THE SEPTUM MAGNETS FOR THE FAST EJECTION SYSTEM OF THE SERPUKHOV 70 GeV PROTON SYNCHROTRON

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Abstract

Two single excitation loop septum magnets, one moving, the other stationary, have, respectively, magnetic lengths of 1.5 m and 3 m and produce fields of up to 1 T and 1.4 T in apertures of 35 x 30 mm^2 and 60 x 30 mm^2. Field corrections resulted in a spatial homogeneity of the kick of better than 0.1 % for excitation levels corresponding to ejection at proton energies between 30 and 76 GeV. Construction and performance are described.

Introduction

A septum separates two adjacent regions of strongly different magnetic field. Septum magnets are therefore generally used as second stages of ejection systems[1] in high energy particle accelerators, where they permit to minimize the beam deflections to be given by the first stage (fast kicker, resonance quadrupole, fast bump magnets) and provide the strong field for bending the beam out of the accelerator.

The Serpukhov fast ejection system uses three stages, i.e. a fast kicker magnet followed by two septum magnets[2]. The first septum magnet is mobile and goes to a rendezvous with the central proton orbit, the second is stationary and ejects the beam. Both magnets are in the accelerator vacuum. Their design parameters are collected in Table I. An impression of the general arrangement of the magnets in their vacuum tanks is given by Figs. 1 and 2.

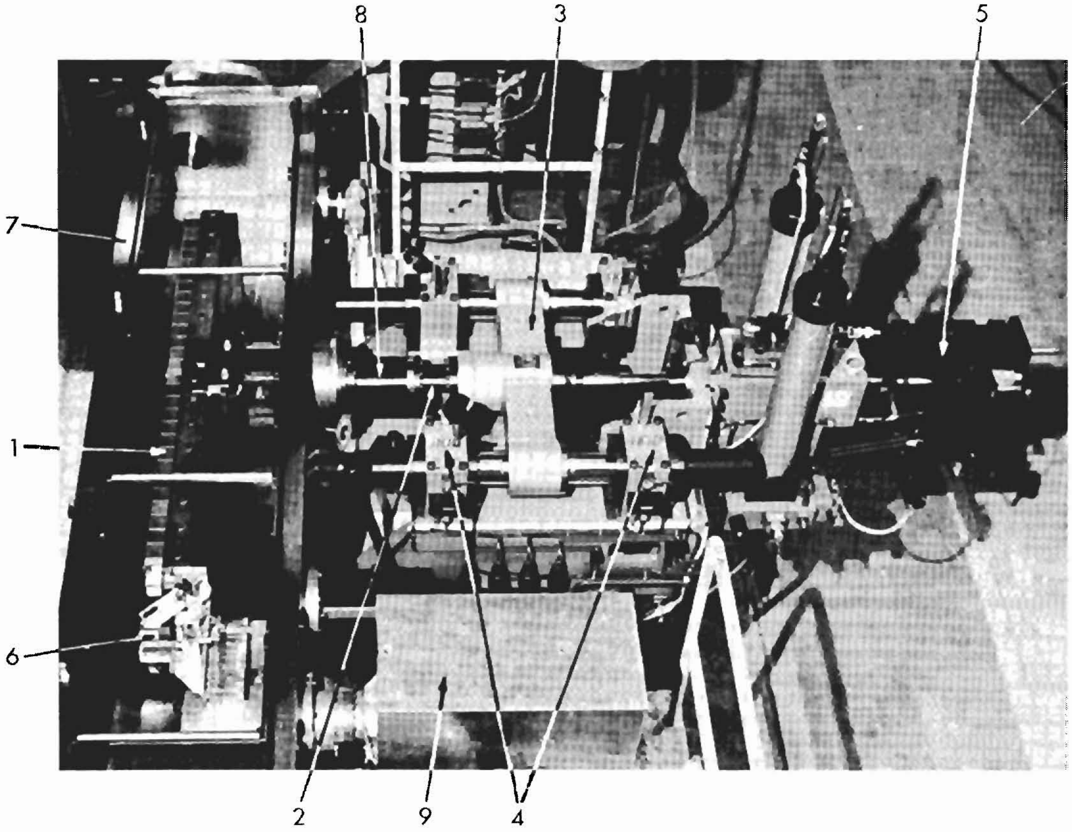


Fig. 1. Mobile septum magnet in vacuum tank with guiding carriage and hydraulic actuator.
1 = Magnet; 2 = Shaft with current feedthroughs; 3 = Carriage; 4 = Hydrostatic bearings; 5 = Hydraulic servoactuator; 6 = Beam diagnostic equipment; 7 = Vacuum tank; 8 = Dynamic bellows; 9 = Sputter ion vacuum pump.

TABLE I. Septum magnets system parameters

	Symbol	Unit	Mobile SM	Stationary SM
MAGNETS				
Magnet length	ℓ	m	1.5	3.0
Aperture width	w	mm	35.0	60.0
Aperture height	h	mm	30.0	30.0
Septum thickness	e	mm	3.0	5.0
Magnet inductance	L_m	μH	2.4	7.9
Magnet resistance	R_m	mΩ	0.6	0.75
Peak kick for 70 GeV	K	T.m	0.85	3.55
Peak field for 70 GeV	B	T	0.57	1.18
Peak current for 70 GeV	I	kA	14.0	29.0
Kick stability on 5.1 s flat top	$(\frac{\Delta K}{K})_c$	%	<±0.1	<±0.1
Kick stability from cycle to cycle	$(\frac{\Delta K}{K})_s$	%	<±0.1	<±0.1
Radial inhomogeneity of kick (in good field region)	$\frac{\Delta K}{K}$	%	<±0.1	<±0.1
Kick from leakage field	$(\frac{\Delta K}{K})_\ell$	%	< 1	< 1
Capacity	C	μF	1000	500
Total circuit inductance	L	μH	3.9	8.9
Total circuit resistance	R	mΩ	50.0	30.0
Quality factor	Q		1.2	4.5
Crowbar resistance	R_2	mΩ	30.0	60.0
Circuit frequency	f	kHz	2.3	2.4
Current rise time	t_c	μsec	75.0	100.0
Charging voltage for 70 GeV	V_c	kV	1.8	5.3
Stored electrical energy for 70 GeV	W_e	kJ	1.6	7.0

A special feature of these magnets is the requirement for 0.1 % spatial homogeneity of the magnetic kick (field integral along the trajectory) for a wide range of excitation levels. This is not trivial, since the finite permeability and geometry give already deviations from homogeneity up to 1 % inside the gap, and there are strong local non-linearities at both ends of the magnet due to the stray fields. There is local distortion also at the centre where the current feeds come through a hole in the magnetic circuit. Furthermore, these effects tend to be field dependent.

For these reasons full size prototype studies have been made already early in the project, in order to find the nature of these field distortions and to develop means for their correction. The results were presented at this conference in 1970[3]. The obtained methods were used to define the final correction shimmings on magnet dummies of final geometry, but of reduced length. The correction shimmings defined on these dummies were then built into the real magnets and yielded the desired homogeneity.

The magnets are pulsed to reduce the cooling problem created by the high current densities in the septums. The high current pulses cause mechanical shocks, hence a risk of eventual fatigue rupture. The 3 mm septum thickness of the mobile magnet is a compromise between the requirements for good mechanical strength and minimum deflection from the kicker magnet. The septum thickness for the stationary magnet is less critical, since it is only a small fraction of the deflection given by the preceding mobile magnet, so 5 mm is chosen mainly for mechanical strength.

System[4]

For good field homogeneity and to avoid organic insulation on this most radiation-exposed component, the septum makes contact over its entire length with the magnet poles. Since the current feeds come in the centre through the mag-

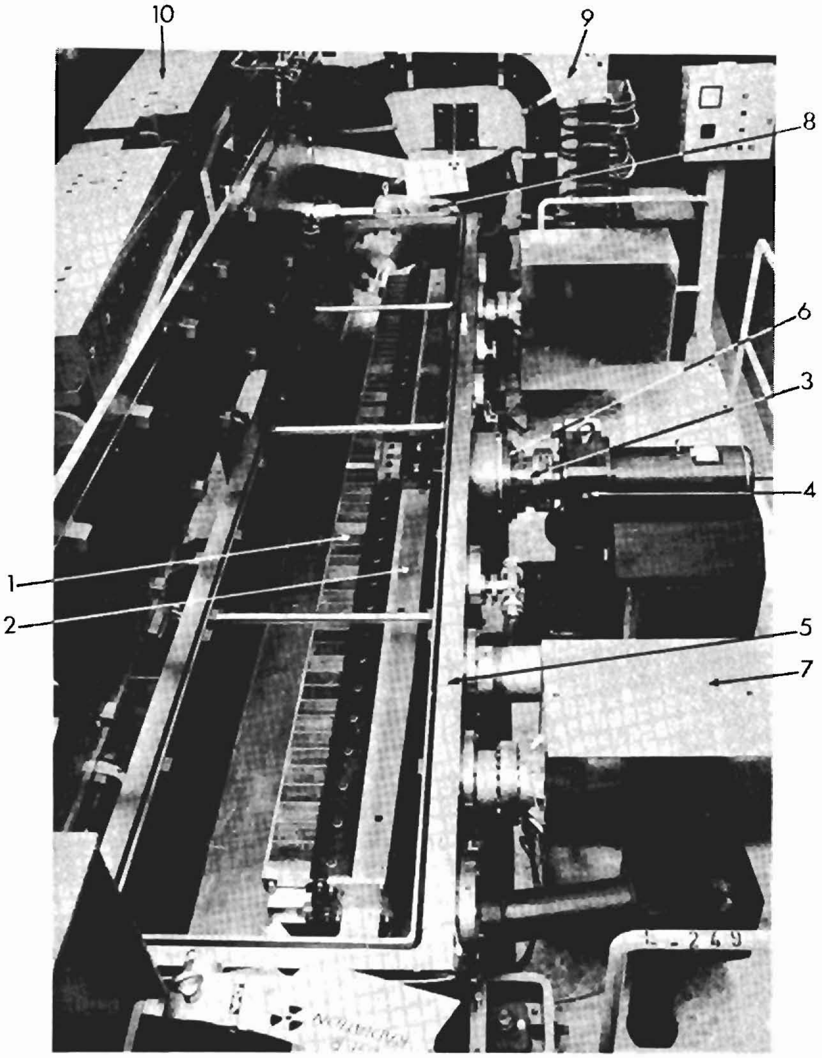


Fig. 2. Stationary septum magnet in vacuum tank. 1 = Magnetic circuit; 2 = Supporting profile beam; 3 = Shaft with current feedthroughs; 4 = Magnet support; 5 = Vacuum tank; 6 = Static bellows; 7 = Sputter ion vacuum pump; 8 = Vacuum section valve; 9 = Downstream accelerator magnet; 10 = Magnets of adjacent secondary beam channel.

netic circuit, the magnet forms a divided inductance with an earthed centre-tap (Fig. 3a). During the excitation pulse the magnet terminals, pulse transmission cables and pulse generator terminals assume symmetrical voltages w.r.t. mass. The pulse generator and the secondary of the HV charging supply are therefore floating, except for an artificial earth through the balanced HV divider.

The pulse generator uses a conventional capacitor discharge through an ignitron, a crowbar diode suppressing current inversions. The pulse is then roughly a half sine-shape of about 200 μsec base (Fig. 3b). Ejection, i.e. beam deflection, occurs during the 5 μsec on the pulse crest, where the current variation is less than 0.1 %.

The charging supply is a transformer-rectifier set with SCR switches in the primary circuit. The SCR switches open and charging begins with a start pulse from the timing system and stops when the required voltage is reached. Each magnet has its own pulse generator and power supply and works at a different voltage and timing.

Cycle-to-cycle current variation is less than 0.1 % by corresponding stabilization of the capacitor charging voltage. The voltage regulation is essentially a zero crossing discriminator which issues a stop pulse when the measured voltage is equal to a preset reference voltage. The latter may be programmed differently for the three shots inside one acceleration cycle. The stop pulse acts on the SCR switches and, for the

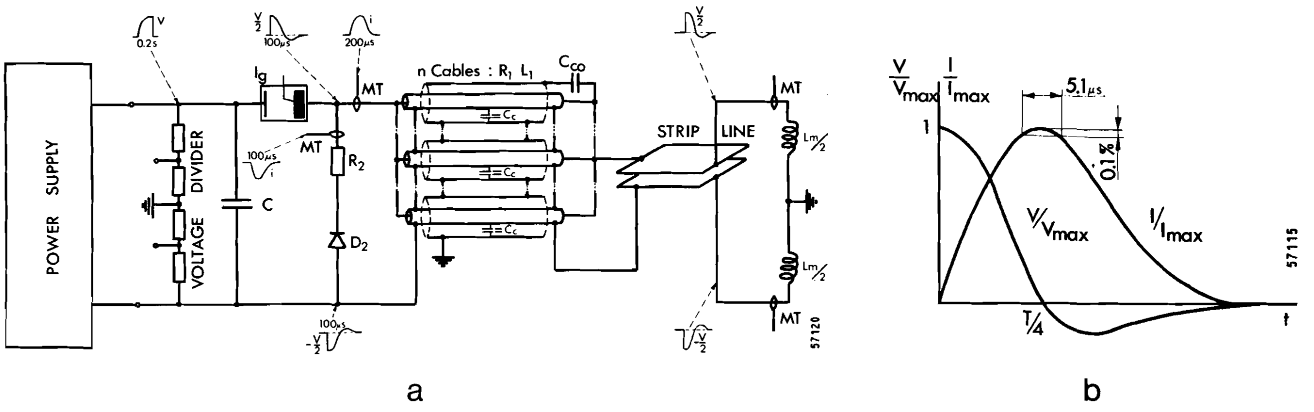


Fig. 3. a) Septum magnet circuit: C = Storage capacitor; Ig = Ignitron; L_m = Magnet inductance; C_c = Earth capacity of coaxial cables; R_1, L_1 = Resistance and inductance of the same; C_0 = Circuit balancing capacity; D_2 = Crowbar diode; R_2 = Crowbar damping resistor; MT = Current monitoring transformer;
b) Current and voltage pulses of septum magnet.

0.1 % reproducibility, simultaneously triggers a thyratron which instantaneously short-circuits the secondary, a diode preventing discharge of the capacitor.

Pulses are transmitted over about 200 m through a number of low impedance high voltage cables in parallel. For the last few meters in the radiation zone a strip transmission line is used, so that - in case of radiation damage - the insulating mylar sheets may be simply replaced. The capacity C_0 compensates the capacitive asymmetry introduced by the earth shield around the coaxial cables, thus suppressing parasitic oscillations.

Construction

The mechanical realization of the two magnets is similar (Figs. 4 and 5). A number of components such as feedthrough, water and current connections are identical, others are alike, but the dimensions of magnetic circuit and excitation loops are different (Fig. 6).

The magnetic circuits are stamped out of 0.5 mm thick silicon transformer laminations. They are bonded into blocks by means of epoxy resin, thus reducing the surface exposed to the vacuum and simplifying assembly.

The most delicate part of each magnet is the excitation loop, since the conductors undergo strong repelling forces due to their high currents. Each pulse excites damped mechanical oscillations with their proper frequencies, which may lead to fatigue rupture in particular if the loops are not rigidly fixed. Although heat production is only 10 J/shot and 60 J/shot for the mobile and stationary magnets respectively, the absence of good thermal contact with the surroundings necessitates forced cooling, hence a hollow conductor. The hole is round since the corners of the cushion-shaped "square" holes proved to initiate fatigue fissures. Oxygen-free copper is taken for the better fatigue characteristics, but some doubt as to its purity after brazing may be justified.

The excitation loop for the mobile magnet is manufactured in one piece from copper tubes of 3 x 3 mm^2 section and a 1 mm diameter hole. These are brazed together into a strip, which is then milled down to final dimensions^5. Due to its length of 3 m, the excitation loop of the stationary magnet is manufactured in three pieces: the septum and the two inner conductors. It is brazed together from copper tube of 5 x 5 mm^2 section and a 2 mm diameter hole. The extremities of all coils have brazed-on copper reinforcements, increasing the mechanical rigidity and diminishing the leakage fields at the end. Some construction details are shown in Figs 7 a,b,c.

A number of beryllium bronze springs press the inner conductor against the magnet yoke and the septum against stainless steel fixation plates, which are screwed to the magnet over its whole length. This guarantees constant pressure, even if the pressure points become slightly deformed. Between each two magnet blocks, there are five laminations of special profile, leaving space for the springs.

The magnetic circuit of each magnet is mounted on a steel profile beam, borne in the centre by a shaft coming through a hole in the wall of the vacuum chamber. This shaft contains the coaxial current feedthroughs and cooling water connections.

The supporting shaft of the mobile septum magnet (Fig. 4) is borne at the outside of the tank by a carriage sliding on four hydrostatic bearings. The magnet is brought to the chosen working position near the orbit by the hydraulic actuator acting on the carriage. The height

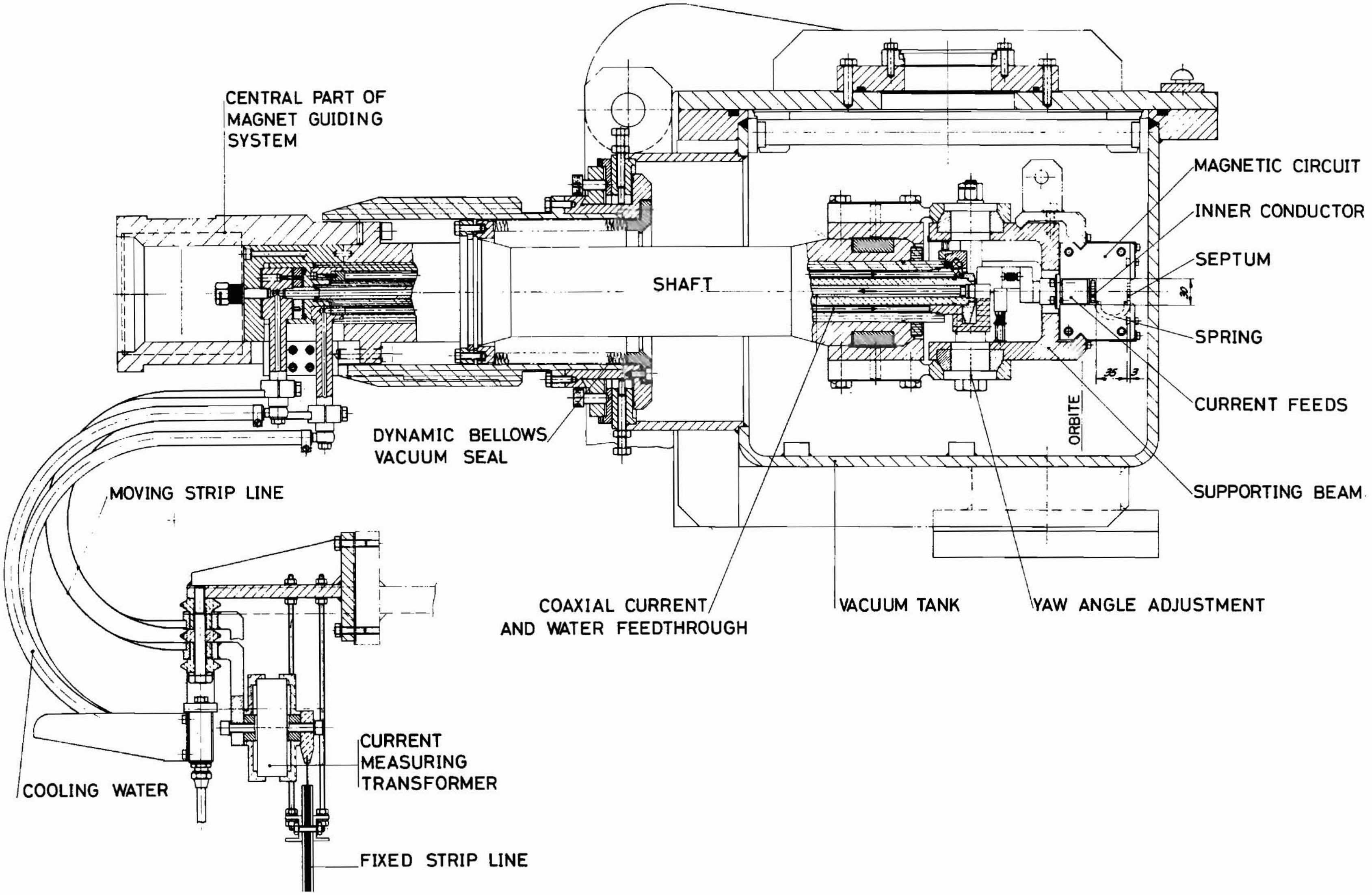


Fig. 4. Sectional drawing of the mobile septum magnet. Carriage and hydraulic actuator are not shown.

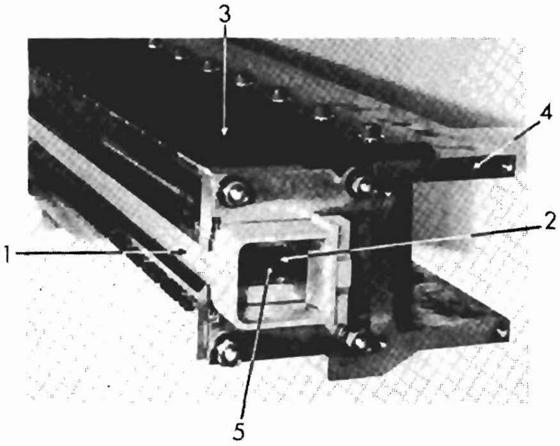
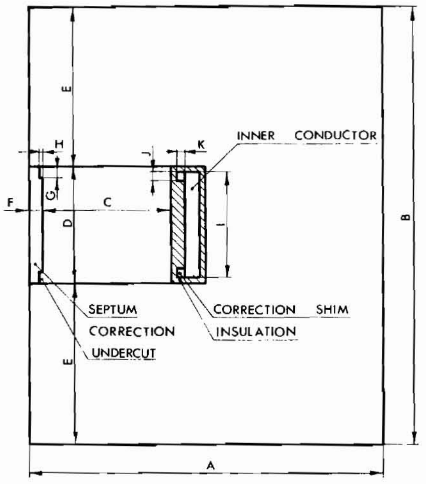


Fig. 5. Extremity of stationary septum magnet.
1 = Septum; 2 = Inner conductor;
3 = Magnetic circuit; 4 = Supporting profile beam; 5 = Beryllium bronze springs.



	SM24	SM26
A	81.0	135.0
B	112.0	150.0
C	35.0	60.0
D	30.0	30.0
E	41.0	60.0
F	3.0	5.0
G	0	3.0
H	0	0.25
I	26.0	26.0
J	2.0	2.0
K	0.8	0.9

Fig. 6. Main dimensions of magnetic circuit and current conductors.

position of the magnet is fixed by the actuator to the nominal height of the orbit. Pitch and yaw angles of the magnet are adjustable locally by spanner, after opening the vacuum tank.

The shaft of the stationary septum magnet is borne by a steel support fixed outside the tank to the tank supporting chassis. Radial and vertical positions and pitch and yaw angles are adjustable locally by spanner, after opening the vacuum tank.

Corrections and Performance

The region of 0.1 % field homogeneity in the mobile septum magnet must extend from the septum 20 mm into the gap. For the stationary septum magnet, this must be around 55 mm. These values allow a number of different trajectories and beam diameters up to 20 mm.

Since the mobile magnet is almost brought to contact with the beam, the specification of

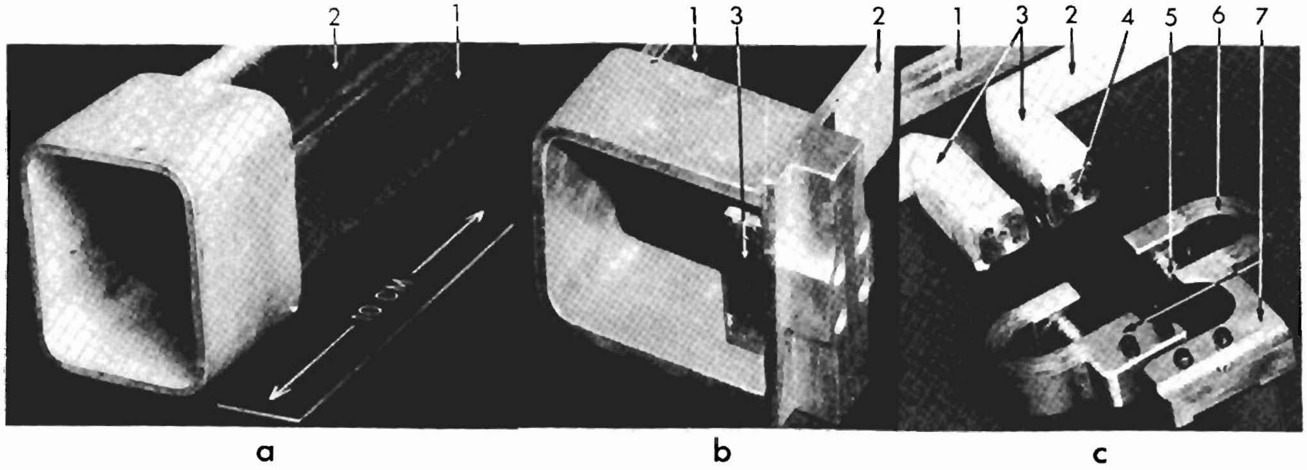


Fig. 7. Constructional details of current conductors:
a) Extremity of excitation loop for mobile septum magnet. 1 = Septum; 2 = Insulated inner conductor.
b) Extremity of excitation loop for stationary septum magnet. 1 = Septum; 2 = Insulated inner conductor; 3 = Joint between these two conductors.
c) Current feeds and connections at centre of magnet. 1 = Septum; 2 = Insulated inner conductor; 3 = Current feeds going through magnetic circuit; 4 = Cooling water channels; 5 = Stainless steel bellows for cooling water, permitting yaw angle adjustment; 6 = Flexible current conductors; 7 = Connection pieces screwed on coaxial feedthrough of shaft.

1 % leakage field holds for right in front of the septum. The field is decreasing with distance anyway.

These specifications should be fulfilled for the energy range of 30-85 GeV, i.e. for field levels between 0.3 and 0.7 T for the mobile magnet, and between 0.6 and 1.4 T for the stationary magnet.

A number of corrections had to be made to satisfy these requirements.

In order to have certainty on the 0.1 % homogeneity, variations of the order of 10^{-4} must be measured. Therefore a differential method, using a moving coil in opposition with a fixed reference coil was taken. The difference signal is integrated, sampled at the moment of maximum current, digitized and printed out. The two identical coils have 100 turns and a surface of 210 x 1 mm^2, and measure therefore the field integral over 210 mm along the magnet[3].

As already mentioned, three regions (Fig. 8) may be distinguished in the magnets: (i) the ends where the field is three-dimensional and the main non-linearities arise; (ii) the gap where the field is essentially two-dimensional and homogeneous to better than 1 %; (iii) the centre, where slight non-linearities are introduced by the current feeds and by their hole in the yoke.

The required homogeneity is achieved first by correcting each region separately, then by compensating remaining non-linearities of different regions with each other[3].

In the gap the field is corrected by shimming the conductors (Fig. 6). The two strips added on the inner conductor tend to decrease the field at that side. Similarly the two negative shims on the septum lift the field up there. The result is obvious from figure 9a.

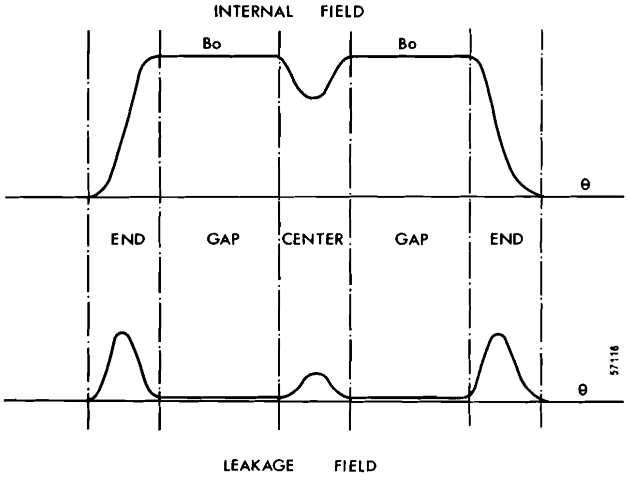


Fig. 8. Magnetic field (qualitative) along the centre line of the aperture and in front of the septum outside the aperture.

The centre region, although showing a field reduction, has no stronger non-linearities than the gap and is therefore corrected by the same shims going through (Fig. 9c).

At the end region, the non-linearities may be interpreted as radial variations of the equivalent magnetic length (Fig. 9b). They have been corrected by relevant radial variation of the physical ends. This is done by adding a number of special laminations that give the required end profile.

The total field inhomogeneities are shown in Fig. 9d.

The leakage field (Fig. 10) satisfied the specifications right from the start, so no intervention was necessary. Figure 8 shows that the main contribution to the leakage field comes from the ends.

Figure 11 shows the magnetization curve for the two magnets.

Life tests of several million pulses have proved the validity of the construction. During test sessions with the accelerator the achieved stability and field homogeneity proved adequate.

Acknowledgements

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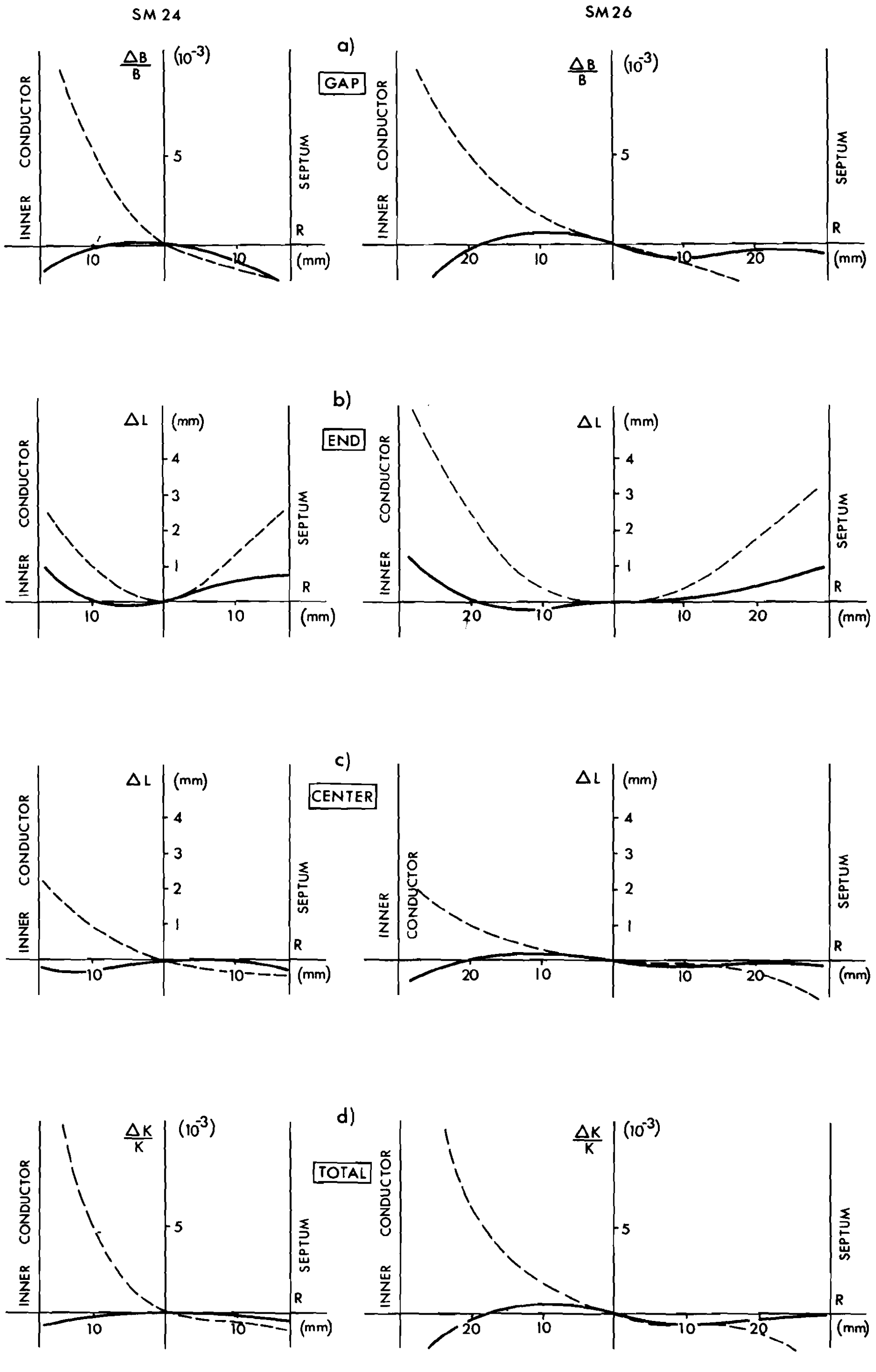

Fig. 9. Original non-linearities (dotted line) and field after correction (solid line). a) in gap; b) at magnet extremities; c) at centre; d) total. SM24 = Mobile magnet; SM26 = Stationary magnet. Field levels corresponding to 70 GeV extraction.

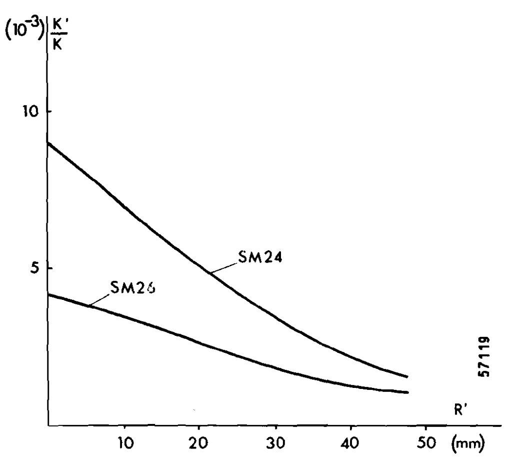

Fig. 10. Leakage field, in terms of field integral K_l on a line parallel to the septum, as a function of the distance to the latter. Represented as fraction of the main kick K. SM24 = Mobile magnet; SM26 = Stationary magnet.

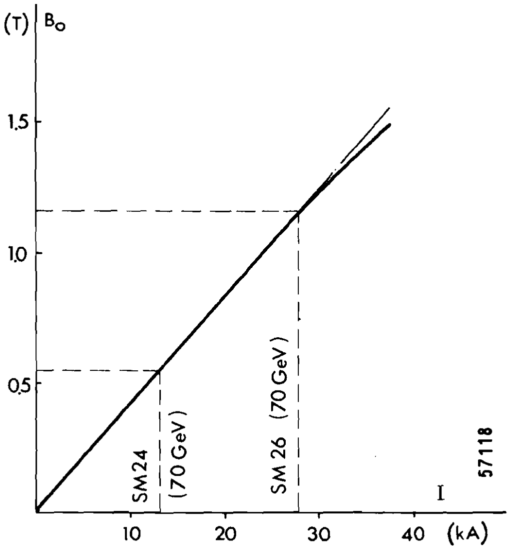

Fig. 11. Magnetization curve. SM24 = Mobile magnet; SM26 = Stationary magnet.