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Analysis of the maximum potential proton flux to CNGS

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Abstract

In this note we investigate the limitations to the proton flux which can be sent to the CNGS facility and estimate the maximum that can be attained.

In the first part, the injector chain remains unchanged and the limitations are reviewed for operation up to the so called "ultimate CNGS intensity", $7x10^{13}$ protons per CNGS cycle.

In the second part, the limitations of the SPS accelerator and CNGS facility are described in the scenario of operating with the new injectors - LINAC4, SPL and PS2, as proposed by the PAF working group [PAF].

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1 Proton flux for CNGS with the present injectors

1-1 Assumptions and estimations made during the CNGS conceptual technical design phase

1-1-1 CNGS Conceptual Technical Design report

In the CNGS conceptual technical design report [CTD, Addendum], the value taken for the nominal CNGS intensity relied on the SPS peak intensity of 4.8×10^{13} protons per 14.4 s cycle obtained in 1997. For the 1997 scheduled run of 137 days, a total number of 2.2×10^{19} protons were delivered, giving an efficiency of 55% (i.e. $2.2 \times 10^{19} \times 14.4/(137 \times 24 \times 60 \times 60 \times 4.8 \times 10^{13})$) [Stats]. This efficiency includes downtime as well as the non-optimised operation of the acceleration chain.

Based on this achieved performance, the hypothesis taken for the SPS nominal intensity to CNGS was 4.8×10^{13} protons per 6 s cycle with an overall efficiency of 55%.

Moreover, the CNGS beam time was estimated to be 60% of the total SPS beam time (leaving 40% for other SPS users) [CTD, Addendum].

Therefore a year with 200 days of operation, with 55% machine availability and 60% of the SPS beam sent to CNGS, leads to the expected nominal number of protons on the CNGS target (pot) of **4.5×10^{19} pot per year**. With the same assumptions, but without sharing (CNGS as a single user of the SPS), the maximum number of protons on target reaches **7.6×10^{19} pot per year.**

The first line in Table 1 summarises the evaluation of protons on target per year for nominal intensity operation.

1-1-2 Approval of the CNGS facility

The CNGS facility is committed to deliver **4.5×10^{19} pot per year** for a period of 5 years.

For 2006, CNGS has been approved for commissioning and operation by IRSN (L'Institut de Radioprotection et de Sûreté Nucléaire) for a maximum number of protons during the commissioning phase (3 weeks) of 1×10^{17} and for 1×10^{19} protons during the OPERA run (5 weeks) [INB]. IRSN approval of the 2007 CNGS operation will be part of the approval of the entire SPS fixed target physics programme.

1-1-3 Design of the CNGS facility

As mentioned, the nominal number of protons on target per 6 s cycle (committed for the CNGS facility) is $2 \times 2.4 \times 10^{13}$ pot.

In the design phase of the facility, it was considered important to provide some margin for improvements of the proton accelerator chain and therefore build components – as far as technically and financially possible – for possible higher intensities than the nominal $2 \times 2.4 \times 10^{13}$ protons. Guided by information from SPS experts, the scenario of **$2 \times 3.5 \times 10^{13}$ pot per 6 s cycle** was adopted as the "ultimate intensity" for CNGS (Table 1, second line). It must be stressed that this value requires significant improvements throughout the accelerator chain (see section 1-3). This "ultimate intensity" value has been taken for the design of equipment for which the important limiting effect was the total intensity per extraction or in a single cycle – e.g. for the target integrity.

For the design of components for which long term effects are the limiting factor, it was decided to take $2 \times 2.4 \times 10^{13}$ pot per 6 s cycle, together with the scenario of dedicated CNGS operation (no sharing of protons), a 100% efficiency of the accelerator chain and 200 days of operation per year. This very conservative (and certainly unrealistic) scenario for design therefore assumes **13.8×10^{19} pot per year**, also expressed as **8×10^{12}pot/s**. This value was for example taken to evaluate the activation of components in the target chamber in order to define the strategy for their exchange procedure (e.g. horn exchange).

Table 1: *Summary of the evaluation of proton on target per year for the design of the CNGS facility. The case of 3.5×10^{13} protons was only considered as a maximum limit for the intensity per batch and per cycle, not as an upper limit for the integrated number of protons on target per year – i.e. numbers in parenthesis are only mentioned for information. Numbers in bold have been used for designing the facility.*

I per PS batch	**Number of PS batches**	**I per SPS cycle (protons per cycle)**	**Cycle length (s)**	**200 DAYS, 100% efficiency, no sharing, pot per year**	**200 DAYS, 55% efficiency, no sharing, pot per year**	**200 DAYS, 55% efficiency, 60% CNGS sharing, pot per year, CNGS WORKING HYPOTHESIS**
2.4×10^{13} "Nominal CNGS"	2	4.8×10^{13}	6	**1.38×10^{20}**	**7.6×10^{19}**	**4.56×10^{19}**
3.5×10^{13} "Ultimate CNGS"	2	**7×10^{13}**	6	(2.02×10^{20})	(1.11×10^{20})	(6.65×10^{19})

1-2 Up-to-date estimation

The estimations made almost 10 years ago can now be refined for the future operation of the CNGS facility taking into account the latest experience and knowledge about possible beam sharing.

1-2-1 Maximum achieved intensity in the SPS

The 1997 intensity record of 4.8×10^{13} protons was reached after a careful tuning of all accelerators, while the average SPS operation intensity was around 4.2×10^{13} protons.
In the following years the CERN accelerator chain has been upgraded, mainly in preparation for the nominal LHC beam, which has a much higher (10 times) bunch intensity than the nominal CNGS beam, but a lower total beam intensity and therefore a different production scheme along the accelerator chain. The SPS had to undergo a significant impedance reduction programme, with the removal of lepton equipment and the shielding of different elements including kickers, septa and ~ 800 vacuum ports.
In 2004, a 3 week beam test with one CNGS cycle per SPS supercycle was dedicated to high intensity. The aim was to evaluate the results of this upgrade for the CNGS beam, to identify and study the intensity restrictions and to look for possible improvements [2004run]. At the end of this run a maximum intensity of 5.3×10^{13} protons was obtained at 400 GeV. The main limitation for further intensity increase was the beam loss (see section 1-3-1).

1-2-2 Beam sharing

After the LHC commissioning there will possibly be three main modes (supercycles) of SPS operation [ref. HIPWG]:

- CNGS-FT mode (possibly 1 FT (16.8 s) + 3 CNGS cycles (18 s) + MD cycle (4.8 s), no LHC), - 85 % of the SPS beam time,
- LHC set-up mode (LHC single bunch per batch (7.2 s)+ 2 CNGS (12 s)), -10 % of the SPS beam time,
- LHC filling mode (LHC as single SPS user), - 5 % of the SPS beam time.

It should be noted that the 2006 changes to the length of both the FT and the LHC pilot cycles (see section 1-3-4) are already taken into account in the above estimation.

The HIP Working Group estimated that after the LHC commissioning, the LHC filling time will take about 5% of the SPS running time. The two other supercycles have correspondingly three and two CNGS cycles and approximately half the time is shared between CNGS and non-CNGS users. Therefore, the percentage of time the SPS will be used for CNGS is ~95% / 2 = 47.5%, with LHC and other SPS physics users in parallel. In the absence of other FT users of the SPS beam, the CNGS beam would be available 90 % of the time.

In our study, we have decided to take the following possibly more realistic values:

- 45% for the SPS beam time used for CNGS, with LHC and other SPS physics users in parallel.
- 85% for the SPS beam time used for CNGS, with only LHC as other SPS user.

This approximately corresponds to 10% of the SPS operation in LHC filling mode (compared to 5% assumed by the HIP WG) and 10% in LHC setting-up mode.

For well-established performance and routine operation the machine efficiency is around 80%; however every increase in beam intensity leads unavoidably to a decrease in efficiency. As a consequence, estimations below show the upper (and optimistic) limit for the accelerator performance. It is noted that the time for setting-up and dedicated machine development studies has already been subtracted from the SPS beam time, leading to the final result of ~200 days of operation (corresponding to the 4700 hrs quoted in the reference HIPWG).

1-2-3 Maximum possible proton flux from operational experience

With the present injectors, it was demonstrated that a maximum intensity of 3 $x10^{13}$ protons can be injected into the SPS every **1.2 s**. Taking into account beam losses, this could lead to a total intensity of 5.7 x 10^{13} protons at 400 GeV in the SPS (this intensity was so far only accelerated to just above transition, not to 400 GeV)

In addition, special tests in the PS demonstrated the possibility of delivering the record intensity of $4x10^{13}$ protons at 14 GeV/c every **2.4 s**, using double batch injection from the PSB. Taking into account beam losses this can lead to a total intensity of $7x10^{13}$ protons at 400 GeV in the SPS.

For 200 days of operation with 80% machine efficiency and with 45% of the SPS time available for CNGS, we obtain nearly $5x10^{19}$ pot per year for the nominal CNGS intensity ($4.8x10^{13}$ per 6 s cycle) and $5.9x10^{19}$ pot per year for an intensity of $5.7x10^{13}$ at 400 GeV (see first rows of Table 2).

If no other user of the SPS is scheduled (85% SPS beam time for CNGS), these values increase respectively to about $9.4x10^{19}$ and $1.11x10^{20}$ pot per year.

For the ultimate CNGS intensity of $7x10^{13}$ accelerated in the SPS and 7.2 s long cycle (double batch injection in the PS from the PSB), we obtain about $6x10^{19}$ and $11.4x10^{19}$ pot per year in the two cases of 0.45 and 0.85 beam sharing. Taking into account that relative beam losses increase with intensity, the scheme with double batch injection in the PS does not seem attractive in comparison to single batch.

Table 2*: pot per year [x10^{19}] for 200 days of operation with 80% machine availability*

	SPS cycle length	6 s		7.2 s		4.8 s		6 s	
	Injection momentum	14 GeV/c		14 GeV/c		26 GeV/c		50 GeV/c	
	Beam sharing / Max SPS intensity @ 400GeV [x10^{13}]	0.45	0.85	0.45	0.85	0.45	0.85	0.45	0.85
Present injectors: numbers within reach with machine improvements	4.8 – “nominal CNGS”	5	9.4						
	5.7 – “Max. SPS”	5.9	11.1						
Present injectors + SPS RF upgrade	7 – “ultimate CNGS”			6	11.4				
Future injectors	7							7.2	13.7
Future injectors + SPS RF upgrade	7					9	17.1		
Future injectors + SPS RF upgrade + CNGS new equipment design	10 – “maximum PS2”							10.3	19.6
Future injectors + new SPS RF system + CNGS new equipment design	10					12.9	24.5		

1-3 Injector chain limitations

1-3-1 Beam loss

Beam loss is the most critical issue for the CNGS beam, leading to induced radiation and a loss of protons on target. At present, to provide the nominal CNGS beam intensity, approximately 3 times more particles are needed from the Linac. The radiological impact of losses is in general increasing with particle energy. Consequently, losses in the PS and especially at high energy in the SPS must be minimised. Due to many reasons (collective effects, beam size and others) relative losses increase with intensity (see present data in Table 3). This goes against the requirement of keeping the radiological impact constant, which necessitates keeping the absolute number of lost particles constant and hence decreasing the relative losses with intensity - as assumed in Table 3 for the ultimate CNGS intensity. This implies that, for planning an intensity increase, special measures should be found and implemented to improve the machine performance. The losses at extraction from PS will be reduced from 10% to 3% thanks to the new multi-turn extraction (planned to be available in 2008) [MTE]. In the SPS, losses occur during beam capture and at high energies due to emittance blow-up during transition crossing. Bunch-to-bucket injection above transition energy with the future PS2 should significantly improve this situation. Short term improvements were studied in the specially created Working

Group on Beam Loss and Radiation and they include further SPS impedance reduction, beam-control upgrade, removal of aperture restrictions and others [BLRWG].
These short term improvements are the key to reach higher intensity than nominal and go beyond 5.3×10^{13} protons as achieved so far at 400 GeV.

***Table 3**: The relative beam loss in the accelerator chain (after injection into the PSB) for different beam intensities at the SPS extraction.*

Beam	FT	CNGS		
	2004	nominal	record	ultimate
Intensity at 400 GeV/c [10^{13}]	2.6	4.4	5.3	7
Relative loss [%]	16	24	38	must be < 20

1-3-2 Equipment heating

SPS Extraction kickers: For the nominal CNGS beam parameters, the beam induced heating of the ferrite of the SPS extraction kicker magnets has been evaluated to be 210 W/m per extracted batch of 2.4×10^{13} protons [MKE]. For the two nominal batches, the corresponding temperature of the ferrite is about 110°C. Note that above 120°C these ferrites lose their magnetic properties. The evaluation of ferrite heating is based on measurements of both the nominal CNGS bunch spectra and the magnet beam coupling impedance. For evaluating temperature rise, the nominal CNGS beam was considered, assuming the dedicated CNGS operation (continuous CNGS 6 s cycle) and kicker water cooling system switched on.
In order to reduce the beam coupling to the ferrite, and thus the induced heat, a spare kicker magnet has been equipped with shielding stripes: simulations and laboratory measurements show that the ferrite heating, attributable to the nominal CNGS beam, is reduced by a factor of approximately 7 [MKE1]. An extraction kicker magnet equipped with such shielding stripes has been installed in the SPS in LSS6 and measurements with beam will be performed in 2007 in order to confirm the models.
The same calculations for the ultimate CNGS beam (3.5×10^{13} protons per batch, for a total of 7×10^{13} protons per 6 s cycle) give an increase by a factor of about 2 of the heat deposition in the ferrite. Therefore, either reducing the beam duty factor or equipping all the SPS extraction kicker magnets with shielding stripes is mandatory for this intensity.
Summary: The extraction kicker magnets must be equipped with shielding stripes in order to reduce the ferrite heating which will be caused by the ultimate CNGS beam intensity. The principle of these shielding stripes has been tested in the laboratory and will be verified, for one extraction kicker magnet, in the presence of beam during the 2007 SPS run. If the model is validated, it would be the solution for the ultimate CNGS intensity and the remaining extraction kickers would need to be equipped with stripes.

Other equipment: Other devices are likely to suffer from the increased intensity in SPS because of beam induced heating (e.g. HOM couplers, beam instrumentation etc.).

1-3-3 RF voltage and power

The voltage programme for the present CNGS cycle is shown in Fig. 3 of Annex A. It is similar to the FT cycle and requires the maximum available voltage (8 MV) at 200 MHz even for modest beam intensities. Any reduction of the voltage at high intensities during the 2004 run led to beam losses. Increasing the intensity above 5.7×10^{13} can cause larger longitudinal emittance blow-up during transition crossing, leading to beam loss due to the limited longitudinal acceptance. Upgrade of the low-level beam control could possibly improve the situation [RFMD2004].

Presently the RF power per cavity is limited at 700 kW for a full SPS ring. For the voltage programme presently used in operation, the required RF power for nominal and ultimate CNGS intensities is shown in Fig. 3 of Annex A. At the end of the cycle it limits the beam intensity to about 6×10^{13} protons/cycle.

The 800 MHz RF system used for beam stabilisation against coupled bunch instabilities also requires an upgrade for intensities above 7×10^{13} protons/cycle.

1-3-4 Beam availability

As discussed, the total number of protons delivered to the CNGS target depends not only on the peak beam intensity but also on the beam availability and the beam sharing with other users. The lack of protons for different SPS users was highlighted by HIPWG [HIPWG], different improvements were proposed and some of them already tested or implemented (e.g. <u>fast SPS supercycle change, 30 % shorter pilot cycle for LHC set-up [pilot], longer SPS flat top for slow extraction [GA],</u> etc.).

The reliability of the present complex should also be improved due to the re-start of the consolidation programme which includes refurbishing of the PS and SPS magnets and new PS power supply. However, a significant improvement in the beam availability can only be expected after the replacement of the present PSB and PS by the SPL and PS2.

1-4 CNGS facility limitations

1-4-1 Radiation protection calculations: maximum intensity assumed

All calculations of soil / concrete activation have been done for **4.5×10^{19} pot per year**, corresponding to nominal intensity, 55% machine efficiency and 60% beam sharing [RP].

All calculations for air and water activation have been done for **7.6×10^{19} pot per year**, corresponding to nominal intensity, 55% machine efficiency and dedicated CNGS operation.

In the context of the HAZOP (HAZard and OPerability) study, all calculations of dose rates for equipment exchange / repair (horn, target, target motors…) have been performed for 100% machine efficiency and dedicated CNGS operation i.e. **1.38×10^{20} pot per year** (4.8×10^{13} per 6 s or 8×10^{12} protons/s).

<u>Summary:</u> All RP related calculations/studies have to be revised for any scenario beyond nominal (4.5×10^{19} pot per year) (see Table 1). This also includes radioactive waste studies and corresponding area classifications. A new INB approval from IRSN is required.

1-4-2 Target limitations

Presently the target is estimated to operate with a safety factor of 2 at ultimate CNGS beam intensity - i.e. at 0.5 of the rupture limit under the worst assumptions for 3.5×10^{13} protons per extraction [Target1, Target2]. Any increase of the beam intensity per extraction would reduce this safety margin if nothing else (e.g. number of extractions) is changed (see section 2-3-2).

The radiation damage still deserves more investigation but it has been estimated that the target will survive up to 2×10^{20} pot (see section 2-3-2).

<u>Summary</u>: The CNGS target is designed to stand the ultimate CNGS intensity value of 3.5×10^{13} protons per batch and an integrated intensity of 2×10^{20} pot.

1-4-3 Horn limitations

The horn limitations are twofold:

a- The mechanical fatigue of the inner conductor, which is proportional to the number of pulses applied on the horn. The expected fatigue lifetime requested in the horn specifications is to withstand 2 x 10^7 pulses (corresponding to 3.5 years of continuous 200 days of operation in CNGS dedicated mode) with 95% confidence level. This requirement was used to check the mechanical fatigue of the inner conductor in dynamic mode (transient dynamic analysis of stress distribution over time and related fatigue analysis) and to estimate the remaining lifetime of the capacitor banks. This design includes a safety factor of 1.8 [Horns1].

b- The heating due to particle interactions in the horn and due to the current applied to the horn.
The water cooling system of the horns has been designed for an intensity of 3.6x10^{13} protons per extraction, with a maximum of 7.2x10^{13} protons per 6 s cycle. The corresponding total power to be evacuated by the horn water cooling system is 25.8 kW.
Calculations of the energy deposition in the horn regions have been performed for 8x10^{12} pot/s [Horns2]. The air cooling system has been designed accordingly [Horns3].
It is stressed that experience accumulated in running the CNGS facility with beam over a longer period is now crucial in order to check the effectiveness of the air cooling system and to cross-check with the calculations - this will allow extrapolation to higher beam intensities.

Summary: The horn and its water cooling system are designed for ultimate intensity (up to 3.6x10^{13} protons per extraction and 7.2 x10^{13} protons per 6s cycle), for a maximum integrated proton flux of 1.38 x10^{20} pot per year (energy deposition in the horn) and for a total of 2x10^7 pulses (mechanical fatigue).

1-4-4 Other equipment

Shielding

All calculations have been done assuming 8x10^{12} pot/s (1.38 x10^{20} pot per year).

Decay tube

The energy absorption in the steel pipe of the decay tunnel and the induced radioactivity and dose rates in the decay tunnel were calculated for a proton intensity of 8×10^{12} pot/s – i.e. 4.8x10^{13} protons per dedicated 6 s CNGS operation, **1.38x10^{20} pot per year** [DT1, DT2].
Decay tube entrance and exit windows: heating and cooling calculated for 8×10^{12} pot/s [DT3, DT4].
The Ti windows (He tube and decay tube entrance windows) have been designed to stand the full proton intensity of 7x10^{13} protons which misses the target during one cycle. After one cycle, the proton beam is interlocked. The evaluation of the Ti windows for higher intensity would have to be performed [DT4].

Hadron stop

Design was performed to operate with **1.38x10^{20} pot per year** [HS].

1-5 Conclusions for operating at ultimate CNGS intensity

With the present injectors, including SPS, the nominal intensity (4.8×10^{13} per cycle) is feasible. The achievable maximum SPS beam intensity with the present injectors is estimated to be 5.7×10^{13} protons at 400 GeV, after careful, dedicated machine tuning and beam control upgrade. Increasing further the intensity to the ultimate CNGS value (7×10^{13} per cycle) will require many improvements in the accelerator chain – as listed above - and an upgraded RF system to provide the required RF power.
Target and horn equipment of the CNGS facility have been designed to operate at ultimate CNGS intensity. It should however be noted that the lifetime of the horns and target assembly will require their replacement for operation after the nominal CNGS run.
All CNGS-RP related calculations/studies will have to be revised. This also includes radioactive waste studies and corresponding area classifications. A new INB approval from IRSN will be required.

2- Proton flux for CNGS with the new injectors (LINAC4, SPL, PS2) and an upgraded SPS

2-1 Estimation of the proton flux for CNGS

2-1-1 SPS cycles with PS2

With the new SPS injector, PS2, and assuming up to 1×10^{14} protons per cycle accelerated to 50 GeV/c every 2.4 s, the length of the SPS cycle for CNGS can in principle be reduced to 4.8 s. However, such a short repetition period will not leave enough time for PS2 to provide a slow extracted beam to its FT (Fixed Target) users. A FT cycle with acceleration to 50 GeV/c would need 3.6 s, leading to a minimum CNGS+FT supercycle length in the PS2 of 6 s [PS2WG].
However if the PS2 extraction momentum for CNGS is reduced to 26 GeV/c, 1×10^{14} protons can probably be accelerated in 0.6 s with a cycle length of 1.2 s, leaving the 3.6 s time needed for FT users in PS2, within the SPS-CNGS cycle of 4.8 s.
A 4.8 s supercycle is also compatible with FT physics in PS2 at 26 GeV/c and a slow extraction, or at 50 GeV/c and a fast extraction.
Possible CNGS acceleration cycles in the SPS with injection at 26 GeV/c (acceleration time of 3 s) and injection at 50 GeV/c (acceleration time of 4.2 s) are presented in Figs.1-2 of Annex A.

2-1-2 Maximum proton flux

The maximum intensity that PS2 will be able to deliver at **26** or **50 GeV/c** to the SPS is estimated to be ~$\mathbf{1.1 \times 10^{14}}$ protons [PS2WG]. This intensity is well beyond the maximum intensity that the SPS can accelerate in 3 s with the present RF system (see section 1-3-3). The impact of the PS2 on the RF system and other equipment of the SPS is discussed in section 2-2.
If we assume 10% relative beam loss during the acceleration to 400 GeV (lower loss than at present because transition crossing in the SPS is avoided) then 1×10^{14} protons could be accelerated in the SPS to top energy.
The total number of protons which would then be sent to the CNGS target at 400 GeV during 200 days of operation, assuming a 4.8 s or 6 s long SPS cycles, a beam availability of 80% and two assumptions for beam sharing (as assumed above for the present injectors) are summarised in the bottom rows of Table 2.

2-2 Impact on the SPS accelerator

2-2-1 Beam structure in the SPS with PS2 as an injector

It is assumed that the SPS will be filled by the 5-turn resonant island extraction (MTE) from PS2 [MTE]. It is also assumed that the normalized transverse emittances in PS2 will be similar to the ones of the present high intensity CNGS beam. As a result, the normalized transverse emittances in the SPS will be smaller because of the improvements with the MTE.

In the longitudinal phase plane, a bunch-to-bucket transfer will be used. The beam bunched at 40 MHz in PS2 (25 ns distance between bunches) will be captured in 200 MHz buckets in the SPS (only every fifth 200 MHz bucket will therefore be populated, as for the LHC beam). The bunch intensity in PS2 is five times the bunch intensity in the SPS. Moreover, there must be a gap of 1.1 μs in the circulating beam in SPS for the rise-time of the extraction kicker at 400 GeV. With the present PS, this is easily obtained with a proper timing of the second transfer from PS to SPS. With PS2 which fills the SPS in a single pulse, such a gap must already exist inside PS2. Because of the 5-turn extraction, this gap will appear 4 times in the circulating beam in the SPS. Assuming that the **SPS circumference = 5 x PS2 circumference**, the beam structure in the SPS will be 5x(3.5 μs beam + 1.1 μs gap) and the maximum bunch intensity will be of 7.8×10^{11} protons per bunch in PS2 (respectively 1.4×10^{11} protons per bunch in the SPS). If the **SPS circumference = 5.5 x PS2 circumference,** the maximum bunch intensity will reach 8.9 $\times10^{11}$ protons per bunch in PS2 and 1.6 $\times10^{11}$ protons per bunch in the SPS.

2-2-2 Intensity limitations in the SPS

With PS2, the CNGS beam in the SPS will become similar to the present ultimate LHC beam, which has an intensity per bunch equal to 1.7×10^{11} protons and a bunch spacing of 25 ns. However, the beam structure is different: the CNGS beam will occupy 76 % of the ring (for SPS=5xPS2) with five kicker gaps of 1.1 μs to provide separate fast extractions at 400 GeV.

As the LHC beam, this beam will suffer from electron-cloud instabilities. This problem can be cured by replacing the SPS vacuum chamber or by coating the present one with some material with a low secondary emission yield. This possibility is now under investigation.

The transverse damper should be upgraded to compensate resistive wall instability.

Significantly increased local current will cause heating of many accelerators components which should be upgraded (i.e. kicker magnets, section 2-2-4).

However, the most important changes will concern the main 200 MHz RF system.

2-2-3 Impact on RF system

The voltage programmes for the CNGS cycle with injection at 26 GeV/c are shown for different longitudinal emittances in Figs. 4-5 of Annex A. Although the emittance is small (0.4 eVs) at injection, it has to be blown up to stabilise the beam against coupled bunch instabilities at high energy. For the present nominal LHC beam with an intensity of 1.1×10^{11} protons per bunch it is necessary to increase it to 0.6 eVs. Due to the short acceleration time (3 s), similar to the present FT cycle, the maximum available voltage (8 MV at 200 MHz) is therefore needed to have enough acceptance. For the intensity of 1.6×10^{11} protons per bunch corresponding to SPS=5.5xPS2, the emittance must be brought up to 0.75 eVs and the consequences for the RF are shown in Fig. 4 (top left for the voltage – bottom right for the power per cavity). For the intensity of 1.4 $\times10^{11}$ protons per bunch corresponding to SPS=5xPS2, an emittance of 0.7 eVs should be sufficient and the consequence for the RF are shown in Fig. 5 (top left for the voltage – bottom right for the power per cavity).

The operation of the 800 MHz RF system as a Landau damping system is also indispensable.

The RF current used for RF power estimations calculated for different CNGS intensities and SPS filling schemes is shown in Table 1 of Annex A. With the actual RF power limitation at 700 kW per cavity for a full SPS ring, the total CNGS intensity will be limited at the present nominal value or practically at half of what could be delivered by the future PS2. This is due to the increased local beam density. The required RF power for a total beam intensity of $4.8x10^{13}$, $7x10^{13}$ and $1x10^{14}$ protons/cycle are shown in Figs. 4-5. From the technological point of view the upgrade needed to reach 1 MW power limit for the full ring is challenging and will require significant R&D efforts for a new RF system.

Increasing the acceleration time from 3 s (a 4.8 s cycle) to 4.2 s (a 6 s cycle) in the case of injection at 50 GeV/c reduces the voltage needed for the emittance of 0.7 eVs to values below 7.5 MV, but does not sufficiently reduce the RF power to allow for the maximum intensity available from the PS2. Moreover, the cycling rate being reduced by the ratio 4.8/6, keeping the proton flux constant requires increasing the intensity per SPS cycle in the same proportion (+25 %).

Summary: The situation is better if the size of PS2 is larger and close to 1/5 of the SPS. This will also be beneficial for the slow extracted FT beam in the SPS where the spill structure is very important.

The RF voltage and power required for different SPS filling schemes and cycle lengths are summarised in Tables 4 and 5.

Table 4: *Maximum RF voltage during the whole cycle, $V_{1,}$ and above 250 GeV, $V_{2,}$ required for different acceleration cycles and filling schemes (and for the maximum longitudinal emittance needed for beam stability with intensity of $1x10^{14}$), see also Figs.4-6 in Annex A.*

	SPS = 11 PS	**SPS = 5.5 PS2**	**SPS = 5 PS2**	
Acceleration time	3 s	3 s	3 s	4.2 s
V_2 [MV]	7.5	8	7.5	6
V_1 [MV]	7.6	11	10.5	7

Table 5*: Maximum RF power [MW] required above 250 GeV for different beam intensities, acceleration times and filling schemes with PS2, see also Figs.4-6 in Annex A.*

N	**SPS = 11 PS**	**SPS = 5.5 PS2**	**SPS = 5 PS2**	
$[10^{13}]$	3 s	3 s	3 s	4.2 s
4.8	0.65	0.9	0.75	0.5
7	0.85	1.15	1	0.7
10		1.6	1.4	1.1

2-2-4 Impact on kicker magnets

With the PS2 beam parameters, and the SPS dedicated to CNGS (6 s cycle), the beam induced heating of the ferrite of the SPS extraction kicker magnets is expected to increase by a factor of almost 7 [MKE]. This is at the borderline of what the extraction kicker magnets, equipped with both cooling and shielding stripes, can stand. Results of the SPS measurements on the extraction kicker magnet equipped with shielding stripes are crucial to confirm the models and to draw a conclusion on the possible use of these kicker magnets under these very high intensities. It is likely that a new design of these magnets will be necessary – possibly similar to the LHC injection kicker magnets, which have 24 shielding stripes in the aperture.
In order to accommodate the extraction of 5 batches (vs nominal 2) from the SPS into the CNGS transfer line, 3 more resonant charging power supplies will have to be built. From operational experience, it is clear that these additional supplies will increase the number of faults and erratics (thus reducing the machine efficiency). Also a location will have to be found for these supplies, and it is most probable that a new building will be needed.
<u>Summary:</u> Beam measurements for the temperature increase of the SPS extraction kicker magnet equipped with shielding stripes are needed to draw conclusions on its suitability for use with a beam intensity of 1×10^{14} protons. Simulations indicate however that the situation will be very marginal and the extraction kicker magnets may have to be re-designed or the CNGS duty cycle factor changed. Additional resonant charging power supplies will have to be built and adequate space made available to host them.

2-3 Impact on the CNGS facility

2-3-1 Impact on radiation protection

a - **General considerations**. A higher proton flux will unavoidably convert into higher activation of components and longer waiting time before access. Longer ventilation time for the air exchange will be needed. Risk of radiation damage of components will be increased.

b - Release of **activated water** from the sumps needs to be revised.

c - **Air activation**. All calculations were done for **7.6×10^{19} pot per year,** with the result of a release to the public of 11 µS per year. This value takes into account both the activation from the ventilation leak mode (release of 500 to 800 m^3 continuously) and the ventilation access mode (wait time of 2 hrs before switching on the access mode ventilation). This scenario of released air has been optimised taking into account the decay of both short and long lived isotopes and averaged meteorological conditions during the continuous release (leak mode) and worst meteorological conditions for flushing the air of the target chamber before access. This value of 11 µS per year relies on the assumption that the filters will retain 90% of the aerosols – the result of FLUKA simulation with no filter is 110 µS per year. This value has to be validated with experience of running the facility: in 2007, after a complete CNGS run, the validity of the assumption will be assessed. If the assumption was too pessimistic – i.e. filter retaining >90% of the aerosols – then the increased intensity might be possible without any modification. Otherwise, a study will have to be done to improve the filter system and/or re-design it.
With the maximum PS2 intensity and without any modification of the ventilation system, the release value will increase in proportion to intensity to about 30µS per year. It is recalled that beyond 10µS per year, permission to operate a facility is difficult to obtain.

d – **ECA4**. During the CNGS run lasting from August 18 until August 31, 2006 a total intensity of 7.8×10^{17} protons was extracted. Within this period a total dose of 72 µSv (background corrected) was measured at the ECA4 floor close to the TA40 entrance. The corresponding total

dose in the barracks was 97 μSv. This translates into a dose rate of $9.2x10^{-23}$ Sv per proton and of $1.24x10^{-22}$ Sv per proton respectively. Assuming an intensity of $8x10^{12}$ pot/s during CNGS operation ($4.8x10^{13}$ protons per cycle), a dose rate of 2.7 μSv/h has to be expected during beam operation on the ground floor.
The dose rate estimated in the barracks is 3.6 μSv/h. Presently, the nominal integrated proton flux for CNGS is $4.5x10^{19}$ pot per year. This will generate a yearly dose of 4.1 mSv on the ground floor and of 5.6 mSv in the barracks. With the quoted (annual) PS2 intensity the existing dose limit in ECA4 (6 mSv per year for a supervised radiation area) will be exceeded and the zone will have to be reclassified or the shielding of ECX4/ECA4 improved. Reclassification to a simple controlled area will imply that proper work and dose planning is necessary before any work can be performed. Furthermore, the use of an operation dosimeter, in addition to the personal dosimeter, is required.

e - **Equipment manipulation**: Re-evaluation needed.

Summary: All RP related calculations will have to be revised and consequences on the design of the corresponding systems evaluated. Radioactive waste studies are needed and possible re-classifications of areas might be required. Experience from running the facility during a longer period is crucial to assess the performance of the systems – i.e. ventilation filters, release of activated water from the sumps etc. - and to compare the theoretical models with measurements in view of future high intensity runs. New INB approval from IRSN is mandatory.

2-3-2 Impact on the CNGS target

The structural limits of the CNGS target have been calculated during its design phase [Target1, Target2].
The mechanical limits are set by the dynamic stresses (intrinsically linked to the beam time structure) and static stresses (linked to the beam profile).
The thermal limits are determined by the cooling system with consequences on the target density and thermal load dilution.
The radiation damage will lead to defects (annealing at high temperature) and target failure (in-situ spares and quick remote exchange were included in the design of the target system).
Presently, the limit of the CNGS target is set by the dynamic stresses. However, spreading the extracted protons into more batches and increasing the spacing of the proton extractions would allow increasing the proton beam intensity up to the maximum deliverable by PS2 (10^{14} protons per cycle in the SPS). In fact, the average beam intensity per cycle can even be made higher if the number of protons per extraction does not exceed $3.5x10^{13}$, the number of extractions is increased and the time interval between them is made longer than the nominal 50 ms – e.g. 200 ms.
In these conditions, the target cooling would become the limiting factor because of graphite sublimation (target rod Temp. < Tmax = 1400^{o} C) and degradation of the helicoflex seals of the target unit (seal Temp. < 250^{o} C).
Graphite sublimation is expected to be the dominant problem. It will be reached with a maximum average thermal power on target of 1.5 MW (i.e. $1.4x10^{14}$ pot per 6 s cycle or twice the present ultimate CNGS intensity).

Radiation damages have also to be considered. The design value with a circular beam spot of 1 mm radius is $2x10^{20}$ pot per year, which corresponds to a continuous operation at ultimate CNGS intensity. Under these conditions, a target is estimated to survive approximately one year. This estimate is based on the following information, weighted by safety factors:

- experimental results at TRIUMF which show that graphite targets fail after about ~$2x10^{23}$ pot/cm^2 with a 500 MeV-dc beam [Sievers] (safety factor 10).

- published data which indicate that isotropic polycrystalline graphite fails at a fluence of ~$1x10^{22}$ fast neutrons/cm^2 (safety factor 2).

Simulation codes such as FLUKA could be used to provide the damage (expressed in dpa) in the target rods and to compare this value with the dpa due to neutron damage (also available in literature).

<u>Summary:</u> With the foreseen operating mode (less than $3.5x10^{13}$ protons per extraction and less than 1.4 $x10^{14}$ protons per cycle), the CNGS target can be used with the maximum beam expected from PS2 (section 2-1).

However, more simulation work would still be required to optimize the time between extractions. Going to higher values than nominal (much more than 50 ms) will have the benefit of decreasing the static stresses.

If the integrated proton flux remains below $2x10^{20}$ pot, the present CNGS target can be used, with an estimated lifetime of about one year. Beyond this value, target failure will increase - requiring frequent target exchange- and a new design is to be performed.

It must however be underlined that, after the planned 5 years run for CNGS, the target chamber will be so activated that the replacement of the present target and its shielding by a new assembly will be extremely challenging if not impossible.

2-3-3 Impact on the Horn systems

The water cooling systems of the horns have been designed for the maximum proton flux of $7.2x10^{13}$ protons every 6 s. Upgrade and/or new design of the cooling system will be required for increased intensity.

The ventilation cooling system of the equipment along the target chamber has been dimensioned for a flux of $1.38x10^{20}$ pot per year.

The horns need to be operated during at least one SPS running period, in order to benchmark the validity of the design and the models. Thermo sensors positioned all along the equipment in the target chamber will give essential information on the effectiveness of the air cooling system and will indicate as well if there is indeed a safety margin in the cooling system. These measured values will allow extrapolating equipment temperatures to operation at higher intensity.

If the CNGS facility has to run at higher flux, beyond the presently planned 5 year run with 4.5 $x10^{19}$ protons/year, it is likely that new horns will have to be designed, using the knowledge gained during the first run.

Moreover, if more than 2 extractions per cycle are used or if the total cycle length is decreased, the entire cooling system will have to be redesigned. In addition, an additional capacitor bank will have to be installed for each additional extraction. It is recalled that it currently takes 4 s to re-charge them. Installation of additional capacitor banks will require the construction of an additional surface building at SPS point 4. In addition, space will be needed for new transformers in the service gallery.

Finally, the effect on the horn of increasing the time interval between 2 extractions beyond 50 ms requires detailed investigations.

<u>Summary:</u> Beyond $7x10^{13}$ protons per CNGS cycle, and $1.38x10^{20}$ pot per year, upgrade / new design of the cooling systems (water and ventilation) will have to be performed. By design, the mechanical lifetime of the horn is set at $2x10^7$ pulses. Therefore, after the presently planned 5 year run, new horns will have to be designed, built and installed.

As for the target, it must be underlined that, after the planned 5 years run for CNGS, the target chamber will be so activated that the removal of the horn of the first generation and its replacement with a newly designed device will be extremely challenging if not impossible.

2-3-4 Impact on CNGS proton beam line instrumentation

All equipment is designed for a dynamic range from $1x10^{12}$ to $3.5x10^{13}$ protons per extraction, with a 200 MHz bunch structure. Deviation from these nominal parameters will require changes in the beam instrumentation systems.

3- Summary

The intensity limitations coming from equipment in the CNGS facility are summarized in Table 6.

***Table 6**: Intensity limitations from equipment in the CNGS facility*

Intensity limitation	**Protons per batch**	**Protons per 6 s cycle**	**Proton flux [pot per year]**	**Comments in sections:**
Radiation Protection calculation and optimisation	$3.5x10^{13}$		Soil/concrete activation: $4.5x10^{19}$ Air/water activation: $7.6x10^{19}$	1-4-1 & 2-3-1
Target design	$3.5x10^{13}$	$1.4x10^{14}$	$2x10^{20}$	1-4-2 & 2-3-2
Horn design	$3.5x10^{13}$	$7x10^{13}$	$1.38x10^{20}$	1-4-3 & 2-3-3
Shielding, Decay Tube, Hadron stop design			$1.38x10^{20}$	1-4-4
Kicker system	$3.5x10^{13}$	$1x10^{14}$		1-3-2 & 2-2-3
Instrumentation	$3.5x10^{13}$			2-3-4

On the accelerators' side, the main limitation comes from the SPS RF system. The estimations of the integrated proton flux (pot per year) which can be delivered to CNGS using the most promising scenarios discussed in the report are summarized in Table 7.

Table 7: Protons on target per year [x10^{19}] for 200 days of operation with 80% machine availability

	SPS cycle length	6 s		4.8 s	
	Injection momentum	14 GeV/c		26 GeV/c	
	Beam sharing Max SPS intensity @ 400GeV [x10^{13}]	0.45	0.85	0.45	0.85
Present injectors + machines' improvement	4.8 – "Nominal CNGS"	5	9.4		
	5.7- "Max. SPS"	5.9	11.1		
Future injectors + SPS RF upgrade	7 – "Ultimate CNGS"			9	17.1
Future injectors + new SPS RF system + CNGS new equipment design	10 – "Max. PS2"			12.9	24.5

- With the present injectors: The maximum achievable beam intensity in the SPS is estimated to be 5.7x10^{13} protons per cycle with machine improvements aimed mainly at beam loss reduction (see section 1-3-1). Increasing further the intensity to the ultimate CNGS value (7x10^{13} protons per cycle) is not attractive because it does not increase the proton flux due to the longer cycle of 7.2 s and because it requires an upgraded RF system (see section 1-3-3). With 5.7x10^{13}, about **1.1x10^{20} pot per year** can be obtained in the scenario of 85% of the SPS beam dedicated to CNGS. Target and horn equipment of the CNGS facility are able to sustain this mode of operation. It must however be noted that the replacement of the initial equipment in the target chamber after the nominal 5 year run for CNGS will be extremely challenging. Moreover, before considering any operation beyond the present nominal CNGS conditions, all CNGS-RP related calculations/studies will have to be revised, including radioactive waste studies and corresponding area classifications. A new INB approval from IRSN will be required.
- With new injectors (after 2016): assuming a major upgrade of the RF power plant and solutions to the heating by the beam current of numerous equipment, the maximum number of protons accelerated per cycle can reach 1x10^{14} and the integrated proton flux can potentially attain **2.4x10^{20} pot per year** if the SPS is dedicated 85% of the time to CNGS. The CNGS facility itself will need a major rebuild, because of the difficulty to replace the first generation of equipment in the target chamber (activation and risk of contamination) and also because of the need to re-assess all radiation protection issues and to dimension the new equipment, tunnel and building accordingly. Radiation and waste studies will be required and the re-classifications of the areas will have to be considered. A new INB approval from the IRSN will be mandatory. Beyond 1.38x10^{20} pot per year, the design of most of the secondary beam line components must be reviewed and most probably re-designed to stand higher intensities.

  Most importantly, the experience that will be gained running the present CNGS facility will be very useful to benchmark design values, confirm or improve theoretical models and hence help design any upgraded facility for the future.

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A Acceleration cycles for the CNGS beam in the SPS

A.1 Magnetic cycles

In the present CNGS (or fixed-target, FT) cycle in the SPS beam is accelerated from 14 to 400 GeV/c in 3 s. The total cycle length is 6 s with 1.2 s long flat bottom. Compared to the LHC beam this beam crosses transition energy ($\gamma_t = 22.8$). The variation of the synchronous momentum with time and of its derivative with the synchronous momentum are shown for the present FT/CNGS cycle in Fig. 1.
Two scenarios are possible with the future PS2: injection at 26 GeV/c each 4.8 s or injection at 50 GeV/c each 6 s. In the absence of the flat bottom these cycles give correspondingly an acceleration time of 3 s and 4.2 s. These two new magnetic cycles were designed using the present CNGS cycle and are shown in Figs. 1, 2. The main advantage of the future upgrade is the absence of transition crossing in the SPS which now causes the longitudinal emittance blow-up and beam losses both at transition and at higher energies.

A.2 RF voltage and power requirements

The maximum total voltage available in the 200 MHz RF system is 8 MV (with a maximum of 7 MV in operation). The maximum available RF power in one cavity of the 200 MHz RF system (pulsed mode) is limited at 700 kW for a full SPS ring and at 1.4 MW for a half ring (however the last number is not yet tested experimentally).
The voltage programme used in operation with the present nominal magnetic cycle is shown in Fig. 3 (left) together with the 200 MHz RF power required during the cycle for acceleration of the nominal and ultimate CNGS intensities (right). After injection the 2σ longitudinal emittance (estimated from a Gaussian fit) is 0.18 eVs. A significant blow-up occurs at transition crossing and without additional beam stabilisation by the 800 MHz RF system for the nominal CNGS intensity the average emittance on the flat top is close to 0.5 eVs.
With the PS2 in operation the new filling scheme provides a bunch-to-bucket transfer into the 200 MHz RF system of the SPS using 5-turn extraction from the PS2. For the initially assumed ratio of 5.5 of the SPS and PS rings the beam in the SPS would consist of 5 batches, each 3.1 μs long with a 1.1 μs kicker gap, leaving an additional 2 μs of empty space (a half of the PS2 ring). In this case, for the same total intensity, the local beam density in the SPS is increased by 37%. Changing this ratio to 5 improves the situation, but still leads to an increase in the RF current relevant for the beam loading and RF power limitations by 20% in comparison with the present situation. The RF current calculated for different CNGS intensities and SPS filling schemes is shown in Table 1.
The relevant voltage programme and required RF power for the existing 200 MHz RF system for different total CNGS beam intensities, SPS filling schemes and cycle lengths are presented in Figs. 4-6.
For the SPS-PS2 ring ratio of 5.5 and the SPS 4.8 s long cycle with injection at 26 GeV/c from Fig. 1, the corresponding 200 MHz RF voltage programmes calculated for different longitudinal emittances with a momentum filling factor of the bucket

	I_{rf} [A]		
$N/10^{13}$	SPS= 11 PS	SPS = 5.5 PS2	SPS = 5 PS2
4.8	0.73	1.0	0.88
7.0	1.06	1.45	1.28
10.0	1.51	2.07	1.82

Table 1: The RF current used for RF power estimations calculated for different CNGS intensities and SPS filling schemes.

of 0.95 are presented in Fig. 4 (left) together with the RF power per 200 MHz cavity needed for nominal, maximum and ultimate CNGS intensities. The scaling from the present instability thresholds for the LHC beam in the SPS shows that an emittance of 0.75 eVs is required to provide beam stability for the maximum CNGS intensity (10.0×10^{13}) at high energies (above 270 GeV/c) in the SPS.
For a ratio of 5 between the SPS and PS rings the maximum emittance could be 0.7 eVs. The corresponding voltage programme and required RF power are shown in Fig. 5 for the 4.8 s cycle and injection at 26 GeV and in Fig. 6 for the 6 s cycle with injection at 50 GeV/c. As one can see in the latter case the RF requirements could be significantly relaxed. However one should remember that to provide the same number of pot/year in this case the SPS should run at 25% higher intensities.

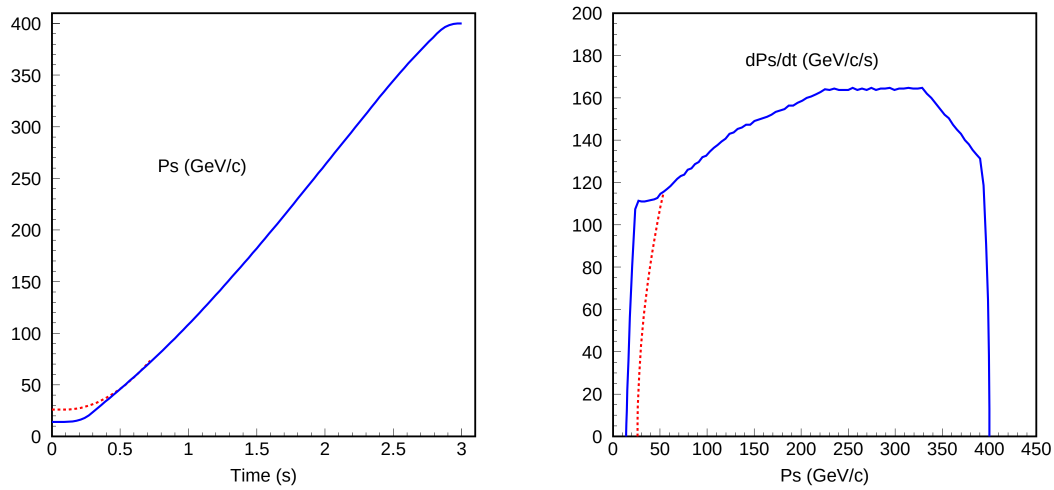

Figure 1: The synchronous momentum (left) and its derivative (right) for the present FT/CNGS cycle (solid blue line) and the first part of the new cycle (red dashed line) with an injection at 26 GeV/c with the future PS2.

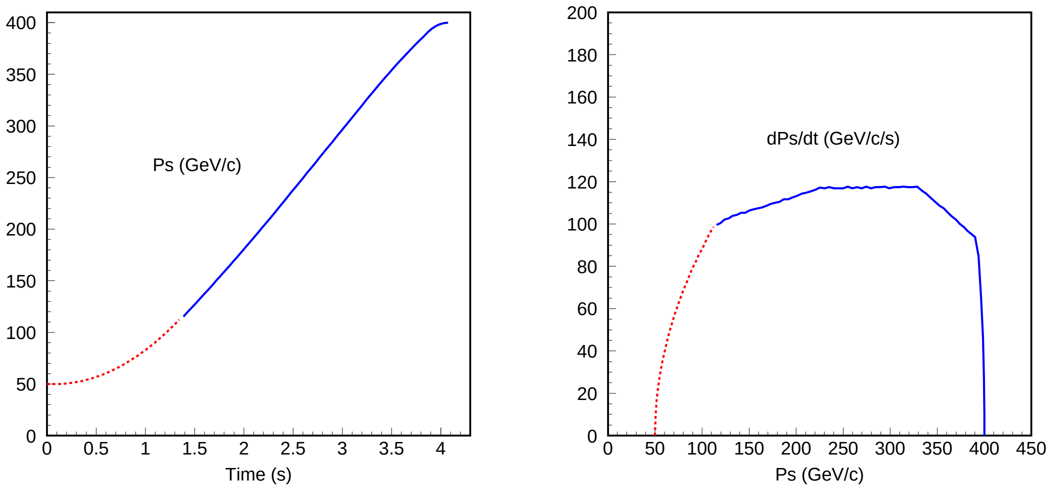

Figure 2: The synchronous momentum (left) and its derivative (right) for the new SPS cycle with injection at 50 GeV/c possible with the future PS2. This cycle is 40% longer then the present CNGS cycle and is produced by stretching the combined cycle which consists of a new initial part (red dashed line) joined to the present CNGS cycle (solid blue line).

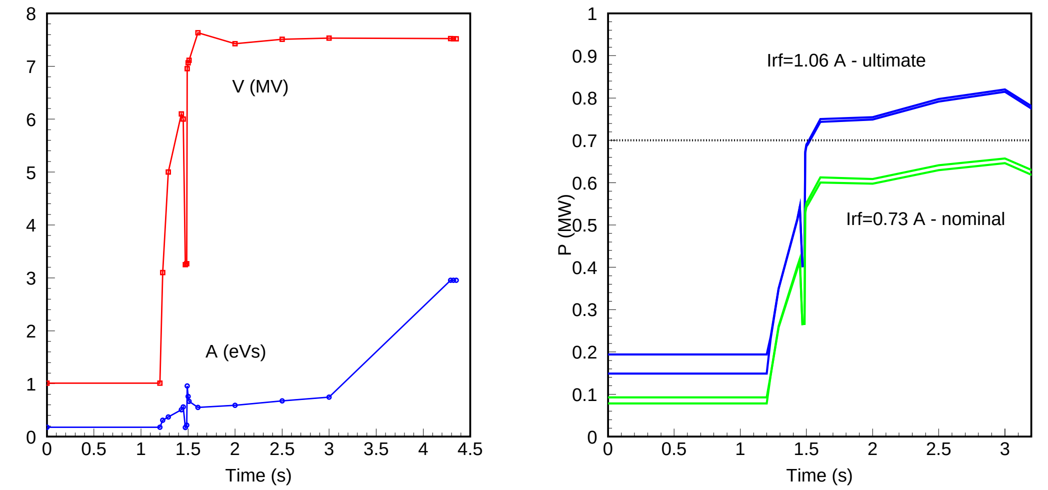

Figure 3: The nominal CNGS cycle in the SPS. Left: one of the voltage programmes used during the high intensity run in September 2004 together with the provided bucket area. Right: peak power per cavity (shown for 4 and 5 sections) corresponding to this voltage programme needed for the total beam intensity of 4.8×10^{13} and 7×10^{13}.

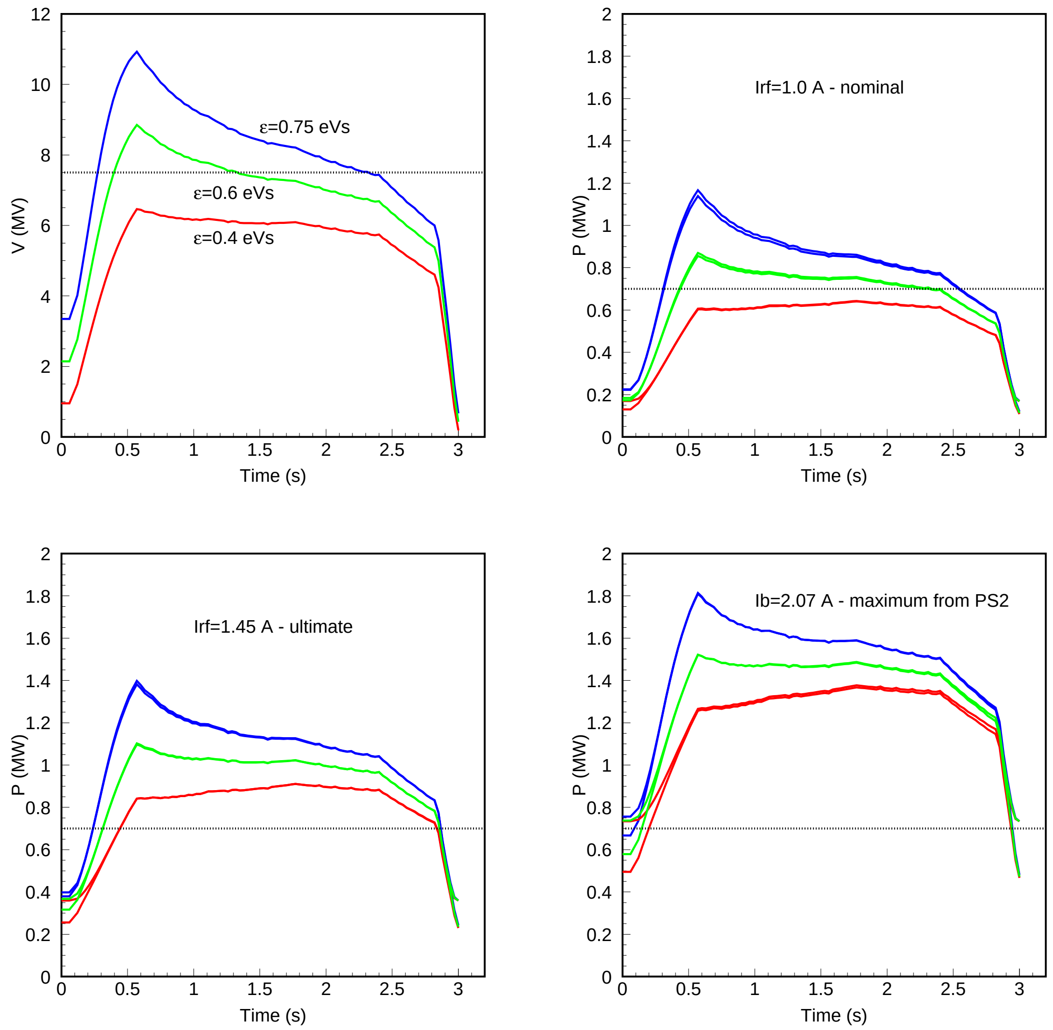

Figure 4: The SPS cycle with injection at 26 GeV/c from PS2=SPS/5.5. Top: voltage programmes found for the longitudinal emittances of 0.4, 0.6 and 0.75 eVs with a momentum filling factor $q_p = 0.95$ (left) and corresponding peak power per cavity (for 4 and 5 sections) needed for the total CNGS beam intensity of 4.8×10^{13} distributed in 5 batches of 3.1 μs each (right). Bottom: RF power for the same filling scheme and total beam intensity of 7×10^{13} (left) and 1×10^{14} (right).

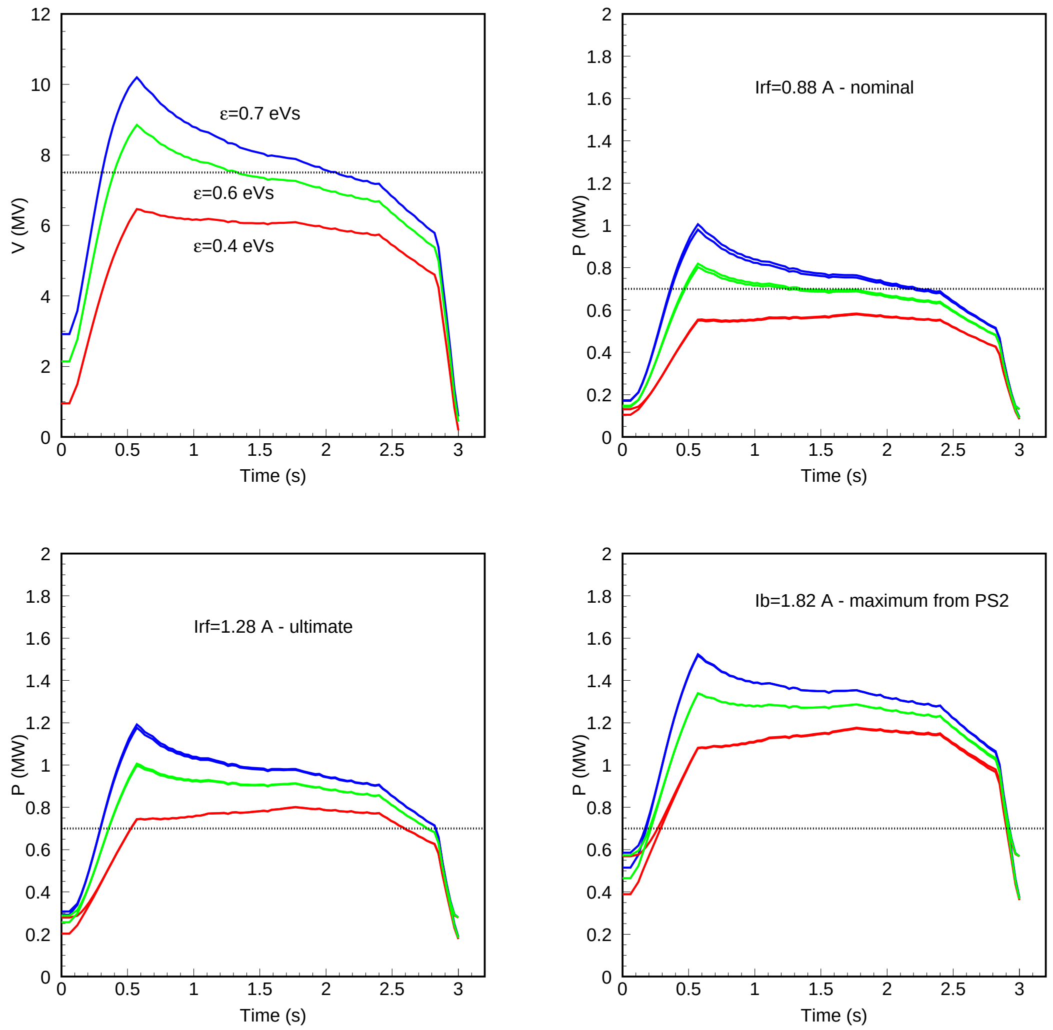

Figure 5: The SPS cycle with injection at 26 GeV/c from PS2=SPS/5. Top: voltage programmes found for the longitudinal emittances of 0.4, 0.6 and 0.7 eVs with a momentum filling factor $q_p = 0.95$ (left) and corresponding peak power per cavity (for 4 and 5 sections) needed for the total CNGS beam intensity of 4.8×10^{13} distributed in 5 batches of 3.5 μs each (right). Bottom: RF power for the same filling scheme and total beam intensity of 7×10^{13} (left) and 1×10^{14} (right).

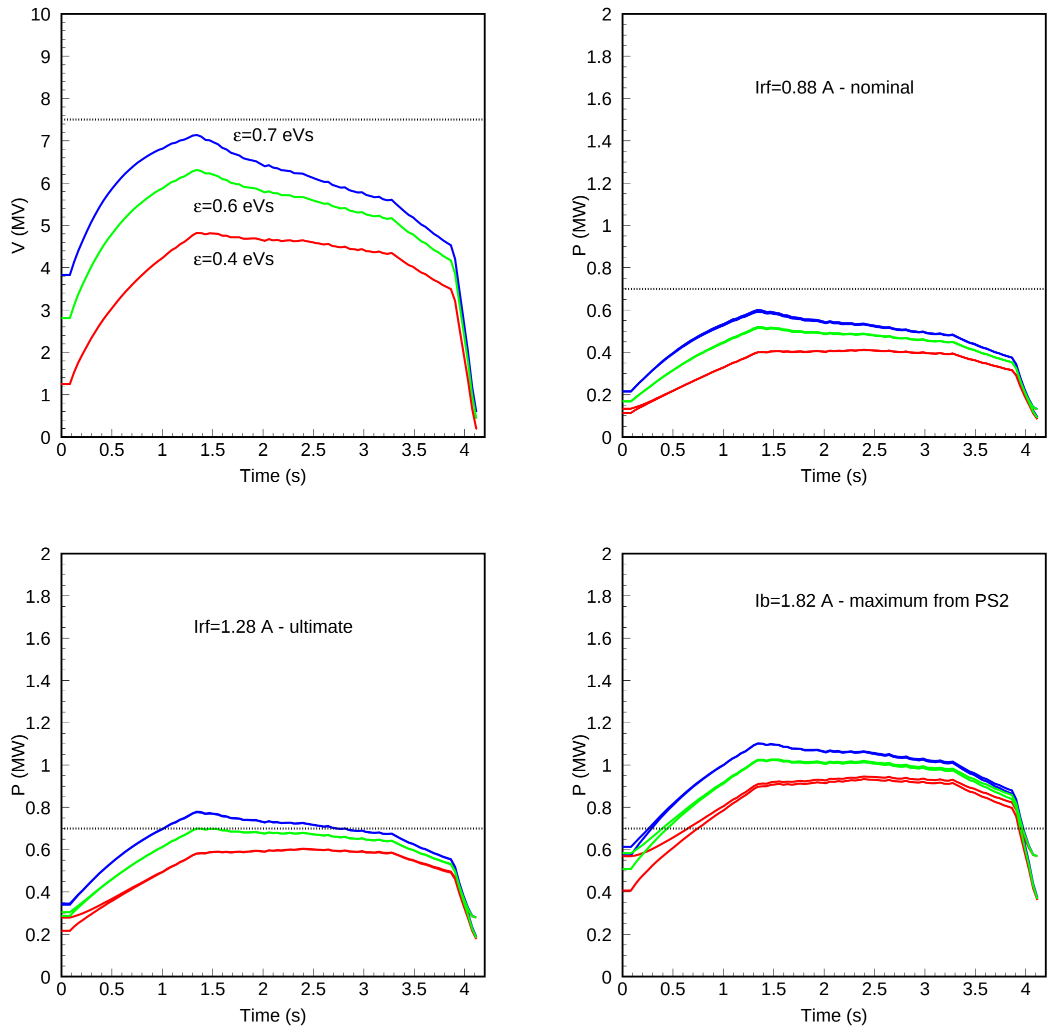

Figure 6: The SPS cycle with injection at 50 GeV/c from PS2=SPS/5 and acceleration time of 4.2 s. Top: voltage programmes found for the longitudinal emittances of 0.4, 0.6 and 0.7 eVs with a momentum filling factor $q_p = 0.95$ (left) and corresponding peak power per cavity (for 4 and 5 sections) needed for the total CNGS beam intensity of 4.8×10^{13} distributed in 5 batches of 3.5 μs each (right). Bottom: RF power for the same filling scheme and total beam intensity of 7×10^{13} (left) and 1×10^{14} (right).