Estimation of the Mechanical Abarration-Limited Energy Resolution in a Model Beam-Analyzing Magnet

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1. Introduction.

The energy resolution of a magnetic analyzer with an ideal detecting system $\Delta E/E$ is limited by a following relationship:

$$\Delta E/E=[\Delta E/E^2(\text{1'st order})+\Delta E/E^2(\text{aberration})+\Delta E/E^2(\text{inhomogeneity})]^{1/2} \quad (1)$$

where $\Delta E/E$(1'st order) is the 1'st order ion optical energy resolution which is determined by the magnet geometry, $\Delta E/E$(aberration) is the ion optical aberration-limited energy resolution due to the higher order focusing and $\Delta E/E$(inhomogeneity) is the mechanical aberration-limited energy resolution resulting from the magnetic field inhomogeneity. The $\Delta E/E$(inhomogeneity) is expressed with the image broadening caused by the absolute magnetic field inhomogeneity along a radial direction in the magnetic analyzer.

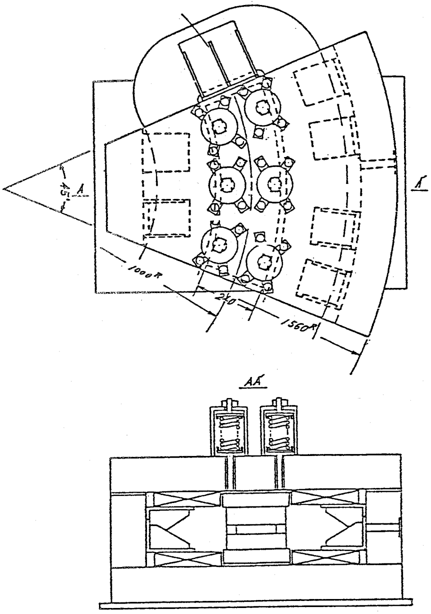

Fig.1

A digital computer program method which integrates the equation of motion or traces the ray of charged particle in the measured magnetic field can not discuss only the mechanical aberration $\Delta E/E$(inhomogeneity). A sector type of a model beam-analyzing magnet had been fabricated to investigate the designs of new electro-magnets, which are installed to the AVF cyclotron of RCNP[1-6].

2. Measurement of the magnetic field inhomogeneity.

The magnet has the homogenizers, the air-gap spacers machined accurately and the pole pieces separated from the yoke[1,7]. The schematic presentation of the magnet is given in fig.1. The specifications and performances of the magnet and the power supply are summarized in table 1[1]. The magnet has two types of pole pieces with a sharp-cornered(SCOF) and a B-constant(B-const) profiles, whose are made of a commercial grade of two kinds of low carbon and forged iron plates (1 and 2) in table 1. A differential probe consisting of the fixed and the search Hall-element probes has been used to detect the small difference of field strength less than 10^{-4}. The fixed probe is set at a point in the uniform field. The search probe is moved along a radius at a given azimuth (θ=1 and 3) over the uniform field on the median plane by a zip-track system. The specification and performance of the analog field-difference detecting system are presented in table 1[1]. The difference between field strengths of two probes had been measured in such a way as to not cause the eddy-current effect and the magnetic after-effect in the pole pieces[1-3].

3. Magnetic field distribution.

Fig.2 shows examples of the magnetic field distributions or the dependences of the field difference ΔB on the radial distance r at a field strength 7.5 kG, and at an azimuth θ=1 in the pole pieces SCOF1 (a) and at an azimuth θ=3 in the pole pieces B-const1 (b)[3].

4. Absolute magnetic field inhomogeneity.

The absolute magnetic field inhomogeneities or the absolute values of the magnetic field inhomogeneities within a beam width w were derived from the magnetic field distributions as shown in fig.2. Fig.3 gives the dependences of the absolute field inhomogeneity $|\Delta B|/B$ on the field strength B and on the azimuth θ. The dependences were measured at two azimuths θ=1 and 3 in the pole pieces SCOF1 and SCOF2 in the magnets with and without the homogenizers and also in the pole pieces B-const1 and B-const2 in the magnet with the homogenizers. They were estimated within two beam widths w=W and 2W.

The properties of the absolute field inhomogeneities are summarized as follows:

1) They are independent of the field strength and the azimuth.
2) They do not depend on the pole-piece iron.
3) They are independent of the field-setting procedure of the magnetization-demagnetization.
4) They have not been influenced by the existence of the homogenizers.
5) Their values in the central part are smaller than those in the edge parts of the pole pieces.

	Design	Measurement
Magnet		
Curvature radius	1000 mm	
Deflection angle	45°	
Gap thickness	40 ± 0.01 mm	39.899±0.004 mm
	(2.5×10^{-4})	(1.04×10^{-4})
Pole-width		
SCOF and n=1/2	240 mm	
B-const	160 mm, having the hyperbolic cosine corners of 40 mm	
Mechanical accuracy of the pole face		
SCOF and B-const	<0.8 μ	
n=1/2	<6 μ	
Field gradient		
SCOF and B-const	0	
n=1/2	0.5	0.48 ± 0.01
Iron material, carbon content and max. relative permeability		
SCOF1, B-const1 and n=1/2	S10C	0.12%, 2100
SCOF2, B-const2	Pure iron	0.03%, 3200
Shift between the upper and lower poles	<0.1 mm	0.04 mm
Spacer	Brass μ=1.005	
Mechanical accuracy of the spacers	<5 μ	
Homogenizers between the upper and lower poles, and yoke	5 mm thickness	
Power supply		
Output power (DC)	70 V, 280 A	
Stability	± 1×10^{-4}/5h	2.5×10^{-5}/6.5h
Ripple	± 5×10^{-5}/moment	2.5×10^{-5}/moment
Field-difference detecting equipment		
Hall generator	InAs Hall element FC-33 with the sensitivity 14.5 μV/G	13.6 μV/G
Constant current controle, stability	<4×10^{-5}	
Temperature controle	Glass thermister Ohizumi 41E6 with the regulative sensitivity 1×10^{-2} °C	1.2×10^{-2} °C
Amplifier	Kikoh Ampet, Model 5612S with the gain 60 db (DC, DL)	
Heater	NEC-D-12	
Zip-track system		
Accuracy setting the Hall element		
Radial direction	0.2 mm	
Vertical direction	0.15 mm	
Inclination	0.8° ($\theta^2/2<10^{-4}$)	

Table 1

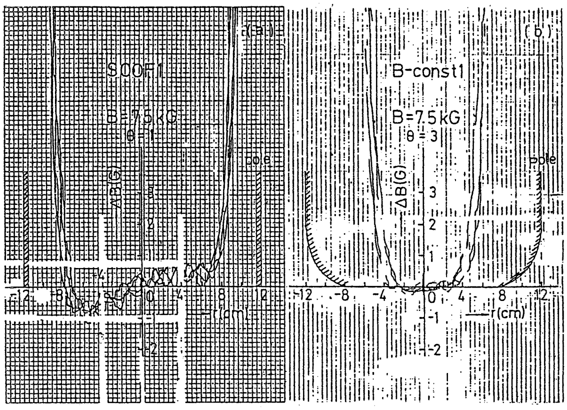

Fig.2

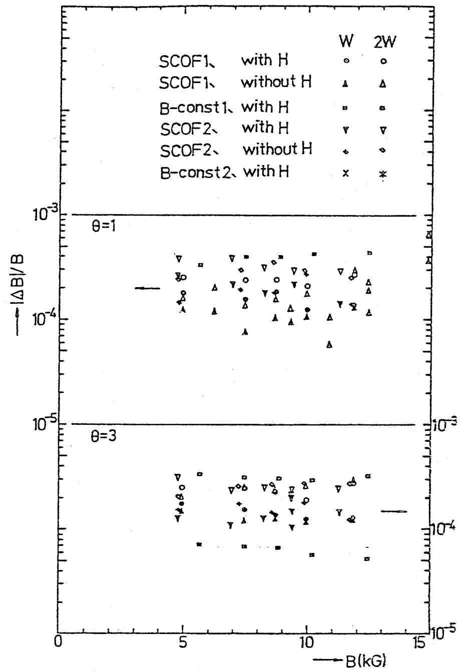

Fig.3

6) They depend on the beam width.
7) They are related to the pole-piece profile. Those in the B-constant pole pieces are better than those in the sharp-cornered pole pieces. In the B-constant pole pieces, they are limited by the effective pole-piece width.

5. Energy-resolution reduction due to the magnetic field inhomogeneity.

A formula for the calculation of the energy-resolution reduction due to the magnetic field inhomogeneity was derived for a uniform field magnetic analyzer [1]. The ability of the magnetic analyzer to separate particles with different momenta is represented by the dispersion D defined as

$$D=S/R\cdot p/\Delta p \qquad (2)$$

where Δp is the change in a moment p that produces a displacement S from the central ray as measured at the image in the magnetic analyzer with the radius of curvature R. The mechanical aberration -limited energy resolution $\Delta E/E$(inhomogeneity) is, as a typical example, examined in a following double focusing uniform field analyzer: deflection angle=90°, object and image distances=2 in the unit of R, and entrance and exit rotating angles=26.5°. The energy-resolution reduction due to the magnetic field inhomogeneity is expressed with the absolute magnetic field inhomogeneity $|\Delta B|/B$ from eq.2

$$\Delta E/E(\text{inhomogeneity})=2\Delta p/p=2S/RD=1.6\,|\Delta B|/B \qquad (3)$$

The whole calculations have been carried out by assuming the sharp-cornered fringing field.

The results in fig.3 are summarized in the column $|\Delta B|/B$ in table 2. Table 2 presents the mechanical aberration-limited energy resolution $\Delta E/E$(inhomogeneity) deduced from the absolute field inhomogeneity $|\Delta B|/B$ according to eq.3. They were estimated within two beam widths w=W and 2W in all pole pieces in the magnets with and without the homogenizers. It will be expected that the data in tables 1 and 2 are usefull in the practical design of the magnetic analyzer because of the lack of this kind of the measurements.

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Beam Width	Pole Piece	Magnet Condition Homogenizers	$|\Delta B|/B$	$\Delta E/E$
W	SCOF1	with	1.41×10^{-4}	2.26×10^{-4}
	SCOF1	without	1.17×10^{-4}	1.87×10^{-4}
	B-const1	with	6.56×10^{-5}	1.05×10^{-4}
	SCOF2	with	1.55×10^{-4}	2.48×10^{-4}
	SCOF2	without	1.80×10^{-4}	2.88×10^{-4}
	n=1/2	with	1.70×10^{-4}	2.72×10^{-4}
2W	SCOF1	with	2.30×10^{-4}	3.68×10^{-4}
	SCOF1	without	2.13×10^{-4}	3.41×10^{-4}
	B-const1	with	3.24×10^{-4}	5.18×10^{-4}
	SCOF2	with	2.71×10^{-4}	4.34×10^{-4}
	SCOF2	without	2.60×10^{-4}	4.16×10^{-4}
	n=1/2	with	2.54×10^{-4}	4.06×10^{-4}

Table 2

References.

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2) the same as the above; Nucl.Instr.Meth. 160(1979)29.
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