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BEAM EXTINCTION MEASUREMENT AT THE PIP-II INJECTOR TEST FACILITY*

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Abstract

The PIP-II particle accelerator is a new upgrade to the Fermilab accelerator complex, featuring an 800-MeV H^- superconducting linear accelerator that will inject the beam into the present Fermilab Booster. A test accelerator known as PIP-II Injector Test (PIP2IT) has been built to validate the concept of the front-end of such a machine. One of the paramount challenges of PIP2IT was to validate the bunch by bunch chopping system in the Medium Energy Beam Transport (MEBT). For PIP-II beam operations, the chopper will implement an aperiodic "Booster Injection pattern" that will roughly select two-fifth of the bunches, decreasing the beam current from 5 mA to 2 mA before injection into the cryomodules. Beam measurements have been taken by two Resistive Wall Current Monitors (RWCM) and recorded by a high bandwidth oscilloscope in order to validate the complete suppression of the chopped beam. This paper aims to present the beam extinction measurements at PIP2IT and their limitations.

INTRODUCTION

The PIP-II Injector Test facility, also called PIP2IT (see Fig. 1), is a model of what will be the Front End of PIP-II which will accelerate the H^- ion beam up to 25 MeV. The Front End is often divided into three sections: the Low Energy Beam Transport (LEBT), the Medium Energy Beam Transport (MEBT), and the High Energy Beam Transport (HEBT) which contains the superconducting RF Half-Wave Resonator and Single-Spoke Resonator cavities [1].

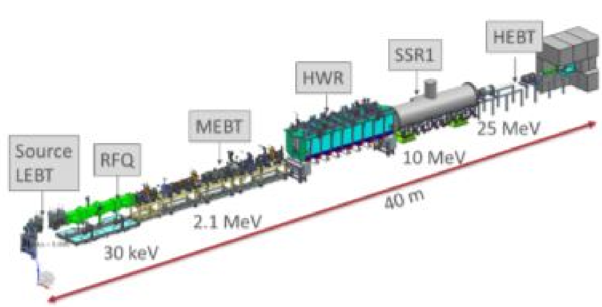

Figure 1: Sketch of PIP2IT.

At the exit of the RFQ, the beam is made of macro-pulses (typically 550 µs), each of them made of short bunches at the frequency of 162.5 MHz.

The bunch-by-bunch chopping system is the heart of the MEBT and one of the most innovative parts of the PIP-II project. The chopper is made of two electric deflectors, called kickers, that kick a pre-programmable set of bunches onto an absorber downstream. The chopper is extremely demanding from a technical perspective, as the kickers voltage reaches 500 V while having the capability to turn on or off in a few nanoseconds [2].

MEASUREMENT SCHEME

Resistive Wall Current Monitor and Cabling

The beam is chopped in the MEBT but the extinction can be measured at any location after the absorber. The data were taken with two identical Resistive Wall Current Monitors (RWCM), one at the end of the MEBT and the other one after the SRF cavities in the HEBT.

A RWCM consists of a resistive gap along a conducting pipe. Charged particles traveling in the vacuum produce a Gaussian shape image current on the surface that has equal magnitude but opposite sign. When this image current passes through the resistive gap, a voltage signal is produced. A ferrite core forces the signal to go through the resistive ring gap made of ceramic rather than allowing it to flow through other conducting paths. The impedance of the ceramic gap is 2.36 Ω (Fig. 2) [3].

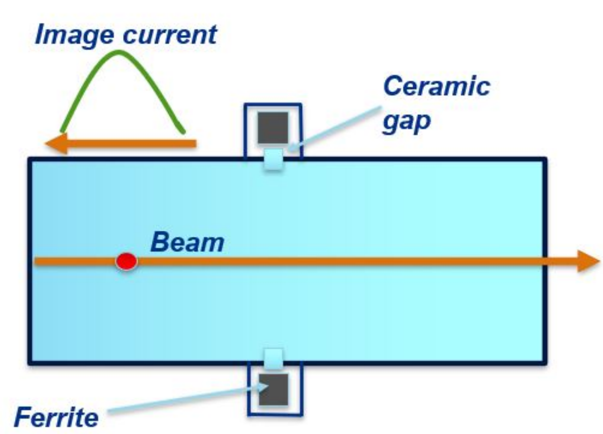

Figure 2: Schematic of the transverse slice of the RWCM.

The RWCM signals are recorded with a Rhode and Schwartz oscilloscope which has an 8 GHz bandwidth.

The same type of cables has been used for the 2 RWCM (but with different cable lengths!), with 4 different cables (including a long Heliax cable) and 5 connectors. The Heliax cable between the MEBT RWCM and the oscilloscope is 30 meters long and is 45 meters long between the HEBT RWCM and the oscilloscope.

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Extinction Calculation

The extinction measurements aim to give an estimation of the chopping extinction in the specified PIP2IT beam configurations: 550 µs pulse, 2 mA, and most importantly the Booster pattern. Only the bunches that (1) will stay stable and (2) keep an optimum longitudinal distribution at injection into the Booster, are kept in the Booster pattern [4].

Practically, we measure the charge that is left in the chopped beam by groups of successive chopped bunches that we call empty spaces. Likewise, two successive passing bunches will be analyzed together. For example, considering the 2 passing bunches followed by 3 chopped bunches, the extinction will be the ratio of the charge in the cleaned space to the charge of the two passing bunches, and normalized by the factor $\frac{2}{3}$ (Fig. 3) [5].

More generally:

$$\text{Extinction} = \frac{\text{N}_{\text{kicked}}}{\text{N}_{\text{passed}}} \frac{\int_{T_2}^{T_3} s(t)dt}{\int_{T_1}^{T_2} s(t)dt} \quad (1)$$

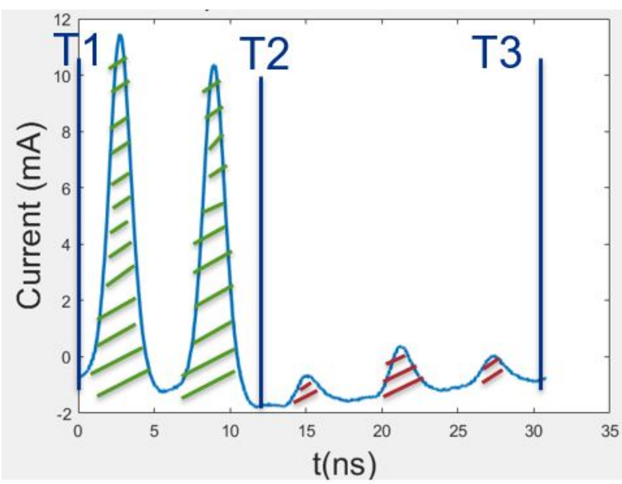

Figure 3: Extinction calculation, non-optimized trajectory (M40CY=−3 A, M50CY=1 A), data taken on March 1st 2021, with the MEBT RWCM (no averaging, 2 passing/3 kicked pattern, 10 µs pulse), Extinction=8% (inspired by D. Frolov's drawing).

ANALYSIS OF THE WAVEFORM DISTORTIONS

Understanding the distortions of the signal (baseline shift, reflections, cable dispersion...) is essential in order to make correct estimations of extinctions. Indeed, the signal left in the cleaned spaces is small (<20 µA) compared to the order of magnitude of the distortions. It is therefore necessary to correct the signal before hand.

Baseline Shift

Measuring beam in the RWCM waveform implies to know its baseline; the remaining charge is the integral of the signal above this baseline. However, knowing the baseline is not obvious in this situation. In Fig. 3 the waveform baseline goes down during the passing bunches and goes up during the cleaned spaces.

This is the consequence of the RWCM frequency response (Fig. 4). The inductance of the cores and the resistance of the gap form a high pass filter with a cutoff frequency of $\frac{R}{2\pi L}$ = 7 MHz. As a consequence, the DC component of the signal is cut and the signal needs time to reach the ground voltage when the kickers are on.

Cable Dispersion

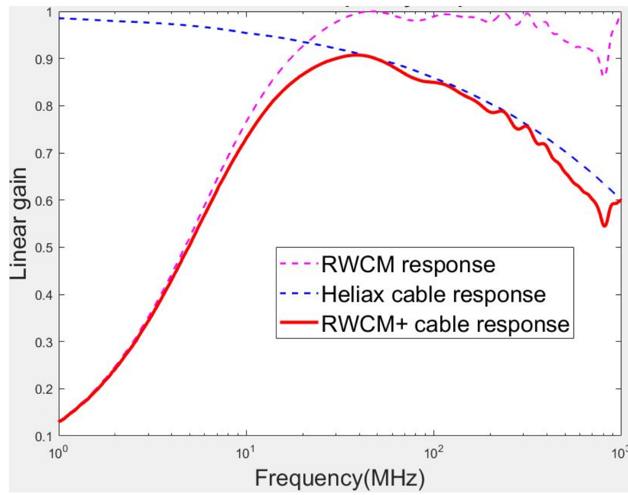

Figure 4: Frequency response of the MEBT Heliax cable (Blue dashed line), the MEBT RWCM (Magenta dashed lines), MEBT cable + RWCM (thick red line).

Dispersion is a signal distortion due to the frequency dependence of the phase velocity of the signal components in coaxial cables. The low frequency components propagate quicker than the high-frequency ones. High frequency components are also more attenuated. Therefore, coaxial cables filter the high frequencies and the beam tails spread in the cleaned spaces.

We use four different cables between the RWCM and the oscilloscope. Only the long Heliax cable significantly distorts the signal and has a cutoff frequency of 1.7 GHz.

Reflections

In addition to the distortions mentioned above, the image current created by the passing bunches is reflected and some of the reflections appear in the cleaned spaces (Fig. 5). At reflection points, a part of the signal power is reflected back to its origin instead of being carried all the way along the cable. This happens where there is an impedance mismatch (between two devices with different impedences for example). The ratio of energy between the reflected bunch and the passing bunch is $\frac{Z_2-Z_1}{Z_2+Z_1}$. RWCM waveforms contains several types of reflections: reflections at the connection between two cables, at the oscilloscope input and at the RWCM output (Fig. 6).

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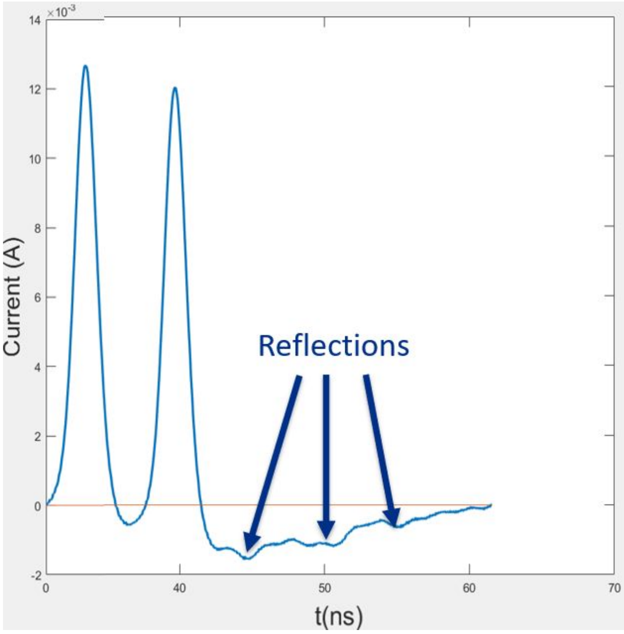

Figure 5: Reflections in the MEBT RWCM waveform with optimum tuning, data taken on March 6th, no averaging, 2 passing/3 chopped pattern, 10 µs pulse, end of pulse.

One of the principal sources of reflection is the connection between the RWCM (2.36 Ω) and the Heliax cable (50 Ω). As the evolution of the impedance between the RWCM and the oscilloscope is not monotonous, we expect both positive and negative reflections.

Figure 6: Cabling between the HEBT RWCM and the oscilloscope (inspired by D. Frolov's drawing).

In order to locate reflections, an instrument called an electrical time-domain reflectometer (ETDR) can be used to locate the points of impedance mismatch. This instrument works by sending a short pulsed signal into the cable and measuring how much time the reflection takes to return. TDR measurements have been performed on April 30th and May 3rd 2021 to locate the sources of reflection between the two RWCM and the oscilloscope. These measurements seem coherent with the set of RWCM waveforms taken during the last week of the PIP2IT run. Although the ETDR is useful to locate the reflections, it could not be used to know accurately the amplitudes of reflections that changed from a shift to another.

The reflections close to the RWCM (with longer round trip time, according to Fig. 7) arrive early in the waveform (3 and 11ns after the passing bunch for the HEBT RWCM) and the reflections close to the scope arrive later in the pulse, after a few hundreds of nanoseconds. Consequently, the beginning

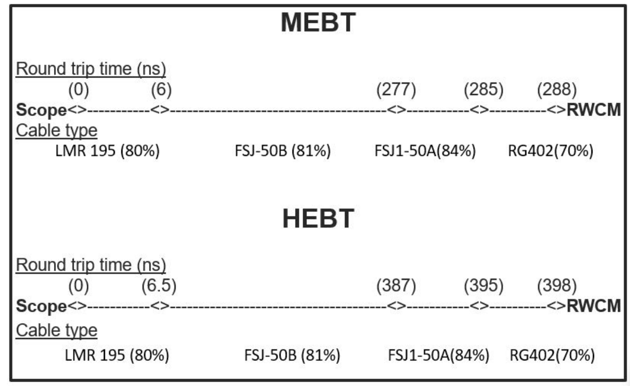

Figure 7: TDR measurements taken on May 3rd for both RWCM.

of the pulse is always cleaner with fewer reflections, and therefore, easier to analyze.

Not Explained Distortions

Despite the previous analysis, some distortions are still not explained by the day this article is written. These distortions are located right after the passing bunch and the first reflections and look like oscillations of the baseline in the HEBT waveform. Bunches in the MEBT RWCM waveforms are too wide for us to notice these oscillations. Most of these oscillations are not where the suppressed bunches are supposed to be and are likely not remaining beam. In Fig. 8, the "predicted" waveform corresponds to a simulation of the image current including only the RWCM+cable frequency response and the explained reflections [6].

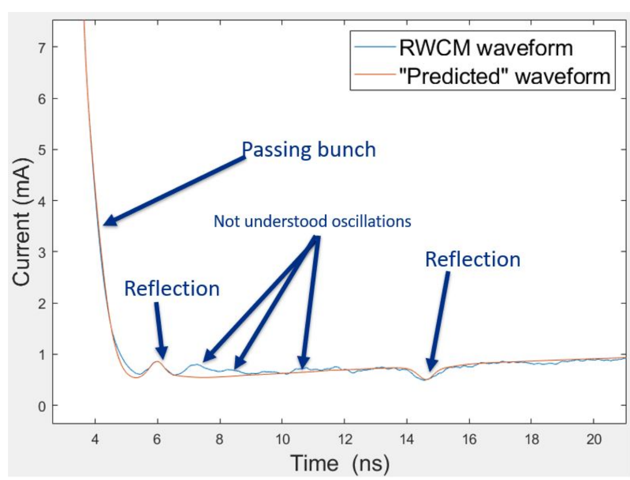

Figure 8: Close up of the not explained oscillations in the data taken on April 15th with the HEBT RWCM, averaging set at 1000, 1 passing/9 chopped pattern, beginning of pulse.

These oscillations are not due to the performance of the chopper since the bumps are not where we could expect remaining beam. The proximity of these bumps to the passing bunch and their orientation leads to the hypothesis of resonances due to the features of the pickup. Multiple reflections likely happen inside the RWCM, between the ceramic

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gaps or at the connectors. However, the TDR measurements and MicroWave studios simulations could not prove this hypothesis.

These oscillations are dominant over the oscilloscope noise during the first 6–8 ns after the passing bunch. The oscillations are damped and have a maximum amplitude of 250 µA. The precision of the extinction measurements is consequently limited during the 6-8 first nanoseconds of the cleaned spaces.

CONCLUSION

Understanding the RWCM waveform distortions is necessary in order to measure extinctions at PIP2IT since no chopped beam is visible at optimum tuning of the chopping system. In all cases, the measured extinction is consistent with zero, and the results differ by the value of the upper boundary of the uncertainty which depends on the quality of the distortions analysis. A calculation of the extinction and its uncertainty has been done in [6].

However, the estimates for the cleaned space immediately following the passing bunch have a significantly larger uncertainty. Partially it comes from the model approximation of the bunch-induced RWCM signal as Gaussian, while the actual shape is more complicated and the tail spills into the following bucket. The accurate shape has been presented in [4]. This effect is small at high energies, but can still explain the deviation between the expected baseline and the waveform in Fig. 8. In addition, there are after-pulse oscillations clearly not associated with the beam remnants but not properly explained.

ACKNOWLEDGEMENTS

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