Engineering Design and Construction of IFMIF/EVEDA Lithium Test Loop: Design and Fabrication of Integrated Target assembly

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Abstract.
The Engineering Validation and Engineering Design Activity (EVEDA) for the International Fusion Materials Irradiation Facility (IFMIF) is proceeded as one of the ITER Broader Approach (BA) activities. In the concept of the IFMIF, two 40 MeV deuteron beams are injected into a liquid Li stream flowing at 15 m/s speed. The Li stream (Li target) is a free-surface flow produced by a double contraction nozzle and flows over a concave flow channel in a vacuum of 10^{-3} Pa. The EVEDA Li test loop (ELTL) is aimed at validating stability of the Li target and feasibility of a Li purification system as the key issues. In this paper, the design of the ELTL especially of a target assembly in which the Li target is produced by the contraction nozzle is presented. There are two concepts regarding to the target assembly: the integrated target assembly and the bayonet target assembly. The both target assembly is outlined in this paper, then the newly proposed design and fabrication of the integrated target assembly for the ELTL are given.

1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is aimed at producing an intense high energy neutron flux generated by a deuteron (D^+) - lithium (Li) nuclear reaction. In the current concept of the IFMIF, two 40 MeV-deuteron beams whose total current is 250 mA are injected into a liquid Li stream flowing at a speed of 15 m/s. The Li stream, hereinafter called the Li target, is a free-surface flow produced by a double contraction nozzle and flows through a concave flow channel in a vacuum of 10^{-3} Pa.

At present, Engineering Validation and Engineering Design Activity (EVEDA) for the IFMIF is carried out under an international collaboration known as the ITER Broader Approach (BA) between Japan and the EU. The EVEDA tasks related to the Li target facility consist of six tasks[1] which are (I) construction and operation of a Li test loop; (II) diagnostics for the Li target; (III) erosion/corrosion for loop structure materials; (IV) a Li purification system; (V) remote handling; (VI) IFMIF engineering design. Among these tasks, as a major Japanese activity, the EVEDA Li Test Loop (ELTL) is now under construction at the O-arai site of the Japan Atomic Energy Agency (JAEA). It is scheduled for completion at the end of Feb. 2011 and for operation for 2 years from May 2011.

Major issues to be investigated and validated in the ELTL are:

- the hydraulic stability of the Li target,
- the Li purification system consisting of three impurity traps.

The ELTL has the major components necessary to produce the Li target. In addition to these components, tasks (II) and (IV) are underway, and will develop and supply the following devices:

- Diagnostic devices for the Li target which is high-speed free-surface flow of Li,
- Two hot traps and three impurity monitors to purify and monitor impurities in Li such as nitrogen (N) and hydrogen (H).

The diagnostic devices and the traps and monitors are scheduled to be fabricated during fiscal year 2010 and installed in the second phase of construction just after completion of the ELTL, excluding the H hot trap and monitor. By using these devices and traps, the stability of the Li target and performance of the traps and monitors are investigated. As a result, the current specifications of the target, traps and monitors are expected to be validated or reevaluated based on the test results for the goal of designing the Li target and the purification system for the actual IFMIF.

This paper focuses on Li target validation, especially the design of the Li target and target assembly, hereinafter abbreviated as TA, in which the Li target is produced. The Li target and TA components are outlined in this paper after description of the whole loop configuration of the ELTL. Then, the TA structure newly designed for the ELTL based on the previous specifications and the result of the fabrication are presented.

2. Overview of the ELTL

FIG. 1 shows the pipe and instruments diagram (P&ID) of the ELTL. The ELTL consists of two major Li loops which are the main loop and the purification loop with the impurity monitoring loop. The main Li loop was designed to supply liquid Li at an adequate flow rate and temperature to the TA. The purification loop with impurity monitoring loop removes impurities in the Li and monitors the concentration. The major design specifications of the ELTL, which contains 5000 L of Li, are described as follows: The design temperature is 400 °C, and the design pressure ranges from a gauge pressure of -0.1 MPa through 0.75 MPa. The maximum flow rate of the main circulation pump is 3000 L/min. The main loop consists of 6-inch Li circulation pipes; the TA; a quench tank; an electro-magnetic pump (EMP); an electro-magnetic flow meter (EMF); a cooler; a surge tank; a dump tank; and valves. These tanks are equipped with nozzles that connect to Ar gas cylinders and vacuum pumps to control pressure.

3. Overview of the Li target and TA

3.1. Specifications of the IFMIF Li target

The fundamental requirement for the Li target in the IFMIF is to remove 10 MW heat power produced by the D^+ beams without boiling or any perturbation of the Li target. Since the Li target flows in a vacuum condition of 10^{-3} Pa, the boiling temperature of Li is decreased to 344 ◦C and there is a high risk of boiling as a result of heat from the D^+ beam. In order to add a margin to prevent boiling, it has been proposed that centrifugal force be applied to the Li target to increase the statistic pressure and then that the boiling temperature inside of the Li target be raised. For that reason, the Li target is designed to flow the concave flow channel. In addition, sufficient thickness to cover the range of D^+ beam penetration is required to protect the flow channel that the Li target flows along. The major specifications of the Li target in the IFMIF are presented in Table I. To fulfil the fundamental requirements, the velocity, the thickness, the width and the curvature radius of the concave channel were selected as shown in Table I based on a thermo-hydraulic analysis [2].

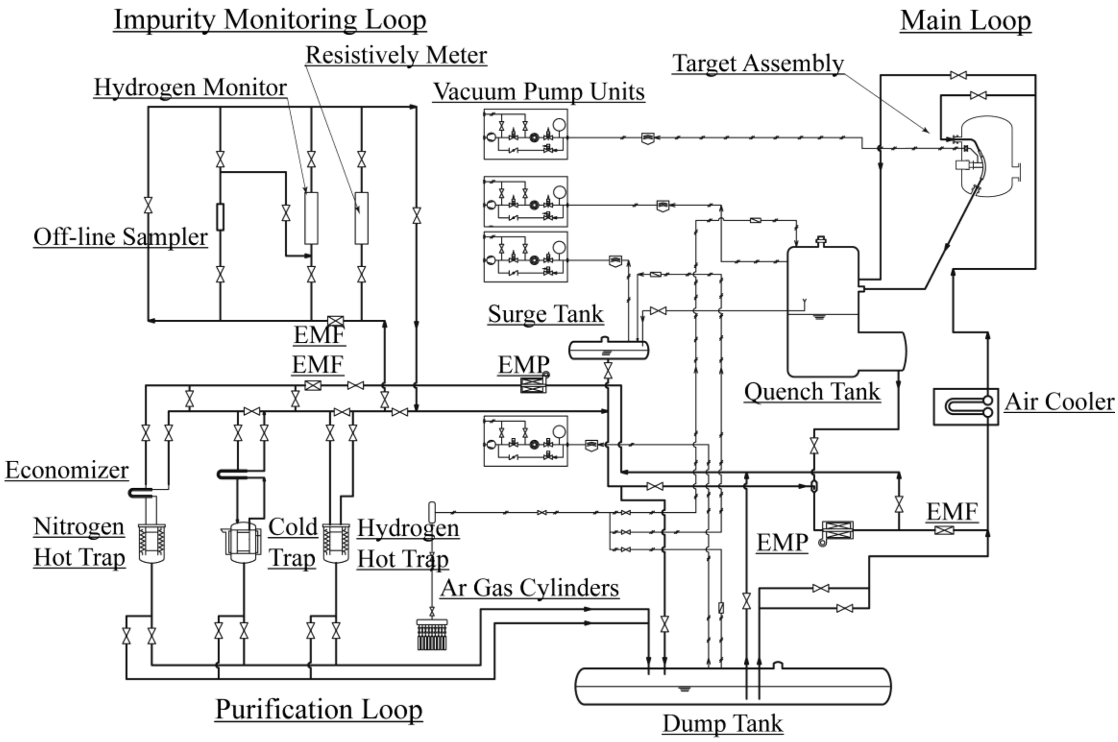


FIG.1. Pipe and instruments diagram of the ELTL

Table I. The major specifications of the IFMIF and the ELTL Li target

	IFMIF	ELTL
Li target velocity at nozzle exit	15 (range 10 – 20) m/s	< 20 m/s
Li target thickness / stability	25 / ± 1 mm	25 mm / To be investigated
Li target width	260 mm	100 mm
Curvature radius	250 mm	Described in Sec. 3.2
Vacuum pressure	10^{-3} Pa	< 10^{-3} Pa
Li temperature	250 °C (at the inlet)	Operation : 250-350 °C Design : 400 °C
Li Pressure	-	Operation : 0.45 MPa Design : 0.85 MPa

3.2. Overview of the ELTL Li target and TA

Table I also shows the specifications of the ELTL Li target. As shown in Table I, the velocity range, the thickness, the temperature and the vacuum pressure of the ELTL cover the range of the IFMIF, excluding the target width that is reduced to 100 mm from 260 mm. Regarding the curvature radius, the ELTL target employed a new profile of the curvature proposed during the initial phase of the EVEDA [3].

The Li target is produced by and in the TA, whose major components are the nozzle and the flow channel to produce and flow the Li target. For the IFMIF TA, a double-contraction nozzle was designed based on a theoretical model proposed by A. Shima. The ELTL also employs the same double-contraction nozzle which is described in detail in the next chapter.

As for the back plate in which the flow channel is fabricated, two types are proposed for the IFMIF; namely, an integrated type and a bayonet type. In the integrated type, the back plate is welded (i.e. integrated) in the TA. On the other hand, in the bayonet type, the back plate can be replaced like a bayonet from the TA. In the ELTL, two TAs characterized by each back plate type are designed, fabricated and tested. The integrated TA is made entirely of stainless steel type 316 L, and the bayonet TA is made of reduced activation ferritic steel (F82H and EUROFER). This paper focuses on the integrated TA.

4. Design of the integrated TA for the ELTL

The structure of the integrated TA, newly proposed by the authors, is illustrated in FIG.2. In consideration of the fabrication process described in later sections, the integrated TA was designed to be comprised of 6 major components denoted by Roman numerals in FIG.2. These are:

- (I) the inlet nozzle
- (II) the rectangle channel with (II-1) the flow straightener
- (III) the double-contraction nozzle
- (IV) the back plate with (IV-1) the flow channel
- (V) target chamber with (V-1) the large viewing, (V-2) the small and (V-3) vacuum ports
- (VI) the outlet nozzle

These components and a confinement vessel, in which both target assemblies are installed, are described in the following sections.

4.1. Inlet nozzle and rectangle channel with flow straightener

Liquid Li comes from the circular pipe of the main loop, whose inside diameter and wall thickness are 155.2 mm and 5.0 mm, respectively, to the rectangle channel (II) of the TA through the inlet nozzle (I). The flow straightener (II-1) consisting of the honeycomb (L100 mm) and the three perforated plates (pitch 100 mm) are prepared to reduce both the turbulence caused at the inlet nozzle and secondary flow, which is generated in bend sections located upstream from the inlet nozzle, and to flatten the velocity profile.

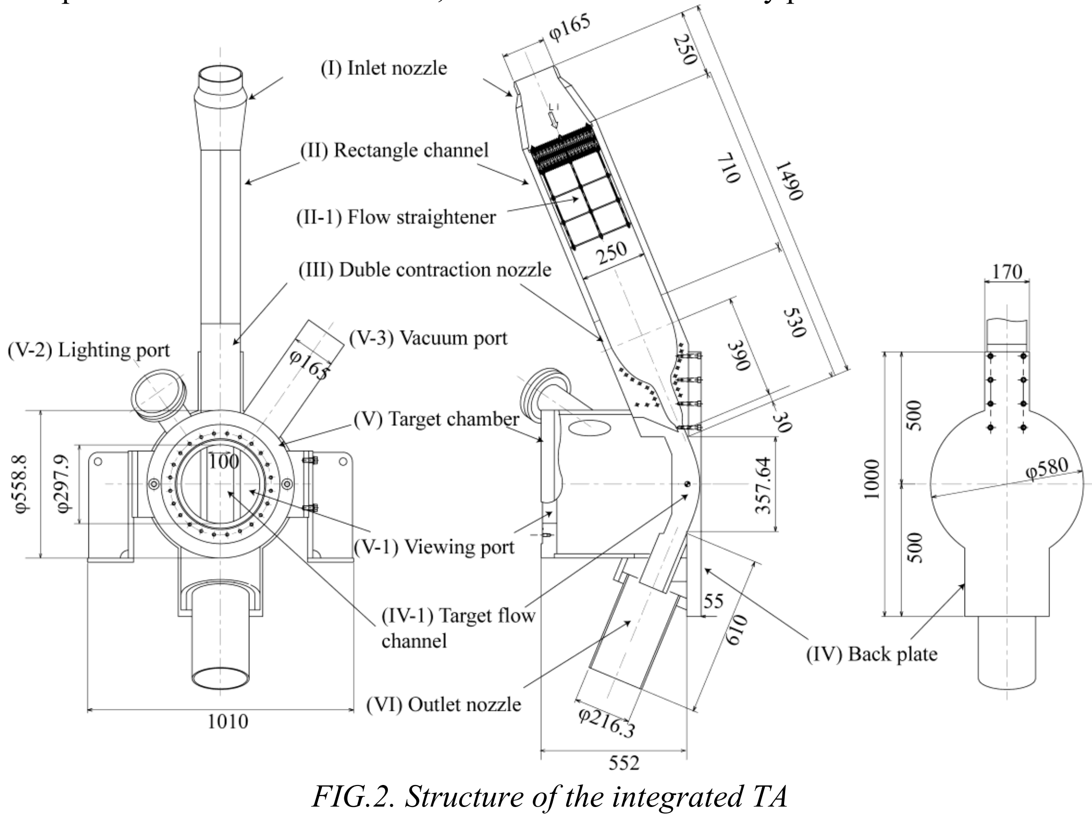


FIG.2. Structure of the integrated TA

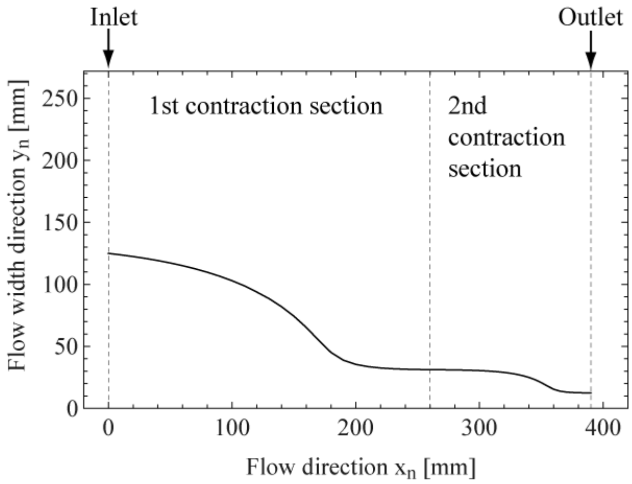


FIG.3. Nozzle coordinate

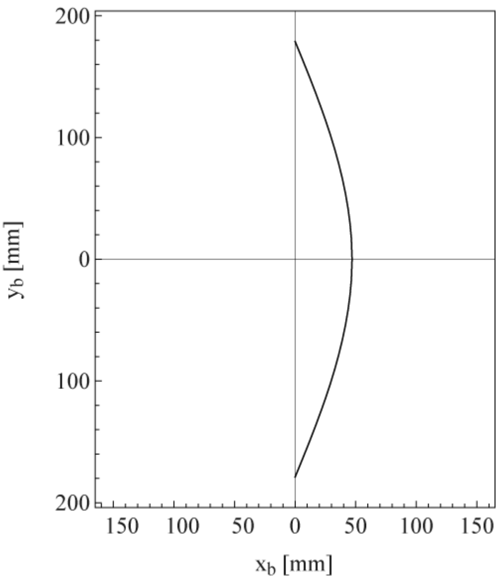


FIG.4. Flow channel curvature coordinate

4.2. Double contraction Nozzle

The integrated TA employs the double-contraction nozzle (III) designed for the IFMIF target, although the width is reduced to 1/2.6. The contraction nozzle is aimed at generating a high-speed uniform Li flow. Since one contraction as large as a ratio of 10 may cause a flow separation in the nozzle at high speed, the maximum contraction ratio was limited to less than 4 based on hydraulic analysis [2], and thus the double contraction nozzle with the ratio of 10:2.5:1 was employed. The curves of both parts are defined based on the Shima nozzle (x, y) as follows:

$$x = \frac{2a \cdot \ln[2\cos(\theta/2)] - 2b \cdot \ln[2\sin(\theta/2)] + \left[\sqrt{2b(a+b)} - (a+b)\right]\cos\theta}{2\pi}$$

$$y = \frac{b}{2} + \frac{(a-b)\theta + \left[\sqrt{2b(a+b)} - (a+b)\right]\sin\theta}{2\pi}$$

where, a: inlet size ($\theta \to \pi$, $x \to -\infty$, $y \to a/2$), b: outlet size ($\theta \to 0$, $x \to +\infty$, $y \to b/2$). For the ELTL, both pairs of curves for the 1st contraction section (x_1, y_1) and the 2nd (x_2, y_2) are defined with the coefficient a_1 = 269.4 mm, b_1 = 62.1 mm for the 1st section ($-140 < x_1 < 120$ mm), a_2 = 62.7 mm, b_2 = 24.9 mm for the 2nd ($-90 < x_2 < 40$ mm), respectively. Both sections are adjusted to be connected at (x_1, y_1) = (120, 62.5) and (x_2 , y_2) = (-90, 62.5). FIG. 2 shows the coordinate of the double contraction nozzle, (x_n, $+y_n$), for the ELTL. In FIG.2, the x coordinate at the inlet of the nozzle is offset to zero. Thus, the 1st and 2nd contraction sections are connected at x_n = 260 mm and the total length is 390 mm.

4.3. The back plate with the flow channel

The flow channel is fabricated on the back plate and connected to the contraction nozzle and the outlet nozzle to the quench tank as shown in FIG.2. The flow channel curvature was determined so as to avoid Li boiling and its curvature radius, Rw, was Rw = 250 mm as the reference, as noted in Sec.3.1. However, the ELTL TA was modified to achieve the new curvature profile proposed in the initial phase of the EVEDA. The newly proposed curvature is gradually modified along the flow direction as shown in FIG.4. This curvature is at first almost straight at the nozzle exit, and gradually changed to the smallest curvature radius at the beam center, and then to almost straight again at the downstream. The requirement $R_w \leq 10$ m indicated in the analysis is maintained in the whole range.

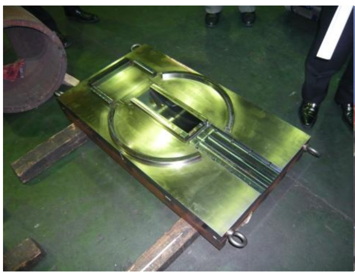
4.4. Target chamber with viewing, lighting and vacuum ports

The target chamber is an S.S. 316L cylinder connected to the back plate, whose inside diameter is 558.8 mm, as shown in FIG.1. The target chamber has a large and a small viewing port for the Li target flow test, and a vacuum port connecting to a turbo-molecular pump. An optical window is installed in the large viewing port through a gate valve. In the ELTL, this large viewing port is used mainly for measurement of the Li target, while this port becomes a beam duct through which D^+ beams are injected in the IFMIF. The small viewing port is prepared as an alternative for viewing and lighting.

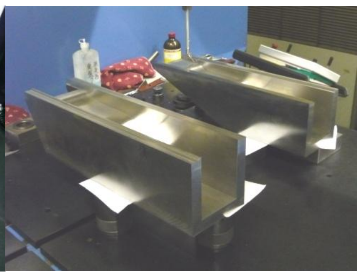
5. Fabrication process and result

The integrated TA is comprised of 6 major components in consideration of the fabrication process. FIG.6 shows pictures on the fabrication and assembling process of the components. Although no specific requirement had been imposed on the fabrication, in order to realize highly accurate curvatures of the double contraction nozzle and the flow channel, a numerical control five-axis milling machine was used for fabrication. This is for the reason that these curvatures are considered to be the heart of the TA, and the integrated TA is focused on the stability of the Li target produced by the hydraulically defined nozzle and flow channel.

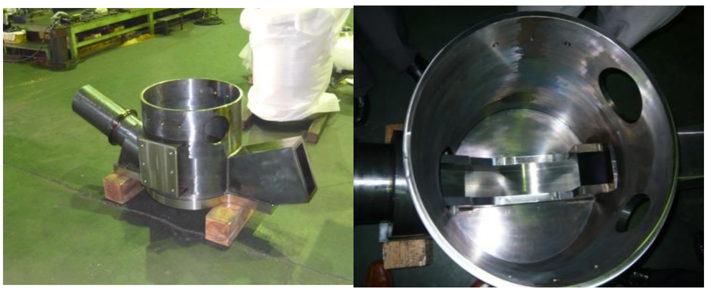
(a) Fabrication of the back plate:
The back plate was designed as the base of the TA structure and to be fabricated initially from an ingot of S.S. 316L. The flow channel and the groove where the nozzle is installed as well as the outer shape were fabricated by NC machine. The flow channel was fabricated halfway at this stage, i.e. several hundred μm layer was left for final fabrication after assembling.



(a)Fabrication of the back plate



(b)Fabrication of the double reducer nozzle



(c)Assembly of the back plate, the double contraction nozzle, the outlet nozzle and the target chamber

(d)Installation

FIG.6. Fabrication process of the integrated TA made of S.S. 316L

(b) Fabrication of the double contraction nozzle:
The double contraction nozzle was also fabricated from an ingot by NC machine. The free-surface side and the back plate side were fabricated separately and subsequently welded by electron beam welding (EBW).

The dimension of the double contraction nozzle curvature was measured by 3-dimensional (3D) measurement tool (Zeiss MMZ 122010). Table II shows the result of the measurement. Three lines along with the nozzle curve in the width direction were measured in both parts (free-surface side and flow channel side) of the double contraction nozzle before both parts were combined by welding. The measurement points in each line were 53 and, the average of the root mean square (RMS) values of error, i.e., input value minus measurement value, are presented as the processing error in Table II. The measurement accuracy of the 3-D measurement was 1.4 μm as the result of a calibration.

Table II. Processing error of the double contraction nozzle

Components	Processing error [μm]
The double contraction nozzle	20.3
The flow channel (curvature)	13.3

(c) Assembly of the back plate, the double contraction nozzle, the outlet nozzle and the target chamber:
The double contraction nozzle was bolted at the groove by 8 bolts, as shown in FIG.1, in order to avoid heat deformation by welding. After fixation, the boundary of the double contraction nozzle and the flow channel and the bolts were welded for seal. Then, the outlet nozzle and the target chamber were installed on the back plate by welding. After assembly, the flow channel was fabricated to cut the seal welding part and the remaining layer.

In this process, the flow channel curvature was measured by 3-D measurement tool (Zeiss PRISMO 10 HTG VAST) which has an accuracy of 1.4 μm. Table II presents the results of measurements performed at 3 different lines in the width direction along with the flow channel. The average of 15 points of each line was measured and the root mean squares (RMS) of errors are presented in Table II. Surface roughness was also measured at this stage. The maximum profile valley depth (Rmax) and the arithmetical mean deviation of the profile (Ra) of the surface roughness were 1.0 and 0.25 μm on an average respectively and lower than the specification value of Rmax = 6.3 μm.

Finally, using EBW, the inlet nozzle and the rectangle channel with the flow straightener were connected to the double contraction nozzle, and a flange was installed at the large viewing port.

(d) Installation in the confinement vessel:
After several tests and inspections, such as pressure test and welding inspections, the integrated TA was installed in the ELTL, as shown in FIG.6. The outlet nozzle, the large viewing port and the vacuum port were connected by bellows, while the inlet nozzle was connected by elbow. Heaters, Li leak detectors and heat insulators will be installed after completion of on-site inspections.

7. Summary

The engineering validation and engineering design activities (EVEDA) for the IFMIF is now underway as one of the ITER-BA activities. This paper presents the design of the EVEDA Li test loop (ELTL), in particular the design of the target assembly (TA) which is the most important component in the Li target facility. The points are summarized below.

i. Design of the ELTL and the main loop:
The ELTL was designed to consist of the two major Li loops, which are the main loop and the purification and impurity monitoring loop. The main loop is equipped with all components necessary to produce the Li target; namely, 6-inch Li circulation pipes, the TA, several tanks and valves. The EMP can supply Li to the TA at the maximum flow rate of 3000 L/min corresponding to 20 m/s in the TA. At the moment, the ELTL is under construction, scheduled for completion in Feb., 2011, and for operation for 2 years from May, 2011.

ii. Requirements and specifications of the IFMIF target and the outline of the ELTL TA:
The fundamental requirement for the Li target in the IFMIF is to remove 10 MW heat power produced by the D^+ beams without boiling. In addition, sufficient thickness to cover the range of D^+ beam penetration is required to protect the flow channel. Based on thermo-hydraulic analysis, the velocity, the curvature radius, the thickness and the width were selected to fulfil the requirements. In the ELTL, the two TAs are scheduled to be designed, fabricated and tested: these are the integrated TA made of S.S. 316L and the bayonet TA made of F82H and EUROFER. Both TAs have the double contraction nozzle designed for the IFMIF, and produce Li targets possessing the same velocity, thickness and temperature.

iii. Detailed design of the integrated TA:
The Integrated TA was designed in consideration of the fabrication process which aimed to assure high processing accuracy. The integrated TA consists of 6 components; namely, the inlet nozzle; the rectangle channel with the flow straightener; the double-contraction nozzle; the back plate; target chamber. The double reducer nozzle is designed based on the Shima nozzle and the same as the IFMIF, and the curvature radius of the flow channel is newly defined.

iv. Fabrication process and the processing accuracy:
In order to realize a highly accurate curvature of the double contraction nozzle and the flow channel, a numerical control five-axis milling machine was used for fabrication. In the fabrication process, the back plate and nozzle were separately fabricated from S.S. 316L ingots, and then combined. In the processing, the processing errors were 20.3 μm for the double contraction nozzle and 13.3 μm for the flow channel curvature. The surface roughness was 1.0 μm in Rmax and 0.25μm in Ra, and both were within the required Rmax: 6.3 μm.

Reference

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