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SLOW EXTRACTION EFFICIENCY MEASUREMENTS AT CERN SPS

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Abstract

The high efficiency of most slow extraction systems makes quantifying the exact amount of beam lost in the process extremely challenging. This is compounded by the lack of time structure in the extracted beam, as is typically required by the high-energy physics experiments, and the difficulty in accurately calibrating D.C. intensity monitors in the extraction line at count rates of ~ 1×10^{13} Hz. As a result, it is common for the extraction inefficiency to be measured by calibrating the beam loss signal induced by the slow extraction process itself. In this paper, measurements of the extraction efficiency performed at the CERN Super Proton Synchrotron (SPS) for the third-integer resonant slow extraction of 400 GeV protons over recent years will be presented and compared to expectation from simulation. The technique employed will be discussed along with its limitations and an outlook towards a future online extraction efficiency monitoring system will be given.

INTRODUCTION

The Induced Radioactivity (IR) of the slow extraction straight, Long Straight Section 2 (LSS2), is a primary concern at the high intensity and energy of the proton beam delivered for fixed target physics by the CERN SPS. In view of ever-tightening regulatory dose limits to personnel and the unavoidable need for hands-on maintenance of the extraction equipment, longer cool-down times will inevitably lead to lower machine availability at a time when the high-energy physics community is requesting ever higher intensity. Presently, an intensity of ~ 1×10^{19} protons is delivered on target per year, but future experimental proposals to search for dark matter candidates are requesting a severalfold increase [1].

The efficiency (ϵ) of the extraction process is a very important figure of merit to be able to quantify and measure during operation because the IR is directly proportional to the number of protons lost in the extraction process,

$$\mathrm{IR} \propto 1 - \epsilon \, . \tag{1}$$

The ability to accurately measure the extraction efficiency is becoming more relevant at a time when global research efforts [2] are intensifying to find loss mitigation methods to meet the demanding requests for higher intensity slow extracted beams. Accurate efficiency measurements are also important in order to compare (i) the expected performance of different extraction techniques with simulation and (ii) the state of the art performance achieved at different laboratories worldwide.

MEASUREMENT TECHNIQUES

The extraction efficiency is typically defined by the ratio of the extracted beam intensity (I_{ext}) measured in the external beam line to the intensity circulating (I_{circ}) in the synchrotron before extraction. For high efficiency, even small systematic calibration errors between the different beam intensity monitors used in the ring and transfer line become important. For systematic errors (δ) on the intensity measurements the error on the efficiency can be expanded as,

$$\frac{\delta_\epsilon}{\epsilon} = \pm \frac{\delta_{\mathrm{ext}}}{I_{\mathrm{ext}}} \mp \frac{\delta_{\mathrm{circ}}}{I_{\mathrm{circ}}} \, . \tag{2}$$

Although non-interceptive pick-ups in the ring can typically be calibrated to about 1%, the D.C. extracted beam current is too low for conventional pick-ups and the use of proportional counting devices, usually employing ionization or secondary emission, is necessitated. The calibration of such devices is challenging at count rates ~ 1×10^{13} Hz and typical calibration accuracies of only a few % can be reliably attained [3]. In addition, secondary emission monitors are sensitive to long-term drifts depending on their age and environment, e.g. temperature and vacuum pressure.

Direct Measurements

For efficient extraction systems it is common to measure non-physical values of $\epsilon > 1$ due to the systematic errors involved. This issue can be overcome by fast-extracting a known quantity of beam measured in the ring onto a proportional intensity monitor in the extraction line, assuming no beam is lost in the transfer and that all devices scale linearly when slow extracting [4]. At the SPS it is possible to fast-extract through the slow extraction channel but it requires a special extraction set-up using kickers 2.3 km upstream and at present would rely on a large scaling of intensity to guarantee the protection of the machine during the fast-extraction [5].

Indirect Measurements

As $\epsilon \longrightarrow 1$, it is more accurate to measure the extraction inefficiency ($\bar{\epsilon}$) and to infer ϵ from the relation,

$$\epsilon + \bar{\epsilon} = 1 \, . \tag{3}$$

Even relatively large systematic errors on $\bar{\epsilon}$ result in small absolute errors on ϵ. To illustrate this point, assume $\epsilon = 0.99$; a systematic error of 10% on a measurement of $\bar{\epsilon}$ yields a systematic error of only 0.1% on an indirect measurement of ϵ. The measured beam loss during extraction, which is proportional to the number of protons lost, can be calibrated and used to measure the inefficiency. The challenge is to carefully calibrate the beam loss measured on a Beam Loss

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Monitor (BLM) system to the number of protons lost. Most laboratories use beam loss measurements to quantify their slow extraction efficiency [6–12].

A common technique to calibrate BLM signals is to lose a known amount of circulating beam on the aperture in the extraction region (on the extraction septum) using a closed orbit bump. This was not attempted at the SPS due to the complicated geometry of the extraction straight, which uses several different septa over a distance of ~ 100 m, and the high energy density of the beam combined with the fragility of the Electrostatic wire Septum (ES).

FNAL Measurement Technique

Instead, a technique developed at FNAL's Main Ring (MR) [13, 14] was applied to calibrate the response of the BLM system as a function of the extraction efficiency by gently skewing the ES. The measurement concept is described schematically in Fig. 1. Equation 3 can be expressed in terms of I_{ext}, I_{circ} and the total beam loss signal summed on the BLM system,

$$\underbrace{k \frac{\sum \mathrm{BLM}}{I_{\mathrm{circ}}}}_{\bar{\epsilon}} = 1 - \underbrace{\frac{1}{C} \frac{I_{\mathrm{ext}}}{I_{\mathrm{circ}}}}_{\epsilon} \ , \tag{4}$$

where k and C are calibration constants. Once the calibration constants are determined empirically, the extraction efficiency can be measured online using the relationship,

$$\epsilon \approx 1 - kC \frac{\sum \mathrm{BLM}}{I_{\mathrm{ext}}} \ . \tag{5}$$

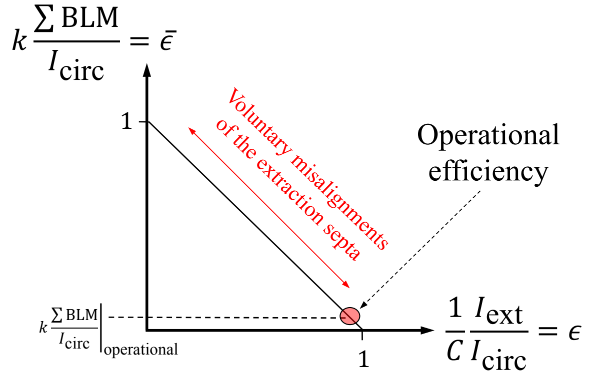
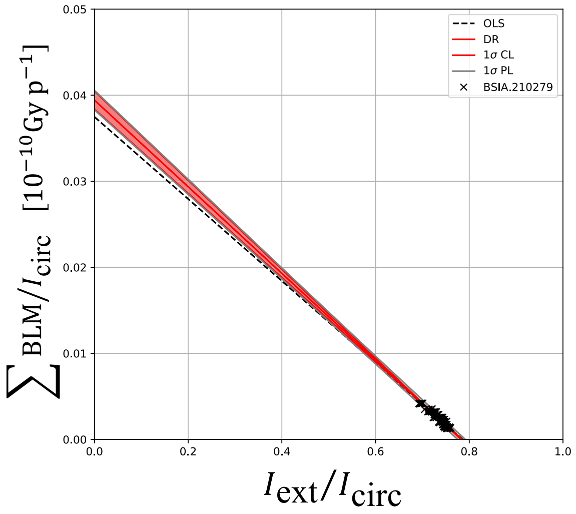


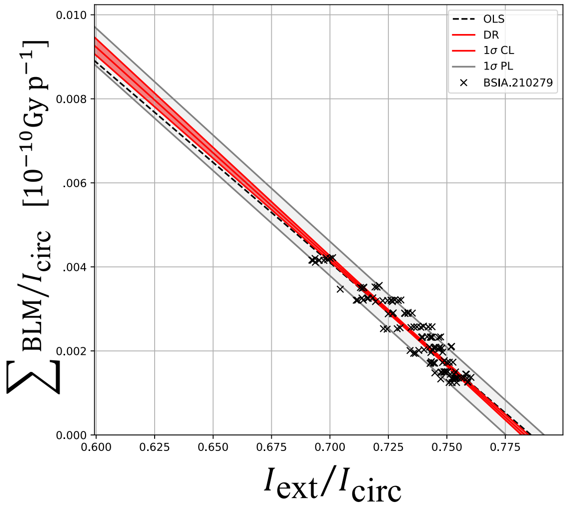
Figure 1: FNAL efficiency measurement concept [13].

RECENT MEASUREMENT RESULTS

The alignment of the ES was voluntarily skewed during dedicated measurement sessions in 2016-17 with low intensity extractions of approximately 2×10^{12} protons. The downstream end of the girder on which all 5 of the ES tanks sit was moved in steps to a maximum excursions of ~ ±1.5 mm, therefore rotating the septum by up to ~ ±100 μrad. The beam intensity in the extraction beam line was measured on a secondary emission monitor (BSI.210279) composed of titanium foils and placed into the beam approximately 200 m downstream of the ES. The results of the measurement campaigns are summarised in Table 1. An example dataset in 2017 is shown in Fig. 2 where an Ordinary Least Squares (OLS) regression analysis was performed alongside a Deming Regression (DR) (to account for errors in both scattered variables) plotted with the corresponding 1σ Confidence (CL) and Prediction Levels (PL).



(a) Large extrapolation to determine $k = (23.8 \pm 0.9) \times 10^{13}$ p$^+$ mGy^{-1}



(b) Extrapolation to determine $C = 0.78 \pm 0.005$

Figure 2: Measurement data: BSIA.210279 taken in 2017.

The inefficiency in 2016 was measured at 4.3 ± 0.8 % and improved by a factor of 20 % in 2017. The measured efficiency should be compared to the theoretical value of approximately 1.5 % computed using MAD-X, `pycollimate` [15, 16] and FLUKA [17, 18] simulations with an ES set to an effective thickness of 200 μm.

The empirical determination of k showed a strong dependence on the direction of the movement of the ES girder, which is an indictor that the changing loss profile as mea-

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Table 1: SPS Slow Extraction Efficiency Measurement Results Using BSI.210279

Year	**BSI Plate**	**Girder Scan Direction**	k **[10^{13} p^{+} mGy^{-1}]**	C **[$\frac{I_{ext}}{I_{circ}}$]**	$\epsilon = 1 - \bar{\epsilon}$ **[% $\pm \delta_{\epsilon}$]**
2016	**A**	**All data**	**24.0 ± 1.2**	**0.66 ± 0.005**	**95.7 ± 0.8**
2017	A	Towards outside ring	21.7	0.78	97.0 ± 0.6
	A	Towards inside ring	26.3	0.79	96.4 ± 0.7
	A	**All data**	**23.8 ± 0.9**	**0.78 ± 0.005**	**96.6 ± 0.7**
2017	B	Towards outside ring	21.3	0.94	97.1 ± 0.6
	B	Towards inside ring	27.0	0.93	96.4 ± 0.7
	B	**All data**	**25.9 ± 1.0**	**0.93 ± 0.005**	**96.6 ± 0.7**

sured on the BLM system is a source of non-linearity and systematic error. The quoted error on ϵ is an estimation based on the systematic variations observed in the girder scan direction, including a propagation of the errors from the regression analysis.

Measurement Limitations

In order to guarantee the protection of the ES, the beam intensity was reduced as far as possible and the girder skewed no further than to create loss levels comparable to normal high intensity operation. As a consequence, the extraction efficiency could only be voluntarily reduced by about 10% and the linearity of the extrapolation needed to determine k could not be confirmed, as illustrated by Fig. 2(a). It is worth pointing out that linearity was respected over a wide-range of efficiency in measurements made at the AGS (BNL) [9] and MR (FNAL) [13].

Unlike at FNAL, where a dedicated longitudinal (co-axial) BLM was installed on the ceiling of the accelerator tunnel, relatively far and vertically above the beam line, no dedicated longitudinal BLM is presently available in LSS2. The BLM's are well distributed but located relatively close to the beam line, in the plane of extraction (horizontal) and biased by their position on the inside of the ring. FLUKA simulations have been launched to understand the dependence of the systematic errors in the measurements on the location of BLM's in LSS2 [19].

There is a BLM on main quadrupole 218 in LSS2 that broke in 2017 and is forced into saturation during high intensity operation. These issues may have systematically increased the efficiency measurements; the impact will be checked in 2018, since it was repaired in the recent shutdown.

Calibration of Beam Intensity Monitors

The first results in 2016 identified a large discrepancy between the calibration of the BSI.210279 monitor located at the upstream end of the TT20 extraction line and the Beam Current Transformer (BCT) in the ring, i.e. $C = 0.66 \pm 0.005$. To complicate issues the BSI assembly is composed of a stack of two measurement plates (A upstream of B) with a bias plate in between [20]. To further understand the discrepancy and behaviour of the BSI, plate A was removed at the end of the 2016 physics run and installed in the TT10 transfer line between the PS and SPS, where a fast-BCT is available for cross-calibration purposes. The difference in the Secondary Emission Yield (SEY) due to the lower beam energy, which is a factor of ~ 30 below the SPS extraction energy, is expected to be negligible. The BSI plates in TT20 were replaced by two new titanium plates with a third new plate installed at position B in TT10.

The measurements in TT10 indicate that exposing the old plate to air during its displacement from TT20 to TT10 affected its SEY, which increased by about 10%. The calibration constant determined using the extraction efficiency measurements in LSS2 was confirmed with the TT10 measurements in 2017, although drifting of the SEY throughout the year was observed, as shown in Fig. 3. The measurements also confirmed a systematically higher signal of ~ 15% measured on plate B compared to A, consistent with the LSS2 measurements, with the likely explanation that secondary electrons generated on plate A reach plate B. Work is actively on-going to provide accurately calibrated intensity measurements in the extraction transfer lines.

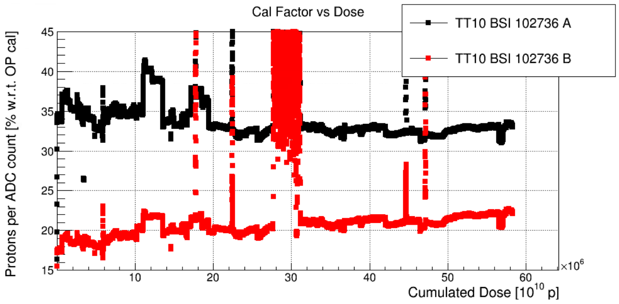

Figure 3: Measured BSI calibration factors in 2017 [21].

CONCLUSION AND OUTLOOK

Efficiency measurements of the 400 GeV proton slow extraction system at CERN SPS were presented based on a technique developed in the 1970's at FNAL. The measured efficiency is somewhat lower than expected and investigations are actively on-going to understand the source of the discrepancy [22]. In addition, large calibration errors on the transfer line intensity monitors were identified, which are far from guaranteeing a few % accuracy. An online measurement of the extraction efficiency will be implemented this year as part of the SPS Quality Control application.

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