Linac4}}^2 + E_0^2\right)^{\frac{1}{2}} - \left(p_d^2 + E_0^2\right)^{\frac{1}{2}}, \tag{8}$$

which is corrected by modifying the energy at extraction from Linac4 (see Section 4).

3 Application to the PSB

3.1 Measurement of ΔR

Sixteen pickups (PUs), one per section, are available in the PSB for trajectory and orbit measurements. The turn-by-turn BPM data from the first 300 turns (while the beam is still partly bunched) are used for the radial position calculation. During the injection process, an injection bump is produced in periods 1 and 16. This can be seen in Fig. 1, which shows the measured orbit with bump enabled (red) and bump disabled (blue) [4]. For this reason, the trajectories measured from BPM1 and BPM16 were removed for this calculation, preventing an incorrect Mean Radial Position (MRP) offset contribution due to the injection bump.

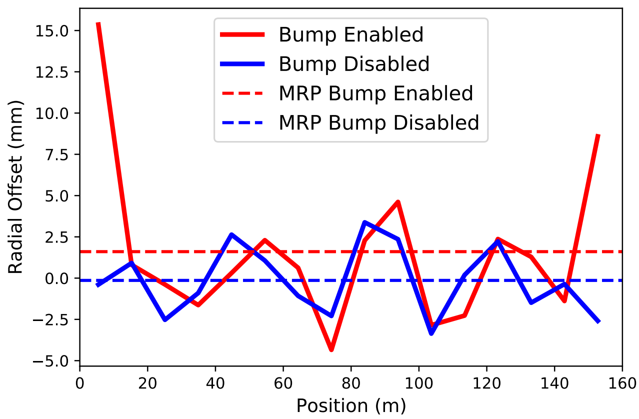

Figure 1: Measured orbit with the injection bump enabled (red) and disabled (blue). The MRP in both cases is shown by the dashed lines.

3.2 Measurement of $\Delta\tau$

The tomoscope digitisers are triggered synchronously with the revolution frequency clock. Therefore, $\Delta\tau$ can be obtained by measuring the slippage of the bunch relative to the measurement window. For simplicity, this has been done by identifying the center of the full width half maximum, which is equivalent to the center of mass when the bunch has a symmetric energy distribution. An example of the measurement of the bunch center is shown in Fig. 2. In cases where this does not give adequate precision, a more accurate measurement can be implemented.

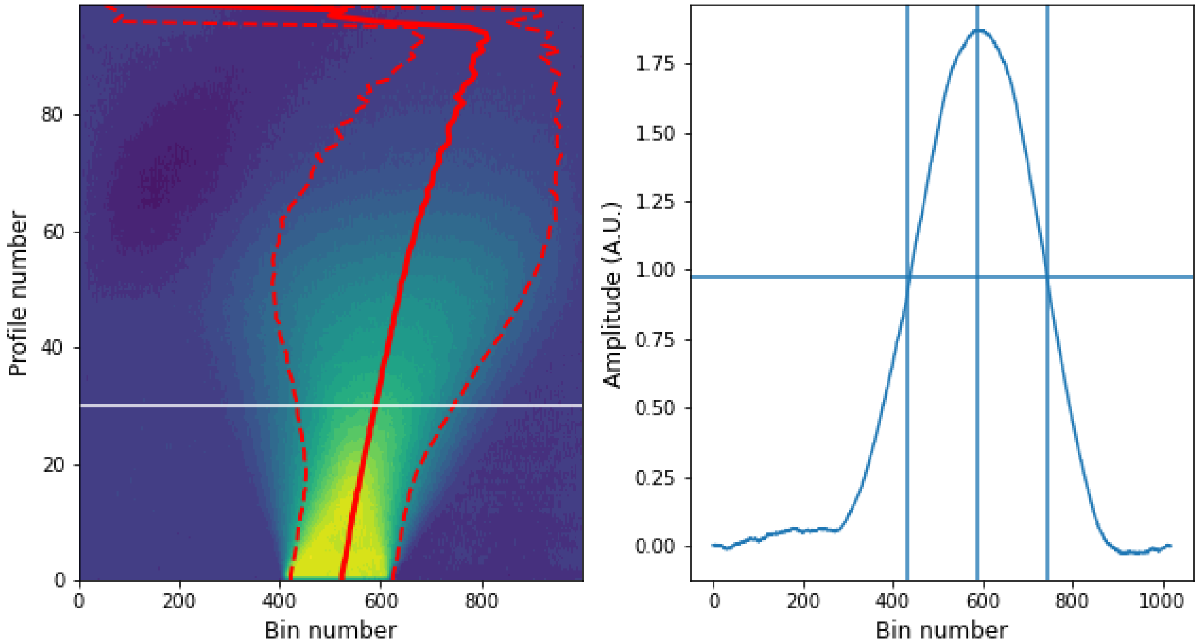

Figure 2: Left: Mountain range surface plot showing the bunch edges from FWHM (red dashed) and bunch center (red solid). The profile indicated by the white line is plotted on the right. Right: Single trace showing identification of FWHM and corresponding central point.

For each profile, the center is easily found as a function of bin number, as long as the full profile fits within the measurement window. In the example shown in Fig. 2, the bunch starts to leave the measurement window by approximately profile 60, at which point the identified center stops being valid. The measurement window here is the length of a PSB turn, therefore a longer window cannot be used without the overlap of the head and tail of the bunch starting to be seen. After removing invalid data, the time slippage can be approximated as the average change in bunch position per turn:

$$\Delta\tau = \frac{1}{N\Delta T}\sum_{n=1}^{N-1}(C_{n+1} - C_n)t_b \tag{9}$$

where N is the total number of used profiles, ΔT is the number of turns between adjacent profiles, C_n is the center bin of the n_{th} profile and t_b is the bin width in time (inverse sampling rate).

4 Energy Correction

The last pair of accelerating structures in Linac4, namely PIMS11 and PIMS12, are designed to adjust the final beam energy for longitudinal painting. For this reason, these cavities operate with a lower average voltage than the others to accommodate an amplitude modulation. Therefore, a static offset can be added to fine tune the extraction energy for energy matching. The knobs that control the peak field amplitude in all RF structures in Linac4 are calibrated in terms of the total electric field yielded by the associated cavities. Therefore, changing the amplitude knob of PIMS1112, which modifies the field in both cavities simultaneously, results in the respective beam energy change in eV.

Whenever the beam energy is corrected, the time-of-flight from PIMS12 to the debuncher changes, therefore the RF phase in the debuncher must also be corrected. The relation between the amplitude of PIMS1112 and the required change of the debuncher phase was measured as 14.2 degrees per 100 kV. The full details of phasing the linac can be found in [5].

5 Long Term Monitoring

Monitoring the energy stability from Linac4 in the longer term is desirable and cannot easily be done without injecting beam into the PSB. Further, the measurements should be available without expert intervention in either machine.

To that end, a simpler but more approximate approach can be used. Using another standard differential relation [3]

$$\frac{dB}{B} = \gamma_T^2 \frac{df}{f} + \frac{\gamma^2 - \gamma_T^2}{\gamma^2} \frac{dp}{p}, \tag{10}$$

and assuming $dB = 0$, gives a direct relationship between df and dp. Then, changing to the difference form, the relationship between Δf and Δp is given as

$$\frac{\Delta p}{p} = \frac{\gamma_T^2 \gamma^2}{\gamma_T^2 - \gamma^2} \frac{\Delta f}{f}. \tag{11}$$

Therefore, once the magnetic field has been well calibrated, an easy monitoring of the relative energy is available[1].

To allow operators to perform quick measurements of the energy matching, an Inspector panel, shown in Fig. 3, has been developed This can be used to perform periodic checks of the relative energy and shot-to-shot energy stability of the injected beam with minimal effort.

[1] In practice, the B field calibration may also change with time. Therefore, these measurements cannot be assumed to be definitive and full energy matching measurements should be performed if the matching is seen to drift.

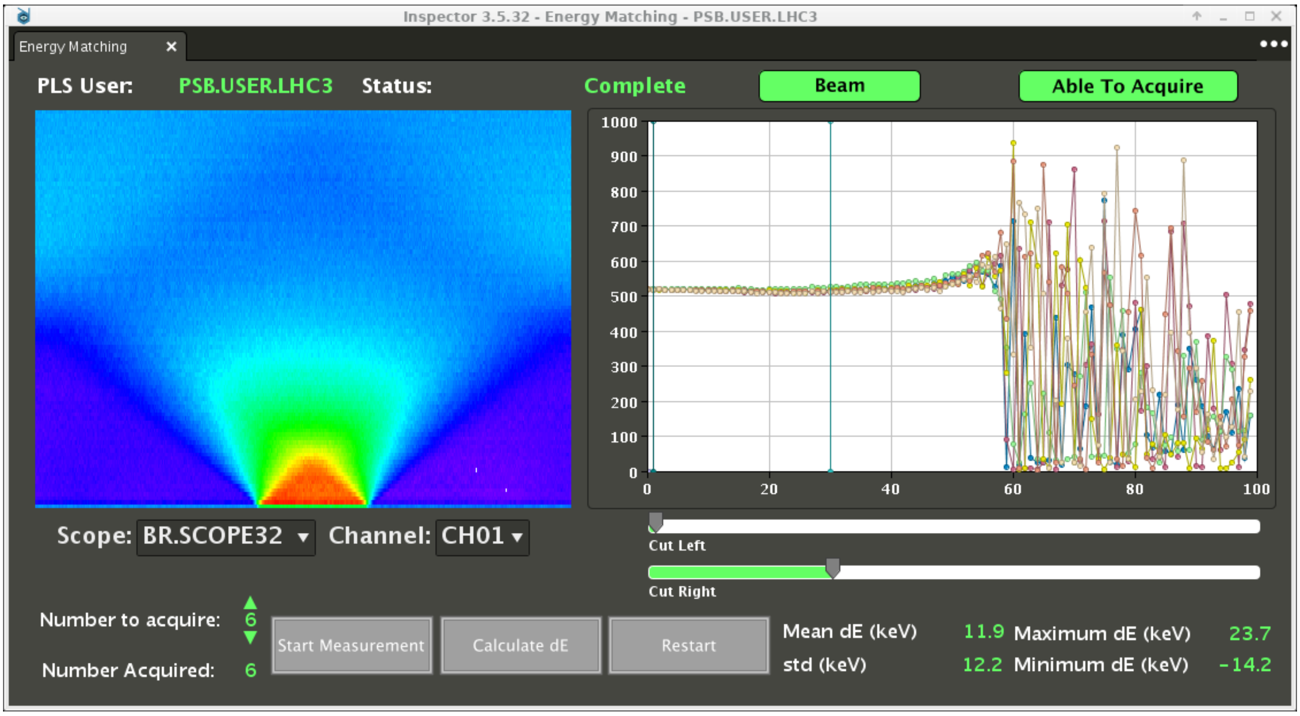

Figure 3: The Inspector panel used for quick measurements of the energy mismatch at injection.

Specific energy matching cycles have been created, with a corresponding tomoscope reference file to correctly set the data acquisition. Once the desired energy matching cycle is being played, measurements can be taken with the following steps:

1. In the tomoscope, load the energy matching tomoscope reference file.
2. Specify the OASIS scope and channel numbers used by the tomoscope, the acquired data will be shown in the left hand pane.
3. Set the number of cycles to be acquired for the measurement.
4. Press "Start Measurement".
5. After all cycles have been recorded, the detected bunch centers will be shown as a function of profile number in the right hand pane.
6. With the sliders below the measured bunch centers, select the linear part of the traces.
7. Press "Calculate dE", the results of the analysis are shown in the bottom right corner.
8. If additional measurements are required, press the "Restart" button to clear the previous result.

6 Conclusion

To optimise the PSB performance, in terms of transmission and emittance, it is essential that the energy of the injected beam be well matched. For convenience, it has been decided that the synchronisation frequency would be fixed, leaving the magnetic field and beam energy available for energy matching. By measuring the radial position and revolution frequency of the injected beam with RF off, the beam energy and magnetic field error can both be calculated and then minimised. This was done several times during and after the PSB beam commissioning phase to correct for changes in the Linac4 energy and the PSB magnetic field regulation. A simple Inspector application has been developed to allow regular monitoring of the Linac4 beam energy to detect any slow drift.

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