Median plane error compensation in the S2C2

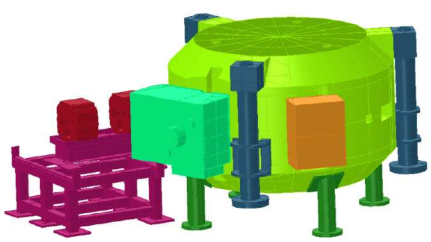
W. Kleeven and E. Forton

The S2C2 is the new compact proton-therapy accelerator for the IBA ProteusOne range of products. It is the first synchrocyclotron as well as the first superconducting cyclotron ever produced at IBA.
A study is made of the median plane error in the S2C2 due to the vertical asymmetry in the magnetic structure. A full OPERA3D model is used to calculate the magnetic field error. The main coils are shifted vertically in order to compensate this error in the extraction region. An analytical formula is derived for the median plane displacement.

INTRODUCTION

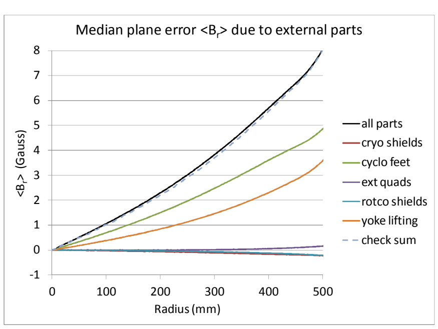
The iron of the S2C2 magnet is almost completely saturated because of the high magnetic field (5.7 Tesla in the cyclotron center) that is applied. One of the consequences of this is that subsystems with moving parts such as the cryo-coolers and also the rotating condenser (rotco) require magnetic shielding. Another consequence is that the cyclotron is more sensitive to magnetized iron that is placed at the exterior of the machine because for such an additional source of flux, the pole and yoke almost behave like air and therefore do not provide any magnetic shielding. Some of the subsystems mounted around the yoke break the median plane symmetry of the cyclotron. These are for example the iron shielding of the rotco, the yoke-lifting system, the cyclotron feet and the support of the external beam line. The median plane errors produced by these parts may be relevant because the synchro-cyclotron is a weak focusing machine for which the vertical betatron frequency is smaller than 0.3 during most of the acceleration period.

MAGNETIC MODEL



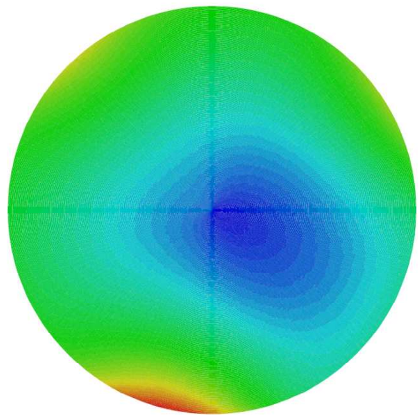
Full OPERA3D model of the S2C2. It contains all external ion systems such as the shielding of the rotco and the cryo-coolers, the yoke-lifting system, the cyclotron feet and the external beam line

MEDIAN PLANE ERRORS



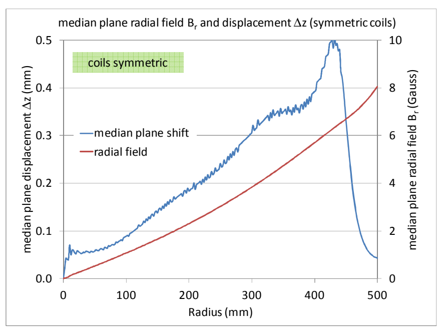
Average radial component of the magnetic field in the median plane as produced by each of the external iron sub-systems

In order to reduce the mesh-induced numerical noise, each contribution was calculated twice: once with the subsystem filled with iron and once with the subsystem filled with air.; the difference map gives the contribution of the subsystem

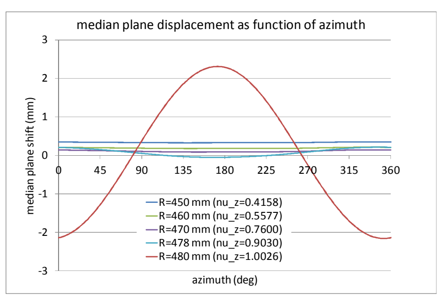


Zone plot of the radial median plane field. The maximum radius is 50 cm. The minimum field is -1.2 Gauss, the maximum field is 15.1 Gauss. The highest (red) zone is aligned with the yoke-lifting system.

MEDIAN PLANE SHIFT



Median plane shift produced by the total radial the magnetic field error in this plane

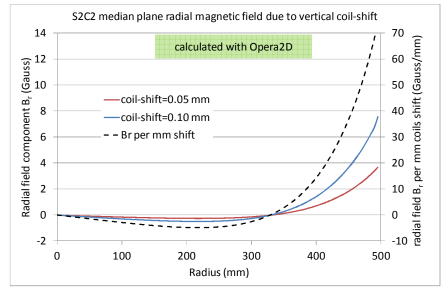


Median plane shift as function of azimuth and at 5 different radii, produced by the average + first three Fourier harmonics of the radial magnetic field error. The integer resonance ν_z=1 is approached at R=48 cm .The beam is extracted earlier at R=45 cm

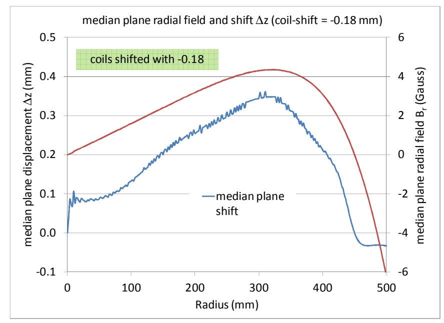
COMPENSATION BY MAIN COIL SHIFTS

The vertical gap in the extraction system regenerator is only 13 mm. The main coil is shifted such that at the extraction radius the coil median plane error exactly compensates the median plane error due to asymmetry in the iron.

The median plane correction induced by vertical coil shifts is calculated below with an OPERA2D model to limit computing time



Radial magnetic field in the median plane due to a vertical shift of the main coils



Radial magnetic field in the median plane after compensating of this error by a vertical shift of the coils. The remaining median plane shift is minimized at the extraction radius R=45 cm.

SOME MATHEMATICS

HILL EQUATION WITH MEDIAN PLANE ERROR B_{r0}

$$\frac{d^2 z}{d\theta^2} + \nu_z^2 z = \frac{rB_{r0}}{B_0}$$

FOURIER ANALYSIS OF FIELD ERROR

$$B_{r0}(\theta) = \sum_{n=0}^{\infty} a_n \cos n\theta + b_n \sin n\theta$$

PERIODICITY REQUIREMENT

$$z(\theta) = z(\theta + 2\pi)$$

MAGNETIC MEDIAN PLANE

$$z_{mp}(\theta) = \frac{r}{B_0}\sum_{n=0}^{\infty} \frac{a_n}{\nu_z^2 - n^2}\cos n\theta + \frac{b_n}{\nu_z^2 - n^2}\sin n\theta$$

GOOD APPROXIMATION

$$z_{mp}(\theta) \cong \frac{r\bar{B}_r}{B_0 \nu_z^2}$$

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