PERMANENT MAGNET QUADRUPOLE FOR THE 1-ST TANK OF LINAC-4*

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Abstract

A rare-earth (REPM) ∅60 mm diameter, 45 mm long quadrupole for the LINAC-4 focusing channel with an integrated gradient of 2.3 T is described. Thin side washers are used for tuning the quad into specified gradient integral with ±0.5 % accuracy. The single washer contribution calculations are discussed. A method for limiting to 30 μm the magnetic axis offset in the REPM quad is discussed to exclude its compensation by the outer diameter machining before inserting into the drift tube. Nonlinearity of the field is less than 1 % in the reference range of 75 % of beam aperture at the central cross-section near the quad axis. The angular quadrupole arrangement in the drift tube will be provided by machining the main groove on the quad surface in the median plane with 1 mrad accuracy. Calculations of the longitudinal gradient distribution between two neighbour quadrupoles showed that some percents should be added to the nominal gradient in the beginning of the LINAC-4 focusing channel because of partial field compensation.

INTRODUCTION

The 3.5 GeV, 4 MW Superconducting Proton Linac SPL has been proposed as a proton driver for a radioactive beam facility and for the high-intensity neutrino beams production at CERN [1]. The aim of the ISTC project #2888 is the design, production and tuning of full-scale Alvarez tank prototype with dummy drift tubes without focusing lenses. Only the first drift tube will be the final one and will be equipped with REPM lens. At the next stage quadrupole magnets will be installed into the drift tubes and high power beam tests will be carried out. In the case of successful results, developed design and production technology may be applied to other tanks of Alvarez DTL structure.

PROTOTYPE QUAD

The REPM quadrupole consists of two 45 mm long aluminum holders with PM rods in them seen in Fig. 1. One of the layers is put into the other with a slide fit. The inner holder of 22 mm aperture consists of 12 compiled rods; the outer holder consists of 18 compiled rods and has outer dimension ∅ 54.6 mm. Every compiled 45 mm long $SmCo_5$ rod consists of two 22.5 mm long rods. The outer holder is pressed into a ∅61 mm (∅60 mm in the final design) aluminium ring in order to provide the possibility of adjustment in the drift tube after machining with 1 mrad accuracy in azimuth direction. Initially we foresaw a magnetic axis offset compensation by machining the outer surface of the ring with corresponding displacement of its centre. However at the tuning stage we found a possibility to reduce the initial offset down to 50 μm in maximum and avoided the eccentric machining of the ring making it being coaxial respect to the quad holder with 20 μm accuracy.

Figure 1: CERN magnetic measurement bench with $SmCo_5$ quadrupole prototype.

Before mounting the lens of 550 g mass in the drift tube a special groove will be cut on the quadrupole surface. Lens calculation is done on the base of data received from the $SmCo_5$ experimental one-layer quad measurements when we identified the magnetic rods.

MAGNETIC MEASUREMENTS

The longitudinal field distribution along *z*-axis was measured by a Hall probe. The Hall probe is mounted on a long thin nonmagnetic holder. 2-coordinate positioning device provided the probe positioning in *x* and *z* with accuracy to better than 20 μm. The Hall probe moved in the median plane along two *z*-lines corresponding to $x_{1,2}$= ±1.5 mm with 2 mm step in *z*. Then the longitudinal field gradient distribution along *z*-axis is calculated. The effective field gradient of 51.5 T/m or 2.32 T integrated in *z* corresponds to the 0.84 T rod magnetisation measured previously. The contribution of the inner barrel was measured separately; it is 70 % of the total quad gradient as it was predicted by calculations.

The magnetic field in the central cross-section of the quadrupole along *x*-axis with 0.5 mm step was measured and approximated by linear function $B = G_0x$. The field deviation from the linear function defined the field non-linearity $\Delta B/B$; it was less than 1 % in 75 % region of the ∅20 mm beam aperture near axis.

The field is measured in numerous *z* =const planes by 2 mm step in four states, which correspond to maximum

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Hall probe signals that are attained when the probe is subsequently rotated by 90° and the normal vector to probe plane is directed at the corresponding lens pole. With the technique we evaluated the magnetic axis offset as a function of z. After tuning the offset was reduced to twice less than 100 μm required. Independent magnetic measurements performed on the CERN bench showed that the magnetic axis deviation from the geometrical one is less than 30 μm. It is not necessary to compensate such small offset in the drift tube.

MAGNETIC MEASUREMENT BENCH

The bench developed in CERN for testing and tuning the REPM quadrupole shown in Fig. 1 provides: electronic readout treatment, as well as 1 hour measurement cycle per a quad. It has movable multi-wire coil, which captures longitudinally the field distribution of the quadrupole. The coil is calibrated in a uniform field known with high accuracy. The field harmonic spectrum being the result of the measurements provides integrated characteristics of the field distribution.

A series of the harmonic spectrum corresponding to different angular orientations of the quadrupole as well as a special technique of the data treatment guarantee high reproducibility of the device for all harmonics numbers. In particular after eliminating the systematic errors in the amplitude of the first harmonic the magnetic axis offset of less than 30 μm was measured.

The gradient integral measured on the bench confirms the measurements by Hall probe previously done in ITEP.

All higher order field harmonics especially of 6-th order are within the specifications. Only the 14-th harmonic, the first in the spectrum, which cannot be principally compensated in the split-pole design with 12 magnetic elements, has rather high amplitude. Nevertheless it becomes dominant near the ∅23 mm magnetic aperture and is negligibly small inside our reference space of ∅15 mm.

In particular we intended to study how strong the magnetic spectrum suffers from the spatial field distortions at gradient integral correction by steel washers technique described below.

GRADIENT INTEGRAL CORRECTION

During quadrupole fabrication the gradient integral may vary because of mechanical errors and the spread of rods magnetization. To provide the gradient integral adjustment with ±0.5 % accuracy it was proposed to attach shim-washers to both sides of the quadrupole. The influence of a single steel shim on the field gradient and integral were investigated.

The simulations were made for the h=0.5÷3.0 mm thick single washer with 0.5 mm step attached to the quadrupole from the left side as shown in Fig. 2. The washers involved in the calculation were of ∅22 mm × ∅49 mm each. It is seen from the dependence that gradient integral is more sensitive for shims with thickness up to 1 mm.

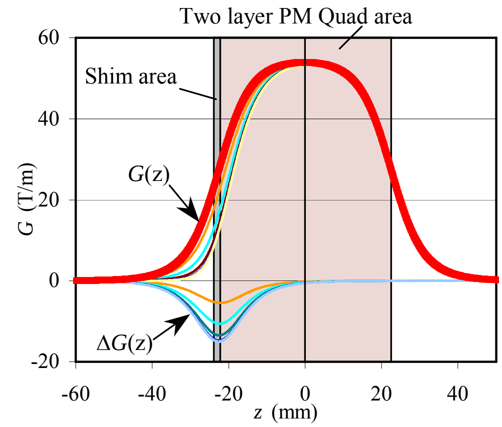

Figure 2: Field shimming with side washer.

To study the washer tuning efficiency, the washer influence on the axial gradient integral has been evaluated and showed in Fig. 3. Even single 0.5-1 mm thick washers provide smooth gradient integral adjustment up to 5 %.

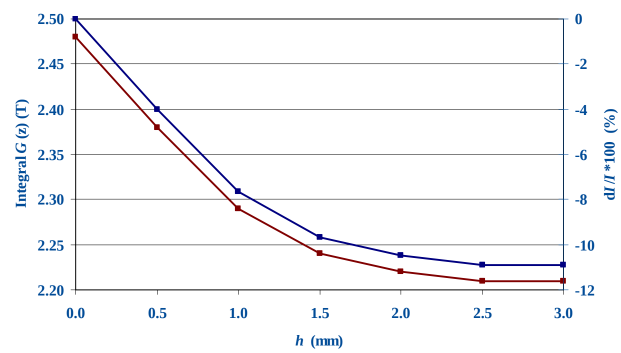

Figure 3: Gradient integral dependence on the shim thickness (lower curve) and loss in percent (upper).

The method of iterative increasing of the inner washer diameter as the variation parameter will be used in practice to tune the gradient integral with required accuracy to better than 1 %. For this we will use 1 mm thick washers at both sides of the quadrupole and because of more than 10 % range of possible adjustment the inside hole in the washers should be much increased reducing the perturbation of the longitudinal gradient distribution.

The focusing channel of the LINAC 4 will contain pairs of neighbouring quadrupoles with opposite polarity. In such configuration the field will partially compensate making the effective strength weaker. To estimate this effect we calculated the longitudinal gradient distribution between two neighbor quads when a space between quadrupoles changes in the 0÷50 mm range as shown in Fig. 4. The calculations were made on the base of measured $G(z)$.

One can see that at small spaces below 10 mm the integral losses can be very high while it is much less than 1 % when the space is of order of several aperture diameters.

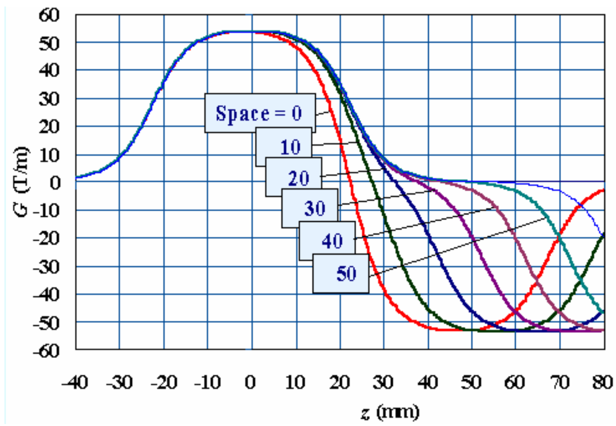

Figure 4: Gradient distribution between F-D quadrupoles.

On the base of the distributions we evaluated partial gradient integral moderation corresponding to one quadrupole in the focusing channel seen in Fig. 5.

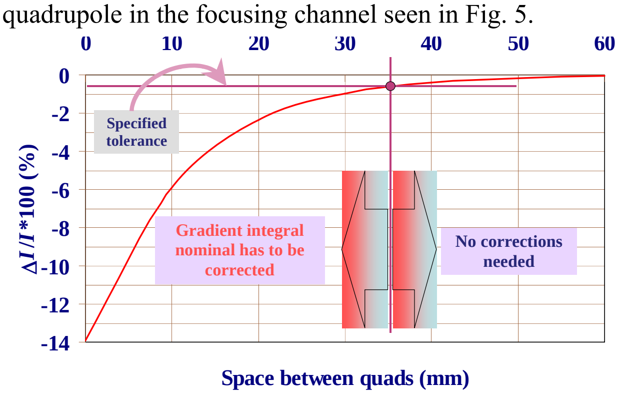

Figure 5: Gradient integral correction.

For space greater than 50 mm the loss of the integral is lower than tolerance (usually ±0.5 %) whereas near the 35 mm space the loss becomes greater than tolerance growing to 10 % and more. In LINAC 4 the minimal space between quadrupoles is near 20 mm so several quadrupoles in the very beginning of the focusing channel need up to 2.5 % correction of the gradient integral.

ON REPM QUADRUPOLE STABILITY

Since samarium-cobalt and neodymium-iron-boron alloys discovery the question of thermal and long-term stability as well as resistance to irradiations at operations in accelerators of REPMs experimented and discussed many times. The REPMs quality increasing attributed to improvement of the technology of their production requires renewing the data on stability.

For the first parameter it is always executed especially when the thermal properties of an alloy are the matter of study or improvement. Due to approximately stable temperature in the drift tubes within <1 K tolerable changes usually 0.5 % tolerance on the quadrupole strength deviation is satisfied even for Nd-Fe-B alloy with its 0.12 %/K remnant magnetisation coefficient.

The second factor requires long whiles for experiments. For its extrapolation to a term of 10-15 years of operation they use as a rule some known data available for REPMs with nearest compositions. In this case they rely upon the statement that aging is approximately the same for all quadrupoles in a focusing channel resulting slight deterioration of ions dynamics in an accelerator. Besides some special technique of artificial aging almost always permits substantial reducing the losses of the gradient during quadrupole operation. For example $SmCo_5$ dipole used in ITEP since 1987 for the Hall probe calibration is verifying every year with NMR magnetometer. The stability within 0.1 % error of measurement is the result of partial demagnetisation technique and natural aging during about 6 years since the magnetic elements production passed before dipole manufacturing.

The REPM multipole resistance under the radiation environment in accelerators has been studied since early 80-th. However it was experimented for REPMs developed to that time and for fast neutrons of reactor energy spectrum. In earlier investigations magnetisation loss in Sm-Co samples remained below 1 % until fluence $2.5\cdot10^{18}$ n/cm^2. It is essential that during the irradiations the samples were in the opened magnetic circuit. Later irradiations at the external magnetic field of 0.55 T showed several percent loss in remnant induction at $\sim10^{15}$ n/cm^2 fluence [3].

Nevertheless the radioactive resistance of some modern REPM alloys of Nd-Fe-B group developed in the last 15 years on extremely high coercivity and low thermal coefficient remains uncertain. Besides there is no experimental knowledge on the modern REPMs behaviour under neutron irradiations of an energy spectrum expected in an accelerator on up to 200 MeV. From the other hand the idea of substantial decreasing of the neutron fluxes irradiating the quadrupole in an accelerator with graphite insertions [4] remains to be attractive.

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