MAGNETS AND WIEN FILTERS FOR SECAR

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Abstract

SECAR is being built for the study of nuclear capture reactions. The high performance magnets and two Wien filters required to reach a very high recoil mass separation factor are being designed and produced at Danfysik. The 35 ton Wien filters have been designed to meet challenging magnetic and electrostatic field requirements. The dipole magnets are special in having the transverse magnetic field boundary described by a 4th order polynomial and stringent effective magnetic length specifications. A wide range of multipole magnets with tight magnetic length tolerances are also required.

INTRODUCTION

The goal of the Separator for CApture Reaction (SECAR) is to allow studies of low-energy nuclear reactions of astrophysical interest [1]. SECAR is based at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). To be used at the ReA3 accelerator with unstable ion beams.

A layout of SECAR is presented in Fig. 1. Unstable beams from ReA3 bombard the JENSA gas target (H or He). Most of the beam particles do not interact and continue their trajectories past the target. As few as 1 reaction per 10^{13} incoming beam particles will take place. The reaction products are moving along with the unreacted beam with about the same momentum. The goal of SECAR is to transport those reaction products to a detection system while rejecting the much more intense beam.

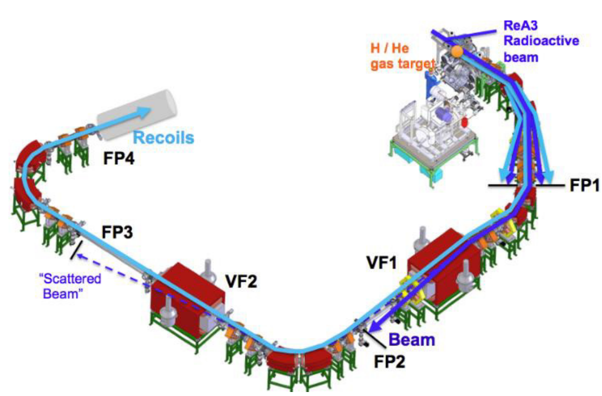

Figure 1: Concept layout of the SECAR recoil separator.

In order to achieve the required beam separation, two Wien filters (VF1 and VF2 in Fig. 1) are used. They select particles with velocities corresponding to the reaction products. SECAR is designed for mass resolving powers of 740 at FP2 and 1300 at FP3 and mass resolutions (including the contribution of higher order aberrations) of 500 at FP2 and 750 at FP3. Careful minimization of higher order aberrations is achieved using properly shaped effective field boundaries of the first 6 dipole magnets as well as 14 quadrupoles, three hexapole magnets, one octupole magnet and one combined quadrupole/hexapole magnet. Stringent tolerances on the effective field boundaries of the dipoles and on the field homogeneities of the Wien filters are required to achieved the needed mass resolution. The shape of the electric and magnetic fringe fields of the Wien filters is also critical.

WIEN FILTER DESIGN

The SECAR spectrometer includes two combined ExB velocity filters, also called Wien filters (Table 1, Fig. 2). These Wien filters are key components in the spectrometer and have been designed to strict effective length specifications and a field uniformity requirement of $4\cdot10^{-4}$ for both E and B. The ratio E/B of the electric and magnetic fields should be constant over the full length, which is challenging since the magnetic gap is four times larger than the electrode gap and thus fringe field profiles differ.

Table 1: Main Wien Filter Parameters

Magnet:		**Electrostatic deflector:**	
Magnetic field, B	0.12 T	Electrostatic field, E	2.7 MV/m
Magnet mass	30 ton	Electrode voltage	± 300 kV
Magnet pole gap	880 mm	Electrode gap	220 mm
Effective length	2365 mm	Effective length	2365 mm

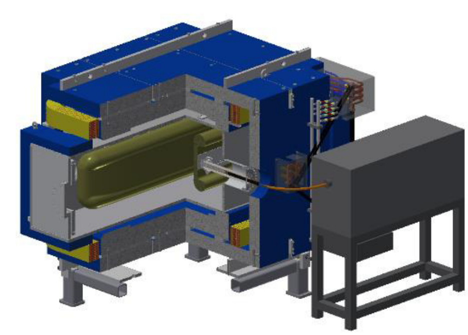

Figure 2: Complete Wien Filter with high voltage supply.

Extensive Opera-3D/TOSCA modelling [2] of the device has been performed. The magnet design includes floating poles for field homogenization, adjustable field clamps of the box type and mirror plates. The electrostatic deflector has tapered ends and rose shims along the sides. The mirror plates are shared with the magnet. The magnet is non-linear and as a result the effective magnetic length varies a few millimeters with current excitation. In contrast the E-field is linear against excitation with fixed effective electrostatic length. Figure 3 shows the normalized E/B field profiles.

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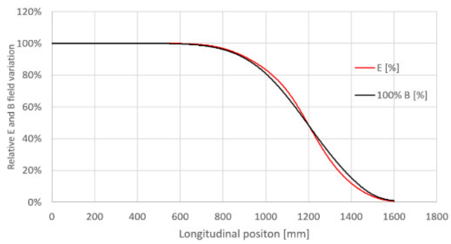

Figure 3: The normalized longitudinal E/B field profiles.

The magnet pole profile is shaped in multiple steps to meet the field uniformity requirements, both longitudinal and transverse. The field clamps, along with the mirror plates, shunt the fringe field to a sharp profile. The field clamp is movable to adjust the effective magnetic length when operated at lower fields. A field of 0.12 T is obtained with 58400 A-turns per coil. Figures 4 and 5 show a model of the magnet and the calculated field homogeneity.

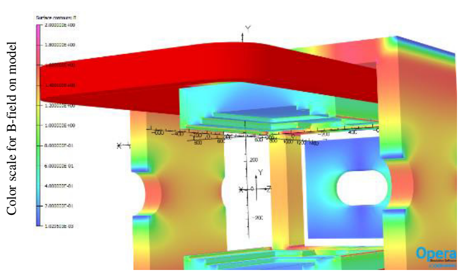

Figure 4: Opera-3D model of half the magnet at 0.12 T. The floating special shaped poles are visible.

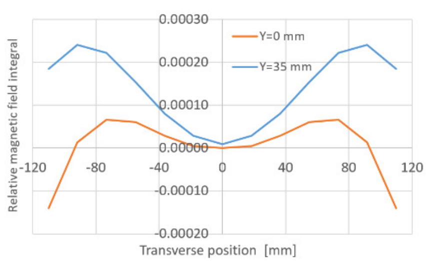

Figure 5: Calculated integrated magnetic field uniformity.

The electrostatic electrodes are shaped with tapered ends and progressive rose shims along the sides. Figure 6 shows the surface electrical field stress at ±300 kV. The shared mirror plate with racetrack hole is shown. The electrodes are machined from a solid titanium block. The integrated electrostatic field uniformity suffers from the racetrack hole as can be seen in Fig. 7.

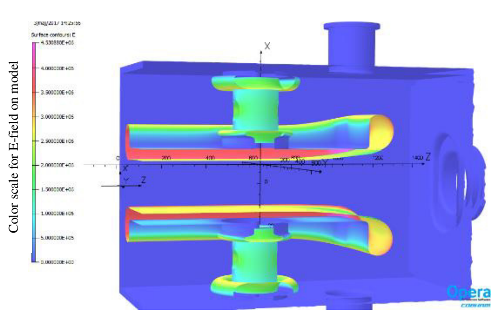

Figure 6: Shows half the electrostatic deflector with a cut.

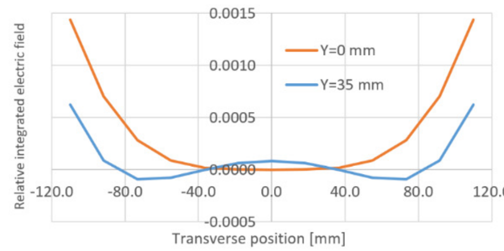

Figure 7: Calculated integrated electrical field uniformity.

DIPOLE MAGNETS

The 8 dipoles have a maximum center field of 0.64 T at a nominal pole gap of 60 mm or 100 mm (B3 and B4). Their beam deflection angles are respectively 22.5° for B1-4, 42.5° for B5-6 and 55° for B7-8. The on-axis effective magnetic length requirement is demanding as it has to be within ±0.5 mm of the nominal value in an excitation range from 15 to 100%. The transverse variation of the effective magnetic fringe field boundary (EFB) for the entrance and exit ends is defined by a 4th order polynomial $Z(x)=a\cdot x+b\cdot x^2+c\cdot x^3+d\cdot x^4$ (see Fig. 8), where the linear a-value defines the shim rotation angle. The very demanding requirement is that the obtained variation has to be within ±0.1 mm of the nominal field boundary in the good field width in a wide excitation range. The good field width is 200mm for B1, B2 and B3 and 100mm for the rest.

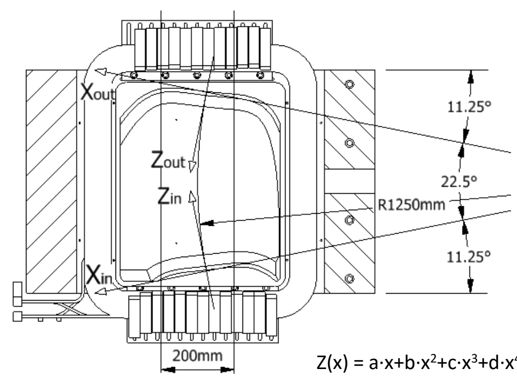

Figure 8: Layout of the B2 dipole with the entrance and exit coordinate system for the fringe field evaluation.

B7 and B8 are identical with the required polynomial terms a=b=c=d=0 so the EFB has to be linear with zero shim angle. The polynomial terms for the mechanical pole profile has, however, to be modified significantly to obtain the required magnetic profile. Figure 9 shows the Opera-3D model which has been used for the magnetic design of the magnet and the determination of the fringe field profile. The magnets are all designed with relatively wide poles for a center field inhomogeneity variation below 0.02% in the horizontal good field region. To meet the fringe field requirements in a wide excitation range the magnet has been designed with vertically chamfered pole ends and extra thick iron yoke in order to keep the field strength in the iron below about 1 T. The model calculation gave a modest 0.25 mm excitation variation of the effective magnet length and a negligible 0.02 mm deviation from the required Z(x) boundary variation.

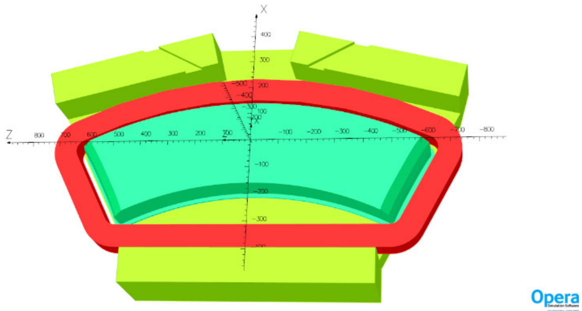

Figure 9: Opera-3D model of the top half of B7/B8.

The entrance and exit fringe field profiles for the remaining magnets are all different and mostly non-linear, as for B2 (see Fig. 8). The 4th order polynomial pole profile can in the B2 exit end be applied in the full pole width, but for the entrance end it is necessary to limit the large Z(x) variation to part of the pole width. This results in a weaker correlation between the mechanical and magnetic profile so that the pole profile variation has to be significantly larger than the desired EFB variation.

Segmented field clamps have been included with longitudinal position adjustment for fine tuning of the field boundary. Opera-3D model calculations have been used to determine the EFB response function for the 13 field clamp positions so that a desired field boundary modification can be estimated numerically before validation with an Opera-3D calculation. The challenging optimization of the pole profile and field clamp positions has required the development of new design strategies. On this basis the B1, B2, B3 entrance and B4 exit end design was made to the specifications while the deviations for B4 entrance and B3 exit ends were up to 0.2 mm and 0.3 mm, respectively.

Validation of the produced magnets was performed by Hall probe mapping each dipole end section. After final optimization of the field clamp positions the measured EFB deviation was in most cases within ±0.1 mm with a few points up to about ±0.15 mm. The result for B2 exit is shown in Fig. 10. The difficult B3 (see Fig. 11) and B4 ends showed deviations of up to 0.6 mm. The magnetic on-axis length was found to vary with excitation by up to ±0.8 mm which is a factor two larger than expected. Similar length variations were measured for the B7 and B8 dipoles produced without field clamps, while their transverse EFB variation was essentially within ±0.1 mm.

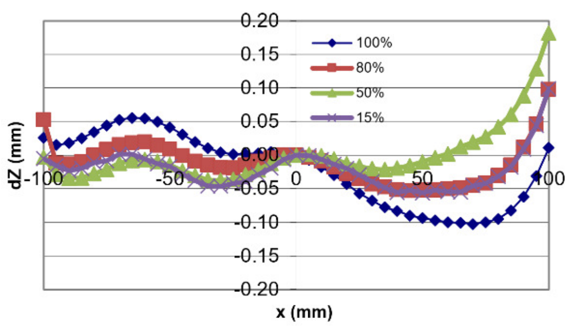

Figure 10: Measured deviations of the effective field boundary as function of horizontal position for the B2 exit end at a range of excitations.

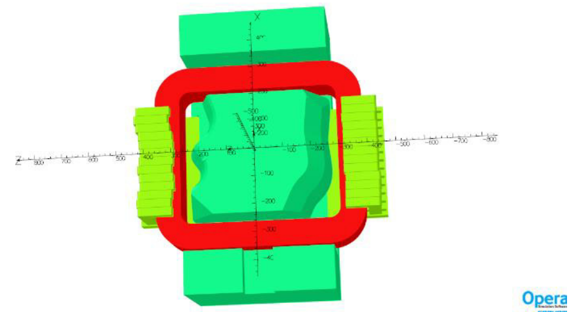

Figure 11: Opera-3D model of the top half of B3.

MULTIPOLE MAGNETS

For the required 15 quadrupoles a total of 12 different designs were made because the pole aperture vary between 80 and 290 mm, effective magnetic lengths between 250 and 350 mm and gradient strengths between 0.77 and 9 T/m. A special challenge was the requirement to keep the effective magnetic length deviation below ±0.5 mm in the magnet center plane in the full good field range from 10% to 100% excitation. The good region extends typically in the full aperture which requires a wide pole profile selected to be equal to the aperture diameter. For two quadrupoles the good field extended to 120 mm for an aperture of 100 mm, which required an increased pole width of 115 mm. With fully optimized pole profile and end chamfering the effective magnetic length could in Opera-3D calculations be limited to less than 0.2 mm from the nominal magnet length in the full good field width and full excitation range. This was, however, only possible for longer magnets with aperture diameter D to magnetic length L ratio of $D/L \geq 2$. For shorter quadrupoles it was not possible due to fringe field effects. Instead the non-linear field integral deviation was reduced to typically $4 \cdot 10^{-4}$. Production and test of the first 11 quadrupoles are completed and show excellent agreement with the calculations.

Three sextupoles and one octupole magnet have been made to similar, but somewhat relaxed tolerances.

CONCLUSION

The design of the very large high voltage Wien filter is finished and accepted. The dipoles have been designed with complex and demanding pole end profiles. The measured transverse fringe field boundary variation is found to be in good agreement with the design calculations. A wide range of multipole magnets have been produced with special focus on the magnetic length.

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REFERENCES

[1] C.R. Brune and B. Davids, Ann. Rev. Nucl. Part. Sci. 65, 87-112 (2015).
[2] OPERA/TOSCA, Vector Fields, Cobham, UK.

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