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Design and Manufacturing of Two High Gradient Quadrupoles Based on Permanent Magnets for the CERN Antiproton Decelerator

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Introduction

The CERN Antiproton Decelerator (AD) based on the Antiproton Collector (AC) ring dating from 1986, started operation for physics in 2000. As part of a consolidation project, the two 1.1-m-long conventional water-cooled quadrupoles with an integrated gradient of 39.28 T and 49.05 T in 60 mm aperture, providing the final focusing before target, were replaced by permanent magnet quadrupoles (PMQ) with identical gradients and length. The main advantages of this upgrade are to provide a maintenance-free solution for this region with relatively high ambient radiation levels and suppression of powering and cooling systems.

The yoke design features four iron pole pieces assembled inside a non-magnetic frame surrounded by an external return yoke. To enhance the structural rigidity, stainless-steel plates are installed on the four outer faces of the assembly. The spaces between the poles and the return yoke and between each adjacent poles are filled with rectangular (type 1) and trapezoidal Samarium Cobalt permanent magnet (PM) blocks. The trapezoidal PM blocks, located close to the pole extremity, concentrate the magnetic flux inside the pole and counter the local iron saturation. Additional PM blocks (type 2) are inserted inside the frame for the high gradient PMQ. These blocks are replaced by iron shims to reduce the field in the low gradient version. The fine tuning of the gradient is made with adjustable shunts. They are displaced radially to locally reduce the return yoke section and adjust the gradient by ±5%. A displacement of 0.1 mm corresponds to a relative gradient adjustment of about $5x10^{-4}$.

Design

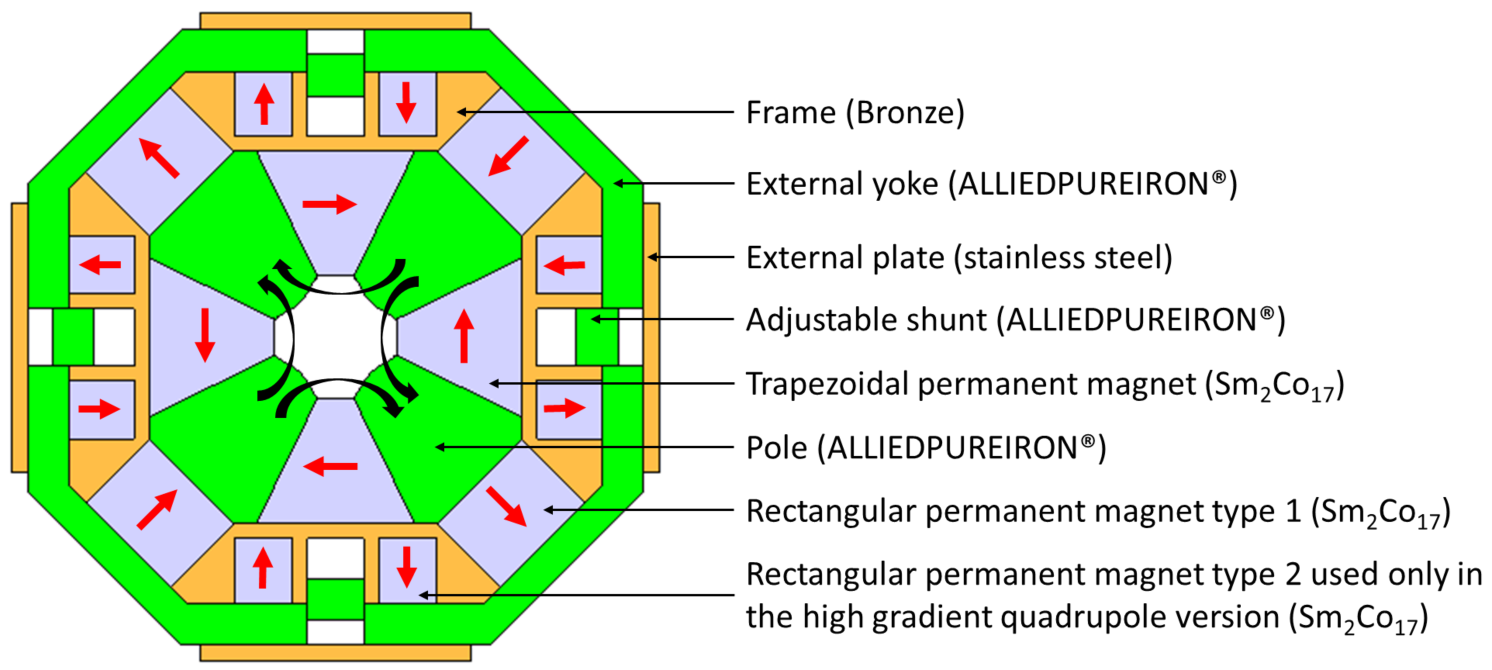

Fig. 1 - Layout of the permanent magnet quadrupole (high gradient).

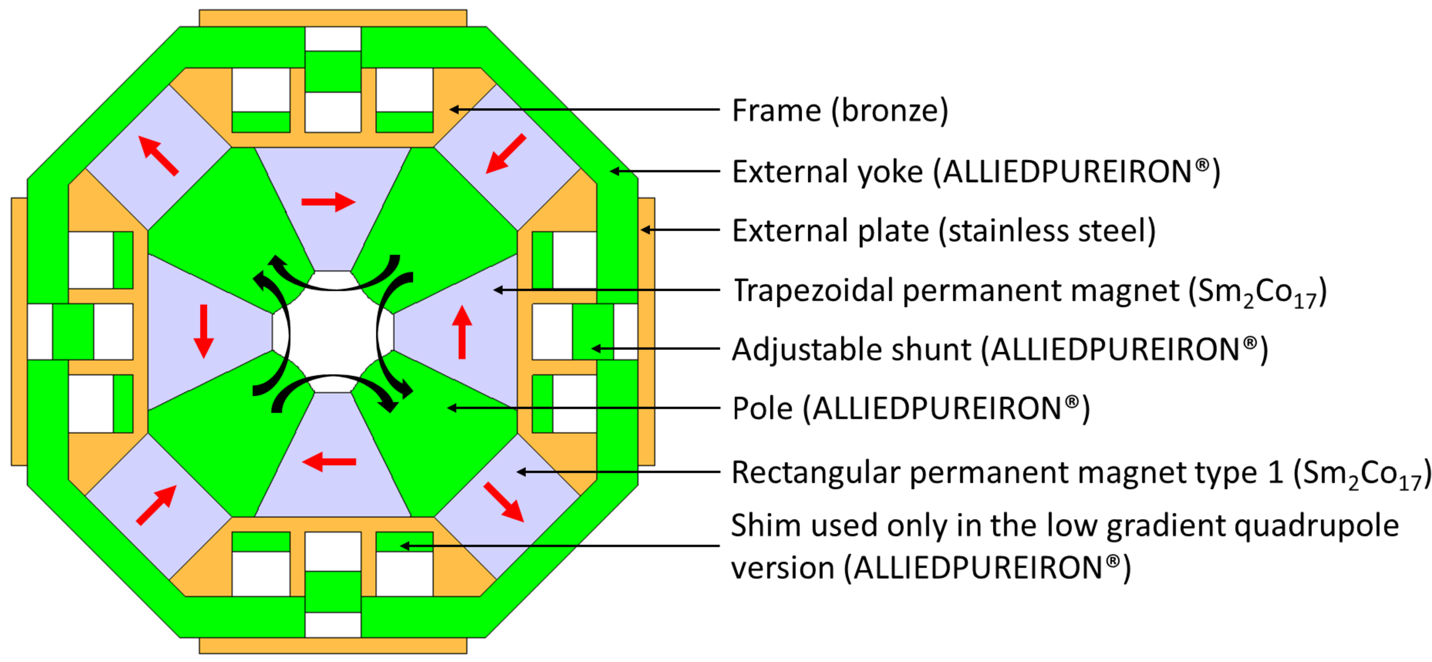

Fig. 2 - Layout of the permanent magnet quadrupole (low gradient).

Magnetic design

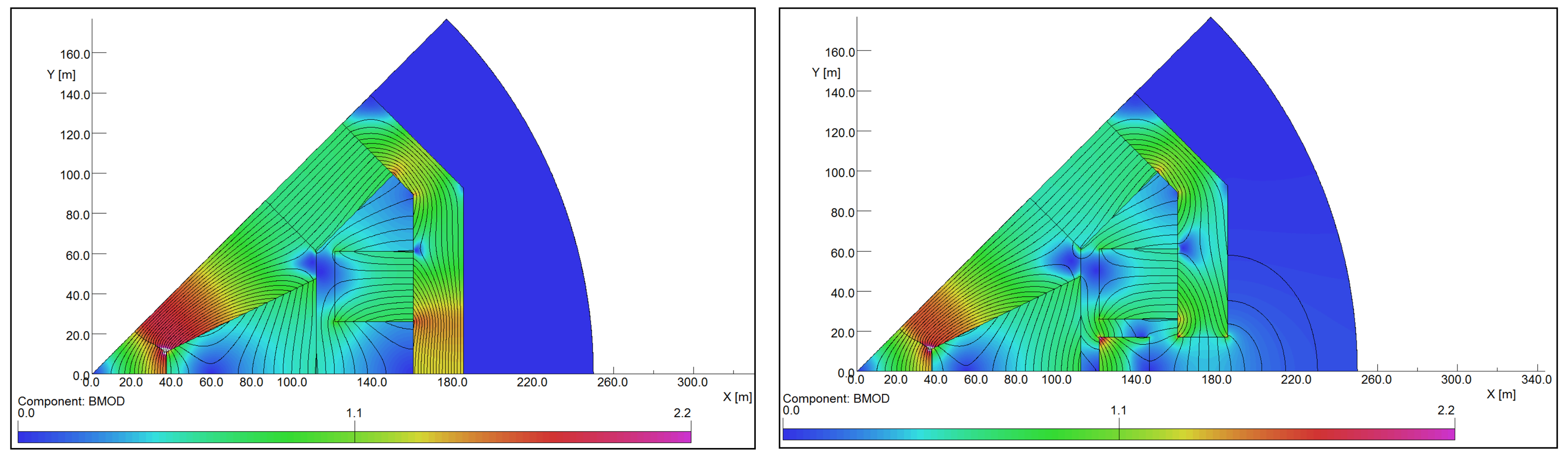

Fig. 3- 2D magnetic field distribution for the high gradient quadrupole set with maximum (left) and minimum (right) field by adjusting shunt positioning.

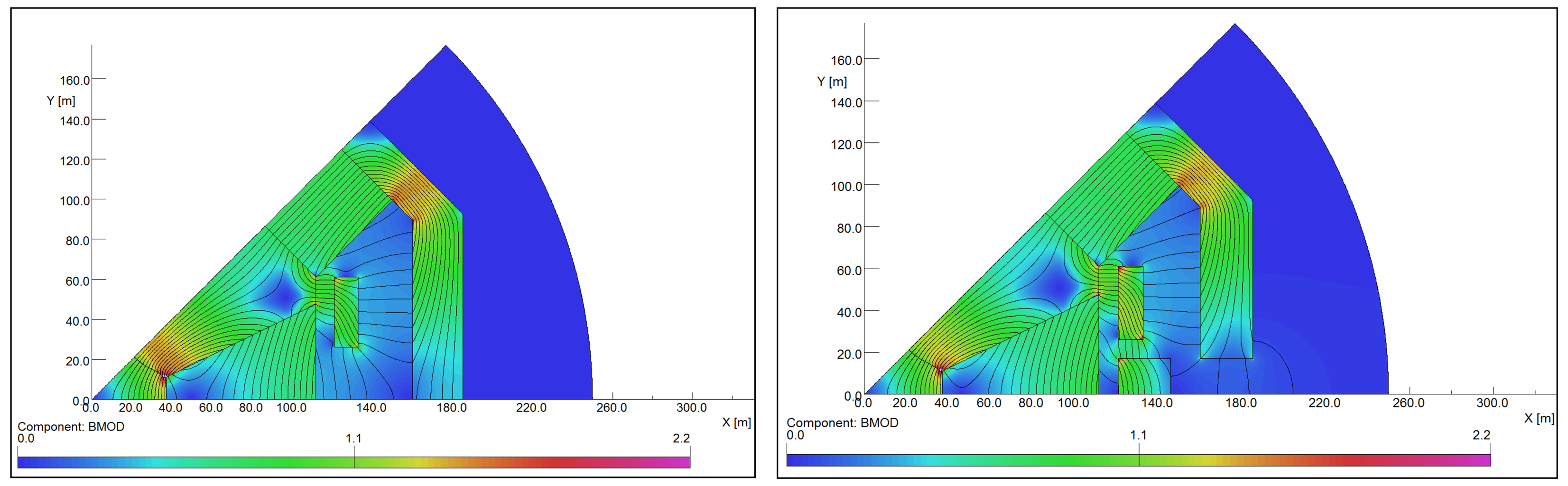

Fig. 4- 2D magnetic field distribution for the low gradient quadrupole set with maximum (left) and minimum (right) field by adjusting shunt positioning.

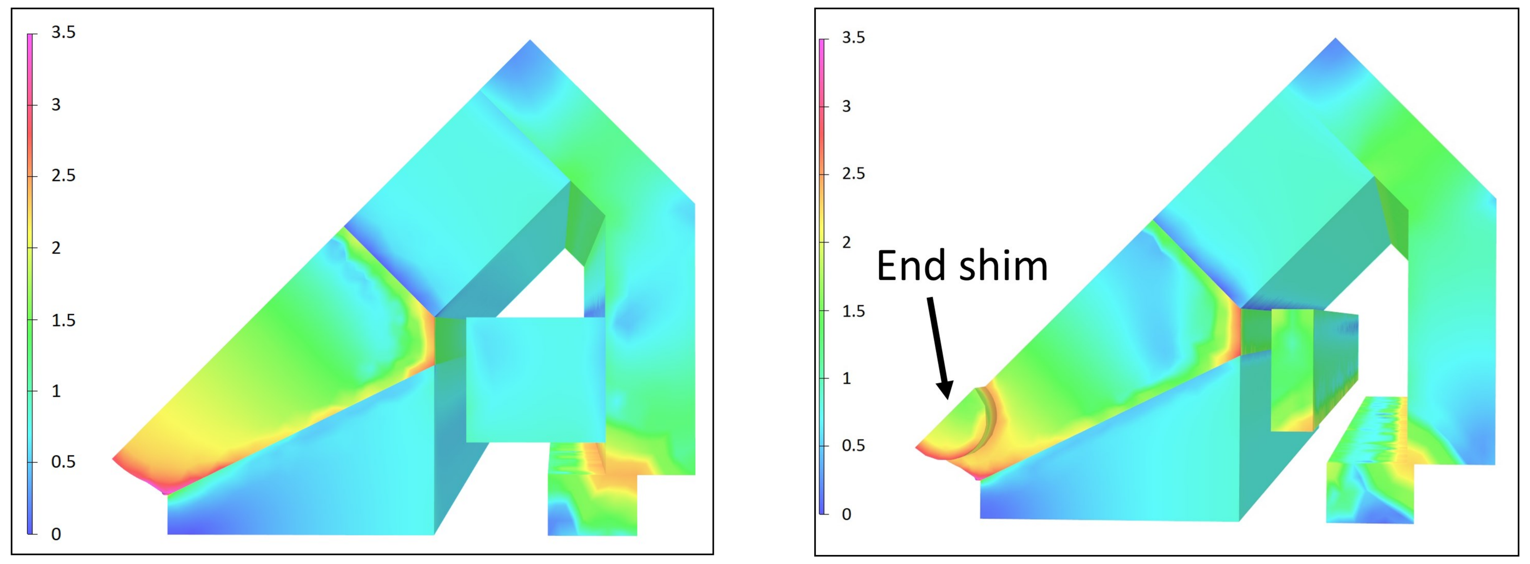

Fig. 5– 3 D magnetic field distribution for the high (left) and low (right) gradient PMQ.

TABLE I
MAIN DESIGN PARAMETERS OF THE AD PERMANENT MAGNET QUADRUPOLES

Parameter	Low gradient	High gradient	Unit
Quadrupole aperture diameter	60	60	mm
Iron length	1092	1092	mm
Mass	1020	1100	kg
Mass of permanent magnet	300	400	kg
Nominal gradient at the center	35.7	45.7	T/m
Nominal integrated gradient	39.28	49.05	T
Good Field Region radius	20	20	mm
Gradient homogeneity in GFR	≤±5	≤±5	10^{-4}
Gradient integral error (rms)	≤±0.2	≤±0.2	%
Gradient tunning range	~±5	~±5	%
Permanent magnet material	Sm_2Co_{17}	Sm_2Co_{17}	

Manufacturing and measurements

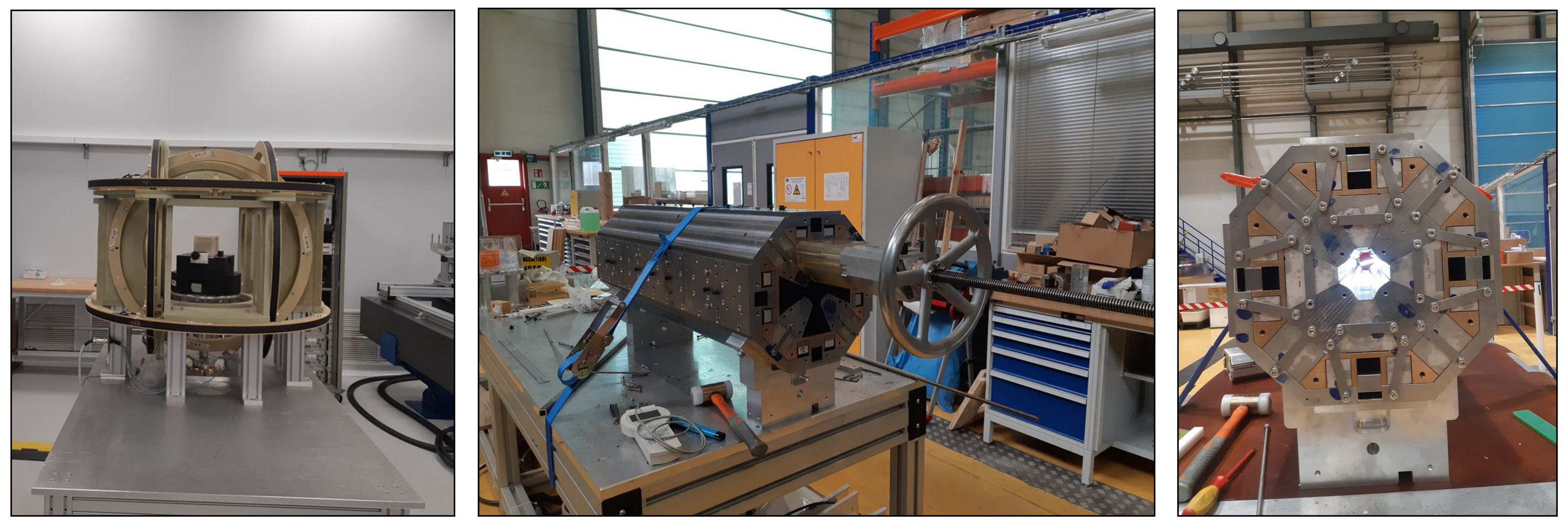

Fig. 6– Measurement of PM blocks with Helmholtz coil (left); insertion of PM blocks (center); assembled PMQ (right).

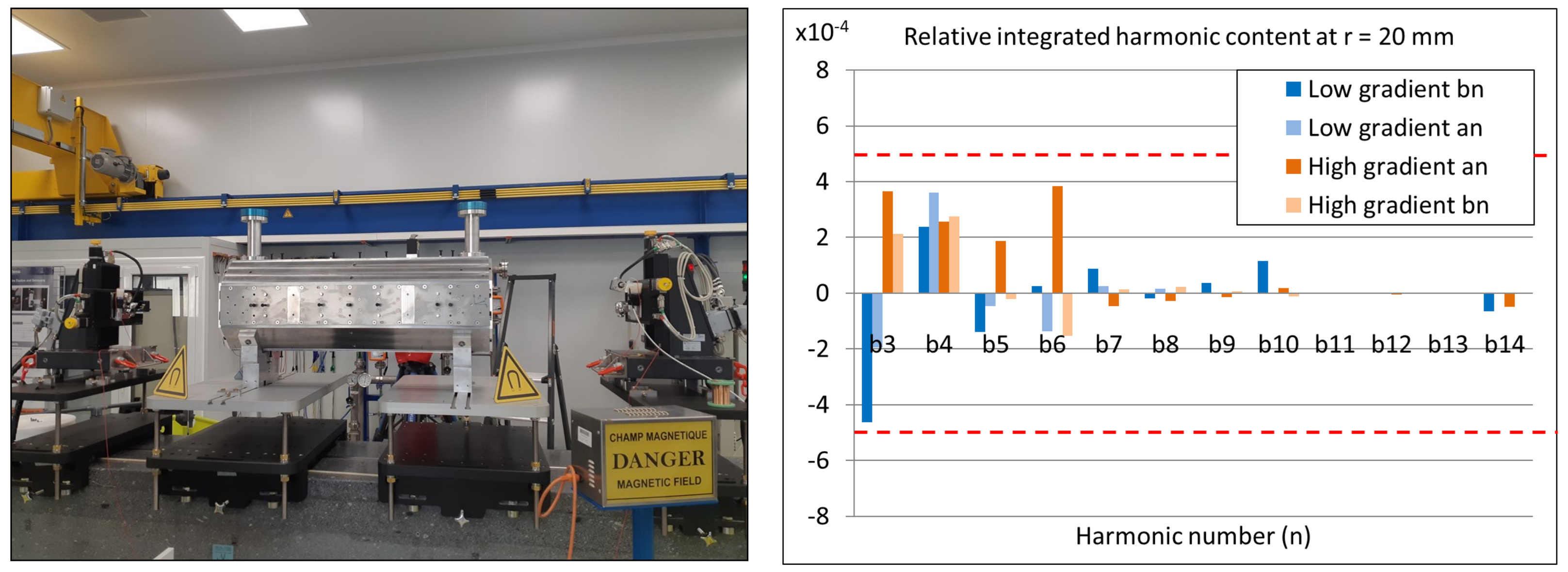

Fig. 7– PMQ measured with stretched wire (left); relative integrated harmonic content expressed in unit of 10^{-4} at r = 20 mm, within ± $5x10^{-4}$ specified value.

Fig. 8– Permanent magnet quadrupoles installed in the AD target area.

Conclusion

The new permanent magnet quadrupoles for AD target area meets the requirements in term of field strength, field quality and maintenance free operation in this high radiation area. This design incorporates several innovative features, such as a novel arrangement with a mix of permanent magnets and soft magnetic components to generate a high field in this 60 mm aperture quadrupole. The gradient strength can also be adjusted by ±5 percent mainly to compensate for the magnetic characteristic uncertainty of the different materials.

This design represents an attractive alternative for transfer lines and experimental area requiring high gradient DC quadrupoles.