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POWER LOADING ON THE BEAMLINER COMPONENTS
AND BEAM DIVERGENCE OF THE NEGATIVE-ION
BASED NBI SYSTEM FOR JT-60U

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Power Loading on the Beamline Components and Beam Divergence of the Negative-Ion Based NBI System for JT-60U

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In JT-60U, a high energy neutral beam injection program with the negative-ion based NBI (N-NBI) has been progressed for non-inductive current drive and core plasma heating studies in high density plasma. The target performance of the N-NBI is the neutral beam injection power of 10MW for 10 seconds at 500keV, and a neutral beam power of 5.2 MW at 350keV has already been injected into JT-60U plasma. The beam divergence and power loading onto the beamline components are two important items to evaluate beam performance. The beam divergence estimated roughly at the beam drift duct in beam injection experiment into JT-60U plasmas is around 4 mrad for horizontal direction and 6 mrad for vertical one, which is close to the design value of 5 mrad. The power loading measured at the beamline components showed a reasonable result as compared with the design value.

Keywords: JT-60U, NBI, Negative-ion, Power Loading,
Beam Divergence, Beamline

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**JT-60 用負イオン NBI システムにおける
ビームライン機器の熱負荷及びビーム発散**

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JT-60 では、高密度プラズマでの非誘導電流駆動及び中心加熱研究のため、負イオン NBI (N-NBI) を使った高エネルギー中性ビーム入射計画が進められている。N-NBI の目標性能は 500keV で 10MW のビームを 10 秒間入射する事であり、これまでに 350keV で 5.2MW の中性ビームを JT-60 に入射している。ビーム発散、ビームライン機器への熱負荷は、ビーム性能を評価する上できわめて重要な項目である。JT-60 プラズマへのビーム入射実験中にドリフト管で評価したビーム発散は水平方向で 4mrad、垂直方向で 6mrad であり、これは設計値の 5mrad に近い値である。ビームライン機器への熱負荷測定値も設計値と比べて妥当な値である。

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1. Introduction

High energy neutral beam injection (NBI) has been considered to be an essential role for non-inductive current drive and core plasma heating in the magnetically confined thermonuclear fusion research. Moreover it can be worked for suppressing plasma instability and improving plasma confinement by delivering the momentum to the plasma in the toroidal direction, and for controlling the spatial distribution of the plasma current. For those purposes, high power NBIs which can deliver tens of MW neutral beams at an energy of 100 keV-class had been developed with positive ion based (P-NBI). The large plasma confinement devices such as JT-60U, JET and TFTR have already attained high performance plasma conditions with D or D-T operation by injecting tens of MW neutral beams at an energy of about 100keV, in particular JT-60U and JET have already reached the breakeven condition which fusion thermal output is equal to plasma heating power.

For the reactor-like fusion devices such as ITER and even the present large tokamak JT-60U, a higher energy (~ 0.5 MeV for JT-60U, ~ 1 MeV for ITER) and a long pulse neutral beam is required for effective central non-inductive current drive and plasma heating at a high plasma density. Considering ion beam neutralization efficiency, the conventional positive-ion based NBI system decreases sharply as increasing of the ion beam energy over 100 keV shown in Fig. 1. Therefore it is necessary to utilize a negative ion beam with neutralization efficiency as high as 60 % with a gas cell.

A negative ion source used in the NBI device is required to accelerate negative ions of a few tens of amperes at a higher beam energy. The researches of negative ion source for increasing negative ion current have been carried out at many laboratories in the world for a long time. The negative ion current achieved, however, was only a level of 100mA until 15 years ago. At JAERI, R&Ds for the negative-ion source have been progressed aiming at a higher beam current more than 10 A and a higher beam energy over 500 keV since middle of 1980's. Concerning a higher current of negative-ion beams, a H^- current of 10 A at 50 keV had been achieved in 1990 using a multi-cusp ion source with seeding Cs [1]. In 1994, a negative hydrogen beam of 180 mA at an energy of 400keV had been accelerated with a higher energy acceleration ion source [2].

In addition to these ion source R&Ds, the high voltage dc power supply for ion source and beamline components had been developed [3]. The design study for a 500 keV negative-ion based NBI system had been also executed for several years. Based on these R&Ds results, the construction of the 500 keV negative-ion based NBI (N-NBI) system [4], shown in Fig.2 and Fig.3, had been judged having no technical problem. It aims at the target: the injection power of 10 MW for 10 seconds at 500 keV. Since the first operation of the N-NBI started in 1996, the negative ion beam power per source has reached 14.3 A at 380 keV (5.4 MW) with deuterium and 18.5 A

at 360 keV (6.6 MW) with hydrogen, and the neutral beam power injected into JT-60 has been obtained 5.2 MW at 350keV with deuterium and 4.2 MW at 360 keV with hydrogen[5,6]. A neutralization efficiency of the negative ion beam has been confirmed to be about 60 % at a beam energy range of 250-385 keV as predicted theoretically as shown in Figure 1.

The estimation of the beam divergence and power loading on the beamline components is a very important item for ameliorating performance of negative ion beam aiming at higher beam power. In this report, the power loading on the beamline components, estimation of neutral beam divergence, and time evolution of the beam parameters for the injection shots in the beam injection experiments of 1998 are discussed. Outline of the N-NBI beamline is described briefly as well.

2. Outline of the 500keV N-NBI beamline [7, 8]

The schematic drawings for the 500 keV N-NBI system are shown in Fig.2 and Fig.3. It is composed of one beamline, two ion sources, a power supply system, a control system and an auxiliary sub-system including water cooling, helium refrigeration and auxiliary vacuum pumping systems.

The negative ion source is composed of a negative ion generator, an extractor and an accelerator. The negative ion generator is a cesium-seeded multi-cusp type. A small amount of cesium vapor is injected into the negative ion generator through a transport pipe from an external cesium oven to drastically enhance the negative ion yield by a factor of about 2-5 higher than that of the pure volume production. Furthermore it makes remarkably decrease the optimum operation pressure without deterioration of negative ion production. The cesium effect strongly depends on the temperature of plasma grid. The optimum temperature is experimentally confirmed to be about 250~300°C. The extractor has three grids; a plasma grid, an extraction grid and an electron suppression grid. The extractor is a multi-aperture type and its aperture size is 14 mm in diameter. The extraction area is 110 cm x 45 cm, which is divided into five segments. The accelerator has also three grids; the first and second acceleration grids, and a grounded grid. The beams are geometrically directed to the focal point of 24 m far away from the ion source with a steering mechanism, and each beamlet focusing has been also made by an aperture displacement technique.

The beamline consists of an ion source tank, a neutralizer tank, an ion dump tank and a neutral beam drift duct. The ion source tank contains a set of cryopumps for minimizing a stripping loss of negative ions in the ion source accelerator. The tank is covered with a magnetic shielding to screen a stray magnetic field from JT-60. The neutralizer tank has two 10 m long neutralizer cells corresponding to two ion sources. The ion dump tank contains a pair of bending coils, a couple of ion dumps for D^- and D^+ , a retractable calorimeter, a beam scraper and cryopumps. The calorimeter placed after the ion bending coils is composed of arrays of a composite

material of molybdenum and copper, and it is used for measuring the neutral beam power. It also serves as the beam target of neutral beams in the ion source conditioning. The neutral beam drift duct is an isolation gate valve, a bellows and a duct containing a series of beam scrapers.

3. Beam characteristics on the operation in 1998

3.1 Estimation method of beam divergence

Estimation of beam divergence[10] is very important item for ameliorating the negative ion beam performance aiming at higher beam power. The estimation procedure of the beam divergence is shown in Fig.4. The beam divergences in the horizontal and vertical directions, ω_x and ω_y , were determined by comparing the heat loads measured on the beam limiters in the drift duct with the numerical computational results. A three dimensional beam trajectory calculation code "BEMPROF" [9] is used for beam fraction calculation deposited on the scrapers.

3.2. Time evolution of the beam parameters during the neutral beam injection into JT-60

The time evolutions of the neutral beam parameters and ion source performance for the injection shots in 1998 are illustrated in Fig.5 and Fig.6, separately. In these figures, open symbols show operation result with two ion sources and solid symbols are with one ion source. Beam species is deuterium before October and hydrogen in October. In the beginning of September, a cooling water leaking trouble broke out at a filament feedthrough inside the arc chamber of the lower ion source during the beam pulse operation. We had need one month for recovering from the trouble.

In the beam injection experiments, the beam energy E_b was around 350 keV and the maximum value was nearly 380 keV. The beam energy is kept a moderate level at around 350 keV because the first priority in this experimental period is to extend the beam pulse duration. In the operation after water leak in the ion source, the beam energy was limited to 300-330 keV in spite of making the inside of the ion source clean. This voltage deterioration seems to be caused by micro-contamination on the surface of the accelerator grids owing to the water leak.

The integrated injection power, $P_{inj,m}$, defined by the product of beam power and beam pulse duration, was around 3 MJ and the maximum value was 6.7 MJ.

Although the beam pulse duration was around 1 s at the beginning of 1998, the pulse length has extended gradually with the operation time, and reached 2.2 s in maximum. The reason why extending the beam pulse is due

to a stabilization of arc discharge by taking a longer pre-arc discharge time in the negative ion generator.

The beam divergence estimated in the beam injection experiments has been confirmed around 4 mrad in the horizontal direction (ω_x), and around 6 mrad in the vertical direction (ω_y). These divergences roughly agree with the design value of 5 mrad. The beam characteristics of E_b , $E_{inj.m}$ and beam pulse duration have kept increasing gradually before October, in the meanwhile the beam divergence did not change, almost kept constant. After the water leak in September, these parameters became bad owing to the contamination of the ion source by the water leak.

The other parameters of acceleration current (I_{acc}), extraction current (I_{ext}) and arc efficiency (η_{arc}), defined by the ratio of acceleration current and arc power (P_{arc}), are shown in Fig.6. In the operation during March and April, the acceleration current with two ion sources reached a level close to 40A. The current in the operation after July, however, had not reached the level of the operation in March and April. This seems to be the reason why an instantaneous air leak had observed sometimes in the beamline during the beam acceleration, though we could not identified the point where the air leaking broke out.

The acceleration current with two ion sources shows the same trace as the arc efficiency. The extraction current had not changed so much during the operation between March and September with deuterium. However the extraction current decreased greatly after changing the gas species in October. This means that the ratio of the electron component in the extraction current with hydrogen beam is smaller than that of deuterium.

The arc efficiency of the ion source, which means the efficiency of negative ion production, had been kept a higher rate of around 0.15 in March and April. After the air break for the ion source maintenance in May, though the efficiency has recovered gradually with the operation time owing to cleaning of the arc chamber wall, it did not reached the level of March and April. This means that bad phenomena for the negative ion production such as a tiny air leakage might break out in the ion source.

Solid symbols in October of Fig.5 and Fig.6 indicate the operation only with the upper ion source. Since the upper ion source had not suffered serious damage as compared with the lower one through the water leak in September, the beam performance is a little better than that of the operation with two ion sources including the lower source.

3.3 Power flow on the beamline components

Power loading on the beamline components is measured with a water calorimetry. A power flow diagram onto the beamline components is illustrated in Fig.7 and current ratios measured in the beamline are shown in Fig.8 as a function of arc power, where the current ratio shows the ratio of

beam current impinged onto each component against acceleration drain current. In the extractor, both negative ions and electrons are extracted, and only negative ions go into accelerator by dumping almost all the electrons on the extractor grid. During the acceleration, 30~40 % of the accelerated ion beams are lost that is due to a wrong beam optics, though the design value of the loss is less than 10 %. The negative ion beams accelerated in the ion source enter the neutralizer cell just after passed through the first beam limiter. The beam losses in the beam limiter and neutralizer cell are 5 % respectively. After the neutralizer cell, the residual negative and positive ion beams, around 15 % each, are reflected to horizontal directions through a stray magnetic field from JT-60U, and are finally captured in the ion dumps. About 5 % of the neutral beam is lost in the drift duct owing to re-ionization loss and geometrical loss, the rest of neutral beams, ~30 %, are injected into JT-60U plasma.

Comparing the performance between the lower and the upper ion source, the operation parameters of both ion sources were shown in Fig.8 and Fig.9. The lower ion source appears higher calorimeter current ratio (neutral beam power ratio) and higher arc efficiency than the upper source and is of no obvious saturation. On the other hand, the current ratio of the each accelerator grid in the upper ion source is higher than that of the lower source.

On the operation with different species of hydrogen and deuterium, it is obvious that the operation with hydrogen is higher performance than that of with deuterium, as shown in Fig.10. In a higher arc power and a higher extraction voltage, there are striking difference between hydrogen and deuterium. The current ratio of the calorimeter with hydrogen is by roughly 10 % higher than that of deuterium at same arc power even in the lower extraction voltage. The arc efficiency with hydrogen is also 30~40 % higher than deuterium. Excess arc power more than 140 kW, in general, brings about the deterioration of both calorimeter current ratio and arc efficiency.

4. Summary

Although some malfunctions such as water leak in the lower ion source took place during the operation in 1998, it can be concluded to be injected a moderate neutral beam power into JT-60U from the whole year's operation data of the N-NBI.

1. Beam divergence of negative ion beam has been confirmed to be around 4.0 mrad in horizontal direction and 6 mrad in vertical direction. These roughly agree with the design value.
2. Power loading measured on the beam components is reasonable. The upper and lower ion sources have the nearly same performance. The operation with hydrogen is higher performance than that of deuterium.

3. Beam performance is kept improved gradually. In 1998 experimental campaign, the maximum beam energy of 380 keV, the maximum beam injection power of 5.2 MW and energy of 7.6 MJ, the longest pulse duration of 2.2 s, and the smallest beam divergence of 3.5 mrad in horizontal direction and 5mrad in vertical direction have been reached.

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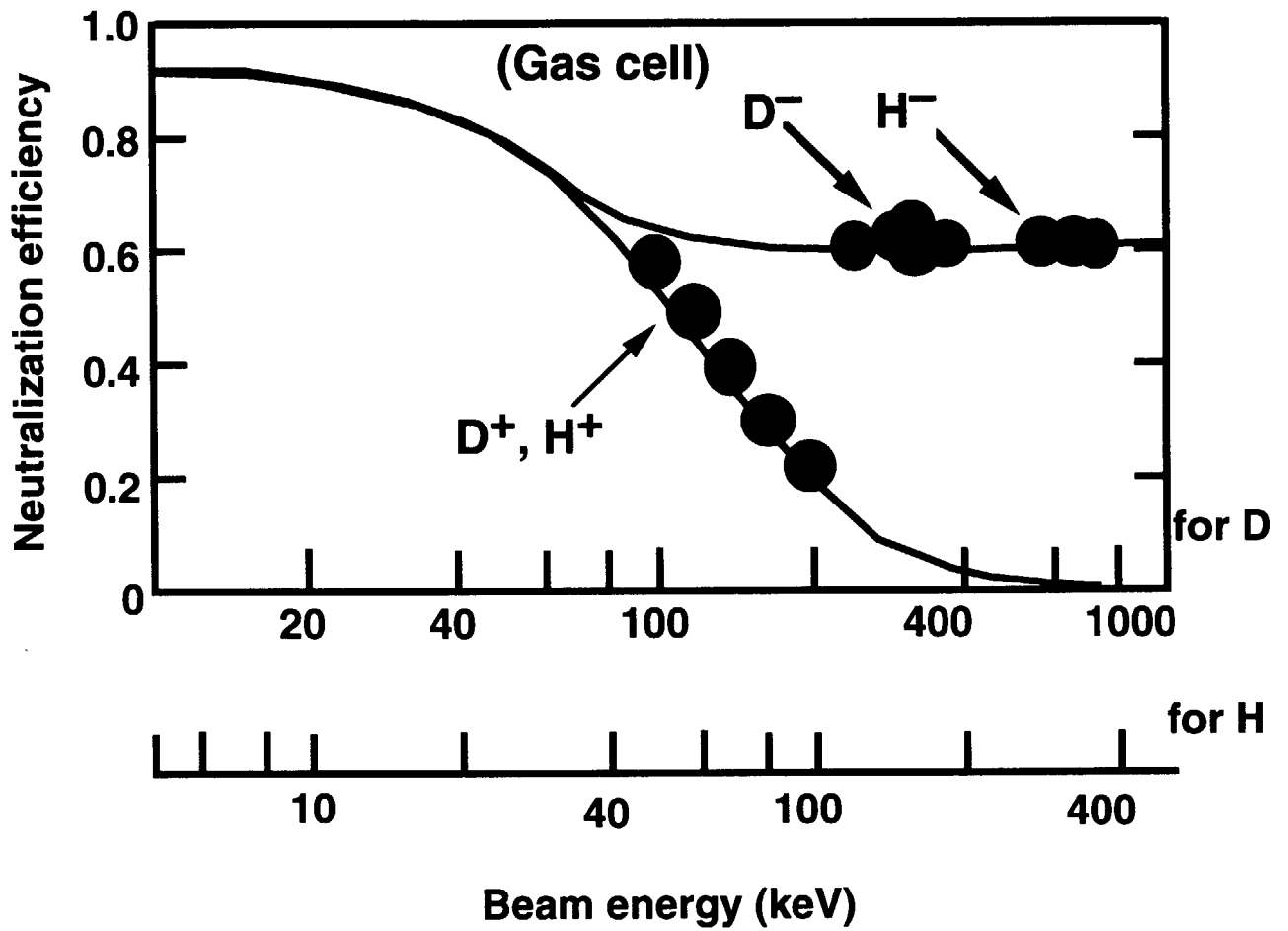


Fig.1 Neutralization efficiency of both negative and positive ion beams (Curves show a theoretical calculation , solid symbols are experimental result)

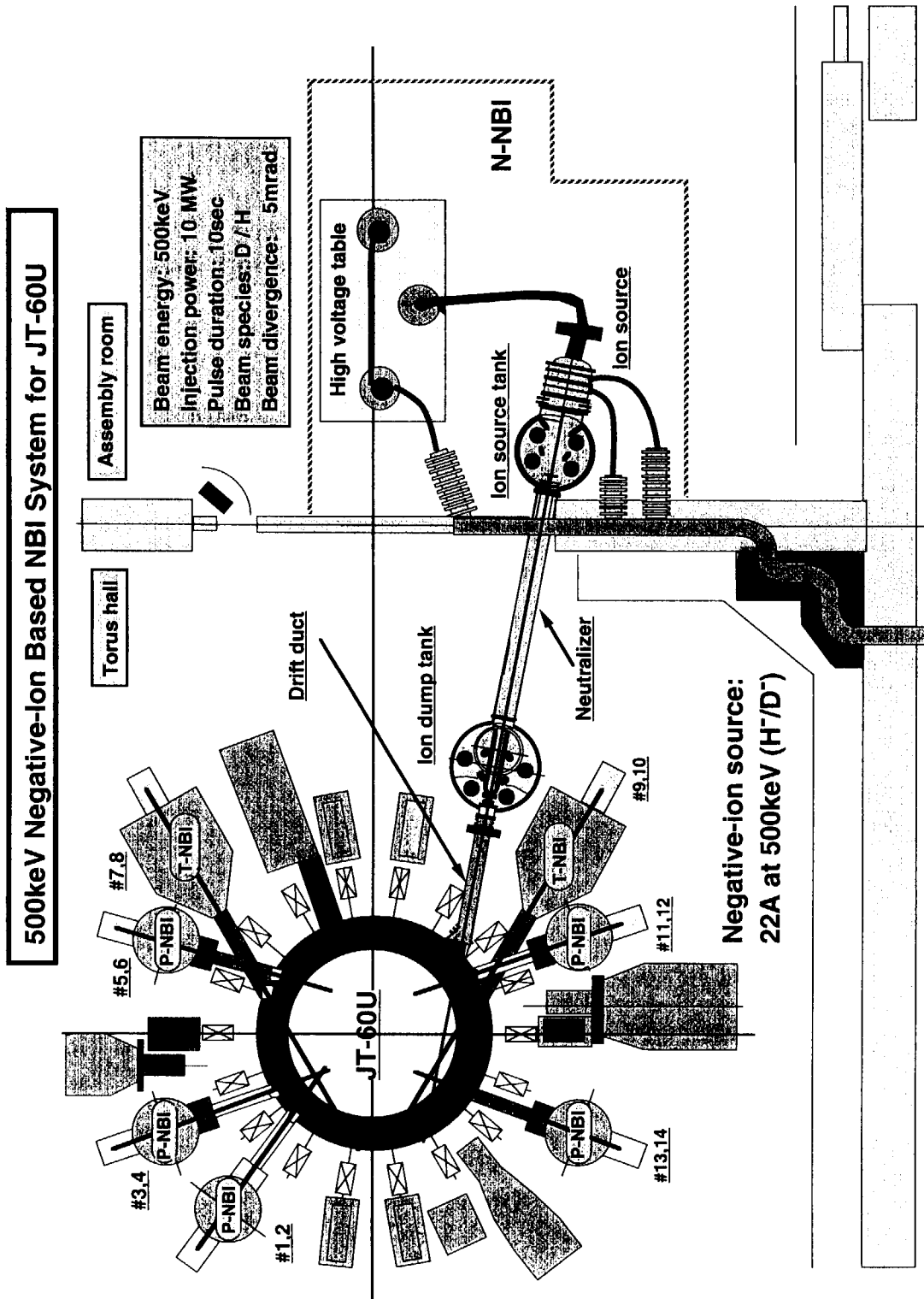


Fig.2 Plane view of the 500keV negative-ion based NBI system in the JT-60 Torus Hall

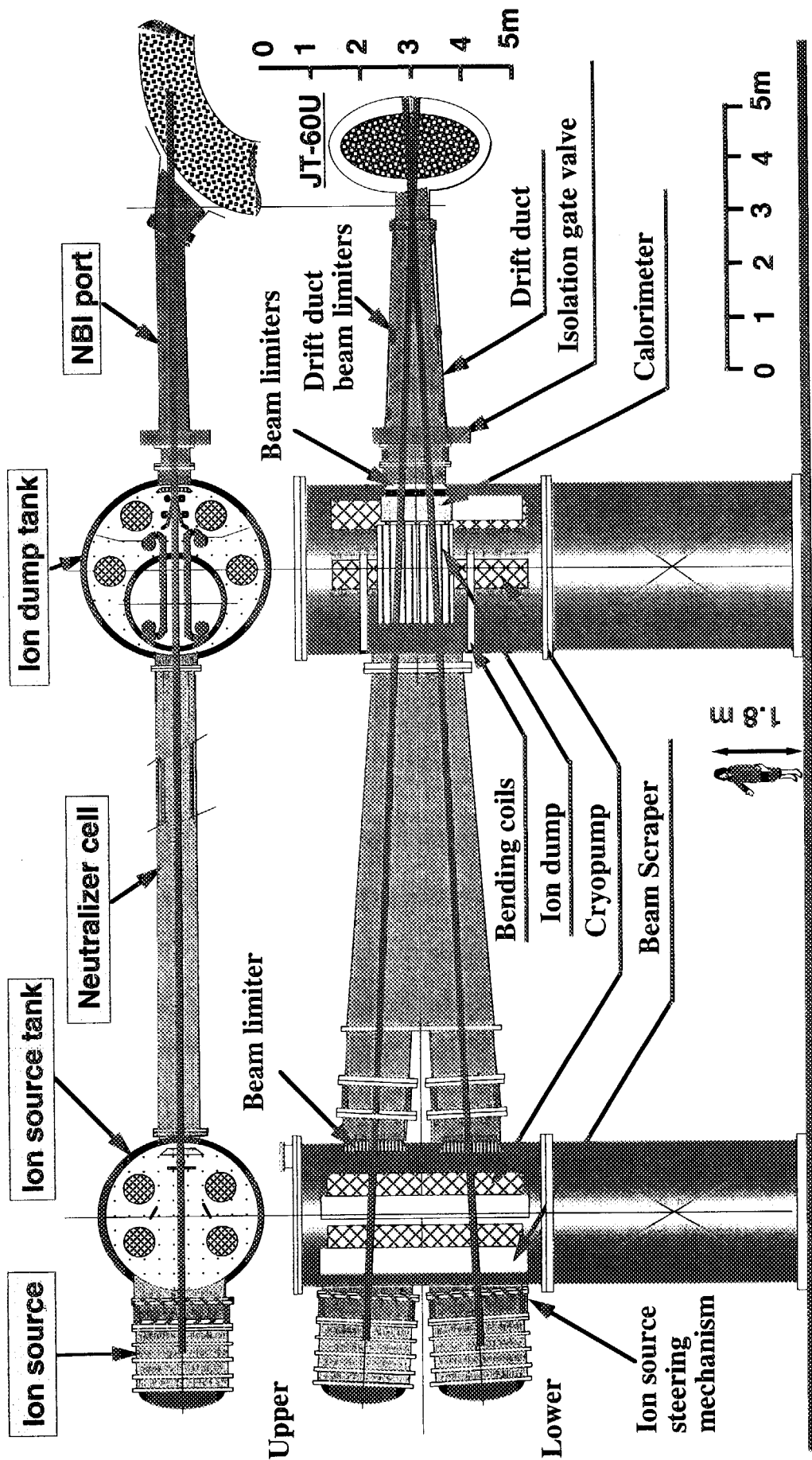


Fig3. A side view of the N-NBI Beamline for JT-60U

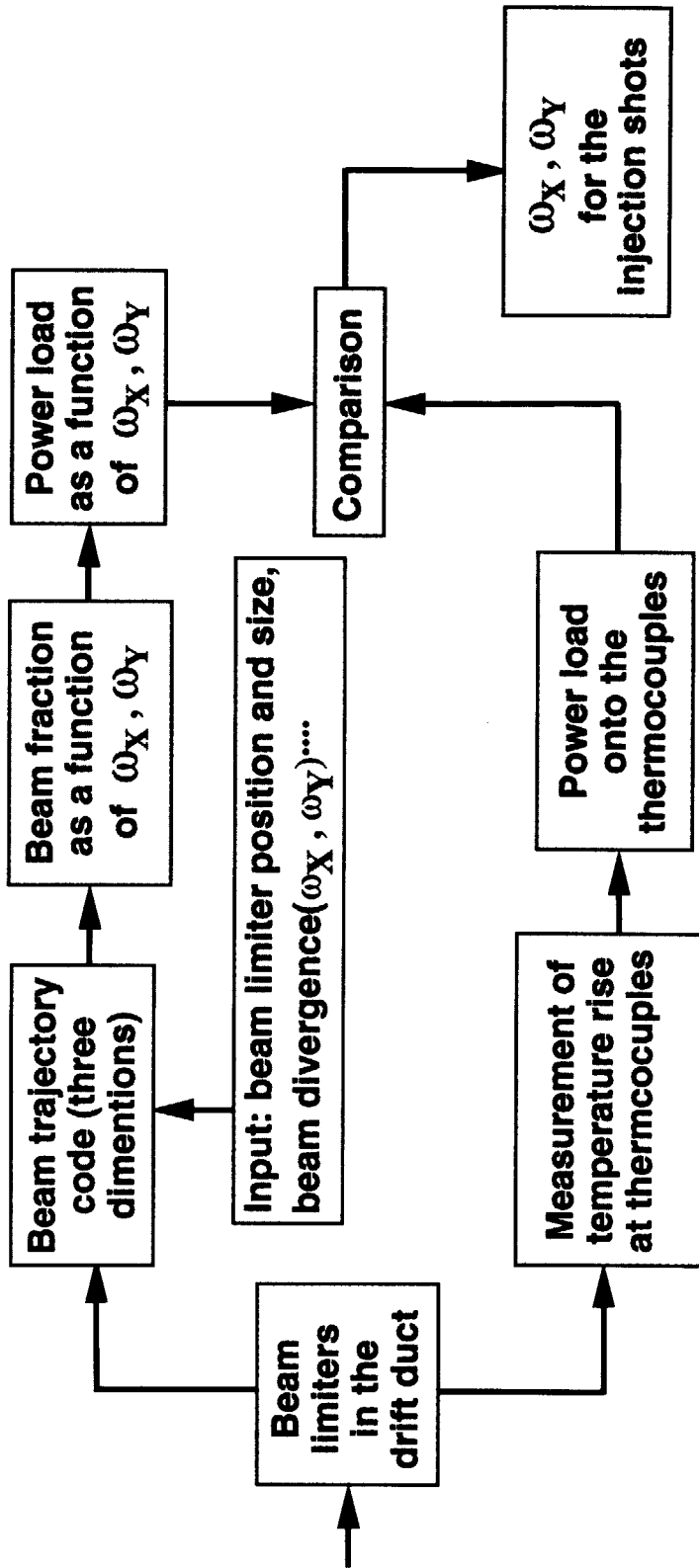


Fig.4 Estimation procedure for the beam divergence

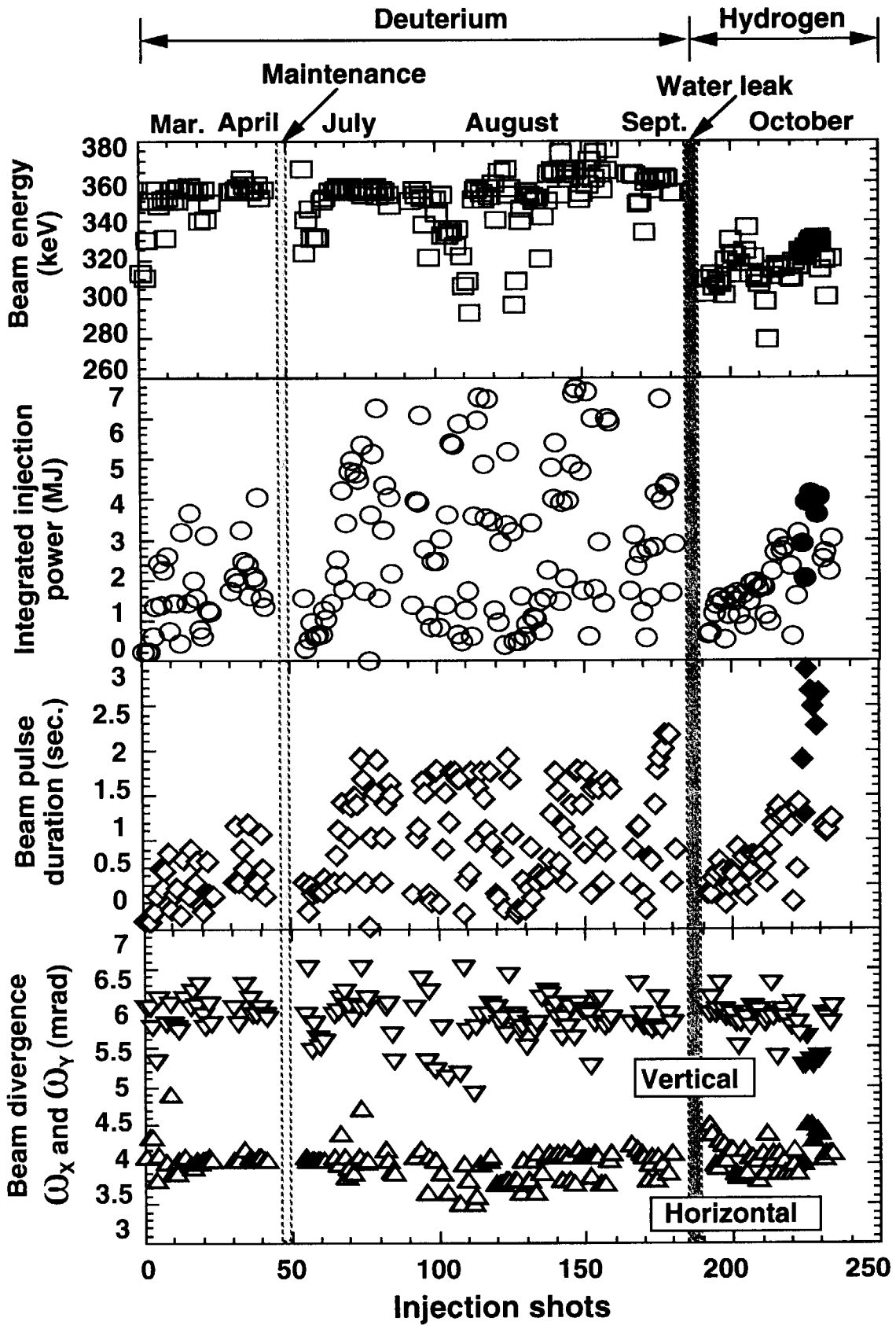


Fig. 5 Time evolution of the neutral beam for injection shots in 1998 Solid dots show the operation with only upper ion source.

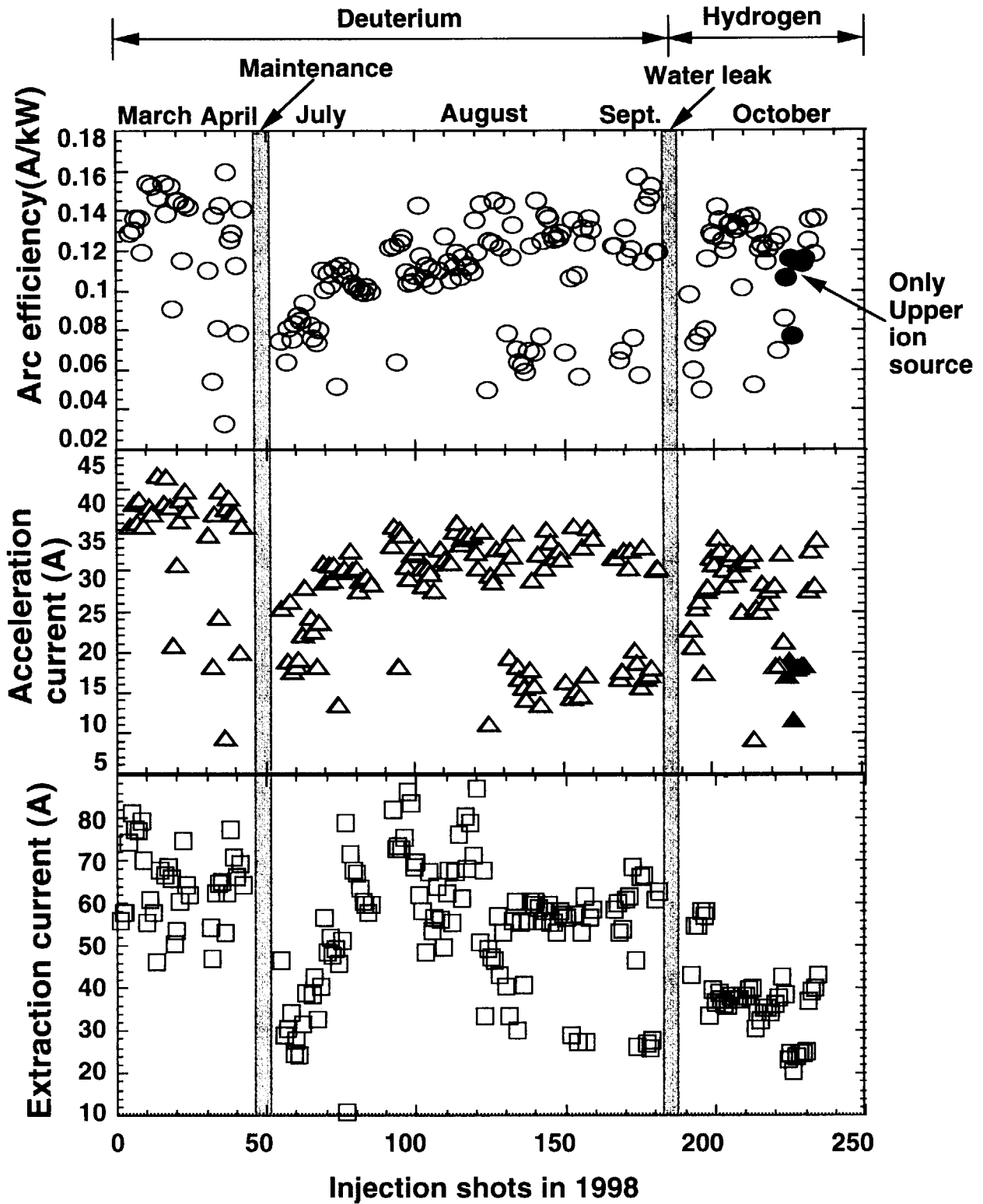


Fig. 6 Time evolution of the ion source performance

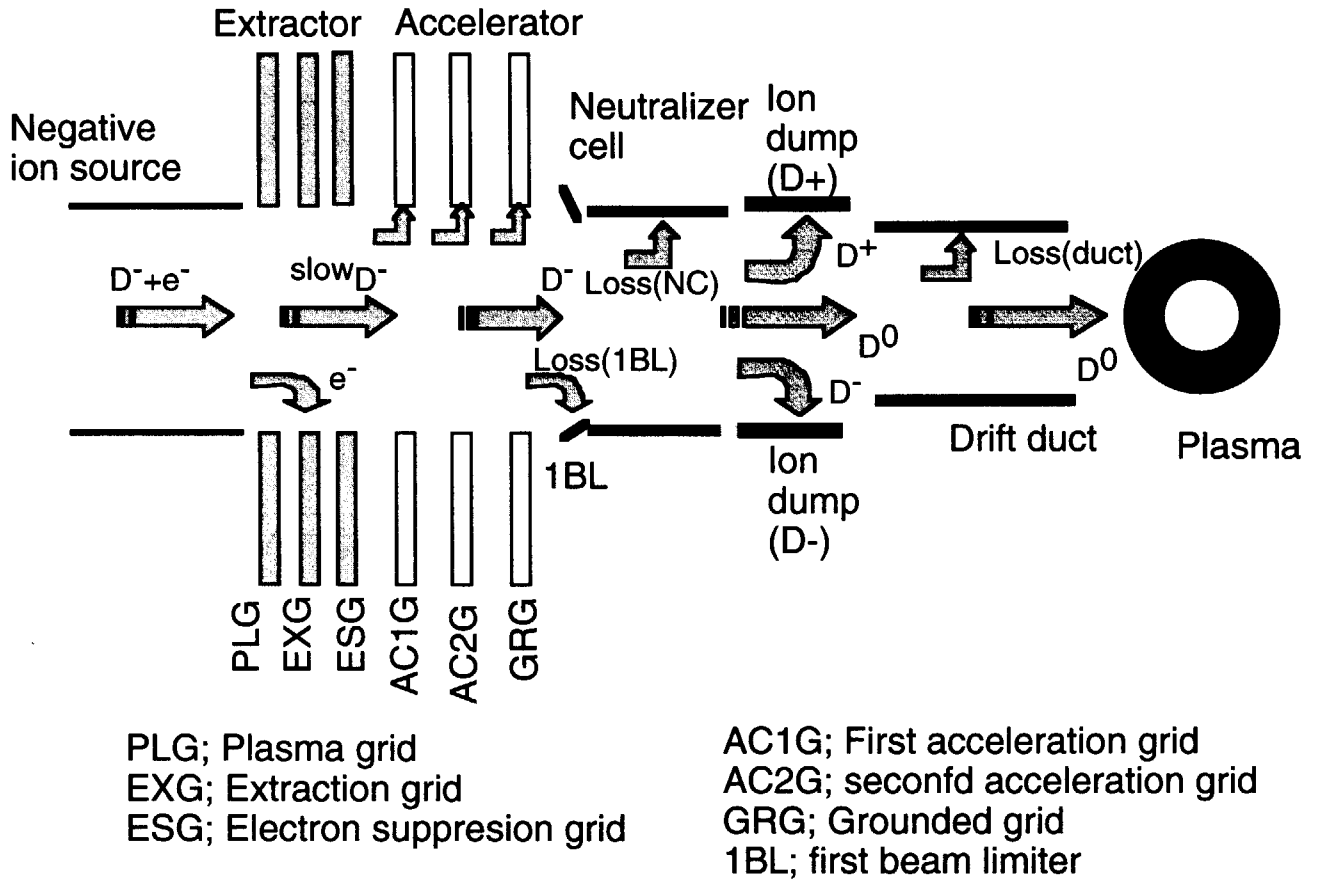


Fig. 7 Schematic diagram of power flow in the beamline

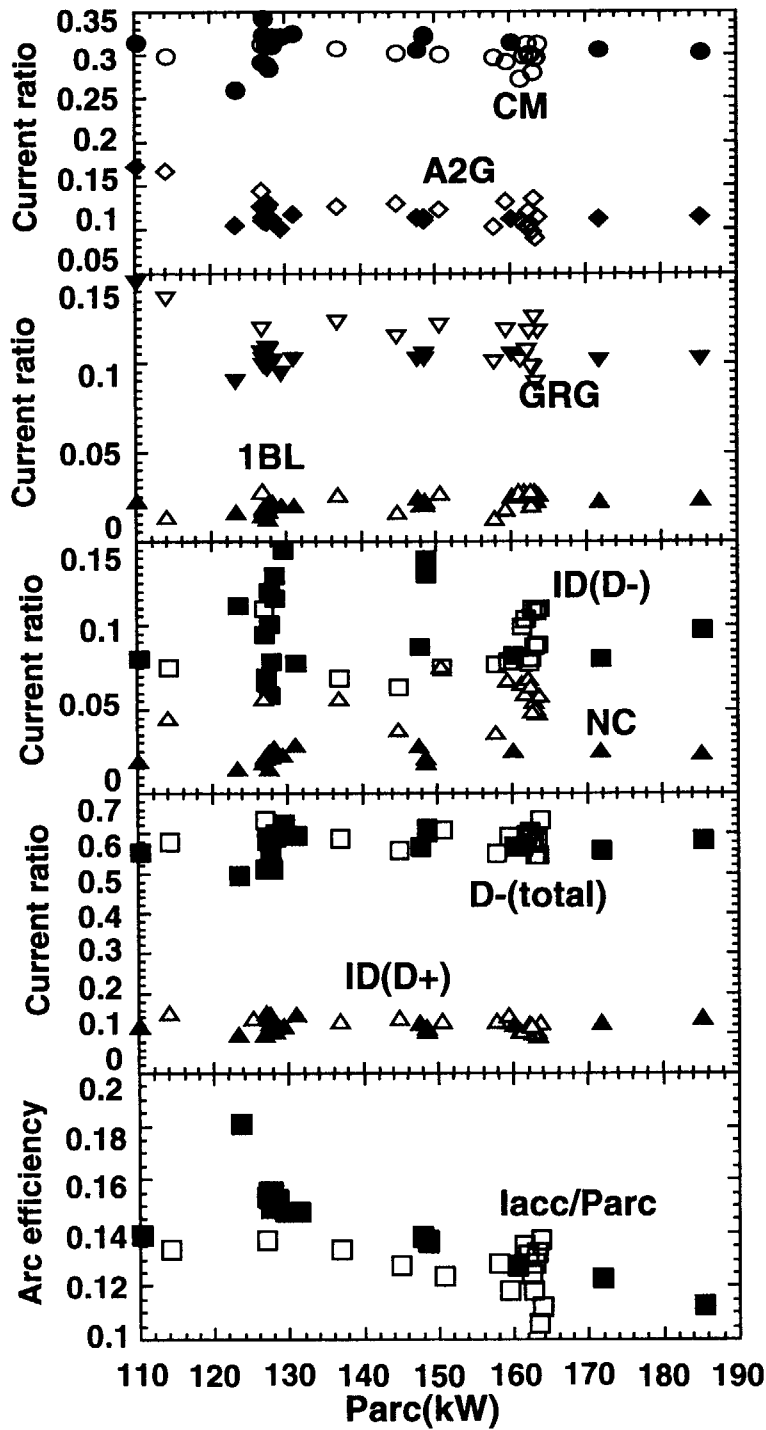


Fig. 8 Comparison between the lower and upper ion source as a function of arc power Parc at the same ion source operation condition (solid symbol: lower ion source, Open symbol: upper ion source, CM; Calorimeter, A1G; 1st Accel.grid, A2G; 2nd accel. Grid, 1BL; 1st beam limiter, NC; Neutralizer cell, ID(D-), ID(D+); Ion dumps for D- and D+, D-(total); D- current.

Beam condition; deuterium beam, $V_{acc}=350kV$, $I_{acc}=15-23A$, $I_{pg}=4.5kA$, $V_b=4.5V$, $V_{ext}=5.9kV$, $I_{pg}=4.5kA$, $V_b=4.5V$, $P_{is}=0.14-0.29Pa$

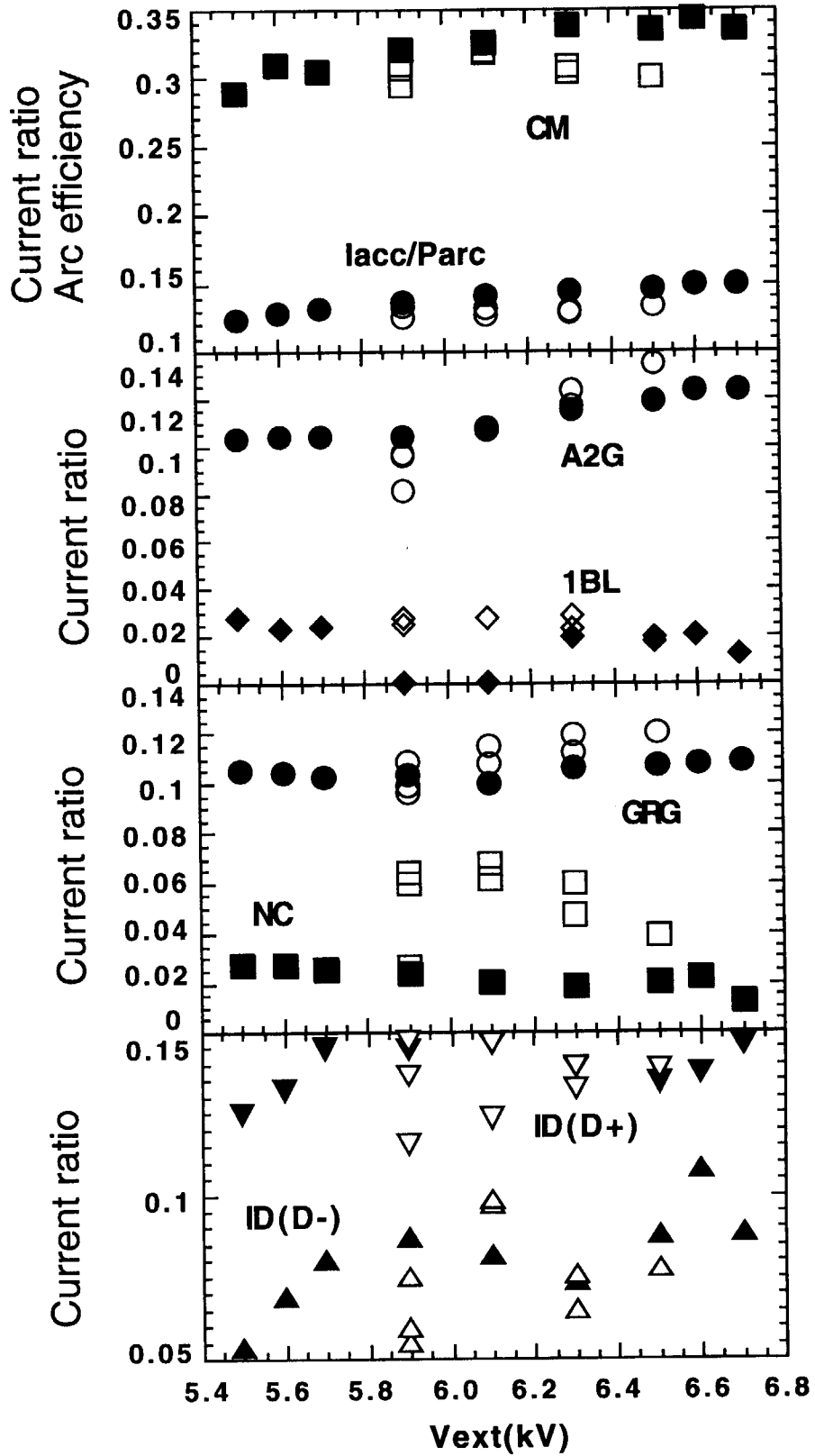


Fig. 9 Comparison between lower and upper ion source as a function of extraction voltage (solid symbol; lower ion source, open symbol; upper ion source)
 Beam parameters; deuterium, $V_{acc}=370kV$, $I_{acc}=19-22A$, $Parc=150kW$,
 $I_{pg}=4.5kA$, $V_b=4.5V$

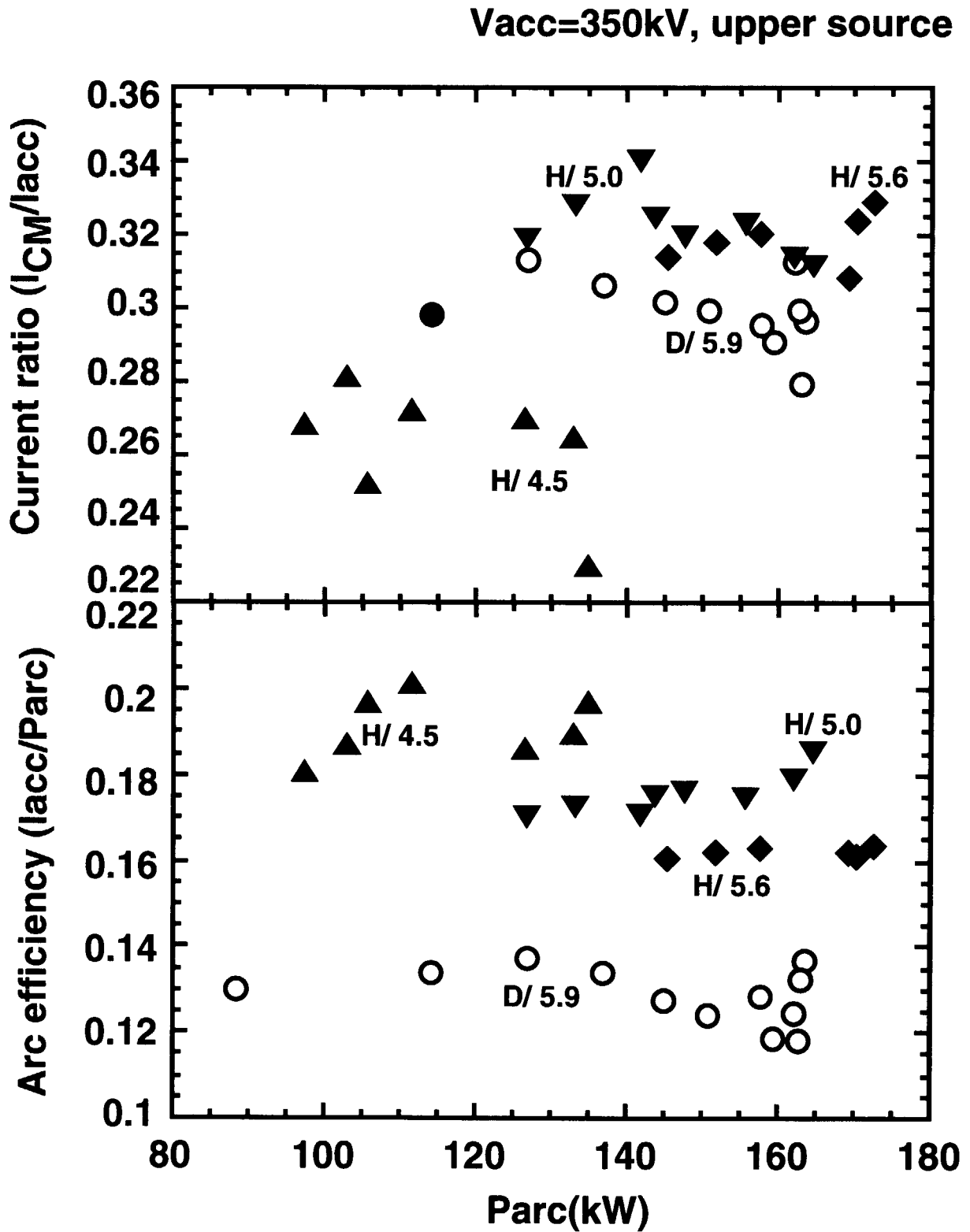


Fig.10 Comparison between different operation species at the same ion source and nearly same condition (solid symbol; hydrogen beam, open symbol; deuterium beam)

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 × 10⁻¹⁹ J
 1 u = 1.66054 × 10⁻²⁷ kg

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

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·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	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	°C	
光束度	ルーメン	lm	cd·sr
照射度	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
バル	bar
ガリ	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 fm² = 10⁻²⁸ m²
 1 bar = 0.1 MPa = 10⁵ Pa
 1 Gal = 1 cm/s² = 10⁻² m/s²
 1 Ci = 3.7 × 10¹⁰ Bq
 1 R = 2.58 × 10⁻⁴ C/kg
 1 rad = 1 cGy = 10⁻² Gy
 1 rem = 1 cSv = 10⁻² Sv

(注)

- 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。
- 表4には海里, ノット, アール, ヘクト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。
- 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。
- 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·s (N·s/m²) = 10 P (ポアズ) (g/(cm·s))

動粘度 1 m²/s = 10⁴ St (ストークス) (cm²/s)

圧	MPa (=10 bar)	kgf/cm ²	atm	mmHg (Torr)	lbf/in ² (psi)
	1	10.1972	9.86923	7.50062 × 10 ³	145.038
力	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 cal = 4.18605 J (計量法)
	1	0.101972	2.77778 × 10 ⁻⁷	0.238889	9.47813 × 10 ⁻⁴	0.737562	6.24150 × 10 ¹⁸	= 4.184 J (熱化学)
	9.80665	1	2.72407 × 10 ⁻⁶	2.34270	9.29487 × 10 ⁻³	7.23301	6.12082 × 10 ¹⁹	= 4.1855 J (15 °C)
	3.6 × 10 ⁶	3.67098 × 10 ⁵	1	8.59999 × 10 ⁵	3412.13	2.65522 × 10 ⁶	2.24694 × 10 ²⁵	= 4.1868 J (国際蒸気表)
	4.18605	0.426858	1.16279 × 10 ⁻⁶	1	3.96759 × 10 ⁻³	3.08747	2.61272 × 10 ¹⁹	仕事率 1 PS (仏馬力)
	1055.06	107.586	2.93072 × 10 ⁻⁴	252.042	1	778.172	6.58515 × 10 ²¹	= 75 kgf·m/s
	1.35582	0.138255	3.76616 × 10 ⁻⁷	0.323890	1.28506 × 10 ⁻³	1	8.46233 × 10 ¹⁸	= 735.499 W
	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	

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

POWER LOADING ON THE BEAMLINE COMPONENTS AND BEAM DIVERGENCE OF THE NEGATIVE-ION BASED NBI SYSTEM FOR JT-60U