ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO107

PREDICTION OF THE FIELD DISTRIBUTION IN CERN-PS MAGNETS

D. Schoerling, CERN, Geneva, Switzerland

Abstract

The CERN Proton Synchrotron (PS) has a circumference of 628 m and operates at an energy of up to 26 GeV. It uses one hundred combined function magnets, with pole shapes designed to create a dipolar and a quadrupolar field component. Each magnet is equipped with a main current circuit and five auxiliary current-circuits, which allows controlling the linear and non-linear magnetic fields.

These magnets were installed in the 1950s, and part of the compensating circuits have been added or modified since then, resulting in the fact that detailed measurements of the field distribution in each individual magnet as a function of the six currents are not available.

This study is performed to estimate, through deterministic and stochastic calculations, the expected mean value and standard deviation of the field harmonics of the installed magnets as input for beam dynamics simulations. The relevant results can be used to design correction schemes to minimise beam losses in the PS and to enable the acceleration of higher brightness beams required to reach the foreseen Large Hadron Collider (LHC) luminosity targets.

INTRODUCTION

To reach the high luminosity targets of the LHC, the CERN injector complex has to generate higher brightness and intensity beams. To this end the Proton Synchrotron Booster (PSB), the PS and the Super Proton Synchrotron (SPS) are upgraded and consolidated and LINAC4 is constructed.

In the framework of this programme, the PS injection energy is increased from 1.4 to 2 GeV to reduce space charged induced tune shift and beam losses [1]. A precise magnetic model of the entire PS is required to optimize the working point for transverse beam stability and to design an efficient resonance compensation scheme to reduce losses. The developed magnetic model enables this by controlling the linear and non-linear magnetic fields making full use of the Pole-Face-Windings (PFW) and the Figure-of-eight (F8) loops of the main combined function magnets installed in the PS [2, 3, 4]. Each magnet is comprised of 10 blocks, of which 5 are "open" and 5 are "closed". The PS combined function magnet, the pole face, the PFWs and the F8-loop are shown in Figure 1 [5].

To enable the simulation and prediction of resonance compensation schemes for the PS a magnetic model of the main magnets that takes into account systematic and random mechanical errors is required. To this end, static magnetic simulations of the main PS bending magnets were pursued to understand the magnetic field behaviour of a nominal PS

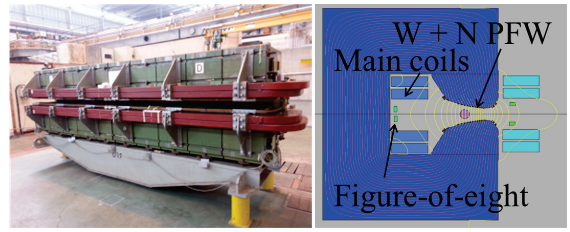

Figure 1: Left: Picture of one PS magnet. Right: Cross-section of PS magnet ("closed" type).

magnet, that means without mechanical errors [3]. Using these results as a starting point, structural and statistical magnetic studies were performed to understand a magnet with a random mechanical error distribution. For the first time, this enabled the implementation of a resonance compensation scheme based on the prediction of magnetic field errors [4]. The resonance compensation scheme is needed to minimise losses of particles while crossing integer and/or 1/3 stop bands due to the large expected Laslett tune shift (≥ 0.3) and to minimise resonances excited in the operational working area.

For a better understanding of the mechanical errors one PS main magnet was geometrically measured during CERN's long shutdown 1 to establish systematic and random mechanical errors. The results of these measurements were then used as input for Monte Carlo 2D and 3D magnetostatic simulations. This paper presents the methodology; the investigations performed on the PS combined function magnet; the analysis of the geometrical measurements; and the simulation results.

METHODOLOGY

If the distribution of the magnetic field in the synchrotron is well known, correction schemes can be designed by using beam dynamics codes such as MAD-X and Polymorphic Tracking Code (PTC). To ease communication and information exchange between magnetic simulation codes and beam dynamics codes, the discrete Fourier transform $(N = 60)$ $B_n = \frac{2}{N}\sum_{k=0}^{N-1} B_r(r_0,\phi_k)\sin n\phi_k$ and $A_n = \frac{2}{N}\sum_{k=0}^{N-1} A_r(r_0,\phi_k)\cos n\phi_k$ is applied on the field distribution on a reference radius of $r = 10$ mm in the free aperture between the magnet poles [6] . The multi-pole components $n > 4$ are neglected in our analysis. Here the presented results $(b_2, b_3, b_4, a_1, a_2, a_3, a_4)$ are scaled with $\frac{(n-1)!}{B_1 r_0^{n-1}}$. This set of parameters describes the field distribution inside the free aperture and can then be easily used in beam dynamics codes. The alignment errors are taken into account directly in the beam dynamics code.

Both systematic and random magneto-static effects were systematically researched. The search included the calculation of the field distribution, taking into account structural deformations due to magnetic forces; the influence on the

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO107

field distribution of the vacuum chamber position; and permeability, material uncertainties and mechanical errors.

STRUCTURAL ANALYSIS

To analyse the influence of the systematic deformation due to the forces acting on the pole, the field distribution of the deformed yoke was evaluated by performing a 2D coupled multi-physics analysis in ANSYS. The structural deformations calculated by using 2D simulation results were compared with measurements taken on the PS reference magnet U101. This measurement was done with a laser tracker at reference marks during powering [7]. The agreement with simulations is within the uncertainty of the measurement. For the structural analysis simulation, a Young's modulus of 152 GPa and a Poisson's ratio of 0.3 [8] were assumed.

The magnetic field distribution was then decomposed in multi-poles, which were then used as input for MAD-X beam dynamics simulations [4]. A difference in tune and linear chromaticity was noticeable only at a high field due to the higher magnetic force.

At the extraction energy of 26 GeV the calculated tunes change from $(Q_x, Q_y) = (6.2686, 6.2219)$ for a machine model without deformed magnets to $(Q_x, Q_y) = (6.2647, 6.2179)$ for a machine model with deformation; and $(\xi_x, \xi_y) = (0.0381, 0.4770)$ to $(\xi_x, \xi_y) = (0.1646, 0.3506)$ for the chromaticity.

This change is only visible for the extraction energy of 26 GeV. For 14 GeV, the effect for the tune is smaller than 10^{-4} and the calculated change of the chromaticity is in the 10^{-3} range. At 26 GeV the deformations account for 0.1% increase in B_1, 0.3% in B_2, 4% in B_3 and -5.7% in B_4.

The dipolar and quadrupolar skew components are $4 \cdot 10^{-4}$ times smaller than their normal counterpart. The sextupolar and octupolar skew components are $9 \cdot 10^{-5}$ and 10^{-1} times smaller than their normal counterpart for the deformed model. Therefore, the structural analysis may only explain partly the effects seen at a high field but not the ones at a low field.

VACUUM CHAMBER

The magnetic permeability of the vacuum chamber made from Inconel 625 was measured and the results were used to simulate with a 2D FEM code the effect on the magnetic field distribution. The measurement was performed by using a Dr. Foerster Magnetoscop 1.069. The measurement is only an estimate, as the vacuum chamber does not have the required minimum thickness of 8 mm.

However, the measurement showed that even at the welding seams, relative permeability is very small (< 1.003). Due to the two-fold symmetry, only the normal multi-poles are changed, and this change was computed through a 2D model. The result was that the change in relative permeability of the normal multi-poles is negligible (in the 10^{-5} range) and does therefore not explain the tune shift and the resonances.

MATERIAL UNCERTAINTY

Uncertainties on the magnetic field in the PS magnet may originate from non-uniformly distributed material properties. To minimise these effects, the electrical steel laminations were shuffled to mix different batches. Care was taken that the spread of the magnetic properties within one pile did not exceed certain thresholds [5]. Due to this precaution, the uncertainty on the material properties is averaged out.

The permeability as a function of the applied magnetic field in the steel was calculated to fit the measured field of the magnet [9]. The prediction of the field was similar to the results obtained by using the steel properties measured with a split-coil permeameter with a packing factor of 0.925 [10].

To check the material isotropy, samples in and perpendicular to the pole faces were cut from an existing spare lamination of the PS magnets. They were then measured by using an Epstein frame system. The measured permeability varied to the rolling direction by between 2-5%, so anisotropy is considered as negligible. The BH curves measured with the split-coil permeameter and the Epstein frame correlated well. Therefore, the BH curve measured with the split-coil permeameter [11] was used for all simulations applying a packing factor of 0.925.

RANDOM MECHANICAL ERRORS

The resonance compensation scheme at injection energy of 2 GeV is of special concern to achieve the required high-brightness beams for LHC. The effects mentioned above did not provide enough distortion on the field distribution to explain the creation of the pronounced resonances $2q_x + q_y = 1$ and $3q_y = 1$ at injection. Skew field components in particular are not present in a perfect magnet due to the two-fold symmetry. Therefore, mechanical measurements performed on one single magnet were used to estimate the mechanical errors. The mechanical errors were then taken as input for Monte-Carlo simulations of the magnetic field distribution as done for the LHC [12]

Geometrical Measurements

The pole faces of each of the ten blocks of the magnet MU 17 were measured by sliding a prism installed in a stainless steel sphere over the pole-profile and tracking and recording its position with a Laser Tracker Leica LTD 500. Due to this measurement principle an offset of 19.05 mm, normal to the measurement plane, is present in the measurement data.

The analysis of the measurement data is not straight forward due to the offset normal to the pole-face and a missing reference system. For analysis the measurement data was compared and fitted to a surface which was offset by 19.05 mm normal to the pole cross-section reference function. Then the standard deviation of the measurement data from this surface was calculated. The mathematical approach is described in detail in [13]. Random error were implemented in the finite element models as described in the following sections.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO107

2D Magneto-Static Simulations

For performing the simulations described in the previous section, a 2D FEM Vectorfields Opera model with up to 24 degrees of freedom was used. For each magnet type 1,000 models were calculated to achieve the needed precision of the Monte-Carlo simulation. The focus of this study was on the injection energy of 2 GeV. The Monte-Carlo simulation output are normal distributed multi-polar random variables with average values μ and standard deviations σ presented in Table 1.

The normal and skew multi-poles were normalised with the main field B_1. The simulation results were calculated by displacing the pole surface in x- and y-direction by $s = 30/\sqrt{2}\ \mu$m (see Figure 1 for coordinate system). The measured standard deviation of the pole surface is 30 μm. For this calculation only the main coils were excited ("bare-machine simulation"). The main excitation coils were displaced in x- and y-direction by 1 mm. The standard deviation of the multi-polar components is small, which shows that there is no big variation in the field distribution from magnet to magnet in PS. The skew components a_n are negligible small. Therefore, it was decided to continue with a 3D analysis to include skew components arising from fringe fields.

3D Magneto-Static Simulations

Performing a similar study with a 3D FEM code is time consuming. It also led to the idea of having the option of deforming or morphing the mesh and starting each model with mechanical errors from the reference model to save on calculation time. This feature was implemented in the software package of Opera Vectorfields. A model with a tetrahedral mesh (creating and re-solving a new model every time called following option 1) and a model with a hexagonal mesh (with the possibility of deforming the mesh as described above called following option 2) were prepared.

Option 1 was used and in the future it will be the benchmark for option 2. In this study, the upper and lower pole surfaces were displaced randomly with a standard deviation of 30 μm in the y-direction. Additionally each of the 10 blocks per magnet was displaced and rotated individually and randomly with a standard deviation of 30 μm and 0.1 deg about the x and z-axis, respectively. The coils were displaced and rotated by x and y, respectively. Some 1,000 simulations of the Monte-Carlo code were performed to achieve convergence. The results are presented in Table 1. The 3D simulation showed again a small variation of the magnetic field distribution from magnet to magnet. However, skew components a_n are no longer negligible and will have a major impact on the performance as already confirmed with beam-based measurements.

DISCUSSION AND CONCLUSION

In this work systematic and random effects influencing the magnetic field distribution were investigated. The deformations of the magnet due to magnetic forces is a systematic effect that has a large impact on the field distribution at high field and only a negligible influence at low field. By estimating the permeability of the beam pipe and calculating the influence on the field distribution it could be shown that this systematic effect is negligible. The influence of anisotropy in the steel of the magnets is negligible. The random effects were investigated by performing Monte Carlo simulations with 2D and 3D finite element models. The 2D simulations showed that skew components are negligible small and the standard deviation is small. The 3D simulations showed larger skew components but also a small standard deviation. Therefore, the field distribution variation from magnet to magnet is expected to be small in PS. The presented data will be used to enhance the resonance compensation scheme after re-start of the CERN injector complex this year and beam-based measurements will be performed. The results of the beam-based measurements will be presented elsewhere.

Table 1: Multi-polar Coefficients at 2 GeV

		b_2, 1/m	b_3, 1/m^2	b_4, 1/m^3	a_1, 10^{-3}	a_2, 1/m	a_3, 1/m^2	a_4, 1/m^3
2D FEM simulations, N = 1000								
C	μ	4.105	-0.083	1.93	0	0	0	0
	σ	0.001	0.011	0.10	$7 \cdot 10^{-2}$	$9 \cdot 10^{-4}$	$2 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
O	μ	-4.116	-0.004	-1.78	0	0	0	0
	σ	0.001	0.01	0.08	$7 \cdot 10^{-2}$	$8 \cdot 10^{-4}$	$2 \cdot 10^{-2}$	$3 \cdot 10^{-1}$
3D FEM simulations, N = 935								
C	μ	3.983	0.30	-42	1.4	-0.03	0.56	-16
	σ	0.001	0.02	4	0.8	0.007	0.03	4
O	μ	-3.988	0.35	41	-0.3	-0.02	-0.22	-6
	σ	0.001	0.02	4	0.8	0.007	0.03	4

ACKNOWLEDGMENTS

I would like to thank M. Juchno for many helpful discussions as well as for handing over scripts and providing many insights into the PS main magnet. I am also grateful to S. Gilardoni for his input which triggered most of the presented research. In addition I would like to thank R. Wasef and A. Huschauer for many discussions on the topic and M. Tortrat for performing the Laser Tracker measurements. I also thank J. Howard-Knight for his contribution to developing a perturbation 3D FEM model.

REFERENCES

[1] H. Damerau et al., TUXA02, New Orleans, IPAC'12.
[2] M. Juchno, Master Thesis, Cracow Tech. U., 2009.
[3] M. Juchno, PhD Thesis, EPFL, Lausanne, 2013.
[4] D. Schoerling et al., CERN Indico 251910, 2013.
[5] K. Reich, "The CERN PS Magnet," CERN, Geneva, 1963.
[6] S. Russenschuck, "Field Computation for Accelerator Magnets", Wiley-VCH, Weinheim, 2010.
[7] M. Buzio et al., "Deformation of the PS reference magnet U101 during operation," CERN, Geneva 2012.
[8] Z. Tang et al., IEEE Trans. Ind. Applicat, 40(3), 748-754, 2004.
[9] A. Asklöv, Master Thesis, Linköpings universitaet, 2005.
[10] A. Huschauer et al., CERN Indico 209746, Geneva: LIU-PS meeting, 2012.
[11] G. Peiro, EDMS 593272, CERN, Geneva, 2005.
[12] P. Ferracin et al., Phys. Rev. STAB 3, 122403, 2000.
[13] D. Schoerling, EDMS 1336186, CERN, Geneva, 2012.