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GEB* REPORT ON PSB CONSOLIDATION

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In March 1995, the PS management appointed a study group* to suggest a consolidation program, on top of the LHC modifications, in view of an intensive machine operation (ISOLDE production and LHC injector) for the next 20 years. A summary of these recommendations is presented in this note.

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1. Introduction

The PS Booster (PSB) was completed in 1972 with the aim to increase the PS intensity to 10^{13} ppp. This goal was attained in 1973 and thanks to the many improvements and modifications the today highest intensity (ISOLDE beam) is >3 10^{13} ppp, see Fig. 1.1. The main limitations come from space charge and longitudinal instabilities together with the loss minimisation in the machine. The main characteristics [1] are :

R = 25m (4 rings superimposed)
E_{in} = 50 MeV
$E_{extr.}$ = 1 GeV
B = 0.687 T
V_{rf1} = 12kV, h_1 = 5
V_{rf2} = 6kV, h_2 = 10
cycle duration = 1.2 s
Q_x ~4.2, Q_y ~ 5.2
α_p = 0.06
.....

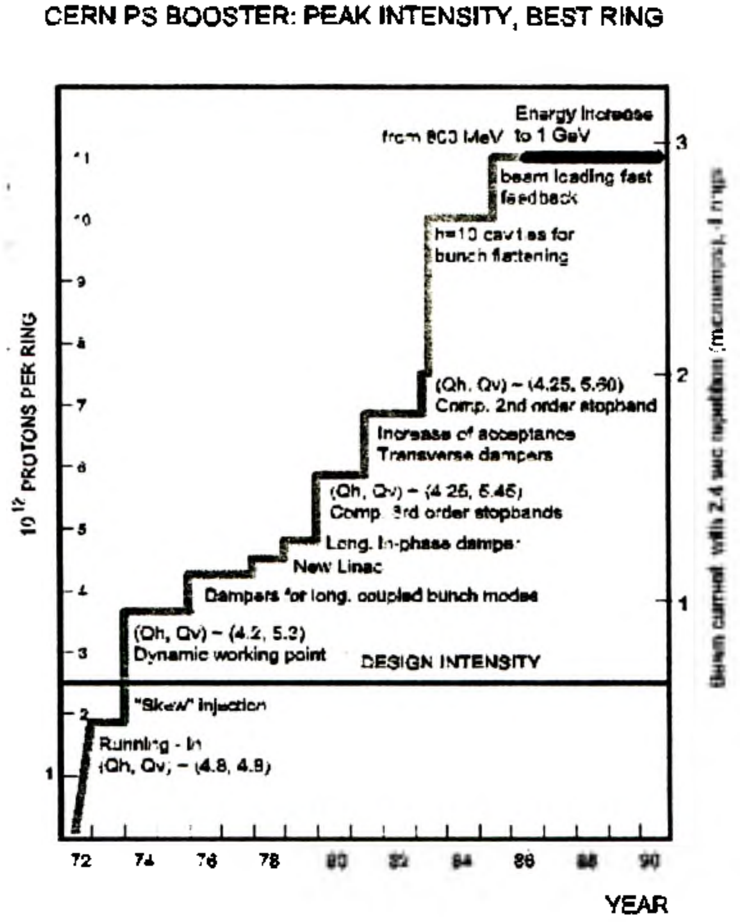

Fig.1.1 PSB beam intensity versus years

The machine receives protons from Linac 2, ions (at present Pb^{53+}) from Linac 3 and it is capable of working in full PPM (pulse to pulse modulation). Machine performance is rather good and beam availability is better than 97%.

Since 1992 the PSB is not only an injector of the PS. It also sends a high intensity beam (>3 10^{13}ppp) directly into two target areas for the production of radioactive isotopes on the spare Booster pulses, about one pulse out of two (ISOLDE facility)[2].

Moreover, as part of the LHC injector chain, the PSB will have to produce a special high intensity (0.7 10^{13}ppp) and small rms emittance ($\varepsilon_x^* \sim \varepsilon_y^* \sim 2.5\mu m$) proton beam [3]. Two major modifications are foreseen for 1999 :

i) an increase to 1.4 GeV of the extraction energy and

ii) new RF systems at h=1 and 2.

These two main users (ISOLDE and LHC) demand a machine lifetime of the order of 20 years.

In March 1995, the PS management appointed a study group to suggest recommendations for a machine consolidation to cope with the above requirements [4]. A summary of these recommendations is presented in this note.

2. Injection lines and injection

The quality of the beam to be injected and captured in the Booster depends on:

i) the quality and stability of the Linac beam,

ii) a good steering in the injection line,

iii) a good injection/capture optimisation.

The Booster is equipped with a monoturn and a multiturn injection system. The old monoturn system has been removed to improve the vacuum for lead beam operation. The possibility of H^- injection is discussed in Chapter 2.5.

2.1 The Linac beam

The quality of the Linac beam is essential for a correct injection into the Booster. The transverse emittances are measured, with SEM grids, in the LBE measurement line (see Fig. 2.1) and an energy measurement with a spectrometer is made in the LBS line just before the entrance into the Booster injection line, BI. These measurements can be done on any beam at any time (PPM). The trajectory from the Linac is measured with pick-up's and screens; it should be well centred on the first two pickups in the BI line.

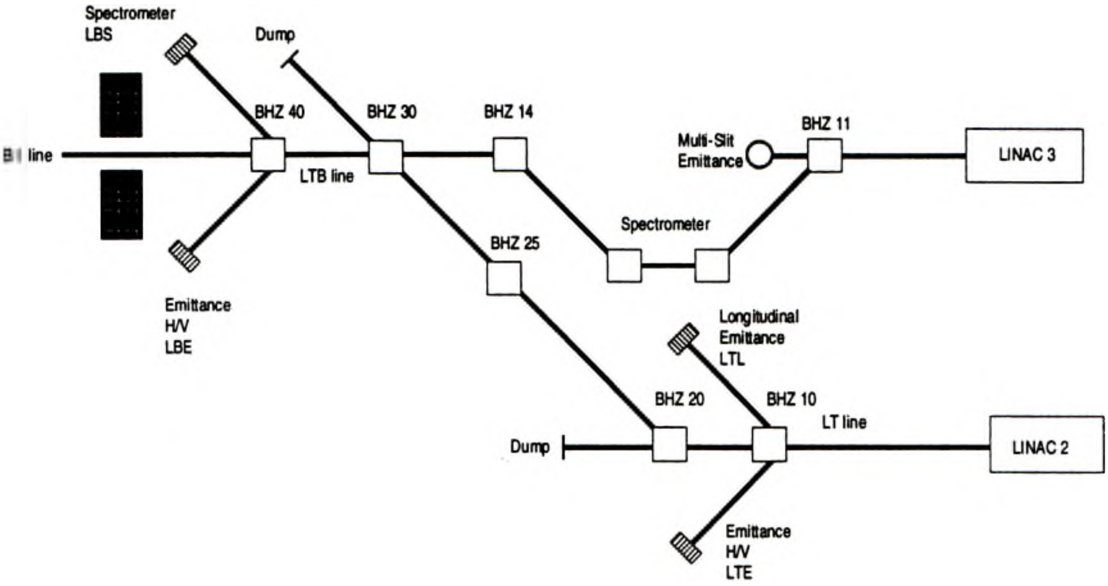

Fig. 2.1 PSB injection line layout

After the Linacs, two emittance measurement lines are available. The LTE/LTB line, installed immediately after the Linac 2 tanks allows measurement of transverse and longitudinal emittance. The LBE/LBS line in the common transfer line Linac 2/3 - Booster measures the transverse emittance and the energy spectrum only. During the Linac controls conversion their readout electronics and data treatment programs have been updated to the latest technologies. The measurements are regularly used and their results are considered reliable. The principle of the measurement is as follows : the beam is swept in front of a slit using two kicker magnets thus defining the particle positions while the angular distribution is read from a SEMgrid downstream.

. Known problems are: the age and limited range of the kicker magnets and hysteresis in the bending magnet of the spectrometer (LBS.BVT10). A cycling procedure for the spectrometer bending has been implemented and an NMR device to measure the field has been installed.

The following points need further studies :

i) blow-up due to space charge effects after the Linac (space charge effects in the transport from LTE to PSB injection must be taken into account etc.)

ii) verification of optics for steering applications (quadrupoles values coming from calculations with space charge used for calculating optics without space charge)

iii) interference with the PS stray field (see Chapter 2.2 below).

2.2 Injection line

The PS ring is situated close to the LTB line. The PS stray field influences the trajectory of the Linac beam. These fluctuations are strictly correlated to the PS cycles. The PS stray field is somewhat compensated by correcting the control value of two dipoles in the LTB line. This is done at present by using information from the PLS. Three cases can be distinguished today: high, medium and low PS fields, but this classification is not sufficiently fine grained. The variation in the proton trajectory between a low and a high PS field is about 5 mm peak to peak and much more for ions. Possible solutions like:

i) an improvement of the present magnetic shielding

ii) a direct feedback to GFAs

iii) a steering matrix compensation by somehow knowing the present PS field indirectly (PLS), like the present compensation system, but more sophisticated

iv) a direct measurement with compensation on the next supercycle

v) an Automatic Beam Steering (ABS) program [5] with the same steering matrix for high field as for low PS field according to PLS line "OCCURRENCE" and not on "USER"

were discussed. Further studies are needed to determine the best solution.

Some enigmas concerning the nominal Linac trajectory persist. An alignment of the Linac 2, Linac 3 and injection beamlines including instrumentation should be implemented.

ABS is particularly important in this beam line since the Linac beam has a tendency to drift. Alignment measurements of screens and pick-ups are essential for a proper ABS procedure..

One SEMgrid per plane and ring is required to check beam size and position. Moreover one SEMgrid (H+V) before the ion distributor, which constitute an aperture restriction, is also important for ion and proton beam centring.

At the entrance of the Booster several Vidicon cameras have been replaced by CCD cameras during the 94/95 shutdown. Due to the short remanence of the light pulse a frame grabber is of big help. In addition a prototype system, digitising the CCD video signal, is about to be set-up. It should permit numerical evaluation of the beam spot (beam profile and position). Several issues are open however :

i) radiation sensitivity of the CCDs and their shielding

ii) linearity of the screens (for reliable beam profiles)

iii) CCD linearity

iv) dimension calibration

v) noise immunity

Recent comparisons between SEMgrids and TV screens / CCD cameras [6] have shown a potential to be exploited.

2.3 Monoturn injection

The monoturn injection was extensively used during running in of the Booster. It was considered and tested for producing the LHC beam. The results were discouraging : the transverse emittances obtained after injection were very much larger than the ones of the incoming Linac beam, very likely due to space charge effects. Finally a 3-turn injection produced the best beam so the kickers for the fast injection were taken out in 1993 to reduce the coupling impedance and improve vacuum. Monoturn injection into one PSB ring of a lead beam with the hypothetical intensity of a few mA from the laser ion source could be a way of producing the LHC lead beam.

Monoturn injection can be done concurrently with multiturn injection in PPM.

Since the LHC beam can be produced with multiturn injection, the study of the beam blow-up for monoturn injection does not have a high priority for the time being. If this type of injection is to be used, the injection kickers must be modified for vacuum compatibility.

2.4 Multiturn injection (horizontal betatron stacking)

Multiturn injection is used for both proton and ion beams. It is also the only way of making full use of the >100 μs Linac 2 (p) and the 400 μs Linac 3 (ions) beam. The multiturn injection efficiency (40 to 60 % corresponding to 3 to 15 turns per ring) is increased by using enhanced linear coupling on Q_x-Q_y = -1 to control vertical blow-up coming from space charge. This is a rudimentary way of "painting". After the horizontal betatron stacking process ε_x is larger than ε_y which is more favourable for accommodating the Q-spread area in the Q-diagram.

Today, injection optimisation is done by looking exclusively at the injected/captured intensity. A more analytical and/or sophisticated way of optimisation would be beneficial. At present, studies have been started to investigate multiturn injection, also including space charge, to understand why multiturn works better for LHC beam than monoturn. For any improvement of the optimisation of the multiturn injection, a fast beam transformer (digitised) to follow the injected intensity is essential. Q measurement at injection is done with the half turn pickup, which needs some modifications in the application program to give [x, x'] at the injection septum. An automatic optimisation technique for the multiturn injection should be envisaged.

An optimisation of the low energy orbit could increase the acceptance and thus improve injection.

2.5 H^- injection

H^- injection is the ideal injection method for high intensity / high brilliance proton beams (e.g. LHC). The injection efficiency is virtually 100 %; there is no inherent beam loss on the injection septum for the H^- injection scheme, as for multiturn injection, because injection can be done directly in the phase space occupied by the circulating proton beam. About 2% of the incoming H^- beam are not fully stripped and can be collected on a dump. However, this method is not useful for injection of positively charged ions.

The emittances of the beam can be as small as those coming from the Linac up to the space charge limit ratio : (number of particles / rms emittance) which for the LHC beam is > 2 10^{12} ppp / 2.5μm. The transverse distribution "form factor" can be optimised by "painting". A more sophisticated painting could raise the space charge limit by 10-20 % at the maximum. The lower H^- current (30 instead of 200 μA) will reduce the Linac beam loading.

H^- injection requires :

i) a replacement of the Duoplasmatron proton source by an H^- source,

ii) a change of the polarities in the Linac after the source, LT, LTB and BI lines,

iii) a rebuilding of the injection straight section SS1 of the Booster ring for H^- injection.

If the Booster is needed also for the heavy ions, the polarity of most magnets in the LTB and the BI lines have to change in PPM. Moreover and more difficult, either a new H^- injection line into 16L1 or 2L1, keeping the multiturn injection in 1L1, or a combined multiturn/H^- injection in 1L1 have to be implemented.

H^- injection seems to be in practice incompatible with ion injection unless major investments are made. However if the PSB is not needed for ion acceleration, a study of the scheme should be envisaged.

3. Booster ring

This chapter treats issues concerning the PSB ring except RF and loss management, which, due to their peculiarity, have been treated in two separate chapters: Ch.4 and 5.

3.1 Magnets

The status of the spares for the PSB magnets are summarised in Table 3.1 [7]. It appears that all the magnets have a spare ready to be installed except:

i) the dipole 1RB1 which has a special vacuum chamber inside,

ii) the dipoles 16 RB2 and 15RB1 which are equipped with special coils (there are eight spare coils). In case of failure, repairs will require several weeks.

If one of the standard main dipole gives some indication of radiation damage (for ex. coils which become brown) it can be interchanged with one from a less irradiated place.

3.2 Magnet covers

During last year some leaks developed on vacuum bellows. It appears that the PVC magnet covers are responsible for the corrosion of the bellows. The PVC degrades after having received a total dose of $5\ 10^5$ Gray (five years with the present dose levels). These magnet protections are going to be replaced with MAKROLON® covers.

3.3 Septa

All the ejection and recombination septa will be replaced in the coming years in the frame of the 1.4 GeV program. The new magnets are of pulsed type. Consequently, the problems of corrosion or obstruction of the coils will be eliminated and the vacuum quality improved.

3.4 Vacuum

The PSB vacuum is already good (below 10^{-8} mbar) for a non-bakeable machine and it is adequate for the operation with protons. However the PSB accelerates Pb^{53+} ions which are very sensitive to the vacuum quality due to charge exchange processes. An improvement plan has been launched for the ions programme [8]. A large number of Ti sublimation pumps [9] has been added. Many elements of the machine were cleaned and "vacuum fired". The measurements during the first lead ion run (Fig. 3.1) show that for section 3 to 13 the vacuum is below 10^{-9} mbar eq. N_2. One sublimation every day in these sections is enough to maintain a sufficiently low pressure. But for sections around extraction and injection the vacuum is well above $3\ 10^{-9}$ mbar. This is the main cause of the poor transmission (<50%) of the lead ions through the PSB. A Ti sublimation needs to be done approximately every hour during lead operation. A major effort has to be dedicated around these sections.

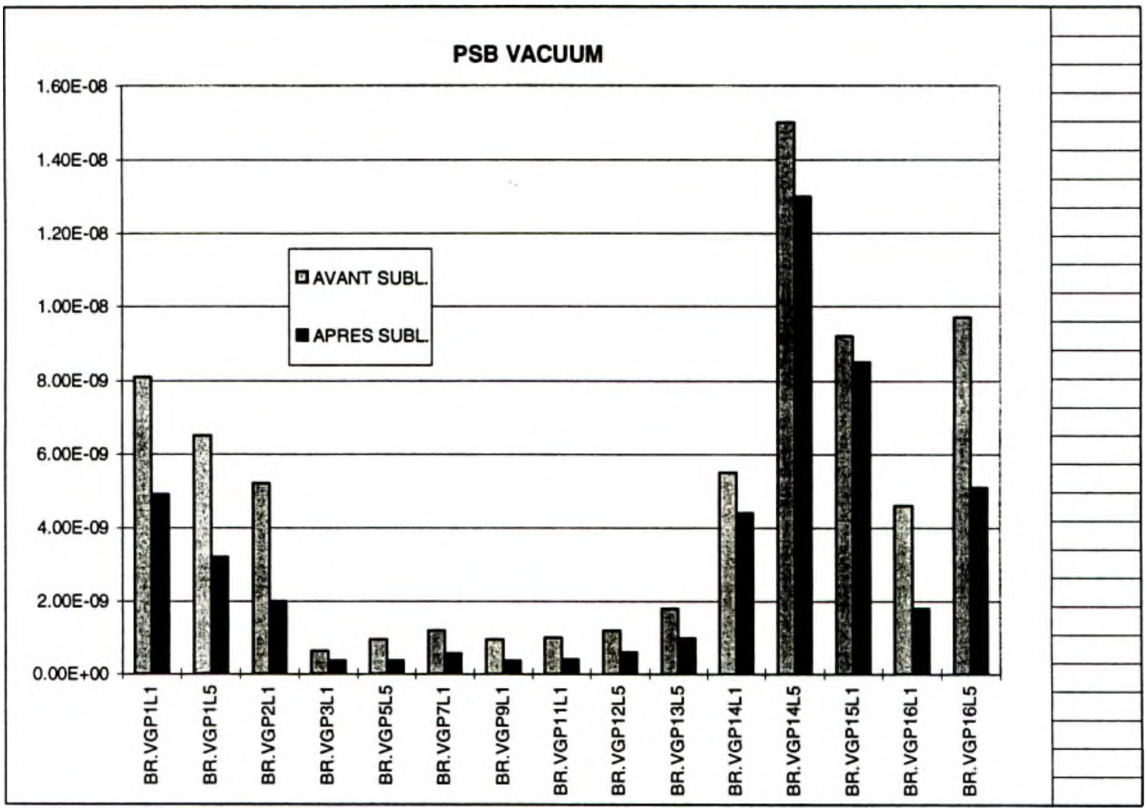

Figure 3.1 : Vacuum along the PSB during dec 1995 lead ions run ,before and after a sublimation. Notice there is more measurements around the injection-extraction region than in the rest of the machine where the vacuum is of better quality.

The present septa tanks are very large. Each of them contain four magnets. The outgassing rate is very high. These tanks cannot be baked due to their construction. However for the LHC programme (1.4 GeV) the extraction septa and the tanks will be redesigned (pulsed septa with laminated yoke). The technique [10] already used with success in EPA and PS, i.e. vacuum firing of the tanks and baking of the septa to 200°C, is adequate. The expected outgassing rate will permit a vacuum of better than 10^{-9} mbar. This program should have high priority.

What to do for 14L1 (kicker)? This tank is full of ferrites and the conductance to the pumping ports is very bad. However the high pressure observed is maybe due to the pressure bump in short section 14L5. It seems there was always a high pressure in that short section. In fact no leak has been detected. Is there a virtual leak or something in the vacuum chamber? A serious investigation has to be done.

What is the influence of the injection / extraction lines to the PSB vacuum? The gauge measurements in the injection / extraction lines show a vacuum worse than 5 10^{-8} mbar. The gas flux entering the machine, estimated to more than 2 10^{-7} mbarls^{-1}, could explain the bad ring vacuum. However a measurement done by closing the ejection vacuum valves did not give any improvement [11]. Investigations are being pursued.

Recently it was found that some bellows were leaking. An urgent replacement of 12 bellows has been launched for January 1996 and probably other bellows will have to be replaced later on.

3.5 The irradiation

Figure 3.2 [12] shows the integrated dose measured on the vacuum chamber at different places around the PSB machine from 1975 to the end of 1994. These measurements give an indication of the dose received by the coils of the magnets. Araldite permits a dose of 2 10^7 Gray [13].

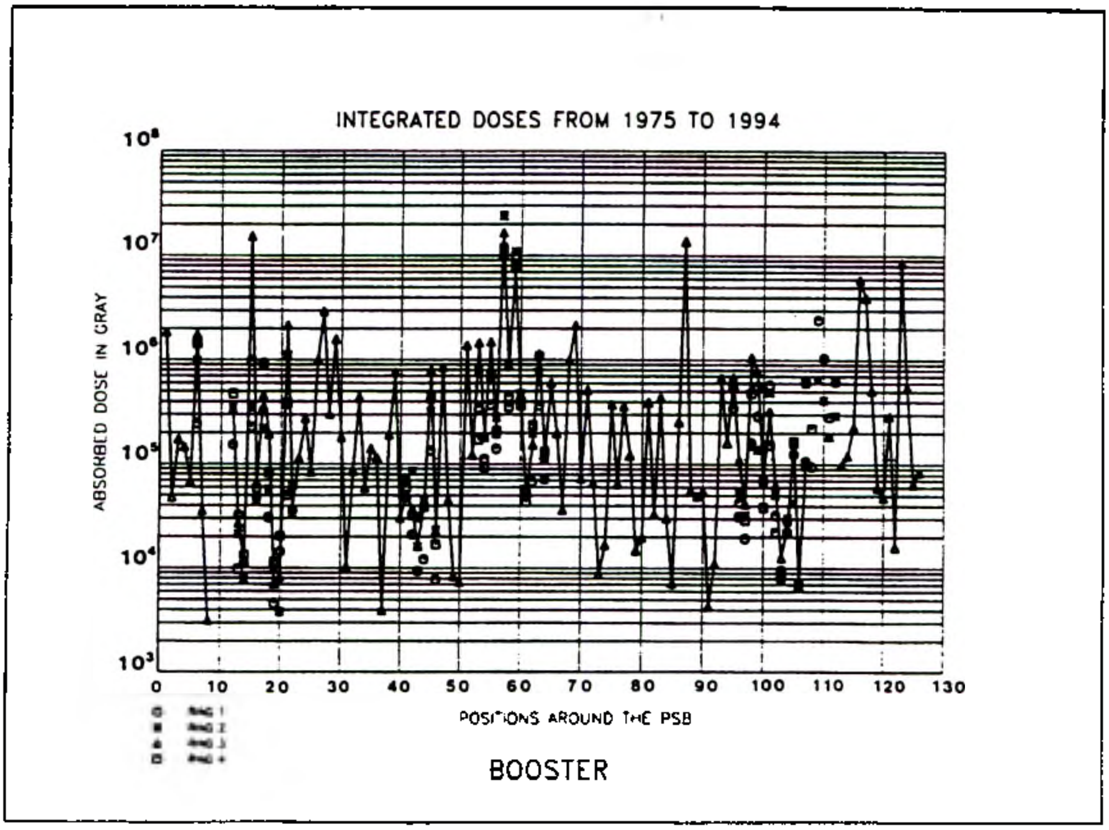

Figure 3.2 : Integrated doses received at different locations of the PSB. 1 to 10 are locations of the injection line, 10 to 110 are in the ring itself and 110 to 130 in the transfer line to PS.

There are three locations where the measured dose approaches this limit :

i) around section 1 (Fig. 3.2), the losses during the multiturn injection at 50 MeV are predominant. At this energy the protons are stopped in 4.2 mm of iron. Therefore a protection of the coils of bending 1RB1 was introduced 15 years ago (it is an assembly of stainless steel sheets with a total thickness of 15 mm). This magnet has been replaced already once (beginning of 80's). A possibility to reduce the losses at injection is to install an H^- injection (see Chapter 2.5).

ii) around section 8, where the Beamscope window [14] is installed, the integrated dose is the highest of the ring. This window is the main aperture restriction of the ring. Hence all the losses during acceleration (instabilities, resonances...) are concentrated on this limiting aperture and induce irradiation of the downstream magnets. Note that it is not the destructive profile measurement itself which is responsible for irradiation but the restricting aperture which acts all along the cycle.

iii) around extraction (at 1 GeV), the halo of the beam is lost on the septum. The bendings downstream are then irradiated. It is important to limit the irradiation of the bending 15RB1 which is equipped with special coils. Setting the extraction kickers to their maximum value since the beginning of 1995 has substantially reduced the losses.

As some of the magnets have already received doses close to the limit of Araldite degradation, concentrating the losses elsewhere is very important (see Chapter 5).

The number of protons accelerated per year has been doubled since ISOLDE is running [12] but the same level was reached already during years 1983 to 1985. The integrated doses for the machine per accelerated protons has been decreased since 1989 by a factor 4 to 5!

It should be noticed that the radioactivity has also increased. Looking at the radioactivity of the machine during shutdown, the 'hot' locations are of course the injection and extraction septa Moreover all the septa locations and aperture restrictions in the transfer lines are very activated. Along these transfer lines, the only way to reduce irradiation is to know and control the beam trajectories and dimensions (see Chapter 6).

BOOSTER - AIMANTS DE RESERVE

Designation		Nb	Lieu de stockage
BBC	Quad. type QDD (No 4) avec chambres	1	Hall d'entree Bat 361
BBC	Quad. type QF1 (No 17) avec chambres	1	Hall d'entree Bat 361
BBC	Triplet monte sur poutre comprenant:		Hall d'entree Bat 361
	Quad. QF1 (No 16) avec chambres	1	Hall d'entree Bat 361
	Quad. QDU (No 8) avec chambres	1	Hall d'entree Bat 361
	Quad. QF2 sans chambre	1	Hall d'entree Bat 361
SMIT	Quad. refroidi eau (poles pas conformes)	1	Bat 361 - BHP - Voir note
ALSTHOM	Bending No 2 avec chambres	1	Hall d'entree Bat 361
ALSTHOM	Bending No 31sans chambres	1	Bat 167 ?
Dipole type 1	stack de 4 dipoles H+V sans chambres	1	Hall d'entree Bat 361
Dipole type 1	Dipoles H+V sans chambres	4	Passerelle Bat 361

BOOSTER - BOBINES DE RESERVE

Designation		Nb	Lieu de stockage
Alsthom	Bobines speciales (Bending)	8	Bat 141-caisse No 5
Alsthom	Bobines normales (Bending)	8	Bat 141-caisse No 6.2
Alsthom	Bobines normales	2	Bat 141-caisse No 6.1
Oerlikon IBV,TBV	Bobines	6	Bat 141-caisse No 8
Smit	Bobines (air)	4	Bat 141-caisse No 9
Smit	Bobines (eau) - (voir note)	4	Bat 141 (retour en Mai 1991)
Tesla *	Bobines TBH	0	Bat 141-caisse No 12.1
Tesla	Bobines TBH	1	Bat 141-caisse No 12.2
Nouveau Multipole	Lentille type A	1	Bat 141-caisse No 13
	Lentille type B	1	Bat 141-caisse No 13
Oerlikon (0 200) (BT.QNO40,50)	Bobine	1	Bat 141-caisse No ?

Table 3.1: Status of the spares for the magnet of the Booster.

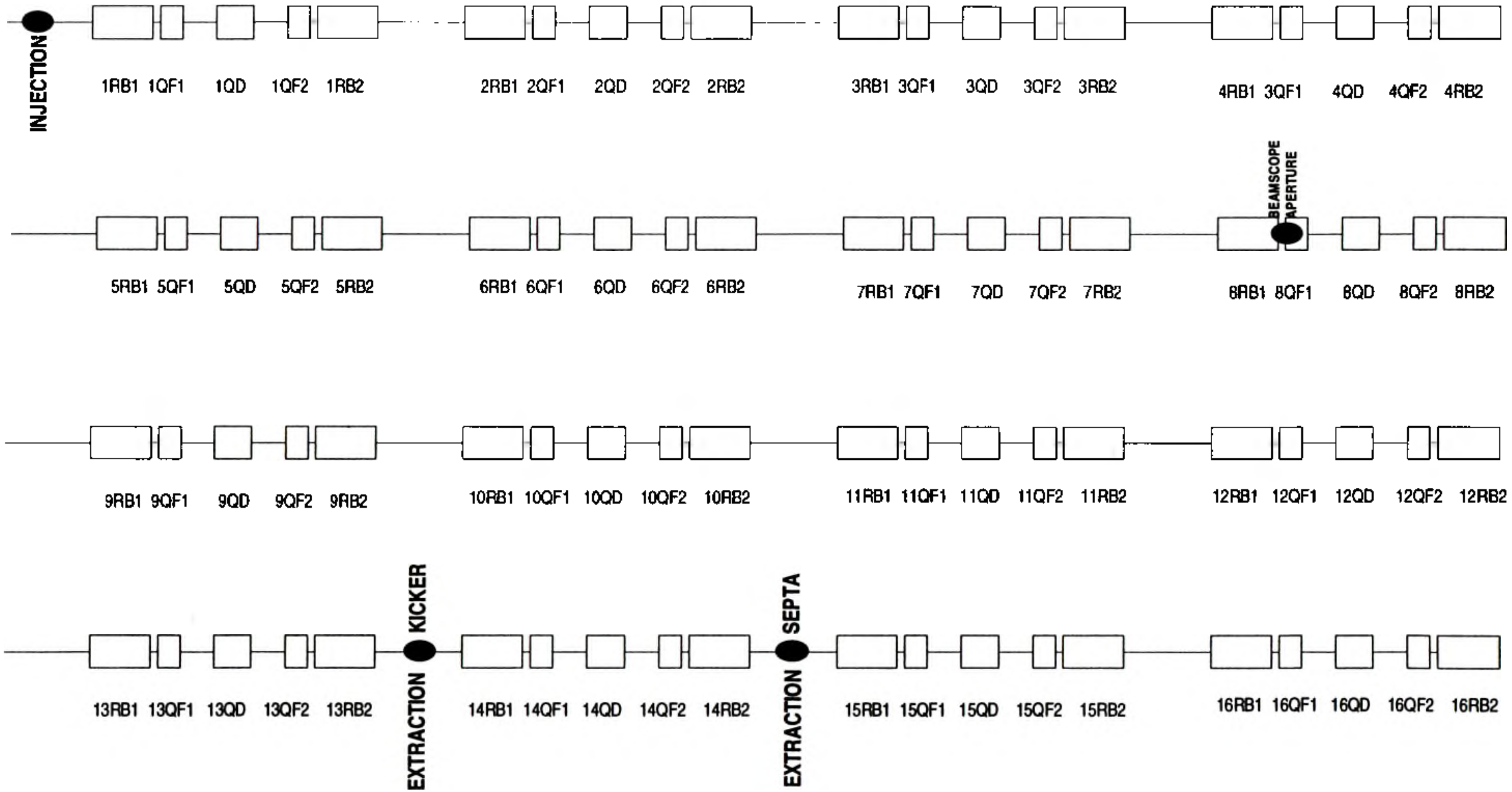

Figure 3.3: Schematic layout of the PSB.

3.6 Instrumentation in the Booster rings

3.6.1 Orbit measurements

128 electro-static position monitors (16 stations, two planes, horizontal and vertical and four rings) are installed in the Booster rings. These pickups are multiplexed onto 16 electronics channels such that a single ring and plane can be observed. In its present state the measurement is done at several fixed timings and at a user selectable predetermined timing. Even though the mean radial position during the whole acceleration cycle is available in the DSC, improvements in the equipment module and the application program are needed in order to make the mean radial position versus time accessible to the operator.

The measurement works reliably and is used frequently.

There is no trajectory measurement in the PSB except p.u. 7L2 (half turn p.u.).

3.6.2 Longitudinal emittance

The longitudinal emittance can be measured using the signal from the wide band pickup (BR.UWBC). A very fast transient digitiser (Tek 7912AD) converts the pickup signal into digital data. Since this digitiser has no adjustable amplification the sensitivity is adapted through external programmable attenuators. The digitiser itself is controlled via GPIB.

The system selects the optimal set-up (digitiser timebase and delay, and external attenuators) automatically. Sometimes the optimal setting cannot be found. No manual intervention is possible and the optimisation procedure cannot be seen in any way.

The Tektronix digitiser, albeit very powerful, must be considered obsolete.

In the PS machine a new Tektronix scope (model TDS 684) is being installed for a similar purpose. It seems reasonable to buy the same device for the Booster as well and to profit from experience and already available software for the PS machine.

3.6.3 Q calculation and Q measurement

The Q calculation program uses current measurements from the magnet power supplies during the cycle in order to calculate the Q value. Its accuracy is difficult to verify. A real Q measurement over the whole acceleration cycle is not available for the Booster at the moment. Such a measurement system, similar to the one used in the PS, is considered an urgent need.

3.6.4 The half turn pickup

Another method to measure the non integral part of Q is the half turn pickup. However Q can only be measured during injection (first few hundred turns) and the number of turns must be modified to get the half turn injection. In addition this pickup allows to measure the injection beam oscillations.

3.6.5 The Beamscope

The transverse emittance of the beam in the rings is presently measured using the Beamscope [14]. The beam is deflected through a local bump and scraped by a known aperture. The evolution of beam losses is detected with a current transformer which allows to calculate the beam profile.

Some problems with this measurement are :

i) the displacement of the beam orbit by the reaction of the RF radial loop,

ii) the linearity of the dipoles used to generate the bump and/or the fields at extreme positions, in particular at 1.4 GeV.,

iii) the influence of possible collective effects during the beam scraping.

Initiatives are underway to consolidate the Beamscope and to complement it with another method of profile measurement. Possible candidates, with their main drawbacks indicated in parentheses, are :

1) fast wire scanners (having problems at very low energy)

2) fast mechanical scrapers (this device should have a speed of app. 5 m/s which is difficult to reach)

3) new "measurement targets" (mechanical vibrations, complicated and slow in operation)

4) residual gas monitors (sensitive to space charge).

4. Longitudinal Beam Dynamics and RF Systems

4.1 Longitudinal Beam Dynamics in the PSB

At high intensity the strong longitudinal space charge force plays a very important role in the PSB throughout its energy range. Firstly the space charge reduces substantially the bucket area, which must be compensated for by more RF voltage. Secondly and most importantly, the space charge totally disables Landau damping above a certain threshold.

With a single harmonic RF system (C08, h=5, where C08 indicates a RF system working up to 8 MHz) operating, these thresholds are well understood both theoretically and experimentally [15]. Typically Landau damping is lost above $2\ 10^{12}$ protons per ring for the dipole mode ($m = 1$) and above $3\ 10^{12}$ protons per ring for the quadrupole mode ($m = 2$), see Figures 4.1 and 4.2. Thresholds for the higher order modes like sextupole ($m = 3$), octupole ($m = 4$) and decapole ($m = 5$) are higher, but since routine high intensity operation presently is about $7.5\ 10^{12}$ protons per ring, most of these modes are not damped by Landau damping at peak intensity. The within-bunch mode number m indicates the number of density modulation periods per synchrotron period.

These Landau damping thresholds could in principle be raised by a higher longitudinal emittance E_L but this would require a much increased RF voltage since the maximum E_L at present is limited by the longitudinal acceptance during the first half of the cycle.

With the second harmonic RF system (C16, $h = 10$) operating, these thresholds are less well known both experimentally and theoretically, but experience seems to indicate that they are probably lower, especially for the higher order modes.

The coupled bunch mode number n indicates the bunch to bunch phase shift of the longitudinal motion. It is useful to separate the discussion of the in-phase modes $n = 0$ from the discussion of the non-zero modes $n = 1, 2, 3, 4$.

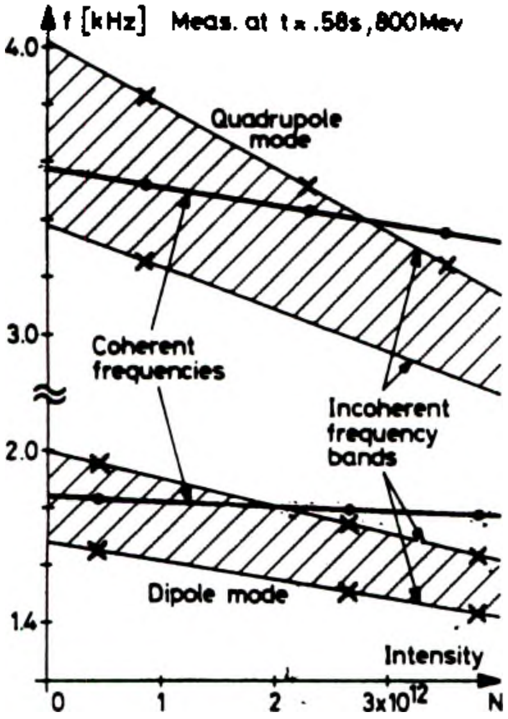

Figure 4.1. Coherent dipole and quadrupole mode frequencies and incoherent frequency bands from BTF measurements.

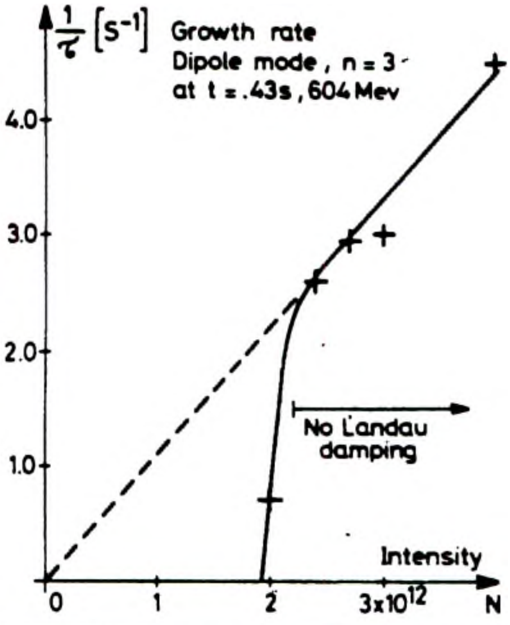

Figure 4.2. Growth rate of $n = 3$ dipole mode versus intensity.

A fast growing longitudinal 'micro-wave' instability with associated losses has since long been observed at high intensity in ring 4 in the later part of the cycle. The associated loss can be reduced by the phasing of the second harmonic RF and the RF voltage.

4.2 The $n = 0$ Modes

The spectral components of these modes are located around the bunch frequency $(h = 5)$ and its higher harmonics, so these modes interact mainly with the fundamental resonance of the RF cavity and the many feedback loops associated with it. Once the intensity threshold for loss of Landau damping is exceeded, even slow growth rates are harmful to the beam.
The tuning loop automatically detunes the cavity to compensate the reactive part of the beam loading which automatically tunes the cavity to a frequency above the operating frequency, and all $n = 0$ are in principle damped by the cavity (Robinson damping).

The dynamics of the relatively fast feedback loops required to operate an RF system of a fast cycling proton synchrotron change this completely. The fast tuning loop drives the dipole mode unstable [16] but the beam phase loop stabilises this mode again. Also the quadrupolar mode is unstable, so a quadrupolar feedback loop ('Hereward' damping) is needed above $4\ 10^{12}$ protons per ring to avoid losses from this mode.

When the second harmonic RF system is operating (to improve the bunching factor at low energy) the situation gets even worse. Firstly the Landau damping threshold appears to be lower, especially for the higher order modes, and secondly the form factor for these modes at the frequency of the second harmonic RF system $(h = 10)$ is high so these modes can be excited very efficiently by this system.

Sextupolar ($m = 3$), octupolar ($m = 4$), and decapolar ($m = 5$) modes are observed and can create losses. A major improvement in stability was observed by driving the second harmonic RF system from a beam derived RF signal. The stability of these modes appears to have somewhat degraded after the renovation of the low level RF electronics (tuning, AVC) and addition of direct RF feedback in 1990. There are no specific damping loops to damp these higher order modes although some damping of the octupolar mode by the 'Hereward' damping loop has been observed.

4.3 The $n \neq 0$ Modes

As for the $n = 0$ modes, the loss of Landau damping at high intensity due to space charge is a necessary (but not sufficient) condition for instability. Once Landau damping is lost, even relatively small parasitic coupling impedances are harmful for the beam. As the spectral components for these modes are near revolution harmonics different from the RF harmonics, they do not interact with the RF systems (exception: HOM in RF cavities) and their feedback loops, but rather with passive parasitic longitudinal coupling impedances of the vacuum chamber components. The coupling impedance responsible for the fastest growing dipole mode ($n = 3$ at 604 MeV) was identified to be caused by the unterminated cables of the extraction kicker already in 1978.

A mode by mode coupled bunch feedback system [15] was installed in 1976 to enable operation above the Landau damping threshold for the dipole, quadrupole and sextupole modes. It uses the C08 RF system ($h = 5$) as feedback kicker around the 6th and 7th harmonic of the revolution frequency. Voltages up to about 100 Volts can be generated this way and are sufficient. The system damps all coupled bunch modes $n = 1, 2, 3,$ and 4 of the three lowest orders $m = 1, 2, 3$. Octupolar modes can be artificially driven by the system, but are not damped significantly.

Its rather trouble free operation was somewhat disturbed in 1991 after the direct RF feedback was added on the C08 cavities, as this feedback causes different effective group delays for the 6th and 7th harmonics. The problem was cured by inserting compensating group delays in the two branches [17].

4.4 History and Outlook of PSB RF System Evolution

Many of the PSB intensity records achieved over the first 15 years of its existence are associated with improvements of the RF system. The main events are :

1973 : So-called 'Magnani' shaking [18] to combat longitudinal coupled bunch instabilities by longitudinal blow-up shortly after the midpoint of the cycle, where the bucket is no longer full. It allowed the Booster, together with other improvements, to achieve its design intensity.

1976 : Coupled bunch feedback system which allowed the PSB to be operated above the space charge Landau damping threshold for dipole and quadrupole modes.

1977 : 'Hereward' type quadrupolar feedback loop to damp the $n = 0$, $m = 2$ quadrupole mode driven by the C08 RF system.

1982 : Second harmonic RF systems added (C16, 6 - 16 MHz, 8 kV_p, $h = 10$) to improve bunching factor and transverse space charge limit.

1985 : Two tube operation of C08 system to cope with the high beam loading power.

1990 : Upgrade of C08 final power amplifiers for direct RF feedback to improve beam loading instabilities.

1993 : Pre-prototype $h = 1$ cavity installed in ring 3, C08 system in ring 3 modified to operate on $h = 2$ in addition to normal operation on $h = 5$. New standardised (PS & PSB) digital beam control system used to accelerate nominal LHC beam at $h = 1$ & 2 to 1.4 GeV for LHC MD[19].

1994 : New controls interface installed and commissioned. Digital beam control commissioned in all four rings for lead ion acceleration on RF harmonics $h = 17$, 10 and 5. Screen grid protection systems installed on the C08 RF systems to reduce tube failure rate.

1996: New tuning and AVC low level electronics in C08 systems. Prototype C08 cavity capable of operating at $h = 2$ (8 kV$_p$) or $h = 5$ (12 kV$_p$) in PPM for studies and with direct RF feedback in both cases.

1997 : Prototype $h = 1$ cavity (8 kV$_p$) to be installed in ring 3.

1998 : C02 ($h = 1$ with 8 kV$_p$) RF systems [20] to be installed in all rings. All C08 systems converted to $h = 2$ operation (C04). The C16 RF systems will be retained for controlled longitudinal blow-up and control of bunch shapes.

4.5 Second Harmonic RF System

Raising the bunching factor (B_F = average current / peak current) by modifying the longitudinal density distribution and/or modifying the potential well improves the transverse space charge limit in the same proportion. Both hollow distributions with decreased central density and a prototype second harmonic RF system [21] was extensively studied during the years 1978 - 1980. The hollow distributions were abandoned for stability reasons, while the potential well modification by a second harmonic cavity was retained and second harmonic RF systems [22] (C16, 6 - 16 MHz, 8 kV$_p$, $h = 10$) were put into operation for all four rings in 1982.

Double peaked bunches are obtained whenever the second harmonic RF voltage exceeds 50% of the fundamental RF. The optimum bunching factor improvement of almost 40% is obtained when the two voltages are equal, well into the double peaked regime. The design voltage was however limited to 67% as this gave a bunching factor improvement (37%) close to the optimum value, see Figure 4.3.

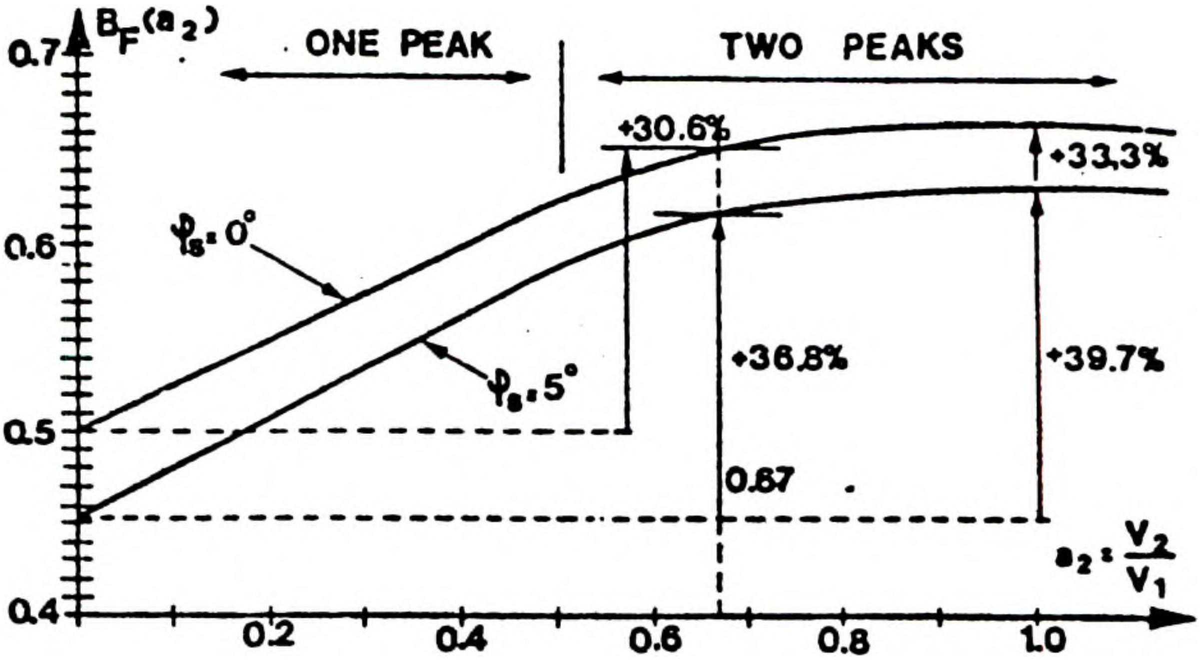

Figure 4.3 : Bunching factor versus second harmonic voltage

In addition to the improved bunching factor, the bucket area is improved substantially, especially when the reduction in bucket area by space charge is considered: 44% bucket area increase for 67% second harmonic RF voltage at 8 10^{12} protons per ring, see figure 4.4.

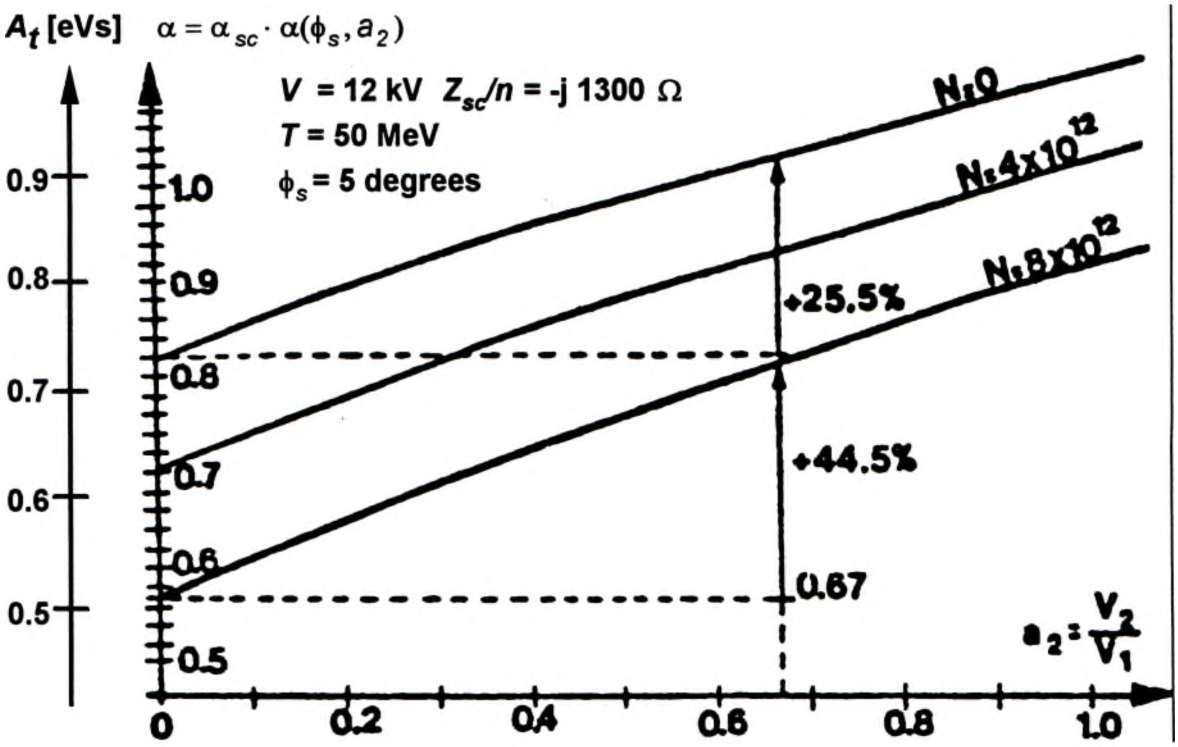

Figure 4.4. Bucket area versus second harmonic voltage with space charge.

Severe stability problems with sextupole and decapole modes were observed during commissioning. A major improvement was obtained by feeding the second harmonic RF system with the RF signal derived from the beam; this change of loop dynamics appears to improve stability, and a new intensity record of 10^{13} protons per ring was obtained in one ring.

Initially the tuning loop for the C16 system often tripped the system under certain conditions of phase setting and beam loading. A superheterodyne system was installed, but did not cure the problem. Finally it was realised that the system became unstable under zero or reverse power flow conditions due to the way the tuning correction signal is created (phase discriminator). A normalised reactive power detector [23] was installed in 1984, which made the tuning loop insensitive to the direction of the power flow.

Although the direct RF feedback cured the beam loading instabilities at low voltage, it had several undesired side effects. Firstly as mentioned above, the C08 RF systems appears to have different group delays at the 6th and 7th harmonic frequencies, which are used by the coupled bunch feedback. This was eventually cured by inserting different delays in the two branches. In addition the sextupole, octupole, and decapole coherent instabilities, which has always plagued the C16 second harmonic RF system, became worse after this conversion. It is not obvious whether this change is due to the addition of the direct RF feedback or the renovation of the low level feedback loops. The result is that the C16 system rarely is operated above 6 kV_p and often much lower to minimise the losses due to coherent instabilities. The resulting intensity gain from using the second harmonic RF system is therefore more like 15% than the expected 37%. In addition the system is difficult, delicate and time-consuming to operate.

4.6 Improvements to the High Power RF Systems

Beam loading instabilities under low voltage operation during capture was initially cured by pulsing the spare tube (acting as a controllable resistor). Later when both tubes were needed for extra beam loading power, a low level feed-forward scheme similar to that which was used in the PS [24] was installed [25] and activated during the capture process.

Due to intensities up to 4 times higher than design intensity and a faster rising magnetic cycle, the increase in beam loading required more power than a single tube could provide, and the power amplifiers of the C08 RF system were modified to operate two tubes in parallel in 1984 (originally one tube was foreseen as an immediately available spare).

Solid state driver amplifiers similar to the ones developed for the second harmonic cavity [22] and direct RF feedback to improve stability during low voltage operation were added to the C08 RF systems in 1990 as well as a total renovation of low level electronics for tuning and AVC loops. EIMAC final power tubes were replaced by Siemens tubes with higher transconductance. A drawback of this modification was that it took some time to realise that this direct RF feedback changed the relative group delay at the 6th and 7th harmonics, which is important for the coupled bunch feedback system.

New standardised interlocks were installed in the C08 systems in 1991, and in the C16 system in 1994. A new control system interface was introduced in 1994.

A prototype $h = 1$ RF cavity (0.6 - 1.7 MHz) with 6 kV_p maximum gap voltage was installed in ring 3 in 1993 as well as modifications to the C08 cavity in the same ring allowing it to be used at harmonic $h = 2$ (to improve the bunching factor and acceptance of the $h = 1$ system). These RF systems were used to confirm the feasibility of the PS complex as an LHC injector during an extended MD in December 1993.

The solid state amplifiers were upgraded to a version using more recent power transistors in 1994 and a conceptual design error in the RF feedback (single summing junction) was corrected.

The high voltage anode supplies for the C08 and C16 systems are not equipped with crowbars as in the PS. After the conversion of the C08 systems to direct RF feedback in 1990, there has been an increased rate of damage to the final power tubes due to excessive power. Although the failure mechanism is not fully understood, the addition of a protection system acting on the screen grid has reduced this failure rate.

New standardised tuning and AVC feedback loop electronics will be installed during the 1996 shutdown. Preliminary operational tests on one ring has not shown adverse effects on high intensity operation.

4.7 Most Needed MD's and Improvements.

When the second harmonic RF system is not used, the longitudinal stability is satisfactory, but the maximum intensity is lower. With the second harmonic RF systems in use, *longitudinal stability of the* $n = 0$*,* $m = 2, 3, 4$ *and 5 modes is marginal,* even when the second harmonic RF system is driven by the beam derived RF signal. The second harmonic RF system cannot be operated at its nominal 8 kV_p voltage due to losses from coherent instabilities such that the full 35 - 40% potential gain in bunching factor and intensity cannot be achieved.

The 'Hereward damping loop' detects the quadrupolar coherent motion by peak detection of the bunch envelope, which becomes ineffective at second harmonic voltages larger than 50%. In addition it appears that sextupolar, octupolar and decapolar instabilities become worse at higher V_{10}/V_5 ratios. Since a second harmonic RF system is retained for the future $h = 1$ and 2 operation, it is important that the dynamics of these instabilities are understood and if necessary cured with additional active feedback systems. Mode detection using synchronous detection at the second harmonic of the bunch frequency could be used to overcome the 50% limitation for the present quadrupole damping system and extended to cover also the other $n = 0$ modes, namely $m = 3$, 4, and 5. The second harmonic RF system has a high form factor for these higher order modes.

The installed RF power of the present C16 systems is marginal and can easily be exceeded when the phase of the second harmonic RF system is changed away from the value that flattens the bunches (AA production beam for example). The phase of the fundamental of the phase pick-up signal exhibits large variations throughout the cycle due to reflections in the transmission lines between phase pick-ups and BOR. These reflections will be strongly reduced during the 1996 shutdown.

It is mainly for these reasons that the RF systems of the Booster are very tricky to operate at high intensity, and most of setting up, operation and daily fine tuning of these RF systems are done by RF experts rather than the MCR operators.

Although the December 93 MD proved the validity of the future $h = 1$ and 2 operation for the 'ultimate' LHC beam (2 10^{12} p/ring), we have at present no high intensity experience with this system or the new digital beam control system driving these cavities. It is *very important to confirm operation of this system at high intensity* for ISOLDE, fixed target physics and possibly antiproton production beams before all rings are irreversibly converted in 1998. Pre-prototype $h = 1$ and 2 systems with feedback will be available for test with beam in 96 in ppm, and a full scale 8 kV_p, $h = 1$ prototype will be available in one ring in 1997.

In principle the much larger acceptance of the new $h = 1$ and 2 systems results in a much smaller space charge reduction factor that should increase the Landau damping. The total acceptance at low intensity of all buckets goes up to 1.2 eVs (1.6 eVs with 2nd harmonic) versus 0.7 eVs (0.9 eVs with 2nd harmonic) with $h = 5$ and 10 systems.

The mode analyser system used to observe these modes throughout the cycle have several shortcomings as it has not been upgraded for almost twenty years. Its tuning does not take into account the second harmonic voltage, the troublesome $n = 0$ modes are not detected, and it is not designed for modes with m higher than 3. An upgrade is on the way for 1996.

The mode excitation system, which permits check of natural mode growth rates and damping rates with feedback on has recently been re-installed. This system also permits verification of C08 voltage calibration (a frequent source of trouble) by measuring the coherent dipole frequency.

Additional studies of the 'R4 micro-wave instability' should be done, for example at reduced voltage, reduced longitudinal emittance, debunched at an appropriate flat top, or using the prototype $h = 1$ and 2 systems. The larger longitudinal emittance possible using the new RF systems should raise this threshold.

Unlike the old analog beam control systems, which derived their frequency program from the mean radial position of the beam, the new digital beam control systems are completely dependent on the B-train for generating their frequency program. The present B-train generator has a *stability* of only +/- 10^{-3}, which corresponds to +/- 1 Gauss at injection energy and about +/- 5 Gauss at high energy. Studies are in progress on how to improve this. The *resolution* of only 1 Gauss is marginal, and if a generic frequency program is used, which requires the use of a B-rate multiplier, this resolution is not adequate for lead ions. A B-train generator with a better than 1 Gauss precision and 0.1 Gauss resolution should be developed.

4.8 Ease of Operation

High intensity setting up and operation of four rings (unfortunately each behaving differently) for three main users (AA, SFT and ISO) represents a high work load on the RF/LL section. Function generators for voltages and phases are fine tuned individually for each ring to combat coherent instabilities which at present constitute the principal intensity limit.

In order to ameliorate beam performance, it would be highly desirable to improve beam stability, beam and RF diagnostics available in the MCR, ease of operation, documentation, and training of MCR operators. In this way the RF/LL experts would only be called in cases of genuine hardware failures.

The lead ion beam does not suffer from the above mentioned high intensity problems. However, the fast capture process required by the high dB/dt during injection and RF capture requires a complex frequency correction function for each ring, which at present is modified only by RF experts. Any major change in injection field, number of turns, dB/dt at injection, or capture duration requires a substantial GFA editing effort, which takes several hours.

Two solutions are proposed:

i) a hardware solution: i.e. a modification of the B-train being sent to the Digital Frequency Program' using additional control parameters and timings.

ii) a software solution: i.e. an application program similar to the 'Q setting program' which automatically generates the first part of the GFA tables for this frequency correction from a few machine parameters.

The new $h = 1$ and $h = 2$ digital beam control systems will also profit from this improvements.

4.9 Theoretical Work

The major problem is the marginal longitudinal stability with dual harmonic RF systems. The theoretical understanding of this problem is complicated for two reasons :

i) The beam transfer functions (BTF's or stability diagrams) are complicated by the highly non-linear potential well and the beam interacting with the RF systems at two harmonics instead of one.

ii) The properties of a very large number of feedback loops (in the order of 10) are important to predict the stability of the $n = 0$, m = 1,2, 3,... modes.

The first problem has been addressed by Shaposhnikova [26], It would also be highly desirable to confirm the calculated transfer function by some numerical examples and compare with measured BTF's as it was done for the single harmonic case, see figure 4.1. A collaboration with S. Koscielniak at TRIUMF is in progress to model the feedback loops and confirm the validity of the model experimentally, possibly by simplified test cases.

5. Beam Losses and Beam Loss Management

5.1 Status Quo of Loss Occurrence in the PSB

A look at high-intensity, space-charge limited, machines suggests that beam loss in these accelerators is virtually inevitable, and the PSB with its unusually large incoherent tune shifts is no exception. On top of this it has to suffer the injection loss inherent of the multiturn scheme. Fortunately, these losses are in general confined to lower energies, where they are less harmful. For this reason and also due to the rather conservative design intensity, no particular attention had been paid to a systematic loss management in the ring - with the exception of the so-called "Standard Scrapers". These are 2 mm thick stainless-steel aperture limitations inserted at edges of all bending magnet chambers where the vertical beam envelope comes closest to the vacuum chamber. Later, a single more massive (40 mm thick graphite) window has been added as a precision aperture for the Beamscope emittance measurement system, of which the second function was that of a “loss concentrator”. With its acceptances (for ideal closed orbit) of $A_{x,y} = 345, 136\,\pi$ mm mrad it constitutes indeed the dominant aperture restriction in the horizontal plane. In the vertical plane, however, it does so only if the closed orbit amplitudes at the standard scrapers do not exceed 1.5 mm. As these constraints are not always met, loss from vertical blow-up may occur at any of the standard scrapers. They define acceptances (for ideal closed orbit) of $A_{x,y} = 565, 145\,\pi$ mm mrad. While their horizontal acceptance is comfortably larger than that of the Beamscope window, the margin in the vertical plane has been chosen small in order to allow for highest intensities - the space charge limit at injection is proportional to the vertical acceptance.

Apart from losses at lower energies, the high-intensity beam may suffer from other loss mechanisms; the known ones are listed in the Table 5.1 below, and their occurrences indicated on the photograph Fig. 5.1 of the beam currents in the four rings.

Table 5.1: Loss Mechanisms in PSB

#	**Type**	**%**	**Occurrence**	**Cure**
1	Injection	40	Septum, 1st Bending	none
2	Capture	10	Beamscope Aperture[1]	none
3	Stopbands	15	< 150 MeV	done as far as possible
4 4 a	Long. Instab. Dual RF syst. marginal stab.	5-10 >10	0.4-1 GeV ; Beamscope Aperture[2].	Improvement Programme cf. ch.3
5	Slow Loss	3-5	Diffusion out of bucket Spurious transverse inst.	h=5, h=10 voltage & phase programs Transverse Feedback[3]
6	R4 “μwave” instability	0-5	590 MeV; Beamscope Aperture[2].	Septa tanks damped, h=10 voltage & phase program
7	Ejection Loss	< 1 3-4	Halo scraped on inner sept. face outer edge: kicker volt., flat top	less important Improved: max. kicker ampl.

1) not too bad at low energy
2) insufficient at a few 100 MeV
3) New kicker cables constitute higher coupling impedances;
some possible effects observed in Ring 4

Although percentually less important, losses occurring above 100 MeV are thought to cause most of the irradiation of the machine. At these energies lost protons are not easily stopped and may continue to travel many meters downstream the locus of their first encounter with matter.

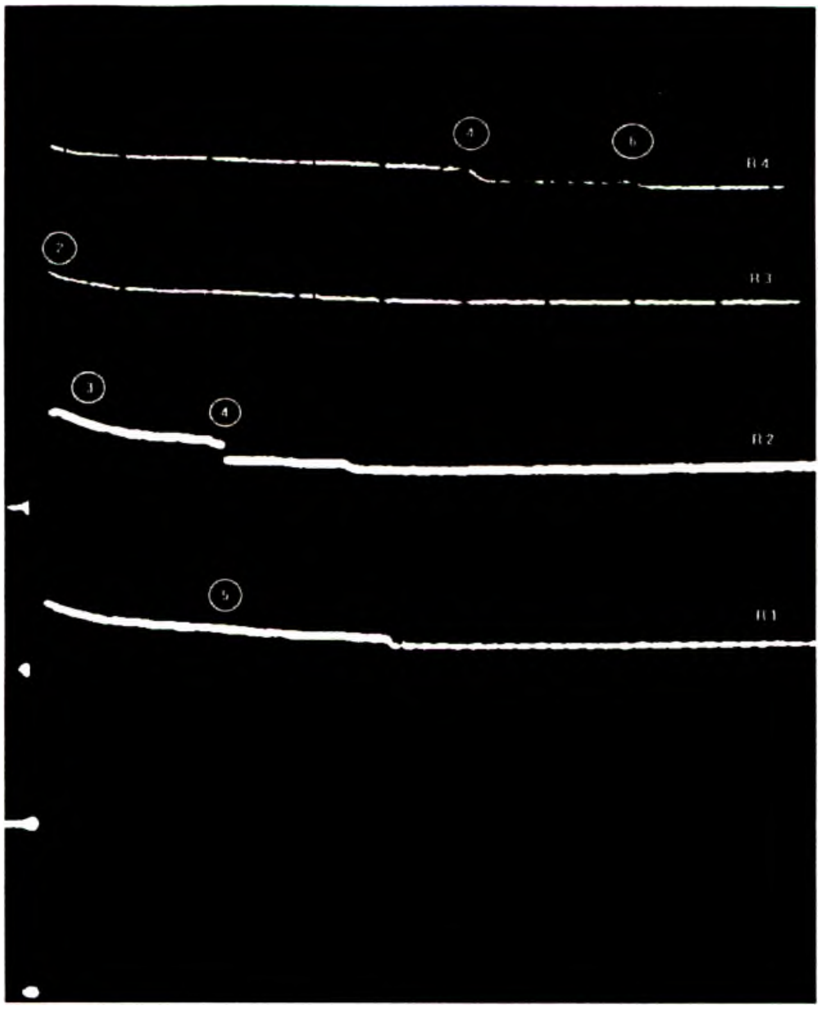

Figure 5.1 : High-intensity beam currents of the 4 rings with their typical losses (injection loss not visible on the slow beam current transformers)

5.2 Generalities of Collimation Problems

As well known, the stopping power of matter for charged particles is characterised by three major mechanisms [27]:

i) Energy loss by energy transfer to electrons (ionisation loss)

ii) Multiple scattering on nuclei

iii) Nuclear interactions (elastic or inelastic)

If the collimator face is hit at shallow depth, a fraction of the impinging protons is backscattered into the machine aperture by the second mechanism. These particles, which have in general gained enough transverse emittance to exceed the machine acceptance and have lost some energy, continue to circulate until they hit another aperture limitation. The hitting depth is the smaller and the outscattered fraction the larger, the slower the primary particles drift towards the collimator. The drift speed may be determined by betatron amplitude growth, by spiralisation of particles lost from the accelerating bucket, or both. For drift speeds < 1m/s in small machines, typically >2/3 of the primaries are outscattered. They have to be stopped by a secondary collimator. Unfortunately, the latter is only efficient if placed at somewhat less than 180 degrees betatron phase downstream, a distance which the swarm of outscattered particles has to travel without being intercepted, i.e. the machine designer should provide a very large acceptance in this part.

Note that 180 degrees phase advance in the PSB corresponds to about two machine periods. In recently designed high-current machines one foresees two very long drift sections separated by shielded quadrupoles [28].

Figure 5.2 illustrates the situation in phase space. The outscattered particles are plotted at 90 degrees from the primary collimator and at the optimum location φ for a secondary one.

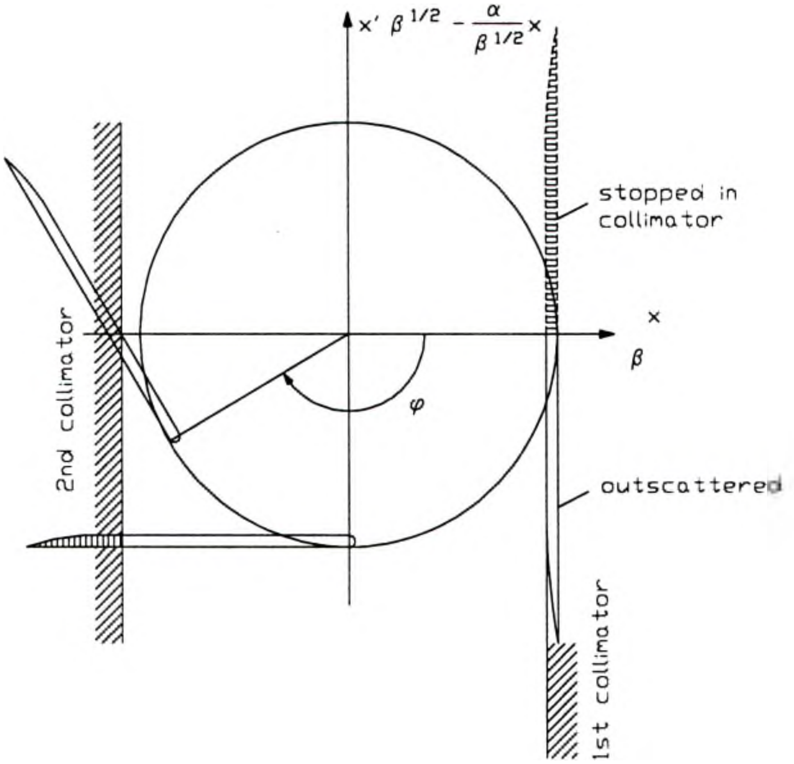

Figure 5.2 : Effect of outscattering from a collimator

Apart from the outscattering problem, actually stopping particles of energies higher than 100 MeV is not trivial: e.g. the range of 1 GeV protons in Cu is about 0.5 m. This means that the main collector/absorber has to be rather massive at GeV energies. Nevertheless a fraction of protons is stopped before that path length by nuclear interactions (interaction length of the order of 10 cm).

5.3 Computer Study of Loss Management : Present Situation and Possible Collimator Configurations.

A simulation of the proton loss distribution in the present situation and with the a priori most promising collimator configurations (within the frame of available straight-sections) has been carried out by T. Trenkler [29]. He used his proper tracking code [30] derived (and adapted to energies below 1 GeV) from one used to study the LHC cleaning insertions. All configurations were investigated at energies of 50, 100, 400 MeV and 1GeV; at the higher energies only momentum loss was assumed, in conformance with the loss mechanisms outlined above, where the drift speed of the lost protons is given by the spiralisation of non-accelerated particles. For the lower energies betatron amplitude growing with 0.5 m/s were simulated. From the five configurations studied we retain here the following two:

i) the present Beamscope window as the collimator and

ii) a collimator system occupying a whole L1 section.

The latter would consist of a 1.5 m long graphite collimator matching the acceptance envelope at the inner horizontal side (to intercept the momentum losses) followed by a 0.5 m long rectangular tungsten window as the final collector. Four slightly protruding U-shaped thin tungsten scrapers are inserted at 25 cm distance into the upstream part of the graphite collimator. For more details we refer to Ref. [29]. Such a composite collimator represents about the maximum imaginable effort, to be justified by its efficiency. The tabulated results of Trenkler's study are condensed in the following Figure 5.3 and Figure 5.4.

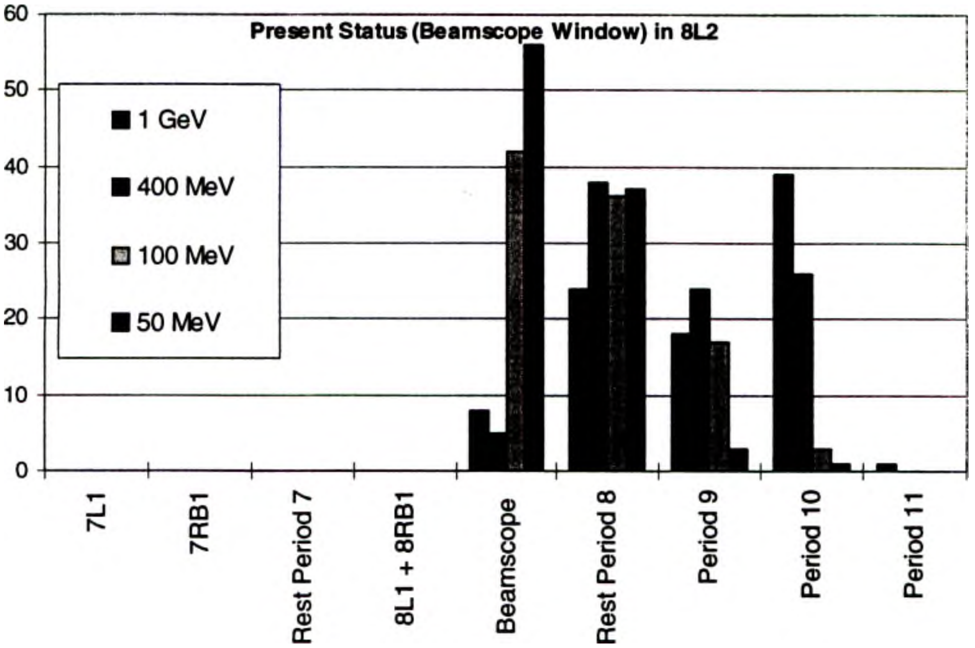

Figure 5.3 : Distribution of momentum losses on the present 'collimation system', i.e. the Beamscope Aperture in 8L2, in %. Note the large fraction of losses downstream of the collimator at higher energies

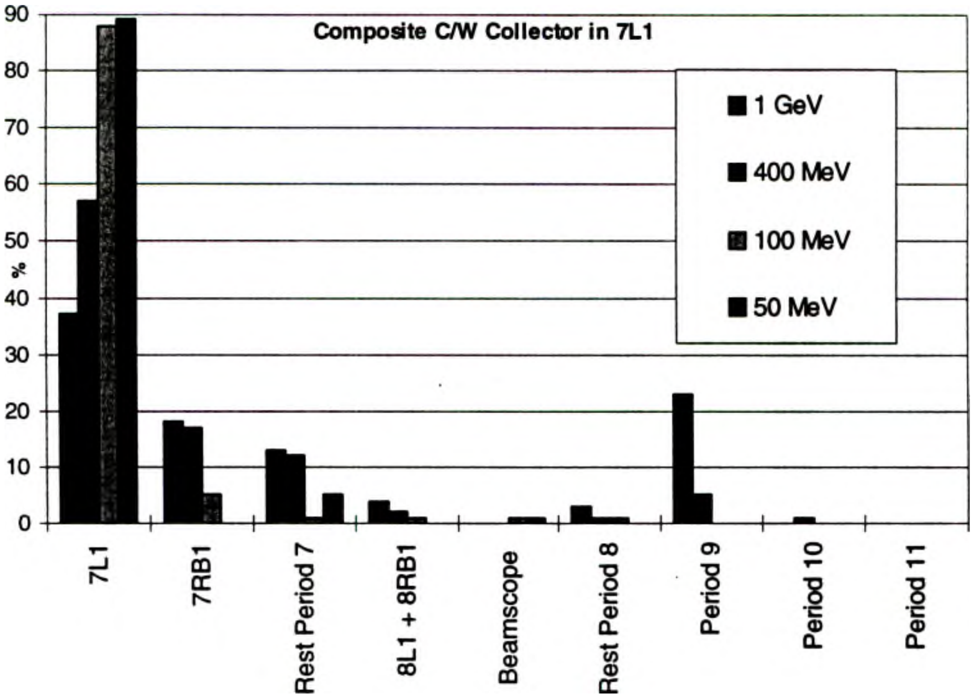

Figure 5.4 : Distribution of momentum losses on a potential collimator candidate, i.e. a composite C / W collimator in 7L1, in %. Still non-negligible losses after the collimator.

The candidate ii) for a future collimator is placed in the long straight section 7L1 which is unused at present. The Beamscope aperture i) is located in the short straight section 8L2. These results have been essentially confirmed by comparisons with the ACCSIM code [31].

5.4 Vertical Collimation

The vertical losses due to stopbands at low energies <100MeV are more or less satisfactorily absorbed by simple collimators, even the present Beamscope window, and horizontal losses will be removed by the momentum collimator. A rectangular tungsten scraper at the end of the collimator section (7L1 in our study), part of the collimator configuration ii) studied by Trenkler, and part of the shielding of the downstream bending magnet in the wire-septum scenario, would be more efficient than the Beamscope window. While the latter could then be slightly increased, the new collimator again requires a reduction of the vertical acceptance, which, as said above, is directly proportional to the intensity ceiling. The amount of the acceptance reduction depends of the assumed quality of orbit, and therefore on whether it will be corrected or not. Although there are 18 dipoles per plane installed, only 14 are available (18 minus the 3 Beamscope bumpers minus 1 dipole used as shaver), correction is not straightforward, as there are only 32 power supplies (26 years old; can be patched to any dipole). But even if more power supplies plus controls will be provided, orbit correction in periods 7, 8 and 9 appears difficult due to unavailability of the Beamscope dipoles for this purpose. By coincidence, the orbits show their worst peaks in these periods.

The potential correction of the vertical orbit at standard scraper locations by 8 (present number of power supplies per ring) vs. 14 dipoles per ring needs to be studied. Depending on the results a decision will have to be made whether a simple acceptance reduction is accepted to eliminate parasitic losses on standard scrapers, or the existing power supplies have to be complemented and/or replaced.

5.5 A Wire-Septum as Loss Collimator

Improved loss collimation by a specially designed electrostatic wire-septum was proposed in Ref.[32]. The basic idea is to have a septum of not too precisely aligned wires such that the particles being lost are deflected by few wires first to quickly gain emittance until they pass inside of all wires and get the full kick necessary towards a collector. In this way the majority of the lost particles hit the collector sufficiently deep to prevent outscattering. It also renders the collimator system less sensitive to the drift speed. Such a septum concept is shown in Fig. 5.5. Because of its rather modest performance requirements it should not present major technological problems.

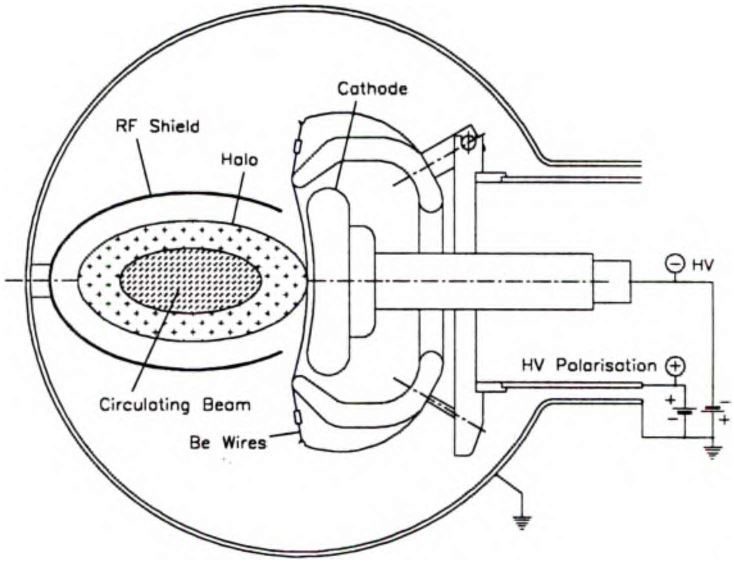

Figure 5.5 : Possible layout for a wire-septum for loss collimation

Downstream the wire-septum there has to be the collector; its geometry and position can only be optimum at one given energy. A preliminary check with ACCSIM [31], which can simulate a wire-septum, of a momentum collimator featuring a 0.5 m long septum and a 0.5 m long tungsten absorber in the 7L1 straight section, gave the following results:

Table 5.2 : Collection Efficiency of a Wire-Septum Collimation System

Energy [MeV]	Fraction stopped in W-Collector	Fraction into Bending 7RB1 - potentially stoppable by a shield	Fraction lost in Rest of Period 7 and Period 8
50	99 %	1	-
100	100	-	-
400	84	11	5
1000	70	15	15

These figures can probably be improved with a more thorough study; results obtained so far indicate that septum and collimator may even be shorter. Shielding the downstream magnet for losses at higher energy contributes to overall efficiency.

The mechanical and thermal constraints (septum wires will heat up in presence of heavy loss) have not yet been studied in detail.

5.6 Conclusions

The facts emerging from the studies above can be summarised as follows:

I) In the present situation the Beamscope window collects at low energies (around capture) about one half of the lost protons; most of the rest hits the same period. At higher energies (losses from marginal rf loop stability, longitudinal coupled bunch instabilities), the quasi-totality of the lost particles is spread over the three periods 8, 9 and 10.

ii) A future collimator, even sophisticated, would not collect more than half of the higher-energy losses; 15-20% of them end in the first downstream bending magnet. Placing a second collimator somewhere downstream would not change much and would only stop a few per cent. The lower-energy capture losses, however, appear to be localised in the collector to about 90 %.

iii) A wire-septum plus a simple collector block appears clearly superior at higher energies. A more refined study may further improve the efficiency. The potential mechanical and thermal problems remain to be investigated.

6. Transport Lines from PSB to PS and ISOLDE

For a discussion on the shortcomings of these lines, one has to take into account the modifications which will be carried out before the end of the decade for the LHC.

6.1 Elements to be renewed for the LHC upgrade

Many magnets and power supplies of the line to the PS will be renewed in the framework of the "PS Conversion for LHC" Project (PS 14) [33]. The reasons for the modifications are

i) Increase of $\int Bdl$ by 26.3%, corresponding to the energy increase from 1 GeV to 1.4 GeV.

ii) Magnets have to be laminated so as to enable PPM between 1 and 1.4 GeV and to make them compatible with pulsed power supplies.

The elements to be renewed for the LHC upgrade are compiled in Table 6.1.

The transport lines dealt with in this chapter are sketched in Fig. 6.1. For each part of the lines, problems and shortcomings to be tackled are discussed in the following paragraphs.

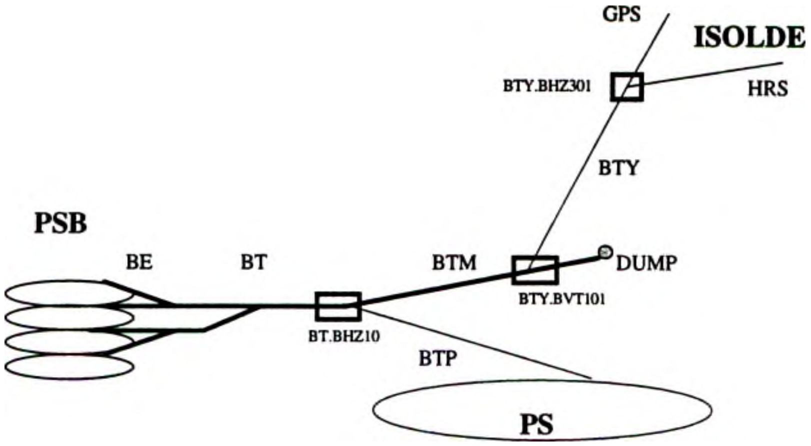

Figure. 6.1 : Transport lines from PSB to PS and ISOLDE. Bold lines and elements are or will be PPM after the conversion for the LHC.

Table 6.1 : Magnets and power supplies to be renewed for the "PS conversion for LHC".

Elements	**Name**	**Magnets**		**Supplies**		**Comments**
		#	to be changed	#	to be changed	
Ejection bumpers	BE.BSW	12	no	3	yes	
Ejection kickers	BE.KFA	4	no	4	yes	modules to be short-circuited. ∫Bdl doubled. Rise time doubled: incompatible with h=5
Vertical recomb. kickers	BT.KFA10, 20	3	no	3	yes	same as above
Ejection septum	BE.SMH	4	yes	1	yes	capac. discharge supply
Vertical recomb. septa	BT.SMV10, 20	3	yes	3	yes	capacitor discharge supplies
Vertical bending magnets	BT.BVT10, 20	3	yes	3	yes	pulsed (or ramped) supplies
Vertical correct. magnets	BT.DVT10, 20	4	yes	3	yes	capac.discharge supplies (4 if BT3,2.DVT20 separate)
Recombination quadrupoles	BT.QNO10, 20,30,40	6	yes	4	yes	pulsed (ramped) supplies
20^0 magnet to ISOLDE or ML	BTM.BHZ10	1	yes	1	yes	2.5 Tm needed. Pulsed (ramped) supply

6.2 Ejection (BE) [34]

The ejection of high intensity beams, with their large horizontal emittances, causes beam loss and irradiation of the ejection septa and the downstream elements. The situation has been improved recently by setting the ejection kickers to their maximum voltage, but the losses have not been completely removed. For the LHC, these kickers will be short-circuited in order to double their kick strength; moreover, beams will be smaller in the LHC era (1.4 GeV), so the losses should diminish. Meanwhile, ways to minimise machine irradiation by beam collimators are under study (see Chapter 5).

The three (per ring) bumper magnets BE.BSW perturb the orbit outside the bump. This can be avoided by a better adjustment of their respective deflection - to be done in the near future.

6.3 Recombination (BT) [34]

Ideally, the PS should not notice the fact that the beam comes from four largely independent accelerators; in practice, there are always ring-to-ring differences in beam steering and focusing. Making these differences small turns out to be more difficult than anticipated by the machine builders. A vigorous improvement program for this part of the line is required, especially in view of conserving the small-emittance beams for the LHC, but also to reduce activation of and around the vertical septum magnets.

Recombination trajectories are adjusted by means of two dipoles (each H+V) per ring. There are indications of coupling between planes and neighbouring rings (the dipoles of the four levels are superimposed), in particular at large deflections. Already now, there are copper plates between superimposed dipoles so as to avoid coupling of the pulsed fields by eddy current shielding. This issue deserves further study because coupling would jeopardise automatic steering procedures such as ABS.

The recombination of large-emittance beams (ISOLDE, SPS fixed target, production beam, Pb ions) calls for large acceptances; they have been increased in the 1980ies at the expense of further complications in the recombination. Beams from all four levels pass off-centred through quadrupoles, and the nominal beam positions in pick-up electrodes are far off-center (~ 30 mm) as well. The ABS procedure tested recently has the merit of pinning down alignment errors of position monitors, scintillator screens, quadrupoles, and other imperfections. The following tasks are proposed :

(Urgent) Increase of the deflection of vertical correction dipoles BT3,2.DVT10. Their nominal value is non-zero, in fact almost at their maximum, because they are used to compensate the off-center passage through quadrupoles. Vertical trajectories of rings 3 and 2 cannot be correctly adjusted without a 25% increase of these dipole strengths (problem: the magnets get too hot; will be changed for LHC, see Table 6.1).

An extra power supply to enable BT3.DVT20 and BT2.DVT20 to be adjusted separately (one common supply at present). This is foreseen for the LHC.

(Urgent) Nominal trajectories (geometry) and nominal settings of magnets have to be revisited. Some of the operational settings do not correspond to the theoretical ones. Clarifying this may help in understanding the difficulties encountered by ABS.

How relevant are matching differences between the four levels due to vertical bending/septum magnets? Are they measurable? Studies should be continued.

The most intricate way of recombining the beams is by RF recombination [35] a process involving a transverse RF dipole and employed to generate the p-bar production beam. Adjustment and operation are cumbersome and ways to facilitate them may have to be contemplated should this beam be required beyond 1996. (Note that there will be a much simpler way of squeezing beams from the four PSB rings into one half of the PS once the PSB is operated with RF harmonic 1 after 1998/9, should the need arise).

6.4 Transfer line towards PS (BTP)

A priori no changes are foreseen to run this line at 1.4 GeV (constant momentum). Whereas the quadrupoles tolerate PPM of a few % for small optics changes between users, the steering dipoles, which are unlaminated, and their supplies are incompatible with PPM. In routine operation, steering differences between bunches from different rings are about 2 mm in the PS. It is hoped that with the ABS procedure, smaller deviations will be attained. The LHC beam will profit from a damper eliminating injection oscillations in the PS, but it can only tackle errors of less than 1 mm. The present situation allows to optimise only one PS User, generally the highest intensity beam. With a PPM of steering dipoles all PS Users could be optimised independently, in particular taking full advantage of the ABS facilities.

6.5 Measurement/Beam Dump Line (ML)

The purpose of this line is:

i) dumping the beam on "parasite" cycles (used for PSB MD's)

ii) emittance and matching measurement ("Measurement Line") with 3 SEM grids [34]

iii) transport the ISOLDE beam between BT.BHZ10 and BTY.BVT101 (Fig. 6.1).

The quadrupoles in this line are already PPM (including sign) to adapt the optics to the various destinations: ISOLDE, Dump, Horizontal Emittance, Vertical Emittance. It is planned to replace the present 20^0 bending magnet BTM.BHZ10 by a longer (laminated) one in the 1996 winter shutdown in view of the energy increase (the quadrupoles BTM.QNO10-20 have to be displaced and the various optics setting recalculated).

A long-standing issue is the "Measurement Line" which has never reached the stage of routine use although the hardware (3 SEMgrids in either plane) and software apparently work fine. The optics is not perfect yet and there is a small dispersion in the horizontal plane, but these facts do not explain why the emittances measured in ML are systematically larger, up to 50%, than the ones determined by the Beamscope or by SEMgrids at PS entry. Obviously, deviating a beam through an extra line of some 15m to measure its emittance rather than measuring it in the transport line proper, isn't an advantage. Nevertheless, it is proposed to invest more effort into this line to render it operational.

6.6 ISOLDE Line (BTY) [36]

This line transports the highest beam intensity ($3\ 10^{13}$ p every 2.4 s) in CERN, but is rather poor in terms of beam diagnostics. A few percent beam loss can have very serious consequences on the material and its activation and may render certain parts inaccessible to maintenance and repair. Therefore an urgent program for adding beam instrumentation has been proposed recently :

i) beam current transformers in front of both GPS and HRS targets will enable beam losses to be determined more accurately (they will eventually be employed by a "watchdog" type surveillance device). For both GPS and HRS, one of the two dipoles to steer the beam onto the target has to be taken out so as to free space for the beam transformer; the remaining ones have to be refurbished with four (GPS and HRS, both planes) 60 A ramped or pulsed power supplies

ii) a pair of SEMgrids (H+V) will be installed in front of each target (HRS & GPS) to measure beam size and position.

Moreover, there is an urgent need for at least five electrostatic position monitors which will allow non-destructive observation of the beam steering and eventually some further steering dipoles in the HRS branch (to be studied).

This more complete beam monitoring should enable an ABS procedure and a better understanding of the imperfections in beam steering and optics causing the "hot spots". Some more automatic setting process, e.g. to focus the beam on the target according to the particular user's request, could be envisaged.

ISOLDE Line to 1.4 GeV? By the end of this decade, the PSB will operate with 1.4 GeV for the PS. The idea of delivering a 1.4 GeV proton beam also to ISOLDE is gaining popularity as the yield of very unstable (neutron- or proton-rich) isotopes, ISOLDE's speciality, is improved at this higher energy (albeit with longer targets, still to be developed). Besides this physics argument, there are also two operational advantages :

i) the smaller beam size, ~12% less, of the ISOLDE beam should reduce beam losses in the BT, BTM, BTY lines.

ii) The same magnet settings for all users in the ejection (BE) and recombination (BT) line (except BT.QNO40, 50 for the different optics) would ease operation. Note that if ISOLDE operates all the time at 1.4 GeV, the unlaminated quadrupoles BT.QNO10, 20, 30 and their power supplies do not have to be replaced for LHC, saving a few 100 kCHF (see Table 6.1).

The upgrading of the ISOLDE line to 1.4 GeV is relatively simple:

i) all (laminated) quadrupoles and their supplies are compatible with the energy increase (but the latter not with PPM between 1 and 1.4 GeV, see Table 6.2) ;

ii) the four identical big bending magnets BTY.BVT101, BTY.BVT116, BTY.BHZ301, BTY.BHZ308 (deflection 200 mrad each) can attain 26% higher $\int Bdl$ but their power supplies would have to be rebuilt (200-300 kCHF).

Some of the ISOLDE targets appear to suffer destructive shock-wave effects due to the "simultaneous" (within 2.4 μs) extraction of the four rings. A possible cure has been proposed where the four rings are ejected with some ring-to-ring time delay ("staggered ejection") so as to lower the instantaneous beam intensity by a factor of 4. With many of the ejection and transfer magnets pulsed for the LHC upgrade, this delay cannot be made larger than ~0.5 ms, and zero between rings 2 and 1 (both deflected by vertical recombination kicker BT.KFA20). Major investments, probably in the MCHF range, would be required to obtain significantly longer time delays. Recent studies on liquid targets suggest that staggering times of as short as 10 μs may suffice to avoid shock waves. In any case, staggered extraction would necessitate substantial modifications of the beam current transformers on which the "Watchdog" surveillance system is based. Also the transfer line pick-up's have to be made compatible.

6.7 PPM Aspects

It may be useful to summarise the PPM capabilities (with cycles every 1.2 sec) of all these lines in the future (with the modifications included in the "PS conversion for LHC" project).

Some ISOLDE users have expressed interest in operating with proton energies down to 0.6 GeV. At first sight, this looks feasible, provided that :

i) all ramped DC supplies foreseen for the "PS Conversion for LHC" can change currents by a factor of ~2 within 1.2 seconds;

ii) ISOLDE accepts a limit of ~1.8 10^{13} p/p (about the same transverse emittances as at 1 GeV with 3 10^{13} p/p; this limitation has to be quantified experimentally).

Table 6.2 : PPM of the PSB-PS and PSB-ISOLDE transport lines with the modifications foreseen in the "PS Conversion for LHC" Project.

Line	**PPM** 1/1.4 GeV	**PPM** Optics (Quads)	**PPM** GPS/HRS	**Comments**
PSB ejection (BE)	yes	-	identical	
Recombination (BT)	yes	yes	identical	
Transfer to PS (BTP)	no	a few %	-	No PPM of steering dipoles
Measurement/Dump (BTM)	yes	yes	identical	
ISOLDE (BTY)	no	no (1)	yes	(1) except BTY.QNO179, 182, 184 for GPS/HRS

For completeness, a PPM in energy between GPS and HRS (should anybody ask for this one day) could only be made feasible after changing the DC power converters of one bending magnet (BTY.BVT116) and 10 quadrupoles (BTY.QDE104 through BTY.QFO153) to ramped supplies.

7. Operational aspects and controls

7.1 Organisation

The operation technicians have in general a high competence level, which for reasons like "term contracts", heavy "second jobs", etc. is not fully used for learning machine physics, improving machine performance, etc. On the other hand second jobs as programming for instrumentation, machine settings or MD participation, could be a good way of learning the machine, provided the programming effort is kept within reasonable limits. The Technical Supervisor has a decisive role in continuous follow-up, careful optimisation of the machine and education of the operators. To fully cover operational periods two Technical Supervisors are needed. Improvement programmes (short and medium term) are followed up during the weekly Booster Supervisor meetings. Booster Supervisor complements the technical supervision by scientific support and stand-by availability around the clock.

Concerning the difficulties during start-up's please refer to Ref.[37].

7.2 The tools

The beam behaviour is observed and controlled via the instruments and the control system. The generic part of the new control system (console manager, knobs, working set presentation, etc.) is a clear improvement. Some real time aspects are however not yet satisfactory (difficulties due to the architecture of distributed processing power). For example: some values of the Beam Current Display do not belong to the same cycle.

Most of the application programs treating the instrumentation work "in principle", which means that there is a high probability of finding the instrument in a strange state or giving non-interpretable results.

There are possible explanations for this :

i) The standard "framework" for the application programs, proposed and developed for the Booster slice, still needs: a) refinements like exhaustive and comprehensible error handling at all levels, b) standardised and well analysed access and control procedures.

ii) Lack of close supervision of both the programming style and the operational aspects. The programming style and the software specification and analysis (software analysis rarely exists at all in our programming environment) have to be carefully respected for maintenance reasons. This is particularly precarious for visiting programmers.

iii) Lack of rigor in the utilisation of units (a classical examples is the emittance values given without any indication of how many standard deviations).

In the MCR we still lack many tools (observation of several RF-parameters, RF voltage sampling, detected WBPU, possibility to observe transverse and longitudinal instabilities, logging machine performance, vary-log, loss monitoring and statistics, archives, etc.).

Very few automatic checks or optimisations exist. Some problematic hardware (for ex.: PS field compensation) was treated in previous chapters. The Booster documentation, like instrument and machine description and operational information, is rudimentary, old or not satisfactorily classified. The use of WWW could be envisaged (should be done with divisional guidelines and support). Presently a database is set up for the machine elements. This information could be used for optics checks and modifications. Automatic logging including beam measurements are also planned but need extra programming effort.

8. Study time

The following Table 8.1 represents an attempt to list the topics to be studied and to quantify the time (prime or 'parasite' time) required to implement the modifications and improvements described in this document. The added-up totals for the years 1996/97 are clearly beyond the capacities of the present staff. Some activities will have to be dropped or postponed to 1997/8, but it is very likely that the agenda for 1998 will fill up with new topics.

Other noteworthy comments:

i) The present practice of 8 hour machine time blocks allocated on Wednesdays (in parallel with lepton production) has proven to be an efficient tool to solve upcoming questions and problems.

ii) One should take note of the particular situation of ISOLDE: the top-intensity beam requires frequent readjustments, not all of which can be performed during operation. Upon request, one parasite ME cycle should be made available even (and in particular then!) during highest-intensity ISOLDE operation.

iii) Studies of the ISOLDE beam line optics require a dump target and SEMGrids at the target position. The necessary time has to be included in the ISOLDE schedule.

Table 8.1: PSB Machine Development Time Forecast

Topic	Customer	Remarks/Requirements/ Contribution	Prime Time	1996 hrs	1997 hrs	1998 hrs
h=5/h=10 Dual RF System: - study of basic properties: gap-derived or beam-derived h=10 phase; - test cases for theory - new HW: Synchr. Detector for quadr./octup. modes; new mode analyzer	ISOLDE, SFT	relevant also for futur h=1, h=2 system S. Koscielniak / TRIUMF collaboration	P	30		
h=1 / h=10 RF Systems	LHC	Controlled bunch flattening with h=10	Y	10	10	10
h=1 / h=2 Dual RF System	PSB		P	20	30	30
Loss Analysis	PSB	Loss occurrence and loss dynamics, BLM and TIS measurements	P 1)	20	10	10
Steering and Focusing inTransfer Lines	LHC,SPS,	ABS improvement	Y	10		
	ISOLDE	ISOLDE line optics to be reviewed	P	20	10	
		Staggered extraction		8		
	ISOLDE	SEM grid measurement's at target position	P	8	8	
"μwave" Ring 4 Instability	SPS	Unknown mechanism	P	10	20	
Beam Transfer Function Measurement	PSB	Momentum distribution of injected beam measured in the ring	P	30		
Comparison Wire Scanner / Beamscope / (Guillotine)	LHC	before ordering 8 wire scanners from TRIUMF	P	10	10	
1 GeV Measurement line	LHC	Render operational		20	10	
"Initial" Beam for LHC	LHC	$\varepsilon^* = 0.75$ μm at 26 GeV/c	P		20	
Scintillator Screens Inj. Line CCD cameras	Pb Ions	Test of new SW developments	Y	8		
Transverse Stability with New Kicker Cables	PSB, LHC	Unknowns in acceleration to 1.4 GeV		20		
Damper Tuning			P	10		10
Ion Injection Steering Improved Focusing	Pb Ions	Correction from Screen Position (Matrix Inversion)	P	8		
Multiturn Injection Study	Pb Ions, LHC	(PhD Thesis)	P	10	20	
B-Train Generation	Pb Ions	Test of NMR markers Integration into control system	Y	8		
Ion Lifetime Measmt's	Pb Ions	At varying Energy, with AT (PhD Thesis)	Y	20		
Integer Stopband Compensation	PSB	Successful at ISIS - against theory!		10	20	
Total				**290**	**168**	**60**
1) P = Partially during prime time						

9. Recommendations

This chapter summarises the study group recommendations for PSB improvements.

We recall that the GEB mandate was to suggest machine consolidations beside the modifications already foreseen for LHC. However some overlaps have been unavoidable (e.g. RF).

Some topics (e.g. resonance compensations) were not specially treated, as they have been extensively worked out in the past and no major improvements are expected.

Linac beam :

1. Studies are needed to identify the causes of beam trajectory variations.

Injection lines :

1. PS stray field effects on beam trajectories should be compensated by
   - i) a better magnetic shielding,
   - ii) a compensation method linked to "OCCURRENCE" (cycle position) rather than "USER".
2. Alignments of various elements in LT, LTB and BI including p.u.'s, screens, to implement ABS for the complete transfer Linac-PSB.
3. Install, before PSB entrance, one SEM-grid per plane per ring (foreseen for LHC).
4. Install, before the ion distributor, one SEM grid (H+V).
5. Install more frame grabbers on TV cameras (screens).

Multiturn injection :

1. Implement optimisation methods to minimise losses:
   - i) theoretically, with simulation programs (taking account the space charge)
   - ii) experimentally, by making use of an improved instrumentation (e.g.: half turn pick up plus a digitised fast transformer to be built)
   - iii) by studying injection line matching with space charge.
   - iv) investigate implementation of an automatic injection procedure.
2. Feasibility study of H^- injection to be used when no more ions in the PSB

Ring :

1. Equip all (112) ring correction dipoles with power supplies and associated controls and applications (to correct orbit and minimise losses all along the cycle).

2. Interchange magnets when necessary (i.e. replace irradiated by non-irradiated).

3. The new septa (for LHC) will be welcome a.s.a.p. to improve vacuum.

4. To obtain a better vacuum, we suggest a baking by hot nitrogen, to 50/70 degrees and at least add some pumping and gauges at critical places.

5. Investigate vacuum problems in injection and extraction regions.

6. Revisit shavers (e.g.: new power supplies).

7. BTFM should be made operational for E and ΔE measurements of the 50 MeV circulating beam.

8. Renew the longitudinal emittance measurements. Use the same hardware (digitiser) and software (adapted to PSB) as in the PS.

9. A Q measurement, similar to the PS one, is urgently needed (foreseen for LHC).

10. A transverse emittance measurement, complementary of the present Beamscope, should be installed, (foreseen for LHC). The best candidate seems to be the wire scanner (final decision in ~6 months).

11. Upgrade a.s.a.p. QF/QD power supplies to cope with the new faster MPS field rise (foreseen for LHC).

12. Upgrade BLM system to display and record losses vs time and USER.

13. Optimise beam orbit at extraction, e.g. new weighting of extraction bumpers.

RF :

1. Studies of dynamics of in-phase bunch oscillation modes m = 2, 3, 4,.. (n=0).
2. Reduce reflections in transmission lines for phase p.u. signals.
3. Study h=1,2 prototype RF systems with high intensity beams (e.g. ISOLDE).
4. Upgrade the mode analyser system.
5. Study microwave instability in R4.
6. Improve resolution and stability of B train generator (for frequency progr. generation).
7. Study a better operational system for digital frequency progr. correction functions.
8. Compare theory vs experiments in two harmonic systems.
9. Compare theory vs experiments in systems with many feedback loops.
10. Study longitudinal blow-up and stability of hollow distributions.

Loss management:

1. Study the possibility of installing an electrostatic septum to cut beam halo and concentrate losses in a selected region. In particular, the following items should be subject of more detailed studies:

    i) Machine experiments to confirm (or alter..) the present assumptions about loss mechanisms as given in Table 5.1.

    ii) Computer simulations to refine the specifications and performance expectations of mini-wire septa for horizontal collimation

    iii) The mechanical and thermal feasibility of these septa.

Extraction lines :

1. (BT, BTP) Upgrade BT3,2.DVT10 (magnets and power supplies) and make the PS injection steering PPM.

2. (BT) Revisit vertical recombination : geometry, nominal trajectories and magnet settings. The ABS will be exploited to pin down inconsistencies.

3. (BTM) Make the Emittance Measurement Line operational.

4. Equip the ISOLDE line with very basic beam diagnostics : 2 beam current transformers, 5 pick-ups, 2 SEMgrids pairs.

5. Modify instrumentation to cope with "staggered" extraction requirements following formal specifications from ISOLDE.

6. To upgrade ISOLDE to 1.4 GeV four new power supplies are needed for BTY.BVT101,116 and BTY.BHZ 301, 308 and possibly an improvement of the tunnel air cooling.

7. Study flatness of extraction and recombination kickers.

Operational aspects and controls:

1. For operation technicians:
   i) advocate long term contracts and careers
   ii) stimulate active interest in accelerator physics.
2. Encourage beam performance follow-up and optimisation as well as task oriented MD participation.
3. Keep improving tools (instrumentation, signal observation, controls, etc.).
4. At the PSB console the necessary facilities (e.g. signals and instruments) should be present to diagnose beam behaviour and in particular beam instabilities (transv. and long.).
5. Study on the advantages and disadvantages of re-installing the "inflector region" allowing PSB and ISOLDE operation independent of the PS access status.
6. Take more professional care concerning the application program production to diagnose, maintain and document these programs.
7. Rejuvenate the BS team.

MD requirements:

1. Machine physic team should be strongly reinforced, already to cope with the study requirements of coming years.

2. MD time should be regularly scheduled with ISOLDE for beam adjustments on parasitic cycles and also on the target.

In conclusion, the present PSB is a machine in a good state, its performance and availability (97%) are excellent. No drastic action (again besides the modifications for the LHC) seems necessary or extremely urgent. However many improvements of various nature could facilitate and consolidate substantially its operation and, last but not least: a rigorous maintenance program of all equipments is a mandatory and obvious requirement.

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