Rates, Duty Factors, and Bunch Sizes in Mu2e Reduced Scope Scenarios

Eric Prebys

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Abstract

This note briefly summarizes rates, duty factors, and bunch issues under the most likely scenarios for a reduced scope Mu2e experiment, as well as under more speculative schemes in which beam is extracted directly from the Recycler. A general discussion of the relative merits of the schemes will be deferred to a later time. A general knowledge of the baseline beam delivery scheme is assumed throughout.

1 Introduction

The Mu2e Task Force has been charged with reducing the cost of the Mu2e experiment, by modifying the beam delivery scheme, with reductions of up to an order of magnitude in average beam intensity, if necessary. It was generally agreed that in order to achieve sufficient reduction in cost, one must at the very least eliminate the pBar Accumulator from the configuration and handle all beam conditioning with some combination of the Recycler and Debuncher.

For the moment, we are focusing two types of schemes. Each of them results in a single bunch in the Debuncher, which is resonantly extracted as before; however, the size of that single bunch varies varies between them.

The proposals are:

- "Pass-through" - in which a single Booster batch is passed directly through the Recycler to the Debuncher. There, it is captured and phase rotated into as single bunch.

- "g-2" - This scheme is based on the proposed bunch creation for the g-2 experiment. A single booster batch is injected into the Recycler, where it is divided into 4 2.5 MHz bunches. These are transferred one at a time to the Debuncher, where they are captured and slow extracted. Where exactly the final phase rotation, if any, occurs is still a matter of discussion.

Each of these schemes has a potential variant in which two Booster batches are sent to the Debuncher.

These schemes are similar in that the Accumulator has been eliminated from the configuration, as has the complex "threading" through the Recycler. In both cases, Booster batches are only in the Recycler during the 8 (out of 20) 15 Hz Booster ticks prior to the loading of the NOvA batches in each Main Injector cycle. In the "Pass-through" scheme, the batch simply passes through the Recycler without completing even a single turn. Thus, extraction could be done with a simple pulsed magnet rather than a kicker. In the "g-2" case, an extraction kicker would be required, but the specifications are not nearly as challenging as those currently in the baseline.

We have also considered more speculative proposals to extract beam directly from the Recycler. Numerous ideas have been presented, but the details are not relevant to this discussion; all involve some sort of slow extraction which results in one Mu2e bunch each Recycler period ($11.2\mu sec$). Again, we will consider the case of one or two Booster batches handled in this way.

2 Rates, Duty Factors, and Bunch Sizes

Symbol	**Definition**	**Likely Range (ms)**	**Assumed Value (ms)**
T_B	Booster "tick"	-	66.7
t_D	Time to capture and condition the beam in the Debuncher in the "Pass-through" scheme	100-500	300
t_R	Time to split Booster batch into 4 bunches in Recycler and prepare for transfer	50-160	90
t_E	Time to prepare each "g-2" bunch for extraction in Debuncher	1-10	5
t_{RO}	Time to set up for extraction in the "Recycler-Only" schemes	?	10
f	Ratio of the Recycler period to that of the Debuncher	-	6.6
T_t	Total time associated with each "g-2" bunch transferred to the Debuncher	*(calculated)*	
ϵ	Effective Duty Factor[1]	*(calculated)*	

Table 1: Definitions of symbols used in this note. Refer to figures for schematic representations.

It will be assumed in the rate estimates that the size of the individual Booster batches will be the same in all the schemes, and the same as that proposed in the baseline; namely, 4×10^{12} protons. Thus, the one and two batch schemes will provide 1/6 and 1/3 of the nominal flux, respectively. However, there are some factors which may affect this:

Scenario	Booster Batches	Duty (Factor %)	Bunch Size (% of baseline)	Ave. Rate (% of baseline)
Baseline	6	94	100	100
Pass-through	2	78	20	17
	2	25	125	33
g-2	1	43	37	17
	2	32	97	33
Recycler Only	1	6	265	17
	2	6	536	33

Table 2: Duty factors and rates for the various scenarios, using the "assumed" values in Table 1. Note that for the Recycler only scenarios, the duty factors have been corrected for the difference in bunch spacing relative to the Debuncher-based schemes. In all cases, batches of 4×10^{12} protons are assumed. The baseline values for protons/bunch and average protons/hour are 3.3×10^7 and 6.5×10^{16}, respectively.

- The "Pass-through" schemes results in a bunch in the Debuncher which is 1/3 larger than in our current baseline, and it's possible that this could cause some problems and we would have to reduce the batch size somewhat, resulting in a further reduction in total flux. Running with the same bunch size as the baseline would reduce total flux to 1/8 or 1/4 of the current baseline for the one and two batch cases, respectively.
- Conversely, in the"g-2" schemes, the bunch in the Debuncher is only 1/3 the size of that in our current baseline. That, along with the elimination of the complex beam manipulations in the Accumulator might allow us to run with slightly larger Booster batches. This could result in an increase on the order of 20% over the nominal flux ratios.

Possible implications to batch size for the Recyler-only schemes are unknown at this time.

In subsequent discussions, the maximum duty factor/minimum instantaneous rate will be presented, based on the assumed values of various setup times. In all cases, a higher instantaneous rate could be produced if required by the instrumentation controlling the slow extraction.

The details of the individual schemes are discussed below. The definitions and values of the key symbols are shown in Table 1. The bunch sizes and average beam rates are shown in Table 2, where they are expressed as a percentage of the baseline values of 3.3×10^7 protons/bunch and 6.5×10^{16} protons/hour, respectively.

2.1 "Pass-through" Scheme

This is conceptually the simplest scheme and that which results in the lowest instantaneous rate. As shown in Figure 1, a single Booster batch simply passes through the Recycler and is injected into the Debuncher. In the Debuncher, it's captured, bunched into a single bunch, and prepared for slow extraction, which can in principle take up the entire remainder of the supercycle. Thus, the minimum duty factor will be

$$\epsilon = 1 - \frac{t_D}{20T_B}$$

where T_B is the cycle time of the Booster and t_D is the total setup time in the Debuncher, including bunching time and setup for slow extraction.

The two batch version of this scheme is illustrated in Figure 2. The second Booster batch is delivered on the eighth Booster tick, just before the first NOvA batch, so there is a gap between the two batches of 7 Booster ticks, leading to a duty factor of

$$\epsilon = \frac{2(7T_b - t_D)}{20T_B} = \frac{7}{10} - \frac{1}{10}\frac{t_D}{T_B}$$

We see that in this scheme, the instantaneous rate is strongly dependent on the setup time in Debuncher (t_D). It is the only case where that rate is higher than the baseline for the assumed parameters.

2.2 "g-2" Scheme

In this scheme, a Booster batch is injected into the Recycler, where it's split into 4 2.5 MHz bunches. Each of these is individually extracted to the Debuncher, where it is slow extracted. Whether the final bunch rotation is done in the Recycler or the Debuncher is a detail which has not been finalized at this time.

The transfer of particles from the Recycler to the Debuncher occurs asynchronously to the Booster clock, as shown in Figure 3. Thus, the first bunch can be transferred as soon as they are created (t_R), and the fourth just before the first NOvA batch appears. The time associated with each bunch (T_t) is then

$$T_t = \frac{8T_B - t_R}{3}$$

Each bunch will take some time (t_E) to condition in the Debuncher, so the duty factor will be

$$\epsilon = \frac{4(T_t - t_E)}{20T_B} = \frac{8}{15} - \frac{1}{15}\frac{t_R}{T_B} - \frac{1}{5}\frac{t_E}{T_B}$$

The two batch version is illustrated in Figure 4. Following the same logic as before, the time associated with each transfer to the Debuncher is

$$T_t = \frac{8T_B - 2t_R}{6}$$

and the duty factor will be

$$\epsilon = \frac{8(T_t - t_E)}{20T_B} = \frac{8}{15} - \frac{2}{15}\frac{t_R}{T_B} - \frac{2}{5}\frac{t_E}{T_B}$$

2.3 Recycler-only Schemes

We have investigated the possibility of extracting beam directly from the Recycler to the experiment, without using the pBar enclosure at all. There are several proposals for doing this, but the differences are not relevant to this discussion. Recycler-only time lines for the one and two batch cases are shown in Figure 5.

There are many advantages to doing this, but one *disadvantage* is that that in all techniques considered, the bunch spacing will be equal to the Recycler period of $11.2\mu sec$, and thus no longer optimized for the experiment.

This makes the concept of "duty factor" somewhat problematic when comparing the Recycler-only schemes to those involving the Debuncher, as the latter all have the same bunch spacing as our current baseline. Because the number of interest to the experiment is the number of protons per bunch on the production target, we will adopt the convention of quoting an "effective" duty factor, which is the fraction of time beam is being delivered divided by the ratio of the Recycler period to that of the Debuncher ($f \equiv 11.2/1.7 = 6.6$).

The effective duty factor for the single batch case thus becomes

$$\epsilon = \frac{1}{f}\frac{(8T_B - t_{RO})}{20T_B} = \frac{1}{f}\left(\frac{2}{5} - \frac{1}{20}\frac{t_{RO}}{T_B}\right)$$

and the two batch case is

$$\epsilon = \frac{1}{f}\frac{2(4T_B - t_{RO})}{20T_B} = \frac{1}{f}\left(\frac{2}{5} - \frac{1}{10}\frac{t_{RO}}{T_B}\right)$$

We see in Table 2 that this leads to intensities per bunch that are significantly higher than the baseline, which may be a problem. It's possible that variations might exist wherein a single booster batch is distributed around the Recycler and extracted from multiple points simultaneously, but given the speculative nature of the proposed schemes, introducing an added level of complexity at this point does not appear prudent.

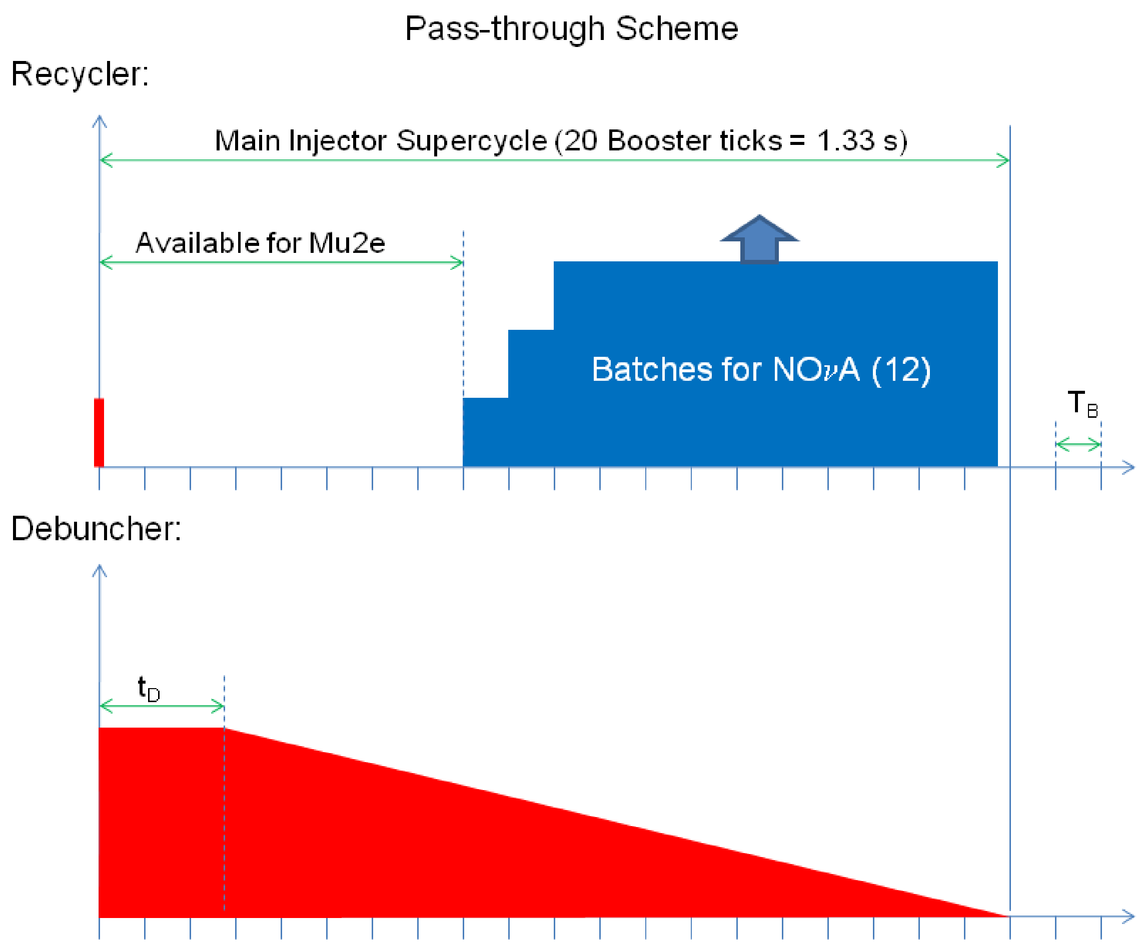

Figure 1: Pass-through scheme, in which one batch is passed through the Recycler and then bunched in the Debuncher.

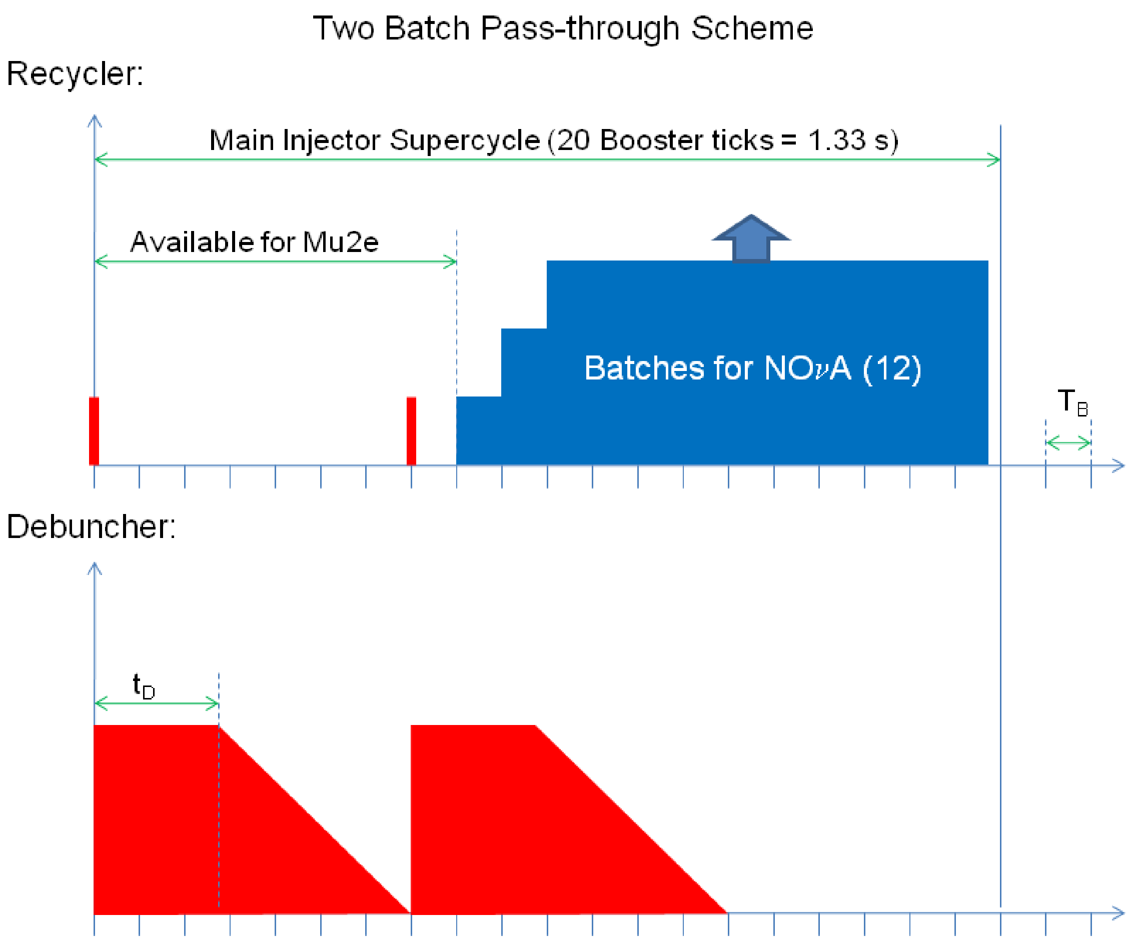

Figure 2: Two batch version of the pass-through scheme.

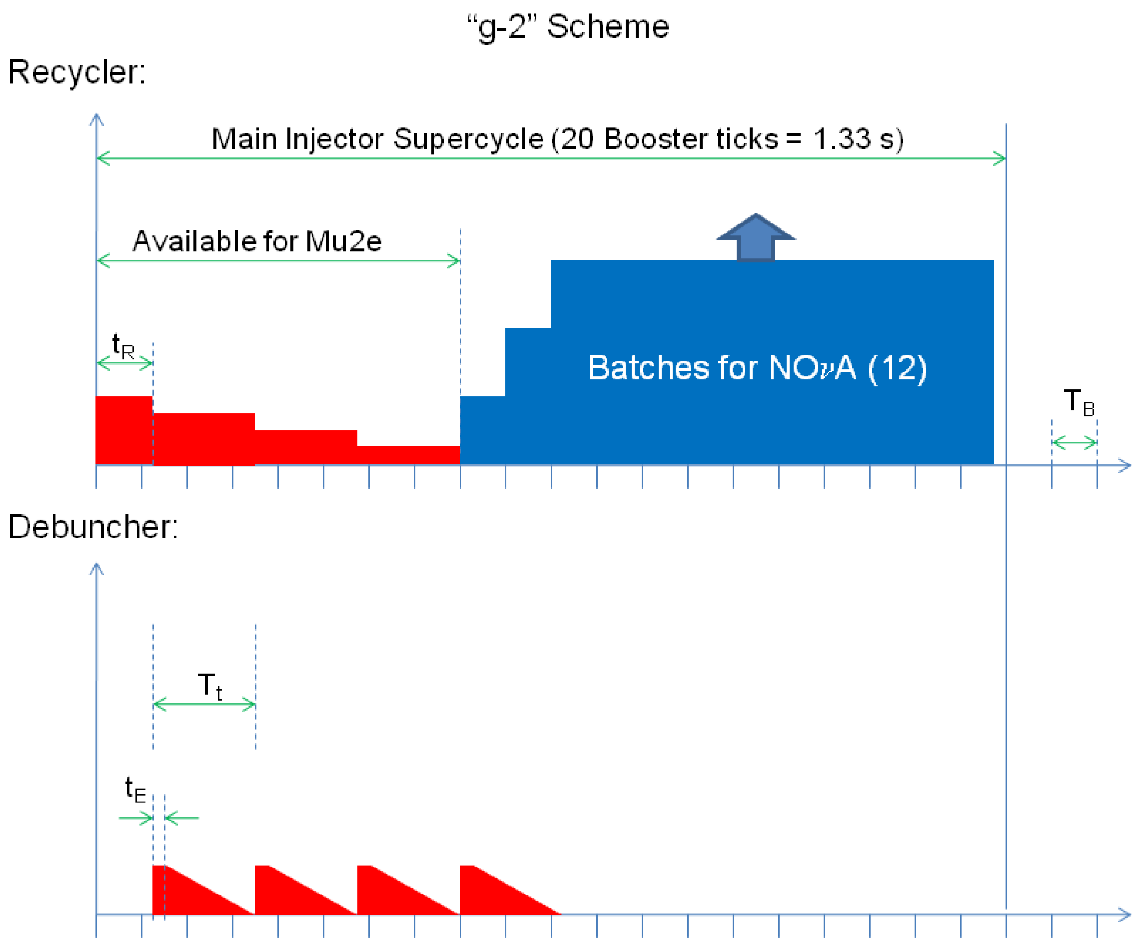

Figure 3: "g-2" Scheme, in which a Booster batch is stored in the Recycler and divided into four bunches, which are transferred individually to the Debuncher.

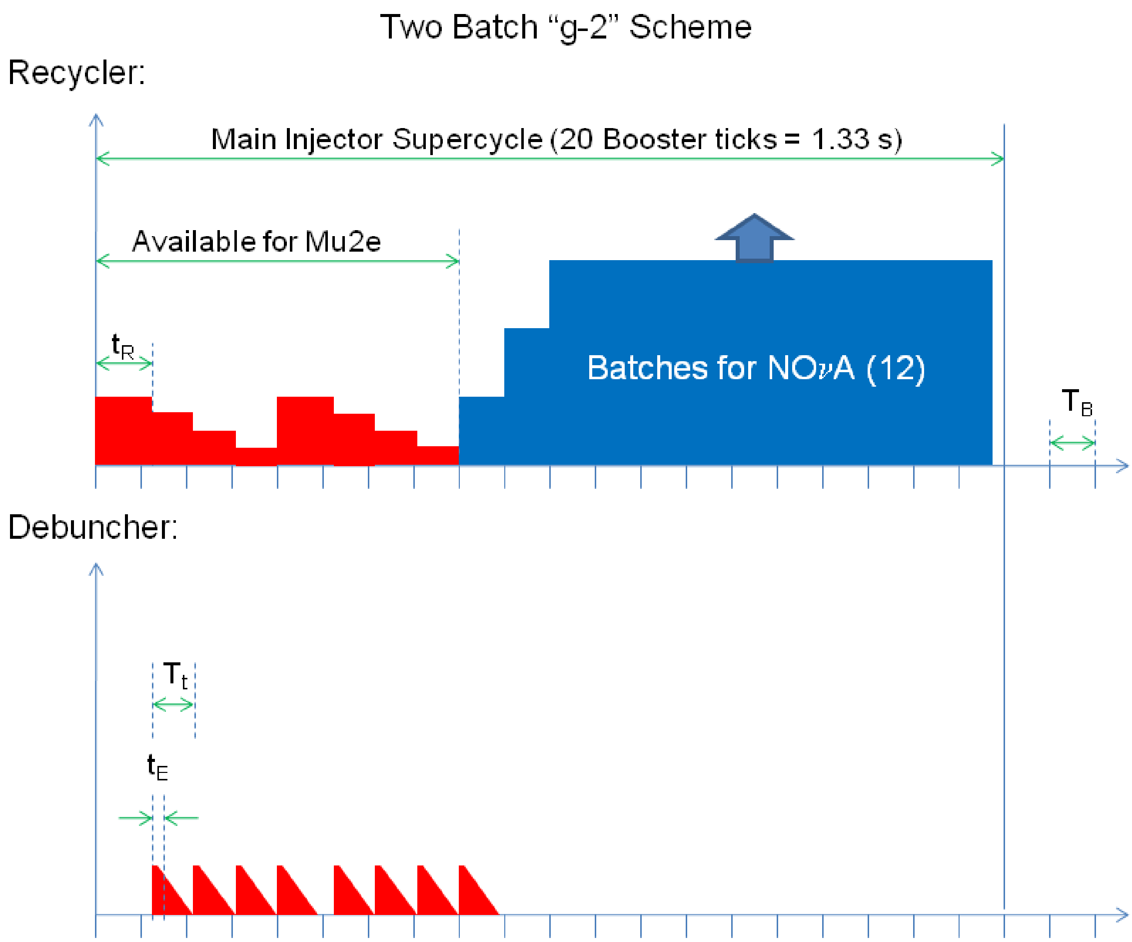

Figure 4: Two batch version of the "g-2" Scheme.

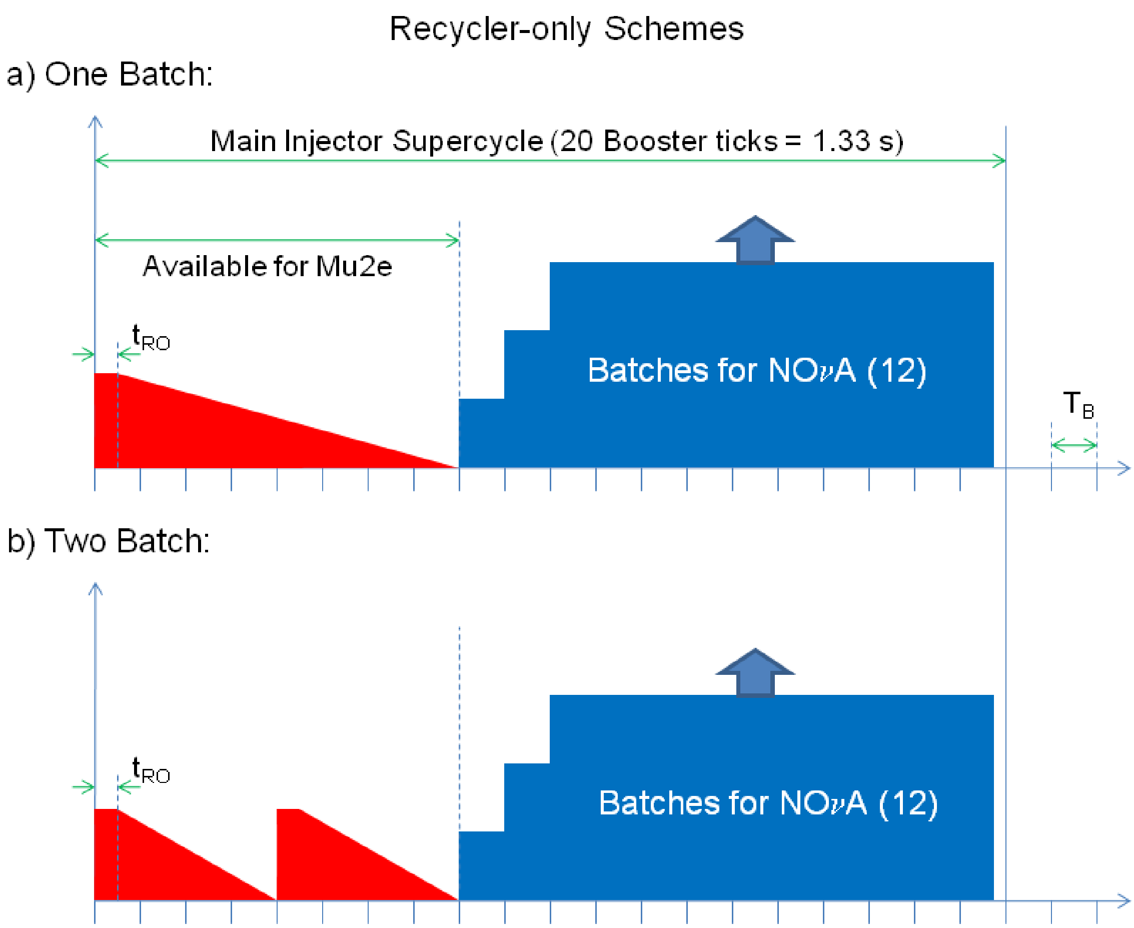

Figure 5: Time line for beam extraction directly from the Recycler.