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ACCELERATION OF DEUTERONS IN THE KEK ACCELERATOR

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Abstract

A possibility for acceleration of deuterons in the KEK accelerator is presented with some modifications required to the present machine. Deuteron beam of an intensity as high as 350 mA was obtained in the present duoplasmatron ion source. The emittance and acceptance of the 20-MeV proton linac are calculated for deuterons. A modification in the field distribution by means of tuners is considered to save the rf power and to improve the longitudinal emittance. Acceleration in the booster and main synchrotrons as well as in the 180-GeV intersecting storage ring proposed for a KEK future project are discussed. Intensity of the obtainable neutron beam is also estimated.

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1. Introduction

Deuteron beams will make it possible to achieve wider variety of physics experiments. By establishing a deuteron beam, we can obtain both proton and neutron beams. The total cross sections of p-p, p-n and n-n scatterings can be measured in a similar set-up. In the interaction of p+d → p+d, the exchange of I=0 objects can be studied. In the interaction of d+d → d+d+ (particles), the particles have a simplicity of I=0, and useful informations about the particles will be obtained. The high energy neutron beam produced in the final stage of acceleration will be a clean and valuable tool which supercedes the neutrons in nucleus targets. Preparation of deuteron option in a future project such as the 180-GeV intersecting storage machine under discussion will also have a significant value. For example, the total cross section of p-p, p-n and n-n can be compared up to the laboratory system energy of 19 TeV. An information could be obtained about isoscalar nucleon-nucleon scattering amplitude.

Both deuteron and neutron beams can be polarized by using a polarized deuteron ion source. They will be important tools for both the 500-MeV booster and the 12-GeV PS. The extracted beam of polarized deuterons from the 180-GeV ring is also strongly desireable for physics experiments. Due to a low luminosity ($\sim 10^{-6 \sim 8}$ times the luminosity for unpolarized beams), however, the colliding beam experiments of polarized beams will have less merit without future improvement in the luminosity or intensity.

In Table 1 are presented results of deuteron acceleration in various laboratories, including plans under discussion. The present report gives a discussion about a deuteron ion source, and the acceleration in the 20-MeV (for proton) linac, the 500-MeV booster synchrotron, the 12-GeV PS and the 180-GeV intersecting storage accelerator. The expected neutron beam is also estimated in the final section.

2. Production and Acceleration of Deuterons

A. Ion Source

A duoplasmatron, the same one[10)] which is in operation as an ion source for the KEK injector, was tested for deuterium gas instead of hydrogen gas. Current ($D^+ + D_2^+$) obtained was as high as 350 mA for extraction voltage of 50 kV across the extraction gap of 15 mm from the plasma cup to extractor. The current is about 20 % lower than for protons in rough agreement with the dependence of $(\text{Mass})^{-1/2}$ in the space charge limited current formula. The discharge parameters were similar to those for protons; arc current = 40 A, magnetic field ≈ 2 kG and the source gas pressure = 0.6 Torr on a Pirani gauge calibrated to air. The emittance (normalized) was 0.14 πcm·mrad. It will have no serious problem to get higher than 200 mA D^+ beam at 390 keV within the emittance (normalized) of 0.15 πcm·mrad at the end of preaccelerator.

B. Acceleration in the 20-MeV Linac

B-1 Longitudinal Motion

Acceleration of deuterons in existing proton linacs has already been studied as seen in Table 1. In each study the mode of acceleration is the second harmonic mode (i.e. 4π mode), in which deuterons progress each cell in two rf periods. The acceleration of deuterons in the KEK proton linac is also possible in this mode. Deuteron acceleration in 2π mode is practically impossible because it requires the rf field exactly twice as high as in the case of proton acceleration.

The KEK 20-MeV proton linac is a single cavity and 15.51 m in length. The cell dimensions are designed for axial average field of 1.5 MV/m at the low energy end and 2.1 MV/m at the high energy end, with a linear field tilting between the two ends. This field intensity is relatively low in the low energy region. In this respect, the KEK linac may have an advantage that a room remains to increase the field intensity in the low energy region where the transit-time-factors drop seriously. On the other hand, the linac has a disadvantage that the dimensions such as bore radius, drift tube corner radius and number of stems are not the same through the linac. As a result, the transit-time-factors or eventually the necessary rf field intensity is not smoothly decreasing or increasing as a function of the distance from the end of cavity. Though we can easily adjust field tilting to some extent, it may be very difficult to adjust locally the field intensity.

We can accelerate deterons with the present field distribution if the field level is increased at the expense of rf power. Our cavity has 14 movable tuners distributed along the cavity. Our new attempt is to investigate whether one can adjust the field distribution by means of these tuners in order to make the longitudinal acceptance of deuterons as large as possible with a less rf power.

We have already measured the transit-time-factors and the S-coefficients for deuterons[11)] in the second harmonic mode by a perturbation method. The results are shown in Fig.1. In this section we will proceed with the discussion based on these data. The velocities of synchronous deuterons at the exit of each cell are given by $v_n = L_n f/2c$, where f is the operating frequency (= 201 MHz), L_n the distance from the n'th to (n+1)st gap center, c the velocity of light. Then, we can obtain the energies and the energy increments of the synchronous deuterons in each cell. Putting the energy increments obtained equal to the energy gains from rf field: $W_n = e E_n L_n T_n \cos \phi_s$, we find the field intensities E_n's required of each cell. Here, T_n and L_n are known and $\cos \phi_s$ may be put 0.9. The field intensities obtained are shown in Fig.2 together with their ratios to the field intensities required for acceleration of protons. Fig.2 shows that the field should be increased in the low energy region, decreased around the middle of the cavity and restored at the high energy end. Of course, there would be no problem if we could get such a field distribution.

Assuming the field distribution given in Fig.2, we computed the longitudinal motions of deuterons injected with various phases and energies neglecting the transverse motion. The input acceptance and output emittance are shown in Fig.3. The emittance was calculated for a rectangular input phase space area of $-90° \leq \phi \leq 90$ and 340 keV $\leq E_{in} \leq 436$ keV. The calculation of longitudinal motion was made for the field distribution which is now set to accelerate protons. As the field level increases gradually, the output deuterons appear around the energy of 10 MeV and thereafter the longitudinal acceptance increases. The longitudinal acceptance and emittance are shown in Fig.4 for a case where the rf level is increased by a factor of 1.3 higher than the usual level for protons. The average field intensities of each cell are shown by dots in Fig.6. Choosing the optimum injection energy, we can get the same width of phase spread for acceptance as in the ideal case shown in Fig.3. It will not be difficult for the present rf amplifier system to produce the rf field level plotted in Fig.6. Therefore, it will be rather easy to accelerate deuterons in the KEK linac.

If the present field distribution is replaced by another distribution which is closer to the shape given in Fig.2, the emittance will be improved and rf power will be saved. The optimum tuner positions for deuteron acceleration should be explored experimentally, since a method of theoretical approach to get a desired field distribution by the use of tuners has not been established so far. But it is difficult to do so for the present because of full schedule of ordinary operations. Therefore, we examine the effect of tuners on field distribution and try to get the desired distribution in an analytical method. An equivalent circuit presented in ref.12 is used to express the field distributions as a function of the resonant frequencies of each cell. The field intensity I(z) is assumed to be given in a differential equation;

$$\frac{d^2I(z)}{dz^2} + m^2\ I(z) = 0 \quad . \qquad (1)$$

with $$m^2 = k(\omega^2 - \omega_0^2) \ , \qquad (2)$$

where k is constant, ω the exciting frequency and ω_0 the resonant frequencies of each cell.

The boundary condition can be put as

$$\frac{dI(z)}{dz} = 0, \quad \text{at } z = 0 \text{ and } z = L \quad ,$$

where L is the total length of the cavity. The function $m^2(z)$ can be found from the initial field distribution which is expressed in a Fourier expansion. In order to introduce the effect of a change in the tuning condition, a step function with a width of L/20 is added to $m^2(z)$ at the position of the tuner moved. The height is taken as a variable parameter. The width of step function is chosen by taking the size of the tuners into consideration, which does not introduce any speciality in discussion.

An agreement between computation and measurement is satisfactory as shown typically in Fig.5. Since the usefulness of Equation (1) is verified, the optimum condition of the 14 tuners for deuteron acceleration is searched by solving Equation (1) for various $m^2(z)$'s. One of the most promising field distributions is shown by a solid curve in Fig.6. The heights of step function used to produce the field distribution are also shown in Fig.6. A computation for the case of tuning only by one tuner shows that the full movement (= 10 cm) of the tuner gives the change in $m^2(z)$ from 8 to 16 depending on the position of tuner. The change in $m^2(z)$ of minus sign in Fig.6 will be easily realized if extensions for some of the present tuners are taken into consideration. It may be troublesome to obtain the change of plus sign in Fig.6 since it requires to lower the resonant frequency. This trouble, however, will not be the case in the middle of the cavity, since the tuners in this region are fully plunged in at present to raise the resonant frequency and they can be pulled back to lower the frequency. The tuning around both the ends of the cavity may be obtained by adding tuners on the end plates. The acceptance and emittance calculated for the optimum distribution obtained above are shown in Fig.7. They are surely approaching to the ideal case shown in Fig.3. Since the excitation power is approximately proportional to an integral of the square of field intensities, we see from Fig.6 that rf power will be remarkably saved when the field distribution is replaced by the calculated curve instead of a dotted curve.

B-2 Transverse Motion

When deuterons are accelerated in the second harmonic mode, their momenta in each cell are equal to those of protons. So the focusing action of quadrupole magnets is equivalent for both particles. However, the rf defocusing force for deuterons in each gap is twice larger than for protons if the same synchronous phase is assumed. A cell by cell calculation of transverse motion of deuterons was carried out on the assumption that the synchronous phase is constant ($\cos \phi_s = 0.9$) through the linac and that the flux density gradient of quadrupole magnet is 100 Wb/m^2 at the injection end. The acceptance obtained is 1.9 πcm·mrad (normalized by multiplying $\beta\gamma$), which is nearly the same as the acceptance obtained in the same way13) for protons.

Taking into account a successful acceleration of 26 % of injected deuteron beam up to 5 MeV in BNL7) and also no loss found from 5 to 23 MeV in CERN1), we can expect a trapping efficiency higher than 20 %. It will be reasonable to expect D^+ current as high as 40 mA at the exit of the linac.

C. Acceleration in the 500-MeV Booster Synchrotron

We must modify the rf accelerating system to meet the new revolution frequency region for deuterons. The revolution frequency for deuterons ranges from 0.82 MHz (at 10 MeV) to 4.0 MHz (at 294 MeV), while the rf frequency of the present accelerating cavity is designed to be from 1.6 to 6.0 MHz. The FM ratio defined as the ratio of the maximum frequency to the minimum frequency must be increased from 3.9 to 4.9. It may be quite difficult for the present system to realize such an increase in the FM ratio.

One possible method for acceleration of deuterons is to use the second harmonics in the first stage of acceleration to get rid of the difficulty of the large FM ratio. The frequency is changed from 1.64 to 3.62 MHz in the second harmonics, the two bunches in a ring are debunched without rf acceleration and then rebunched into one bunch, which is accelerated to the final energy in the first harmonics from 1.81 to 4.0 MHz. Here we choose the equal FM ratios (= 2.21) for the two modes of acceleration. A similar method for the acceleration of deuterons in two stages was successful in Dubna.[4)] The KEK booster synchrotron, however, is a rapid cycling synchrotron with a sinusoidal excitation current for the magnets. It may be quite difficult to change their current sources to keep the magnetic field constant during a certain time in which the debunching could be fulfilled. Even if the problem for the rf power source will be solved, it may be also difficult to change the bias current for ferrite in a short time of the transition.

Another possible method will be an addition of a cavity which can be used for accelerating deuterons in the first harmonics with the frequency range from 0.82 to 1.6 MHz. One additional cavity is going to be installed to get more stable acceleration for protons. If this new cavity is changed to have the frequency range down to 0.82 MHz by replacing the external capacity of the cavity, the problem to be solved next is the synchronization of the fields in the two cavities at the transition. The problems in this method will be rather easily solved in comparison with those in the first method. The number of deuterons obtained from the booster synchrotron is 8.8×10^{12} deuterons/sec if only the reduction in linac current is taken into account in the estimation.[14)]

D. Acceleration in the 12-GeV Main Synchrotron

Here also we must solve the problems for the rf acceleration. The revolution frequency ranges from 0.44 (294 MeV) to 0.88 MHz (11.1 GeV) for deuterons instead of 0.68 to 0.88 MHz for protons. If the present harmonic number of 9 is fixed, the rf frequency for deuterons is from 4.0 to 7.9 MHz, while the present cavity is designed for the frequency range from 6.0 to 8.0 MHz.

It is too complex to apply the multistage acceleration method fixing the present frequency range. For example, we must accelerate three bunches injected in the main ring in the 15th harmonics from 6.6 to 7.95 MHz reaching an energy of 469 MeV, next in the 12th harmonics from 5.9 to 7.92 MHz reaching an energy of 938 MeV, and finally in the 9th harmonics from 5.9 to 7.9 MHz reaching the energy of 11.1 GeV.

The most simple method will be to modify the present rf system to be able to accelerate deuterons only in the 9th harmonics. The resonant frequency without bias current should be lowered to 4 MHz and power of the bias current source should be raised to changed the resonant frequency up to 8 MHz.

These seem to be not difficult if we think of the present tunable range of the cavity used for the booster.

The number of deuterons in the main synchrotron is 2 × 10^{12} deuterons/sec if the reduction in the injection current is taken into account.

E. Stacking in the 180-GeV Intersecting Storage Accelerator under Discussion

Let us consider stacking of deuterons in the 180-GeV accelerator which is one of typical future plans under discussion for KEK. The 180-GeV accelerator consists of a 50-GeV ordinary synchrotron and a 180-GeV superconducting storage accelerator.

In the 50-GeV synchrotron, the velocity of deuterons in units of the light velocity is already 0.99 at the injection (11 GeV), reaching 0.999 at the final energy (49 GeV). The acceleration of deuterons has no additional problem about the frequency range of rf cavities in comparison with protons. The deuteron current is 2.4 × 10^{13} D^+/turn for the injection of six pulses (12 sec) from the main ring.

There is almost no difference in accelerations of deuterons and protons in the 180-GeV ring. The luminosities of d-d and d-p crossings will be 0.4 times the luminosity of p-p (the intensity ratio of deuteron to proton beams is assumed to be 0.4), and will be as high as 4 × 10^{33} $cm^{-2}sec^{-1}$, if the maximum allowable tune shift $\Delta\nu_0$ could be taken the same (0.005) as in the case of p-p crossing.15,16)

3. Neutron Beam

Besides the importance of deuteron itself, neutron beam from break-up of deuterons will be a valuable tool for physics experiments. Let us make a rough estimate for the neutron beam intensity which can be expected into a given angular spread around the axis of deuteron beam. Break-up of deuterons into protons and neutrons occurs through two main processes of stripping and dissociation. Dissociation occurs through both Coulomb and nuclear interactions. While the dissociation due to Coulomb interaction will depend on the deuteron energy, both the stripping and dissociation due to nuclear interaction may be very roughly taken as independent of energy. Let us assume a simple approximate formula16) of $d\sigma/d\Omega = \sigma_{tot}\, P_c^2/2\pi\alpha^2\hbar^2$ for the differential cross section of break-up at zero degree, where P_c denotes the center value of neuteron momentum distribution and $\alpha\hbar$ = 46 MeV/c. Let us take 172 mb,17) a measurement at the deuteron momentum of 2.7 GeV/c, for the total break-up cross section σ_{tot} in Be target. The thickness of target for break-up can be given as below by a condition that the root mean square value of multiple scattering angle should be as small as a certain angle θ_0:

$$t \sim 2\ (P_d \beta_d c/21\ \mathrm{MeV})^2\ \theta_0^2\ X_0\ . \qquad (3)$$

Here P_d and $\beta_d c$ are momentum and velocity of deuterons respectively, and X_0 the radiation length of material. The probability of break-up into an angular spread $\Delta\Omega = \pi\theta_0^2$ around the deuteron beam axis is given by

$$(d\sigma/d\Omega)_{\Omega=0}\ \Delta\Omega t N/A\ , \qquad (4)$$

where N is the Avogadro's number and A the atomic weight of material. The break-up probability is roughly proportional to ${P_d}^4{\theta_0}^4$ and is 6.8×10^{-5} for the booster synchrotron's beam, if θ_0 is taken to be 6 mrad. The neutron intensity will be 5.4×10^8 neutrons/sec.

At the deuteron momentum from the main synchrotron, the formula (3) gives a much bigger thickness than the nuclear mean free path. Instead of formula (3), let us take 4 cm of Be which correspond roughly to 0.35 times the nuclear mean free path. If θ_0 is taken to be 2 mrad, the break up probability is roughly 0.0034, giving 6.8×10^9 neutrons/sec. At both 50 and 180 GeV/c, higher break-up probability is expected into a fixed angular spread, because of much forward-peak distirbution of neutrons.

Materials with low atomic number Z are favourable for the target. The number of target atoms is given by tN/A, which is roughly proportional to Z^{-2} at low energies where t is given by formula (3) or to Z^{-1} at high energies where t is taken nearly constant. The break-up corss section increases with Z only according to $Z^{0.42\sim0.67}$ [6,18] As a result the break-up probability decreases as Z increases.

Acknowledgement

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Table 1. Deuteron acceleratations achieved under discussion (marked by *)

	Ion Source and Preinjector	Injector	Synchrotron	Notes
CERN[1)] (1964)	R.F. Source, 60 mA, 270 keV E_n = 0.34π+)	Linac 7 mA, 23 MeV E_n = 0.47 π+)		
CERN*2)		Linac 20 mA, 23 MeV	≥5 × 10^{11} D^+/s 23 GeV	A few turn injection and 50 % loss is assumed in PS.
PPA[3)] (1969)		Van de Graaff 3 MeV	6 × 10^{11} D^+/s 600 MeV	
JINR[4)] Synchro- Phasotron (1970)			5 × 10^9 D^+/s 7.6 GeV	
Bevatron[5,6)] (1973)	Duoplasmatron 30 mA, 260 keV PIG Source 5 mA, 260 keV	Linac 0.25 ~ 1 mA 10 MeV	1.6 × 10^{10} D^+/s 4.2 GeV	
BNL[7)] (1970)	Duoplasmatron 125 mA, 390 keV	Linac 18 mA, 5 MeV		
BNL*8,9)	Duoplasmatron 125 mA, 390 keV E_n = 0.2 π+)	Linac 25 mA, 30 MeV E_n ~ 0.36 π+)	9 × 10^{11} D^+/s 30 GeV E_n ~ 0.64 π+)	4 × 10^{14} D^+/Ring L_{dd} ~ 7 × 10^{32}/cm^2/s in ISABELLE
KEK*	Duoplasmatron 200 mA, 390 keV E_n = 0.15 π+)	Linac 40 mA, 10 MeV E_n ~ 0.3 π+)	8.8 × 10^{12} D^+/s at 290 MeV, 2 × 10^{12} D^+/s at 11 GeV	2.4 × 10^{13} D^+/Ring L_{dd} ~ 4 × 10^{33}/cm^2/s in 180-GeV colliding rings

+) Normalized emittance is in units of cm·mrad.

Figure Captions

Fig.1	Transit-time factors and S-coefficients measured for acceleration of deuterons in the second harmonic mode.
Fig.2	Average axial field required for acceleration of deuterons. Correction factor means the ratios of this field to the field required for proton acceleration.
Fig.3	Longitudinal acceptance and emittance of deuterons for the field distribution given by Fig.2. The emittance is calculated for a rectangular input phase space area of $-90° \leq \phi \leq 90°$ and $340\ \mathrm{keV} \leq E_{in} \leq 436\ \mathrm{keV}$.
Fig.4	Longitudinal acceptance and emittance of deuterons when only the rf level is increased by a factor of 1.3 higher than in the case of proton acceleration.
Fig.5	Change in the field distributions when one tuner is plunged in. Solid lines show the result of computation.
Fig.6	Field distribution obtained by solving the differential equation for a change of function $m^2(z)$ given below. A dotted line shows the field distribution for which Fig.4 is obtained.
Fig.7	Longitudinal acceptance and emittance calculated for the field distribution given by a solid line given in Fig.6.

Fig. 1

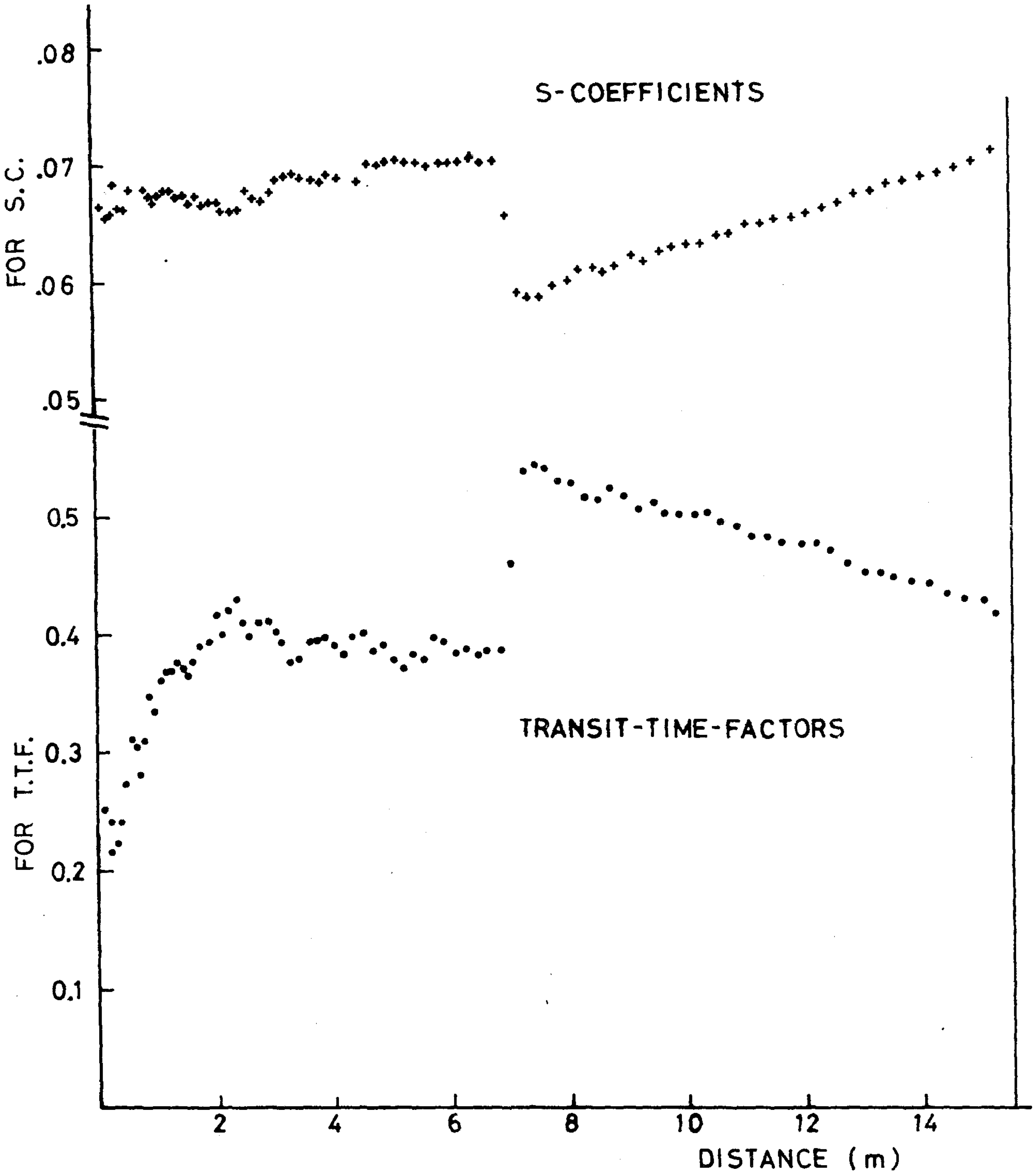
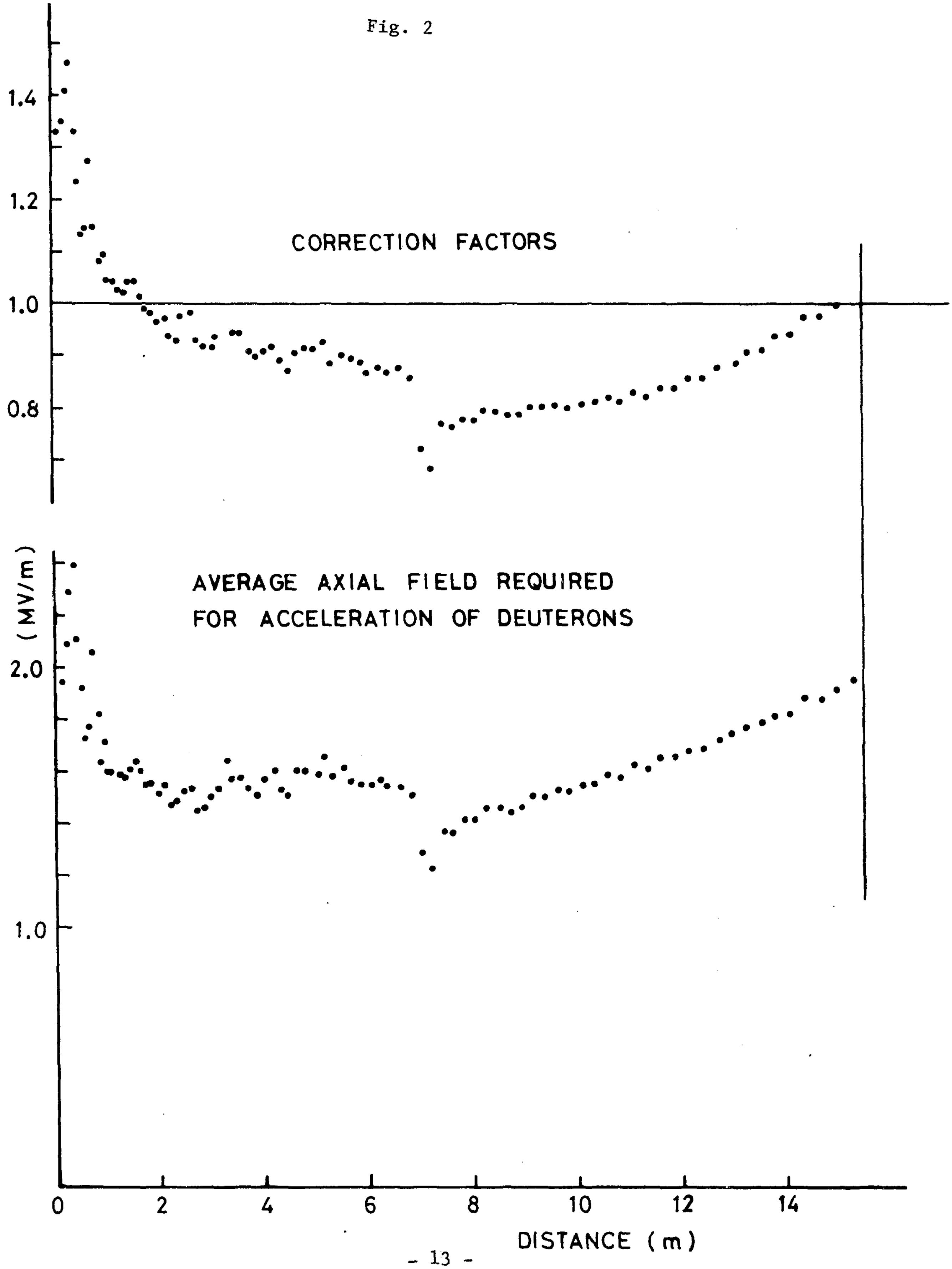

S-COEFFICIENTS
TRANSIT-TIME-FACTORS
FOR S.C.
FOR T.T.F.
.08
.07
.06
.05
0.5
0.4
0.3
0.2
0.1
2
4
6
8
10
12
14
DISTANCE (m)

Fig. 2


CORRECTION FACTORS
1.4
1.2
1.0
0.8
AVERAGE AXIAL FIELD REQUIRED
FOR ACCELERATION OF DEUTERONS
(MV/m)
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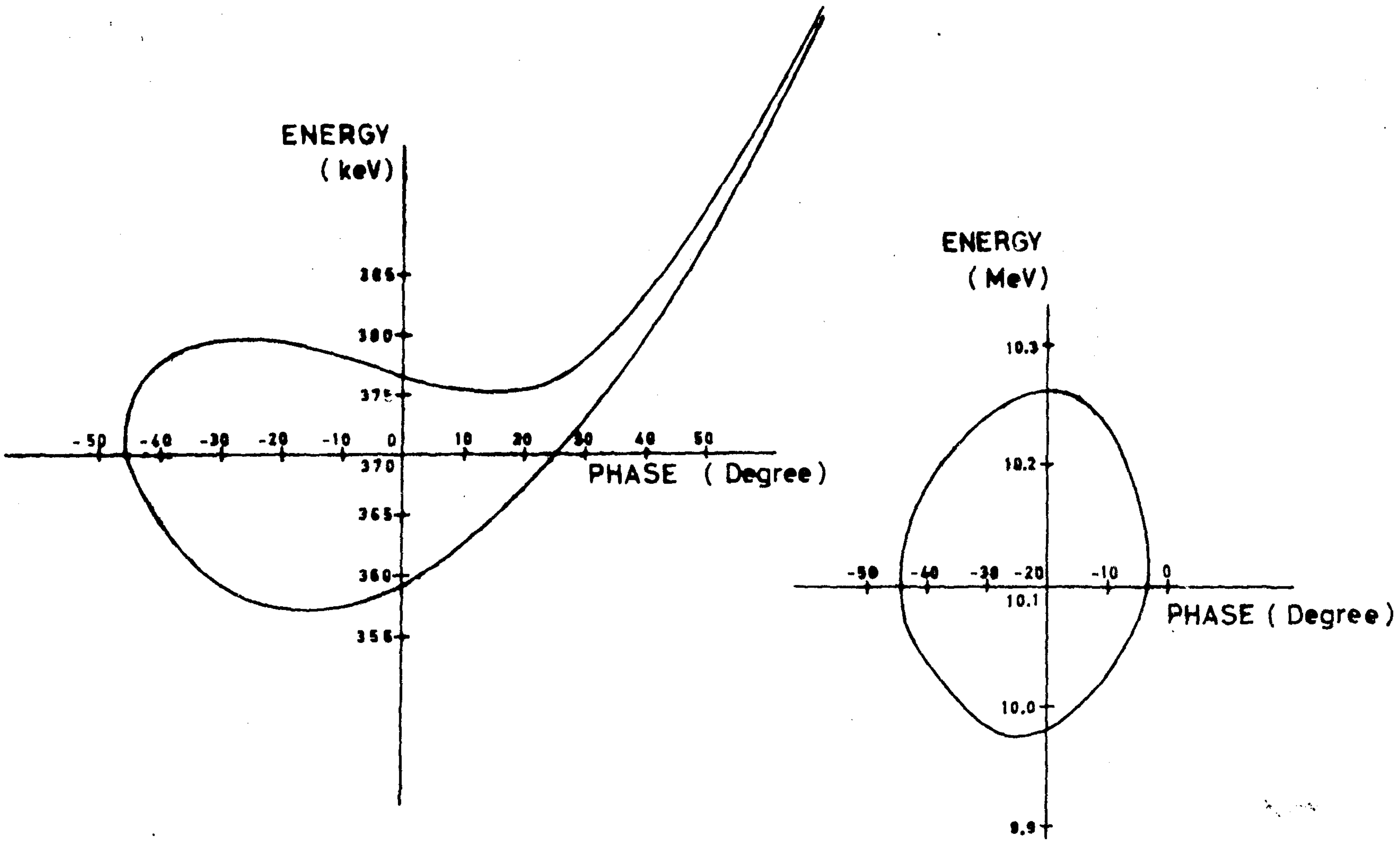
1.0
0
2
4
6
8
10
12
14
DISTANCE (m)


ENERGY
(keV)
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380
375
370
365
360
355
- 50
-40
-30
-20
-10
0
10
20
30
40
50
PHASE (Degree)
ENERGY
(MeV)
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10.0
9.9
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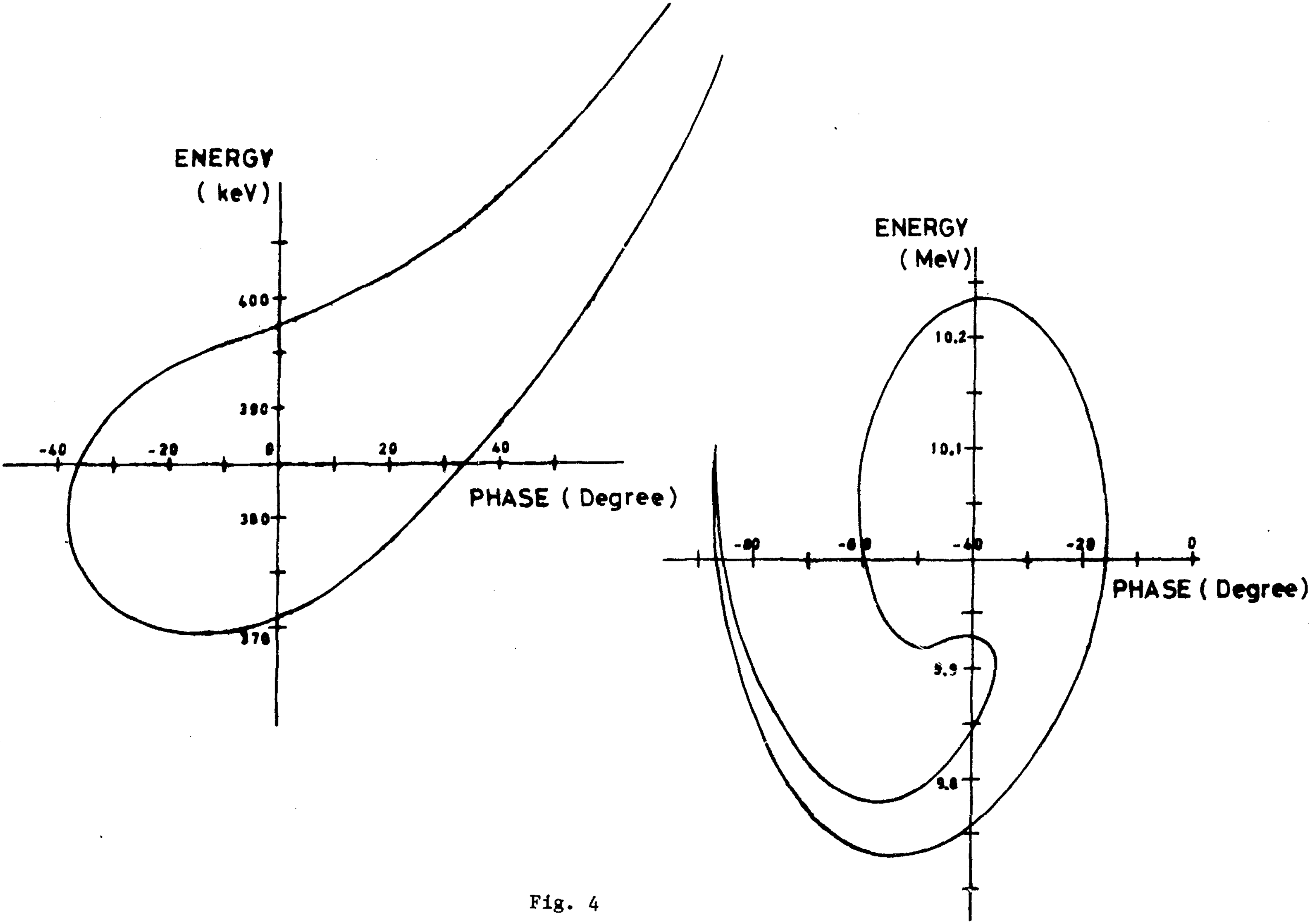
-30
-20
-10
0
PHASE (Degree)

Fig. 3


ENERGY
(keV)
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390
380
370
-40
-20
0
20
40
PHASE (Degree)
ENERGY
(MeV)
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9.9
9.8
-80
-60
-40
-20
0
PHASE (Degree)

Fig. 4

Fig. 5

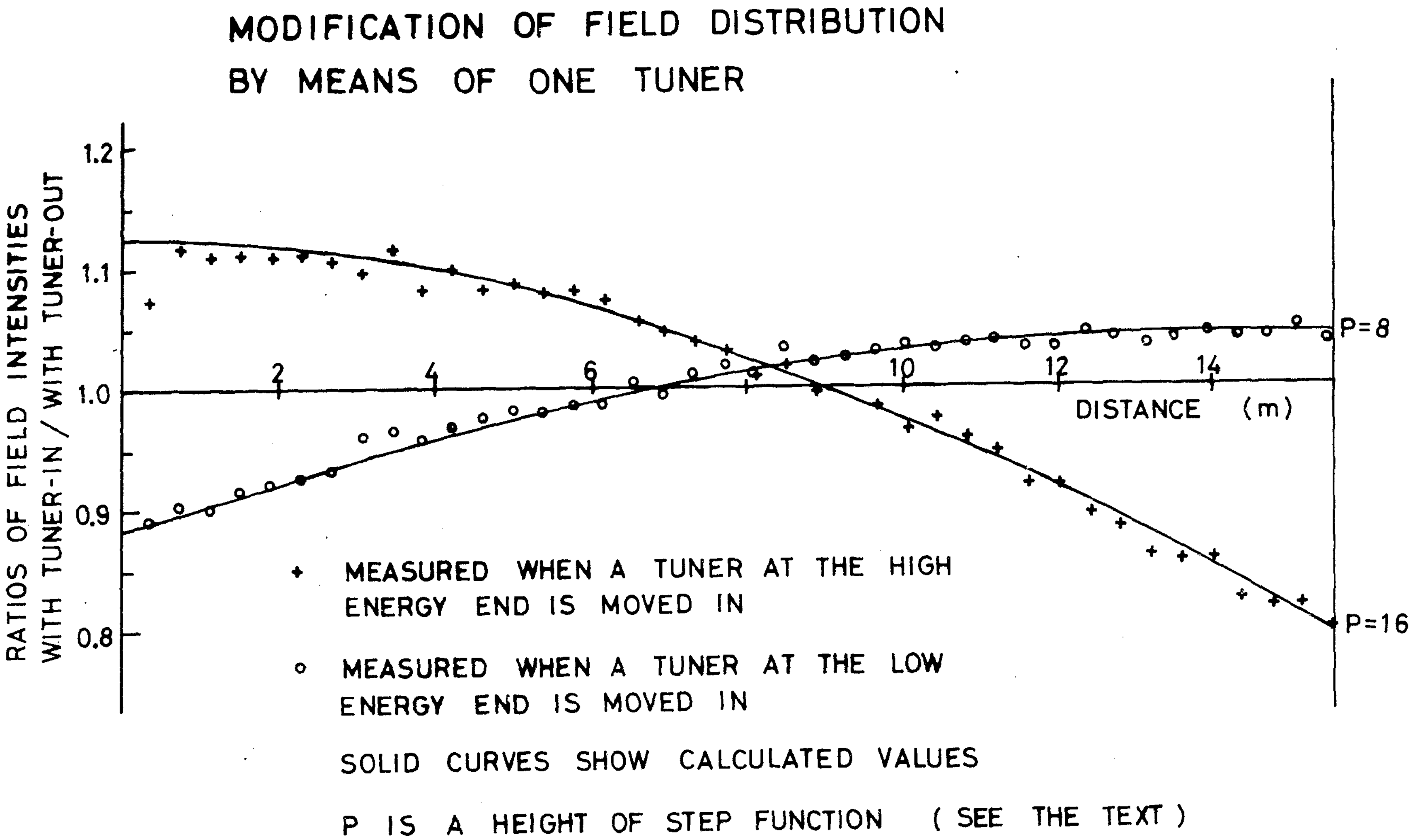
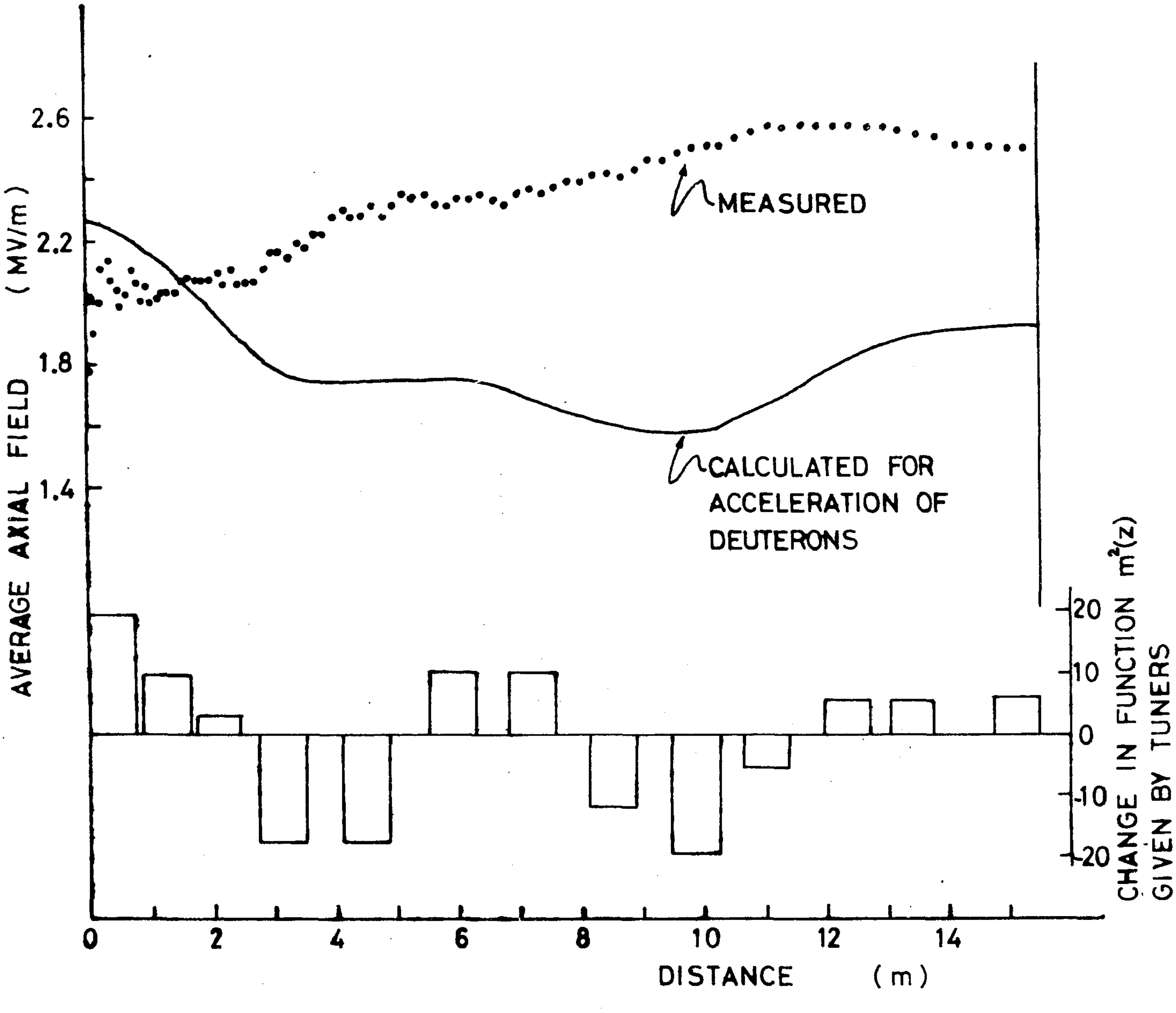

MODIFICATION OF FIELD DISTRIBUTION
BY MEANS OF ONE TUNER
RATIOS OF FIELD INTENSITIES
WITH TUNER-IN / WITH TUNER-OUT
1.2
1.1
1.0
0.9
0.8
2
4
6
10
12
14
DISTANCE (m)
P=8
P=16
+ MEASURED WHEN A TUNER AT THE HIGH ENERGY END IS MOVED IN
o MEASURED WHEN A TUNER AT THE LOW ENERGY END IS MOVED IN
SOLID CURVES SHOW CALCULATED VALUES
P IS A HEIGHT OF STEP FUNCTION (SEE THE TEXT)

Fig. 6


AVERAGE AXIAL FIELD (MV/m)
2.6
2.2
1.8
1.4
MEASURED
CALCULATED FOR ACCELERATION OF DEUTERONS
CHANGE IN FUNCTION $m^2(z)$ GIVEN BY TUNERS
20
10
0
-10
-20
0
2
4
6
8
10
12
14
DISTANCE (m)

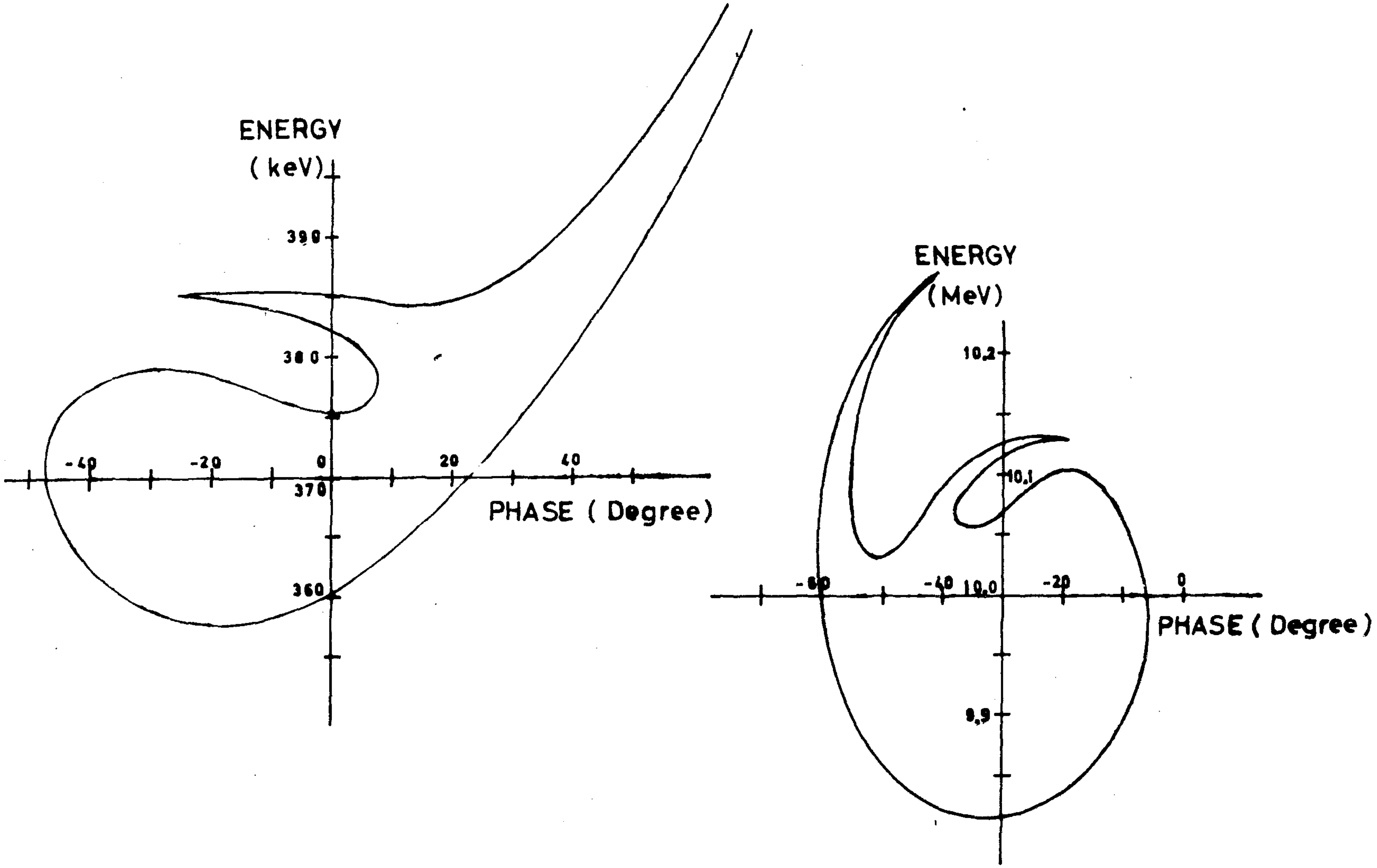

ENERGY
(keV)
390
380
370
360
-40
-20
0
20
40
PHASE (Degree)
ENERGY
(MeV)
10,2
10,1
10,0
9,9
-60
-40
-20
0
PHASE (Degree)

Fig. 7