Fast computation of magnetic shimming in a high field environment

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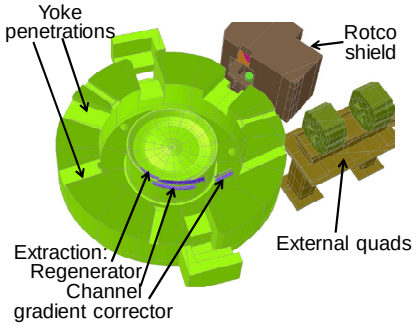
During the development of the new S2C2 at IBA, it was found that the axial field harmonics may have an impact on the machine performance. Shimming may be necessary to adjust these errors.
In this communication a simulation method for shimming a first harmonic in a cyclotron is described. The shimming is done with multiple iron shims with rectangular or sector shape in the pole gap. It is assumed that these iron shims are completely and uniformly saturated by the external magnetic field. Analytical expressions are given for the magnetic field produced by a single shim. A program is described that calculates the magnetic field produced by multiple shims. As an example, the method is applied for shimming of the first harmonic field error due to the extraction system. The calculations are very fast and allow a quick convergence to a good final solution. Good agreement was found with OPERA3D.

INTRODUCTION

In the S2C2 several asymmetric features are present in the design. These create very large first harmonic field errors.
The main contributors to these field errors are the regenerator, the extraction channel, the shielding of the rotco, the gradient corrector, the external beam line and also several yoke-penetrations.



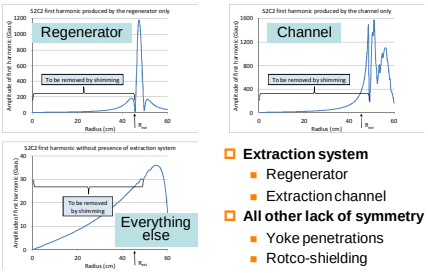
View of the layout of the S2C2 with highlight on the elements that produce first harmonic field errors

If these field-errors are not reduced to a sufficiently low level, then they may have
adverse effects on the beam such as:

1. orbits approaching extraction may be so much off-centered that they hit the dees
2. orbits in the center of the machine may be not well-accelerated due to large off-centering
3. increase of emittance and/or loss of beam quality may occur during acceleration in a magnetic field with a large first harmonic error

Field errors can be removed by placing small iron shims at the right places in the pole gap. Finding all the correct shims at all radii is a tedious process if one has to rely on the usual finite element calculations. For this reason a simplified method has been developed, where the contribution of each shim is calculated (semi-) analytically and multiple shims are added together. This allows to iterate and converge very quickly. A numerical program was written that calculates the total field contribution of a layout of multiple shims. The method is tested by comparing the results with OPERA3D.

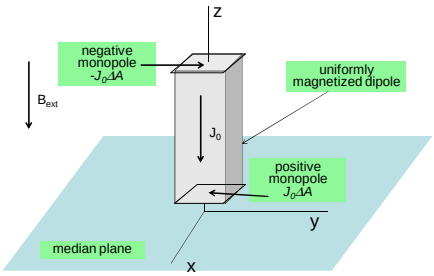
FIRST HARMONIC ERRORS



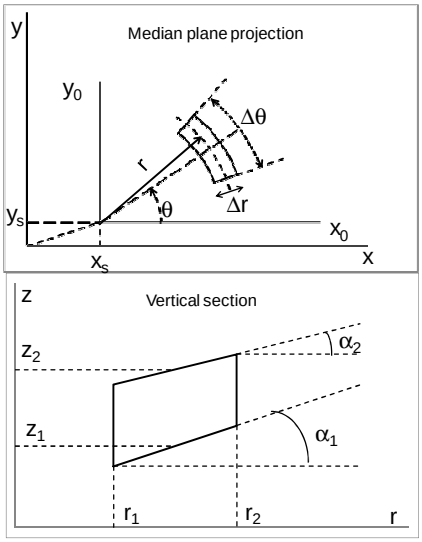
- **Extraction system**
  - Regenerator
  - Extraction channel
- **All other lack of symmetry**
  - Yoke penetrations
  - Rotco-shielding

Amplitudes of first harmonic field errors produced by the regenerator (upper left), extraction channel (upper right) and all other asymmetries in the S2C2 (lower left). The field errors should be removed up to the extraction radius R=45 cm.

MODEL DESCRIPTION



A small iron shim placed in a very high magnetic field immediately becomes completely saturated and uniformly magnetized parallel to the external magnetic field . It can be considered as the sum of a positive magnetic monopole attached to the lower surface and a negative magnetic monopole attached to the upper surface. The magnetic charge density is equal to the polarization strength J_0 of the iron.



Definition of the geometrical parameters of a sector-shaped shim

MAGNETIC MONOPOLE POTENTIAL FUNCTION

$$d^2\psi = \frac{J_0 \Delta A}{4\pi\mu_0 r}\cos\alpha$$

MEDIAN PLANE MAGNETIC FIELD CONTRIBUTION

$$d^2 B_z = \frac{J_0 \Delta A}{4\pi}\frac{z}{|\vec{x}-\vec{x}_0|^3}\cos\alpha$$

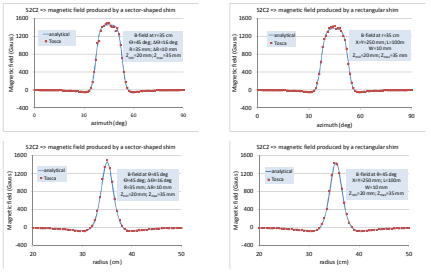
INTEGRATE OVER SURFACE OF MONOPOLE

SECTOR SHAPED SHIM

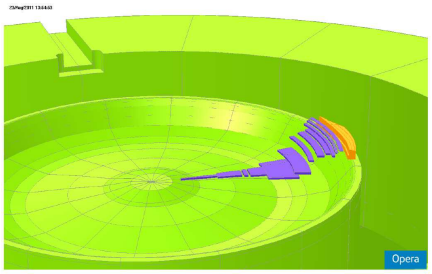
$$d^2 B_z = \frac{J_0}{4\pi}\frac{z r dr d\theta \cos\alpha}{\sqrt[3]{(r - r_0\cos(\theta-\theta_0))^2 + r_0^2\sin^2(\theta-\theta_0) + z^2}}$$

SOME RESULTS

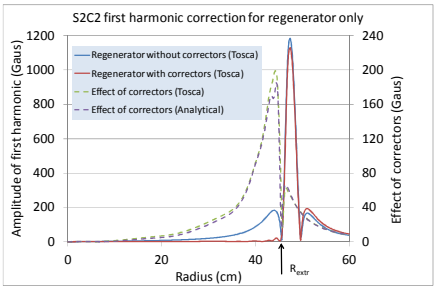
Sector shape **Rectangular shape**



Magnetic fields calculated by the analytical program (blue solid lines) and OPERA3D (red markers). On the left for sector-shims and on the right for rectangular shims. On the upper plots for a radial track and on the lower plots for an angular track.



Layout of the shims constructed for the removal of the first harmonic field error due to the regenerator only.



Results of shimming of the first harmonic field error produced by the regenerator. The left scale shows the first harmonic calculated with OPERA3D (blue solid line without compensation and red solid line after compensation). The right scale shows the effect of the correctors (green dashed line for OPERA3D and black dashed line for the analytical program)

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