DESIGN, CONSTRUCTION AND PERFORMANCE OF THE DESY II MAGNETS

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Abstract

Dipoles, quadrupoles and sextupoles have been designed and constructed for the new separated function synchrotron, DESY II. The special constraints for the magnets were: 12.5 Hz repetition frequency and a 50 MeV to 10 GeV energy operation range. Special care was taken in selecting the steel, chosing the thickness of laminations and designing the endfield shape. To ensure easy access to the vacuum chamber, and because there are nine inlet and outlet beam pipes to be installed, a c-type pole shape design for the dipole was chosen. The quadrupoles and sextupoles have the same cross section as the PETRA magnets, but they are different in length, lamination thickness, coils and endfield shape. Back-leg windings are applied on the dipoles to enable horizontal orbit displacements to be made. The major part of the vertical orbit correction will be made using four coils mounted on the return yokes of the sextupoles so as to create superimposed horizontal magnetic fields.

Introduction

After the approval of the new synchrotron DESY II in 1983 most of the components of the machine have been built and installed in the DESY ringtunnel side by side with the old DESY I synchrotron. The status of the project is described in /1/. The basic parameters of the machine are given in /2/. Only minor changes have taken place in the meantime. Due to the eddy current effects in the steel vacuum chamber of DESY II additional sextupoles had to be introduced /3/. Fig. 1 shows the modified lattice. Those parameters that affect the design of the magnets are listed in Fig. 2. The construction of the quadrupoles and sextupoles is partly based upon the PETRA magnet design. This allowed use of existing tools and saved construction- and fabrication costs.

The dipoles which are of a completely new in-house design, fabrication and assembly, are made in close cooperation between various firms and the DESY workshop. During 1984 the magnets were built, shipped and tested. A new method for precise AC-measurement of the magnetic field has also been developed /10/.

Lattice and magnet parameters

Due to the strong chromaticity effects caused by the sextupole component of the eddy currents in the dipole vacuum chambers the lattice described in /2,4/ has been slightly modified by adding extra sextupoles. It has been shown that with this modified lattice (Fig. 1) the acceptance can be made large enough to capture the injected beam from LINAC I /3/. The same calculations allow the aperture on field quality to be deduced. Further constraints are given by the fact that existing power supplies and resonant circuits determine the impedance, the cycling frequency and the power consumption limit of the dipoles. The parameter list for magnet design is given in Fig. 2.

repetition frequency	12.5 Hz
max. energy (for magnet design)	10 GeV
1st completion stage	8 GeV
injection energy	50/200 MeV
acceptance (dp/p=1%) Ax, Az	10 mradmm
dipoles	
number of magnets	48
length	3.55 m
bending radius	27.12 m
good field region	80x40 mm^2
inductance	34 mH
quadrupoles	
number of magnets	48
length	.58 m
strength	.44 m^{-2}
pole radius	50 mm
sextupoles	
number of magnets	24 (16 D + 8 F)
eff. length	216 mm
strength	.25 m^{-3}
pole radius	60 mm
correction elements at 200 MeV	
24 dipoles backleg	2.86 mrad
24 vertical	1.5 mrad

Fig. 2: Parameter List

Element	Type	Physical length/mm
B	Dipole	3550
QF	Quadrupole (hor. foc.)	580
QD	Quadrupole (hor. defoc.)	580
SD	Sextupole	180
SF	Sextupole	180
C	drift space for cavity	2220
D1	drift space	225
D2	" "	705
D3	" "	135
D4	" "	245
D5	" "	195
D6	" "	405
D7	" "	295
D8	" "	635

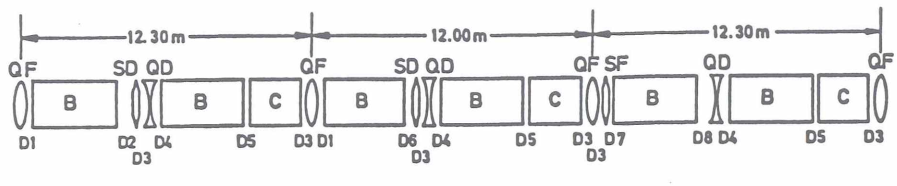


Fig. 1: Final DESY II lattice

Choice of steel

The 12.5 Hz cycling frequency of the synchrotron dictates that the magnets have to be laminated. The choice of lamination thickness is influenced by various factors, the eddy current losses within the magnet core, the costs for stamping and the availability of laminated iron on the commercial market. The eddy current losses are given by /5/:

$$N_w = \frac{1}{24} \varkappa \, \omega^2 d^2 B_m^2 \, V \, F(x) \qquad (1)$$

$$\text{with} \quad F(x) = \frac{3}{4} \frac{\sinh x - \sin x}{\cosh x - \cos x} \qquad (2)$$

$$\text{and} \quad x = d \cdot \sqrt{\pi f \varkappa \mu_o \mu_r} \qquad (3)$$

We estimate for the DESY II-iron:

conductivity	$\varkappa = 3\times10^6 \, m/\Omega m^2$
repetition frequency	$\omega = 2\pi f = 2\pi\times12.5 \, s^{-1}$
thickness of lamination	$d = 1\times10^{-3} \, m$
rel. permeability	$\mu_r = 3000$
eff. AC-magnetization	$B_m = 0.42 \, T$

and get the specific losses

$$N_w/V = 140 \, W/m^3$$

It is thus obvious that there is no need for extra water or air cooling of the magnet core.
The uniformity of the magnet flux within the core is characterized by the cut-off frequency f_g of the laminations. From (3) we get with x = 1

$$f_g = 1/\pi\mu_o\mu_r\varkappa \, d^2$$

Putting in the parameters for the DESY II iron we get

$$f_g = 28 \text{ Hz}$$

This is well above the operating frequency of 12.5 Hz and so we deduce that there will be no significant influence on flux suppression. We want the synchrotron to operate within a wide momentum range from 50 MeV/c to 7...10 GeV/c. This implies that the good field region of the dipoles must be kept within the limits $\pm 5\times10^{-4}$ over the full horizontal aperture $\pm$ 40 mm between 62 Gauss and 1.23 Tesla. Calculations with the magnetostatic computer code MAGNET 80 /6/ indicate that for this to be achieved the following specification on flux density B vs. magnetization force H is required:

H (A/m)	20	30	50	100	500	1000	5000	30000
B (T)	.06	.13	.34	.82	1.36	1.44	1.63	1.995

It is obvious that the remanent field caused by the coercive force H_c should be as small as possible. At H_c = 40 A/m we expect about 5...7 Gauss remanent field within the gap. This implies that the iron should be carbon-free (<100ppm). Pure iron heated in a hydrogen atmosphere has $H_c \simeq 4$ A/m and the relative permeability is quite large over the full range of magnetization. However the electrical conductivity is comparatively large ($\varkappa = 10^7 \, m/\Omega \, m^2$) and thus the lamination thickness has to be small in order to keep eddy current effects low. Since this material is rather expensive the more economic way is to use iron containing about 1...4 % silicon. Silicon helps precipitation of carbon into graphite, increases the electric resistance and the permeability at low flux densities but reduces the saturation level of induction by about 500 Gauss per percentage of silicon. About 14 firms were invited to tender. But only a few of them were able to offer steel according to our specification. The steel we received has the following properties

type of material	300-100 a (EBG Bochum)
coercive force	$H_c = 40 \pm 8$ A/m
conductivity	$\varkappa = 2.3\times10^6 \, m/\Omega m^2$
rel. permeability (max)	$\mu_r = 6550$
saturation induction	$B_s = 1.995$ T
lamination thickness	d = 1 mm
insulating phosphate coating (Stabolit 50)	2µm
chemical analysis (%)	

C	Si	Mn	P	Al	N
.003	2.4	.25	.04	.35	.004

Fig. 3 shows the measured magnetization curve

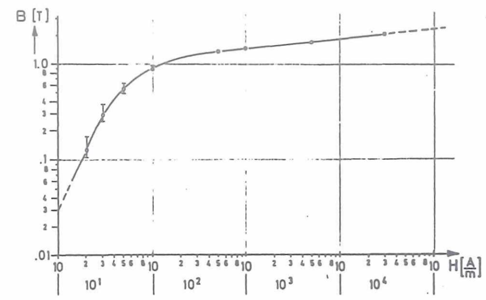


Fig. 3: Magnetization curve of the DESY II steel

Dipoles

A novel fabrication technique for the metallic vacuum chamber has been developed that allows the vertical beam profile to use nearly the complete dipole gap height /7/. Consequently the pole width can be made small and the stored energy in the gap is minimal. The installation costs as well as the costs for powering the magnets also become small. For ease of access to the vacuum chamber a C-type cross section was chosen and the good field region with $\Delta B/B = 5\times10^{-4}$ within the 80x40 mm² free aperture of the vacuum chamber was achieved with 45 mm gap height and 160 mm pole width. Fig. 4 shows the dipole cross-section.

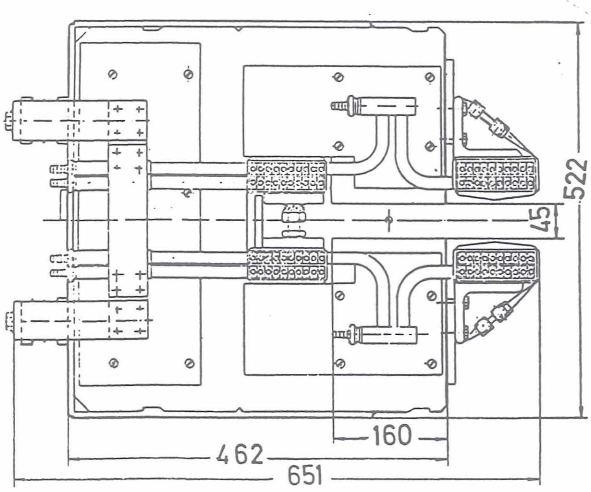


Fig. 4: Dipole cross-section

The laminations which are shuffled in a way designed to equalize the remanent field effects are stacked on a segment of a circle to avoid the sagitta. The endfield blocks, a stack of 90 mm thickness glued together are then added and the whole core is surrounded with strenghtening plates and welded together. In order to avoid eddy currents in the endfield region which would cause heating losses and magnetic field distortions, the endfield blocks are shaped following W. Hardt's design for the DESY I synchrotron magnets in 1963 /8/.

Because of the fact that DESY II is mainly an injector synchrotron for the storage rings DORIS and PETRA, and later on also for HERA, we expect the machine to be turned on to full power only for about 25 % of the total operation time of the storage rings. Therefore the current density of the excitation coils has been chosen comparatively high (5.5 A/mm²) and for ease of assembly the two excitation coils became simple flat pancakes that correspond well with the gap dimensions. Each pancake has 20 turns of 16.5x9mm² conductor with a 5.1 mm central cooling hole. We estimate the additional eddy current power loss within the solid conductor to be less than 15 % of the mean RMS power dissipation. A number of dipoles is equipped with backleg windings for various purposes: there is a four turn coil of 7x7mm² solid conductor for high energy ejection beam bumping and four different 2 turn coils of 4 mm² copper for injection orbit correction and diagnostics.

Quadrupoles and sextupoles

In design and construction the DESY II quadrupoles and sextupoles are similar to those of the PETRA storage ring /9/, but some modifications have been made to get a better fit to the DESY II parameters. The core length of the quadrupole is reduced from 660 mm to 580 mm and for the sextupole from 250 mm to 180 mm. In order to avoid eddy current in the endfield region the compression plates of the quadrupoles are replaced by a stack of laminations glued together with epoxy resin and the endfield blocks are properly shaped. As a result of this the magnetic length of the quadrupoles is identical with the magnet core length. The coils of the quadrupoles are wound from solid copper conductors 16x16 mm² with a 7 mm central cooling hole. These coils do not completely fill the window as is the case with the PETRA aluminum coils. However, the savings on tools and construction time bring significant compensations. The sextupoles are built in the same manner but without extra endfield shaping. The defocussing sextupoles are equipped with extra return yoke windings for vertical injection orbit correction. The horizontal dipolefield quality is sufficient for this task.

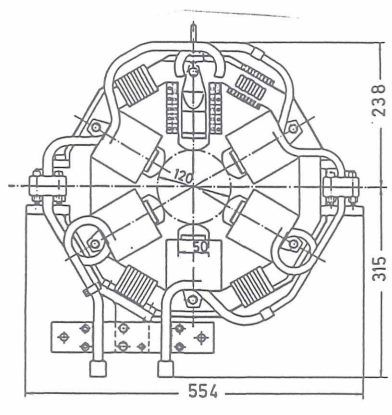
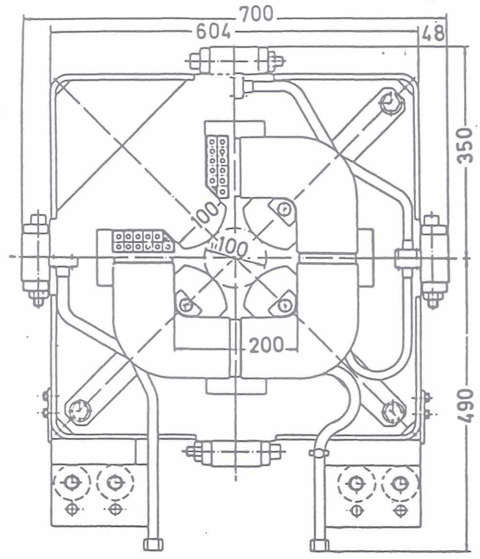


Fig. 5: Sextupole cross section

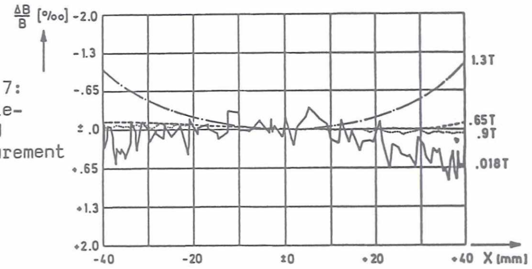
Fig. 6: Quadrupole cross-section



Performance of the magnets

The permissible tolerances on the magnets had been discussed in /4/. Mechanical and magnetical measurements show that the deviations are well within the allowed limits. Details about the magnetic field measurements and some results are given in /10/. As an example Fig. 7 shows a typical dipole field error curve at different excitation levels. Though up to now we only have very first impressions about the beam behaviour in the new synchrotron we are convinced that the DESY II magnets are quite sufficient for the task for which they have been built.

Fig. 7: Dipole-field measurement



References

/1/ G. Hemmie, Status report on the DESY II Synchrotron, this conference H47

/2/ G. Hemmie, DESY II, A new injector for the storage rings PETRA and DORIS, IEEE NS-30 (1983)

/3/ G. Hemmie, J. Roßbach, Eddy current effects in the DESY II dipole vacuum chamber, DESY M-84-05

/4/ J. Roßbach, F. Willeke, DESY II Optical design of a new 10 GeV electron positron synchrotron, DESY M-83-03

/5/ f.ex. K. Küpfmüller, Theoretische Elektrotechnik, p.263, Springer, Göttingen 1955

/6/ C. Iselin, CERN Prog. Lib. T600, (1971)

/7/ J. Kouptsidis, R. Banthau, H. Hartwig, A novel fabrication technique for thin metallic vacuum chambers with low eddy current losses, this conference S9

/8/ W. Hardt, Über die Gestaltung des DESY Magneten, DESY A 1.5 (1959)

/9/ PETRA Proposal, updated version, DESY Febr. 76

/10/ U. Berghaus, W. Kriens, S. Pätzold, Magnetic field measurements of the DESY II magnets, this confernece H29