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CHMIL

ON MEASURING THE UNK SC-DIPOLE BENDING STRENGTH WITH ROTATING PICK-UP COIL

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Abstract

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The experience in measuring the SC-dipole bending strength with the spotting method shows this measurement to be the most complicated and expensive. A convenient and simple method of rotating pick-up coil, which can not provide the required accuracy, may be used for this measurement combined with NMR measurements in the dipole central part. The physical ground and description of the method are given in the paper. The analysis of the errors and measurement results of the series SPDM1 SC-dipoles are presented.

Abstract

Смирнов Н.Л., Тихов А.В. Измерение отклоняющей силы СП-диполей УНК методом вращающейся рамки: IHEP Preprint 93-2. – Protvino, 1993. – p. 19, figs. 7, tables 3, refs.: 9.

Опыт измерения отклоняющейся силы СП-диполей методом точечной магнитометрии показывает, что эти измерения являются наиболее сложными и дорогостоящими. Удобный и простой метод вращающейся рамки, не обладающий требуемой точностью, может быть применен для этих измерений в сочетании с измерениями ЯМР в центральной области диполя. В работе дается физическое обоснование и описание метода. Проводятся анализ погрешностей метода и результаты измерений моделей СП-диполей серии СПДМ1.

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Н.Л.Смирнов, А.В.Тихов
Измерение отклоняющей силы СП-диполей УНК методом вращающейся рамки .

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INTRODUCTION

The bending strength of the accelerator dipole is one of the important parameters which requires a very high accuracy of its measurement ($2 \cdot 10^{-4}$). A big number of SC-dipoles for UNK (2500 dipoles) demand that the method of the bending strength measurement should be simple and reliable as well as highy efficient and accurate.

The experience in using the spotting methods (NMR and Hall-gauges) for the bending strength measurements shows that these measurements do provide the required accuracy, however they are most complicated and expensive out of all magnetic measurements carried out for SC-dipoles [1,2].

The rotating pick-up coil method does not provide the desired accuracy due to the reasons described below and therefore can not be used in a pure case. The reference method, which assumes the presence of the reference dipole allows us to reduce the requirements for the measuring equipment. However, this method can not be used for SC-dipoles due to many reasons.

The proposed method is some combination of the rotating pick-up coil method and NMR method. The bending strength here is measured with the rotating coil, and NMR gauge is used for absolute calibration of the measuring frame and electronics. This calibration is performed by the central field measurement of the tested magnet, and the reference magnet, therefore, is not needed.

The SC-dipole bore has such peculiarities as high humidity, significant gradient and deviation of the temperature etc. To provide the measuring equipment stability under such conditions is a very serious problem. The proposed method can cancel all these obstacles.

The description and physical grounds of this method are presented in this paper. The analysis of the errors and ways of taking into account all factors

influence upon the errors are given. The results of the series SPDM-1 SC-dipole measurements are presented.

1. DEFINITION OF THE DIPOLE BENDING STRENGTH

In order to define the dipole bending strength it is necessary to consider its function in the accelerator. This function consists in deflecting the accelerated protons in the orbit plane. The direction of the bending force is normal to the particle velocity vector coinciding with the dipole longitudinal axis and averaged over the dipole length field vector. The plane normal to the average field vector is called a median plane. Different methods of the magnetic field measurement allow us to get either the module of the field vector, or the field projection on the measurement system plane. Therefore the measured dipole angular position should coincide with the measurement system [5].

Let us consider the Cartesian coordinate system where z axis coincides with the longitudinal dipole axis, X and Y axes have been chosen so that the following condition is realized:

$$\int_{L_m} sin\alpha(z)dz = 0, \tag{1}$$

where $\alpha(z)$ is the angle between the field vector $\vec{B}(z)$ and Y axis, L_m is the magnet length. Equation (1) determines the median plane, i.e. the plane w.r.t. which it should measure the dipole bending strength. In this coordinate system the dipole strength may be defined as:

$$F = \int_{L_m} |\vec{B}(z)| cos\alpha(z)dZ, \qquad [T\ell \cdot m]. \tag{2}$$

The parameter F is called the longitudinal field integral. For the definition of the dipole strength the longitudinal integral normalized by the current is used. $F_n = \frac{F}{I}\ [\frac{T\ell \cdot m}{kA}]$, where I is excitation current during measurements.

We have greatly benefitted from the discussion with K.F.Gertsev and would like to thank our colleagues A.V.Kutigin, U.A.Luzhin, N.V.Krotov and N.N.Latalin for their help with measurements.

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Note that some magnets of this series have a transfer function which significantly differs from the average one over the whole series. The analysis of the harmonics in the central part of these dipoles shows its abnormal magnitudes as well of the allowed normal harmonics B3 and B5. The increase of C_m corresponds to the increase of B3 and decrease of B5. As it follows from the Table of the derivatives of harmonics by the coil sizes [7], this distortion of the coil is corresponding to the elliptical form of the coil distortion. Since a lot of other parameters influence the harmonics magnitude we can say only about the qualitative dependence shown in Table 3, where $\Delta B3$ and $\Delta B5$ are the calculated changes of the harmonics determined by the coil geometry distortion. These changes were calculated from the value of the difference between the average over the series transfer function and the measured one - ΔC_m, assuming that the dipole coil has pure elliptical distortion. B3 and B5 are the measured harmonics. The last column presents the average over the series magnitudes of C_m, B3 and C5 [8].

Table 3.

Dipole Parameter	SPDM1-14	SPDM1-17	SPDM1-18	SPDM1-20	SPDM1-22 series	Average
$\Delta C_m[\frac{T}{kA}]\times$ $\times 10^4$	+3.6	-1.9	-3.4	+3.4	-1.4 I=2 kA	0.9880
$\Delta C3 \cdot 10^4$	+3.4	-0.6	-2.4	+3.2	-0.2	-
$C3 \cdot 10^4$	+1.9	2.6	-3.8	+3.2	-2.3	-0.7
$\Delta C5 \cdot 10^4$	-3.6	+0.6	+2.4	-3 4	0.2	-
$C5 \cdot 10^4$	-4.3	0	4.5	-2.1	-00.2	0.8

It should be noted that the deviation of the parameters shown in Table 2 includes the measurement error as well as the dispersion of these parameters itself in the series. The reproducilibity of measurement was researched with a few dipoles of this series. The carried out research allows one to make the following condusions:

– the suggested method provides the required accuracy of the bending strength measurement in the full field range. The error in the point of attachment to NMR - measurement does not exceed 10^{-4};

– mostly the error is determined by the pick up coil edges misalighment.

The efforts for this method improvement are continuing. In the present time this method is being appleid to the conventional dipoles bending strength measurement. The results of the research and measurement will be published.

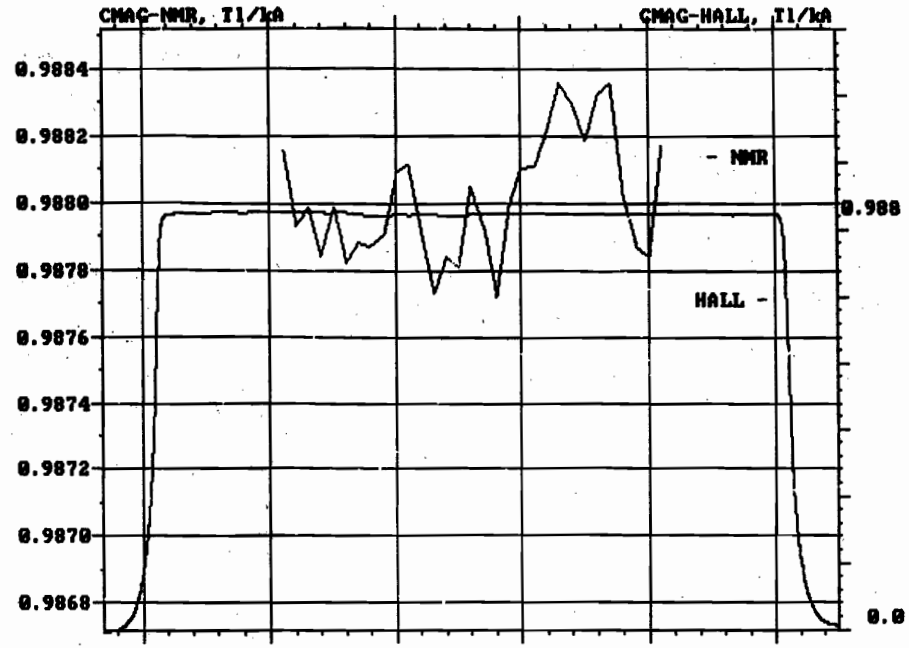

Fig. 1. The longitudinal distribution of the main field for SC-dipoles.

The second form of the bending strength expression is the effective length (or magnetic length):

$$L_{eff} = \frac{F}{\bar{B}_{cent}}, \qquad [m] \tag{3}$$

where $\bar{B}_{cent}$ is the dipole field averaged over central region . It should be noted that the longitudinal distribution of the main field even in the dipole center has significant amplitude of its deviation. Fig.1 shows the typical longitudinal distribution of the SC-dipole field. The field deviation at the flattop can achieve $2 \cdot 10^{-3}$. Therefore $\bar{C}_{cent}$ is determined as:

$$\bar{B}_{cent} = \frac{1}{L_{cent}} \int L_{cent} B(r) dr, \qquad [T\ell] \tag{4}$$

where L_{cent} is the dipole area without edge field (in fact $3 \div 4$ bore diameter inside the magnet end).

The dipole transfer function is an important parameter influencing the bending strength. It is defined as the ratio of the main field to the energization current:

$$C_m(I) = \frac{B(I)}{I}. \qquad [\frac{T\ell}{kA}]. \tag{5}$$

All enumerated parameters describe and characterize the dipole bending strength.

For beam dynamic calculations it's more convenient to use the field integral. The deflecting impulse magnitude might be calculated from the field integral very easily. This parameter is critical to any features of the magnet design and magnetic properties of the materials. Actually, as it follows from definition (2), the local or average dipole field change will affect the longitudinal integral field magnitude. The reason for this change may be the deviation of the coil geometrical sizes, magnetic properties of the yoke or collar, coil or yoke length. Moreover, since this parameter is proportional to the field, the function $F_n(I)$ depends on the yoke, collar and superconductor magnetization.

The magnetic length, as it follows from its definition (3), is not so sensitive to the main field deviation but allows one to control the coil and yoke length changing because of electromagnetic force in the coil, thermo-exspantion or some imperfections in production tools. The excitation current influence on the magnetic length due to different saturation in the central and fringe parts of the dipole is much smaller than this influence on the field integral.

The transfer function, though it is a supplementary parameter, allows one to control important field properties as the saturation at high fields, where B and I lose their proportionality, stability of the coil sizes below iron saturation, nonlinear behaviour of transfer function due to the remnant field at low fields.

The diversification in analysis of all these parameters allows one to characterize the bending strength more completely and reliablely reveal the reason of the SC-dipole bending strength failures as well.

2. THE DESCRIPTION OF THE METHOD

The essence of the method is to measure the longitudinal field integral with the rotating pick-up coil and then to calibrate all measurement equipment. This calibration is realized in the central part of the dipole by NMR – measurements. Figure 2 presents the structural scheme employed for bending strength measurement equipment. This measurement has two steps:

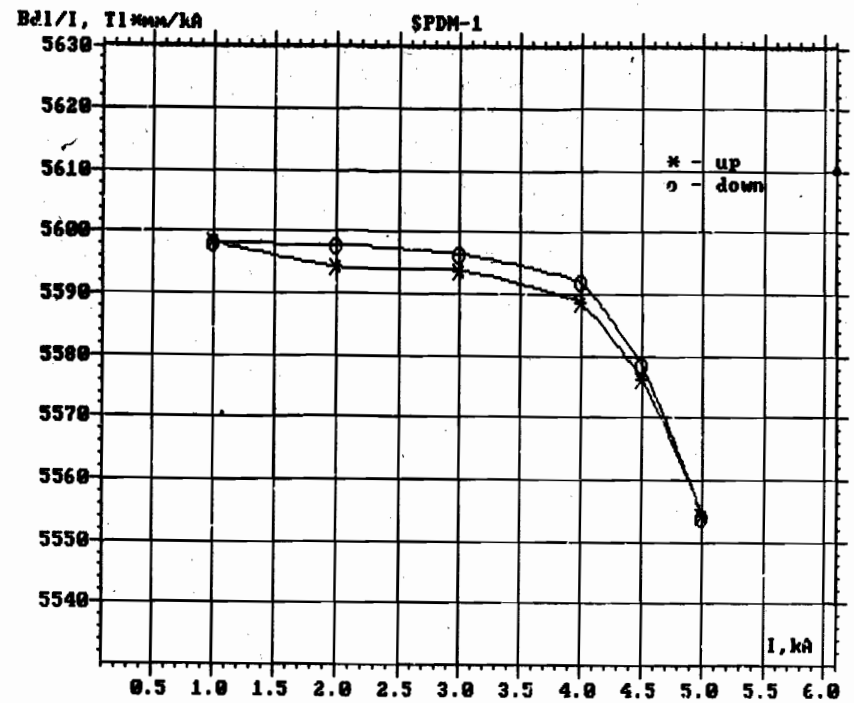

Fig. 7.

Table 2.

Parameter Dipole	L_{eff}, [mm] (2 kA)	δL_{eff} (3 ÷ 5 kA)	F_m $[\frac{Tl\cdot mm}{kA}]$ (2 kA)	C_m $[Tl/kA]$ (2 kA)
SPDM1-12	5664.7	$-8.6 \cdot 10^{-4}$	5596.3	0.98793
SPDM1-13	5663.2	$-7.6 \cdot 10^{-4}$	5595.1	0.987975
SPDM1-14	5670.0	$-8.1 \cdot 10^{-4}$	5604.02	00.988363
SPDM1-15	5665.7	$-7.8 \cdot 10^{-4}$	5597.3	0.987931
SPDM1-17	5666.1	$-7.6 \cdot 10^{-4}$	5596.6	0.98781
SPDM1-18	5663.4	$-7.1 \cdot 10^{-4}$	5594.9	0.98764
SPDM1-19	5661.0	$-7.4 \cdot 10^{-4}$	5592.9	0.98795
SPDM1-20	5664.8	$-8.8 \cdot 10^{-4}$	5598.7	0.988335
SPDM1-21	5668.2	$-8.3 \cdot 10^{-4}$	5602.5	0.988422
SPDM1-22	5663.5	$-8.0 \cdot 10^{-4}$	5594.8	0.987861
SPDM1-23	5664.1	$-8.7 \cdot 10^{-4}$	5595.4	0.987867
SPDM1-24	5662.8	$-8.4 \cdot 10^{-4}$	5595.0	0.988044
SPDM1-25	5662.7	$-8.2 \cdot 10^{-4}$ 5594.9	0.988014	
Average	5664.45	$8 \cdot 10^{-4}$	5596.6	0.987998
σ_n	$4 \cdot 10^{-4}$	0.4 10^{-4}	$6 \cdot 10^{-4}$ $2.3 \cdot 10^{-4}$	

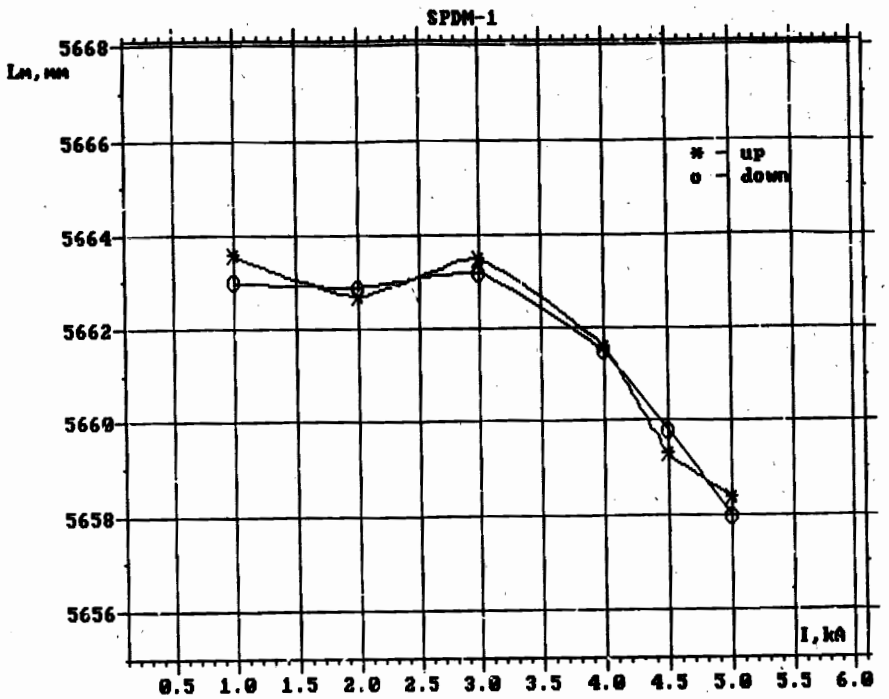

Fig. 6.

Fig.7 presents the typical plot of the normalized field integral $F_n(I)$. The form of $F_n(I)$ curve is almost the same as $C_m(I)$ one. It displays that the field integral is determined mostly by the central field.

The total results of the bending strength measurements for some SPDM-1 series dipole are summerized in Table 2.

Here is a brief analysis of these results. First of all it should be noted, that the relative magnitudes of these parameters changes are in a good agreement with formula (3) in the exciting current range from 3 kA to 5 kA:

$$\delta F_n = \delta L_{eff} + \delta C_m \tag{24}$$

where $\delta L_{eff} \simeq 0.08\%$ as it follows from Table 2, and $\delta F \simeq 0.8\%$, $\delta C_m \simeq 0.7\%$ are not presented in Table 2.

– central part measurement using the NMR-gauge;

– field integral measurement with the rotating pick-up coil (the whole set of facilities is presented on the scheme).

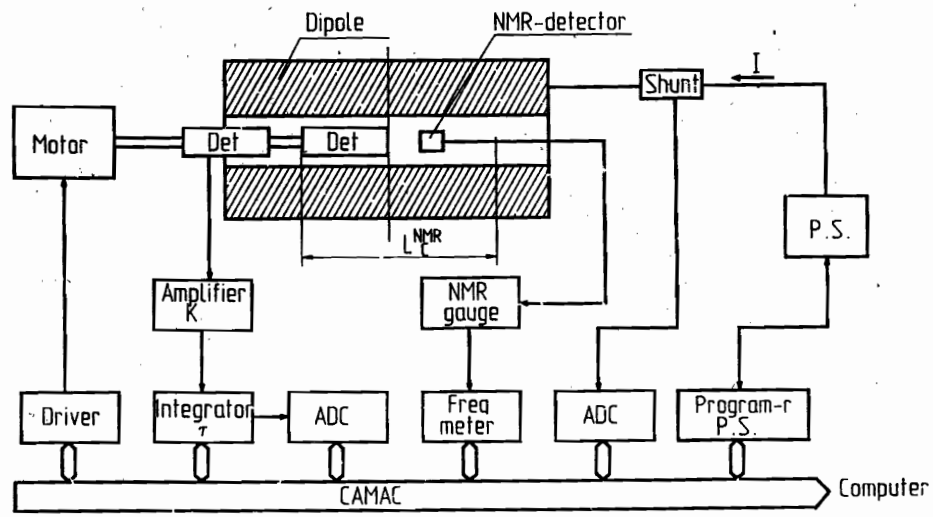

Fig. 2. The structural scheme of the equipment used for SC-dipole bending strength measurement.

Let's consider in detail every step.

Central field measurement.

The nuclear magnetic resonance - detector is put in the center of the SC - dipole with the help of an extending shaft. The magnet is excited with 2 kA current. Under this current NMR-gauge scans 3 m central part of the dipole (±1.5 m from longitudinal centre) with 100 mm step. The signal from the NMR - gauge through the frequency meter goes to the computer. The excitation current is measured at the same rate. The length of the scanning step was chosen from the longitudinal field distribution [1].

As it is known, the NMR-gauge does not sense the field direction within a rather wide angular region, i.e. these measurements give us the module of the field vector [2,6]. If the data are sufficient (scanning step length), the average value of the measured field can be represented as:

[1] "The UNK dipoles bending strength measurement by using of spotting method" – to be published.

$$\bar{B}_{NMR} = \frac{1}{L_{cent}^{NMR}} \int_{L_{cent}^{NMR}} |\vec{B}_{NMR}(z)| dz, \qquad (6)$$

where L_{cent}^{NMR}=3 m is measured by the NMR-gauge central part length.

Rotating pick-up coil measurement.

This method was described in detail earlier [4,5]. Here we'll point out only the features of the method important for the main field measurement.

Mechanically the measuring frame is inserted into the detector provided with all devices needed for installation, rotation and electrical connection. At present one employs a system of two mutually calibrated detectors with a 1.5 m long measuring frame and a set of extending shafts. Placing this system in two longitudinal positions one gets the transfer function in four sections of the SC-dipole. Further it is planned to use one detector with a 2.2 m long frame sequentially installed in three positions.

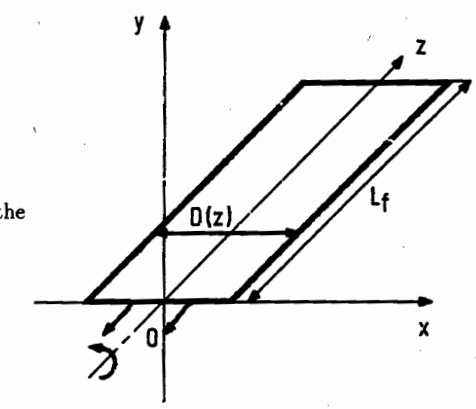

Fig. 3. The ideal measurement frame in the dipole coordinate system.

Figure 3 presents the cross-section of an ideal radial measuring frame in the coordinate system, whose Y-axis coincides with the field vector and Z-axis with the dipole longitudinal axis. Let's suppose, for simplicity, that the measured dipole is ideal, i.e. it has neither longitudinal field component nor nonlinearities or lengthwise twist. The ideal dipole field flux through the frame may be presented as:

$$\Phi = WDcos\theta \int_{L_{fr}} B(z) dz, \qquad (7)$$

where L_{fr} is the frame length, D is the width, W is the number of the frame winding turns, $B(z)$ is the longitudinal distribution of the field, θ is the angle between the frame surface and the XZ plane .

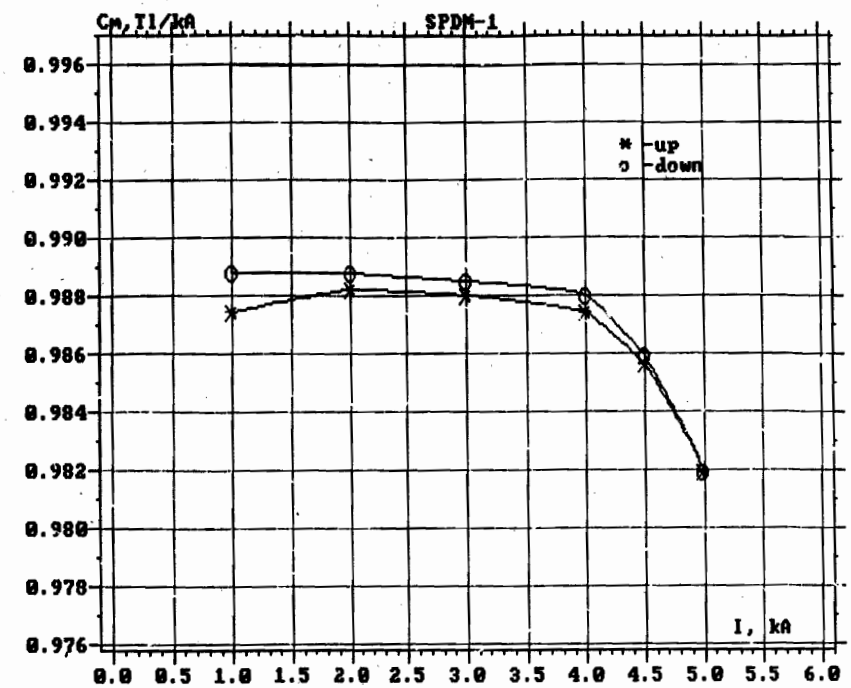

Fig. 5.

On fig.6 we show the dependence $L_{eff}(I)$. Let's point out, that the slope of this parameter is $\sim 8 \cdot 10^{-4}$ in the region of high fields. There are two main factors influencing the behaviour of the L_{eff} curve in the following way.

The magnetic forces in the edge of the dipole coil try to remove the current carrying conductor out of the field. These forces tend to stretch the coil. The calculations [9] show that these forces can reach a few tons at high fields. Obviously these forces tend to increase L_{eff}.

On the other hand, the fact that the edge field slightly exceeds the central field due to the edge effect, leads to more "rapid" saturation of the magnet yoke in the edge region at high field. This phenomenon is similar to some decrease of the yoke length and definitely leads to a decrease of L_{eff} at high field.

As it follows from the presented curve, second factor is excelled at first one. The slope due to the saturation of $L_{eff}(I)$ curve begins earlier than $C_m(I)$ curve, that confirms the correctness of our approach.

Table 1. The table of tolerances for parameters, which influence the measurement errors of dipole bending strength.

Parameter		Tolerance	Conditions of determining the tolerance
Symbol	Explanation		
$\Delta\alpha$	Amplitude of dipole longitudinal linear twist	$< 3.5 \cdot 10^{-2}$ rad	Over the length of the mea- frame L_{fr}=1.5 m suring
$\Delta\theta$	Stability of the amplitude of measurement frame longitudinal linear twist	$< 3.5 \cdot 10^{-2}$ rad	The measurement central region on the frame length L_{fr}=1.5 m
$\Delta\theta_o$	The amplitude of of measuring frame longitudinal linear twist	$< 7 \cdot 10^{-2}$ rad	L_o – frame length outside magnet $L_o = 0.3\ L_{fr}$
δD_c	The amplitude of relative linear longitudinal non-uniformity of the frame width	«30%	Central region. Longitudinal non-uniformity $\delta B \sim 2 \cdot 10^{-3}$
δD_e	$< 2 \cdot 10^{-3}$	End region $L_o \simeq 0.3\ L_{fr}$	
ΔL	The errors of a coincidence of frame ends	1.2 mm	$\delta F < 2 \cdot 10^{-4}$ $L_m \simeq 6$ m
$\frac{\Delta U \cdot t_{int}}{W}$	ΔU-amplitude of drift voltage displacement (Fig.4), $T_{int.}$ – integration time, W – number of turns	$< 0.13 \cdot 10^4$ $[B \cdot sec]$	B_{inj}=0.7 Tl D=16 mm L_{fr}=1.5 m
δI	Current stability during measurement	$< 6 \cdot 10^{-4}$	$\Delta I cos(2\theta + \pi)$

4. MEASUREMENT RESULTS

This section presents the measurement results for the bending strength of some dipoles of series SPDM-1, qualitative analysis of there results and enumerates the main problems of this method. Fig.5 shows the typical transfer function of a SC-dipole of this series. The transfer functions measured with NMR and with a rotating coil have different absolute values due to longitudinal non-uniformity and the fact that NMR measures the field in one point when the coil measures average over the coil length field (Fig.1), however the form of its dependence remains the same. The transfer function hysteresis is explained by the superconductor and magnet yoke magnetization. The slope at high field (starting from 3.5 kA) is due to the yoke saturation.

During the frame rotation around Z – axis E.M.F. will be induced on the frame:

$$U_{fr} = -\frac{\partial\phi}{\partial t} = WDsin\theta\frac{\partial theta}{\partial t}\int_{L_{fr}} B(z)dz, \tag{8}$$

where $\frac{\partial\theta}{\partial t}$ is the angular speed of rotation. After amplification with coefficient k and integration with time constant τ of this E.M.F. we'll get the integrator output voltage as:

$$U^s_{out}(\theta) = \frac{wkD}{\tau}(cos\theta - 1)\int_{L_{fr}} B(z)dz. \tag{9}$$

From the measured amplitude of the voltage peak of the output integrator U^s_{max} one can calculate the field integral on the frame length:

$$\int_{L_{fr}} B(z)dz = U^s_{max}\frac{wkD}{2\tau}. \tag{10}$$

Changing the position of the frame along the dipole length so that the ends of the frame would mutually coincide one will get the longitudinal field integral. The required accuracy can't be achieved due to a number of reasons. These reasons are:

– errors of the frame geometric sizes (D, L_{fr});
– errors of the measuring electronics (τ, k).

The measurement experience shows that the rotating pick-up coil method in a pure case (without NMR-method support) provides the accuracy not better than $\sim 10^{-3}$. However this error can be taken into account using precisely known coefficient $\frac{wkD}{2\tau}$ obtained from the results of the central field measurement with the NMR-gauge (6). The essence of the suggested method is to measure the longitudinal field integral with a simple rotating coil method and simultaneously to calibrate the used equipment from NMR-gauge measurement results. Note, that the field integral is measured with the rotating coil at 11 excitation current levels (0.7; 1; 2; 3; 4; 5 kA rise and 4; 3; 2; 1; 0.7 down). Thus we've got the whole function of the field integral vs current. As it has been said above the results were brought in accordance with the NMR-measurements only at one current level 2 kA. However, since the measurements are performed at the same values of k and τ one level is enough for the influence of an electronics channel nonlinearity is negligible.

Note that the longitudinal integrals defined by expressions (6) and (10) are not identical. Actually formula (10) does not represent potential longitudinal twist of a magnet or detector. These twists can lead to an error that can

hardly be taken into account without a reference magnet. This applies to the longitudinal inhomogeneity of the frame width, as well. Imperfect coincidence of the frame edges also gives the bending strength error. All enumerated errors are systematic.

Moreover, there are random errors like:

- energization current measurement error;
- instability of electronics (k, τ);
- instability of the geometric sizes of the frame.

Two last points need some explanation. The thing is that the calibration is carried out only at the central part of the measured dipole. The fringe field measurement is delayed w.r.t. the central one, that might be a reason of the mentioned parameters deviation.

Note, the geometric deviation of the frame sizes vs temperature may be taken into account via temperature measurement and calculation of the true frame sizes from the coefficient of linear thermal expansion of the detector material or from calibration curve. The temperature measurement may be easily carried out by measuring the coil resistance if we know the TCR of the coil winding material. Thus, measuring the average dipole field with the NMR-gauge and after measuring the same one with a rotating pick-up coil at several values of the frame temperature, we can plot the calibration curve, with which one can calculate the correction factor, that takes into account the frame size changes caused by temperature variations.

3. ERRORS

To make the analysis of errors simpler let's consider each parameter separately, assuming all other ideal.

3.1. Longitudinal twist

First let's consider the case of the magnet longitudinal twist and ideal measurement frame. In this case the average field measured with the frame can be represented as:

$$\bar{B}_{fr} = \frac{1}{L_{fr}} \int_{L_{fr}} |\vec{B}(z)| cos\alpha(z) dz, \tag{11}$$

where $\alpha(z)$ – the angle between the magnetic field induction vector $\vec{B}(r)$ and normal to the median plane.

The systematic error between NMR - measurements and rotating pick-up coil measurements appear during the calibration. This error is the result of

measured, and hence the dependence $U^s_{out}(\vartheta)$ is known as well as dependence $I(\vartheta)$.

In fact the same deviation of the current from the average level will give different contributions to the measured integral depending on the angular position of the measuring coil.

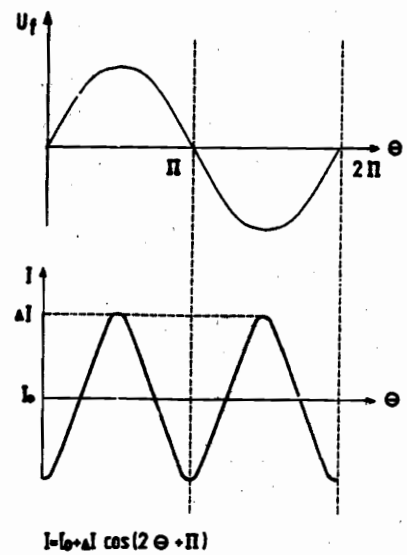

Fig. 4. The influence of the excitation current pulsing on the bending strength measurement accuracy.

Fig.4 shows the time dependences of voltage on the frame U_{fr} and the worst case of the dependence $I(\vartheta)$. Let's point out, that in this case the voltage on the frame will have the form:

$$U_{fr} = U_{fr} D \cdot C_m [I_o sin\theta + \Delta I sin\theta cos(2\theta + \pi)] \frac{\delta\theta}{\delta t}, \tag{23}$$

where ΔI is the amplitude of the current deviation. One can get the tolerance for the current deviation via integrating this expression (23),therefore for the worst case this tolerance is $\frac{\Delta I}{I_o} < 6 \cdot 10^{-4}$. Since this tolerance is softer than full tolerance and, moreover, the form of $I(\theta)$ dependence is random with respect to $\Phi(\theta)$ dependence, actually for calculation one can use the mean value of the current during measurement (period of revolution).

tolerance will be satisfied under the following condition:

$$\frac{1}{2}\Delta U t_{int} < 2 \cdot 10^{-4} \cdot 2DW \int_{L_{fr}} B(z)dz, \tag{21}$$

where t_{int} is integration time, W is the number of the coil turns in the measurement frame. For the least field (injection level) B_{inj}=0.7 T and for typical parameters of the measuring frame D=16 mm; L_{fr}=1.5 m we get the tolerance:

$$\frac{\Delta U t_{int}}{W} < 0.13 \cdot 10^{-4} \text{ B} \cdot \text{sec} . \tag{22}$$

Expression (22) determines the relation between the admissible amplifier noise ΔU and integration time, or in other words – between the rotation velocity and the number of the measuring coil turns. For typical time of the frame revolution ~20 sec and for ordinary operational amplifiers with typical noise ~ 5μv the tolerance may be satisfied when the number of turns of the measurement frame is ~ 10.

3.4. The current measurement error

As it follows from expressions (2), (3), the systematic error of the magnet current measurement will lead to proportional error of the normalized integral F_n and in the first approximation it will not influence the accuracy of L_{eff}. The influence of this error on the L_{eff} is due to exceeding field in the edge parts of the yoke with respect to the central one. It is confirmed by a different form of the transfer function curves (due to saturation) between the central and edge parts. However for insignificant errors of the current measurement this effect is negligibly small.

Let's point out, that the tolerance for the systematic error of the current measurement may be softer than the full tolerance of $2 \cdot 10^{-4}$, if all magnets are measured with the same systematic error, i.e. for measurement of all elements of the ring magnet one current standard is used with stability not worse than $2 \cdot 10^{-4}$.

The random error for the current measurement includes the random error of the measurement equipment and the error caused by current pulsation or its instability. The measurement equipment error, which consists of the magnetic-modulation detector or shunt and of the digital voltmeter or ADC, should not exceed full tolerance for the measurement error of the dipole bending strength ($2 \cdot 10^{-4}$). As it follows from expressions (9), (10), the error due to current pulsation may be taken into account if the instant values of the current are

different measurement methods. From comparison of expressions (6) and (11) one can get the tolerance for the longitudinal twist of the magnet on the frame length:

$$\frac{1}{2L_{fr}} \int_{L_{fr}} \alpha^2(z)dz < 2 \cdot 10^{-4}. \tag{12}$$

The tolerance is $\Delta\alpha < 3.3. \cdot 10^{-2}$ rad for a linear twist with amplitude $\Delta\alpha$. The systematic error which has just been described, is present when the integral of magnetic field is measured by the NMR-device. At first the measuring frame is mounted in the median plane for each section of dipoles. However, when the measurement results are summed up for all sections the systematic error is summed up too. Therefore the tolerance of 35 mrad is a permissible amplitude of the linear longitudinal twist over the full magnet length. It is known from mechanical measurements, that this twist does not usually exceed 15 mrad for SC-dipoles. It is convinient to use an average angle considering the case when the frame has a longitudinal twist and the dipole is ideal. If $\theta(z)$ is the angle between some plane, which coincides with the axis of the frame, and the plane of the frame, then the average angle will be:

$$\theta = \frac{1}{L_{fr}} \int_{L_{fr}} \theta(z)dz. \tag{13}$$

Proceeding from the definition of median plane (1), $\theta = 0$ for the initial position of the frame. In this case magnetic flux through the frame standing in the median plane will be:

$$\Phi = D \cdot B \cdot W \int_{L_{fr}} cos[\bar{\theta} + \Delta\theta(z)]dz, \tag{14}$$

where D is the frame width; $\bar{\theta} = 0$; $\Delta\theta(z)$ – the deviation of the frame plane with respect to the average angle (longitudinal twist). Analogously to what was said above the tolerance for the longitudinal twist of the frame is 35 mrad. However, the twist value (i.e. the change of the frame sensitivity) is taken into account when calibrating with the NMR-device. This tolerance concerns the stability of the longitudinal twist of the measuring frame in the period between calibration and measurement as well as during the measurements themselves. It should be pointed out that this tolerance is rather soft.

In general case, when the measurement frame has some twist and the magnet is not ideal the magnetic flux through the frame can be presented as:

$$\Phi = D \cdot W \int_{L_{fr}} \vec{B}(z)|cos\alpha cos[\bar{\theta} + \Delta\theta(z)]dz, \tag{15}$$

where $|\vec{B}(z)|$ is the longitudinal distribution of the field vector amplitude.

The tolerance for the amplitude of a linear longitudinal twist of the frame $\Delta\vartheta_o$ when measuring the end region of an untwisted dipole with Π - shape of the distribution:

$$\frac{\Delta\theta_o^2}{6(L_{fr}-L_o)L_{fr}^2}(L_{fr}^3-3L_{fr}^2L_o-3L_{fr}L_o^2+L_o^3)<2\cdot10^{-4}, \qquad (16)$$

where L_o is the length of the measuring frame part, outside of the dipole. For real $L_o \simeq 0.3L_{fr}$, $\Delta\vartheta < 7\cdot10^{-2}$ rad.

3.2. Frame width

In this section we assume that the dipole field and measuring frame have no longitudinal twist. For conveniency we introduce the conception of an average width of the measuring frame:

$$\bar{D}=\frac{1}{L_{fr}}\int_{L_{fr}} D(z)dz, \qquad (17)$$

where $D(z)$ is the width of the measuring frame; z is the longitudinal coordinate.

The magnetic flux through the frame, placed in the median plane, in this case can be presented in the form:

$$\Phi = W\int_{L_{fr}} B(z)D(z)dz. \qquad (18)$$

This expression allows one to define the tolerance for the longitudinal nonuniformity of the frame width. For the central region, where the longitudinal nonuniformity of the field does not exceed $2\cdot10^{-3}$, the tolerance for the relative nonuniformity of the frame width is very soft ($\sim$ 30%) and it is easily satisfied.

For the measurement of the edge field, the requirements for the longitudinal nonuniformity of the frame width will depend on the position of the frame w.r.t. the magnet end. The average width of the frame $\bar{D}$, as it follows from the method, is defined in this case in the central part of the magnet. To estimate the tolerance for the longitudinal nonuniformity of the frame width assume, that the longitudinal distribution $B(z)$ has a Π-shape and L_o is a part of the frame in zero field. For this case expression (18) takes the form:

$$\Phi = W\cdot B\int_{L_o}^{L_{fr}} D(z)dz, \qquad (19)$$

where $D(z)=\bar{D}[1-\delta D(1-2\frac{z}{L_{fr}}]$, and δD is a relative amplitude of the linear longitudinal twist. The tolerance for the amplitude of the linear longitudinal twist of the frame width is $\frac{L_o}{L_{fr}}\delta D < 2\cdot10^{-4}$. A real contribution of the edge region to the full integral is $\sim$ 10%. It has earlier been pointed out, that the tolerance depends on the position of the frames and it will be softer than the quoted one. For a general case the tolerance for δD is defined as:

$$\delta D\frac{2L_{fr}(L_{fr}-L_o)}{L_{fr}\cdot L_m}<2\cdot10^{-4}, \qquad (20)$$

where L_m is the magnet length. For the real sizes $L_o \simeq 0.3L_fr$; L_m=6 m the tolerance for longitudinal twist is $\delta D < 2\cdot10^{-3}$. Let's note, that this tolerance is quite strong and it is very difficult to take into account the systematic error of measurements due to that.

The mechanical errors are imperfections in the length of the measuring frame and error in attachment of the frame ends. As is clear from the measurement procedure, the error of the frame length is taken into account from calibration. The frame ends should coincide with $\sim$1.2 mm accuracy. It can be realized observing certain conditions.

3.3. Electronic errors

As it follows from expression (10), the parameters of electronic channel (k,τ) in the formula of the transformation coefficient are determined from NMR - measurements with error $< 10^{-4}$. Hence, here we consider the stability of these parameters from calibration to measurement, and additive errors (noises).

Let's point out, that the stability of the parameters is important only at the very moment of measurements when measuring the central region, i.e. the stability is important within the time interval between the measurement at the current level 2 kA (calibration level) and the moment of measurement at other levels. Since this time makes up several minutes, this instability does not exceed 10^{-4}. At the edge regions these intervals may be tens of minutes. The measurement results show, that the contribution of instability of these measurements does not exceed 10^{-4}. To consider the influence of the bias voltage drift, one should take into account the fact, that the contribution of the integrator bias k times less than the contribution of the amplifier bias. To estimate the influence of the drift of input bias voltage of the amplifier let's consider the worst case when the bias has a sinusoidal form with amplitude ΔU, and it changes synchroniously with the input signal. For this case the