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Reducing the SPS Machine Impedance

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Abstract

The SPS as LHC Injector project has been working for some time to prepare the SPS for its role as final injector for the LHC. This included major work related to injection, acceleration, extraction and beam instrumentation for the LHC beams [1]. Measurements carried out with the high brightness LHC beam showed that a major improvement of the machine impedance would also be necessary [2]. In addition to removing all lepton related components (once LEP operation ended in 2000), the decision was made to shield the vacuum system pumping port cavities. These accidental cavities had been identified as having characteristic frequencies in the 1-1.5GHz range. Since the SPS vacuum system contains roughly 1000 of these cavities, they constitute a major fraction of the machine impedance. As removal of the ports and associated bellows is not possible, transition shields (PPS) had to be designed to insert within the pumping port cavities.

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1 INTRODUCTION

The SPS as LHC Injector project has been working for some time to prepare the SPS for its role as final injector for the LHC. This included major work related to injection, acceleration, extraction and beam instrumentation for the LHC beams [1]. Measurements carried out with the high brightness LHC beam showed that a major improvement of the machine impedance would also be necessary [2]. In addition to removing all lepton related components (once LEP operation ended in 2000), the decision was made to shield the vacuum system pumping port cavities. These accidental cavities had been identified as having characteristic frequencies in the 1-1.5GHz range. Since the SPS vacuum system contains roughly 1000 of these cavities, they constitute a major fraction of the machine impedance. As removal of the ports and associated bellows is not possible, transition shields (PPS) had to be designed to insert within the pumping port cavities.

2 MECHANICAL DESIGN

2.1 The SPS Vacuum System

Most of the ~7km circumference of the SPS ring is comprised of stainless steel vacuum chamber whose sectional profile varies as a function of the inter-pole gap of the different magnets and the punctual machine β. Some 80% of the vacuum system is housed within the 4 types of main magnet, each with its own optimised chamber profile, as shown in figure 1.

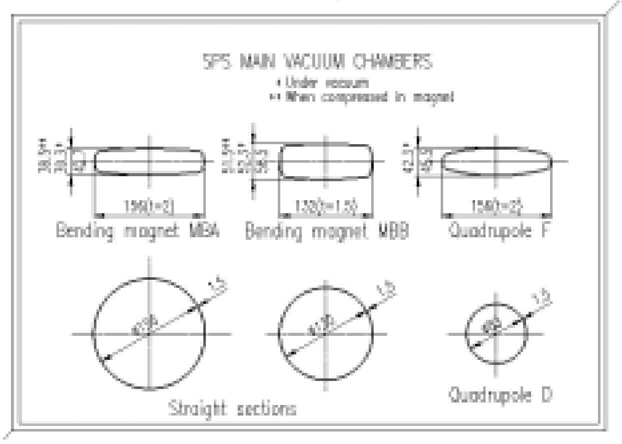

Figure 1: SPS Chamber Profiles

The chambers are immovably compressed between the magnet poles and equipped with a flexible bellows at the upstream end and a vacuum pumping port downstream. Since oval bellows are difficult and costly to produce, and in the interests of standardisation, both bellows and ports were made round of a size to accommodate all chamber profiles. A typical cavity is formed by the downstream pumping port connected to the upstream bellows of the adjacent magnet and is approximately 300mm long by 156mm diameter.

2.2 Shield Design

The PPS design was complicated by the fact that considerations of RF shielding and vacuum pumping rate are contradictory. In addition, as shown in figure 2, the cavities are located for the most part in the restricted gap between heavy main magnets. To accomplish the installation, the removal of every second machine dipole would be required.

In order to take full consideration of the different aspects involved in the design phase of the shields, a conceptual team was composed of representatives from the fields of Radio Frequency, Vacuum, Magnets and Mechanical Design. Input was also taken from the Surveyors and Heavy Handling specialists.

The primary RF consideration was to bridge the gap across the cavity as smoothly as possible. In those cases where the chamber profile changed across the cavity the transition was made as gently as possible by use of a transition cone. Electrical continuity was also to be assured across the cavity. However, it is clear that the better the shield from the RF point of view, the more difficult it would be to pump the interior of the shield. Much time during development was spent in designing the pumping holes so as to allow an adequate pumping rate while not unacceptably compromising the RF characteristics.

Stainless steel (type AISI 304L) was chosen for the construction of the shields themselves as this exhibits good out-gassing properties. After an early abortive attempt at stainless contacts, CuBe was adopted, being the universal standard for this type of application. Early design iterations included contacts brazed or riveted to the steel of the shield, both of these solutions were found to be unacceptable on the grounds of out-gassing. The clip fixing, which was based upon off-the-shelf components, gave a good electrical contact and no out-gassing problems. Unfortunately no standard parts were found to fulfil the PPS prerequisites; therefore new contact profiles were designed and specially produced in industry.

Shield design was further complicated by the necessity for compatibility with already installed synchrotron light tungsten masks that were installed for operation of the SPS with leptons. These masks also occupied space within the bellows and pumping ports.

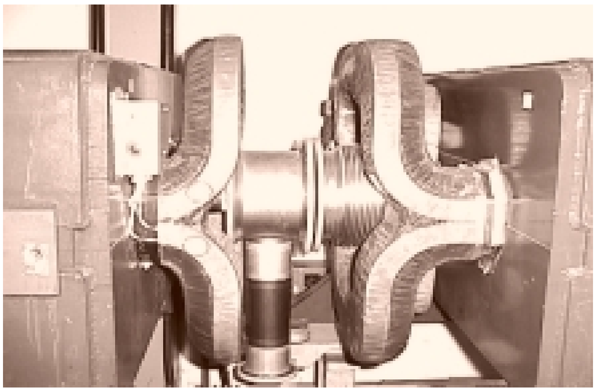

Figure 2: The Pumping Port and Bellows Assembly Between two Main Dipole Magnets

2.3 Mechanical Tolerances

In the longitudinal plane, the range in the length of inter-magnet gaps around the machine came as something of a surprise and a full survey of all the cavity lengths was found to be necessary. Since the translation range of shields was limited by the cam and length of the central contact, it was necessary to produce each shield type in **S**hort, **N**ormal and **L**ong versions. Given that 13 different sub assembly types were necessary to cover all profile combinations, the need to produce S, N & L versions resulted in 27 subassembly models. In certain cases chambers on the short straight sections have bellows at both ends and therefore 'float ' to some extent. Whenever this situation was encountered the chamber was placed in a position which allowed the fitting of an 'N' type shield and clamped such that the bellows remained free.

Since the chambers are compressed between the poles of the main dipoles, the profile at the end of the chamber is somewhat deformed. Early shields were based upon short pieces cut from standard chambers, but it soon became evident that very slightly different profiles were necessary; consequently special shield pieces were produced in industry.

The contacts at either end of each shield making contact with the magnet chambers needed sufficient spring range to accommodate inconsistencies in the chamber to back-plate welds. These welds were hand done with a certain inevitable roughness, their only constraint being vacuum leak tightness. Some deformation of the back-plates is inevitable due to the weld. The tension/compression arrangement of six fixing bolts enabled accurate alignment of the shield with respect to the magnet chamber in both horizontal and vertical planes.

Apart from the straight sections, the SPS is a circular machine. The magnets are, however, straight and consequently the dipoles are set at an angle of 4.2mrad. (hence the necessity for flexible bellows). Sufficient flexibility to accommodate this angle had to be built in to the sliding contact. The accumulation of offset in each half-cell (32m) resulting from building a curve with several straight components is taken up at the entry of the quadrupole by a 4mm radial offset. Asymmetric shields were therefore necessary to compensate this offset.

2.4 The sliding contact

It is easy to imagine from figure 2 the impossibility of installing the shields without displacing the magnets. It therefore became mandatory to invent an opening and closing mechanism to allow installation and intervention at a later date. The same mechanism would allow vacuum gasket fitting between the flanges at the cavity centre. This mechanism took the form of a spring assembly to close the contact and a cam shaped bar introduced via the pumping port to compress the springs in the open position. This is illustrated in figure 3. One implication of this arrangement was that any transition cone had to be limited to the bellows sub assembly as the upper and lower sliding contacts relied upon parallel axes.

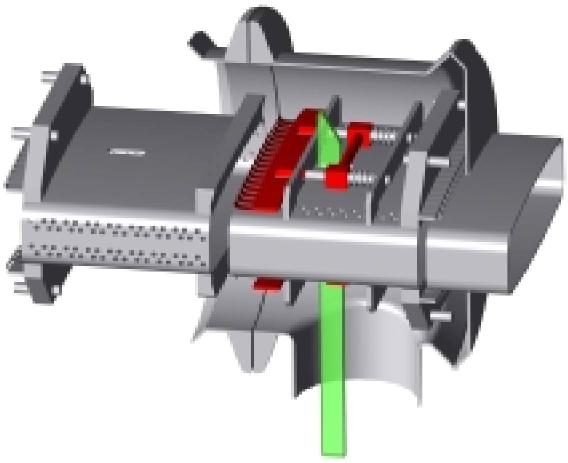

Figure 3: A PPS Assembly

3 LABORATORY AND MACHINE TESTS ON PROTOTYPES

3.1 Pumping Speed Tests

As stated above, a compromise was necessary between shielding/electrical continuity and the need to effectively pump inside the shield to an acceptable vacuum pressure (typically 10^{-7}-10^{-8} mbar) within an acceptable time. A value for pumping conductance was calculated and a test-bed set up to measure pumping times. At first it was hoped that the space left around and between the fingers of the spring contacts would allow sufficient pumping speed but tests showed that supplementary holes were needed. These holes were arranged and dimensioned in such a way as to minimise the impact on the RF performance.

3.2 Measurements with beam in the SPS

Laboratory RF bench tests proved to be of limited value in this case and it quickly became obvious that measurements with beam in the SPS machine would be needed. The lab tests did however prove conclusively the need for a very good electrical contact between the various components of the shield and the machine.

A 12m portion of an SPS straight section was equipped as a test bed with 6 representative cavities each fitted with an RF probe. One bellows/pumping port assembly was left empty as reference and the others received iterations of the shield design and later, the various different profile models. The test-bed PPS were fitted with thermo-couples to measure the heating effect of image currents induced by the high intensity LHC type bunches.

Once the basic concept of the shields was validated by the SPS test bed, the size, shape and position of the supplementary vacuum pumping holes were optimised with beam. It came as no surprise to find that the holes were best placed on the vertical edges of the chambers (or as near as possible on the round profiles. Best results were expected from oval holes with the long axis parallel to the beam direction, surprisingly however circular holes gave better results. Figure 4 compares measurements of the empty reference cavity (green) and the much cleaner final shielded cavity (blue). Interestingly the peak at 2.4 GHz (marked by the cursor) corresponds to International data transmission frequency of norm 802.11 and was found to be noise on the signal cable.

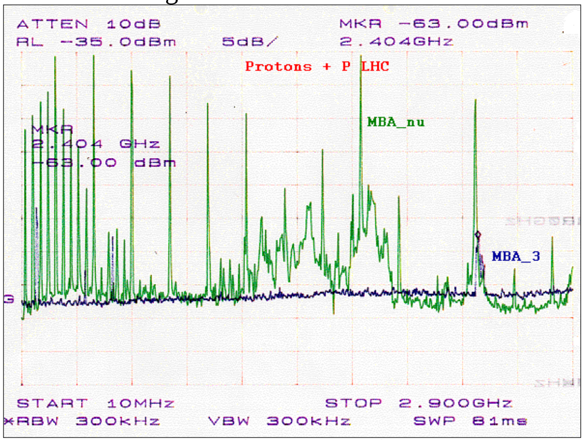

Figure 4: Comparison of RF signals from a Pumping Port Assembly in the Presence of the LHC beam, with (Blue) and Without (Green), Shields fitted.

4 INSTALLATION

4.1 Tools

Special jigs were developed which located in the magnet chamber to position and hold the fixed studs during welding to the back plate. High power spot welding was chosen for fixing the studs as being rapid, efficient and above all relatively clean with respect to the vacuum system. Several spot-welding machines were purchased to allow both ends of a magnet to be treated consecutively and as a reserve in case of breakdown.

4.2 Installation within a standard SPS Period

A typical SPS 32m half-cell is made up of a 3m quadrupole (alternately QF & QD) followed by four 6m main dipoles (2 MBAs + 2MBBs) and a 3m SSS girder supporting a variety of magnetic correction or beam-extraction elements, beam instruments, etc. In order to access freely either end of each magnet chamber, the optimum method was to remove the first and third dipole of each half-cell. Every second 17t magnet of the SPS was therefore removed from the beamline and the shields fitted while supported by the handling machine. The missing magnet allowed access to fit shields to the thus exposed half cavities of the adjacent magnets. All of the ‘normal’ sections of the SPS arcs were treated in this way. Many other parallel activities had to therefore be planned around the fact that the magnet-removing machine blocked the SPS tunnel.

Full-scale installation trials were carried out in the workshops and once the installation teams were ‘run-in’ an average of 3 magnets were equipped per day throughout the 2000/2001 SPS shutdown.

4.3 Alignment

Whenever an SPS magnetic element is moved, an alignment is carried out using the local quadrupoles as reference of the machine position. Since the impedance reduction campaign involved removing half the main dipoles together with a good percentage of the auxiliaries, a complete realignment of the SPS was carried out for the first time since its initial installation.

4.4 Overall Installation Figures

In the order of 20% of the SPS was equipped with impedance reduction shields during the shutdown from November 1999 to March 2000. The remainder of the installation being carried out between end 2000 and May 2001 after the end of LEP operation.

Around 370 main dipoles together with a hundred auxiliary magnetic elements were removed, equipped, replaced and realigned before vacuum leak detection. In all, over 1200 bellows/pumping port cavities are now equipped with impedance shields.

5 SUMMARY OF RESULTS WITH BEAM

Single bunch measurements carried out in 2001 [3] showed a much-improved longitudinal bunch stability, a factor 7 decrease in bunch lengthening with intensity was observed. The onset of the previously observed microwave instability was no longer encountered up to the nominal (10^{11}) bunch intensity. Measurements with LHC beam on the 26GeV injection plateau showed a clear increase in beam lifetime and absence of losses [4,5].

6 REFERENCES

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