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Commissioning of the CNGS Extraction in SPS LSS4

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Abstract

The CNGS project (CERN Neutrino to Gran Sasso) aims at directly detecting ν_μ - ν_τ oscillations. For this purpose an intense ν_μ beam is generated at CERN and directed towards LNGS (Laboratori Nazionali del Gran Sasso) in Italy, about 730 km from CERN. The neutrinos are generated from the decay of pions and kaons which are produced by 400 GeV protons hitting a graphite target. The protons are extracted from the SPS straight section 4 (LSS4) in two 10.5 μs batches, nominally 2.4×10^{13} protons each, at an interval of 50 ms. The high intensity extracted beam can cause damage to equipment if lost in an uncontrolled way, with the extraction elements particularly at risk. In addition, the beam losses at extraction must be very well controlled to avoid unacceptably high levels of radiation. To guarantee safe operation and limit radiation, the LSS4 extraction system was thoroughly commissioned with beam during the CNGS commissioning in summer 2006. The obtained results in terms of aperture in the extraction channel, longitudinal loss patterns, extraction losses and radiation during nominal operation are summarised in this note.

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1. INTRODUCTION

The aim of the CNGS (CERN Neutrino to Gran Sasso) project is to prove the existence of neutrino oscillations [1,2]. The ingredients for this endeavour are an intense neutrino beam of a single neutrino type directed at remote detectors. The distance to the detectors must be sufficiently large that the neutrinos can undergo oscillations into a different type. In the case of CNGS, ν_μ neutrinos are generated using the CERN complex and sent to the Gran Sasso laboratory (LNGS) in Italy at a distance of 732 km, which will detect ν_τ appearance events. OPERA is one of the main experiments at LNGS with the goal to measure neutrino oscillations. CNGS provides ν_μ neutrinos with energies in the range 5 and 30 GeV, chosen to optimise the detection at Gran Sasso of ν_τ neutrinos.

At CERN the neutrino beam is produced by extracting 400 GeV protons from SPS point 4 (LSS4) and transporting them onto a graphite target. Between the extraction point and the target the proton beam is guided through about 940 m of transfer lines TT40/TT41, and deflected by 33 degrees in the horizontal plane and 3.2 degrees in the vertical plane, such that at the point of the target it is directed exactly towards Gran Sasso. The secondary kaons and pions generated in the target are focussed and energy selected by two pulsed magnetic lenses called “horn” and “reflector”. The kaons and pions are then allowed to decay into muons and neutrinos in a 1 km long evacuated decay tube. All primary protons which have not interacted in the target and all secondary particles which have not decayed are absorbed by a dump block called the “hadron stop” at the end of the decay tube.

The required extracted intensity for one of the 6 s long CNGS cycles in the SPS is 4.8×10^{13} protons. Due to the limited robustness for shock impact of the CNGS target, this intensity is delivered in two SPS extractions of 10.5 μs batches of 2.4×10^{13} protons separated by 50 ms. These two batches of beam have a 5 ns bunch spacing and fill the entire circumference of the SPS (23 μs) except for two ~1 μs gaps required to accommodate the rise and fall time of the fast extraction kicker system in LSS4. The beam characteristics are summarised in Table 1.

CNGS was successfully commissioned with beam in summer 2006, including careful commissioning of the high intensity extraction and quantification of the loss mechanisms during the extraction process and the associated induced radiation. The details of the commissioning of the extraction system in LSS4 are described in this note. The results for available aperture in the extraction channel, longitudinal loss patterns, losses and radiation close to the extraction region during normal operation are summarised.

Table 1 : Nominal CNGS beam parameters.

Beam Parameters	Nominal CNGS Beam
Nominal energy [GeV]	400
Normalised emittance [μm]	H = 12, V = 7
Emittance [μm]	H = 0.028, V = 0.016
Momentum spread $\Delta p/p$	0.07% (± 20 %)
# extractions per cycle	2 separated by 50 ms
Batch length [μs]	10.5
# bunches per pulse	2100
Intensity per extraction [10^{13} p^+]	2.4
Bunch length [ns] (4 σ)	2
Bunch spacing [ns]	5

1.1. Description of the LSS4 Extraction System

The LSS4 fast extraction [3] is based on a horizontal closed orbit bump generated by four orbit bumpers, five fast horizontal extraction kicker modules (MKE) and six DC horizontal electromagnetic septum (MSE) magnets. The closed orbit bump moves the beam close to the septum magnets and thus reduces the strength needed of the fast kicker magnets. Three enlarged quadrupoles (QDA417, QFA418 and QDA419) are installed in the region to provide enough aperture for the bumped and the extracted beam. Their good field region extends to 90 mm, compared to 70 mm for standard lattice quadrupoles. The QDA419 defocusing quadrupole has a horizontal opening (window) in its coil which is equipped with a vacuum chamber for the passage of the extracted beam. The field in this window is quadrupolar, horizontally focusing with a gradient of 16 % and opposite sign of the main gap field and the zero-axis displaced by 0.3009 m with respect to the main quadrupole axis.

To extract the beam, the MKE kicker field rises during the 1 μs gap in the circulating beam and deflects the beam across the MSE septa. The two extractions per cycle required for CNGS impose short fall and rise times of about 1 μs on the kickers and a flat top length of ≥10.5 μs. The MSE septa then deflect the beam by about 12 mrad out of the SPS vacuum chamber into the QDA419 coil window and then into the transfer line TT40, the first part of the CNSG proton line. The MSE magnets are mounted on a girder and pre-aligned to follow the trajectory of the extracted beam to provide maximum aperture. The girder is motorised to allow retraction of the septum and optimisation of the local aperture when setting up the SPS at injection.

The trajectory of the extracted beam was matched with MAD-X, using as constraints that the SPS orbit has to be flat outside the extraction region, the maximum extracted trajectory excursions have to be 31.5 mm at the beam position monitor BPCE.418 right upstream of the extraction septa, 85 mm in QFA418 and 260 mm at the coil window of QDA419. The required element strengths are summarised in Table 2. The kick angle corresponds to an applied MKE voltage of 50.0 kV.

Table 2 : Nominal strengths for extraction bump, kickers and septa in LSS4 for CNGS beam. The MSE angle is the final value after beam steering.

Element	**Strength** [mrad]
HB1	-0.001
HB2	0.496
HB3	0.348
HB4	0.124
MKE-S	0.110
MKE-L	0.121
MSE	2.1133

2. EXTRACTION CONSTRAINTS

2.1. Machine Protection

The nominal extracted intensities for CNGS are an order of magnitude above the energy density limit for equipment damage in case of beam loss. Active and passive protection systems are provided to minimise the risk of damage in the event of equipment malfunction. Passive protection is provided by an absorber in front of the septa - the TPSG. It protects the septa from kicker failures or mis-steered beam due to other reasons, see Fig. 1. The TPSG in LSS4 is a 2.9 m long diluter with a sandwich structure made of 2.1 m graphite (1.77 g/cm^3) and 0.8 m aluminium alloy. Active protection is provided by a sophisticated extraction interlock system, which only gives the extraction permit to the extraction kickers in case all monitored parameters are within specified tolerances. The beam position at the extraction point, beam losses, bumper and septum currents, the kicker charging voltages and MSE girder position are all interlocked [4,5].

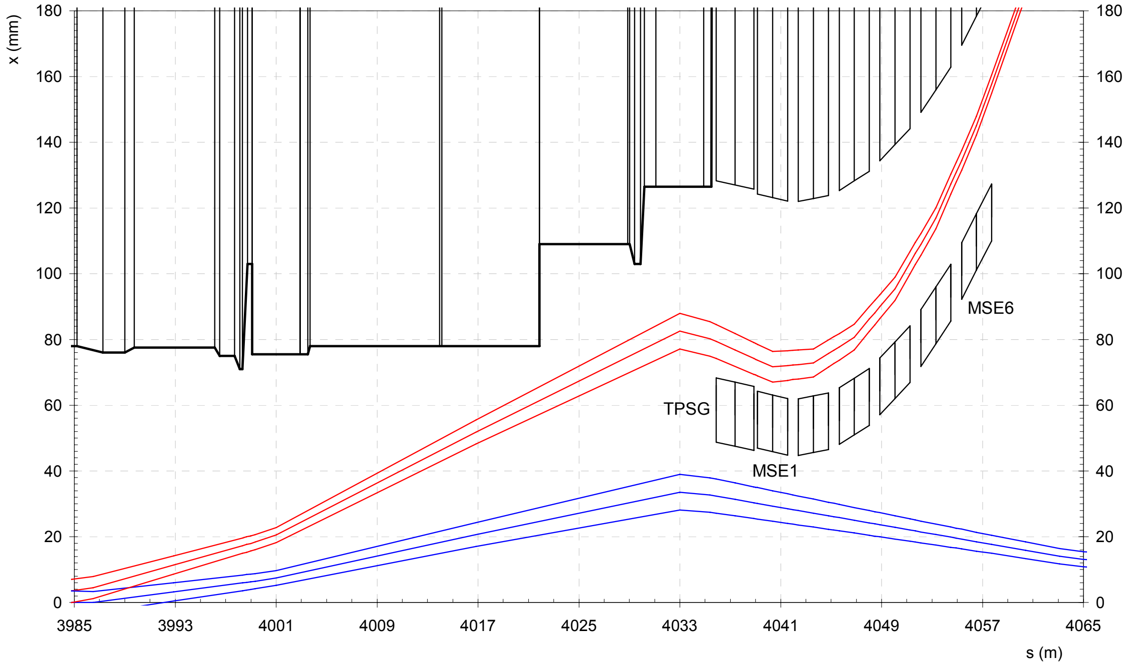

Figure 1 : Extraction region LSS4 with TPSG and septa and the circulating bumped orbit in blue and extracted trajectory in red.

2.2. Aperture in the Extraction Channel

The aperture must be adequate for the injected beam, the circulating bumped beam and extracted beam in the extraction channel, in order to minimise the beam losses in the extraction region and also to minimise the risk of damage to the septa during e.g. a kicker failure. The design value for the aperture of the circulating bumped beam is $\geq 9.3\ \sigma$ between orbit and TPSG inside edge. For the extracted beam the design is $\geq 6.5\ \sigma$ between the outside edge of the TPSG and the beam centre, and for the injected beam $\geq 5.7\ \sigma$ between the TPSG and the beam axis, Fig. 2.

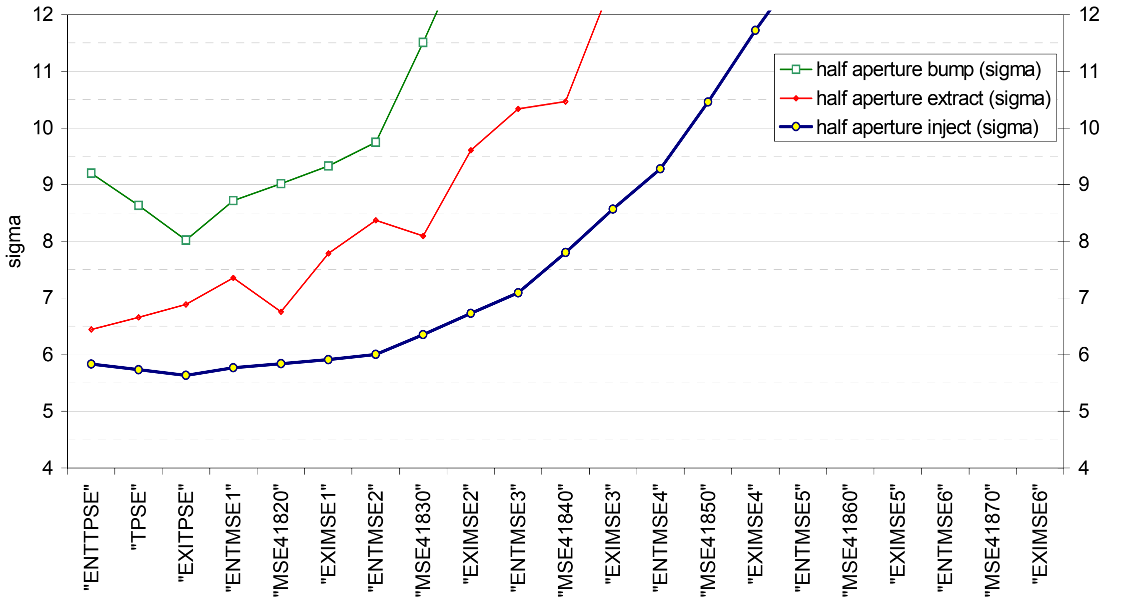

Figure 2: Calculated half aperture in the horizontal plane for the CNGS beam (14 – 400 GeV/c, 12 μm emittance, ± 1 mm mechanical tolerance).

2.3. Beam losses and radiation levels in ECA4

ECA4, a zone close to the extraction region, see Fig. 3, is unlimited accessible for radiation workers during operation with beam. Radiation monitors are in place to monitor the equivalent dose rate. The interlock thresholds on the monitors on the floor (PAXTA40) and in the barracks (PAXU405) were set to 5 μSv/h. Simulations [6,7] have shown that this dose rate corresponds to a beam loss at the TPSG of about 0.1 % of the nominal extracted CNGS intensity per batch. The loss level and radiation measurements in 2006 were very important in order to benchmark the aforementioned simulations and to determine whether additional shielding measures would be required, for instance local shielding at the TPSG (which is technically very difficult), or whether the access to the ECA4 area would need to be restricted for areas where radiation levels exceed the legal limits.

Beam losses in the extraction region are monitored with eight Beam Loss Monitors (BLMs). The monitor layout along the extraction channel can be seen in Fig. 4. The first monitor is on the TPSG absorber, each septum magnet is equipped with one BLM and the last loss monitor is right downstream of the septa. The layout names of the monitors are listed in Table 3.

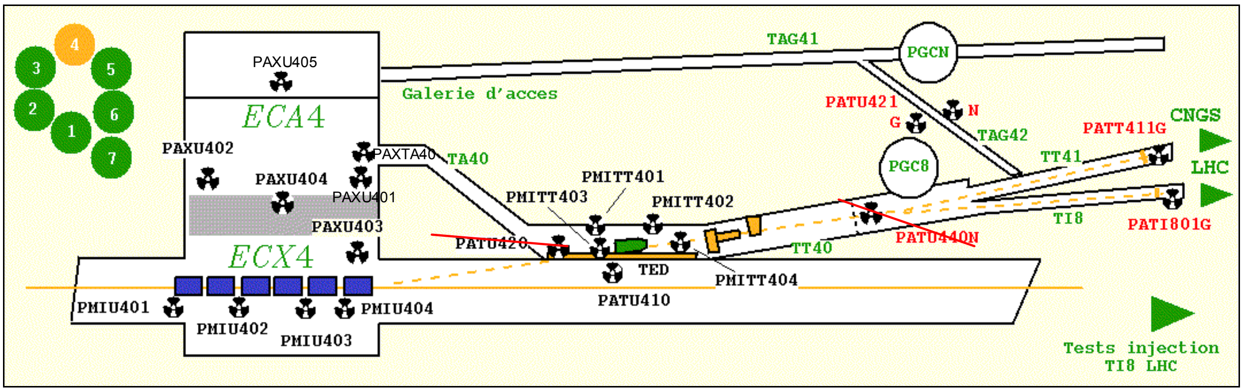

Figure 3: Layout of the access zones and radiation monitoring devices close to the extraction region ECX4.

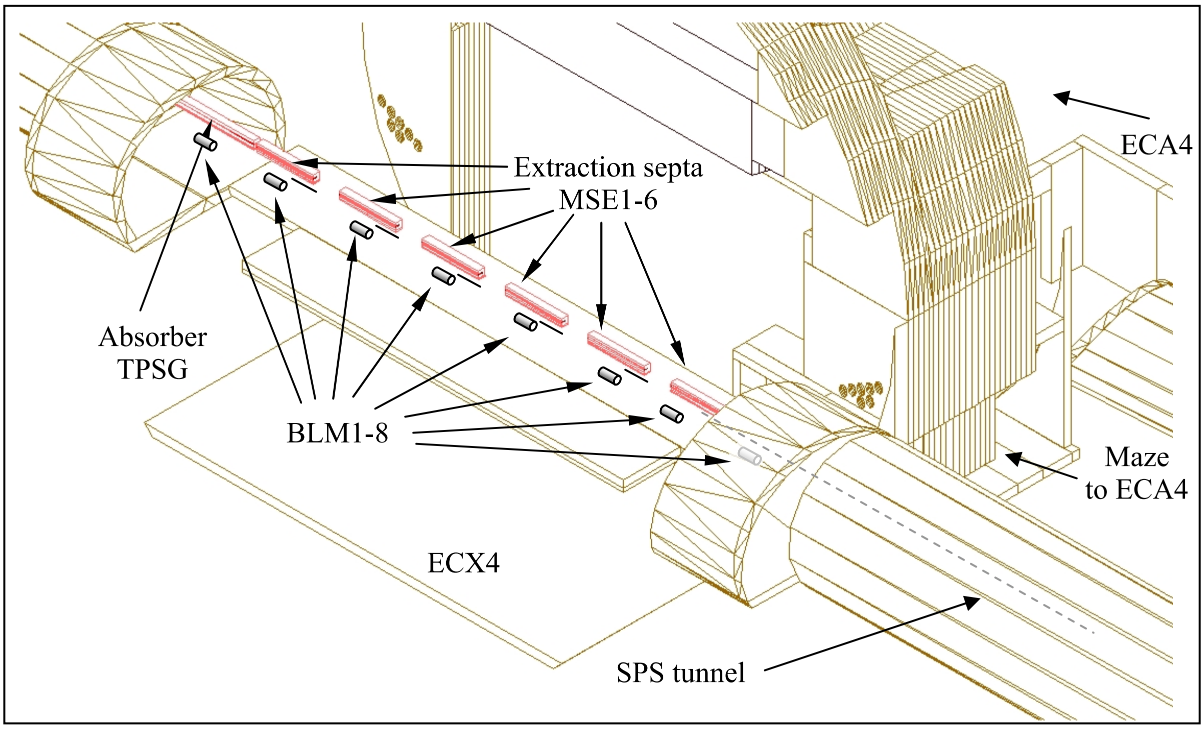

Figure 4: Tunnel, platform, shielding and beam loss monitor layout in the extraction region.

Table 3: Naming convention for beam loss monitors.

BLM layout name	
BL41835	BLM1
BL41839	BLM2
BL41854	BLM3
BL41859	BLM4
BL41874	BLM5
BL41879	BLM6
BL41884	BLM7
BL41897	BLM8

3. COMMISSIONING OF THE CNGS EXTRACTION – CALIBRATION

Three weeks of the 2006 SPS run were dedicated to commissioning of CNGS with beam (weeks 28, 30 and 33). In each commissioning week about half a day (3 – 5 hours) was spent purely on calibrating and measuring extraction related equipment and parameters yielding the required beam loss monitor thresholds to protect the extraction region and verifying the aperture in the extraction channel. All tests were carried out with low intensity beam ($3 \times 10^{11} – 2 \times 10^{12}$ protons), single extractions only. The tests involved loosing considerable fractions of the beam on the TPSG absorber in front of the septa causing elevated radiation levels in the nearby zone ECA4. ECA4 hence had to be closed throughout these half days of extraction setting-up. For all the tests described in this section the TED in TT40 was in beam to avoid badly extracted beam hitting the target and to minimise radiation in TT41.

3.1. Calibration of Beam Loss Profiles

The TPSG is in the vacuum of the circulating beam (inside edge) and the extracted beam (outside edge), Fig. 5. The beam loss profiles in mGy along the extraction channel for BLM1-8 were measured for beam lost on the inside and on the outside of the TPSG. Since the large steel support block will act as shielding for secondary particles lost towards the extracted beam side, the measured beam loss profiles for impact on the inside or outside of the graphite diluter block were expected to be different.

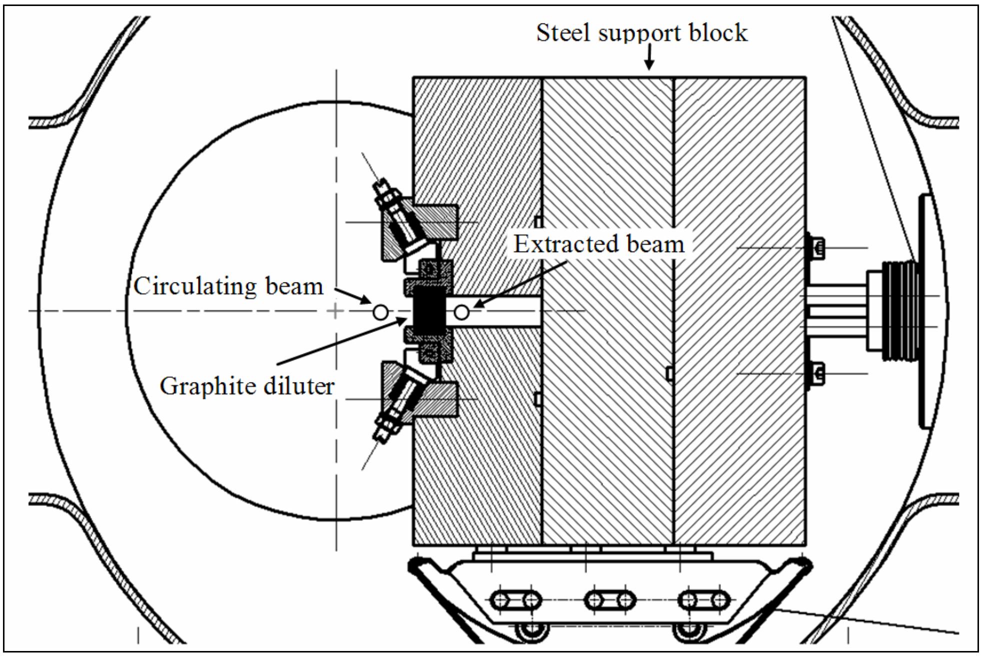

Figure 5: Cross section of the TPSG diluter.

The two profiles were obtained by steering the beam onto the TPSG:

- Inside edge: circulating beam, no extraction, increasing the extraction bump amplitude until the beam was lost.
- Outside edge: extracted beam, reducing the kick voltage (nominal bump amplitude) until beam was lost on the TPSG.

The measurements showed that, for the same number of lost protons, beam loss on the inside of the TPSG gives almost a factor 10 higher loss reading at BLM1 than for loss on the outside. The calibration curves mGy versus number of lost protons were established. The profiles in mGy per number of protons are the result of combining data of the BCTs in the SPS and in TT40 with the beam loss monitor readings at BLM1 to BLM8, see Fig. 6.

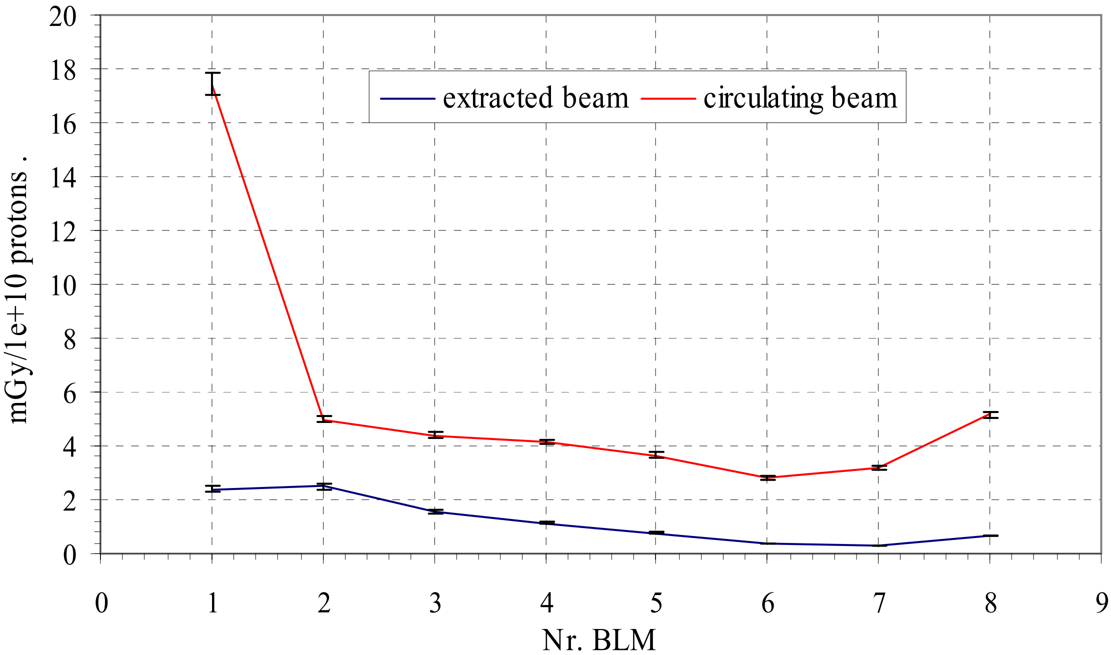

Figure 6: Beam loss per 10^{10} protons for extracted (outside edge of TPSG) and circulating (inside edge of TPSG) beam.

During normal operation the possible mechanisms for loss at the extraction elements are scraping of the beam tails on the inside or the outside of the TPSG or septa, and swept beam which originates from synchronisation errors or jitter between the kicker waveform and the beam gaps, spurious particles or bunched in the beam gap or too-lengthy kicker rise/fall times. These swept beam scenarios all lead to part of the beam being kicked during the fall or rise time of the kickers with 0 – 100 % of the required kick strength. Part of this insufficiently kicked beam stays in the SPS vacuum chamber, part of it is lost on the inside of the TPSG, part of it is swept across the TPSG block and part of it is either extracted badly or lost on the outside of the TPSG. The profile for an extreme case of a swept beam was measured as part of the commissioning of the extraction. For this purpose the kick delay was changed by 5 μs and 1 μs of the extracted batch was swept with 0 – 100 % kick angle. Fig. 7 summarises the beam loss ratios BLM(n)/ BLM1 (n = 1…8, for the 8 monitors) for swept beam, pure beam loss on the outside edge of the TPSG (kicker voltage set to 40 kV) and pure loss on the inside edge (bump set to 43.5 mm). It can be seen that the loss profile obtained with the sweep is a combination of the inside and outside loss profiles, with the curve lying between these two extremes.

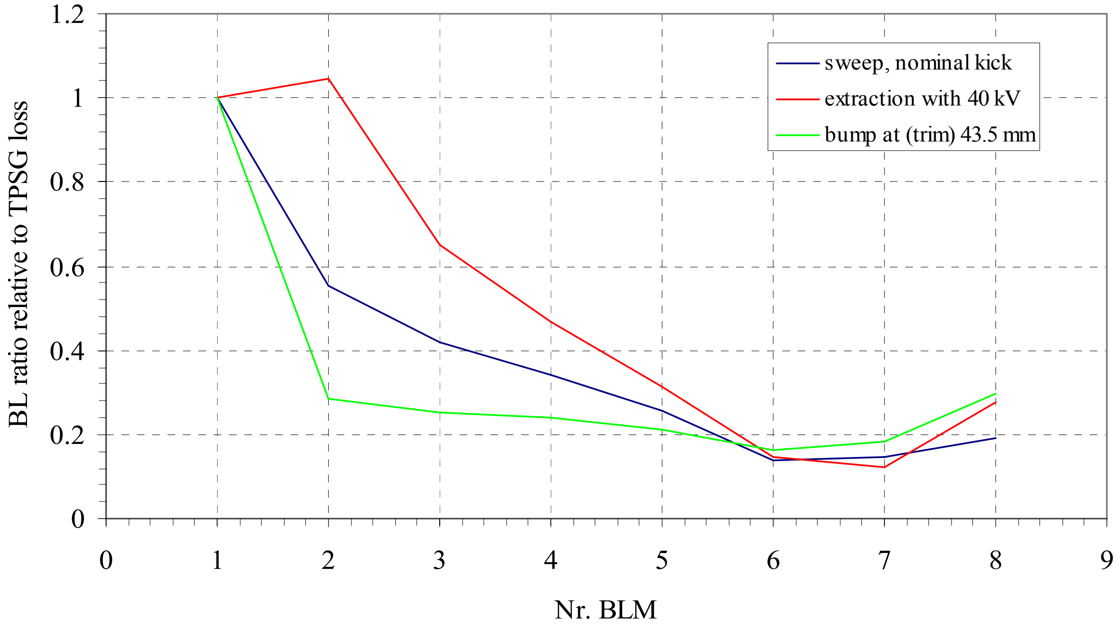

Figure 7: Comparison of loss patterns for losses on the inside, outside and swept across the TPSG.

3.2. Aperture Measurements

The horizontal emittance was ~ 4 μm normalised throughout the commissioning of the extraction channel, about a factor 3 smaller than nominal. The available aperture in the horizontal plane for the circulating and extracted beam at the TPSG was calculated from the calibrated beam loss profiles, see Fig. 8 and 9, together with the emittance information. Nominal optics (β_x=84.4 m at TPSG) and Gaussian beams were assumed. The beam position at the TPSG was calculated with MAD-X using the measured (calibrated) beam position at the beam position monitor BPCE.418. The resulting aperture for the circulating bumped beam and extracted trajectory is summarised in Table 4.

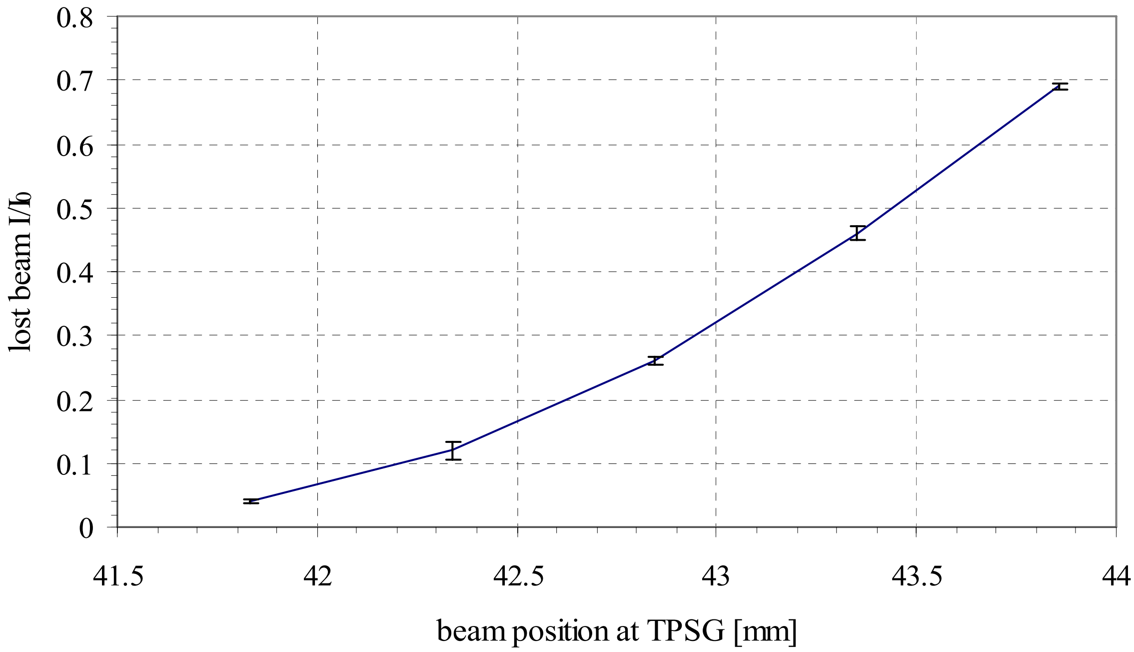

Figure 8: Relative losses at TPSG versus beam position.

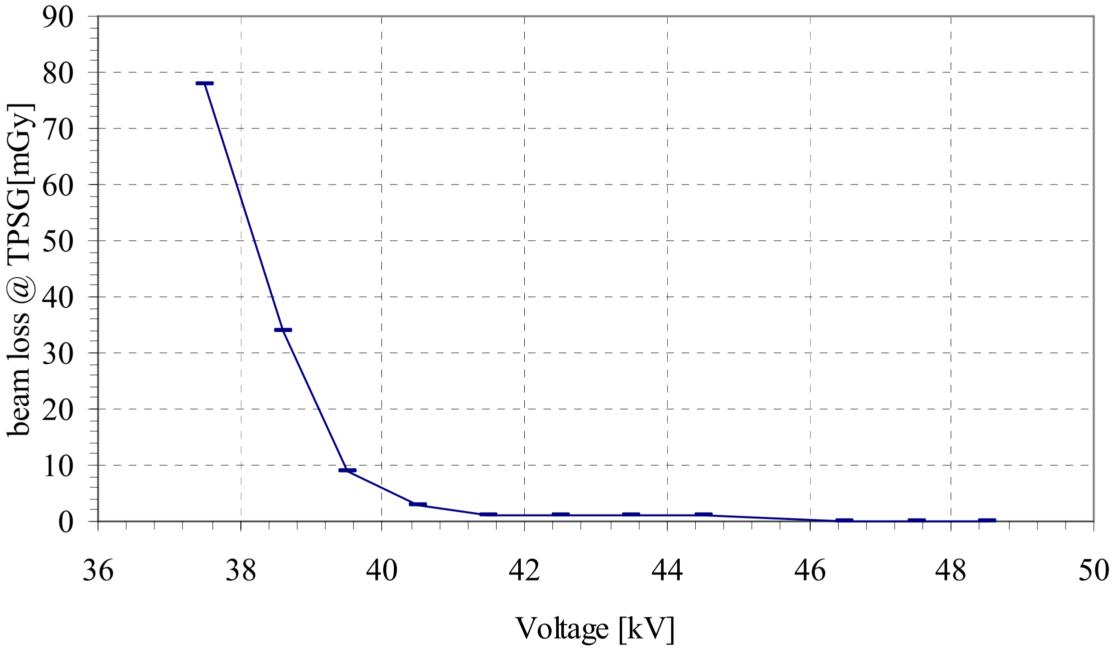

Figure 9: Kicker voltage versus beam loss at TPSG.

Table 4 : Measured aperture for circulating bumped beam and extracted trajectory.

Aperture for	**measured in [mm]**	**measured in [nominal σ]**	**design [σ]**
Circulating bumped beam	13.0 ±0.3	8.3 ±0.5	9.3
Extracted trajectory	10.6 ±0.3	6.8 ±0.5	6.5

As can be seen from Table 4, the aperture for the circulating bumped beam is slightly smaller than the design value and the extracted beam aperture is slightly larger. The overall error for this measurement over this very short period was estimated at ±0.5 σ, including ±300 μm on the position measurement (statistical) and estimated uncertainties on the wire scanner calibrations, 10 % beta beat, etc. Considering machine protection, sufficient aperture for the single pass of the extracted beam is more important than sufficient aperture for the circulating beam. Both apertures can be considered as sufficient.

3.3. Radiation Measurements in ECA4

The radiation measured in ECA4 on the different monitors was compared to the simulations carried out with FLUKA [6,7]. The results summarised in Table 5 were obtained for an intensity of 1.3×10^{11} protons lost on the inside edge of the TPSG, and compared to the predictions scaled to this intensity.

Table 5: Measured radiation in ECA4 during loss of 1.3×10^{11} protons on the inside edge of the TPSG.

	Calculation	**Measurement**
Top of shielding	~ 1230 nSv	~ 700 nSv
Barracks	~ 30 nSv	~ 20 – 27 nSv
ECA floor (entrance TT40)	~ 30 nSv	~ 14 – 20 nSv

The results are reasonably consistent with the measurements and less than a factor of two smaller than the predictions. Possible explanations for the discrepancies are:

- The real wall thickness between the ECA4 zone and the extraction region is in fact varying between 4.8 m and 5 m. In the simulation 4.8 m continuously were assumed.
- A new wall (40 cm thickness) at the “ECA4 maze exit” was not considered in the simulation.
- The radiation monitors were calibrated with an AmBe source (AmBe neutron spectrum is ranging up to 11 MeV), and the real response for the particle spectrum may be slightly different.

4. NORMAL OPERATION – EXTRACTION LOSSES

The three commissioning weeks were followed by two weeks of OPERA run. The interlocking thresholds had been adjusted according to the commissioning results, see [8] and below. During this period the number of extracted protons per batch was 1.7 x 10^{13}, with two extractions per cycle.

4.1. Beam Loss Monitor Measurements

Fig. 10 shows the averaged losses on the eight beam loss monitors in the extraction region for a 9 h period on 27th of August. Two earlier obtained profiles are also shown, scaled to the loss at the TPSG monitor – one for loss on the inside on the TPSG and one for loss on the outside of the TPSG.

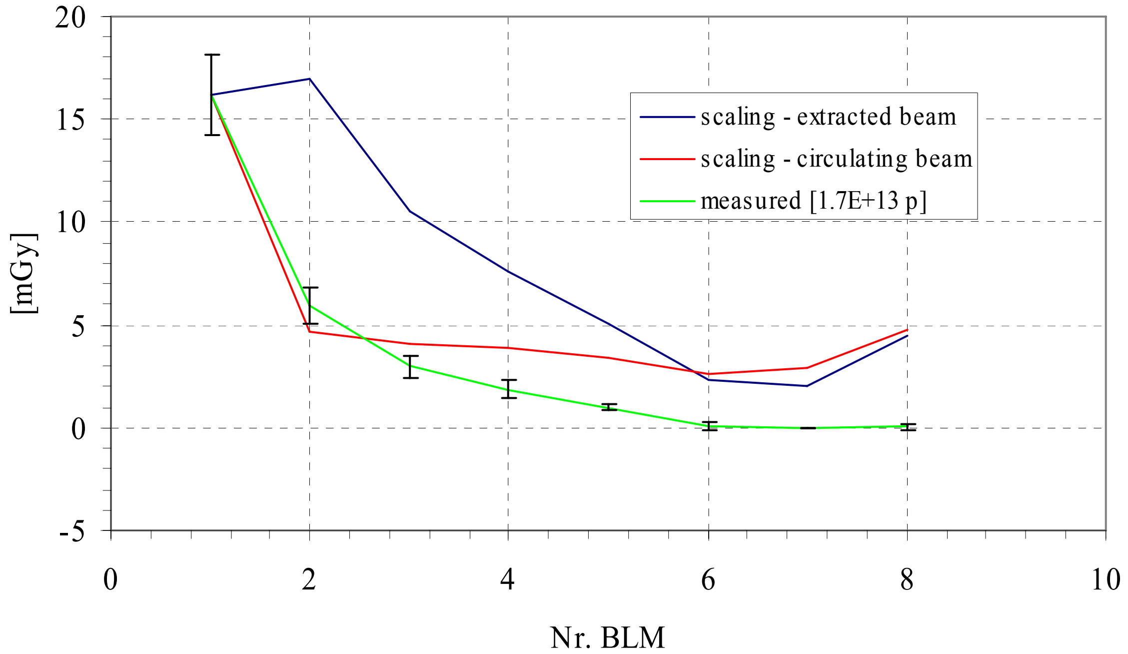

Figure 10: Comparison of beam loss profiles. The green curve is the measured averaged profile. For the red and blue curves the profiles for loss on the inside and outside were scaled to fit the loss on the TPSG.

By equating the number of protons lost at the TPSG with the measured mGy at the first monitor using the calibration curves from losses on the TPSG allowed an estimate to be made for beam loss per extraction, summarized in Table 6 for both inside and outside loss assumptions. However, the measured profile, Fig. 10, tends to follow the red profile (losses on the inside of the TPSG), indicating that the losses are mainly on the circulating beam side. The estimated extraction loss level is 0.05 %.

Table 6: Estimated loss per extraction during normal operation scaled with the profiles for losses on the outside of the TPSG (extracted beam) and on the inside of the TPSG (circulating beam.

	[%]
Scaling – extracted beam	0.39
Scaling – circulating beam	0.05

The origin of the extraction losses becomes clear when comparing the losses during first and second extraction. Fig. 11 shows the reading of the loss monitor at the TPSG over a period of 9 hours for the extraction of the first batch in blue and the second extraction in pink. For virtually all of the ~6000 extractions beam loss occurred only during the first extraction. In only one single case was there any beam loss recorded during the second extraction.

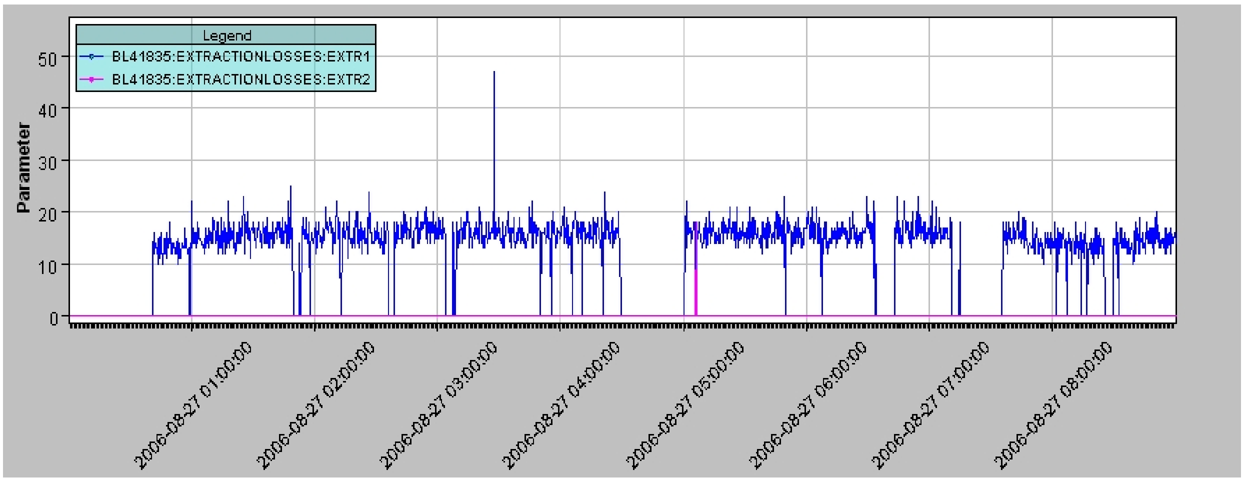

Figure 11: Logged beam loss data for first (blue) and second (pink) extraction for the beam loss monitor on the TPSG.

An explanation for this observation can be found with Fig. 12 and can be summarised as the following: losses during normal CNGS operation stem only from particles in the ~ 1µs long gaps between the two batches. These particles are swept over the TPSG during the rise and fall time of the extraction kick of the first extraction which takes place during these gaps. In this way both gaps are cleaned during the first extraction and no particles remain in the gaps for the second one.

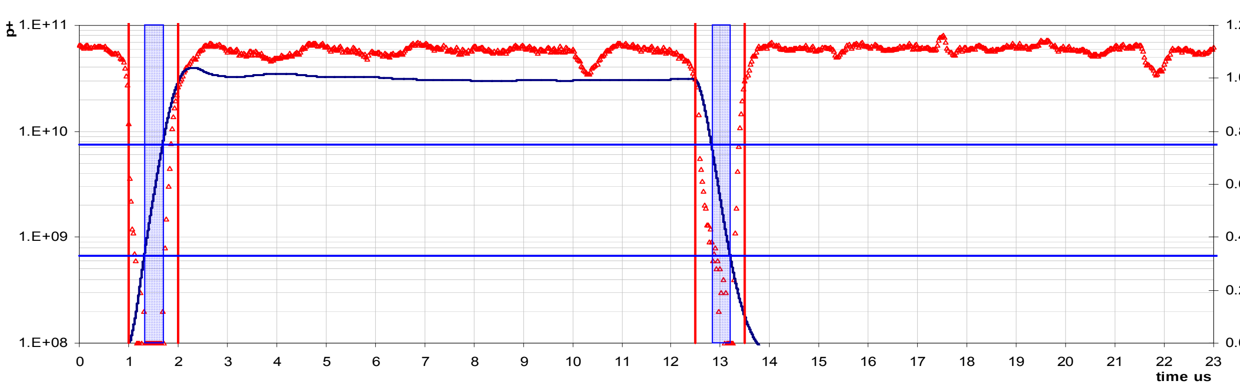

Figure 12: Measured particle distribution (red) around the SPS circumference and kicker waveform (dark blue) during first extraction.

The origin of losses during CNGS extraction could therefore be traced to spurious gap population causing beam to be swept across the TPSG during extraction. Since losses on the inside of the TPSG lead to larger signals on the BLMs than loss on the outside as demonstrated before, for the case of swept beam losses on the inside dominate the BLM reading. The calibration curves for mGy versus lost particles to determine the number of lost particles during normal running and to set the interlock thresholds is hence the one obtained with losing beam on the inside of the TPSG.

4.2. ECA4 Radiation Measurements

Fig. 13 presents the dose rate values measured at three different places in the ECA4 area during the CNGS OPERA operation. Within this period a total dose of 72 µSv (background subtracted) was measured on the ECA4 floor close to the TA40 entrance. Scaling with the monitor at the top corresponds to 0.043 % of the extracted intensity lost on the TPSG per extraction, scaling with the monitor at the floor level results in 0.057 % of the extracted intensity. The monitor on the top of the shielding has a lower uncertainty level due to the higher counting rate. These numbers confirm the result of about 0.05 % of the extracted intensity lost on the TPSG during normal operation obtained above in 4.1.

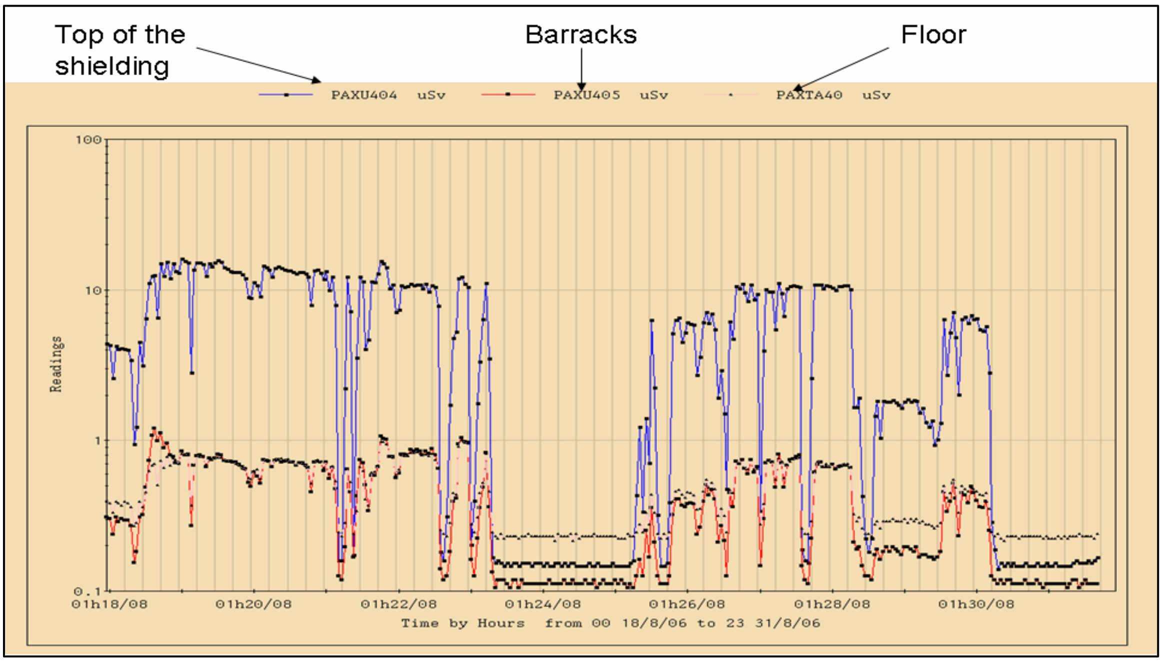

Figure 13: Dose rate measured at three locations in the ECA4 area during the CNGS opera run in August 2006. The dose rates are presented as average values over one hour.

5. MACHINE PROTECTION

5.1. Interlocking

The different parameters monitored and interlocked to guarantee safe operation for CNGS are described in detail in [8], including the powering interlocking of the septa. The interlock tolerances for the other monitored parameters of extraction equipment were verified during the commissioning of the LSS4 extraction and are summarised below.

The bumped beam position is monitored with the beam position monitor BPCE.418 in front of the TPSG. The interlock tolerance on the required bump amplitude was set to ± 1 mm. As there is no interlock on the angle another monitor in the region of the bump was included in the extraction position interlock plus also 2 monitors in the vertical plane.

The movable girder of the TPSG and the septa has to be aligned such that optimum protection for the septa with the TPSG can be obtained for both 450 GeV LHC and 400 GeV CNGS beams. The calculated values for the upstream and downstream end are 49 mm and 110 mm. A scan of the girder positions was carried out to verify the chosen settings and set the interlock thresholds. The upstream end was kept at its nominal setting of 49 mm, which is defined by the bump amplitude and the required aperture. Only the downstream end was moved. The results for scanning the downstream girder position while simultaneously dumping beam on the TPSG from the inside (bump of 43.9 mm measured at the monitor BPCE.418) can be seen in Fig. 14. The interlock thresholds were chosen to be ± 2 mm with respect to the nominal setting. The measurements show that within these limits the loss readings at the monitors on the septa stay the same. Outside of these limits, especially for values smaller than 108 mm, the loss reading increases with respect to the one at the TPSG and the protection deteriorates. The same scenario was also investigated for beam loss on the outside edge of the TPSG by reducing the kicker voltage to 38 kV for nominal bump amplitude. At this point of the CNGS commissioning the interlocking on the girder position was already activated and the scan could only be carried out within the interlocking thresholds, Fig. 15, where no increase in losses was observed.

The beam loss monitor thresholds for the monitors on the TPSG and the septa were adjusted to respect the radiation limit in ECA4, which corresponds to losing 0.1 % of the nominal CNGS extracted intensity as mentioned earlier. The calibration curve shown in Fig. 16 was used for this purpose. The measured profile along the extraction channel was taken into account. The interlock thresholds are summarised in Table 7.

The interlock limit on the set value for the MKE kick voltage was set to 50 kV ± 2 kV, Fig. 9.

Table 7: Beam loss monitor thresholds to respect the radiation levels in ECA4.

Monitor	BLM 1	BLM 2	BLM 3	BLM 4	BLM 5	BLM 6	BLM 7	BLM 8
[mGy]	38	18	18	18	18	18	18	18

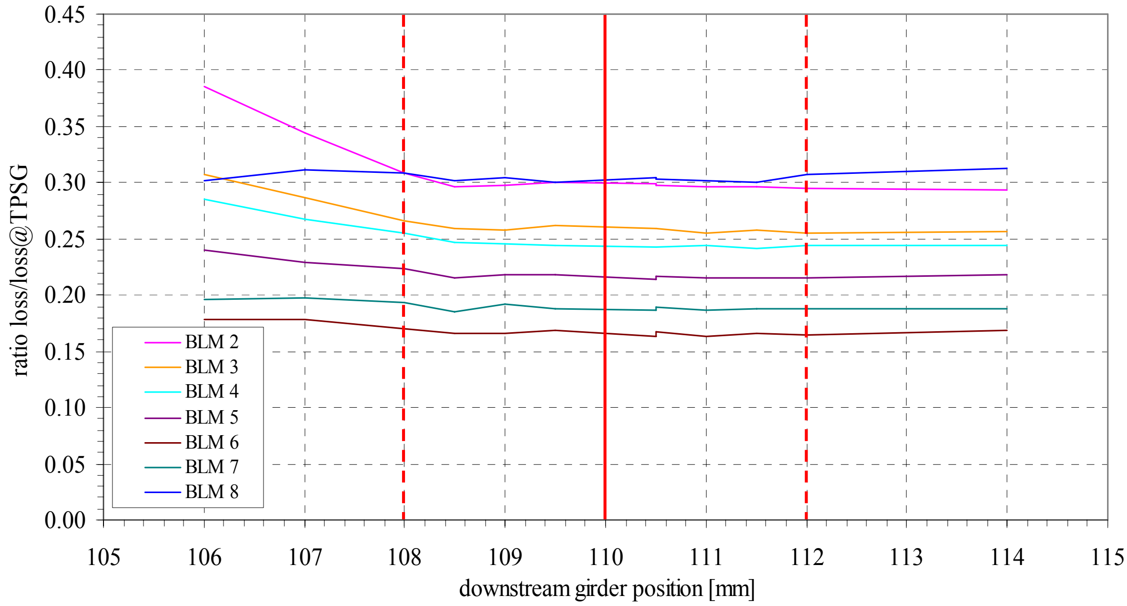

Figure 14: Ratio of beam loss to beam loss at TPSG at the different loss monitors during girder scan with circulating beam. The solid red line indicates the nominal position of the downstream girder end and the dashed lines the interlocking thresholds.

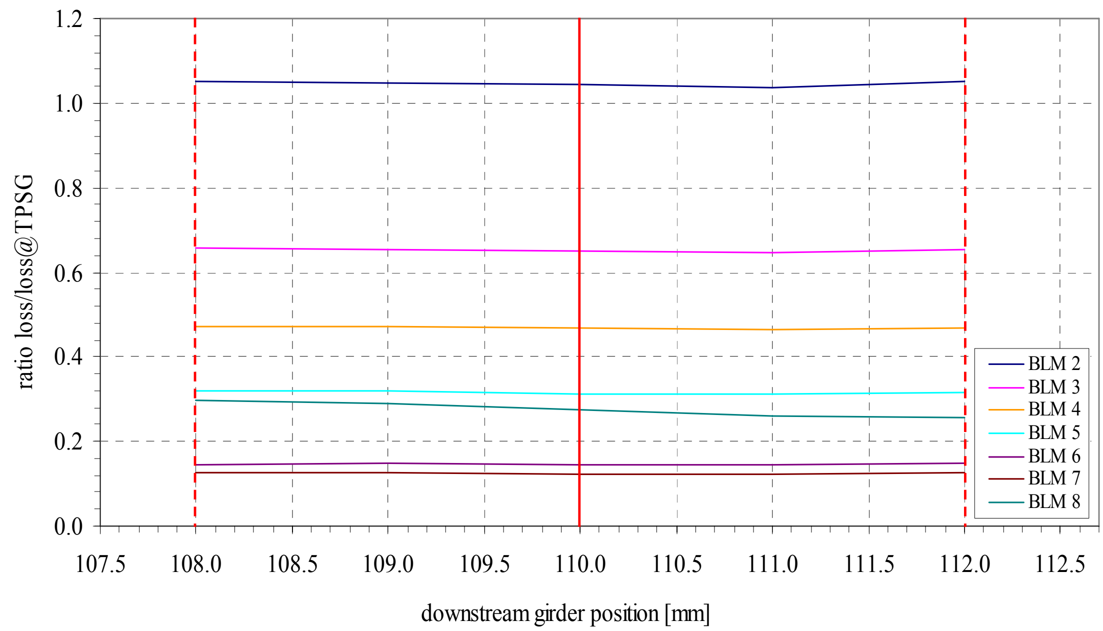

Figure 15: Ratio beam loss versus beam loss at TPSG at the different loss monitors during girder scan with extracted beam.

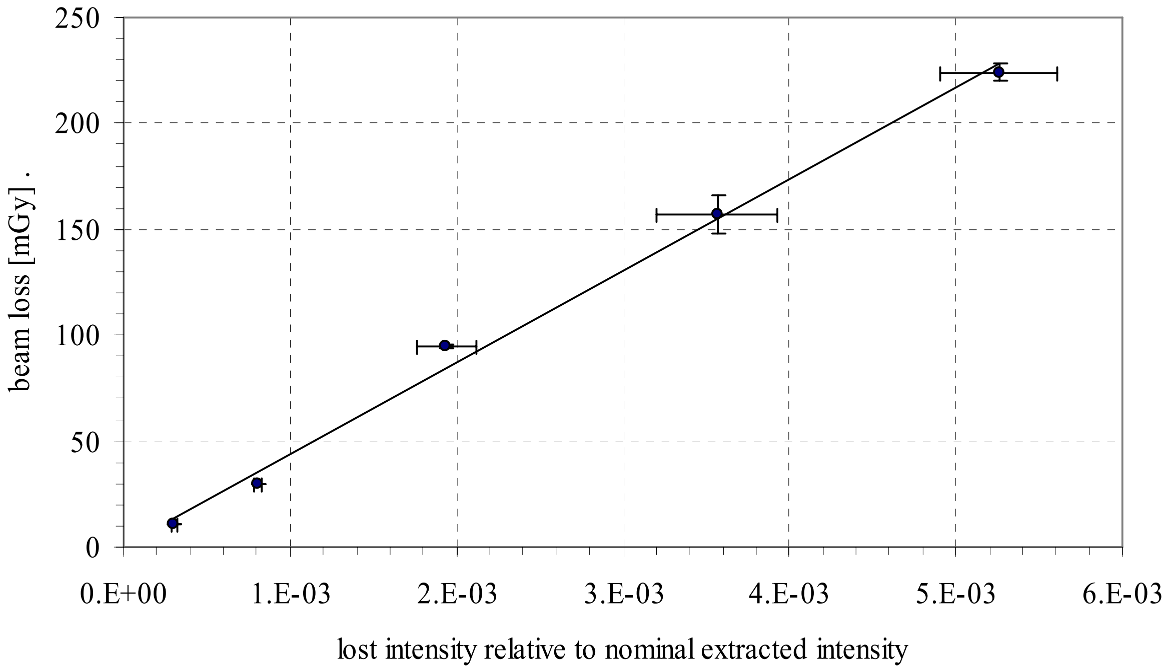

Figure 16: Measured correlation between beam loss reading and number of lost particles at TPSG.

5.2. Extraction Kicker Failures

The beam loss profile during normal operation is dominated by particles lost on the inside of the TPSG. The BLM interlock thresholds are set to follow the obtained profile. These thresholds' main purpose is monitoring of beam quality and reducing radiation. However, specific problems with the extraction kicker system during extraction can cause beam loss purely on the outside of the TPSG. Fast failure detection systems within the MKE system and passive protection with the TPSG are the only means of protecting CNGS and the extraction channel against MKE failures.

The five extraction kicker magnets MKE are terminated travelling wave systems. The main gas switches (thyratrons) are used to discharge PFNs (Pulse Forming Networks) into the magnets when the extraction trigger signal arrives. Additional clipper switches are needed to dump the rest of the energy in the PFNs to obtain the short fall times of the kicks required for CNGS. Gas switches can spontaneously fire when the PFNs are charged up or not fire, which can result in erratics or missings.

In case of an erratic on a main switch the circulating beam is kicked with about 20 % of the total MKE strength causing large oscillations around the SPS. In the case of a missing main switch the beam would be extracted with about 80 % of the nominal strength. An erratic on a clipper switch while the mains are fired would lead to the same situation as a missing on a main switch. In all cases the internal MKE failure system detects such faults and fires all (or all remaining) clipper switches to minimise the duration of the erroneous kick and empty the remaining PFNs. This results in a sweep of part or all of the beam across the TPSG for the case of a missing main switch or an erratic clipper switch.

As part of the extraction system commissioning a worst case failure scenario, extraction with 80 % of the nominal kick, was simulated with beam. Instead of disconnecting one of the 5 kicker modules, all 5 magnets were operated with about 80 % of the nominal voltage (40 kV, measured about 39.6 kV). The TED in TT40 was moved out and the badly extracted beam was sent down TT41 on to the target (intensities ~ 6×10^{11} and ~ 2×10^{12} protons). The resulting difference trajectory excursions on the beam position monitors down the line can be seen in Fig. 17. The peak oscillations are >10 mm and the excursion at the target is >2 mm. No beam loss was recorded in TT41 for any of the intensities used. The corresponding beam loss profile for the extraction region and TT40 is shown in Fig. 18. The numbers are scaled to the nominal intensity of 2.4×10^{13} protons per extraction.

In such an event the trajectory at the target would be far out of the tolerance of ± 0.5 mm. However, the target has been designed such that it can survive one impact out of tolerance with nominal intensity, and in any case the kicker system should internally curtail such a pulse with the clipper switches to around 2 μs long, or about 20 % of the full intensity. The interlocking of the trajectory along the line and beam loss monitors would inhibit any further extractions. For a swept or mis-steered beam which impacts the TPSG, the MSE septa are sufficiently protected by the TPSG for nominal CNGS intensity; for a full impact the beam loss reading at the septa would reach approximately 1.5 Gy.

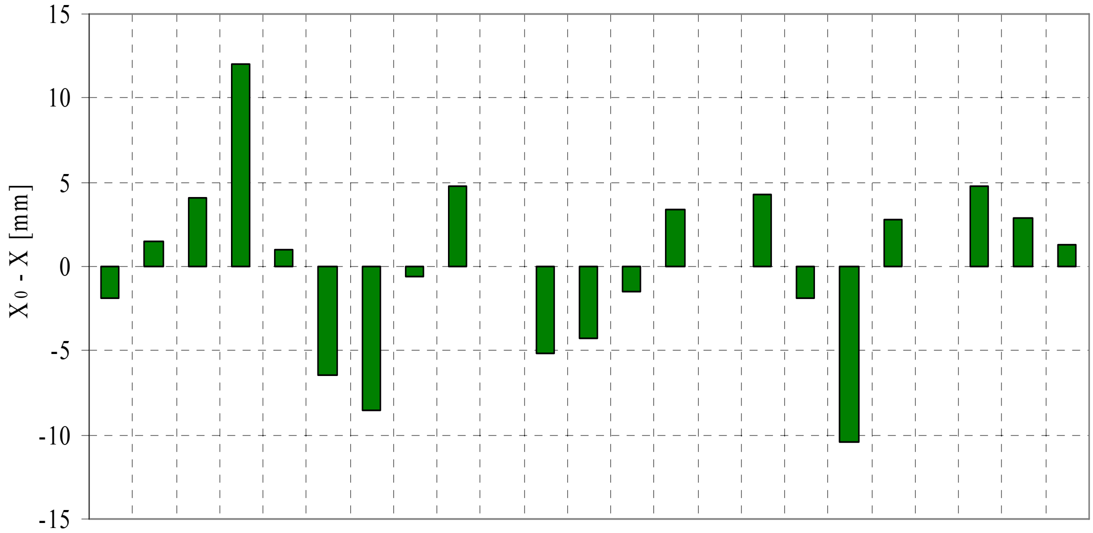

Figure 17: Horizontal difference trajectory at the beam position monitors along TT40 and TT41 for a 40 kV kick of the MKE system.

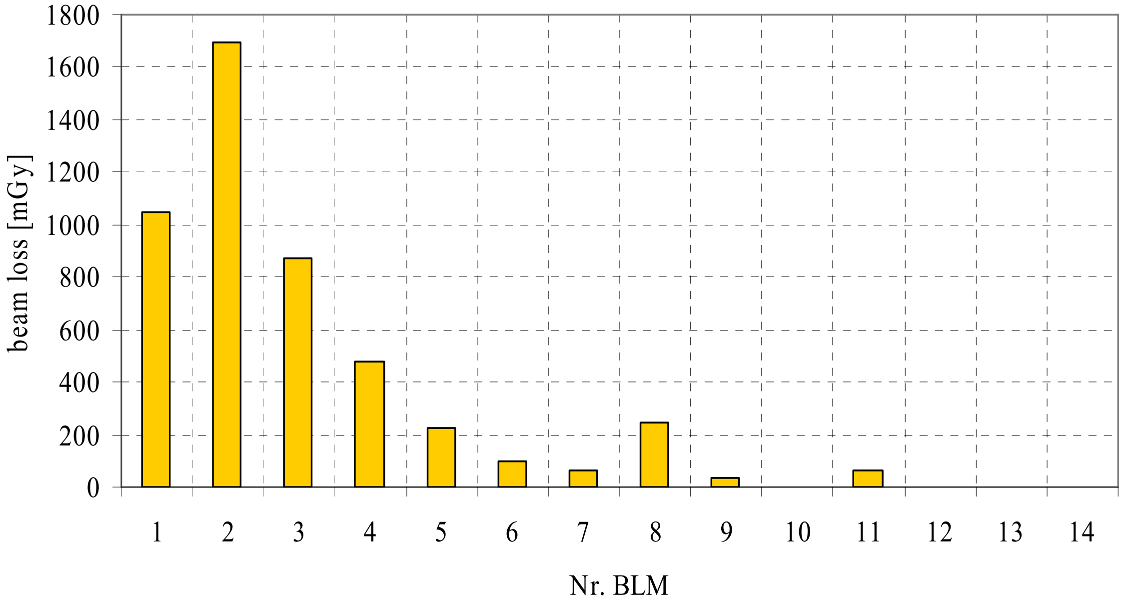

Figure 18: Beam loss reading in LSS4 and TT40 for a 40 kV extraction scaled to nominal intensity. No loss was recorded on TT41 BLMs.

6. CONCLUSIONS

The extraction system in LSS4 was successfully commissioned with high intensity beam as part of the CNGS commissioning in summer 2006. About three half-days out of three commissioning weeks were dedicated to setting up the extraction and verifying the extraction system parameters and response. The response of the extraction beam loss monitor system and radiation monitoring system in ECA4 close to the extraction region were calibrated with beam and interlocking thresholds could be set to respect the radiation limits in the critical ECA4 zones. The aperture in the extraction channel and for the circulating bumped beam was measured and confirmed to be as expected. Interlock thresholds for other extraction equipment were verified. A worst case failure scenario, a kicker failure resulting in beam extracted with 80 % of the required kick strength, was studied and demonstrated to be covered by the existing machine protection system.

Extraction losses during normal operation were measured in the two weeks of normal CNGS run after the three weeks of commissioning. The conclusion is that the CNGS extraction was cleanly set up in the transverse plane, with little or no losses arising from transverse scraping of beam tails. The measured losses on the TPSG were shown to be due to beam present in the kicker rise/fall time gaps. Both beam loss monitor calibration and radiation monitor calibration delivered the same result of about 0.05 % of the extracted intensity lost on the TPSG during the first extraction. Assuming this loss rate for a continuous CNGS operation with an intensity of 4.8×10^{13} protons per double extraction, a dose rate in the range of 3 uSv/h can be expected in accessible parts of the ECA4 area.

7. REFERENCES

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