COMMISSIONING OF THE CERN SPS PROTON - ANTIPROTON COLLIDER

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SUMMARY

The construction period of the CERN pp project culminated in July 1981 only three years after it had been launched, with the observation in the SPS of the first man-made collisions of particles at a centre-of-mass energy of 540 GeV.

This report outlines the most salient features of the SPS collider commissioning period, which stretched from June to December, 1981. The procedures used to inject and store counter-rotating beams of protons and antiprotons are described. The beam-dynamics problems (beam-beam limit, radio-frequency noise-induced debunching, effect of asymmetric low-beta insertion) which had previously raised considerable concern, are shown to be under control; they will not catastrophically affect the functioning of the collider.

Performances attained so far are reported, as well as developments which can be hoped for in the near future.
I. Introduction

The CERN pp project \(^{(1)}\) was approved in July 1978. The Antiproton Accumulator (A.A) was ready exactly two years after. During the running-in of this machine, which constitutes the heart of the whole pp system, the SPS was shut down for ten months in order to be converted from a fixed-target accelerator into a pp storage ring.

The commissioning of the SPS collider started in June 1981, one month after the machine had recovered from this long shut-down, with tests of the 26 GeV transfer lines, the magnetic cycle and the low-level radio-frequency system, which had been completely rebuilt to reduce the noise level and improve the bunch lifetime. The CPS had already tested the complicated gymnastics which ensure proper compression and synchronization of the bunches to be injected each in one predetermined 200 MHz SPS bucket. Everything went rather well at this stage, except that the bunch lifetime was found to be only half an hour, much lower than anticipated, and worse than the previous year with the old RF system.

On July 7, antiprotons (about \(3 \times 10^{10}\) accumulated in the AA) were ready for transfer. As it often happens in such circumstances this first trial, carefully prepared, was a big success. The first pulse (about \(10^9\) antiprotons) extracted from the AA was well accelerated in the CPS, but not properly ejected. After adjustment of the CPS extraction kicker timing, the second pulse was beautifully ejected and entered the SPS where it circulated for a dozen turns. It took two more shots to finely adjust the narrow time window of the SPS injection kicker, and the 5th pulse was accelerated and stored in the SPS at 270 GeV together with a bunch of \(5 \times 10^{10}\) protons. Calculated luminosity was around \(10^{29} \text{cm}^{-2} \text{s}^{-1}\) but no high-energy physicist was prepared to see the collisions.

Three more days were left in this machine development (M.D.) period to exercise transfer and storage, but then things went awry! A successful storage demands that almost all CERN machines (Linac, Booster, CPS, AA, PS, and all the transfer lines between) work properly together during the few hours needed for the final adjustments. We were soon led to realize that this would not be the case very often, especially with two thunderstorms a day over the area. Nevertheless, hard work and determination finally paid off and on Friday 10th July, at 5 a.m. collisions between protons and antiprotons at a center of mass energy of 540 GeV were observed in the UA1 detector installed in straight section 5(2).

In August, two M.D periods were scheduled with antiprotons, of which one was a success and one was completely lost due to insufficient reliability of the accelerator chain. In October, things became more serious. The UA1 detector in section 5, the UA5 streamer chamber and UA4 small angle scattering experiment in section 4 were ready to profit from any opportunity to take data. To give equal treatment to the different teams, we injected two bunches of protons which in turn collided with one antiproton bunch in the two sections equipped with detectors.
This configuration was to be kept until Christmas, giving full satisfaction. Nevertheless, it was not introduced without any apprehension. At the beginning of October, the bunch lifetime was still half an hour, the noise level in the RF loops incomprehensibly high despite all the attempts of the RF team to reduce it. As the RF phase loop is locked to one bunch (the master) it was feared that the second bunch would suffer even more from the noise. Fortunately, a malfunction of the phase discriminator was soon discovered and cured and the lifetime of both proton bunches went up to more than 100 hours: the RF noise was no longer a scare.

This was only to reveal another problem: the lifetime of the proton bunch had remained at the one hour level. It was too easy to blame again the RF noise, as the antiprotons have their own accelerating system, separate from the protons. But the RF team very elegantly proved that this was not the case: they debunched the proton beam, and the antiproton bunch lifetime shot up to above 20h. The culprit was evidently the beam-beam effect experienced by the weak antiproton bunch to a much larger extent than the strong proton ones. By steering the working point through resonances, it was soon after possible to reach luminosity lifetimes of the order of 5 to 10 hours, enough to give some useful data-taking periods to the eager experimenters. This was a very exciting time, with pp collision events relayed on-line from the streamer chambers into the accelerator control room, and exploding every second or so on a TV screen like fireworks.

From the 26th November to the 23rd December, the SPS was entirely devoted to pp physics and machine development. The UA2 detector had replaced the UA5 streamer chamber in section 4. It was the time to commission the low-beta insertions, whose components had already been tested in August and October. This was done in two steps, first lowering the betas in both sections 4 and 5 to 3.5 m vertically and 7m horizontally (from a normal 50 m) thus boosting the luminosity by a factor 1.92 and finally "squeezing" them down to 0.75 m and 4.5 m respectively. The record luminosity achieved this way was $5 \times 10^{27}$ cm$^{-2}$s$^{-1}$ but good physics conditions could be sustained only for lower values between $5 \times 10^{26}$ and $10^{27}$, with the "intermediate" low beta (3.5m x 7m). Initial fears that the low beta systems would induce a reduction of the beam-beam limited lifetime by breaking the symmetry of the machine were not justified: the lifetime was even better with low-betas than without.

This commissioning period ended with a beautiful run where beams were kept in collision for 36 hours, with a luminosity lifetime near to the design value of 24 hours. High energy experimenters had time to gather hundreds of thousands of events before operators were forced to kill the beams when the SPS was shut down for Christmas.
II. Transfer and storage procedures

1. Magnetic cycle

Two proton bunches and one antiproton bunch are injected at intervals of 2.4s (the CPS repetition rate for a 26 GeV cycle) over a 4.86s flat bottom at 26 GeV. Then the beams are slowly accelerated in 5s up to 270 GeV where they are stored. During setting up with protons only, a repetitive cycle is used, with the same flat bottom and rise but with a 2s flat top at 270 GeV and a cycle time of 14.4s (6 times the CPS cycle time).

2. First adjustments with 20 bunches

As the beam position measurement system used for orbit correction in the SPS is not suited to a dense single bunch (normally the beam is spread over 4620 bunches) it is imperative to start the setting-up procedure with the injection at 26 GeV of a full CPS beam of 20 bunches. With $10^{12}$ p this beam gives sufficient accuracy without saturating the pick-up amplifiers by a too high peak current.

The injection and acceleration is adjusted with the two low-beta insertions powered to their "detuned" injection values of $\beta^*_x = 7m$, $\beta^*_y = 3.5 m$. The closed orbit is corrected at 26 GeV in this configuration, with special emphasis on the proton and antiproton injection regions. This is done in two steps: first disconnecting the position monitors in the insertion regions and minimizing the orbit in the normal machine with the usual automatic programme, then correcting the insertions. On the 270 GeV flat top, the $\beta^*_x$s are "squeezed" in 1 second down to $\beta^*_x = 1.5 m$ and $\beta^*_y = .75m$. The closed orbit must be corrected inside the insertions during this process with specially pulsed correction dipoles.

3. Final adjustments with a single proton bunch

A bunch of $10^{11}$ protons is prepared in the CPS with the same longitudinal emittance as the nominal antiproton bunch. It has to be blown up at low energy to .5 eVs, then captured on harmonic 6 on a flat part of the CPS magnetic cycle at 3.5 GeV. Subsequently, it is submitted to the same treatment as the p bunch directly injected from the AA at this energy: synchronization with a predetermined SPS 200 MHz bucket and compression to a length of 4ns by the classical method of stretching on the unstable phase followed by rotation in the bucket.

Its transverse emittances are adjusted by scraping in the CPS booster to the desired values. These are determined by considerations of beam-beam effects in the SPS, and have been fixed so far to $\epsilon_{0\gamma} = 20 \pi mm mrad$, giving the canonical beam-beam parameter $\xi = .003$.

At injection in the SPS, the best possible match is provided by setting the RF voltage to 1.65 MV (perfect match is impossible since the non-linear compression produces a distorted bunch). The emittance of .5 eVs is sufficiently high to ensure longitudinal stability, and in fact no turbulent pathology has been discovered.
In the transverse phase planes, on the contrary, space-charge effects have important consequences (5) as illustrated in fig. 1. Incoherent Losseitt detuning is as high as 0.05, whereas the high frequency broad-band coupling impedance of the machine induces a coherent tune shift of 0.03. It is just possible to accommodate this beam between the 3rd and 4th order resonances (the presently used working point) especially if the beam-beam effect suffered by the weak antiproton beam is taken into account. Consequently, the tune of the machine on the flat bottom and during the early rise has to be set to a high precision, and the beam emittances and intensity as well as the RF voltage, must be kept close to the pre-determined values, as they strongly affect the working diamond.

The first incoming proton bunch (the "master") is captured longitudinally by the fast phase loop, so that its phase and energy errors could be large (say half a bucket length or height, $\Delta \phi = \pm 2\pi$ and $\Delta p/p = \pm 2.10^{-3}$) without causing much harm. On the contrary, the second bunch (and the subsequent ones) must fall close to the bucket centre, otherwise dilution and particle losses would occur. Although the CPS did a very good job in synchronizing their bunch to the SPS radio frequency with a jitter of $\pm 0.5$ ns, this posed difficult problems in the beginning. The solution was individual phase loops for all the bunches. This is made possible by the wide frequency band of the travelling wave cavities (2 MHz) which allows a rephasing of the RF between bunch passages. These loops are slow (they damp in a few synchrotron periods) but are very efficient against the above mentioned longitudinal injection errors, they prevent coherent dipole oscillations and reduce the RF noise level effectively seen by the bunches during storage.

After proper adjustments, efficiency of capture and acceleration of protons exceeds 95%, with hardly any noticeable deterioration of beam density. The next important step is to adjust the antiproton injection path by ejecting protons from the SPS in the opposite direction and re-injecting them into the CPS. If the protons were re-injected with a good overall efficiency and no injection oscillations, and in addition circulated on the same orbit and with the same frequency they had 2.4s earlier on the previous CPS cycle before being ejected towards the SPS, the antiprotons, as they follow the same treatment, would arrive in the SPS with no injection errors and at the correct energy. In practice though, imperfect re-injection and stability of the transfer line elements are translated into antiproton injection errors in the SPS. Longitudinal ones are taken care of by the individual bunch phase loops described above, and transverse errors will eventually be damped by a powerful active feedback (6). Unfortunately this feedback damper was not operational in pp mode in 1981, and injection errors of some millimetres certainly account for part of the observed large antiproton emittances.

4. Antiproton pilot pulses

When every possible check has been made with protons (and this is valid as well for the AA-CPS injection also pre-adjusted with protons transferred in the reverse direction) the whole transfer system from AA stack to SPS storage at 270 GeV is checked with a few pilot shots of about $10^9$ p. These are extracted from the least dense part of the stack, but apart from their reduced intensity, just sufficient to make them observable, they have the same properties and are submitted to the same treatment as the final shot. They are followed all along the chain
by intensity monitors, position detectors and emittance measuring devices (secondary emission grid monitors in the transfer lines, wire scanner (7) in the CPS and SPS rings). This automatically triggered observation system is vital to the p operation, and a large fraction of the problems encountered during the start-up period can be blamed on the insufficient development and reliability of this system.

Pilot pulses are necessary in particular for the final adjustment of antiproton RF parameters. In the CPS, phasing of the cavities is not the same for protons and antiprotons. In the SPS, the 4 travelling-wave cavities are split into two pairs, one of them equipped with power switches to accelerate antiprotons in the reverse direction. Thus proton and antiproton accelerating systems are partly independent, and require separate adjustments.

The first successfully stored beam is used to check that collisions take place in the middle of the detectors (all bunches in the right buckets) and that lifetimes are as expected. The lifetime of the strong proton bunches is determined by RF noise and is normally in excess of 100 hours. The lifetime of the weak antiproton beam is limited to lower values (from 10 to 40 hours) by the beam-beam effect. It is strongly dependent on the beam-beam parameter $\xi$, the tune, the emittances and the stability of the main power supplies and low beta power supplies. The Schottky noise observation system (8) is extensively used at this stage to check and adjust the tune. While in a weak-strong regime, the betatron Schottky lines of the protons are sharp ($\Delta Q < 10^{-3}$) and any power supply instability shows up as a widening of these lines.

5. Storage

Usually two to four pilot pulses are sufficient and when everything is considered ready, the AA is requested to send the dense shot, normally around $10^{10}$ p. Initially, the requests were made by telephone and intercom, several operators relaying the count-down to the RF control room and auxiliary buildings. But soon a less primitive system was implemented, and nowadays at a push of a button an automatic request is initiated and count-down over three SPS cycles is made by a synthetic voice. The count-down can be interrupted automatically by surveillance programmes or manually by operators if malfunctions are detected, or if for instance one proton bunch is not properly captured. This facility proved to be very efficient and useful and will certainly be extended.

As soon as the big shot is stored, the tunes are measured and if necessary adjusted to their predetermined best values with a precision of $2.10^{-3}$. Continuous monitoring is provided during storage by the Schottky system, betatron lines being recorded every few minutes; any drift in $Q$ larger than a few $10^{-3}$ is corrected by the operators. A harmonic of the revolution frequency is also recorded, giving indications of possible radio-frequency drifts.

Then the experimental area magnets are switched on and the background situation is surveyed; if necessary, halo scraping is applied. Experience in this domain is still meager, but it is clear that large antiproton emittances create a high background rate and that intermittent halo scraping is efficient in reducing it (more on this subject in the chapter concerning beam-beam).
III. Beam behaviour

Theoretical studies and experiments(9) carried out with protons in 1980 and before, had revealed two classes of problems which could adversely affect the performance of a pp collider: noise induced diffusion of the particles out of the RF buckets and beam-beam effects. The most important message of this report is that these two problems, although serious, are not likely to prevent the pp collider from reaching its goal.

1. RF noise induced diffusion

The first storage of a dense single bunch in the SPS revealed a catastrophic behaviour: particles stayed bunched only a few minutes, spilling rapidly outside the RF bucket and filling the whole machine. This was soon traced to an excessive noise level on the accelerating radiofrequency. This problem had been considered before in different machines, but took in our case an overwhelming importance. It was vigorously attacked on two fronts, theoretical and experimental(10).

The equations governing diffusion in a very non-linear system (the RF bucket) were solved, and comparisons with experiment showed good agreement. Transmission of noise in the intricate low-level RF loops was carefully investigated. For short bunches, the phase loop is very effective in reducing the noise level seen by the beam around the synchrotron frequency. On the contrary, when the bucket is almost full, the large spread in synchrotron frequencies strongly reduces the effectiveness of the phase loop. Experience shows that for a long bunch, large amplitude particles are rapidly lost, until a certain equilibrium depending on the intrinsic noise level of the system is reached. On the other hand, short bunches have a good initial lifetime, but slowly grow towards the equilibrium value. With the old low-level RF system, lifetime at equilibrium was very low, so that the only means to get reasonable lifetimes was to inject short bunches (less than one third the bucket length). Now at nominal intensity, these short bunches are extremely unstable (modes up to octupole were currently observed) and tend to grow until their frequency spread produces enough Landau-damping, leaving them quiet but prone to noise-induced diffusion.

Clearly the problem has to be attacked from both sides: damp the lowest order coherent modes (at least dipole and quadrupole) of the bunch with feedback loops, and reduce the noise level. If this is not enough, the brute-force method of strongly increasing the RF voltage has to be applied: strong focussing gives shorter and at the same time more stable bunches. A year ago, the necessity of this last step was seriously envisaged, and early development of standing wave cavities of the type to be used for electron acceleration in the LEP project was pushed forward. Fortunately, the SPS RF team was so successful in reducing the noise level in their new system that this is no longer considered urgent. Nominal bunches of 2.2 ns length are stable once their dipole and quadrupole modes are damped. Lifetimes in excess of 100 hours are measured over long periods without any sign of bunch lengthening, a situation drastically different from last year.
type of operation characteristic of $\bar{p}$ systems make it a true challenge. First experience has shown that the transfer chain is well conceived and reliable. But this is obviously not enough to make it a success. Bottlenecks are at injection in the SPS: the transverse acceptance is limited to $1.1 \times 11 \text{ mm.mrad}$ vertically and $1.4 \times 14 \text{ mm.mrad}$ horizontally by the injection septum, so that any large blow-up, mis-steering or mismatch occurring earlier in the chain reveals itself at this point. Smaller errors which cause no losses at the septum will nevertheless produce large emittances in the machine and lead to losses during acceleration and early storage. The same thing happens in the longitudinal plane: a bad synchronization or compression of the bunches results in capture losses on the rise of the magnetic field in the SPS. It was soon realized that monitoring the intensity of the bunches is not sufficient to understand and cure misadjustments; it is also essential to have precise enough measurements of emittances, positions and matching all along the transfer channels. In this spirit our monitoring system was very deficient at the beginning and still far from complete at the end of the commissioning period. It is hoped that transfer can be improved in the future with a better system.

3. Impact of reliability

Again it is evident that $\bar{p}$ can work only if the reliability of each link of the chain is sufficiently high. It seems as though we had underestimated the critical degree of reliability below which no operation is possible altogether (or had we just put aside our fears?). It is certainly not exaggerated to say that during commissioning we were half the time below this critical level.

It is during preparation for transfer and transfer itself, when all devices from Linac to SPS are required to work at the same time that the system is most vulnerable. Series of breakdowns or malfunctions can snowball and delay the launching so much that one has to start again from scratch (once it took us four days to obtain a decent transfer).

After a successful transfer, the beam stored in the SPS is much less susceptible to mishap. The main reasons for beam loss or degradation that could be isolated are the power supplies (main magnetic system or low betas) and accelerating cavities. Very seldom did we lose the beam for other (usually unknown) reasons. Many runs could be sustained during more than 20 hours.

V. Future developments

The commissioning period has shown that the collider is viable. It has also revealed deficiencies and indicated in which directions one must work to improve its potentialities for physics.

Clearly reliability and operational efficiency together with improved diagnostics are the domains in which most of the available effort must be invested. At the same time, one must increase the luminosity to a point where physics on the intermediate boson can start. This is estimated to be in the $10^{28} - 10^{29}$ range.
1. **Reliability**

To help dig out and suppress the weak points a "post mortem" analysis system had been proposed in the SPS: parameters would be continuously memorized and a specially generated trigger event would freeze the memories in case of beam loss, thus allowing a subsequent analysis. The necessary hardware (MATRACE modules) has been built, but the system has not been implemented up to now due to lack of time. Furthermore, as already mentioned, the dominant culprits were last year RF cavities and power supplies, both items already well equipped with convenient alarm systems, so that the urgency of the "post-mortem" was not felt strongly. The picture could well change in the future, as a great effort has been deployed to improve the reliability and stability of both RF and power supplies. The "post-mortem" must be kept up the sleeve, and if necessary activated to chase more subtle or hidden causes of beam loss. In the same spirit continuous analog recording of some sensitive signals will be provided to help find correlations. It is felt very desirable for instance to have simultaneous recording of the tunes, the current in the main quadrupoles, and the background rate in the experimental areas.

2. **Transfer efficiency**

As we have seen here lies for the moment one of the main limitations of the scheme. Apart from an increase in the general reliability of the CERN machines (but no dramatic change can be hoped for in this domain) improvements are expected from a more complete and efficient monitoring system all along the transfer chain.

As beam deterioration can start at extraction from the AA, secondary emission grids are being installed in the transfer path from AA to CPS to check emittance and matching. In the CPS machine itself, the emittances of the circulating beam will be monitored by a wire scanner of the type used in the SPS. At the CPS end of the TT70 (CPS-SPS) transfer line special secondary emission foils will be used to exactly fix the position and angle of the proton beam reinjected into the CPS (this was done previously with scintillating screens). This way it is hoped to better decouple adjustments in the CPS from those in the SPS and TT70. The sensitive foil monitors and directional couplers in the injection line will be used to follow the antiproton trajectory and compare it with the prerecorded proton ones. The intensity measurement system will be completed by adding an electrostatic monitor before the SPS entrance.

Once in the SPS the intensity of the individual bunches will be measured every turn during the 256 first revolutions and then every 30 ms until the beam is stored at 270 GeV. This information, together with the injection trajectory will be acquired automatically and retained for analysis. The tune of the machine will be monitored continuously during the cycle with a new system (14) phase-locked into a beam frequency, thus allowing a very precise setting.
If all this can be made reliable enough it should be possible with the adequate operational know-how to reach transfer efficiencies of the order of 80% with a minimum deterioration of the beam density. But we cannot hope to make such a step forward already in 82: our aim is to reach a routine transfer efficiency of 50% (instead of 30%) with a blow-up of the transverse emittances reduced by a factor 2 (from 10 to 5). In the present context this should ensure, with a decent luminosity, favourable beam-beam lifetime and background.

3. Luminosity

The low beta insertions have already been pushed beyond their nominal performance and no further improvement can be hoped for this year in this domain. The intensity of the proton bunches can be increased to the nominal 10^{11} p without much difficulty, but is limited in this range by different space-charge phenomena. Hence the only means to boost up the luminosity is to increase the number of bunches and the intensity per antiproton bunch. It was originally proposed to collide 6 bunches of protons against 6 bunches of antiprotons. Whereas this option is still open for the future, it is not envisaged in the short term for different reasons: operational complication, insufficient supply of p, and also perhaps difficulties with beam-beam tune spread. On the other hand, the intermediate solution of 3 p against 3 p seems attractive, provided sufficient progress is made concerning reliability and operation efficiency. The accumulation rate of antiprotons in the AA was last year 3.5 \times 10^{9} p/hour (as compared to the 2.5 \times 10^{10}/h nominal). Improvements are being made in the AA and this value is expected to slowly increase. But to be safe, let us count for 1982 on an accumulation rate of 3.5 \times 10^{9} p/h.

Now with a luminosity lifetime of 16 to 20 hours it will be necessary to refill the collider every day. Suppose the general reliability is such that half the attempted transfers are successful (this way we introduce a "reliability factor" of 50%, quite optimistic referred to last year!) we see that 4.2 \times 10^{10} \bar{p} are available per transfer. After 3 pilot pulses of 2 \times 10^{9} p each have been drawn for test purposes, 3.6 \times 10^{10} \bar{p} remain which can be divided into 3 bunches of 1.2 \times 10^{10} each.

With a 50% transfer efficiency this makes three bunches of 6.10^{9} each circulating in the SPS, and as shown in Table II, a luminosity of 3 \times 10^{28} is within reach.

In this range of p intensities, the collider still works in a weak-strong regime (negligible space-charge of the \bar{p} bunches) and any increase in the available p intensity should increase the luminosity. Let us remark that the above scenario demands an extremely reliable accumulator: the AA is required to hold continuously of the order of 1.5 \times 10^{11} p to allow 3 bunches of 1.2 \times 10^{10} to be extracted within the nominal longitudinal emittance.
Table II

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VII. Conclusion

The SPS pp collider has been successfully commissioned. The low beta insertions work as expected, and the RF noise problem has been solved. The beam-beam interaction is the limiting phenomenon, but does not seem to be more severe than expected. Therefore, the nominal performances of the collider as defined in the parameter list still appear as a reasonable goal for the future and a considerable effort both in the AA to supply more antiprotons and in the SPS to learn how to use them more efficiently, is perfectly justified.

Acknowledgements

The pp running-in was a success because of the close collaboration, enthusiasm and hard work of a large part of the staff in both the PS and SPS Divisions.

A report like this one is limited in its scope and cannot do justice to all of them. We would like to express our gratitude first to our colleagues in the PS Division who worked incredible hours to supply protons and antiprotons whenever requested.

In the SPS, the detailed knowledge of the machine controls which is essential to such an enterprise was provided by the Operations Group. The Beam Instrumentation group was hard pressed to give suitable diagnostic tools without which no progress is possible. The Power Supply and RF Groups are on the front line in the struggle for reliability, and as such were most exposed to criticism. It is a good opportunity to acknowledge their continued effort and progress. In the heroic times of early commissioning, it was a pleasure to work with people from the Beam Transfer group. However, they soon disappeared from the control room, their hardware proving stable and reliable enough. Other people, like for instance the Vacuum Group, we just never heard about: this certainly gives a measure of the excellence of their work.

Finally, a special mention is due to D. Boussard and T. Linnecar who mastered the low-level RF problems and to P. Faugeras, who first reflected on the operational procedure and with a small team of engineers-in-charge, prepared and commissioned the low-beta insertions. Their brilliant contributions in these fields were invaluable for the success of the pp project, and it is with great pleasure that we thank them for their friendly and long lasting cooperation. Their work will be published in detail in separate papers.
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Fig. 1. Tune Diagram at 26 GeV

- 3p bunches - nominal parameters
- small intensity p bunches

$Q_o$: single particle $Q$

$Q_m$: $Q$ measured with protons ($Q_o - Q_m =$ Coherent $Q$ shift)

$Q_p$: $Q$ of central proton ($Q_o - Q_p =$ Laslett $Q$ shift)

$Q_{\bar{p}}$: $Q$ of central antiproton ($Q_{\bar{p}} - Q_o =$ beam-beam $Q$ shift)
Fig. 2  a) Tune diagram with working points (hatched: antiproton tune spread). Sum resonances are drawn up to order 13.

b) Lifetime versus tune (no low betas)
plates in: $\text{Acc} = 1\text{mm.mrad}$
plates out: $\text{Acc} = 2.5\text{mm.mrad}$

**Fig. 5** Diffusion speed of large amplitude antiprotons (no low betas) $\xi'' = 0.0025$