SIMPLE CHARACTERIZATION METHOD OF SMALL HIGH GRADIENT PERMANENT MAGNET QUADRUPOLES

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Abstract

The application of quadrupoles with high or ultra-high gradient and small apertures requires a precise control over harmonic components of the field. A simple, fast, low cost measurement method on small size PMQs (Permanent Magnet Quadrupoles) is described. It is based on the same principle of the familiar "rotating coil technique", but in this case, profiting of the small dimensions of the PMQ, it consists in rotating the PMQ itself instead of the coil. In such way a gain on accuracy and measure time is obtained. It has been applied to characterize a set of commercial PMQs with a gradient around 200 T/m and an internal radius of 3.5 mm to be mounted in a SCDTL (Side Coupled Drift Tube Linac) structure for the acceleration of a proton beam from 7 to 12 MeV. This structure has been developed in the framework of the Italian TOP-IMPLART (Intensity Modulated Proton Linear Accelerator for Radiotherapy) Project.

INTRODUCTION

Small aperture high gradient permanent magnet quadrupoles [1] are of particular interest for focusing particles in compact accelerator setup based on high frequency accelerators injected by conventional injectors or ion laser sources [2,3]. An example is given by the 3GHz SCDTL (Side Coupled Drift tube Linac) proton accelerating structure using for particle focusing small 3 cm long PMQs with a gradient around 200 T/m placed in the inter-tank space [4].

For these applications the control of the field quality is very important because the contribution of harmonic field components different from the quadrupole can distort the beam, producing an emittance increase or a reduction of the beam transmission in the accelerating structure. The dipole component is the most undesirable one, because the propagation of the proton beam in the small aperture SCDTL structure (4 mm diameter bore hole) requires a coincidence of ±50 μm of the magnetic and mechanical axis. To achieve this purpose the PMQ harmonic field center position has to be measured with high accuracy.

Common approaches use rotating coils [5] that give problems in the measurement within small apertures as require the fabrication of miniature coil and the suppression of vibrations during the measurement. The simple quick and low cost method described here consists in keeping fixed the coil and rotating around it the small PMQ under measurement mounted on a lathe. In such way the accuracy in the determination of the center of the harmonic field is few micrometers. The signal of the induced voltage on the coil is analyzed by Fast Fourier Transform (FFT) to obtain the field component amplitudes.

PMQS FOR A 3GHz SCDTL

SCDTL (Side Coupled Drift tube Linac) is a RF structure that has been invented to accelerate with high efficiency low energy (4-7 MeV) protons by using a high RF frequency (3 GHz).

It consists in short DTL tanks composed by few βλ long cells (4-7) coupled by a side coupling cavity. Due to the high operating frequency the structure dimensions are compact and the drift tubes are too small to allocate quadrupoles for particle focalization (as it is usually done in low frequency DTLs): so the beam focusing is done by an array of 3 cm long PMQs with an internal diameter of 7 mm placed in the inter-tank space arranged in a FODO lattice scheme.

A SCDTL module has been realized to accelerate protons from 7 to 12 MeV [6] in the framework of the TOP-IMPLART project [4] launched by ENEA in collaboration with the Italian National Institute of Health and Regina Elena National Cancer Institute-IFO-Rome aimed to realize a protontherapy plan based on a 150 MeV, 3GHz linear accelerator injected by a 7 MeV-425 MHz RFQ+DTL linac.

The high frequency linac consists in four SCDTL modules (up to 35 MeV) followed by a CCL (Coupled Cavity Linac) structure: the two types structure both operating at 3 GHz require small high gradient PMQs (55 up to 150 MeV) for the focusing.

For the first SCDTL module 11 Halbach-type [7] eight-segmented demountable PMQs have been built by BJA-Magnetics Company [8] using SmCo magnets according with ENEA design (Fig. 1).

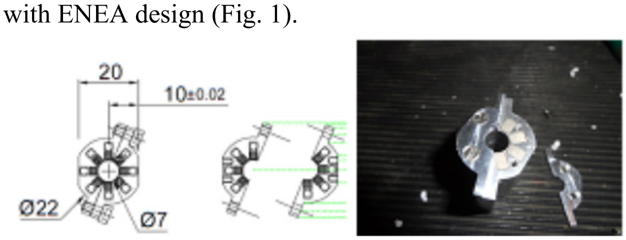

Figure 1: Demountable PMQ.

The possibility to demount each quadrupole in two parts simplify its mounting and alignment in the structure: the photo in Fig. 2 shows the PMQs mounted on the SCDTL in the inter-tank space.

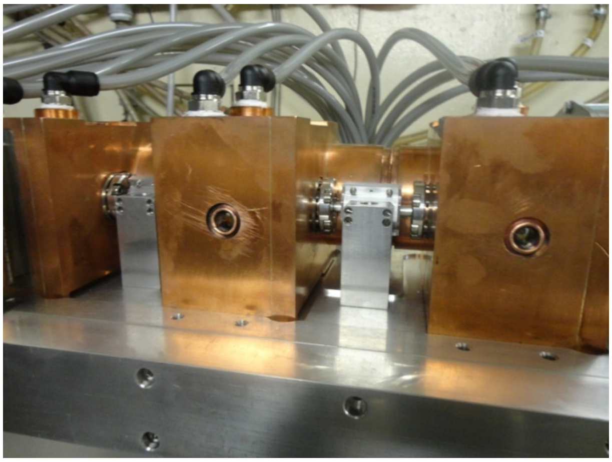

Figure 2: PMQs mounted on the SCDTL module.

If the magnetization directions of some pieces among the eight segments were considerably different from the designed direction, undesirable components would appear in the bore field and the accelerated beam would be badly affected by them. Accordingly we set a fast and precise method of measurement in order to check if the characteristics of the realized devices satisfy the required specifications.

MEASUREMENT OF THE HARMONIC FIELD IN THE PMQ APERTURE

Measurement System

The measurement system is shown in Fig. 3: the PMQ is placed on a lathe where is put in rotation and a 9- turns, 40 mm long and 1.4 mm wide coil is placed on the tool rest so to gave the possibility to be aligned very precisely in horizontal transverse dimension. A further micrometer adjustment in vertical dimension is added. Adjustment in coil rotation is also possible. The measurement procedure is as follows: the PMQ is rotated and the induced voltage on the coil is measured and recorded. The data are analyzed by FFT to obtain the harmonic field component amplitude. The light of a simple lamp is screened by a large black disk bolted to the rotating spindle. The disk has a small hole and a simple optical diode detector, positioned on the headstock, gives a synchronism spike signal.

Figure 3: Measurement setup.

Coil rotation error is nulled positioning the coil slightly inside the PMQ and apparently along the PMQ magnetic axis and inserting further on the coil and checking the constancy of the signal as coil moves longitudinally. If the quadrupolar component rises, this detects a coil rotation error. After this zeroing, coil magnetic center is found for a vanishing quadrupolar signal. Only a residual dipolar component can appear. A high sensitivity oscilloscope (1 mV/div) is used for this purpose. Figures 4 and 5 show the oscilloscope output for one measurement respectively at a distance of 1 mm from the quadrupole axis and on axis: the cyan trace is the voltage on the coil, the yellow one is the trigger signal and the red one is the FFT. The interval between two trigger spikes marks the beginning and the end of a PMQ revolution: at 1 mm this interval corresponds to two complete oscillations (typical of a quadrupole behaviour), while on the quadrupole axis it correspond to one complete oscillation corresponding to the residual dipole. This setup allows to evaluate the center of rotation with micrometer precision.

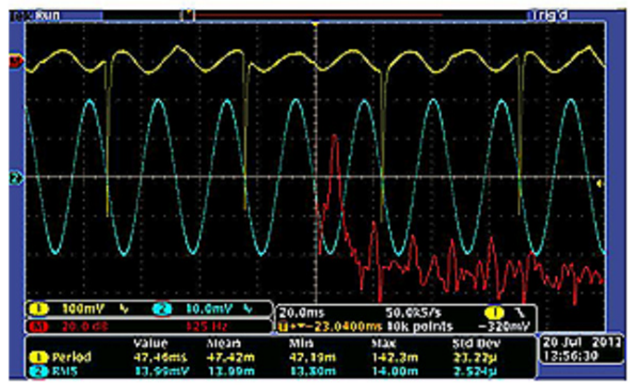

Figure 4: Measurement at R=1mm on PMQ #8 (oscilloscope screen).

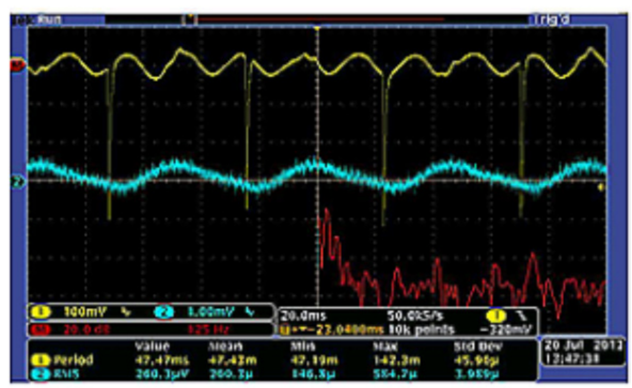

Figure 5: Measurement at R=0 on PMQ #8(oscilloscope screen).

Measurements Analysis and Results

The measurements have been analyzed by performing a Fourier analysis of the signal and retrieving the harmonic content from the following relation:

$$V = a_0 + \sum_{n=1}^{\infty} a_n \cos(nwt) + \sum_{n=1}^{\infty} b_n \sin(nwt) \quad (1)$$

n=1 (dipole), n=2 (quadrupole), n=3 (sextupole), n=4 (octupole).

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The value of the gradient is given by:

$$G = c_2 \cdot T / (N 4\pi L_{eff} d \cdot R_{rif}) \qquad (2)$$

with $c_2 = \sqrt{a_2^2 + b_2^2}$,T=period, Leff =3cm (effective length), N=9 (number of coil turns),d=1.4 mm (coil width).

The displacement between the magnetic and geometrical axis of the quadrupole is given by:

$$\delta r = 0.5 \cdot R_{rif} c_1 / c_2 \qquad (3)$$

with $c_1 = \sqrt{a_1^2 + b_1^2}$.

The main results of the measurements on the 11 PMQs are summarized in the plots of Figs 6, 7, 8.

Figure 6 reports the measured gradient values, that result to agree with the design value within 2%.

Figure 7 shows the amplitude of the harmonic components represented by the ratio against that of the quadrupole component, putting in evidence a negligible content of multipolar components.

Figure 8 shows the difference between the magnetic and mechanical center for each quadrupole: the values are all well below the specified tolerance of 50 µm.

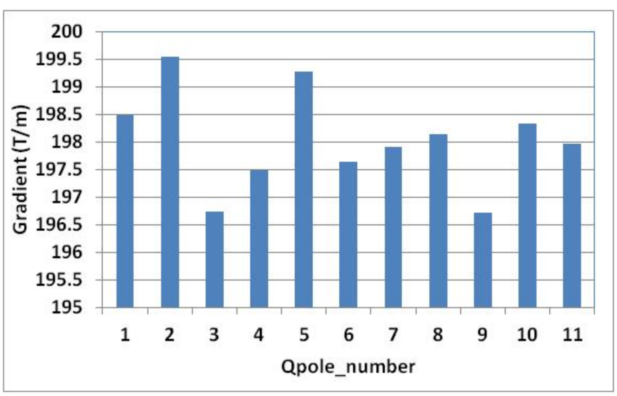

Figure 6: PMQs measured gradient values (Rrif=1 mm).

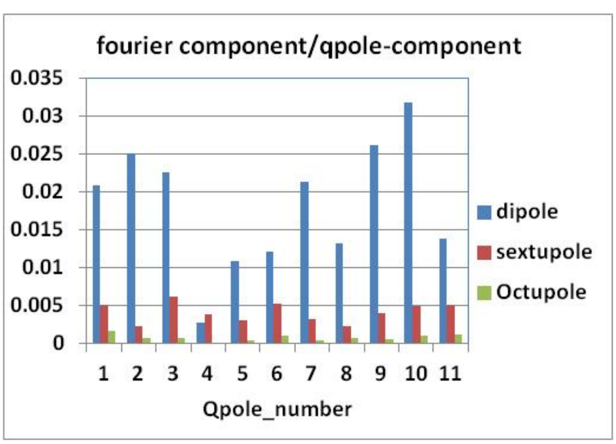

Figure 7: PMQs multipolar components (Rrif=1 mm).

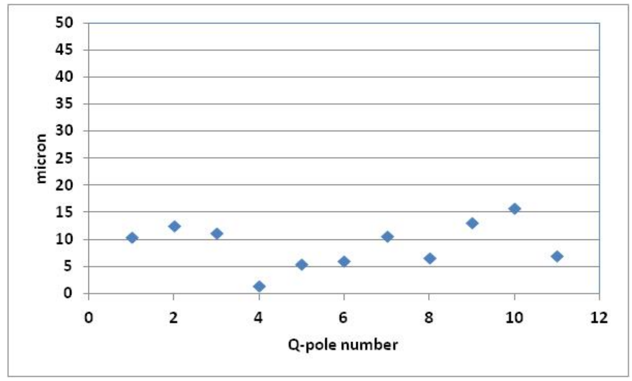

Figure 8: Measured PMQs difference between magnetic and mechanical axis (Rrif=1 mm).

The above plots refer to measurements done at Rrif=1 mm. In order to evaluate the precision of the retrieved value the measurements have been repeated at different Rrif: the results concerning G and δR are listed in table 1, showing that the measurements are very weakly affected by the position of the coil.

Table 1: Difference between Mechanical and Magnetic Axis Measured at Different Radius

Rrif(mm)	δR (µm)	G(T/m)
0.25	6.113	198.71
0.5	6.124	197.72
0.75	6.097	198.23
1.0	6.035	197.64
1.25	5.874	198.24

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