

DESIGN OVERVIEW AND PROJECT STATUS OF THE PM GRADIENT DIPOLE AT MAX IV*

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Abstract

As part of the RF2.0 project*, a permanent-magnet (PM) gradient dipole has been designed at MAX IV Laboratory to replicate the performance of a conventional electromagnet gradient dipole in Unit Cell-1 of the MAX IV 3.0 GeV storage ring. The new PM gradient dipole follows a modular design and utilises NdFeB permanent-magnet blocks. The main advantage of this design is the expected reduction of up to 42% in the power consumption of the ring's magnet system, assuming replacement of all dipoles. Moreover, the use of PMs enables a more compact dipole magnet, potentially freeing space within the existing Unit Cell footprints for the integration of higher-performance multipole magnets anticipated for the MAX 4^U upgrade. This report summarises the electromagnetic and mechanical design, installation planning, and the overall project status.

INTRODUCTION

The magnet system of the MAX IV 3 GeV storage ring consists of 20 multi-bend achromats, each containing seven unit cells (MC1, UC1, UC2, UC3, UC4, UC5, and MC2). Each unit cell is a precision-machined iron block designed to accommodate different types of magnet elements [1].

A permanent-magnet (PM) gradient dipole, shown in Fig. 1, has been designed for the UC1 unit cell to match the footprint and performance of the existing UC1 conventional electromagnet gradient dipole while reducing power consumption and cooling requirements. This work is aligned with the RF2.0 project's vision of developing energy-efficient accelerator technologies. The concept is also relevant for future upgrades of MAX IV, as a more compact dipole could free space for higher-performance multipole magnets within the current cell footprint. This PM solution is being developed as a demonstrator and will be qualified under realistic operating conditions.

PM GRADIENT DIPOLE DESIGN

The primary magnetic design objective was to retain the magnetic behaviour of the installed UC1 gradient dipole while replacing the main excitation source with permanent-magnet material. The magnetic material used for the PM

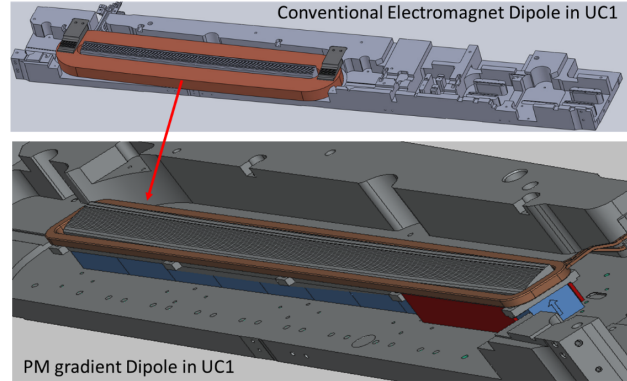


Figure 1: PM Gradient Dipole in UC1

gradient dipole is NdFeB. The various sub-components of the PM dipole are shown in Fig. 2.

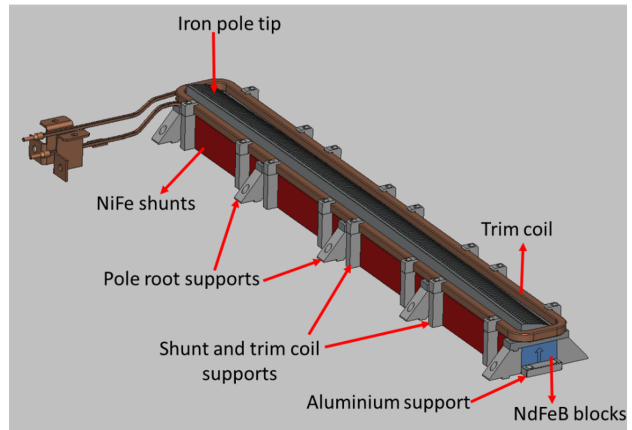


Figure 2: Key components of PM Dipole

As shown, the PM blocks will be installed below the removable pole tip. A common aluminium support structure has been designed to support both the trim coils and the pole tips. Thin strips of NiFe are placed around the PM blocks to compensate for the temperature-induced variation in the remanence of NdFeB. The aluminium support design allows for the change in the overall thickness of the NiFe strips, so that it can be changed during the experimental validation of the performance of this magnet. The main design parameters of the PM dipole are given in Table 1.

MAGNETIC DESIGN OF PM DIPOLE

The PM dipole design was optimised using Opera 3D. The simulation results were compared with experimental values obtained from measurements on one of the installed electromagnet gradient dipoles in the 3 GeV storage ring of MAX IV. As shown in Fig. 3, the simulation results of the key parameters of the PM dipole such as integrated field strength,

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Table 1: Main design parameters of the PM gradient dipole.

PM Material	NdFeB
PM Br / HcB	1.35 T / 1015 kA/m
PM Temp coeff $\alpha(\text{Br})$:	-0.12 %/°C
Integrated Dipole / Gradient	0.5 T.m / 8.6 T
Pole Face Strip	Air cooled, ± 150 A Tuning range $\pm 5\%$
NiFe shunt thickness	4.6 mm nominal
Temperature stability	<25 ppm / °C
Trim coils	Water cooled, ± 300 A Tuning range $\pm 2.2\%$
Support structure	Aluminium

integrated gradient and field quality are comparable to the corresponding measured values for the existing conventional UC1 electromagnet gradient dipole.

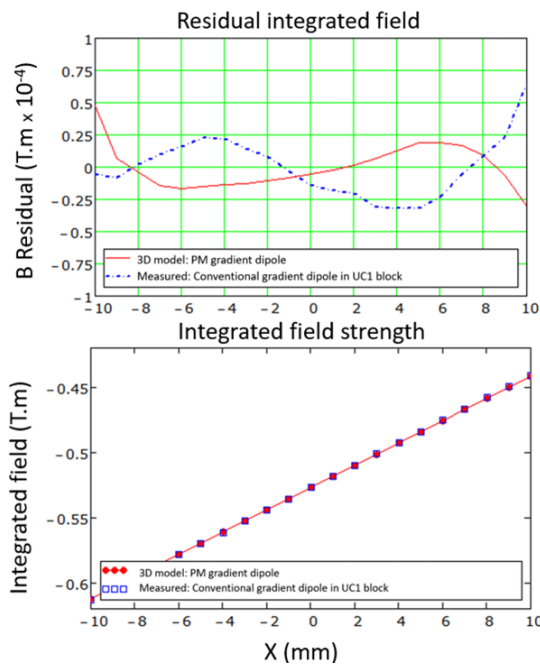


Figure 3: Predicted Magnetic performance of PM Dipole

Field clamp optimization within the magnet block

Field clamps are used to reduce fringe fields and improve field uniformity and effective length at the magnet ends. Fig. 4 shows the field clamp designed for the PM dipole together with the corresponding simulation results. Its width was optimised to free up space within the magnet block, thereby allowing the use of longer multipoles, which may be beneficial for future upgrade projects. As shown in the simulation results in Fig. 4, the field clamp width of the PM gradient dipole can be reduced by 30 mm on each side while still providing performance comparable to that of the conventional gradient dipole with a 67 mm field clamp.

Temperature Compensation using shunts

Simulations were carried out to evaluate the mitigation of temperature induced changes in the remanence 'Br' of Nd-

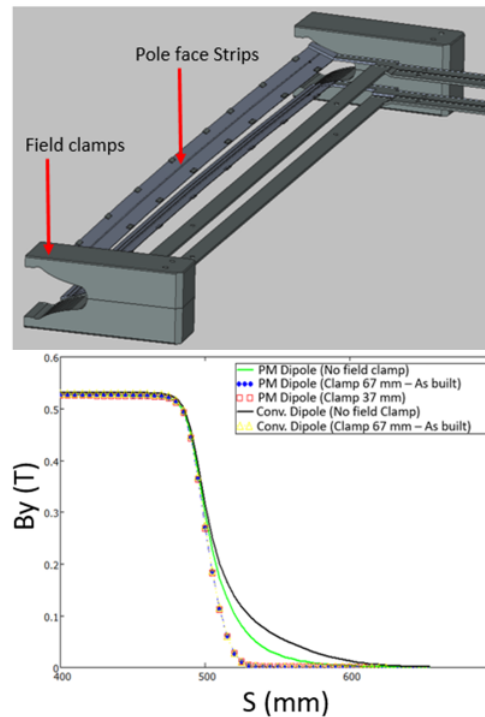


Figure 4: optimization of field clamp width

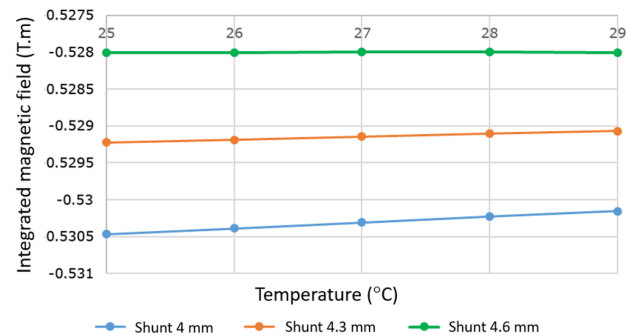


Figure 5: Effect of shunt thickness on stability the integrated magnetic field

FeB by using different quantities of NiFe thermal shunts. A 4.6 mm thick NiFe shunt was found to provide effective magnetic field compensation in the desired temperature operating range of $27 \pm 2^\circ\text{C}$, as shown in Fig. 5. With this configuration, a field stability better than 25 ppm/°C is achieved.

MECHANICAL DESIGN, ASSEMBLY TOOLING DEVELOPMENT AND ASSEMBLY PLANNING

The PM Dipole will be assembled in a new reduced size iron block based on the existing Unit Cell 1 iron block design. The new iron block will house 2 sextupole magnets identical to those used in UC1 block of the MAX IV 3 GeV ring and the newly designed PM Dipole in place of the existing electromagnet Dipole. The manufacturing tolerances of all sections of this iron block will be identical to those of the

original UC1 iron block. The overall dimensions of the reduced size block are shown in Fig. 6.

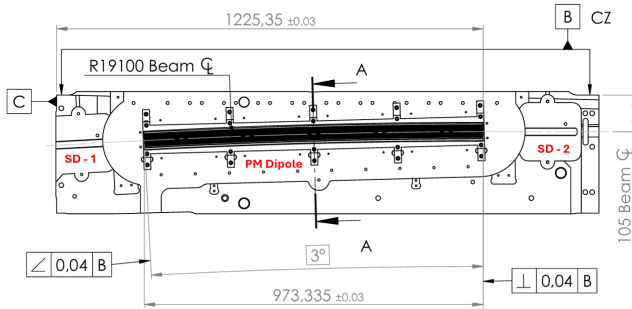


Figure 6: Reduced size UC1 block qualification of PM Dipole

The NdFeB blocks of the new PM dipole structure will be supported by aluminium rails, which are accurately mounted within the iron block and precisely aligned using locating tabs and mechanical indents to ensure reproducibility and mechanical stability. This support system ensures that the PM blocks remain securely positioned during both assembly and operation, minimising misalignments that could affect field quality. The magnetic field of the PM gradient dipole is shaped by newly designed pole tips. For field tuning and control, pole face strips and field clamps have been designed in accordance with the existing UC1 design. However, based on the simulation results, the field clamps width has been reduced by 30 mm on each side.

To qualify the PM gradient dipole under realistic operating conditions, the two nearby sextupole magnets (SD-1, SD-2) from the original UC1 are planned to be integrated into the new iron block of the PM Dipole. These elements are representative of the standard MAX IV lattice and provide a relevant magnetic environment for assessing the performance of the new dipole. Their inclusion enables the evaluation of field quality, integrated field strength, and potential magnetic crosstalk between the dipole and surrounding magnets. This setup ensures that the prototype is evaluated in a configuration that closely reflects actual operating conditions, thereby increasing the relevance and applicability of the test results.

A dedicated non-magnetic assembly tooling set was developed for the precise and safe installation of the PM blocks,

pole tips, NiFe shunts, and trim-coil components into the split UC1 yoke. The tooling includes non-magnetic worktables, fixed and adjustable aluminium support rails, a linear insertion actuator, precision alignment tools, a clamping bridge, a pole-tip lifting tool, and jacking screws for the controlled closure of the two yoke halves. This tooling improves assembly accuracy, repeatability, and handling safety, while reducing the risk of block misalignment or damage during assembly.

QUALIFICATION PLAN

Detailed magnetic measurements will be carried out on the PM gradient dipole using Hall probes and rotating coils on a dedicated magnetic bench. The measurement program will include good-field-region mapping, evaluation of field homogeneity, verification of thermal compensation, characterization of trim and gradient tuning, and repeatability checks following top-yoke reassembly. In addition, crosstalk measurements will be performed with the neighbouring sextupole magnets to evaluate the PM Dipole's behaviour under realistic operating conditions.

CONCLUSION

A permanent magnet based gradient dipole has been designed. At the time of writing, the fabrication of all major components, namely; the reduced size UC1 iron blocks, pole tips, pole face strips, aluminium supports, assembly tooling and trim coils had been completed and were undergoing final inspection before delivery for the start of PM dipole assembly. The NdFeB permanent magnet blocks, NiFe strips had been procured and are available for assembly. The assembly is expected to start soon and will be followed by magnetic measurements and other qualification tests. These results will be reported at a later stage.

REFERENCES

- [1] M. Johansson, B. Anderberg, and L.-J. Lindgren, "Magnet design for a low-emittance storage ring", *Journal of Synchrotron Radiation*, vol. 21, no. 5, pp. 884–903, Sep. 2014. doi:10.1107/S160057751401666X