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Focussing of multibeamlets produced from a large accelerator grid is a key issue of ion beam application to the neutral beam injector (NBI) of fusion devices. Another issue is highlighted in a case of negative ion based NBI to compensate beamlet deflection inside the extractor, where magnetic field is applied for suppression of electron extraction. Steering of H^- beamlet was carried out by displacing apertures in an electrostatic extractor/accelerator composed of four grids, where the beam energy was in the range of ~50 keV. Out of a few combination of grid displacement, displacement of ESG (3rd grid) and/or GRG (4th grid) was found to be successful: 1) The beamlet steering angle of 50 mrad was obtained by displacing the apertures of 9 mm dia. up to 3mm. It was confirmed that the steering angle was proportional fairly well to the displacement. The characteristic of the steering, i.e., the steering angle as a function of displacement, agrees well with the analysis based on the linear optics theory. 2) Neither significant divergence growth nor the beam interception were observed in the steered beams over a wide range of operation. The H^- beams, of which divergent angle was 5 mrad, was obtained even under the beamlet steering. Thus the steering by displacement is suitable for the focusing of negative ion beam generated from multi-aperture grids. 3) It was found that the steering angle was independent of the magnetic field direction in the present extractor structure. This is an advantage of the steering technique for compensation of the beam deflection inside the extractor by magnetic field.

Keywords: Nuclear Fusion, ITER, Neutral Beam, NBI, H^- Ion, Accelerator, Ion Beam, Beam Optics, Thin Lens Theory, Beam Focussing, Beam Steering

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孔変位によるH^-イオンビームの偏向

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核融合実験炉用中性粒子入射装置（NBI）では、大面積から発生する大電流負イオンビームを集束するとともに、引き出し部での電子抑制磁場によるビーム偏向を補正することが必要となる。本研究は、上記ビーム集束と磁場偏向の補正を孔変位によるビーム偏向で行うための基礎研究である。4電極からなる引き出し部・加速器内の電極孔を意図的に変位させることにより、ビームエネルギー 50 keV までの H^-イオンビームを偏向した。4電極のうち電子抑制電極（ESG：第3電極）および接地電極（GRG：第4電極）に孔変位を設けることにより、以下のように良好な偏向特性が得られることが明らかになった。1）直径9 mmの孔を3 mmまでの変位させることにより最大50 mradの偏向角が得られた。偏向角は孔変位量に比例し、偏向角と孔変位量の関係は線形光学理論に基づく解析結果とよく一致する。2）孔変位による偏向を受けたビームレットでは、その発散角の増大またはビームレットの電極への直接衝突は観測されず、5 mradの発散角を持つビームレットが偏向後にも得られた。このように孔変位によるビーム偏向は、多孔静電加速器から発生する負イオンビームの集束に適していることが明らかとなった。さらに、3）今回使用した引き出し部体系では、孔変位によるビーム偏向が引き出し部内の磁場の方向に依存しないことを確認した。これは磁場によって偏向されたビームレットの軌道補正にも孔変位によるビーム偏向が適用可能であることが判明した。

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1. INTRODUCTION

A technique to steer positive ion beamlet by aperture displacement[1-5] has been utilized to focus the high current beam produced from a wide extraction area toward a narrow beamline of neutral beam (NB) injectors for fusion application. In JT-60 NB injectors[6] based on positive ion beam, the deceleration grid was displaced to focus the multi-beamlets extracted from an area of 12 cm x 27 cm toward a focal point (8.3 m away from the source) in the port on the tokamak.

As the fusion R&D's progress, a requirement in high energy (500 keV ~ 1.3 MeV) NB was increased not only to heat the plasma but also to drive the plasma current. The negative ions (H^- or D^-) are used as primary beams, instead of the positive ions, to obtain a high neutralization efficiency (~ 60 %) even in the high energy regime.

A unique design of negative-ion-based NB system[7] is in the slender beamline, which prevents both neutrons streaming from the reactor plasma and high gas consumption rate in the neutralizer. Then the steering technique for beam focusing has more importance in the negative-ion-based NB system. The other unique point is in the negative ion extractor: In general, magnetic field is formed in the extraction gap in order to suppress electrons accompanying negative ions. For example in the sources manufactured at JAERI, small permanent magnets are embedded in the extraction grid (2nd grid) to form dipole magnetic field. Such magnetic fields formed in the extractor cause beamlet deflection.

Beamlet steering by aperture displacement is an attractive technique to fulfill above mentioned requirement; beamlet focusing and compensation of the deflection. The first experiment on the H^- beamlet deflection and steering was carried out displacing grid apertures in an extractor/accelerator with four grids. Among several combinations of the grid displacements, two sorts of grid displacement were found to be successful in the present experiment. The results are discussed on a base of the linear optics theory in the present paper.

2. EXPERIMENTAL SETUP

An illustration of the JAERI electrostatic extractor is shown in Fig 1. All negative ion sources manufactured at JAERI have the extractor of such a structure. The extractor is composed of three grids called plasma grid (PLG), extraction grid (EXG), and electron suppression grid (ESG), from source side to downstream, respectively. A pair of small magnet is embedded around each aperture in EXG to form a dipole magnetic field in the extraction gap. On single stage acceleration, another grid (GRG) is installed in the downstream at the grounded potential. Negative potentials are applied in PLG and EXG against GRG. ESG is electrically tied to EXG. Then negative ions are extracted from source plasma through PLG aperture toward downstream. Electrons are also extracted from the plasma, however, they are deflected by the magnetic field and dumped on EXG. The negative ion trajectory is deflected slightly by the magnetic field.

The cross sectional view of the extractor/accelerator aperture is shown in Fig. 2. In the figure, both ESG and GRG were displaced with respect to the others as an example. (Hereafter this is referred to as "ESG-GRG displacement".) The aperture was drilled in each grid to form multi-apertures of a 4 x 5 lattice pattern as shown in Fig. 3. In each displacement case, apertures in a column and a row were kept aligned to obtain beamlets without steering. In the rest of the apertures, i.e., 3 x 4 apertures, the displacement was examined every 0.5 mm, up to 3 mm. In the case of ESG-GRG displacement, the apertures were displaced not only for the direction parallel to the magnetic field (Fig. 3b), but also for the perpendicular direction (Fig. 3c).

The extractor/accelerator were installed in "Multi-Ampere Negative Ion Source[8]". The H^- beams of up to 60 keV, 7 mA/cm^2 were produced by pure volume operation.

Through the experiment, the pressure in the beamline was kept to be as low as 0.03 ~ 0.06 Pa by H_2 gas so that the beam does not blow up due to the space charge.

A Faraday cup, of which opening is 1 mm in diameter, located 827 mm downstream from the source, was used for the beamlet diagnoses: By scanning the Faraday cup in a plane perpendicular to the beam axis, spatial map of the beam "foot print" was obtained. Peaks of the Faraday cup signal were identified as center of the beamlets from the map.

The beamlet steered angle was determined from a distance between center of steered and unsteered beamlets in the same row, which affect the same direction and strength of magnetic deflection. Thus the effect of beamlet steering was observed separately from the deflection due to magnetic field.

3. RESULT AND DISCUSSION

3.1 BEAMLET DEFLECTION BY MAGNETIC FIELD

An example of beamlet "foot prints" is shown in Fig. 4. This foot print was obtained when the beamlets were generated from the grid with aligned apertures of the extractor/accelerator, i.e none of apertures were displaced. Each closed circle indicates positions of the maximum output corresponding to center of the beamlets. As found in the picture, well aligned beamlets were observed in horizontal direction. Distance of each beamlet in the direction was the same as that between apertures. However, in vertical direction, the beamlets produced from a same column of apertures show a zigzag pattern as if the beamlets are deflected line by line. This is the deflection of beamlet by the magnetic field in the extraction gap.

The beamlet deflection of 5 ~ 10 mrad was observed at the H^- beam energy of less than 50 keV. Obviously, such a beamlet deflection increases area of beam footprint, and hence, reduces the beam transmission in a reasonably compact negative-ion-based NB system. Some method to compensate the deflection is desired.

3.2 BEAMLET STEERING BY APERTURE DISPLACEMENT

3.2.1 Beam quality

A picture showing the beam about 1 m downstream from the source is presented in Fig. 5. In the picture the beamlets were steered in the direction perpendicular to the paper by ESG-GRG displacement. The five lines of beamlets corresponding to that produced from five rows of apertures are easily distinguished as shown in the picture. Thus well converged beamlets were obtained even if the beamlets were steered by aperture displacement.

Consequently both in ESG-GRG and GRG displacements, the divergent angle of each beamlet was decreased by 5 mrad by optimizing the source operation. Significant beam divergence growth or direct interception due to the displacement was not observed over a wide range of the operation.

3.2.2 Analytical formula

Here we attempt to derive relations between these displacements and the steering angle by the linear optics theory, which was widely used in the positive ion beam steering.

In thin lens approximation, the focal length of electrostatic lens in grid aperture is derived as; $F_1 = 4V_1 / (E_2 - E_1)$ for ESG and $F_2 = 4(V_1 + V_2) / E_2$ for GRG. The strength of the electrostatic field, E, is simply calculated by dividing the voltage by the gap length as the first approximation.

Now it is not appropriate to adopt the thin lens approximation for the ESG lens, since EXG seems thick enough to isolate the ESG lens from E_1. If we neglect E_1, the focal length, F_1, is simply given as;

$$F_1 = 4V_1 / (E_2 - E_1) \sim 4V_1 / E_2 \tag{1}$$

When ESG is displaced by δ_1, the steering angle θ_1 at ESG exit is expressed as

$$\theta_1 = \left(\frac{V_1}{V_1 + V_2}\right)^{\frac{1}{2}} \frac{\delta_1}{F_1} \tag{2}$$

Here the first part of the product, $[V_1/(V_1+V_2)]^{1/2}$, is the energy compensation for the extracted negative ion beam.

The steered beamlet trajectory is compensated by an axial acceleration:

$$\theta_{acc} = -\frac{2\{V_1(V_1 + V_2)\}^{1/2} - 2V_1}{V_2} \frac{\delta_1 \delta_2}{F_1 F_2} \tag{3}$$

In the GRG, the steering angle θ_2 is written as a function of GRG displacement δ_2;

$$\theta_2 = \frac{\delta_2}{F_2} \tag{4}$$

If both ESG and GRG are displaced, the beam suffers steering in ESG, axial acceleration, and another steering in GRG, eventually. Then the sum of these angles appears as the actual steering angle measured at the downstream experimentally.

3.2.3 Steering angle

The beam steering angles as functions of ESG-GRG and GRG displacements are shown in Fig. 6. It is confirmed that the beamlet steering angle is proportional fairly well to the aperture displacement. For the displacement up to 3 mm, the beamlets were steered by 50 mrad in ESG-GRG displacement, and 20 mrad in GRG displacement.

Analytical results obtained by the formulae (1) ~ (4) are also shown in the figure. The experimental and the analytical results show a good agreement in GRG displacement, while the steering angle obtained in the experiment was about 20 % smaller than the analytical prediction in ESG-GRG displacement. This seems due to that E_1 affects to ESG lens to some extent, though the effect was neglected in the previous formula (1).

In GRG displacement, the steering angle was measured with a constant ratio of extraction / acceleration voltage to be $V_1 / V_2 = 1 / 11$. The result is shown in Fig. 7. The steering angle did not vary over the acceleration voltage of 30 ~ 50 keV. If the ratio V_1 / V_2 is kept constant, the formula (4) becomes independent of the voltage. As the result, the steering angle is to be 6.5 mrad by the GRG displacement of 1 mm. This is also a good agreement with the experimental result. Thus a constant steering angle is obtained in the GRG displacement if the extractor / accelerator is operated at a constant perveance.

3.2.4 Effect of magnetic field

A result of ESG-GRG displacement is presented again in Fig. 8. This result contains both displacements of parallel and perpendicular directions with respect to the magnetic field. In the displacement of parallel direction, the beamlet steering by the displacement and the deflection due to the magnetic field take place toward perpendicular direction each other, while the perpendicular displacement, the steering and the deflection occur in the same direction.

There is no significant difference with the displacement directions as in the figure; i.e., Proportionality of the steering angle with respect to the displacement, and the maximum steering angle were the same in both directions of displacement. The reasons are; i) the deflection angle due to the magnetic field is relatively small, and ii) since the distance between EXG and ESG is short, the deflected beamlet is deposited immediately onto ESG lens with few deflections. Thus the beamlet steering by the aperture displacement is almost independent of the direction of magnetic field in the present extractor structure. This indicates that the beamlet deflection due to the magnetic field can be compensated by steering the beamlet to the opposite direction with proper displacement in ESG aperture.

4. SUMMARY

Displacing apertures in electrostatic extractor/accelerator composed of four grids steering experiment of H^- beamlet was carried out. Out of a few combination of grid displacement, displacement of ESG and/or GRG was found to be successful. The results are summarized as follows.

1) Neither significant divergence growth nor the beam interception were observed in the steered beams over a wide range of operation. The H^- beams of which divergent angle was less than 5 mrad was obtained even under the beam steering by the aperture displacement.

2) The beamlet steering of 50 mrad was obtained by displacing the apertures of 9 mm dia. up to 3mm.

It was confirmed that the steering angle was proportional fairly well to the displacement. The characteristic of the steering; i.e. the steering angle as a function of displacement, agrees well with the analysis based on the linear optics theory. Thus the steering by the displacement is suitable for the focussing of the negative ion beam generated from multi-aperture grids.

3) It was found that the steering angle was independent of the magnetic field direction in the present extractor structure. This is an advantage of the steering technique by the

displacement for compensation of beam deflection by the magnetic field.

ACKNOWLEDGMENTS

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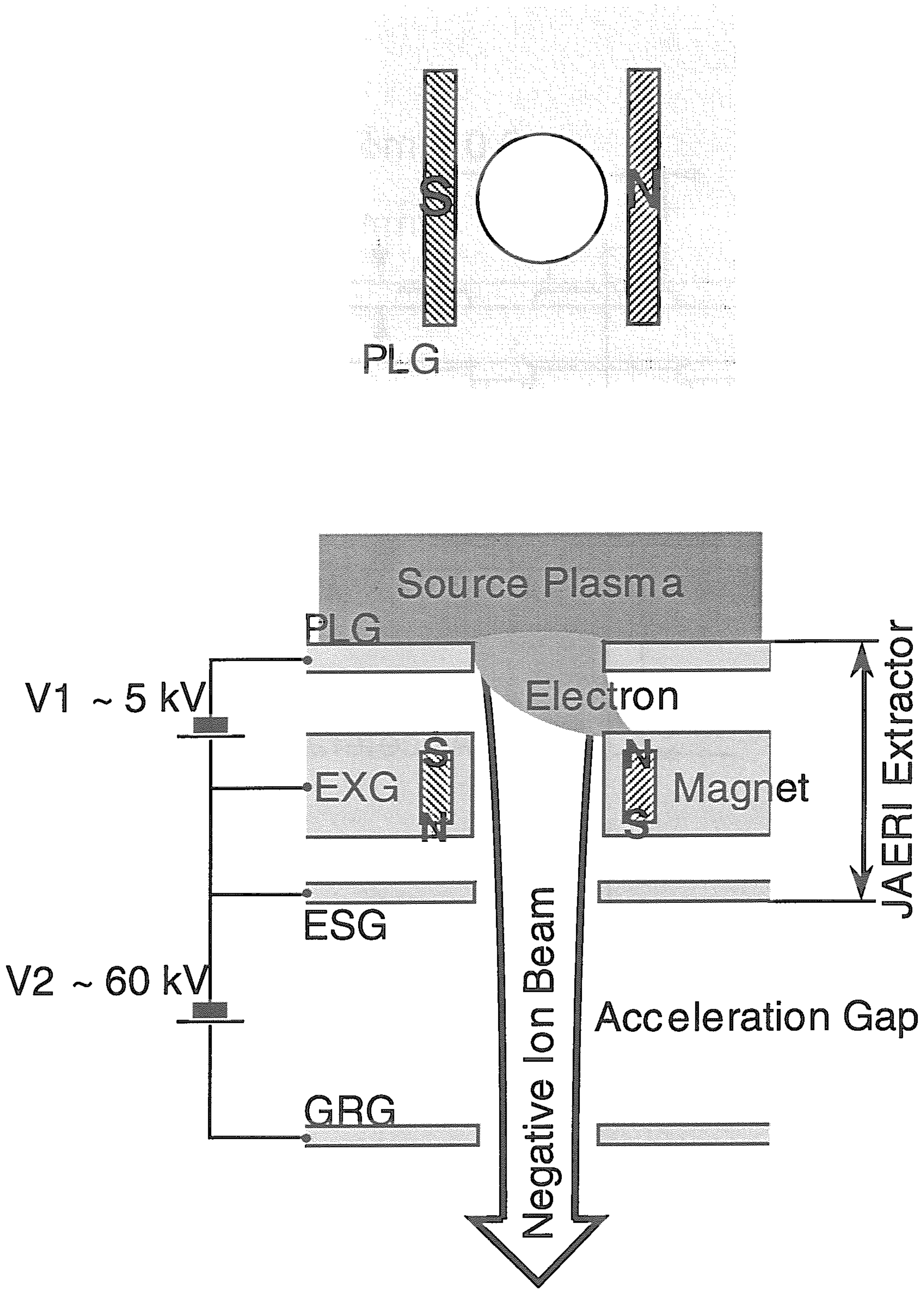

Figure 1. An illustration of the JAERI extractor with single stage acceleration gap. Electrons extracted together with the ions are deflected by the magnetic field formed by a pair of magnets.

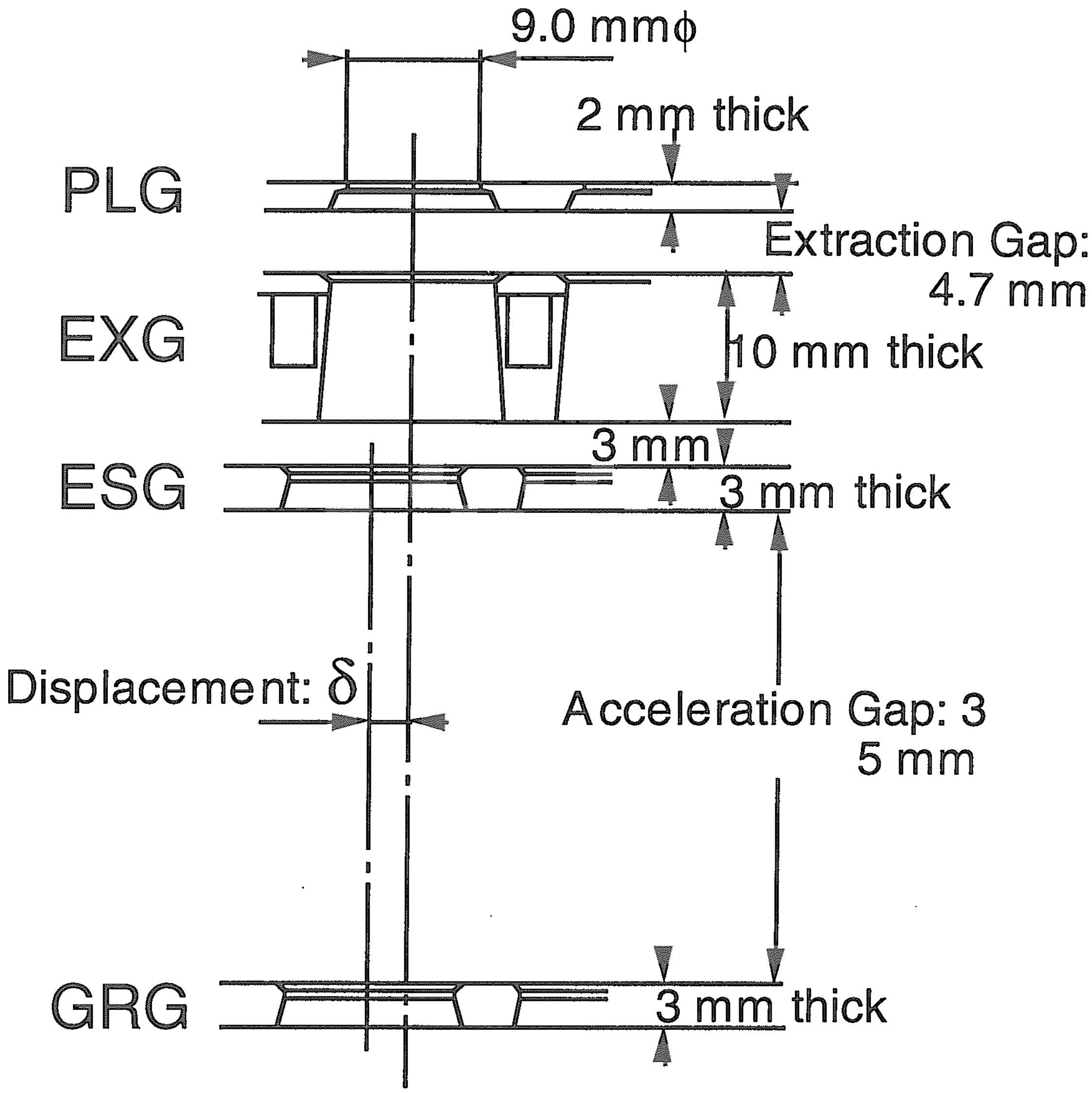

Figure 2. A cross-sectional view of the aperture in JAERI extractor / accelerator. The figure shows that ESG and GRG are displaced parallel direction to the magnetic field.

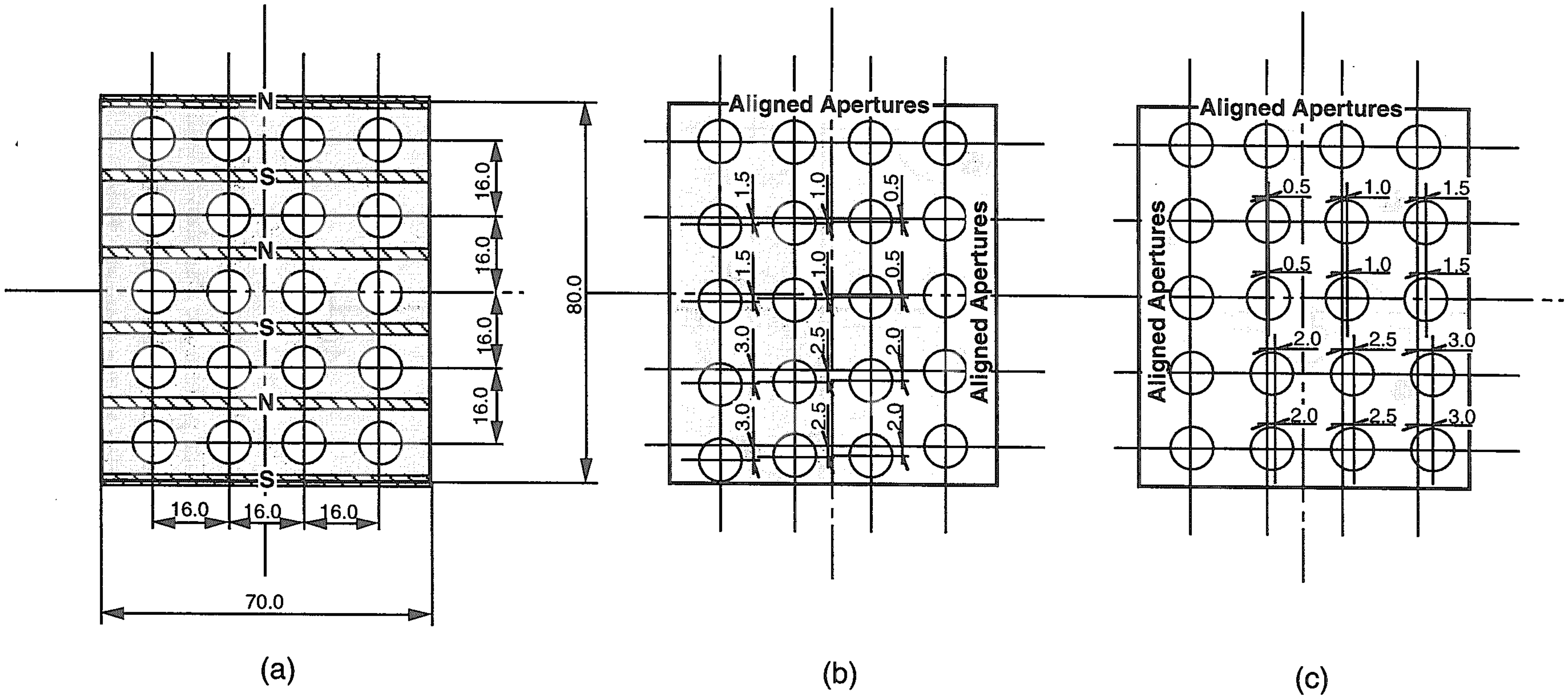

Figure 3. A plane view of the grid with multi-apertures of a 4 x 5 lattice pattern. (a) Grid with aligned apertures (PLG, EXG and ESG). The magnet arrangement in EXG is also shown in the figure. (b) Aperture displacement in the direction parallel to the magnetic field (ESG and GRG). (c) Aperture displacement in the direction perpendicular to the magnetic field (ESG).

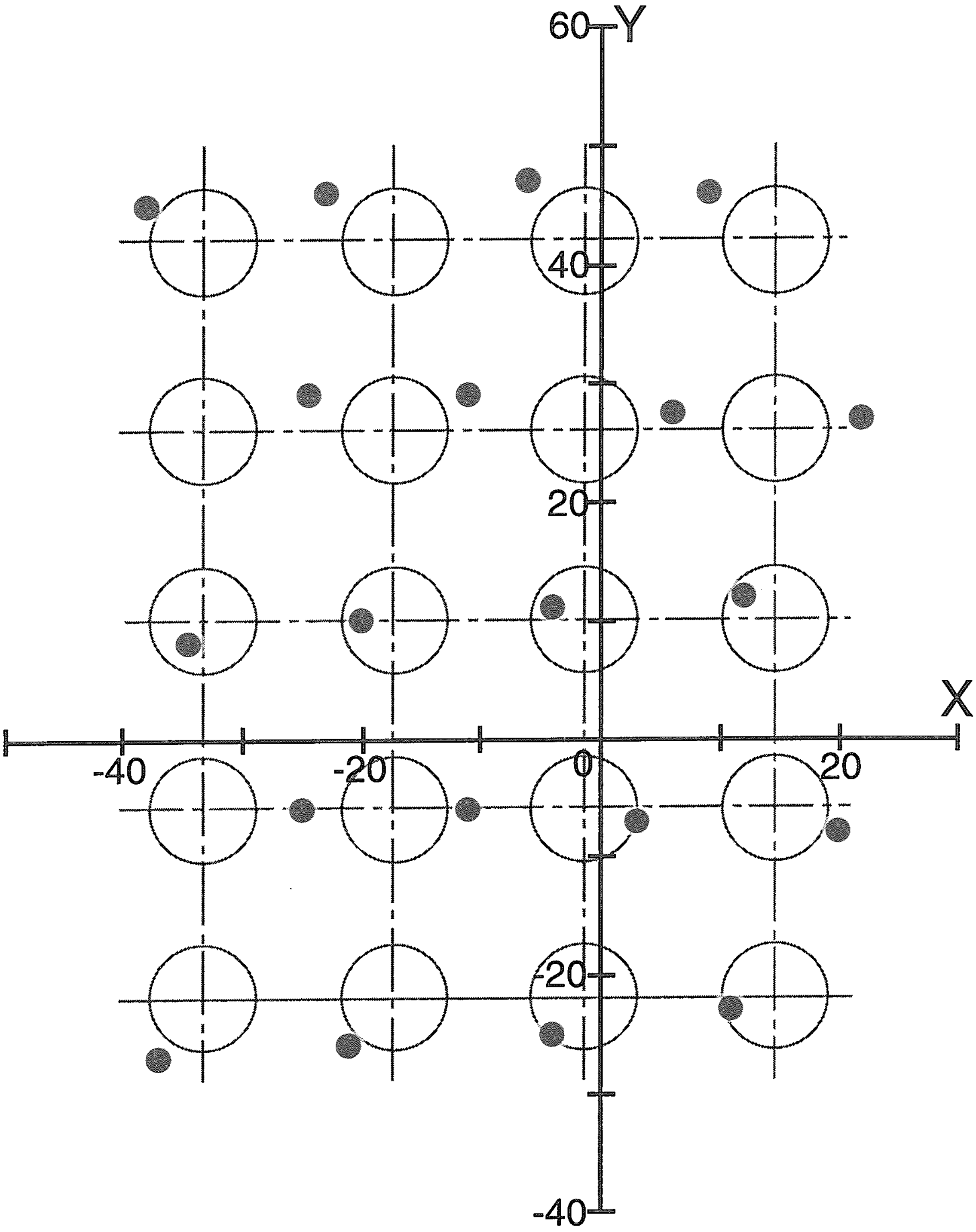

Figure 4. A "foot print" of the beamlets observed at 827 mm downstream from the source. The grid apertures of a 4 x 5 lattice pattern are also shown with shaded lines and large open circles. Center of beamlets (closed circles) show a zigzag pattern in vertical direction, as the result of beamlet deflection by the magnetic field.

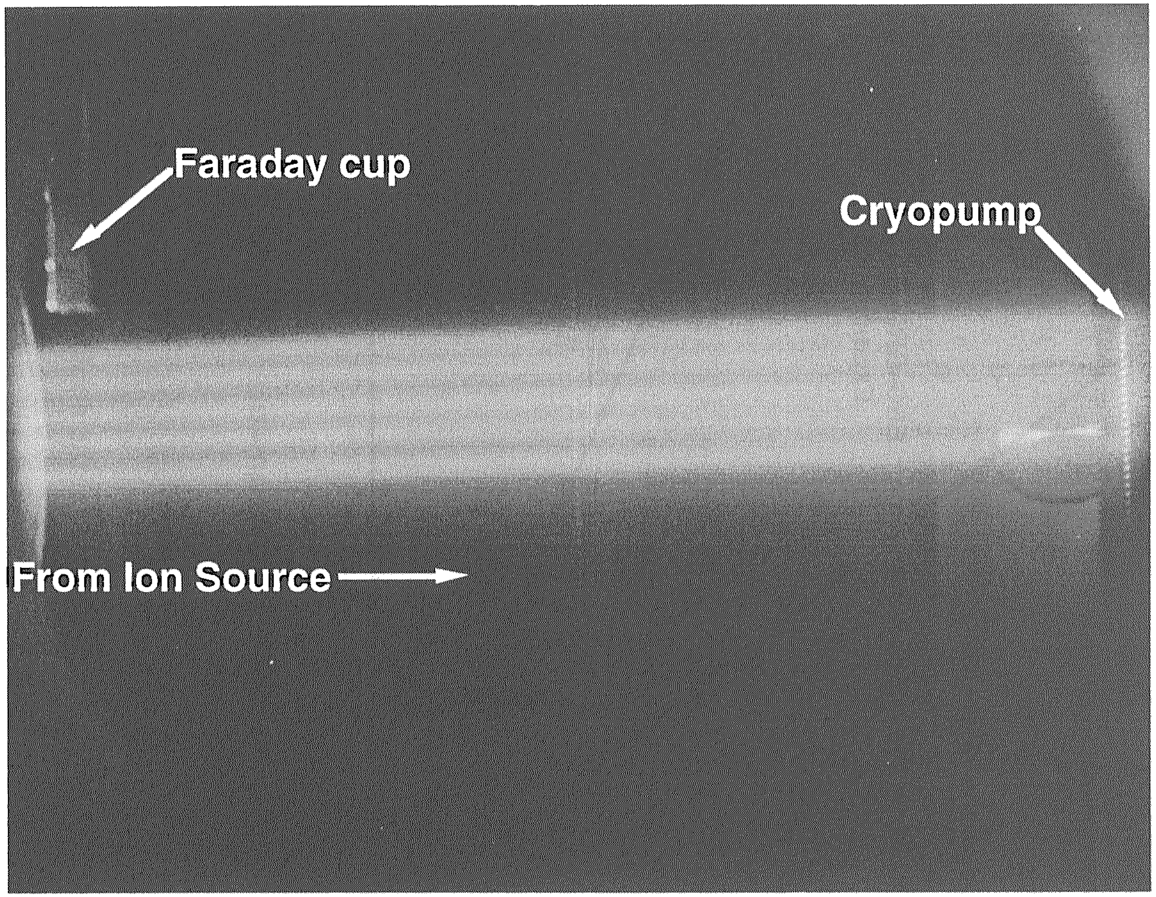

Figure 5. A picture of the beam (side view) taken at about 1 m downstream from the source. The five lines of beamlets corresponding to that produced from five rows of apertures are easily distinguished.

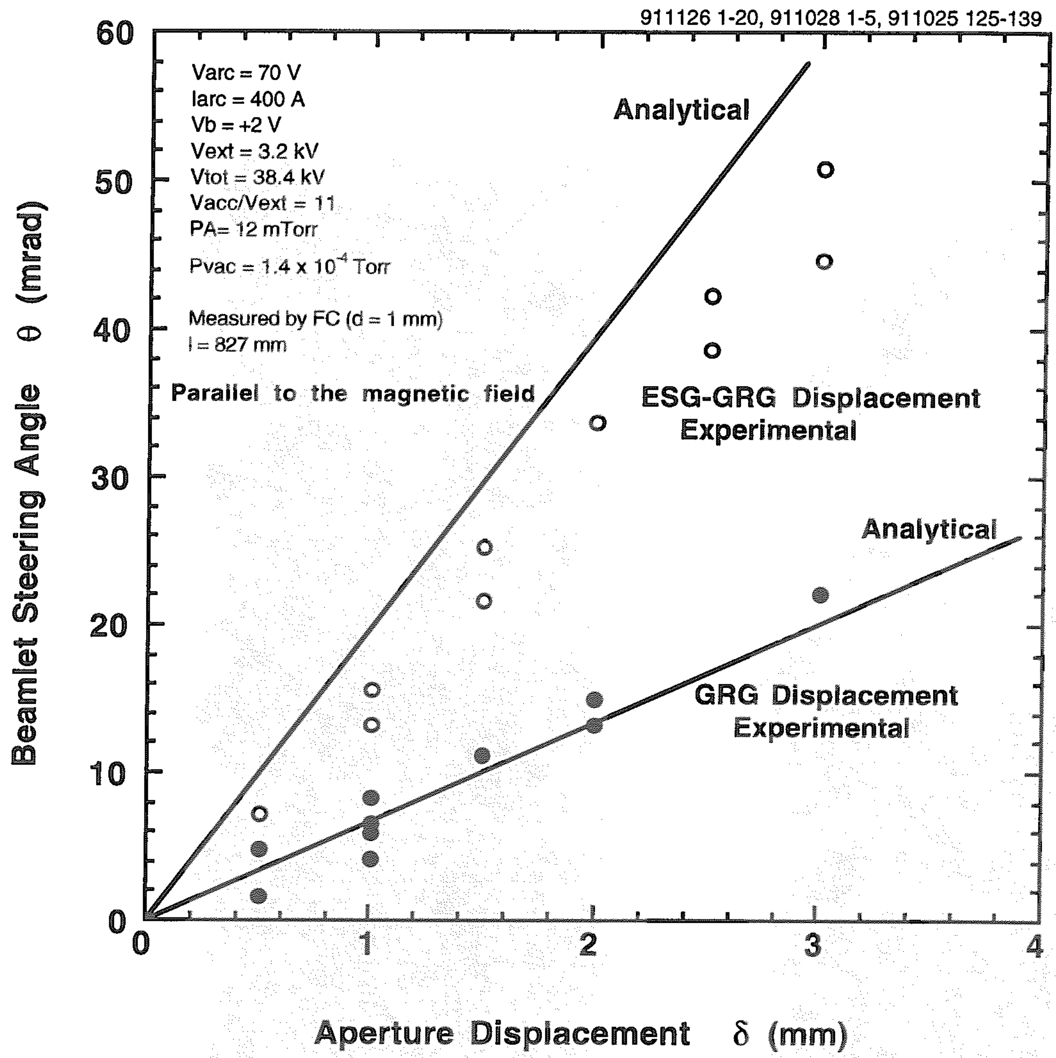

Figure 6. A beam steering angle as a function of the displacement. The steering angle increased proportionally by 50 mrad with the displacement of up to 3 mm. This characteristics are well agree with the analytical result based on linear optics theory.

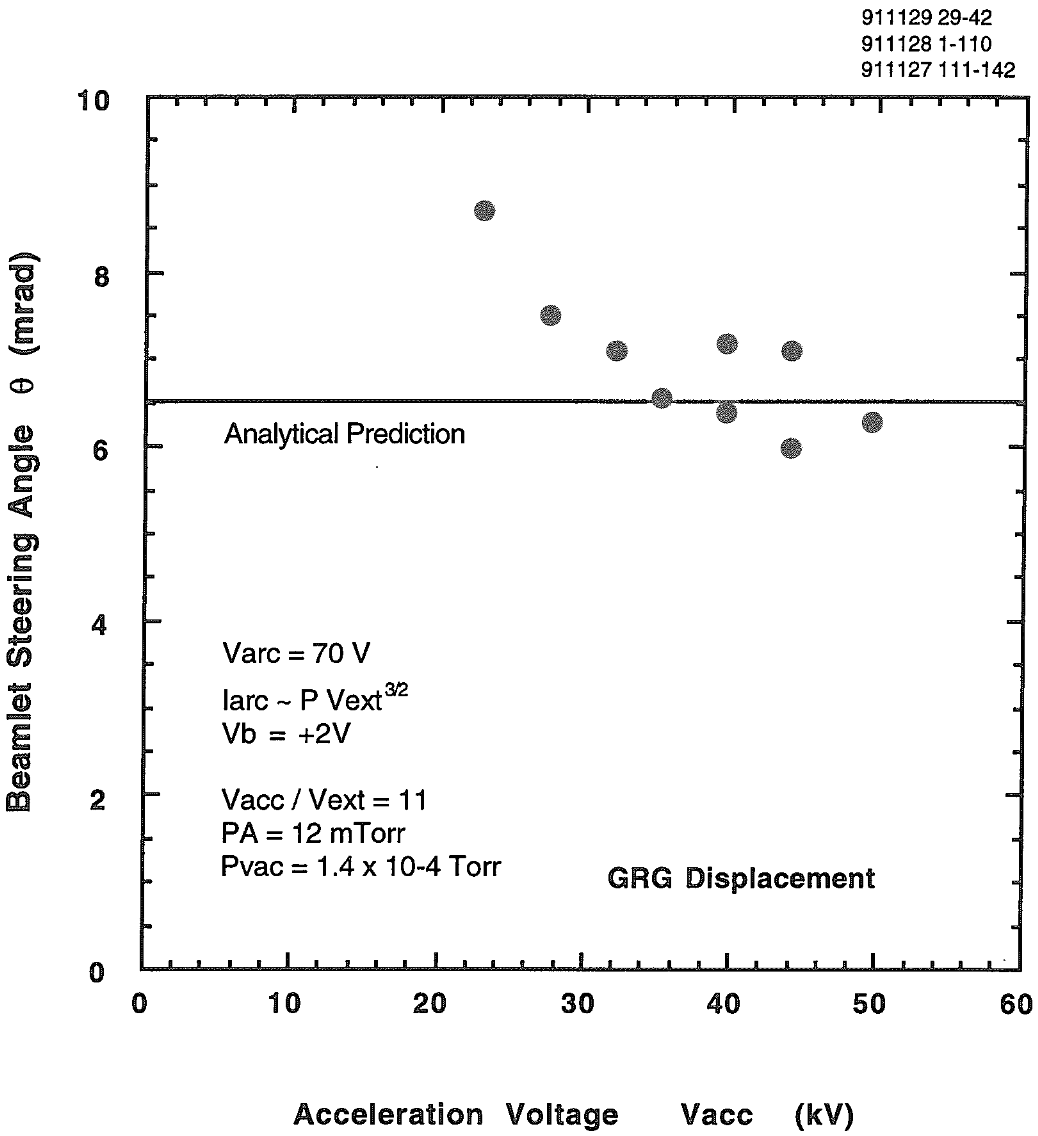

Figure 7. The steering angle in GRG displacement. The beam was produced at a constant ratio of extraction / acceleration voltage of V_1 / V_2 = 1 / 11. This is also a good agreement with the analytical result.

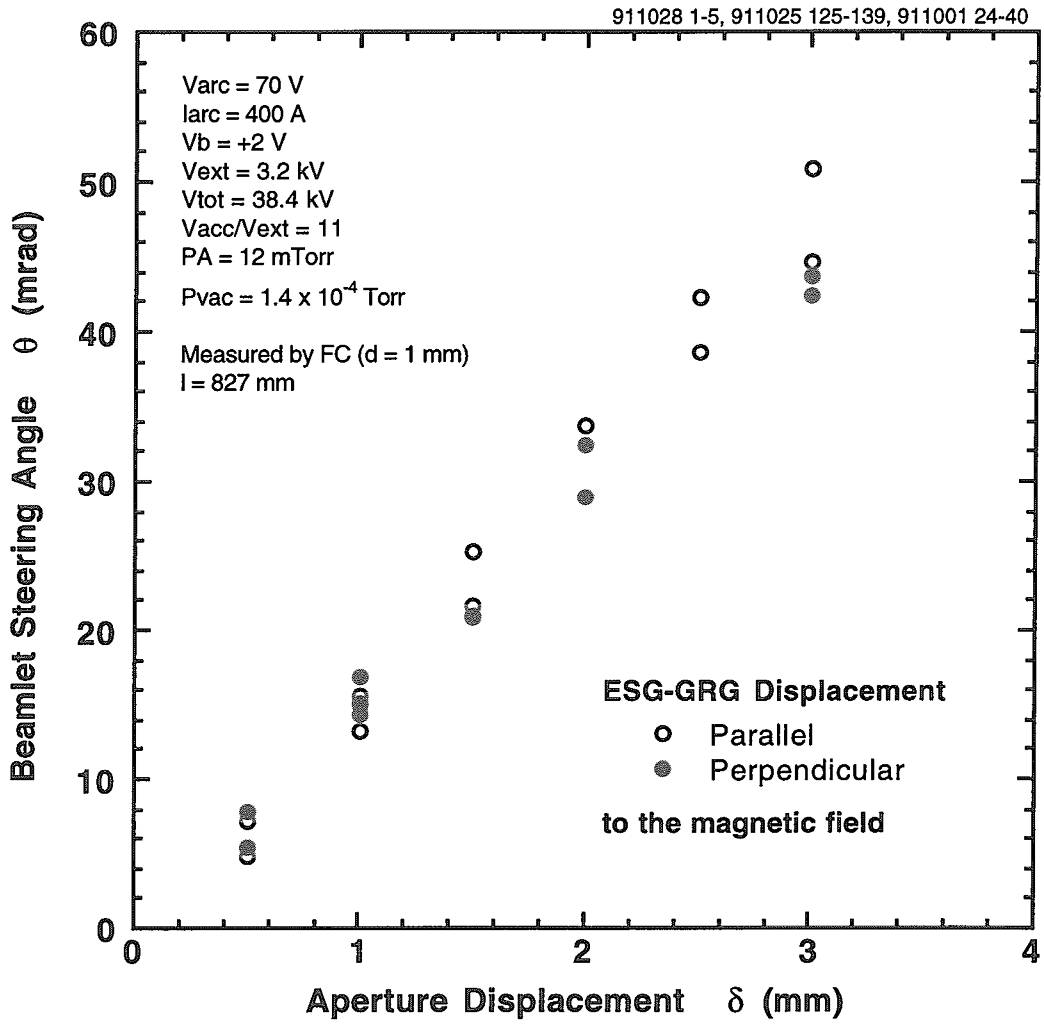

Figure 8. A comparison of the steering angle in perpendicular and parallel directions to the magnetic field. The same characteristic of beamlet steering was observed in both directions.

国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名　称	記　号
長　さ	メートル	m
質　量	キログラム	kg
時　間	秒	s
電　流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光　度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 3　固有の名称をもつ SI 組立単位

量	名　称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー, 仕事, 熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 2　SI と併用される単位

名　称	記　号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV = 1.60218 \times 10^{-19}\ J$

$1\ u = 1.66054 \times 10^{-27}\ kg$

表 4　SI と共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å = 0.1\ nm = 10^{-10}\ m$

$1\ b = 100\ fm^2 = 10^{-28}\ m^2$

$1\ bar = 0.1\ MPa = 10^5\ Pa$

$1\ Gal = 1\ cm/s^2 = 10^{-2}\ m/s^2$

$1\ Ci = 3.7 \times 10^{10}\ Bq$

$1\ R = 2.58 \times 10^{-4}\ C/kg$

$1\ rad = 1\ cGy = 10^{-2}\ Gy$

$1\ rem = 1\ cSv = 10^{-2}\ Sv$

表 5　SI 接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1. 表 1 − 5 は「国際単位系」第 5 版，国際度量衡局 1985 年刊行による。ただし，1 eV および 1 u の値は CODATA の 1986 年推奨値によった。
2. 表 4 には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表 2 のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表 2 のカテゴリーに入れている。

換　算　表

力	N($=10^5$dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ Pa \cdot s(N \cdot s/m^2) = 10\ P$(ポアズ)$(g/(cm \cdot s))$

動粘度　$1\ m^2/s = 10^4 St$(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J($=10^7$erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）
　= 4.184 J　（熱化学）
　= 4.1855 J　（15 °C）
　= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）
　= 75 kgf·m/s
　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86 年 12 月 26 日現在）