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A prototype neutral beam injector for JT-60 was constructed to test and demonstrate a single beam line performance before fabrication of fourteen injector units for JT-60.

The system has been operated over 4 months without serious troubles. Ion beams of 10 sec/75 keV/70 A were extracted repeatedly and most of design values were achieved. Accelerator grids were stable during 10 sec pulse, and other components of the system were confirmed to be sufficiently reliable.

The system was also operated with a magnetic field which simulated a stray field from JT-60 tokamak. With the stray field applied, no choking effect in a drift tube like PLT or Culham effects were observed at all.

Keywords: JT-60, NBI, Ion Beam, Long Pulse, Beam Extraction, 10sec/75keV/70A, Prototype Injector Unit, PLT Effect, Culham Effect

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JT－60 原型ユニットにおける
10秒／75 keV／70 A イオンビームの引出し

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（1982年4月20日受理）

JT－60用原型ユニットは，JT－60に取り付けられる14基の中性粒子入射装置の建設に先立ち，その性能を実証するために建設された。本装置は1981年11月に完成し，直ちに性能実証試験が開始された。その結果，初期目標である10秒，75 keV，70 A のイオンビームを，繰り返し安定に得られ，その他の設計値についても，そのほとんどを達成した。この75keVという運転条件は，JT－60の実験で用いられる典型的な運転条件である。10秒のイオンビーム引き出し中に，イオン源電極の変形も認められず，装置の各機器も設計通りの性能を持つことが確認された。また，JT－60プラズマからの漏洩磁場を模擬した外部磁場を発生させ，その影響も調べたが，従来報告されたようなPLT効果やCulhum効果は見られなかった。

装置はすでに4カ月以上，安定に運転されており，この運転結果及び経験は，実機の製作に反映される。

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1. INTRODUCTION

JT-60 is one of the largest tokamaks presently under construction, where neutral beam injection heating is planned.[1] For this purpose, neutral beam injectors which consist of 14 beam line units must be provided to deliver 20 MW neutral hydrogen beam at an energy of 75-100 keV.[2] Possibly, the most significant feature of this system is its pulse length of as much as 10 sec. However, these high power long pulse injectors are quite difficult to develop because of their heat removal problems. Innertial cooling system which is applicable to many short pulse injectors can not be applied any more. Active cooling system should be adopted in almost every heat deposition materials exposed to a high heat flux.[3] Other than handling of thermal problems, beam line components such as ion sources, cryopumps, ion reflecting magnet etc. must be developed.

Since 1975, elaborate research and development have been made at JAERI to develop long pulse injectors for JT-60. In 1979, we had succeeded to produce 10-30 sec ion beams at 60-75 keV, 4-6 A level by a small scaled ion source.[4] Meantime, extensive measurements on the heat loading to the electrodes including those due to backstream electrons have been made,[5,6] while manufacturing technology of water cooled grids has been advanced.[6] In this course of development, we proposed a lambdatron ion source for high energy proton sources above 80-90 keV, where heat loading due to backstream electrons becomes quite significant.[7]

A middle scale cryopump, which has a pumping speed of 60,000 l/s, was made and tested as one of the R&D work to evaluate the pumping speed, heat loss, and interaction with the beam.[8,9]

Actively water cooled finned tube was employed as beam dump element and was subject to the burnout tests done by irradiation of the intence beam[10] as well as to the detailed thermal stress and deformation analysis.[11]

R&D and the design of the ion reflecting magnet required the most elaborate effort. Reflected ion beam trajectories are directly coupled with the heat loading of the beam dump. The form of the magnet is also magnetically coupled with magnetic shielding structure which is provided to shield external stray magnetic field in a tokamak environment. Therefore these hardwares should be developed altogether. For this purpose, magnetic systems were developed based on the 3-D ion trajectory calculations in a magnetic field obtained by numerical analysis or by measurements made by small scale models.[12,13]

On the basis of these research and development, the prototype injector unit has been designed and constructed. Detailed design started in 1978 and was most extensively done in 1979. Construction started in April, 1980 and was completed in November, 1981. After some preliminary operation of the cryogenic system, the overall system tests have been made since last December. By the end of FY 1981 (March 1982), we intended to confirm the predetermined system performances at a beam energy of 75 keV, which is the standard, the most frequently usable energy regime of JT-60 experiments. Here, we intend to report, for the first time, on the typical test results of the prototype injector unit at 75 keV level.

2. SYSTEM DESCRIPTION

A schematic view of the prototype unit is shown in Fig. 1. The system consists of a beam line chamber, a drift tube, a target chamber, a power supply unit, and auxiliary subsystems, such as helium refrigeration system and cooling system. Details on the system have been reported elswhere.[3,14] In this section, outlines of the system are described.

Main components in the beam line chamber consist of two ion sources,[6,7] two neutralizer cells, a reflecting magnet with a water jacket,[14] a beam dump,[15,16] a calorimeter,[11] the first and the second beam limiters, and six modules of cryopumping panels.[3,8,14] A part of the ion beam is converted to a neutral beam as it passes through the neutralizer cells, and residual ions are guided to the beam dump by the reflecting magnet. The calorimeter is used as a neutral beam target during source conditioning. In the target chamber, a beam target and four modules of cryopumping panels are installed. The drift tube, simulating an injection port of the JT-60 vacuum vessel, connects the beam line chamber and the target chamber. A fast shutter, a hard seald gate valve and horizontal and vertical scanning calorimeter are also mounted in between. The scanning calorimeters can measure neutral beam profiles calorimetrically. A magnetic mass analyzer is set up behind the beam target to measure ion and impurity species. The heat loadings to each component can be measured by the temperature rise of cooling water. A set of coils which produces a simulating stray magnetic field from JT-60 tokamak is installed around the beam line chamber and the drift tube. A set of canceling coils,[13] measurements made by small scale models.[12,13]

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A schematic of the ion source is shown in Fig. 2. A plasma source is a rectangular bucket type source with a backstream electron beam dump. This source has been developed primarily for 75 keV operation. A two-stage accelerator is used for the ion source. It consists of water cooled four grids, called a plasma, a gradient, a suppressor and an exit grid, respectively. Each grid has 1020 apertures of 4 mm in diameter within a rectangular area of 12 cm by 27 cm. A detail of the prototype ion source was reported in references.[6,7]

3. EXTRACTION OF 10 sec/75 keV/70 A ION BEAMS

Operation of the prototype injector unit started in November, 1981. The beam energy, the beam current and the beam pulse length were increased step by step verifying the compatibility of all system components. Especially, attentions were paid to the operation of the cryopumps, to the power supply unit, and to the heat loading of the beam dump and the accelerator grids. Cryopumps were cooled down for about two weeks every month, and the rest of the time were spent for checking the system and preparation for the experiments. The cryopumps have been operated without serious troubles. The pumps were cooled down within 24 hours, stationally worked for about ten days without processing of condensed hydrogens. Pumping speed of the cryopumps was measured and was found to be 1.43×10^3 m^3/s.

In February, 1982, ion beams of 10 sec/75 keV/70 A were extracted repeatedly with two ion sources. The waveforms in Fig. 3 show the characteristics of arc discharge and ion beam when a 10 sec/75 keV/70 A ion beam was extracted. The waveform of each grid current indicated that the accelerator grids were thermally stable during the pulse. The arc efficiency, defined by the ratio of acceleration current to the arc power, was 1.1 A/kW in this case. The gas flow rates into ion sources-I, a lower source, and -II, an upper source, were 1.26 $Pa.m^3/s$ and 1.20 $Pa.m^3/s$, respectively. Each gas flow rate gave about 90 % equilibrium neutralization line density for 75 keV proton beam. The percentage power one of which is assembled around the reflecting magnet and the other around the neutralizer cells, produces a magnetic field which cancels the stray field. Therefore, the ion beam trajectories are not disturbed by the stray field.

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The prototype injector unit was also operated with the simulating stray magnetic field applied. The typical sequence of operation is shown in Fig. 6. This mode was copied after that of envisaged JT-60 neutral beam injection. Prior to real injection, the ion sources are conditioned with short pulse beams of up to 0.5 sec, where the calorimeter is used as a beam target. About 30 sec before injection, the calorimeter is retracted. Then the fast shutter is opened just before injection and closed after injection. During neutral beam injection into the target chamber, the simulating stray field coils and the canceling coils are excited. With the stray field, ion beams of 10 sec/75 keV/70 A were also extracted repeatedly. The system components, especially the cryopumos, the calorimeter and the fast shutter were operated without troubles. The power deposition to each component with the stray field was a little different from that without the field, and no choking effect in the drift tube like PLT or Culham effects were observed at all.

4. CONCLUDING REMARKS

The prototype neutral beam injector unit has been operated successfully since November, 1981, and total running days of the system are over 50 days. Our first experience in handling the 10 sec ion beams up to 70 A were finished successfully at an energy level of 75 keV. The energy of 75 keV is the most frequently operable regime in the JT-60 experiments. The accelerator grids were stable during the 10 sec pulse, and the ion sources, the beam dump, the calorimeter, the reflecting magnet, the cryopump, the canceling coils and other components were confirmed to be sufficiently reliable. Typical performance characteristics of the unit are summarized in Table 1. Most of design values were deposition to each beam line component is shown in Fig. 4 as a function of pulse length. It should be noted that the power deposition to each component does not change during the 10 sec pulse. This means that the accelerator grids are not deformed and the beam optics does not change during the pulse. Figure 5 shows the power flow when 10 sec/75 keV/71 A ion beams were extracted. The injected power into the beam target reached 1.44 MW, which equals to the design value. The neutralization power efficiency was 41 %. The heat loading to each component was within the design value.

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With the stray field applied, little influence on the power deposition on each component and no choking effect in the drift tube like PLT or Culham effects were observed at all. Operation of the unit at 100 keV level will be made in near future.

ACKNOWLEDGEMENT

The authers would like to express their appreciations to Drs. Y. Obata, Y. Iso, and S. Mori for their supports and encouragements.

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Table 1 Summary of the experimental results.
(including design values)

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TYPICAL PERFORMANCE CHARACTERISTICS OF JT-60 PROTOTYPE NBI

	DESIGN VALUE	ACHIEVED VALUE				
BEAM ENERGY (keV)	75 (50∼100)	75		75	85	100
BEAM CURRENT (A)	70 (80) TWO SOURCES	70 TWO SOURCES		71 TWO SOURCES	37 ONE SOURCE	32 ONE SOURCE
PULSE LENGTH (Sec)	10	10		10	2	0.5
GAS SUPPLY INTO ION SOURCES(IS) AND NEUTRALIZER(N) ($Pa\cdot m^3/S$)	<2.67×2 INTO IS <2.67×2 INTO N	1.30×2 INTO IS		0.93×2 INTO IS 0.53×2 INTO N	1.47 INTO IS	1.20 INTO IS 0.67 INTO N
BEAM DIVERGENCE 1/e (Deg)	1.0 (0.9∼1.2)	1.05 1)		1.1 1)	0.95 1)	0.7 2)
ION CURRENT DENSITY (A/cm^2)	0.27	0.27		0.28	0.29	0.25
ATOMIC FRACTION (%) $H_1^+ : H_2^+ : H_3^+$	75:20:5	——		82:13:5 3) 77:12:11 4)	——	——
IMPURITY IN NEUTRAL BEAMS	Low Z ≲1 % High Z ≲0.1 %	——		Low Z ≃ 0.3 % 3) < 0.5 % 4) High Z < 0.1 % 3)	——	——
SIMULATING STRAY FIELD	ON	OFF	ON	OFF	OFF	OFF
RE-IONIZATION LOSS (%)	5	——	4	——	——	——
COLD GAS FLOW THROUGH THE INJECTION PORT ($Pa\cdot m^3/S$)	0.05	——		0.07∼0.08	——	——
CRYO PANEL PUMPING SPEED (m^3/S)	1.3×10^3	1.43×10^3				
REFRIGERATION CAPACITY (W)	300 at 3.7°K	280∼300 at 3.6°K				
NEUTRAL BEAM POWER THROUGH THE INJECTION PORT (MW)	1.43	1.31	1.26	1.44	0.72	0.73

1) Beam divergence of 0.1 Sec neutral beam measured at the focal point 8 m apart from the ion source.
2) Extrapolation by the data of 75 kV beam divergence.
3) Measured by the magnetic mass analyzer.
4) Measured by the doppler shift spectrometer at the beam current of 60 A.

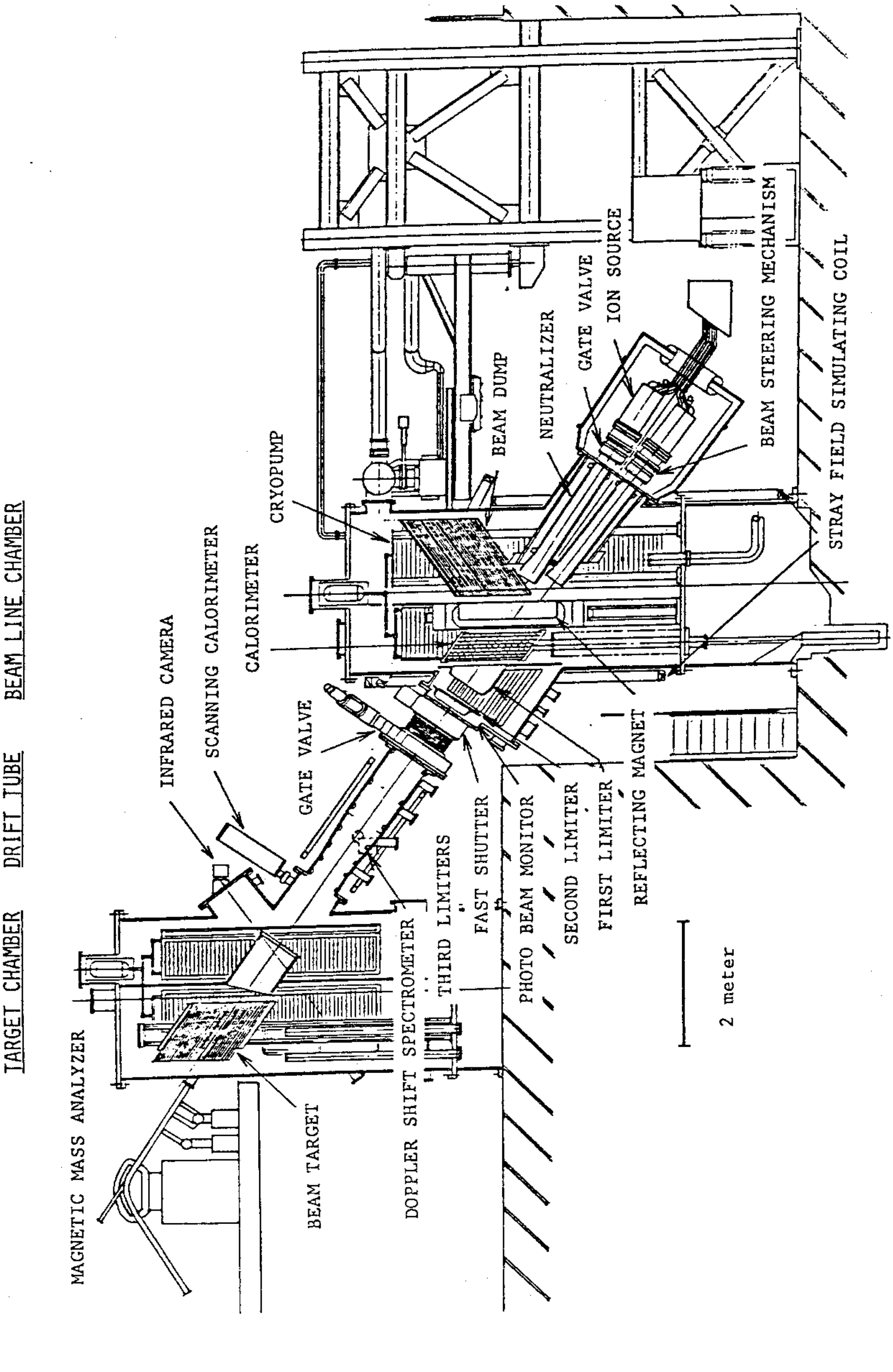

Fig. 1 Schematic of the prototype neutral beam injector unit for JT-60.

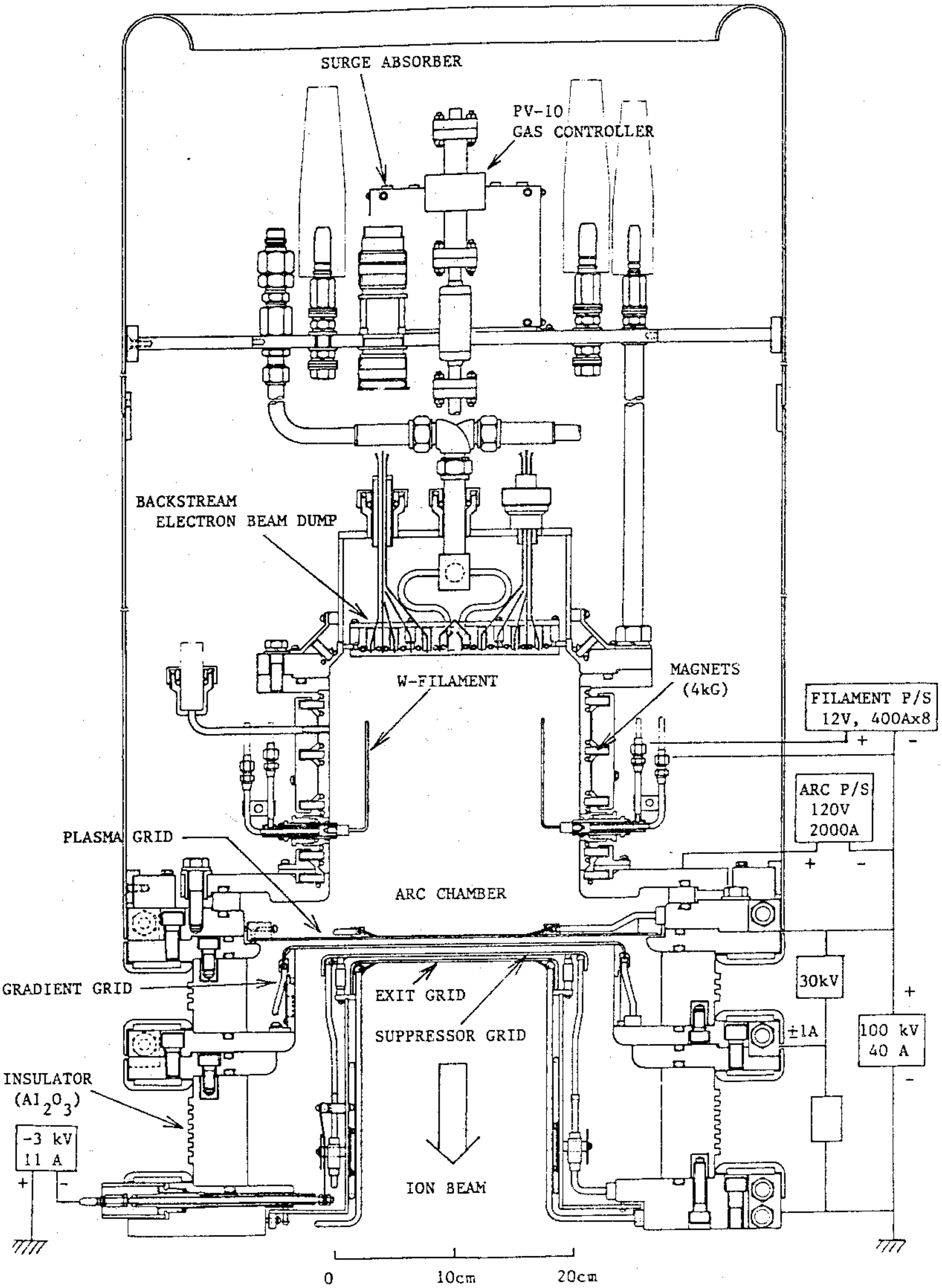

Fig. 2 Schematic of the prototype ion source.

75 kV, 70 A, 10 SEC OPERATION

FEBRUARY '82

MAGNETIC FIELD OF BENDING MAGNET

FILAMENT VOLTAGE I * (10V/div)

FILAMENT CURRENT I (100A/div)

FILAMENT VOLTAGE II * (10V/div)

FILAMENT CURRENT II (100A/div)

*) Cable drop of 0.9V is included.

ARC VOLTAGE I ** (50V/div)

ARC CURRENT I (250A/div)

ARC VOLTAGE II ** (50V/div)

ARC CURRENT II (250A/div)

**) Potential drops by cable resistance and arc limiting resitance of 18V are included.

ACCELERATION VOLTAGE (20kV/div)

GRADIENT GRID VOLATGE (20kV/div)

SUPPRESSOR GRID VOLTAGE (2.5kV/div)

ACCELERATION CURRENT (20A/div)

GRADIENT GRID CURRENT (1A/div)

SUPPRESSOR GRID CURRENT (5A/div)

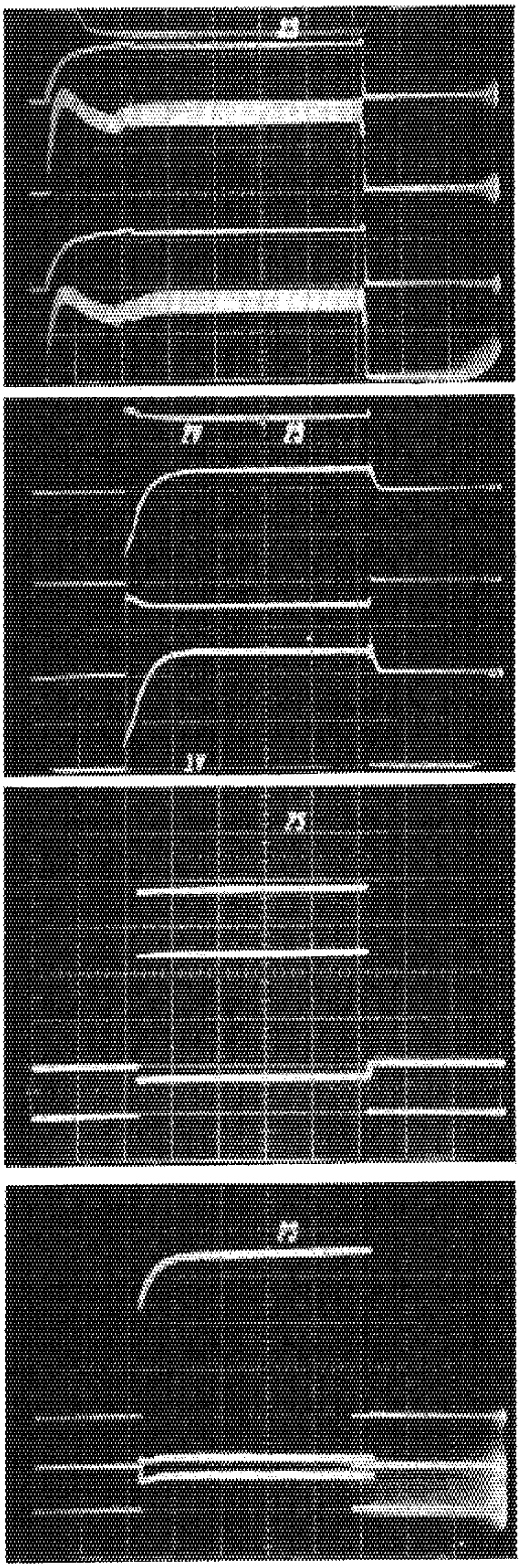

Fig. 3 Typical waveformes of the 10 sec/75 keV/70 A in beam.

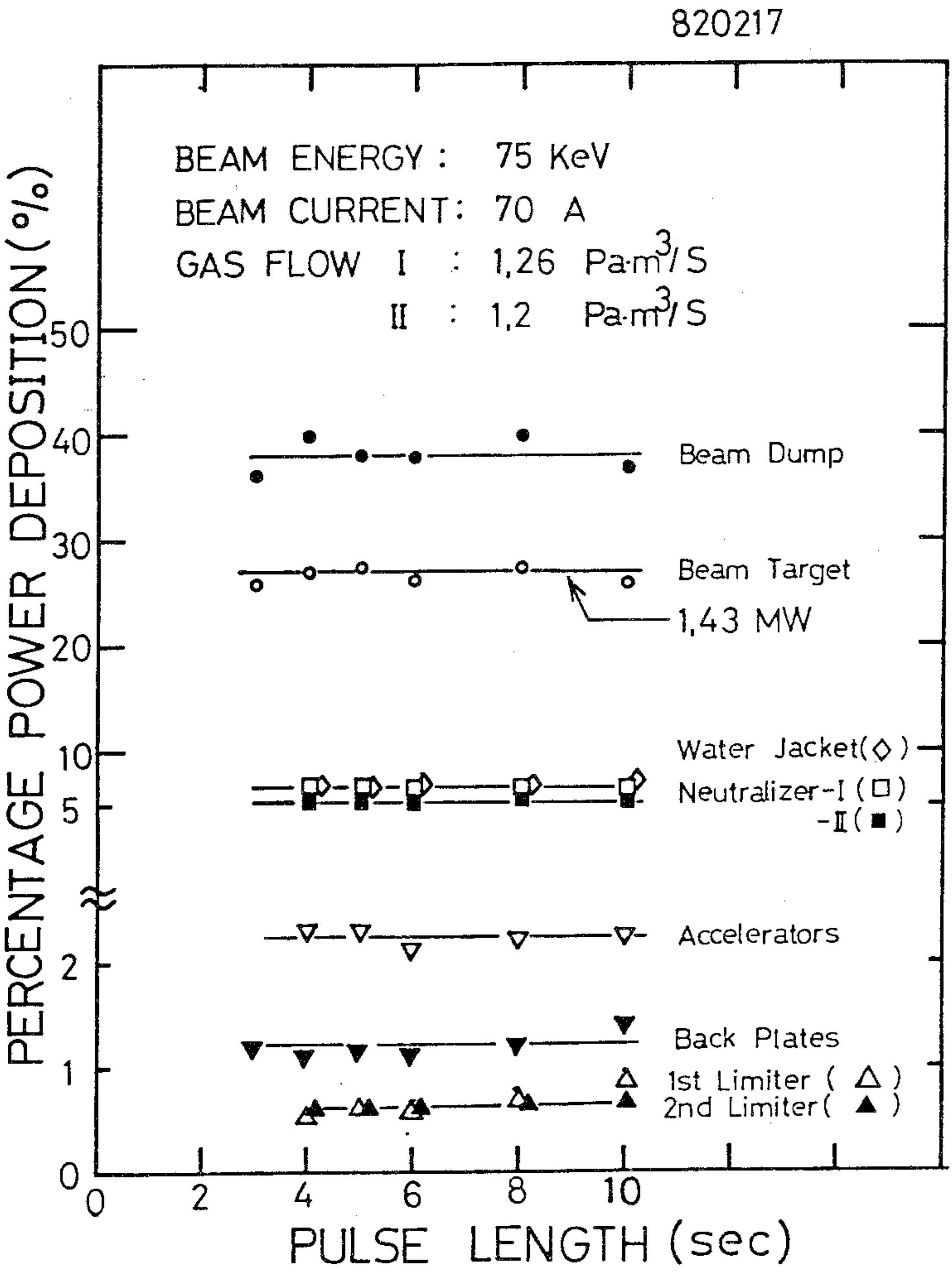

Fig. 4 Percentage power deposition to components of 75 keV/70 A ion beams as a function of pulse length.

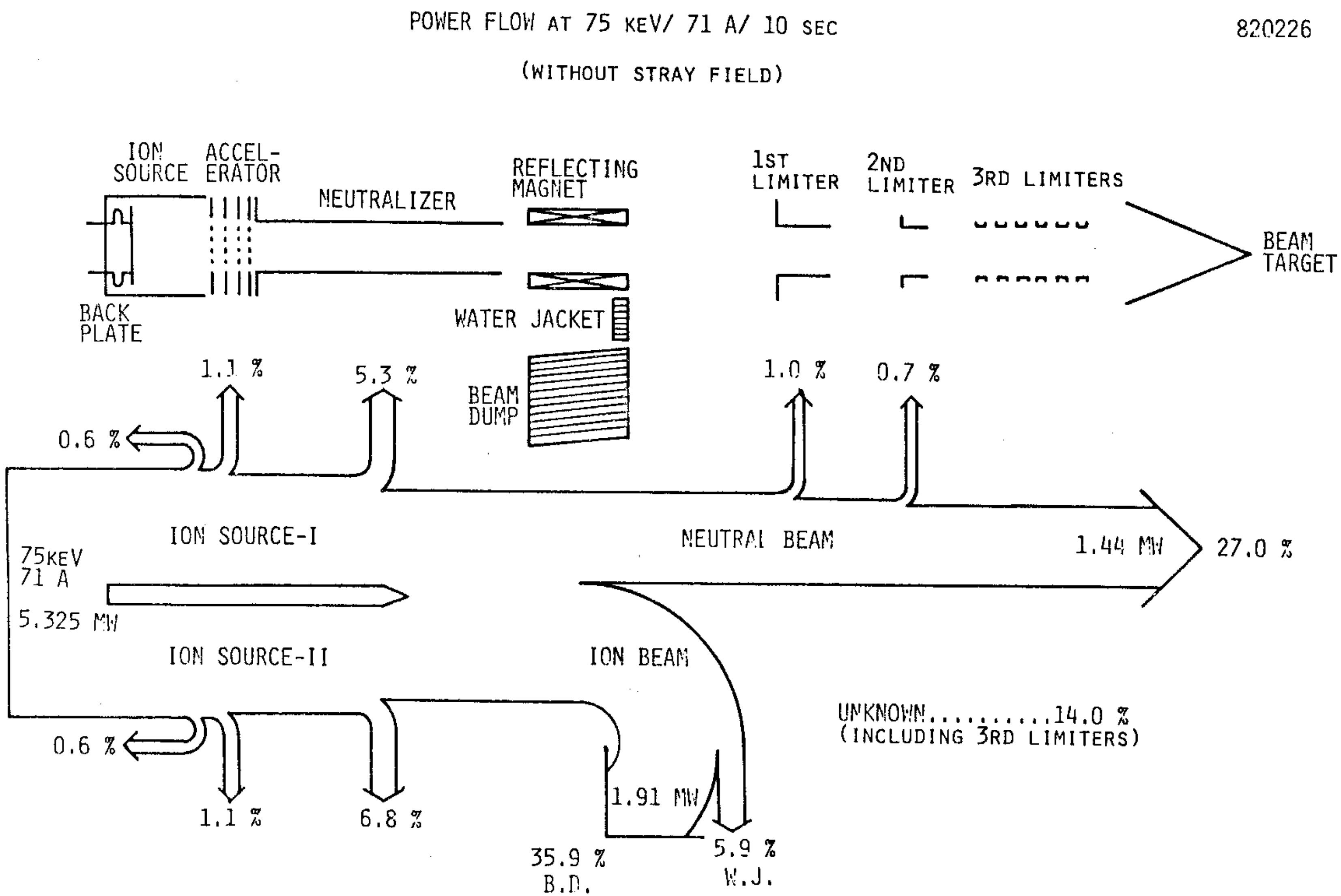

Fig. 5 Power flow of the 10 sec/75 keV/71 A ion beam.

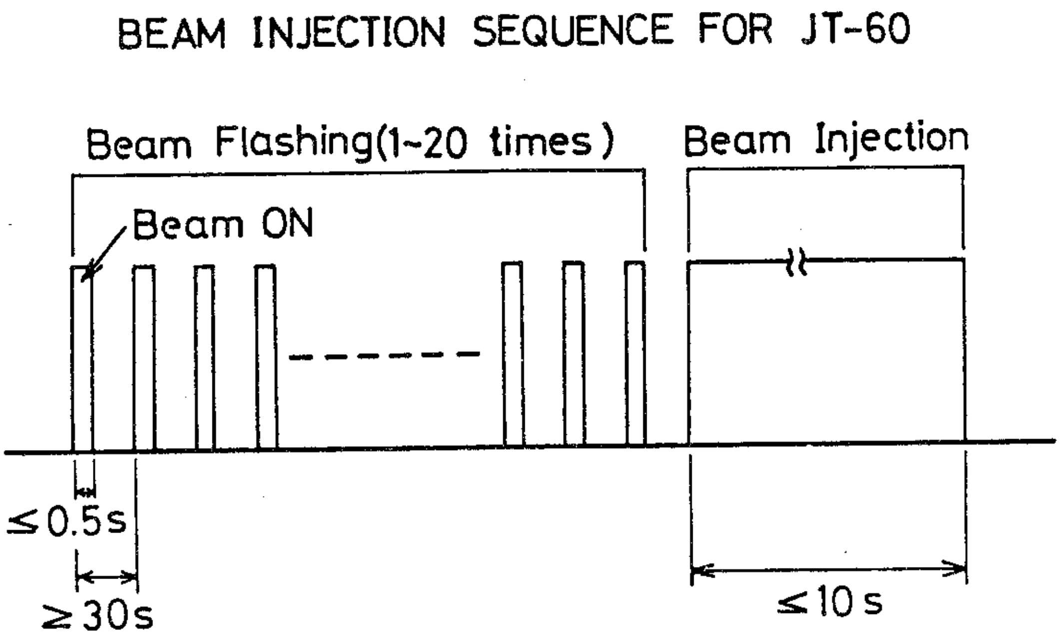

Fig. 6 Typical beam injection sequence for JT-60.