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SPS Operation and Future Proton Sharing Scenarios for the ECN3 facility

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Summary

In the framework of the Physics Beyond Colliders (PBC) study, a future high intensity facility at the existing ECN3 experimental hall of the North Area (NA) complex is under study [1]. A task force is investigating ECN3 intensity upgrade scenarios concerning beam delivery and related infrastructure, considering solutions compatible with consolidation plans and post-LS3 experimental scenarios [2]. As input to this study group, the sharing scenarios for the amount of protons on target (PoT) delivered to such a future high intensity fixed-target facility and the existing North Area experiments are presented in this report. Based on demonstrated Super Proton Synchrotron (SPS) performance for CERN Neutrinos to Gran Sasso (CNGS) and the recent SPS performance for fixed target beams following the successful completion of the LHC Injectors Upgrade (LIU) project [3], the expected proton sharing between the TCC2 targets and ECN3 is estimated. AWAKE and HiRadMat are taken into account in the future supercycle composition while the maximum possible power dissipation of the SPS magnets is respected. In the note it is also assumed that measures will be taken to address beam loss and activation at extraction and transfer compatibly with the transmission efficiency presented here [4]. Finally, also considerations on power consumption are made for the different operational scenarios.

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1 Introduction

In the framework of the Physics Beyond Colliders (PBC) study, a future high intensity facility at the existing ECN3 experimental hall of the North Area complex is under study [1]. A task force has been formed in order to investigate ECN3 intensity upgrade scenarios concerning beam delivery and related infrastructure, considering solutions compatible with consolidation plans and experimental proposals for operation after the upcoming Long Shutdown 3 (LS3) of the accelerator complex at CERN [2]. As input to this study group, the proton sharing scenarios for such a future high intensity fixed target facility and the existing North Area experiments have been studied.

A detailed study of the future proton sharing scenarios had already been performed in the context of the proposed Search for Hidden Particles (SHiP) experiment, as reported in [5]. In 2018, this study was refined taking into account the more recent operational experience in terms of machine time usage and Super Proton Synchrotron (SPS) users, supercycle compositions, limitations from activation and recent progress in loss reduction for the SPS slow extraction on the third order resonance achieved in machine development (MD) studies, as reported in [6]. Here, we present another update of the future proton sharing scenarios, taking into the performance of the CERN accelerators after the implementation of the LHC Injectors Upgrade (LIU) project [3]. The scope is extended to a variety of different scenarios of potential high intensity experiments in the ECN3 experimental hall, with different requirements on maximum proton flux and spill duration. Furthermore, considerations and estimations on power consumption for the different operational scenarios are made.

2 SPS intensity reach for slow extracted beams

2.1 SPS intensity reach

The maximum beam intensities accelerated so far and extracted from the SPS (peak values) in the last 25 years together with the peak operational parameters from the 2018 and the 2022 runs are listed below (ppp stands for protons per pulse and the duration in seconds quoted in parenthesis correspond to the cycle lengths):

- 4.8×10^{13} ppp (1997 - slow and fast slow extraction - 9.6 s - 450 GeV/c)
- 4.5×10^{13} ppp (2008 - CNGS - fast extraction - 6.0 s - 400 GeV/c)
- 4.0×10^{13} ppp (2009 - slow extraction - 15.6 s - 400 GeV/c)
- 3.5×10^{13} ppp (2018 - slow extraction - 10.8 s - 400 GeV/c)
- 4.2×10^{13} ppp (2022 - slow extraction - 10.8 s - 400 GeV/c)

The intensity reach for fixed target beams from the SPS was studied in the past in preparation of the CERN accelerator complex serving the CERN Neutrinos to Gran Sasso (CNGS) facility [7]. The maximum intensity accelerated in the SPS during MDs (but not extracted) has been 5.3×10^{13} ppp (2004) [8]. The main intensity limitation for these beams was identified to come from losses in the PS and SPS. In particular, losses were occurring at PS-to-SPS transfer due to the extraction process and in the SPS itself due to vertical aperture and radiofrequency (RF) power limitations.

To mitigate the losses at PS extraction, the "Continuous Transfer" (CT) [9] scheme in which the beam was split by the extraction septum was replaced by the "Multi-Turn-Extraction" (MTE) [10] scheme in which the beam is split magnetically. This scheme is used operationally since 2015 and allowed reducing activation levels in the PS extraction region significantly [11]. Until 2018, the maximum intensity used operationally with MTE has been about 3.5×10^{13} ppp in the SPS. A beam intensity of 4.0×10^{13} ppp could be accelerated in the SPS in a high-intensity test (2017) [12]. During this test no particular issues were encountered related to the high beam intensity in combination with the MTE. The fact that the beam transmission in the SPS was degrading with intensity is mostly related to the increase of the vertical emittance proportional to intensity (due to the beam production in the PSB) and particles lost at the vertical aperture of the SPS. With the connection of Linac4 to the PSB during the second long shutdown (LS2) as part of the LIU project, the vertical emittance of the fixed target beam has been reduced by up to a factor two, which improved the beam transmission in the SPS. In addition, the SPS RF system received a major upgrade as part of the LIU project and thus more RF power is available. This further increased the intensity reach for fixed target beams in the SPS. In 2022, i.e. the second operational year after LS2, the North Area experiments requested high intensity beam delivery and the SPS routinely operated with intensities of about 4.2×10^{13} ppp with a beam transmission of about 95% or higher [13]. Furthermore, losses at PS extraction could be even further reduced by implementing a barrier bucket in the PS in combination with the MTE [14, 15].

A summary of the SPS intensity records is shown in Fig. 1. A beam intensity of 4.2×10^{13} ppp can be safely assumed as future average intensity accelerated in the SPS with the MTE deployed in the PS.

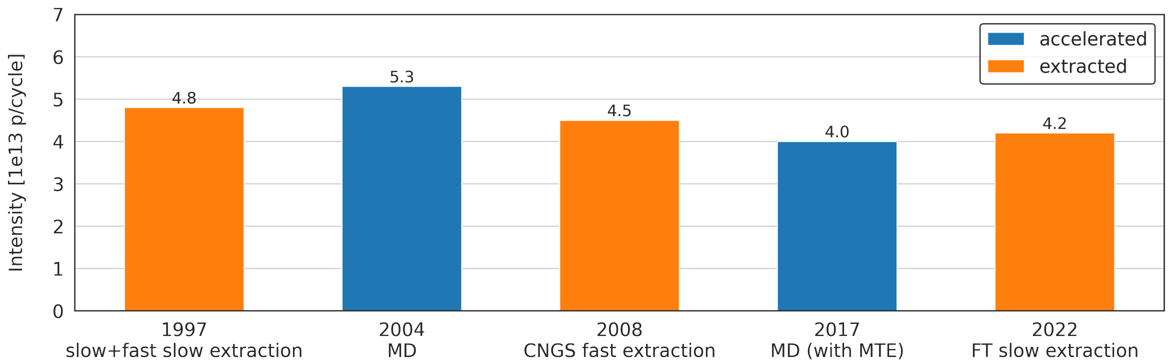


Figure 1: Intensity per cycle achieved in the SPS.

3 Proton sharing

3.1 SPS cycles and time sharing

The SPS is a cycling machine serving different users from cycle to cycle according to a programmable sequence, which is called *supercycle*. In its present configuration, the SPS delivers beam to the LHC, the North Area, the Advanced WAKEfield Experiment (AWAKE) and the High-Radiation to Materials (HiRadMat) experimental facility. In addition, a rich program of MD studies are carried out in order to improve the machine performance and prepare for future beam requests. Table 1 shows a representative selection of cycles used during SPS operation in 2022, together with the cycles considered for the ECN3 study. In particular, a dedicated cycle for ECN3 is denoted as "ECN3_D" while the cycle for all the NA targets is denoted as "SFTPRO". Different flat-top (FT) lengths are considered as specified in parentheses. Note that it is not possible to inject any beam on the "Zero" and the "deGauss" cycles. The latter is typically placed in front of a NA fixed target cycle ("SFTPRO" or "ECN3_D") to achieve reproducible magnetic behaviour of the machine for optimising transmission and slow extraction conditions. The parallel MD cycle has a short flat bottom for measurements (about 3 s) and a short ramp to 200 GeV/c to establish the magnetic reference in the main magnets for the cycle after (typically the NA cycle).

	Cycle duration [s]	Average power (MB+MQ) [MW]
AWAKE	7.2	31.19
HiRadMat	24.0	17.52
ECN3_D (1.2 s)	7.2	34.88
ECN3_D (2.4 s)	8.4	44.84
ECN3_D (4.8 s)	10.8	52.83
ECN3_D (9.6 s)	15.6	63.60
SFTPRO (4.8 s)	10.8	52.83
SFTPRO (9.6 s)	15.6	63.60
LHC filling	24.0	18.03
LHC pilot	13.2	32.50
MD dedicated	24.0	18.03
MD parallel	7.2	2.81
Scrubbing	24.0	18.03
Zero	1.2	0.10
deGauss	3.6	4.77
deGauss (10.8 s)	10.8	2.69

Table 1: Representative selection of cycles used during SPS operation in 2022, together with the cycles considered for the ECN3 study. Cycle duration (in seconds) and resistive average power dissipated in the main dipoles (MB) and main quadrupoles (MQ) (in MW) during the cycle are listed. The power values are calculated using the Super Cycle Load application [16].

The maximum acceptable average resistive power dissipated in the main dipole magnets for the SPS is 36.5 MW, while the total average power for the main dipoles and main quadrupoles is 41.1 MW. The last column of Table 1 shows an estimation of the average power dissipated in the main dipoles (MB) and main quadrupoles (MQ) (in MW) during each cycle. The above-mentioned constraint limits the possible supercycle compositions. Finally it should be mentioned that there are limitations in the NA secondary beam lines infrastructure that have to be taken into account. For example, NA cycles with a FT of 9.6 s need to be followed by a period of 10.8 s with no current in the NA circuits in order to respect these constraints.

We consider the 2018 operational run as a representative reference for the amount of time spent in each of the supercycle configurations. A list of the supercycles used during 2018 operation is shown in Table 2. In both tables the quoted power corresponds to the sum of the average power in the main dipoles and main quadrupoles during the supercycle.

	AWAKE	HiRadMat	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	TCC2	Zero	deGauss	Supercycle duration [s]	Average Power (MB+MQ)[MW]
AWAKE	2	-	-	-	-	-	-	2	-	2	43.2	37.60
AWAKE with parallel MD	2	-	-	-	-	2	-	2	-	-	50.4	32.40
Dedicated MD	-	-	-	-	1	-	-	-	-	-	22.8	16.83
HiRadMat	-	1	-	-	-	-	-	1	-	1	37.2	26.10
LHC filling	-	-	1	-	-	-	-	1	-	1	37.2	26.10
LHC setup	-	-	-	1	-	-	-	1	6	2	37.2	26.48
Physics	-	-	-	-	-	-	-	2	-	2	28.8	40.79
Physics with parallel MD	-	-	-	-	-	2	-	2	-	-	36.0	32.87
Scrubbing	-	-	-	-	-	-	1	1	-	-	33.6	28.39
Thursday MD	-	-	-	-	1	-	-	1	-	-	33.6	28.39

Table 2: SPS supercycles used during the 2018 proton run.

To calculate the number of cycles during proton operation and number of protons to the NA targets, the time sharing between the different supercycle configurations during the operational proton run has to be taken into account. The 2018 machine schedule included a proton run scheduled over 31 weeks, with two planned technical stops of 30 hours, followed by an ion run over 4 weeks. The 2018 proton run consisted of 5148 hours machine time allocated for operation. The time sharing between the different SPS users as obtained from the 2018 injector schedule is summarised in Table 3. The left column shows the bare hours for which the corresponding supercycle (cf. Table 2) was scheduled. The right column shows the effective hours expected taking into account the LHC filling and LHC setup periods. Based on these numbers, the total number of cycles per user over the entire run is obtained.

	Scheduled [hours]	Effective [hours]
Physics	1852.00	1389.00
Physics with parallel MD	1356.00	1017.00
HiRadMat	240.00	180.00
AWAKE with parallel MD	265.51	199.13
AWAKE	742.49	556.87
Dedicated MD	370.00	277.50
Scrubbing	72.00	54.00
Thursday MD	250.00	187.50
LHC filling (15% of time)	-	772.20
LHC setup (10% of time)	-	514.80
Total	5148.0	5148.0

Table 3: SPS supercycle sharing during proton operation in a machine run including proton and ion operation. Proton operation extends over 31 weeks including two times 30 hours for technical stops (time sharing of 2018).

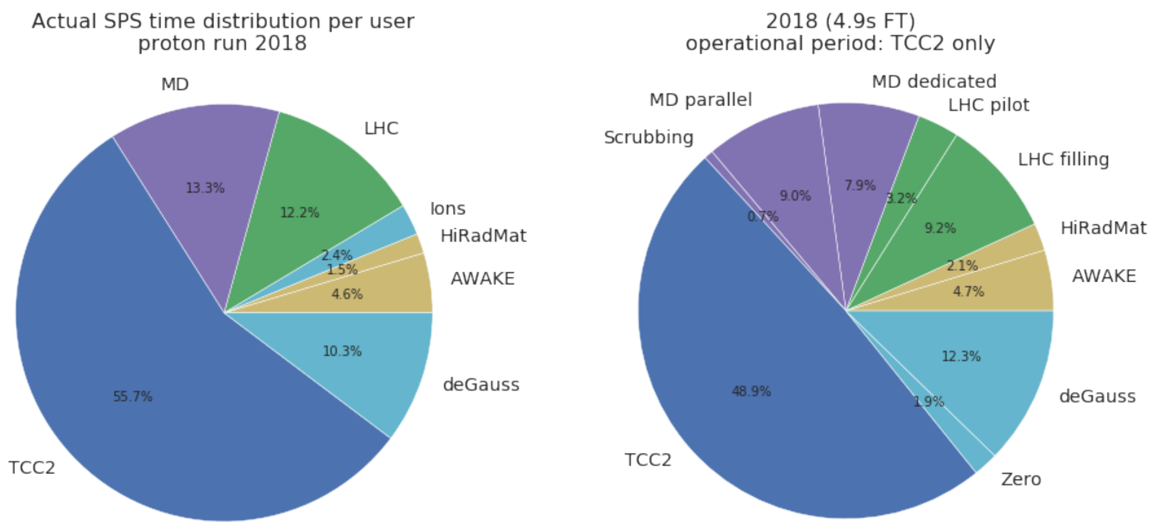


Figure 2: Distribution of the actual machine time sharing in 2018. Data, provided by J. Dalla-Costa (left), are compared to the expectation from schedule (right).

Figure 2 shows the sharing of the SPS machine time per user comparing the actual numbers from 2018 (left) with the expected values obtained from the analysis described above (right). The agreement is very good, thus validating the approach. Small differences are explained by the fact that the ion setting up was not included explicitly in the schedule and the NA cycle ("TCC2") was played slightly more frequently compared to schedule as it was present in the supercycle during some dedicated MDs (without taking beam). In all the future proton sharing scenarios that will be considered, the time percentages for each user are preserved and will be roughly similar to the ones of Figure 2.

A machine run with only proton operation will also be considered in all scenarios. In

	Scheduled [hours]	Effective [hours]
Physics	2332.0	1749.00
Physics with parallel MD	1548.0	1161.00
HiRadMat	240.0	180.00
AWAKE with parallel MD	268.1	201.08
AWAKE	739.9	554.92
Dedicated MD	370.0	277.50
Scrubbing	72.0	54.00
Thursday MD	250.0	187.50
LHC filling (15% of time)	-	873.00
LHC setup (10% of time)	-	582.00
Total	5820.0	5820.0

Table 4: SPS supercycle sharing for a machine run including only proton operation. Proton operation extends over 35 weeks including two times 30 hours for technical stops.

the absence of an ion run, the proton operation extends to 35 weeks including two times 30 hours for technical stops. The time sharing between the different SPS supercycles for this case is summarised in Table 4.

3.2 Transmission considerations

For estimating the number of PoT and the protons per spill (p/spill) delivered to the targets, a set of transmission coefficients are assumed. These are mostly based on experience in typical operational conditions in the SPS and the experimental areas. For the beam transfer to TCC8, FLUKA studies have been performed [17]. The transmission coefficients are summarized in Table 5. Furthermore, a machine availability of 80% is considered, which is a realistic number.

	SFTPRO/TCC2	SFTPRO/TCC8–T4 in beam	ECN3_ D/TCC8–T4 bypassed
Extraction	0.98	0.98	0.98
TT20	0.99	0.99	0.99
Splitting	0.95	0.95	1.0
T4	-	0.78-0.94	0.98
P42	-	0.97	0.99
Total	0.922	0.697-0.840	0.941

Table 5: Assumed transmission coefficients.

Presently the TCC2 targets are served simultaneously with SFTPRO cycles by splitting the extracted beam by means of two Lambertson septa (splitter magnets) in the TT20 transfer line from the SPS to the targets (see Fig. 3–top). The corresponding transmission coefficients to determine the PoT on the TCC2 targets are listed in the first column (SFTPRO/TCC2) of Table 5. In this mode of operation (which is referred to as "shared

ECN3 operation"), the TCC8 target, serving ECN3, receives the fraction of the beam delivered to T4 which is not interacting with the target via the P4 and P42 lines (simultaneously to the other beam lines H2, H4, H6, H8 and M2). The remaining fraction of the beam interacting on T4 serves the H6 and H8 secondary lines. The transmission coefficients to estimate the PoT delivered to TCC8 are listed in the second column (SFTPRO/TCC8–T4 in beam) of Table 5. A new mode of operation (which is referred to as "operation with dedicated ECN3 cycle") can be conceived where beam is transported through TT20 and TCC2 and delivered exclusively to TCC8. This scenario assumes that the primary beam can be cleanly transported without splitting in TT20 to the T4 target station bypassing the target with a trajectory bump (see Fig. 3–bottom). No other NA experiment can receive beam when a dedicated ECN3 cycle is played. The corresponding transmission coefficients are listed in the third column (ECN3_D/TCC8–T4 bypassed) of Table 5. Table 6 summarizes the intensity requirements for the proposed experiments ECN3 in case of dedicated and shared operation.

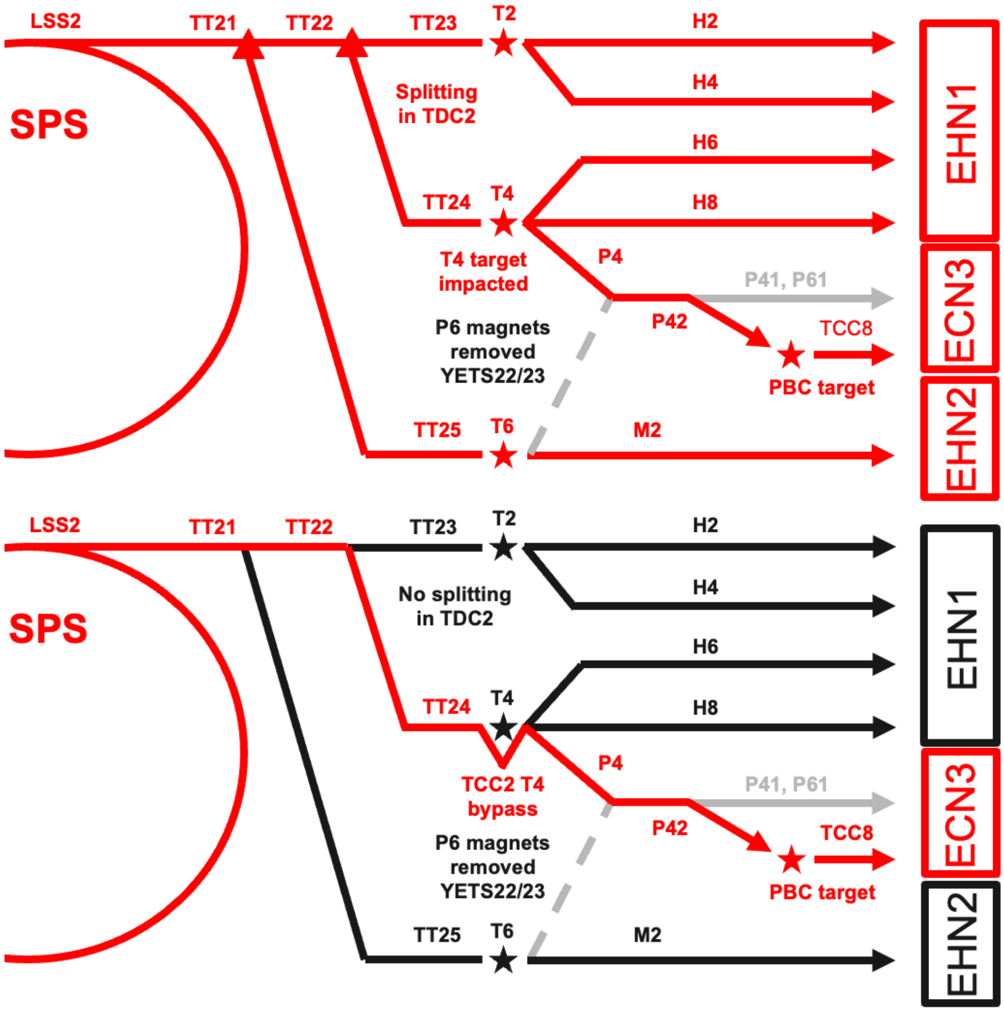


Figure 3: Schematic diagram of the two ECN3 beam delivery scenarios considered: T4 target in beam (top) and T4 target bypassed (bottom).

Experiment requirement	Intensity to TCC8 [p/spill] (PoT/year)	Spill Length [s]	Fastest Repetition Period [s]
BDF/SHiP [18]	up to 4×10^{13} (up to 4×10^{19})	≥ 1.0	7.2
HIKE [19]/SHADOWS[20]	up to 2.0×10^{13} (up to 1.2×10^{19})	≥ 4.5	14.4

Table 6: Experimental requirements for TCC8.

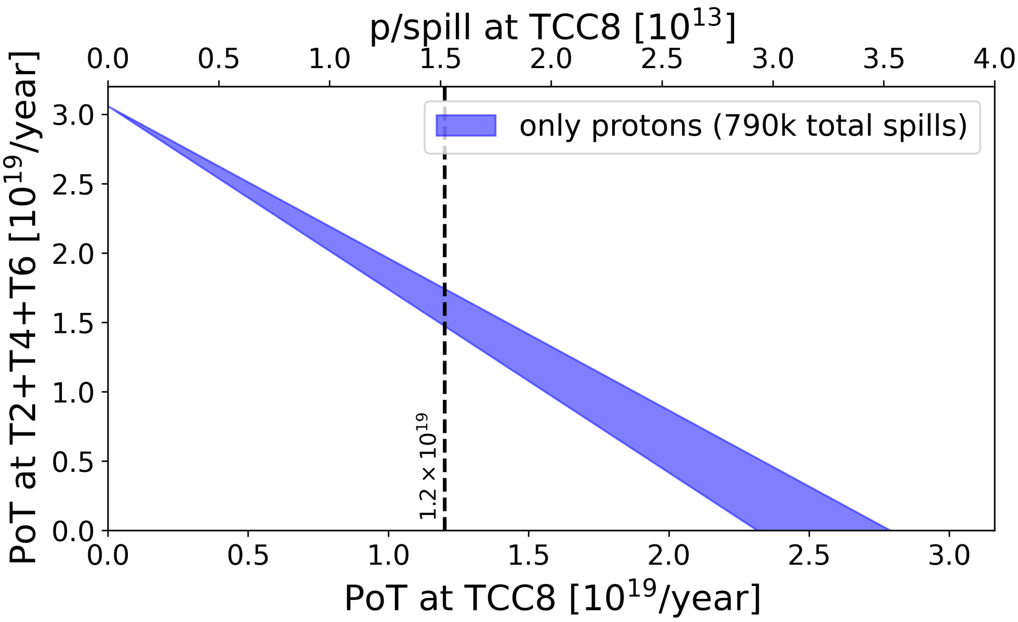
3.3 Future proton sharing scenarios

3.3.1 Shared ECN3 operation (SFTPRO FT 4.8 s)

	AWAKE	HiRadMat	SFTPRO (4.8s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	deGauss (3.6s)	Supercycle duration [s]	Average Power [MW]
AWAKE	1	-	1	-	-	-	-	-	1	21.6	37.61
AWAKE with parallel MD	1	-	1	-	-	-	1	-	-	25.2	32.36
Dedicated MD	-	-	-	-	-	1	-	-	-	24.0	18.03
HiRadMat	-	1	1	-	-	-	-	-	1	38.4	26.26
LHC filling	-	-	1	1	-	-	-	-	1	38.4	26.57
LHC setup	-	-	1	-	1	-	-	-	1	27.6	36.84
Physics	-	-	1	-	-	-	-	-	1	14.4	40.81
Physics with parallel MD	-	-	1	-	-	-	1	-	-	18.0	32.82
Scrubbing	-	-	1	-	-	-	-	1	1	38.4	26.57
Thursday MD	-	-	1	-	-	1	-	-	1	38.4	26.57

Table 7: Supercycles for the shared ECN3 scenario. The last column shows the power dissipated in the main dipoles (MB) and main quadrupoles (MQ) (in MW) by each supercycle.

The first scenario considered is the shared ECN3 operation, in which no dedicated ECN3_D cycles are used. In this case, the beam from the SFTPRO cycles is split at the splitter magnets in TDC2 and shared between the various target stations, including that in TCC8. A FT of 4.8 s is assumed for the SFTPRO cycles in this scenario. The supercycles considered are summarized in Table 7.



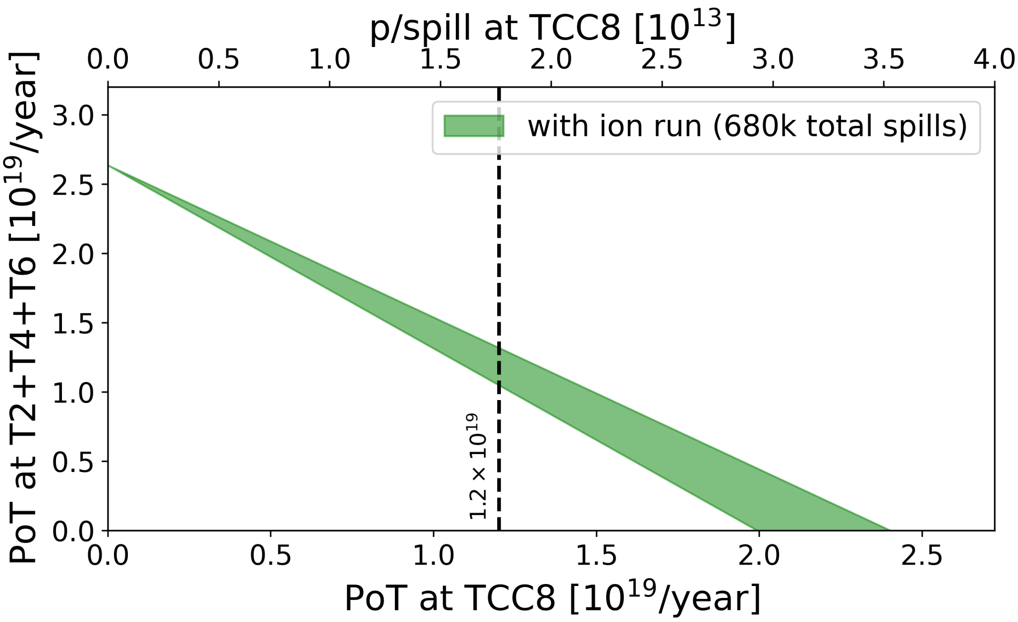


Figure 4: Protons on Target (PoT) for T2+T4+T6 versus TCC8 in case of shared ECN3 operation (SFTPRO FT=4.8s). Due to the uncertainty of the transmission at the T4 target in case of beam delivery to TCC8 (cf. Table 5 middle column), the PoT for TCC8 covers a range as indicated by the shaded area. The vertical dashed line indicates the PoT requested by some of the possible ECN3 experiments.

Figure 4 shows the sharing of the PoT between TCC8 and the rest of the NA experiments. The top graph considers a year with only proton operation (Table 4) and the bottom graph a year with both proton and ion operation (Table 3). In both graphs, the horizontal bottom axis represents the annual PoT delivered to TCC8, the horizontal top axis the p/spill at TCC8 and the vertical axis the annual PoT delivered to the other NA experiments (denoted as T2+T4+T6). The estimations include a total transmission for T2+T4+T6 of 0.922 (first column of Table 5), a total transmission of 0.697 − 0.840 for TCC8 (middle column of Table 5; T4 target in beam), an SPS availability of 80 % and an intensity of 4.2×10^{13} ppp before SPS extraction. It should be noted that approximately 12 % of the time is taken by deGauss cycles, which in some supercycle configurations could be reduced provided good understanding and correction of hysteresis and eddy current effects are achieved.

By sending the full intensity per spill to TCC8 throughout the year, between $2.3 - 2.7 \times 10^{19}$ PoT can be achieved, depending on the transmission efficiency, for only proton operation and $2.0 - 2.4 \times 10^{19}$ PoT when including ion operation. If no intensity is sent to TCC8, the rest of the NA experiments can get approximately 3.0×10^{19} and 2.6×10^{19} PoT for only proton and proton-ion operation, respectively. The intermediate cases, in which the beam intensity is split between TCC8 and the other NA experiments, are shown with the highlighted blue and green areas. For example, 1.2×10^{19} PoT/year can be delivered to TCC8 provided that at least 1.7×10^{13} p/spill impact on T4 target. Considering the presently uncertain transmission losses through the T4 target system and P42, this would bring the value up to 2×10^{13} p/spill, leaving between 1.5×10^{19} and 1.8×10^{19} PoT/year for users other than TCC8, in the absence of an ion run. 1.1×10^{19} to 1.3×10^{19} PoT/year would be available for users other than TCC8 in the presence of an ion run.

3.3.2 Operation with dedicated cycles and different FT lengths

For the scenarios with dedicated ECN3 operation, cycles for the TCC2 NA experiments (SFTPRO) and dedicated cycles for TCC8 (ECN3_D) with different flat-top lengths are considered. The proton sharing curves are generated in the following way: the maximum number of protons to the TCC2 experiments is obtained assuming an operational year without ECN3_D cycles, similar to the analysis performed in the previous section. Here, the supercycle configuration is similar to Table 7 but slightly adjusted in case longer or shorter FT lengths are considered for the SFTPRO cycles. On the other hand, the maximum number of protons for TCC8 is obtained assuming that the SPS serves both TCC8 and the TCC2 targets throughout the entire run using supercycle configurations with a high duty cycle for the ECN3_D cycles. A typical supercycle with high duty cycle for ECN3_D is shown in Table 8. Any intermediate scenario can be obtained by adequate supercycle scheduling.

Figure 5 shows the future proton sharing scenarios with (green) and without (blue) ion operation for the case of SFTPRO FT 4.8 s and ECN3_D FT 1.2 s. The horizontal bottom axis represents the PoT for TCC8 and the vertical left axis the PoT at TCC2 coming from the SFTPRO cycles. Therefore, the far-left values of the lines correspond to the SFTPRO operation only (Table 7), the far-right values to the operation with dedicated ECN3 cycles (Table 8). The intermediate values are obtained by switching between the two supercycle configurations throughout the operational year. As before, an SPS availability of 80 % is considered, while for the ECN3_ D cycles the T4 target is bypassed (transmissions from third column of Table 5). It is noted that an intensity of 4.2×10^{13} ppp has been assumed for both SFTPRO and ECN3_D cycles. The maximum PoT for TCC2 estimations are valid only if this intensity can be accepted by the TCC2 experiments. This intensity is about twice

	AWAKE	HiRadMat	ECN3_D (1.2s)	SFTPRO (4.8s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	deGauss (3.6s)	Supercycle duration [s]	Average Power [MW]
AWAKE	2	-	3	1	-	-	-	-	-	1	50.4	35.52
AWAKE with parallel MD	2	-	3	1	-	-	-	1	-	-	54.0	33.21
Dedicated MD	-	-	-	-	-	-	1	-	-	-	24.0	18.03
HiRadMat	-	1	4	-	-	-	-	-	-	-	52.8	26.99
LHC filling	-	-	1	-	1	-	-	-	-	-	31.2	21.92
LHC setup	-	-	4	-	-	1	-	-	-	-	42.0	34.13
Physics	-	-	4	1	-	-	-	-	-	1	43.2	36.86
Physics with parallel MD	-	-	4	1	-	-	-	1	-	-	46.8	34.09
Scrubbing	-	-	-	1	-	-	-	-	1	-	34.8	28.83
Thursday MD	-	-	2	1	-	-	1	-	-	1	52.8	28.84

Table 8: Supercycles for the dedicated ECN3 operation, with SFTPRO FT=4.8 s and ECN3_ D FT=1.2 s. The last column shows the power dissipated in the main dipoles (MB) and main quadrupoles (MQ) (in MW) by each supercycle.

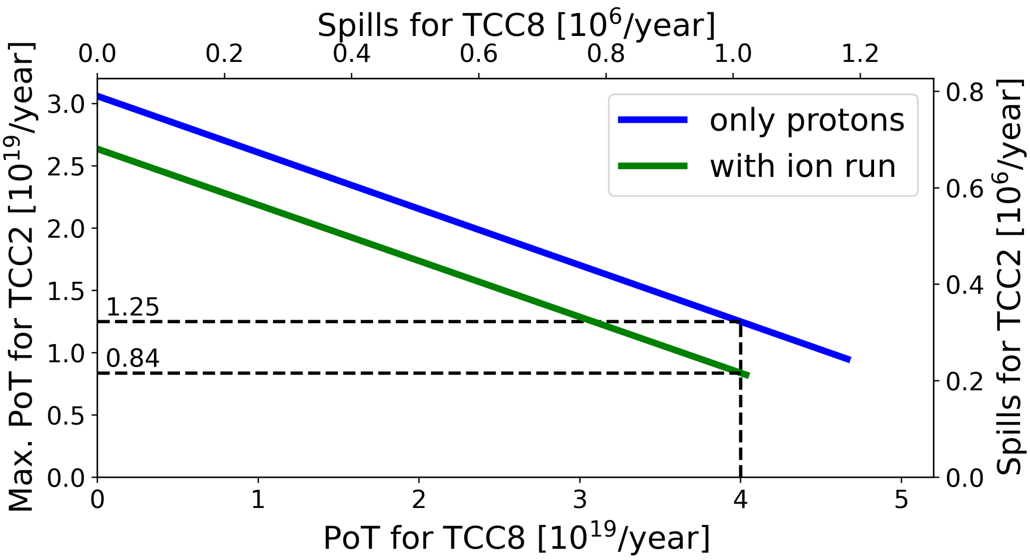


Figure 5: Future proton sharing scenarios with (green) and without (blue) ion operation for SFTPRO FT 4.8 s and ECN3_D FT 1.2 s. An intensity of 4.2×10^{13} ppp before SPS extraction has been assumed for both SFTPRO and ECN3_D cycles.

the maximum proton current extracted during the spill so far. If the experiments cannot cope with these high spill rates, these numbers have to be scaled pro-rata of the maximum acceptable protons per second by the experiments. The horizontal top and the vertical right axis show the number of spills of the dedicated ECN3_ D and SFTPRO cycles, respectively.

Figure 6 shows the PoT for TCC2 and TCC8 in the case of an increased FT length of SFTPRO cycles at 9.6 s while keeping the ECN3_D FT at 1.2 s. The assumed intensity here is also 4.2×10^{13} ppp for both SFTPRO and ECN3_D cycles. The longer FT of the SFTPRO cycles implies a total proton intensity of $\approx 3.9 \times 10^{13}/9.6$ p/s on the TCC2 targets (taking into account extraction, TT20 and splitting transmissions as indicated in the first column of Table 5), which is closer to what has been extracted during the past runs. To respect the constraint of power dissipated in the main dipoles and quadrupoles of the SPS, the supercycle configurations have been adjusted accordingly. The supercycle configurations for all future scenarios can be found in the Appendix A.

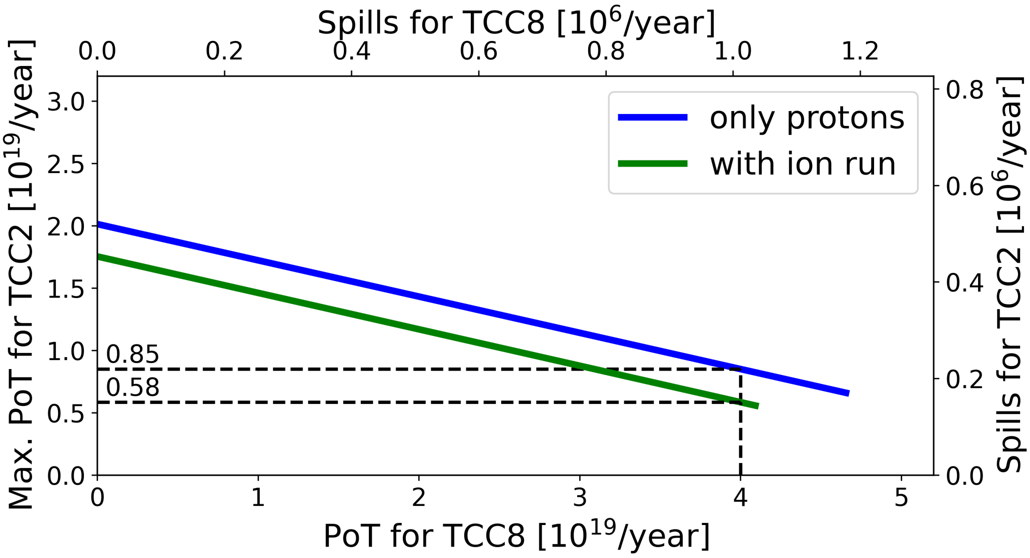


Figure 6: Future proton sharing scenarios with (green) and without (blue) ion operation for SFTPRO FT 9.6 s and ECN3_D FT 1.2 s. An intensity of 4.2×10^{13} ppp before SPS extraction has been assumed for both SFTPRO and ECN3_D cycles.

The scenario of SFTPRO FT 4.8 s and ECN3_D FT 4.8 s is shown in Figure 7. As previously, the assumed accelerated intensity is also 4.2×10^{13} ppp for the SFTPRO cycles. The delivery of this intensity over 4.8 s must be considered as optimistic for TCC2. An intensity of 2.1×10^{13} ppp has been assumed for ECN3_D cycles.

The scenario of SFTPRO FT 9.6 s and ECN3_D FT 9.6 s has also been considered and shown in Figure 8. The assumed accelerated intensity is 4.2×10^{13} ppp for both the SFTPRO and ECN3_D cycles. In this scenario, the intensity is delivered over 9.6 seconds to both the TCC2 and TCC8 targets.

Finally, the scenario of SFTPRO FT 9.6 s and ECN3_D FT 4.8 s is shown in Figure 9. The assumed accelerated intensity is 4.2×10^{13} ppp for the SFTPRO cycles and 2.1×10^{13} ppp for the ECN3_D cycles. The 1.2×10^{19} PoT for TCC8 is reached only when considering operational run without ions.

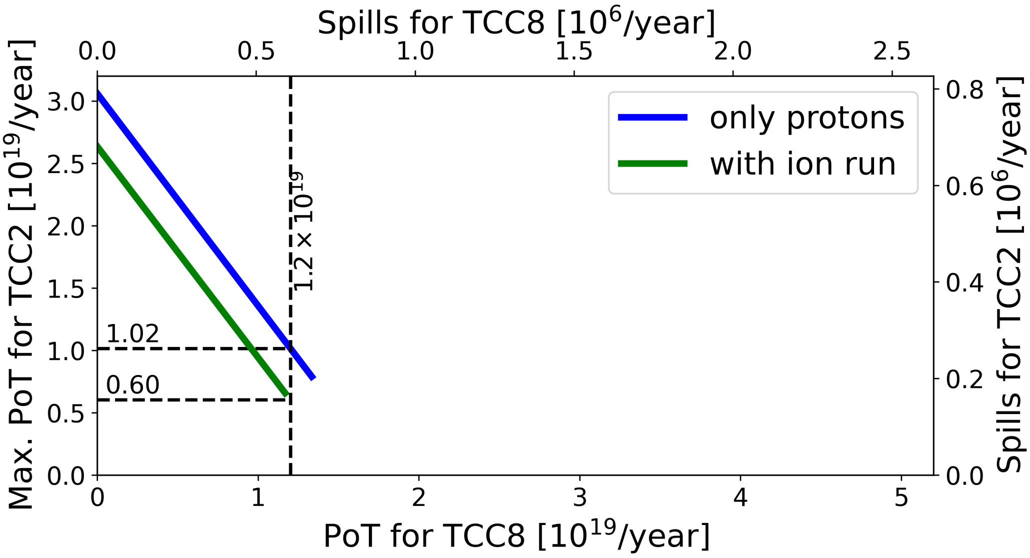


Figure 7: Future proton sharing scenarios with (green) and without (blue) ion operation for SFTPRO FT 4.8 s and ECN3_D FT 4.8 s. An intensity of 4.2×10^{13} ppp has been assumed for the SFTPRO cycles and 2.1×10^{13} ppp for ECN3_D cycles (both before SPS extraction).

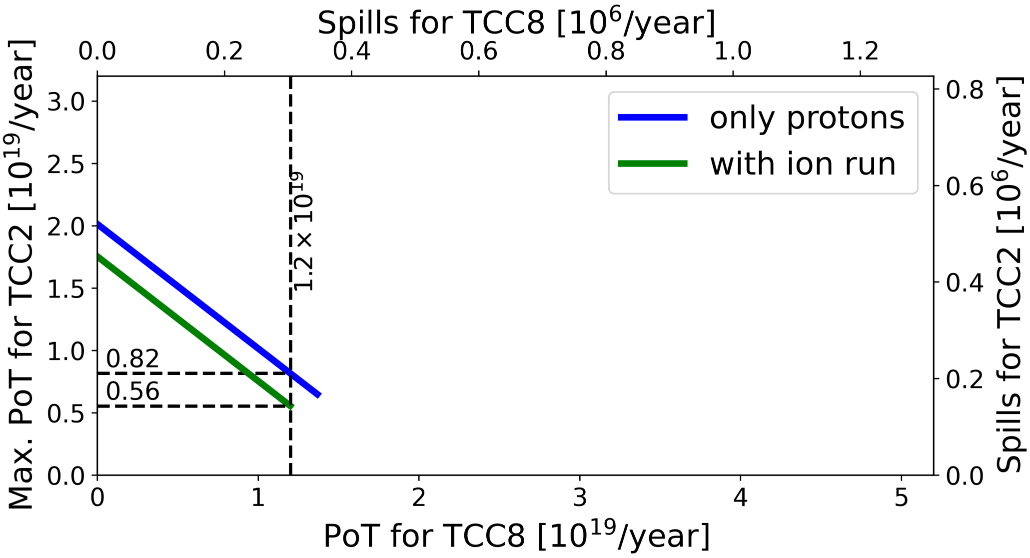


Figure 8: Future proton sharing scenarios with (green) and without (blue) ion operation for SFTPRO FT 9.6 s and ECN3_D FT 9.6 s. An intensity of 4.2×10^{13} ppp before SPS extraction has been assumed for both SFTPRO and ECN3_D cycles.

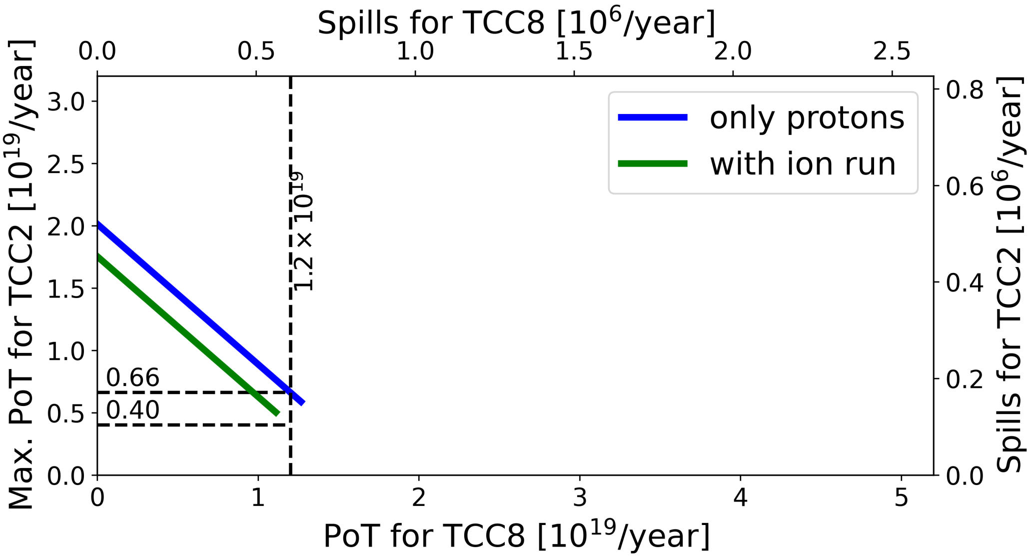


Figure 9: Future proton sharing scenarios with (green) and without (blue) ion operation for SFTPRO FT 9.6 s and ECN3_D FT 4.8 s. An intensity of 4.2×10^{13} ppp has been assumed for the SFTPRO cycles and 2.1×10^{13} ppp for ECN3_D cycles (both before SPS extraction).

3.4 Power consumption estimations

The energy consumption of the SPS main magnets and the NA magnets depends on the cycle composition. It therefore depends on the operational scenario and the corresponding SPS cycle composition. These elements are among the main contributors to the overall SPS and NA energy consumption during beam operation, representing more than 40 % and almost 15 % of the total, respectively. Estimations on the SPS main magnet power consumption of the future proton sharing scenarios have been made. These estimations are based on the supercycle configurations of Table 7, Table 8 and the Tables of the Appendix A and the average power consumption of each user in Table 1. The power estimations include the 80 % availability of the SPS and assume only proton operation. The estimates should be re-scaled in case of larger or lower availability.

Figure 10 shows an estimation of the main magnet power consumption for all the scenarios considered in Section 3.3. For the cases corresponding to dedicated operation for ECN3 the black bars represent the energy consumption (in GWh) when only SFTPRO cycles are executed, while the red bars represent the energy consumption when executing ECN3_D and SFTPRO cycles with maximum proton delivery to ECN3. The energy consumption for the shared ECN3 operation presented in Section 3.3.1 corresponds to the first and third black bars with SFTPRO cycles with FT 4.8 s long. For all the scenarios, a running period with only protons is assumed (245 days including two technical stops of 30 hours each). The grey lines indicate the actual power consumption for the SPS magnets in 2018 and 2022 [16] which include the commissioning periods and the tests after the beam stop that are not taken into account in the presented analysis. The differences of power consumption for the different FT scenarios and the shared/dedicated ECN3 operation are small, even more when considering the overall energy consumption including other contributions that are largely insensitive to

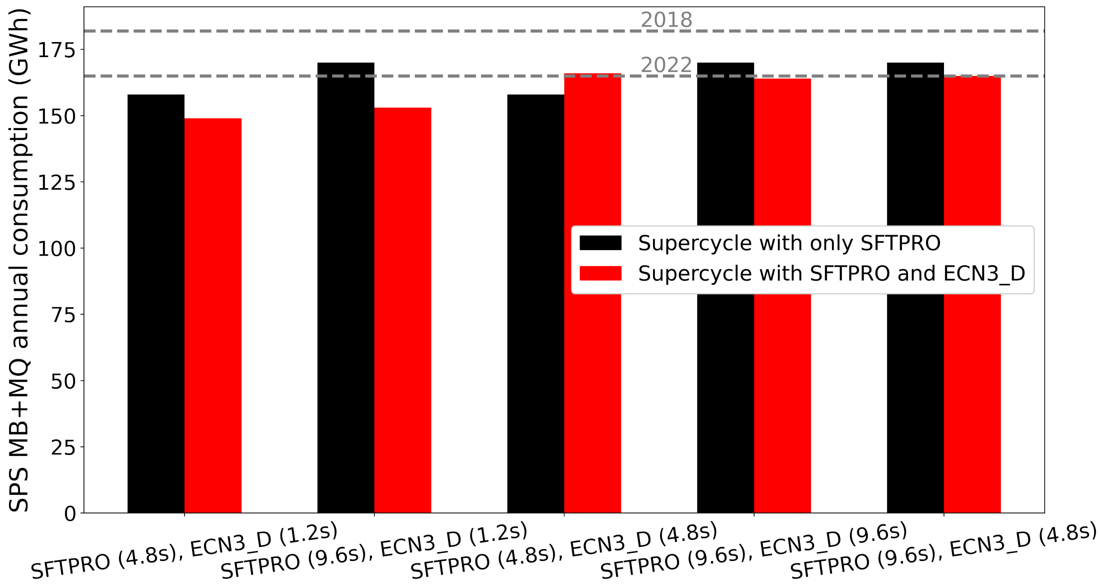


Figure 10: Estimation of the energy consumed by the SPS main magnets for the different FT scenarios presented in section 3.3. The black bars represent the TCC2 operation (only SFTPRO cycles) and the red bars the configurations with ECN3_D and SFTPRO cycles with maximum proton delivery to ECN3. The grey lines show the actual power consumption for the SPS magnets in 2018 and 2022.

the cycle composition.

For 2022 the total energy consumption was 169 GWh. By accessing all the users played in 2022, the total power that was recalculated is 160 GWh. The discrepancy with the real value probably comes from the Dynamic and Full economy of the SPS which is most of the times activated in case of no beam availability (but not always), and the commissioning periods and tests after the beam stop which are not taken into account yet.

4 Summary and conclusions

The SPS serves a large variety of physics users. A detailed analysis has been performed to analyse the compatibility and possible proton sharing scenarios between the TCC2 experiments and proposed future experiments in the ECN3 experimental hall, taking into account the parallel operation of the LHC, AWAKE, HiRadMat and MDs. The analysis is based on the actual operational conditions and constraints of the 2018 proton run, in order to be as realistic as possible. For the future proton sharing scenarios, operational periods with and without dedicated ion physics have been considered. Scenarios with dedicated SPS cycles for ECN3 users as well as scenarios with a shared, i.e. concurrent, beam delivery to the TCC2 experiments and ECN3 have been studied. Different flat top lengths have been analysed taking into account realistic supercycle compositions and respecting the SPS limits on power dissipation in the magnets. The intensities considered are based on operationally achieved values during the 2022 operation of the SPS.

The study demonstrates that up to 1.2×10^{19} PoT/year can be delivered to the NA

TCC2 targets (on SFTPRO with 4.8 s FT) whilst satisfying all high intensity requests for ECN3 experiments with a dedicated beam delivery scenario (significantly reducing losses at the splitters and T4 target) provided no ion run takes place, while 0.8×10^{19} PoT/year can be delivered in case an ion run (1 month) is included.

For the shared scenario, more than 1.7×10^{13} ppp must impact the T4 target in order to achieve the requested PoT delivered to ECN3. Considering the presently uncertain transmission losses through the T4 target system and P42, this would bring the value up to 2×10^{13} ppp, leaving between 1.5×10^{19} and 1.8×10^{19} PoT/year for users other than ECN3 in the absence of an ion run. In the presence of an ion run 1.1×10^{19} to 1.3×10^{19} PoT/year would be available for users other than ECN3.

The integrated PoT was computed to maximise the flux to TCC2, i.e. today's SFTPRO cycle accelerating 4.2×10^{13} protons per pulse with a 4.8 s FT. For some existing NA users this might be problematic due to rate limitations. A careful scheduling of rate-limited NA experiments exploiting longer cycles with a FT of 9.6 s would help optimise beam delivery and alleviate this problem. The study demonstrates that up to 0.8×10^{19} PoT can be delivered to TCC2 on SFTPRO cycles with a 9.6 s FT in parallel to dedicated ECN3 cycles, provided no ion run takes place, while 0.6×10^{19} PoT/year can be delivered in case an ion run (1 month) is included in the operational year.

Finally, it should be stressed that the PoT numbers would be reduced in case of more frequent LHC fillings, as compared to today's operation, during the HL-LHC era.

A Supercycle configurations for the different scenarios

	AWAKE	HiRadMat	SFTPRO (9.6s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	Zero	deGauss (10.8s)	Supercycle duration [s]	Average Power [MW]
AWAKE	1	-	1	-	-	-	-	-	-	1	33.6	37.08
AWAKE with parallel MD	1	-	1	-	-	-	1	-	3	-	33.6	36.82
Dedicated MD	-	-	-	-	-	1	-	-	-	-	24.0	18.03
HiRadMat	-	1	1	-	-	-	-	-	-	1	50.4	28.60
LHC filling	-	-	1	1	-	-	-	-	-	1	50.4	28.85
LHC setup	-	-	1	-	1	-	-	-	-	1	39.6	36.62
Physics	-	-	1	-	-	-	-	-	-	1	26.4	38.68
Physics with parallel MD	-	-	1	-	-	-	1	-	3	-	26.4	38.36
Scrubbing	-	-	1	-	-	-	-	1	-	1	50.4	28.85
Thursday MD	-	-	1	-	-	1	-	-	-	1	50.4	28.85

Table 9: Proposed supercycle configuration without ECN3_ D cycles for SFTPRO FT=9.6 s.

	AWAKE	HiRadMat	ECN3_D (1.2s)	SFTPRO (9.6s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	Zero	deGauss (10.8s)	Supercycle duration [s]	Average Power [MW]
AWAKE	1	-	3	-	-	-	-	-	-	-	-	28.8	33.96
AWAKE with parallel MD	2	-	3	1	-	-	-	1	-	3	-	62.4	35.50
Dedicated MD	-	-	-	-	-	-	1	-	-	-	-	24.0	18.03
HiRadMat	-	1	2	-	-	-	-	-	-	-	-	38.4	24.03
LHC filling	-	-	3	-	1	-	-	-	-	-	-	45.6	26.01
LHC setup	-	-	4	-	-	1	-	-	-	-	-	42.0	34.13
Physics	-	-	4	1	-	-	-	-	-	-	1	55.2	36.70
Physics with parallel MD	-	-	4	1	-	-	-	1	-	3	-	55.2	36.55
Scrubbing	-	-	1	-	-	-	-	-	1	-	-	31.2	21.92
Thursday MD	-	-	2	1	-	-	1	-	-	-	1	64.8	30.19

Table 10: Proposed supercycle configuration with high duty for ECN3_ D cycles of FT=1.2 s and SFTPRO FT=9.6 s.

	AWAKE	HiRadMat	ECN3_D (4.8s)	SFTPRO (4.8s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	deGauss (3.6s)	Supercycle duration [s]	Average Power [MW]
AWAKE	1	-	1	-	-	-	-	-	-	1	21.6	37.61
AWAKE with parallel MD	1	-	2	-	-	-	-	2	-	-	43.2	32.55
Dedicated MD	-	-	-	-	-	-	1	-	-	-	24.0	18.03
HiRadMat	-	1	2	-	-	-	-	1	-	1	56.4	28.35
LHC filling	-	-	1	1	1	-	-	-	-	2	52.8	30.46
LHC setup	-	-	1	1	-	1	-	-	-	2	42.0	38.20
Physics	-	-	2	1	-	-	-	-	-	3	43.2	40.81
Physics with parallel MD	-	-	2	-	-	-	-	1	-	1	32.4	36.37
Scrubbing	-	-	1	-	-	-	-	-	1	1	38.4	26.57
Thursday MD	-	-	3	-	-	-	1	-	-	3	67.2	32.68

Table 11: Proposed supercycle configuration with high duty for ECN3_ D cycles of FT=4.8 s and SFTPRO FT=4.8 s.

	AWAKE	HiRadMat	ECN3_D (9.6s)	SFTPRO (9.6s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	Zero	deGauss (10.8s)	Supercycle duration [s]	Average Power [MW]
AWAKE	1	-	1	-	-	-	-	-	-	-	1	33.6	37.08
AWAKE with parallel MD	2	-	1	1	-	-	-	2	-	6	-	67.2	36.82
Dedicated MD	-	-	-	-	-	-	1	-	-	-	-	24.0	18.03
HiRadMat	-	1	1	1	-	-	-	-	-	-	2	76.8	32.07
LHC filling	-	-	1	-	1	-	-	-	-	-	1	50.4	28.85
LHC setup	-	-	1	1	-	1	-	-	-	-	2	66.0	37.45
Physics	-	-	2	1	-	-	-	-	-	-	3	79.2	38.68
Physics with parallel MD	-	-	1	1	-	-	-	2	-	6	-	52.8	38.36
Scrubbing	-	-	1	-	-	-	-	-	1	-	1	50.4	28.85
Thursday MD	-	-	2	-	-	-	1	-	-	-	2	76.8	32.23

Table 12: Proposed supercycle configuration with high duty for ECN3_ D cycles of FT=9.6 s and SFTPRO FT=9.6 s.

	AWAKE	HiRadMat	ECN3_D (4.8s)	SFTPRO (9.6s)	LHC filling	LHC pilot	MD dedicated	MD parallel	Scrubbing	Zero	deGauss (3.6s)	deGauss (10.8s)	Supercycle duration [s]	Power [MW]
AWAKE	1	-	2	-	-	-	-	-	-	-	2	-	36.0	38.89
AWAKE with parallel MD	2	-	2	1	-	-	-	3	-	3	-	-	76.8	34.42
Dedicated MD	-	-	-	-	-	-	1	-	-	-	-	-	24.0	18.03
HiRadMat	-	1	2	1	-	-	-	-	-	-	2	1	79.2	33.04
LHC filling	-	-	2	-	1	-	-	-	-	-	2	-	52.8	30.46
LHC setup	-	-	2	1	-	1	-	-	-	-	2	1	68.4	38.39
Physics	-	-	4	1	-	-	-	-	-	-	4	1	84.0	40.14
Physics with parallel MD	-	-	2	1	-	-	-	3	-	3	-	-	62.4	35.17
Scrubbing	-	-	2	-	-	-	-	-	1	-	2	-	52.8	30.46
Thursday MD	-	-	4	-	-	-	1	-	-	-	4	-	81.6	34.11

Table 13: Proposed supercycle configuration with high duty for ECN3_ D cycles of FT=4.8 s and SFTPRO FT=9.6 s.

References

[1] G. Arduini, J. Jaeckel, and C. Vallée, "Physics beyon colliders," 2022, Presented at the 110th Plenary ECFA Meeting. [Online]. Available: https://indico.cern.ch/event/1172215/contributions/4922979/attachments/2483928/4264891/PBC_ECFA_22072022_22072022.pptx

[2] C. Ahdida *et al.*, "Findings of the Physics Beyond Colliders2 ECN3 Beam Delivery Task Force," in *CERN-PBC-REPORT-2023-001*, 2023. [Online]. Available: https://cds.cern.ch/record/2847433

[3] J. Coupard *et al.*, "LIU Technical Design Report - Volume I: Protons," in *CERN-ACC-2014-0337*, 2014.

[4] B. Balhan *et al.*, "Improvements to the SPS Slow Extraction for High Intensity Operation," 2019. [Online]. Available: https://cds.cern.ch/record/2668989

[5] G. Arduini, K. Cornelis, L. Gatignon, and B. Goddard, "The SPS beam parameters, the operational cycle, and proton sharing with the SHiP facility," in *SHiP-TP-2015-A2*, 2015.

[6] H. Bartosik *et al.*, "SPS Operation and Future Proton Sharing scenarios for the SHiP experiment at the BDF facility," in *CERN-ACC-NOTE-2018-0082*, 2018. [Online]. Available: https://cds.cern.ch/record/2650722

[7] M. Meddahi and E. Shaposhnikova, "Analysis of the maximum potential proton flux to CNGS," in *CERN-AB-2007-013-PAF*, 2007.

[8] E. Shaposhnikova *et al.*, "Recent Intensity Increase in the CERN Accelerator Chain," in *Proc. of 2005 Particle Accelerator Conference (PAC'05), Knoxville, Tennessee*, May 2005, paper ROPC004. [Online]. Available: http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/ROPC004.PDF

[9] C. Bovet, D. Fiander, L. Henny, A. Krusche, and G. Plass, "The fast shaving ejection for beam transfer from the CPS to the CERN 300 GeV machine," *IEEE Trans. Nucl. Sci. 20*, pp. 438–441, 1973.

[10] R. Cappi and M. Giovannozzi, "Novel method for multiturn extraction: trapping charged particles in islands of phase space," *Phys. Rev. Lett.*, vol. 88, no. 104801, 2002.

[11] S. Abernethy *et al.*, "Operational performance of the CERN injector complex with transversely split beams," *Phys. Rev. Accel. Beams*, vol. 20, no. 014001, 2017.

[12] A. Huschauer *et al.*, "Approaching the High-Intensity Frontier Using the Multi-Turn Extraction at the CERN Proton Synchrotron," in *Proc. of HB2018*, 2018.

[13] K. Li *et al.*, "SFTPRO, SFTION, and Delivery," in *Joint Accelerator Performance Workshop 2022*, 2022. [Online]. Available: https://indico.cern.ch/event/1194548/contributions/5093898/attachments/2560159/4412621/japw_s2_sftpro_22.pdf

[14] M. Vadai *et al.*, "Beam loss and transmission along the chain," in *Joint Accelerator Performance Workshop 2022*, 2022. [Online]. Available: https://indico.cern.ch/event/1194548/contributions/5093944/attachments/2562459/4417094/2022-12-07-beam-loss-in-the-complex-barrier-bucket-vadai.pdf

[15] M. Vadai, "Barrier bucket studies for the ps-sps transfer of sftpro: Status and plans," 2022, Presented at the 9th meeting of the PBC Accelerator Complex Capabilities Working Group. [Online]. Available: https://indico.cern.ch/event/1212850/contributions/5101516/attachments/2539171/4370769/2022-11-01-PS-SPS-barrier-bucket-synchronisation.pdf

[16] "Web energy application." [Online]. Available: https://energy.app.cern.ch/

[17] G. Mazzola and E. L., "T4/tax - efficiency and beam distribution analysis fluka," 2023, EDMS 2822408. [Online]. Available: https://edms.cern.ch/document/2822408/1

[18] O. Aberle *et al.*, "BDF/SHiP at the ECN3 high-intensity beam facility," CERN, Geneva, Tech. Rep., 2022. [Online]. Available: http://cds.cern.ch/record/2839677

[19] E. Cortina Gil *et al.*, "HIKE, High Intensity Kaon Experiments at the CERN SPS: Letter of Intent. HIKE, High Intensity Kaon Experiments at the CERN SPS," CERN, Geneva, Tech. Rep., 2022, address all correspondence to hike-eb@cern.ch. [Online]. Available: http://cds.cern.ch/record/2839661

[20] M. Alviggi *et al.*, "SHADOWS Letter of Intent," CERN, Geneva, Tech. Rep., 2022. [Online]. Available: http://cds.cern.ch/record/2839484