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# MAGNETIC FIELD AND BEAM DYNAMICS CALCULATIONS FOR SUSE[+]

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Abstract

The SuSe magnet system is designed using the program GFUN3D. A small version of this program was connected to a general fit program by means of which the current in the main and trim coils was determined for a given isochronous mean field $\bar{B}(r)$. For beam dynamics calculations with the code GOC accurate fields ($\Delta\bar{B}/\bar{B} \lesssim 1\%$) were used which were obtained by means of the program GFUN400 where the unique part of the magnet iron is subdivided into 400 elements at maximum. Several coil systems have been investigated. In an alternative design all coils have straigth sections which are easier to manufacture than coils with negative curvature. The main coils have a largest radial extension of 3.08 m. There are 22 correcting coils inside each main coil.

## 1. Introduction

SuSe is a superconducting heavy ion cyclotron which is planned as an additional facility for the accelerator laboratory of the two Munich universities. The cyclotron will be the booster of the 13 MV-tandem. The combined accelerator system will deliver heavy ion beams in the whole mass range of rather high energy and intensity. The energy $T_2/A$ at the mean extraction radius $r_2 = 2.4$ m will be $T_2/A = 450$ MeV/n for very light particles, e.g. $^{3}He$. For the very heavy particles , e.g. $^{238}U^{38+}$, $T_2/A = 24$ MeV/n is expected. More about SuSe is described in refs. 1 – 5. In fig. 1 the essential components of SuSe, i.e. four superconducting sector magnets and two rf-cavities are sketched. In the lower parts of fig. 1 the details of one sector magnet consisting of the superconducting main and trim coils, the cold iron poles and the warm iron yoke are drawn. By means of the superconducting coils large fields can be produced which cause an almost complete saturation of the poles and the yoke, respectively. Thus, the sector coils behave similar to air coils yielding high fields within the magnets and large reversed fields outside. For particles with the specific charge $q/A = 0.5$ and the maximum final energy $T_2/A = 300$ MeV/n, e.g., the magnetic guiding field $B(r,\phi)$ ($r$ is the mean radius, $\phi$ the azimuth angle) reaches in the magnet symmetry plane ($\phi = 0$) at $r_2$ the value 4.8 T. Between the magnets the minimum valley field results to be -0.4 T. Because of this large field variation the flutter factor is correspondingly high being in this case $F(r_2) \approx 1$. Therefore, the acceleration of light heavy ions to the above mentioned energies by means of radial sector fields with zero spiral angle becomes feasible. In section 2 the requirements to the magnet programs are described. In section 3 some results of our magnetic field and beam dynamics calculations are presented.

## 2. Computing codes requirements

Two soft ware works had to be done in order to use the GFUN3D-program as a serious tool for designing the SuSe magnet system. By means of a small version of GFUN3D the unique part of the iron, which cannot be represented by mirror reflections (one fourth of one SuSe magnet), is subdivided into 90 iron elements at maximum.

Firstly, the small version of GFUN3D was connected to a general fit program (GFUNFIT). Using GFUN3D the current in the main and layer coils is determined by fitting the produced mean field to the given approx-

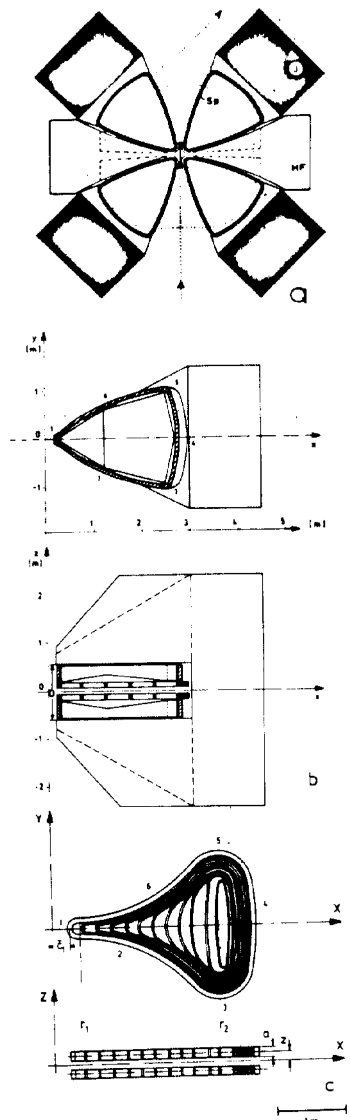

Fig.1. a. Plan view of SuSe.
b. Plan view and vertical section of a SuSe magnet.
c. Cross section through the correcting coil layer.

imately isochronous average field $\bar{B}(r) = B_0\gamma(r)$. $B_0$ is the mean field extrapolated to the cyclotron center. $\gamma$ is the relativistic factor which rises with the mean radius r.

Secondly, in order to get accurate field maps, which are necessary for reliable beam dynamics results, the large version of the GFUN3D-program (GFUN400) was implemented at our CYBER 175-computer.

The unique iron part can be subdivided with GFUN400 into 400 elements at maximum. Two field maps with rough and fine iron subdivision were calculated using the same current in the coils. In one case there are 15 core and 45 yoke, in the other 40 core and 205 yoke elements. The difference $\Delta B(r,\phi)$ between the two calculations is plotted in fig. 2 versus r and $\phi$ for a $90^0$-sector. $\Delta B(r \approx r_1,\phi) \lesssim 120$ Gauss is quite large.

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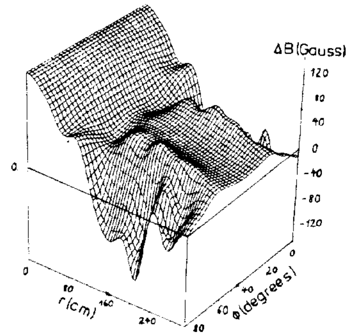


Fig.2. Magnetic field difference $\Delta B$ between calculations with 245 and 60 iron elements versus radius r and azimuth angle $\phi$.

Thus, the subdivision of the pole into rather small elements seems necessary. The maximum relative deviation between the two resulting $\bar{B}$(r)-curves is $\Delta\bar{B}/\bar{B} = 0.028$ which gives an idea on the accuracy of the field calculation for SuSe being with GFUN400 $\Delta\bar{B}/\bar{B} \lesssim 1$ percent which does not affect the tune much. Therefore, field maps for the extreme values of q/A and $T_2$/A have been calculated using GFUN400 with 245 iron elements. The mesh size of the maps has been chosen small enough ($\Delta r = 5$ cm, $\Delta\phi = 2.5^0$) to yield no additional error in the beam dynamics code GOC[6] which uses the maps.

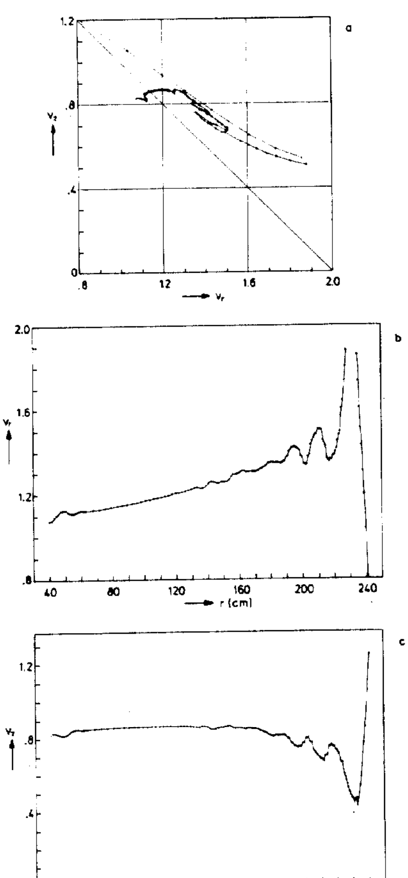


Fig.3.a. Tune diagram $\nu_z$ versus $\nu_r$ for heavy ions with q/A = 0.5, $T_2$/A = 300 MeV/n.

b. $\nu_r$ versus r.

c. $\nu_z$ versus r.

## 3. Magnet system properties

In fig. 3 the $\nu_r$(r)- and $\nu_z$(r)-curves together with the tune diagram $\nu_z(\nu_r)$ for particles with q/A = 0.5, $T_2$/A = 300 MeV/n are drawn. $\nu_r$(r) and $\nu_z$(r) show radially growing oscillations at large r. The period of the wiggles is equal to the distance between the single coils of the correcting layer (c.f. fig. 1c). $\bar{B}$(r) is adjusted only at the radial positions of the layer coils. There are field deviations between these positions of about 70 Gauss which cause additional error gradients $d\bar{B}/dr$ yielding the observed fluctions. $\nu_r$ and $\nu_z$ are roughly given by $\nu_r \simeq 1 \pm 0.5$ n and $\nu_z \simeq \sqrt{F}(1 - 0.5\ n/F)$, where $n \doteq (r/\bar{B})d\bar{B}/dr$ is the field index and F the flutter factor. The phase shift of $\pi$ between the oscillations in the $\nu_r$(r)- and $\nu_z$(r)-curve, respectively, and the radial increase of their amplitudes are explained by these relations. The field deviations cause too large phase oscillations, especially, when the rf-system is operated at high harmonic numbers (h = 16) and must therefore be reduced, e.g., by using correcting layers with more properly spaced single coils. This will also make the oscillation amplitudes of $\nu_r$ and $\nu_z$ small. The sum resonance $\nu_r + \nu_z = 2$ is crossed at $\bar{r} = 0.79$ m. As there is no second harmonic field pertubation, the passage through the resonance will not affect the beam quality. The radial motion becomes unstable close to the extraction radius $r_2$ (c.f. fig. 3b) and decreases then to a very small value because the radial dimension of the main coils and, thus, the range, within which $\bar{B}$(r) was fittet to $B_0\gamma$, were chosen slightly too small.

According to these beam dynamical results and trying to avoid the negatively curved correcting coil windings, whose manufacturing is very difficult, the shape and assembly of the coils were modified. Fig. 4 shows such a system.

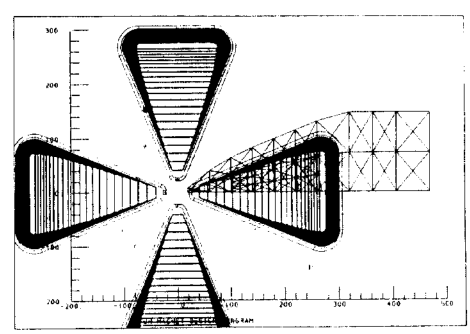

Fig.4. SuSe coil systems with straight sectors. The unique iron part, which is subdivided into iron elements for calculating the magnetic field with GFUN3D, is drawn (c.f. text).

The coils have a triangular shape with round edges. The main coil data is: Maximum radial extension, measured in the vertical magnet symmetry plane, 3.08 m, sector angle $45^0$, axial height a = 38.5 cm, radial width b = 6 cm, minimum distance from the median plane h = 6.5 cm. Within each main coil there are 22 correcting coils with a = 8.33 cm, b = 1.2 cm and h = 5cm. Preliminary results were obtained leaving the iron (poles and yokes) unchanged. In fig. 5 the corresponding isochronous mean field $\bar{B}_{is}$(r) for fully stripped light heavy ions with maximum $T_2$/A is drawn. It is more difficult to produce $\bar{B}_{is}$(r) using sector shaped correction coils than by means of negatively curved ones. The sharp rise of $\bar{B}_{is}$ at $r_1$ causes a mean current density of $\bar{j} = 12600$ A/cm$^2$ in the main and a reversed current $\bar{j} = -7500$ A/cm$^2$ in the largest correcting coils. In the other coils $\bar{j}$ is $\lesssim 5000$ A/cm$^2$. The disturbing fields due to the reversed current must be compensated for by the remaining correcting coils which cannot be completely accomplished, thus, leaving wiggles in $\bar{B}_{is}$ at $r \approx 0.8$ m of an amplitude of $\Delta\bar{B}_{is} \approx 50$ Gauss.

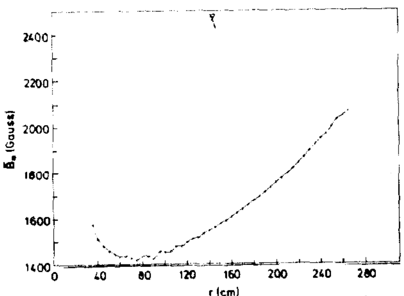


Fig.5. Isochronous mean field versus radius.

These deviations from $\bar{B}_{is}$ can be tolerated even at a harmonic number h = 16 because at inner radii there are only a few turns between two correcting coil positions. The flutter F is quite large ($F \approx 2$) due to the rather small sector angle leading to a large scalloping of the orbit at $r_2$ with an amplitude $\Delta r_2$ = 26 cm. The small oscillations of $\bar{B}_{is}$ at $r_2$ result from a too small radial fitting range and can be removed without changing the coil geometry. These fluctuations show up enlarged in the $\nu_r(r)$ - curve in fig. 6.

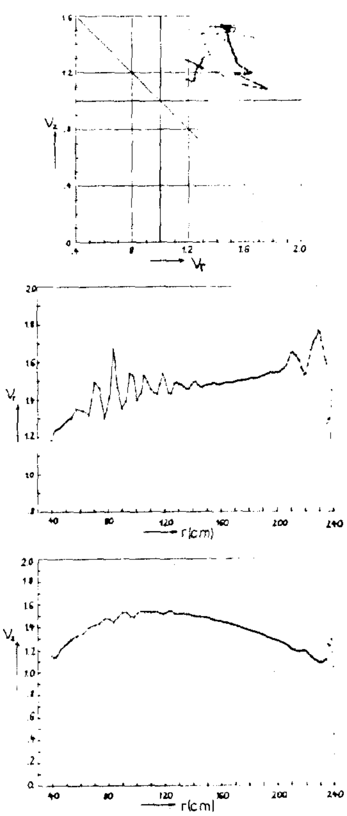

Fig. 6. Analog fig. 3 for the straight sector coil system.

Stability is provided and the tune acceptable, $\nu_z$ being $\nu_z > 1$ in the whole radial range. The $\nu_r = 4/3$ - resonance is crossed three times without reducing the beam quality, as coasting orbit calculations have shown.

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