Magnetic Devices of the Amsterdam Pulse Stretcher Ring AmPS

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Abstract

AmPS is a 900 MeV electron pulse stretcher and storage ring. Installation started early 1991 and commissioning is foreseen from Spring ' 92 on. The ring contains 170 magnetic elements: dipoles, quadrupoles, sextupoles, steering magnets and magnetic septa. Apart from the 2 septum-magnet yokes all magnets are fully laminated. The magnets were designed with help of the Poisson code and by using conformal mapping methods. A prototype was made of each type of magnet , mainly to optimise the pole end chamfering. The required low harmonic content could be obtained by simple cuts of the pole ends.

The steering magnets combine horizontal and vertical steering and have been designed for a low harmonic content as well.

The injection septum with a septum thickness of 3 mm operates at a maximum current of 1075 A. This septum is indirectly cooled. A novel electrical isolation technique is applied which also ensures a good thermal contact between the conductor and the yoke. The extraction septum is directly cooled.

A computerised x-y-z field mapping device was developed as well as an inexpensive rotating coil measurement system.

The design, both magnetically and mechanically, the constructional aspects and the measurement results of the magnets are presented together with a description of the measurement set-up.

1. Introduction

At NIKHEF electrons of energies between 250 and 900 MeV are used as a probe in electron scattering experiments. The major aim of the AmPS project is a considerable duty factor (d.f.) increase of the electron beam. To that purpose a 0.1 % d.f. linac injects electrons into the AmPS ring. The ring has two modes of operation: a so called Pulse Stretcher mode (PS mode) where the injected electrons are extracted slowly and continuously, and a Storage Mode where the injected electrons remain in the ring. Both modes provide an electron beam with a d.f. close to 100 %.

The AmPS ring has a circumference of 212 m. The guide field for the electrons is generated by 32 dipoles; focussing is provided by 68 quadrupole magnets. To control the chromaticity 32 sextupole magnets are installed; another 4 sextupoles are used for extraction control in PS mode. Beam steering for closed orbit correction requires 32 combined horizontal and vertical corrector magnets. The linac beam is injected into the ring through a 3 mm magnetic septum. The beam is slowly extracted from the machine (using the third-integer resonance) by two septa: an electrostatic wire septum and a 5 mm magnetic septum. Table 1 presents the main parameters of the magnetic devices.

Table 1. AmPS magnetic element parameters at 1 GeV.

	Dipole	**Quadrupoles**		**Sextupoles**	**Septa**	
	curve	curve	straight	curve	injection	extraction (0.9 GeV)
Quantity	32	36	32	32	1	1
(Tip) field [T]	1.0	0.3	0.24	0.04	0.135	0.271
Bending angle [deg]	11.25	-	-	-	0.93	3.63
Bending radius [m]	3.300	-	-	-	25	11.1
Septum thickness [mm]	-	-	-	-	3	5
Gap/aperture [mm]	45	71	95	80	10	20
Pole width [mm]	190	74	104	26	20	20
Good field width [mm]	81	57	76	56	-	-
Homogeneity x 10^4	5	10	10	100	-	-
Magnetic length [mm]	647	210	290	150	400	700
Yoke length [mm]	590	180	250	120	400	700
Coil material	Al	Cu	Cu	Cu	Cu	Cu
Ampere turns [A]	39600	17950	20240	1650	1075	4320
Current [A]	320	130	120	19	1075	2160
Power [W]	5400	875	900	30	460	4700
Cooling	water indirect	water direct	water direct	air convection	water indirect	water direct

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2. General aspects

Magnetic design: NIKHEF made the magnetic design of all magnets. Before we started experts from other accelerator laboratories were consulted [2]. All magnets will operate at a maximum energy of 0.9 GeV. To allow for a safety margin it was decided to design the magnets for 1 GeV as an upper limit. As the energy for the extracted electrons is limited to 850 MeV only the extraction septum has been designed for 0.9 GeV.

The optical design of the ring requires a good-field quality of the magnets. The harmonic distortion of the quadrupole fields has to remain within 0.1 % and for the sextupoles this number has to be within 1 %.

In PS mode the extraction process is controlled by the extraction sextupoles. These devices have a rather low integrated sextupole strength of 3 m^{-2}. *The integrated sextupole strength is defined as* k_s^2 *x effective length magnet with* k_s *= sextupole coefficient according to the following power expansion of the normalized field in the transversal direction:* $B(x)/B(0)=1 + (k_q^2\,\rho)\,x^2 + (k_s^2\,\rho)\,x^4 + \ldots$ *with x the transversal axis and* ρ *the bending radius.* The total integrated sextupole strength of the dipole magnets and of the steering magnets should not exceed the few-percent level of the integrated strength of the extraction sextupoles.

The pole profiles of all magnets have been designed with help of the Poisson codes. Most of the magnets are rather short and therefore their fringe field contributes considerably to the field integral. The pole profiles were somewhat over-compensated to counteract this effect. Nevertheless, the requirements for the field quality implied the construction of prototypes of all magnet types. The pole/yoke assembly of each prototype consisted of a fixed core with removable 20 mm core end pieces. Optimisation of the magnetic field was achieved in an empirical way by measuring the effects of various pole/core end chamfers. No changes had to be made on the pole profiles.

Yoke and pole material: the electrons are injected in the ring at the operating energy, so there is no need for ramping of the magnetic field. Therefore, in principle magnets with a solid core could have been used. Nevertheless it was decided to opt for laminated magnets because of their reproducible magnetic field (hardly any field contribution from eddy currents). The ease of manufacturing complex pole shapes and the relative low price when produced in large identical quantities were other considerations.Therefore all magnets except the 2 magnetic septa are laminated. Sheets with a thickness of 1 mm were chosen. The laminations are coated with a thin thermo setting glue layer; this material is commercially available (Stabolit, EBG, Germany) The laminations are properly stacked and pressed to form magnet cores. The fact that none of the laminated magnets is curved eases this process.The core blocks are cured at approximately 200 ° C. Very stable and "solid" cores are obtained this way and no further welding or clamping of the blocks is required.

The steel used for the laminations has low coercitive force: <80 A/m for the dipoles and quadrupoles; <50 A/m for the sextupoles (because of their low field). This same material is also used for the yoke of the steering magnets. The yokes of the septa are made from steel 1010.

Construction: to facilitate the installation of the vacuumpipes all magnets (except two septa) can be split into two parts. The reproducibility of the magnetic field after repetitive splitting and reassembling has been verified with help of the prototypes. As far as possible magnet types are powered in series. The integrated fields of individual magnets of such "families" have to be equal over the operating range within 0.1 % for the dipoles and within 1 % for the quadrupoles and sextupoles. This is mainly achieved by reproducible assembly of the magnets which is eased by the use of laminations. Also, each magnet is carefully fieldmapped. Small deviations of the integrated field could be minimized by using electrical shunts. For alignment purposes the laminations have outer references well-defined with respect to the pole profile. During the assembly the pole profiles are used as stacking reference.

Status: the construction of all dipoles, quadrupoles and sextupoles has been awarded to a Dutch company [3]; NIKHEF has the responsibility for the magnetic design and the measurements. Delivery started end of 1990 and by mid-1991 all magnets will be delivered. The two septum magnets are made in-house. The steering magnets are ready to be ordered.

3. Dipole magnets

The good-field pole width is 81 mm: 65 mm to allow for the large beam excursions during injection and an additional 16 mm for the sagitta (rectangular magnet). To minimize the magnet width, the pole is shimmed with 0.8 mm x 20 mm shims; this allowed to reduce the required pole width from 220 mm without shim to 190 mm with shim. The transverse field intently shows some overshoot to compensate for the longitudinal field drop at the ends of the dipole. Originally end field compensation by external shims was foreseen but by a small two step 45 degree chamfer of the pole ends a low integrated sextupole strength of 0.16 m^{-2} at 1 T could be achieved. As the end chamfering shortened the effective length of the magnet the iron length was increased with 10 mm to 590 mm. The dipole coil is wound of aluminium tape. The insulation between the windings consists of aluminium oxide; the complete coil is vacuum-impregnated with an epoxy resin. The coils are indirectly cooled through a cooling plate.

4. Quadrupole magnets

Two types with different aperture (71 & 95 mm) were designed. The pole profile consists of 3 parts: a hyperbola in the center, a tangent line to the hyperbola and a short straight line at an angle of 45 degree with the pole axix. The latter line is very useful to measure the mechanical symmetry of the quadrupole as well as for alignment purposes.

The field quality of the quadrupoles was optimized by varying the pole width/ aperture ratio (w/a) as well as varying the position of the tangent point with respect to the pole width. The following table gives details of the final design.

aperture	71 mm	95 mm
w/a ratio	1.04	1.08
tangent point	62 %	65 %
45 deg. straight	3 mm	3 mm
chamfer angle	33.5 deg.	30 deg.
chamfer depth	4.5 mm	7.8 mm

The total harmonic content at 90 % of the aperture without pole-end chamfering was in the order of 1 %. This value was reduced to 0.1 % by the listed single cut pole-end chamfers.

5. Sextupole magnets

The sextupole design is based on the ALS [2] booster sextupole. The pole contour consists of a cubic hyperbola in the center and edge bumps to compensate for the end effects. The required harmonic content of 1 % was achieved without pole-end chamfer.

6. Septum magnets

The injection septum is a vertical 16.2 mrad bending magnet located at the very end (downstream) of the injection line. It guides the electrons to be injected through a 10 mm gap to a trajectory parallel to the ring axis but with an offset to the axis of 15 mm. The leak field outside the septum should not deflect the circulating beam by more than 0.1 mrad. A one-turn septum conductor design has been choosen. The required excitation at 1 GeV is 1075 A. Because of the marginal power saving it was decided to make a DC septum also because of the ease and reliability of its power supply. The maximum power dissipation of the magnet is 460 W. As the magnet is so close to the ring axis it is located inside of the ring vacuum envelope. To avoid interference with the circulating beam, the septum conductor thickness at the exit is limited to 3 mm; one side of the yoke is recessed to 3 mm over its full length. Because of the 3 mm conductor thickness it is cooled indirectly through the yoke which itself is water cooled. The insulation between the conductor and the yoke consists of a 0.2 mm layer of ceramic enamel which is strongly adhered both to the yoke and the conductor. This principle was suggested earlier elsewhere [4] and applied successfully at NIKHEF with help of an industrial firm [5].

The magnet has meanwhile been tested in vacuum and withstood extensive thermal cycling. The measured heat transfer coefficient is > 1250 W m^{-2} $°C^{-1}$; the maximum temperature rise of the conductor at a current of 1075 A is 80°C. The measured stray field at the position of the circulating beam is < 10 Gauss.

The magnetic extraction septum bends the beam, extracted by the electrostatic septum, horizontally out of the ring. The clearance between the circulating beam and the extracted beam to the septum conductor (11 and 6 mm respectively, with a 5 mm thick septum) allows to locate this septum outside the vacuum. The conductor is directly water cooled. A two-turn design is used, still requiring 2160 A as excitation.

7. Steering magnets

For orbit correction purposes 32 horizontal and 32 vertical steering magnets have to be installed along the ring. A maximum deflecting angle of 1 mrad is required. A compact design is a must as there are severe space limitations in the ring; in the curved section only 180 mm is available. We therefore tried to combine the horizontal and vertical steering in one unit. Because of the size of the enclosed vacuumpipe the aperture of the steering magnets has to be 100 mm; this results in a large fringe field. As mentioned in paragraph 2, a low integral sextupole field is imperative. A window-frame design was finally chosen. When the coils cover the full length of the window legs a good field geometry is obtained over a large area. A prototype showed an acceptable integrated sextupole strength of 0.015 m^{-2} ; this figure should be multiplied with the number of steerers in the straights (16) and compared with the 3 m^{-2} total strength of the extraction sextupoles.

8. Field measurement equipment

For 3-dimensional field maps a flat bed x-y-z measurement table with 1 m stroke on the x and y axis and 4 m on the z axis (length) is available. The bed has a load capacity of 60 kN. The table is fully computer controlled; the positioning accuracy is in the order of 0.01 mm over the full stroke on all axes. The table is part of a versatile measurement station which furthermore consists of a general-purpose high-stability 350 A, 35 kW power supply, a thermostrated water cooling unit, a high-accuracy temperature compensated Hall probe field measuring instrument [6], all connected to a 80286 PC with IEEE bus. The software allows fully automated fieldmapping, including cycling procedures at various fields.

Quadrupole and sextupole field measurements are performed with a rotating coil system. This system uses some novell ideas and therefore differs from the usual set-ups. A milling-machine is employed as mechanical drive for the rotating coil. The magnets are positioned on the bed of the machine. The coilformers are made of a highly symmetrical glass reinforced cylindrical tube. There is a coil for each magnet type; the diameters of the coils are > 95 % of the magnet aperture. The measurement loop consists of one turn of 1 mm wire connected to the primary of a rotating transformer. The signal is collected from the stationary secondary of the transformer. The winding ratio between primary and secondary is 1:53. A typical output voltage of 2 V is obtained from a quadrupole at a coil rotation speed of 720 rpm. The voltage is analysed by a fast fourier spectrum analyser [7]. The system described allows to measure the harmonic components of the integrated field down to about 0.1% up to the 7 th harmonic without suppressing the main component (quadrupole or sextupole). The analyser also shows non-integer components (e.g. dipole, sextupole and octupole when measuring a quadrupole) which help in tracing misalignments. The measurement results agreed well with results obtained from a "conventional" (i.e. multiturn coil with compensation circuit and contact sliprings) testbench elsewhere [8]. The pole end chamfer of the quadrupoles was determined with the described set-up.

All dipoles, steering magnets, quadrupoles and sextupoles are measured with this equipment prior to their installation. Two faulty devices out of 40 were detected until now.

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