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REDUCED COST DESIGN OF LIQUID LITHIUM TARGET FOR INTERNATIONAL FUSION MATERIAL IRRADIATION FACILITY (IFMIF)

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Reduced Cost Design of Liquid Lithium Target for International Fusion Material Irradiation Facility (IFMIF)

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The International Fusion Materials Irradiation Facility (IFMIF) is being jointly planned to provide an accelerator-based D-Li neutron source to produce intense high energy neutrons (2 MW/m^2) up to 200 dpa and a sufficient irradiation volume (500 cm^3) for testing the candidate materials and components up to about a full lifetime of their anticipated use in ITER and DEMO. To realize such a condition, 40 MeV deuteron beam with a current of 250 mA is injected into high speed liquid lithium flow with a speed of 20 m/s. Following Conceptual Design Activity (1995–1998), a design study with focus on cost reduction without changing its original mission has been done in 1999. The following major changes to the CDA target design have been considered in the study and included in the new design: i) number of the Li target has been changed from 2 to 1, ii) spare of impurity traps of the Li loop was removed although the spare will be stored in a laboratory for quick exchange, iii) building volume was reduced via design changes in lithium loop length. This paper describes the reduced cost design of the lithium target system and recent status of Key Element Technology activities.

Keywords: IFMIF, Fusion Material, Neutron Irradiation, Target System, Lithium Target, Reduced Cost Design

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国際核融合材料照射施設(IFMIF)の液体リチウムターゲットにおける低コスト化設計

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国際核融合材料照射施設(IFMIF)は、核融合炉材料の開発のために、十分な照射体積（500 cm^3）を有し照射量200 dpaまで照射可能な強力中性子束（2 MW/m^2）を発生可能な加速器型中性子源である。このような中性子を発生させるために、最大エネルギー40 MeV、最大電流250 mAの重水素ビームを、最大流速20 m/sの液体リチウム流ターゲットに入射させる。1995年から1998年までに実施された概念設計に続いて、1999年に合理化設計を実施し、当初のIFMIF計画の目的を損なわずにコストを削減し、IFMIFの成立性を高めた。主な設計変更は、液体リチウムターゲットの数を概念設計時の２個から１個に削減、予備の不純物トラップをリチウムループから除去し常時保管、リチウムループ高さおよび建家高さを半減などである。2000年からは、要素技術確証フェーズを開始した。本報告は、低コスト化のための合理化設計の内容と最近の要素技術確証活動の概要について述べた。

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1. Introduction

Development of a practical fusion reactor requires significant progress with respect to a broad set of issues including environmental acceptability, safety and economic viability. In addressing these issues, development and qualification of radiation-resistant and low activation materials will be among the key factors. Materials required for the fusion reactor must be able to survive irradiation in a high intensity neutron field with energy of 14 MeV and annual damage doses on the order of 20 dpa (displacements per atom).

Concepts for an irradiation test facility suitable for identifying and validating such materials have been explored through a number of studies over the period of the last several decades. Having a potential to provide such a facility early in this century, an accelerator-based neutron source using the Deuteron-Lithium (D-Li) stripping reaction has been selected as the basis of the International Fusion Materials Irradiation Facility (IFMIF) studies [1]-[3]. In the IFMIF, 40 MeV deuteron beam with a current of 250 mA is injected into high speed liquid lithium flow with a speed of 20 m/s to achieve 20 dpa/year. Development of the technology for this type of neutron source was first initiated by the Fusion Materials Irradiation Test project [4] and later continued by the Energy Selective Neutron Irradiation Test Facility [5]. In the last decade, this neutron source development was further advanced during the IFMIF Conceptual Design Activity (CDA) study [1]-[3], performed during the period 1995-96 under the auspices of the Fusion Materials Implementing Agreement of the International Energy Agency (IEA) through a cooperation between the USA, EU, Russia and Japan. Following the review of this work, IEA recommended continuation of the effort as a Conceptual Design Evaluation (CDE) phase [6] during 1997-98 in order to complete the database and to evaluate the remaining design uncertainties. In January 1999, the 28th IEA Fusion Power Coordinating Committee meeting (FPCC) requested reconsideration of the IFMIF design with focus on cost reduction without changing its original mission[7],[8]. In addition, the option of staged deployment of the facility was also raised as potentially advantageous in reducing initial investment and lowering annual expenditures during construction. In 1999, cost reduction study and staged deployment scenario evaluation have been done. In January 2000, the 29th FPCC recommended to proceed the Key Element Technology Phase (KEP).

In this paper, considerations on the reduced cost lithium target system and recent activities of KEP are described.

2. Brief Description of IFMIF

The main specifications for the IFMIF facility are summarized in Table 2-1. IFMIF is an accelerator-based D-Li neutron source for production of an intense flux of high energy neutrons within sufficient irradiation volume to enable realistic testing of candidate materials and components up to about a full lifetime of their anticipated use in DEMO and beyond. IFMIF consists of five subsystems: (1) Accelerator Facility which produces the accelerated D^+ beam, (2) Target Facility which produces a flowing Li jet target for converting the accelerated D^+ beam into high energy neutrons, (3) Test Facility which exposes, handles and examines the irradiated specimens, (4) Conventional Facility which provides common utilities such as electric power and cooling, and (5) Central Control & Common Instrumentation Facility which supports the integrated operation of the entire system. The required full value of the D^+ beam current will be generated by two accelerator modules operating in parallel. The two D^+ beams converge on the Li target by overlapping the same spot size as shown in Table 2-1. The target facility consists of the target assembly exposing the flowing liquid Li jet to the beam and the Li loop that circulates the liquid Li.

Table 2-1 IFMIF Specifications

Neutron Flux	≥ 2 MW/m^2 (@ 500 cm^3)
Operation Availability	70 %
D^+ Beam Current	250 mA (CW, 2 x 125 mA)
D^+ Energy	32, 40 MeV
D^+ Beam Size	200 mm (width) x 50 mm (height)
Li Jet Thickness	19, 25 mm (resp. for 32, 40 MeV D^+)
Li Jet Width	260 mm
Li Jet Velocity	10-20 m/s

3. Cost Reduction and Staged Deployment

3.1 Cost Reduction

Under the current budget limitations and the interactions with the International ITER project, the strategy for constructing and operating the test facility had to be reviewed to minimize the associated financial burden without sacrificing essential performance parameters. Therefore, in January 1999, FPCC requested a review of the IFMIF design focused on potential for cost reduction. In addition, staged deployment was to be examined as an option offering a potential reduction of the annual expenditures during construction. The study of cost reduction and staged deployment considered the following major items:

(1) The potential for a future upgrade to four accelerators with irradiation capability twice that of the current user requirements, assumed in the CDA, has been eliminated.
(2) The building volume was reduced as allowed by the above design changes in accelerator systems and lithium loop components.

On the lithium target system, the following major changes to the CDA target design [9], [10] have been considered in the study and included in the new design:

i) Number of the Li target has been changed from 2 to 1,
ii) Spare of impurity traps of the Li loop was removed,
iii) Building volume was reduced via design changes in lithium loop length.

Based on all the design changes, the total cost estimate was reduced to 61% of the CDA estimate, from 797.2 MICF to 487.8 MICF , where 1 MICF = 1 Million IFMIF Conversion Factor units (approximately $1M US in January 1996) [7]. Cost of the Li target is reduced significantly to 35% of the CDA estimate from 115.2 MICF to 40.1 MICF.

3.2 Staged Deployment

Here, the IFMIF deployment was assumed to proceed in three stages, each addressing a specific materials development issue as follows:

1st Stage:	One accelerator with a maximum of 50 mA operation, to be used for material selection of the ITER breeding blanket test modules, fusion-fission data correlation and generic damage studies.
2nd Stage:	One accelerator for 125 mA operation (i.e. 1 MW/m^2 @ 500 cm^3), to be used to demonstrate materials performance of a reference alloy for DEMO-relevant fluences.
3rd Stage:	Two accelerators for 250 mA operation (i.e. 2 MW/m^2 @ 500 cm^3), used to obtain engineering data for potential DEMO materials under irradiation up to 100-200 dpa and a systematic search for high performance materials for fusion reactors.

Figure 3-1 shows a plane view of the IFMIF for the staged deployment. In the 1st stage of deployment, one accelerator is fabricated and installed with enough RF power supplies to generate the 50 mA, 40 MeV deuteron beam. In the 2nd stage, more RF power supplies are added to the accelerator to reach the current of 125 mA. In the 3rd stage, the second 125 mA accelerator is installed to bring the total beam on target to 250 mA. It is also noted that although most of the conventional facilities are constructed in the first stage, the facilities for the second accelerator are constructed in the third stage. The Li target is installed in its entirety in the 1st stage. While most of the test facilities are also installed in the 1st stage, the post irradiation examination facility is installed in the 2nd stage. The staged deployment of the IFMIF facility reduces the initial investment and lowers the annual expenditures while still providing significant interim capabilities for fusion material development for ITER and DEMO. Furthermore, the cost estimate for the 1st stage is now only 303.6 MICF. These cost reductions may make the initiation of the IFMIF construction more attractive.

4. Design Considerations on Lithium Target [11]

4.1 Requirements of IFMIF Target System

Major functions of IFMIF lithium target system are to provide a stable lithium jet for production of intense neutrons (20 dpa/year) by stripping reactions with the deuterium beam. Table 4-1 summarizes the major parameters of the target system. The lithium target system consists of the target assembly and the lithium loop. Under irradiation of 10 MW deuterium beam, averaged surface heat flux on the free liquid lithium flow is 1 GW/m^2. The target assembly needs to handle such an ultra high heat load using liquid lithium jet flow. The lithium loop needs to circulate the liquid lithium to and from the target assembly through the impurity purification system and heat exchange system by an electromagnetic pump. The impurity purification system in the loop needs to maintain tritium, ^{7}Be and other impurities under permissible level to realize required safety condition and to minimize corrosion of the loop materials.

Table 4-1 Major Specifications of IFMIF Target System

Beam Deposition Area on Li Jet	200 mm (width) x 50 mm (height)
Jet Thickness	19, 25 mm (resp. for 32, 40 MeV D^+)
Jet Width	260 mm
Li Jet Velocity	15 (range 10 ~ 20) m/s
Flow rate of Lithium	130 l/s
Inlet Temperature of Lithium	250 ℃
Vacuum Pressure in Target Chamber	10^{-3} Pa at Li free surface
Availability	95 %
Replacement	9 month/fpy (backwall) no replacement for 20 years (other component)

4.2 Target Assembly

The lithium target assembly consists of a flow straightener, a reducer nozzle, a back wall, drain baffles and flanges. Material of the assembly is stainless steel (304 or 316). Figure 4-1 shows cross section of the target assembly. Figure 4-2 shows the conceptual model of the target assembly where the vertical test assemblies are shown. The distances between the target and the test assemblies are intentionally enlarged to show the details. The flow straightener is aimed to change turbulent flow to laminar flow. At the outlet of the straightener, the double-reducer nozzle is adopted. This nozzle has a large contraction ratio with no flow separation in the nozzle by employing Shima's model based on the potential flow theory. Shape of the nozzle exit is rectangular (0.26 m wide by 0.025m thick). To avoid a boiling of the lithium by applying an induced centrifugal force, the curved backwall with a curvature of 25 cm is adopted. The back wall has most sever condition under neutron irradiation among the target assembly. Because of lifetime of the backwall, the target assembly is designed for exchange by 9 month. There are two design options on the backwall replacement. First option is to replace the backwall at the target assembly. But, this option needs special remote handling device and increases cost. Second option is to remove overall target assembly with the nozzle and the backwall and move to the hot cell area. YAG laser device will be used for cutting of lip seals of the flange as shown in Fig.4-1. The backwall will be replaced in the hot cell area.

One of key issues of the target assembly designs is to evaluate thermal-hydrodynamic behavior of the lithium target flow of the double-reducer nozzle. Multi-dimensional analysis has been done using FLOW-3D code [12]. The energy deposition profile of the D^+ beam was separately calculated. Typical result is shown in Fig.4-3 where calculation parameters are beam energy of 35 MeV, a beam current of 250 mA, a lithium velocity of 20 m/s, respectively. Since the maximum temperature in the lithium flow is about 400 °C and a boiling temperature is 1090 °C under a centrifugal force of 160G by the curved backwall, the lithium flow has enough margin to avoid a lithium boiling. To investigate characteristics of the lithium jet flow experimentally, water jet experiments have been performed in JAERI using a prototype nozzle [13]. Non-dimensional numbers such as Reynolds number was preserved to simulate lithium jet flows using water at room temperature. In the previous experiments at 1 atmosphere, free surface was stable although two dimensional to three-dimensional waves with length of about 1 mm were observed at the downstream of the smooth surface near the nozzle exit. To validate a stability of the lithium flow with the double reducer nozzle, a lithium loop experiment is under consideration.

4.3 Impurity Purification System

Impurity purification system consists of a cold trap, a Titanium-hot trap, an Yttrium-hot trap and on-line/off-line. In the CDA design, the impurity purification system has spares for complete redundancy. In this low cost design, the spare of impurity traps was removed from the Li loop although the spare will be stored in a laboratory for quick exchange. For spare traps, there is only space to exchange them with remote handling. Major impurities in the lithium loop are protium (H), deuterium(D), tritium(T), ^{7}Be, and other species (C, N, O). H, T and ^{7}Be are produced by direct reactions of the deuterium beam with the lithium, as well as by the capture of low energy back-scattered neutrons by ^{6}Li. Deuterium from the beam is also contained in the lithium flow. Total production rate of H, D, and T for IFMIF full power operation is estimated to be about 5 g/year, 160 g/year, 7 g/year, respectively. The inventory of tritium and ^{7}Be should be minimized since these could be the dominant hazardous source term in the event of a radiological release. H, D, T are removed by a hot trap with an yttrium getter. As an option, the cold trap with protium sparging, the so-called swamping method will be considered. ^{7}Be is produced from (d,n) and (d,2n) reactions with the lithium and the most highly radioactive impurity (53 day half-life). Without removal, saturated activation level of ^{7}Be is 140 kCi. The cold trap can remove ^{7}Be. But, some ^{7}Be will deposit inside the loop, which might need remote handling system for maintenance. Dominant source of C, O and N impurities is the loop materials. The cold trap will remove C and a hot trap with a titanium getter will remove O and N. Design values of permissible concentration are selected to be 10 wppm for H, D, T, C and O, and 400 wppm for N. These value will be updated when KEP task results become available. To control these impurities within the permissible levels, on-line and off-line impurity monitoring systems are needed. These systems will contain a hydrogen membrane diffusion meter and a resistivity monitor. The latter provides an indirect measurement of the nitrogen concentration. Nitrogen and oxygen monitors will be applied after the development.

4.4 Lithium Loop and Building

Flow diagram of the lithium loop of the reduced cost design is shown in Fig.4-4. The lithium loop consists of the main Li loop, the impurity purification loop and the cooling loop. All piping and tanks are made of austenitic stainless steel. The first loop circulates the lithium and consists of the target assembly, the quench tank, the main electromagnetic pump, the dump tank and the heat exchangers. In the main Li loop, an Annular Linear Induction Pump (ALIP) center return type electromagnetic pump (EMP) are selected for easy maintenance of the induction coils in the failure. To reduce cost of the target system from the CDA design, the layout of components and routing of piping have been reviewed and reduction of the height of the Li loop and the building have been studied. The main loop and the dump tank are located in same cell area although the dump tank is located under the floor. These layout review can reduce the height from a free surface of the quench tank to the inlet of the electromagnetic pump from 13 m in the CDA design to about 6 m.

To satisfy this NPSH (Net Positive Suction Head) of 6 m-Li without cavitation at the EMP, the EMP is modified to reduce pressure drop and flow rate inside the EMP. Outer diameter of EMP is increased from 0.9 m to 1.1m. Flow rate is reduced from 9 m^3/min (150 l/s) to 8 m^3/min (133 l/s). Using this EMP, the height of the lithium loop from a free surface of the quench tank to the inlet of the EMP can be reduced from 13 m to 6.5 m in the improved layout. Addition of 0.5 m is due to the concrete thickness for radiation shield between the test cell room and the Li loop area room. These design modifications can significantly reduce the height from the center of the target assembly to the floor at the pit from 21 m in the CDA design to 10.5 m as shown in Fig.4-5. This rationalization also reduces the Li inventory from 21 m^3 of the CDA design to 9 m^3.

The Remote Handling System to exchange Target Assembly is unified into the URS (Universal Robot System) in Test Facilities. Therefore, the cost is included in that of Test Facilities. Furthermore, the technology of remote handling for URS will be developed in EVP. Another Remote Handling System to exchange Hot/Cold traps is covered by running cost.

5. Activities in Key Element Technology Phase (2000-2002)

In 2000, a 3-year KEP has begun with the objective of reducing the key technology risk factors needed to achieve a CW deuterium beam with the desired current and energy, to reach the corresponding power handling capabilities in the liquid Li target system, and to satisfy the availability and reliability endurance tests. There are 83 proposed KEP tasks, with 27 tasks for the test facilities, 12 tasks for the Li target system, 26 tasks for the accelerator system, and 18 tasks for design integration [14]. In Table 5-1, the KEP target tasks underway are listed which includes a water jet experiment, Li loop experiment, and development of lithium purification and performance monitors for the target system. Aim of the water jet experiment is to simulate characteristics of the liquid lithium flow with same Reynolds number as lithium flow. In IFMIF condition, vacuum pressure around a free surface of the lithium flow is 10^{-3} Pa. In previous experiment, a stable flow was observed under 0.1 MPa[13]. Recent water jet experiment under 0.01 MPa showed that a stable water jet flow was also observed up to a flow velocity of 20 m/s. Effect of nozzle roughness on the flow stability was measured to obtain IFMIF target nozzle design. Two nozzles with 100 μm roughness and 6 μm roughness were compared. As results, the experiment with the nozzle of 100 μm roughness showed larger surface waves beyond a flow speed of 10 m/s than the nozzle of 6 μm roughness. The velocity profile inside the water jet was measured by Laser Doppler velocimeter. Reductions of the flow velocity near a boundary layer were observed for both experiments. But, thickness of the layer with the reduced flow velocity were 0.4 mm for the nozzle of 100 μm roughness and 0.2 mm for the nozzle of 6 μm roughness, respectively. To confirm a stability of the lithium flow with the double reducer nozzle, a lithium loop experiment with a same size nozzle as the water jet experiment is under consideration by University - JAERI collaboration. The experiment is expected in FY2001. For the test facilities, development of temperature control for the test module and miniaturized specimen technologies has been started.

KEP also includes tasks for redesign of the IFMIF components to update the CDA/CDE design with the new elements developed during KEP. This will include a new design of the IFMIF building including facilities for processing of radioactive materials and updates of the controls and instrumentation. In design of the target system, the layout of the components are reviewed considering required space for maintenance. Also, routing of the pipes are reviewed based on a thermal stress analysis. As a result, piping from the quench tank to the EMP has been modified to reduce thermal stress within a permissible level. Figure 5-1 shows three dimensional view of the layout of the components and pipes.

After the KEP results have been reviewed by the international development team, the IFMIF project will be ready for a possible international decision to proceed to the three year Evaluation and Validation Phase (EVP). EVP includes continuous, stable operation of each subsystem: accelerator system, target system and test facilities could be validated. After an international review of the EVP, the construction of IFMIF could be started and first operation could be expected as early as 2010.

6. Summary

An irradiation test facility producing neutrons of high flux and with a proper energy spectrum is indispensable to develop materials required for designing and building fusion reactors. IFMIF is a facility well suited for such a mission, and could be operational within the required time span. This paper described a reduced cost design of the target system and the key element technology development, currently underway.

In the reduced cost design, the following design changes have been done; (1) number of the Li target has been changed from 2 (CDA) to 1, (2) spare of impurity traps of the Li loop was removed, (3) height of the building are reduced from 21 m to 10.5 m by an optimization of the loop layout and reduction of the Li loop height using the modified EMP. Cost of the Li target is reduced significantly to 35% of the CDA estimate from 115.2 MICF to 40.1 MICF, where 1 MICF = 1 Million IFMIF Conversion Factor units (approximately $1M US in January 1996). In KEP, 12 Li target tasks are proposed among 83 IFMIF tasks. Water jet experiment is now underway. Planning of the Li loop experiment is started.

After a check and review, the KEP will be followed by a 3 year Engineering Validation Phase (EVP) which will validate those critical technologies. First operation could be expected as early as 2010. In addition to the fusion materials development, IFMIF will also promote activities on fusion neutronics studies for fusion reactor development[15].

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Table 5-1 List of Key Element Technology Tasks of IFMIF Lithium Target System

Classification		Item	Necessity	Development Item / Method	KEP					EVP
1	2				Task ID	US	EU	RF	JP	
Target	Stability of Li Flow	Stability of Li Jet	Li jet may be disturbed because of high-speed, broad jet and possible erosion/corrosion of reducer nozzle inner surface.	Examination of free surface behavior in water experiment under low pressure condition	TG11				X	
				Design of Li test Loop referring the JAERI and FMIT water jet experiments and simulation results	TG12		X	X	X	
				Remodelling of existing loop and verification of its performance	TG13				X	
				Fabrication of Li test loop and verification of the performance	TG14			X		X
		Cavitation	Cavitation should be avoided for flow stability and loop integrity.	Cavitation at a joint of back wall is examined in water experiment. (Current JAERI proposal does not include replaceable back wall)	TG15		X	X		
				Cavitation at EMP is examined in a small Li loop.	TG16		X		X	
	Damage and Corrosion by Li Flow	Behavior of Erosion/Corrosion	Data base for erosion/corrosion of pipe and target assembly materials under Li flow condition.	Measurement of erosion/corrosion in an existing loop	TG21				X	
				Li flow experiments for erosion/corrosion for the Li loop materials						X
		Inspection Method	Inspection method should be established.	Design of inspection method of damage and corrosion Verification of the method of damage and corrosion in Li test loop						X
	Li Purification	Diagnostic Method of Impurity in Li	On-line/off-line diagnostic and removal of impurities of T, 7Be and C,N,O	Design of both methods of impurity concentration measurement (On-line/off-line diagnostics) and impurity removal	TG31			X	X	
				Verification of the both method in Li test loop	TG32			X		X
	Li Vaporization	Li Vapour Effect on HEBT	Quantify Li accumulation rate on HEBT inner wall	Establishment of estimation methods of Li vapour towards HEBT based on Li loop experiments	TG41			X		X
	Li Safety	Li Leak, Li Fire	Events of Li leak and Li fire should be considered.	Collection and examination of existing data of Li reaction	TG51			X	X	
				Basic tests for Li fire in air contaminated Ar gas Analysis for behaviour of 7Be and T in the Li loop	TG52			X	X	X
	Loop Integrity	Transient Behaviour of Loops	Analyses of startup/shutdown procedures including beam trip	Numerical analyses by a computer code	TG61			X	X	
	Safety Analysis	Safety Analysis for Rationalized Design	Safety analyses should be performed again, because the number of target and the concept of reserved hot/cold traps have been changed.	FMEA, Dependent Failure and Accident Sequence analyses for the changed target system	TG71		X	X		
	Remote Handling	Setup Method of Target Assembly	Development of in-situ welding/cutting methods to mount/replace target assembly using a remote handling technique	Design remote handling devices	TG81		X		X	
				Manufacturing of remote handling devices Establishment of key methods such as a welding between different metals by remote handling						X

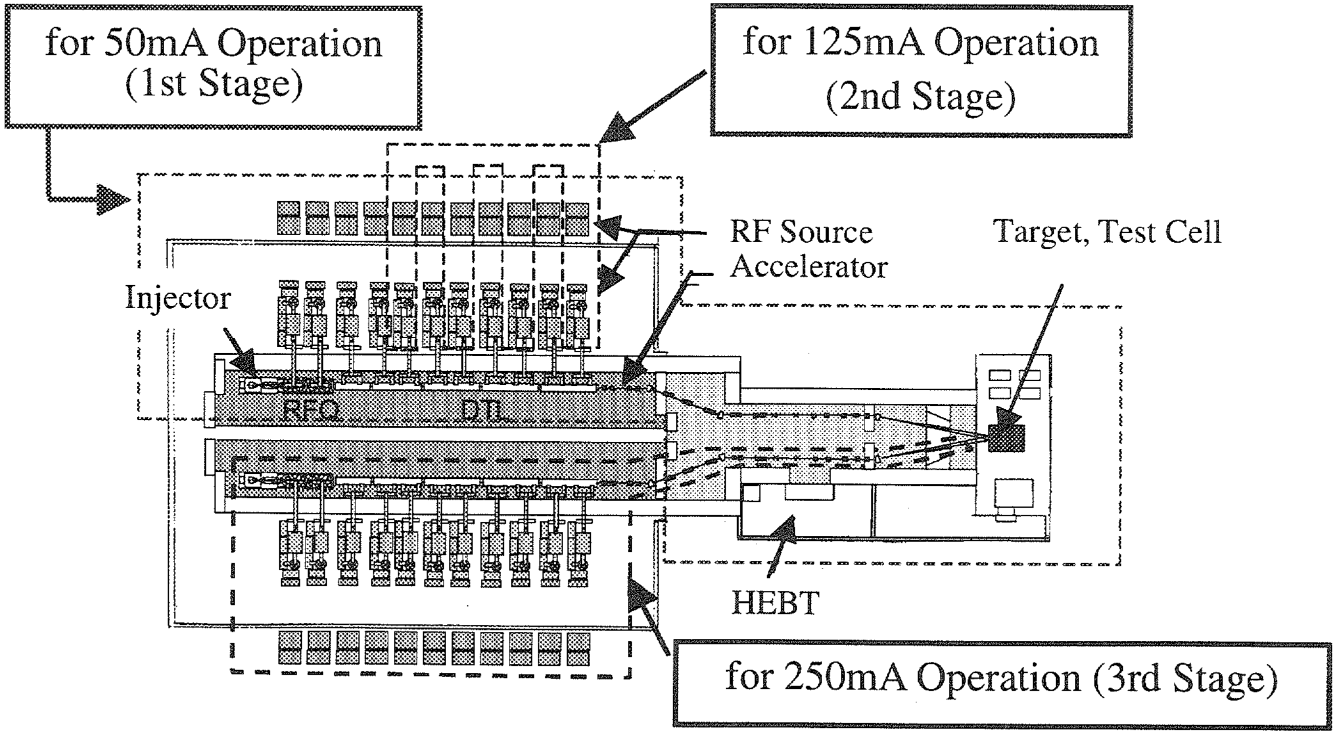

Fig. 3-1 Plane view of IFMIF for staged deplyment

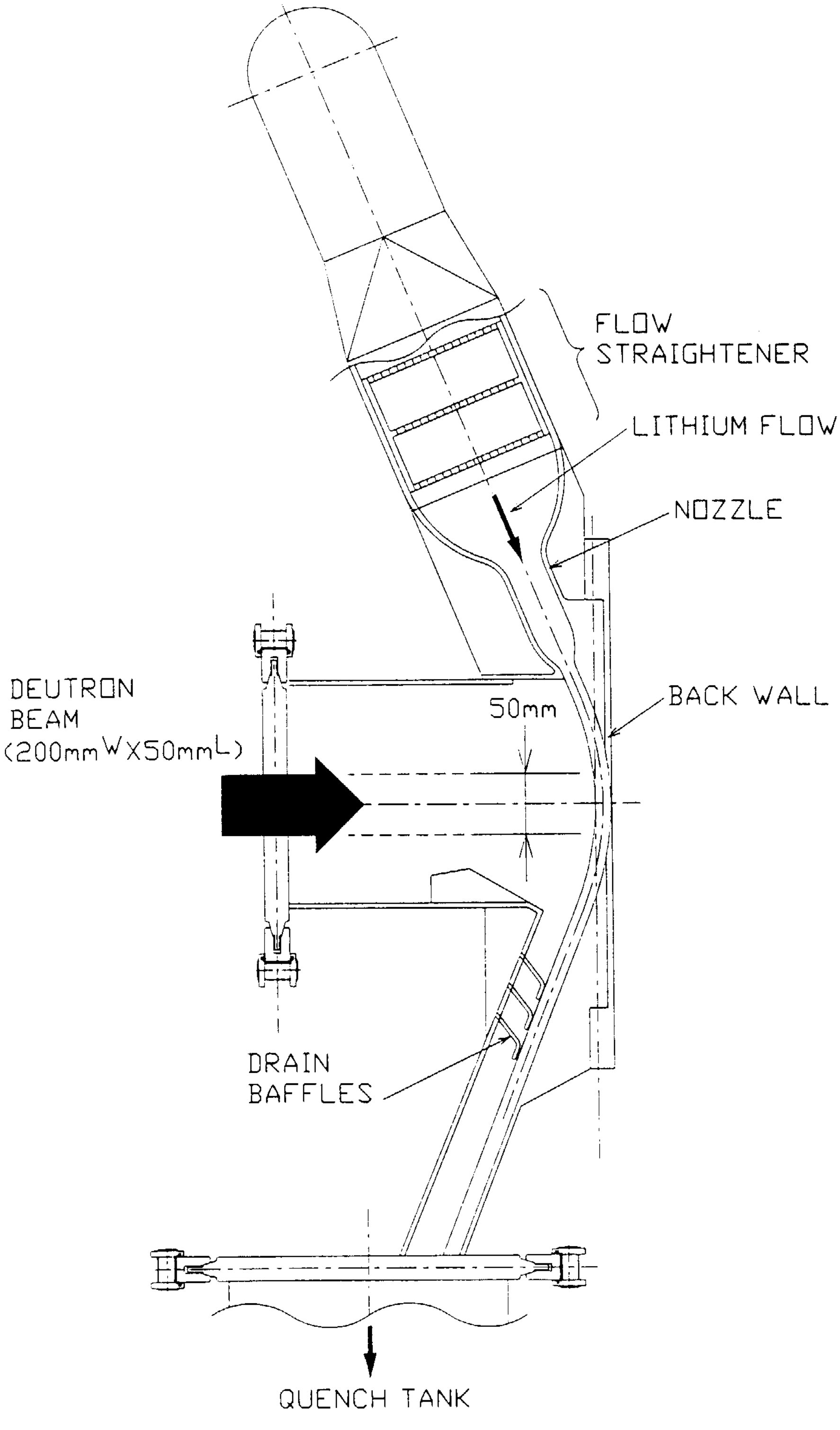

Fig. 4-1 Cross section of IFMIF lithium target assembly

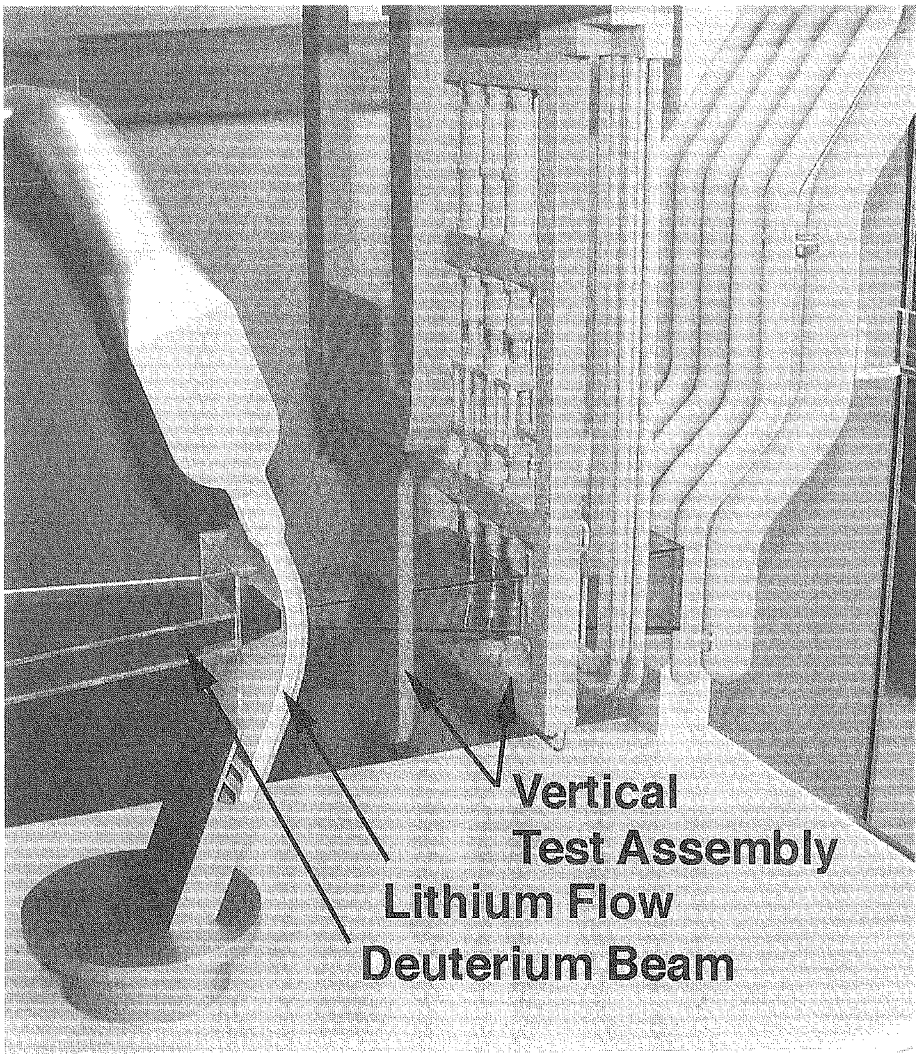

Fig. 4-2 Model of lithium target assembly and vertical test assembly
(Distances among the assemblies are intentionally enlarged to show the details.)

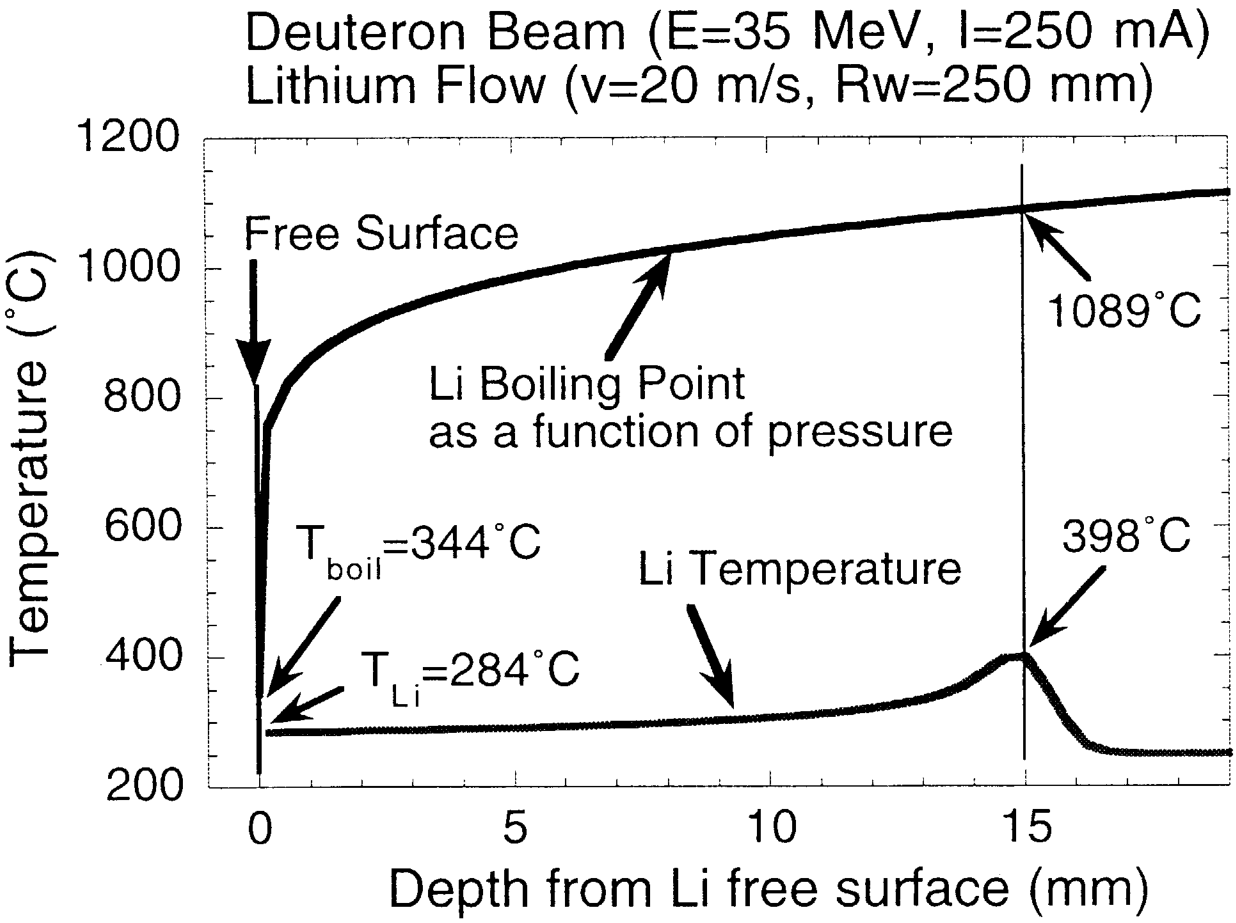

Fig. 4-3 Depth profiles of the lithium temperature and lithium boiling temperature.

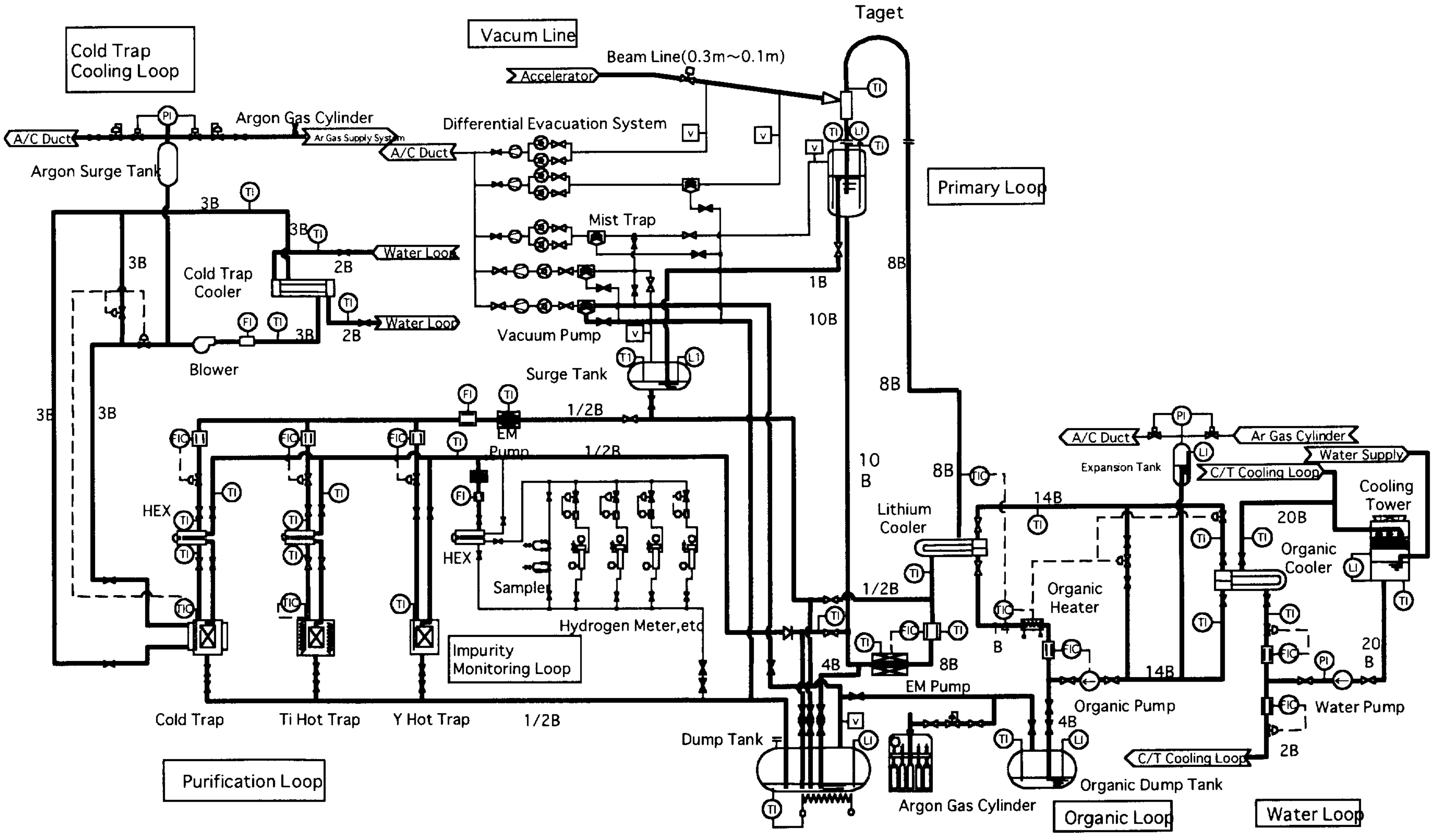

Fig. 4-4 Flow diagram of the lithium loop in reduced cost design.

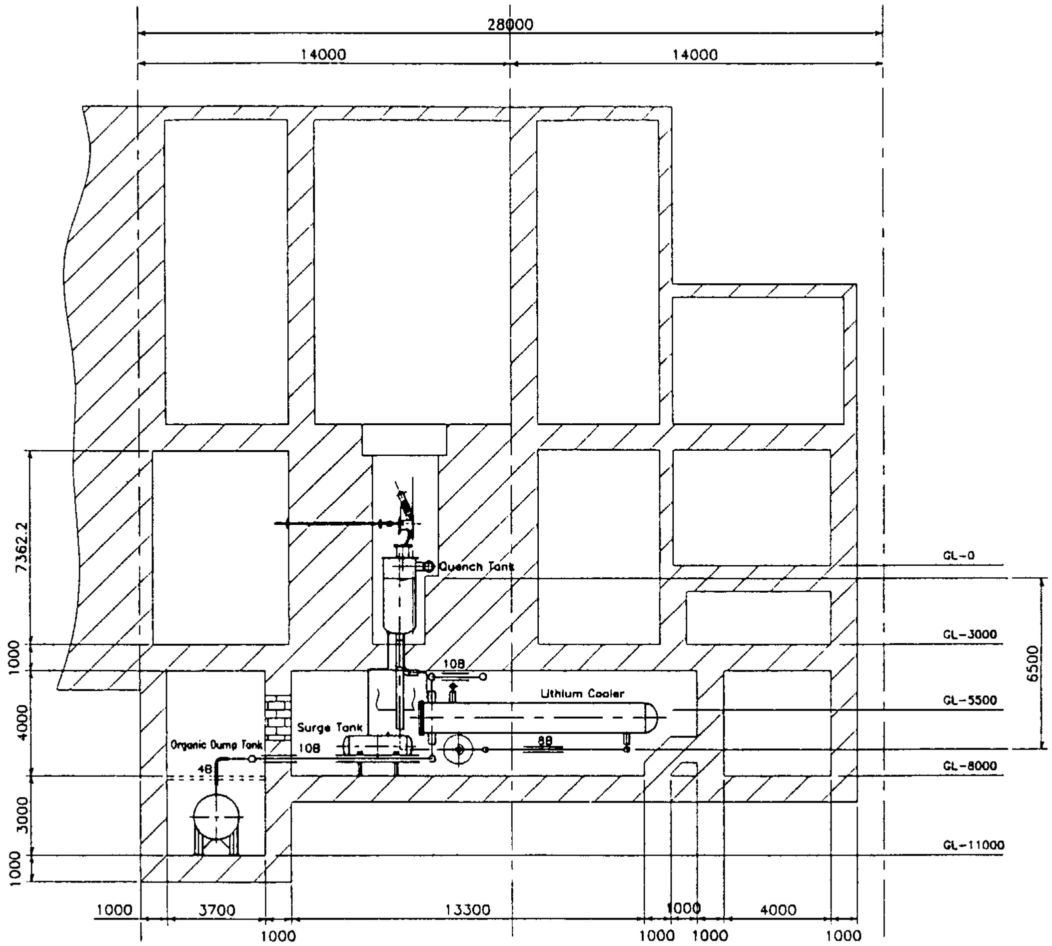

Fig. 4-5 Cross section of IFMIF target system building.

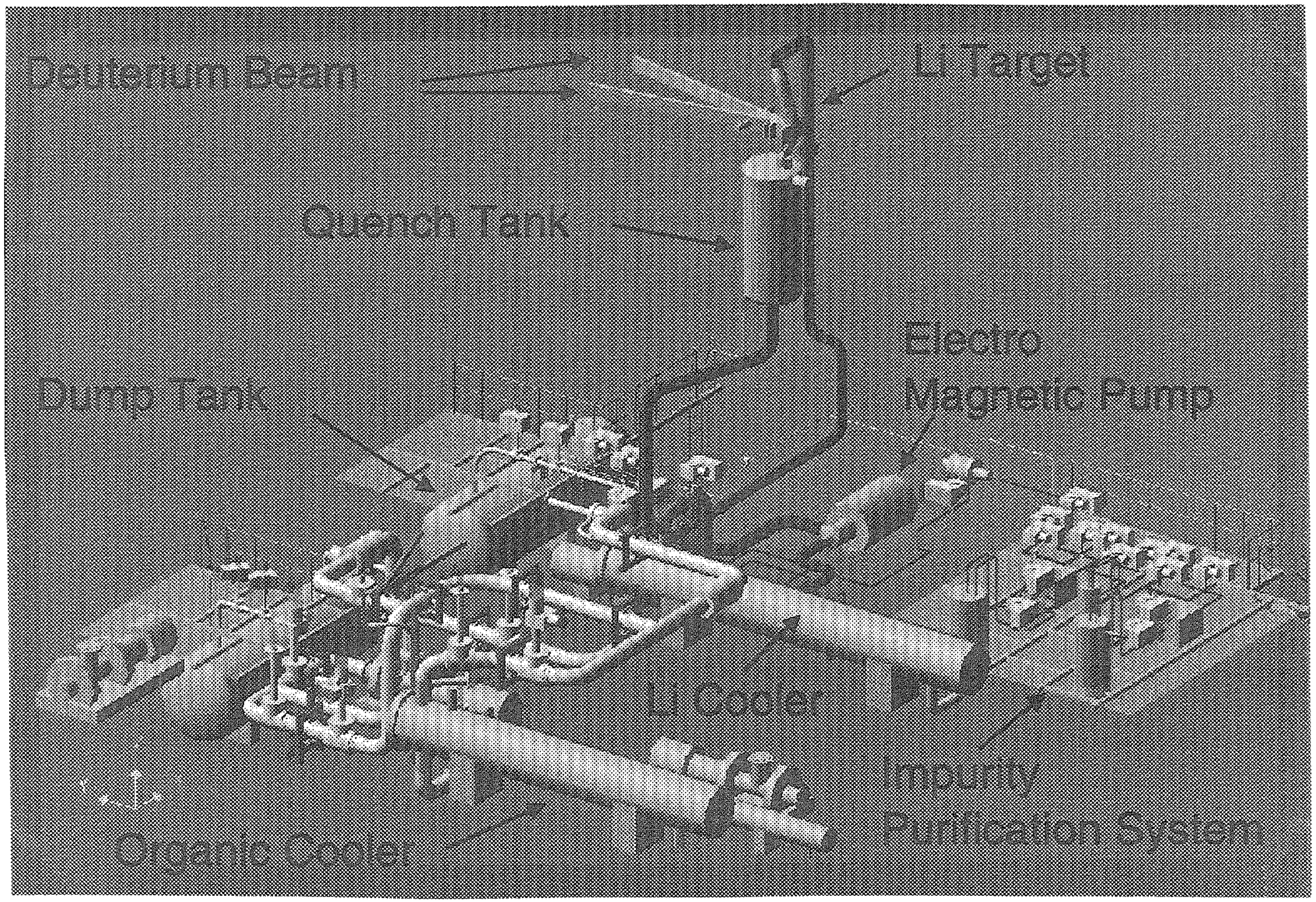

Fig. 5-1 Three dimensional view of layout of the components and pipings.

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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 = 1.60218×10^{-19} J

1 u = 1.66054×10^{-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 = 3.7×10^{10} Bq

1 R = 2.58×10^{-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·s($N{\cdot}s/m^2$) = 10 P(ポアズ)(g/(cm·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)

Reduced Cost Design of Liquid Lithium Target for International Fusion Material Irradiation Facility（IFMIF）