# Concept of the IFMIF Accelerator System

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## Abstract

The conceptual design activity of the International Fusion Materials Irradiation Facility has been carried out for these two years and the final design report was completed. The design will be reviewed to proceed to the next step in both the domestic and the international frameworks. A simple system dynamical model is helpful to understand the behaviors of the IFMIF accelerator system including the injector, the rf linacs, and the transport lines.

## 1 Introduction

The International Fusion Materials Irradiation Facility (IFMIF) provides the intense neutron field to simulate the behavior of the materials in the fusion reactor environment, like the prior proposals as FMIT or ESNIT. The users' requirements for the neutron irradiation field are given in Table 1[1]. The Conceptual Design Activity (CDA) of the IFMIF is proposed to the Fusion Power Program Committee (FPCC) and has been carried out between February 1995 and January 1997. The activity consists of four subgroups (accelerator, target, test cell and integration groups), and Japan, US, EU and Russia participate the design tasks. The final design report [2] is completed in December 1996, however the fully technical details are removed from the report to keep the report size short. As a separated task, the cost estimation is also carried out by each participant country and presented as the informal documents. The report discusses the interface issues among the subsystems of the facility and treats the safety/reliability issues in more details relatively.

Table 1. Requirements for an Intense Neutron Source

| | |
|---|---|
| Neutron Flux/ Volume Relation | Equivalent to 2 MW/m$^2$ in 10 L volume (MW/m$^2$ = 4.5x10$^{17}$ n/m$^2$s) |
| Neutron Spectrum | Similar to First Wall neutron spectrum (PKA/Transmutations) |
| Neutron Fluence Accumulation | DEMO-relevant Fluences of 150 dpa$_{NRT}$ in a few years |
| Neutron Flux Gradient | $\leq$ 10 %/cm based on dimensions of test specimen |
| Machine Availability | 70 % |
| Time Structure | Quasi Continuous Operation |
| Accessibility | Irradiation Volume for experiments and Instrumentation |

As a consequence of employment of such report style, it is necessary to refer each reference document for the technical design details. In the first part of this article the comprehensive summary of the accelerator design concept of the IFMIF is discussed, and in the second part the simple system model to analyze the behavior of the accelerator system is described. As the conclusion some possible alternatives of the accelerator design concept are presented.

## 2 Accelerator System

From the long-term discussion since FMIT proposal, the best neutron source reaction for the IFMIF is the d–Li reaction, which has a broad peak in the neutron spectrum near the half of the incident deuteron energy, Ed, at the forward angle. This property can be used to tailor the neutron spectrum simulating the fusion reactor neutron field for each material at the various reactor environments. However, the energy integrated neutron yield at the forward angle from the thick lithium target behaves like $Ed^{2.5}$, the higher deuteron energy is desirable to obtain the higher neutron intensity effectively. The required energy and intensity of the deuteron beam is estimated as 40 MeV and 250 mA, respectively, to fulfill the volume/intensity guidelines: 0.1 L for > 50 dpa/fpy; 0.5 L for > 20 dpa/fpy; and 6 L for > 1 dpa/fpy. The 40 MeV deuteron provides a good neutron field for most metallic components but it is desirable to reduce the energy for other materials like ceramics. From the result of the accelerator system design, the energy step of 4 MeV is preferred to achieve the best performance and the output deuteron energy can be selected from 32, 36 and 40 MeV.

The cw rf linac is chosen as the deuteron accelerator and two identical 125–mA linac modules are employed as providing the beams to the targets independently. This configuration eliminates both the 250–mA injector and the funneling scheme, which involve the highest technical difficulties. It also improves the overall system availability if the irradiation test can be continued during the beam-off events of either of two linacs. Because the temperature control system of test cell should be shut down to prevent the annealing of the damage when the irradiating neutrons are disappeared.

The frequency of the rf linacs is 175 MHz to eliminate the frequency change in the system and to achieve the best performance for 8–MeV RFQ and 40–MeV DTL. The high power rf source in this frequency range can be available from Thomson CSF and EIMAC, however the long range (> 100 hr as a primary goal) operation is not guaranteed yet.

The beam footprint at three target stations (2 lithium targets and 1 beam calibration dump) should be identical for the beams from two linac modules and the distribution is rectangular (20 cm horizontal and 5 cm vertical) with a flat top region. The sharp edge in the horizontal sides and the smooth tail in the vertical sides are required to keep the liquid lithium flow stable. The energy dispersion of ±0.5 MeV FWHM is also required to make a margin from the maximum temperature to the boiling point inside the lithium target. These requirements influence the HEBT design:

- two-dimensional beam expander using the high order multipoles which has the different characteristics in the horizontal and vertical directions;
- space periodic transport system to carry the beam to three stations with identical manner;
- final bend to place two beams at the same footprint;
- energy dispersion cavity (EDC) at the end of transport.

No combined function bend is considered to simplify the transport design and, as a result, the two-story beam transport with 5m level difference should be designed. The levels of the corresponding linac modules have the same difference. The 5m difference comes from the 10°-injection at the final bend and the protection of the beam transport elements from the neutron back streaming.

The availability goal is 70 % including the scheduled maintenance (one month per year and 8 hours per week), so that the inherent system availability is calculated as 80.7 %. By taking into account the availability goals of the other subsystems, the accelerator system availability is required to be 88 %. The reliability/availability/maintainability (RAM) model has been developed to allocate the availability budget to each subsystem components: the major subsystems of the accelerator module are the injector, RFQ, DTL, RF system, and HEBT, as shown in Fig. 1. The failure modes of the components are considered and then, for each failure mode, the mean times between failures (MTBF) and the mean times to repair (MTTR) are estimated in the steady state operation. The summary table of the RAM model of the accelerator system is given in Table 2.

Table 2. RAM Model of the IFMIF Accelerator System

| Subsystem | MTBF [h] | MTTR [h] | Reliability [%] | Availability [%] |
|---|---|---|---|---|
| Injector | 159 | 2 | 34.8 | 98.7 |
| Linac | 416 | 18 | 76.1 | 95.8 |
| RF system | 191 | 9 | 42.3 | 95.5 |
| HEBT | 417 | 13 | 67.7 | 97.0 |
| Total | 59.5 | 8.5 | 7.6 | 87.6 |

For each component in the subsystems, the negative exponential distribution and the independence among the failure modes are assumed as

$$MTBF = \left(\sum_i (MTBF_i)^{-1}\right)^{-1}, \quad MTTR = MTBF \cdot \sum_i \left(\frac{MTTR}{MTBF}\right)_i ,$$

$$Reliability: R = \prod_i R_i = \prod_i \left(\exp\left(-\frac{mission\_time}{MTTR}\right)\right)_i ,$$

$$Availability: A = \prod_i A_i = \prod_i \left(\frac{1}{1+MTTR/MTBF}\right)_i ,$$

where the suffix $i$ represents the failure mode.

## 3 System Model

In the actual operation of such a high current accelerator system, the beam loss control is the most important problem to keep the hands-on maintenance during the machine lifetime and to maximize the machine availability. From this point of view, some design issues are untouched in the CDA yet:

(1) The current instability of the injector may produce the mismatch to RFQ due to the change of the neutralization process in the LEBT. A beam loss along the RFQ (and DTL, HEBT) can be occurred.

(2) The pulse mode operation is proposed at the startup time and a transient part of the beam pulse may be lost. An

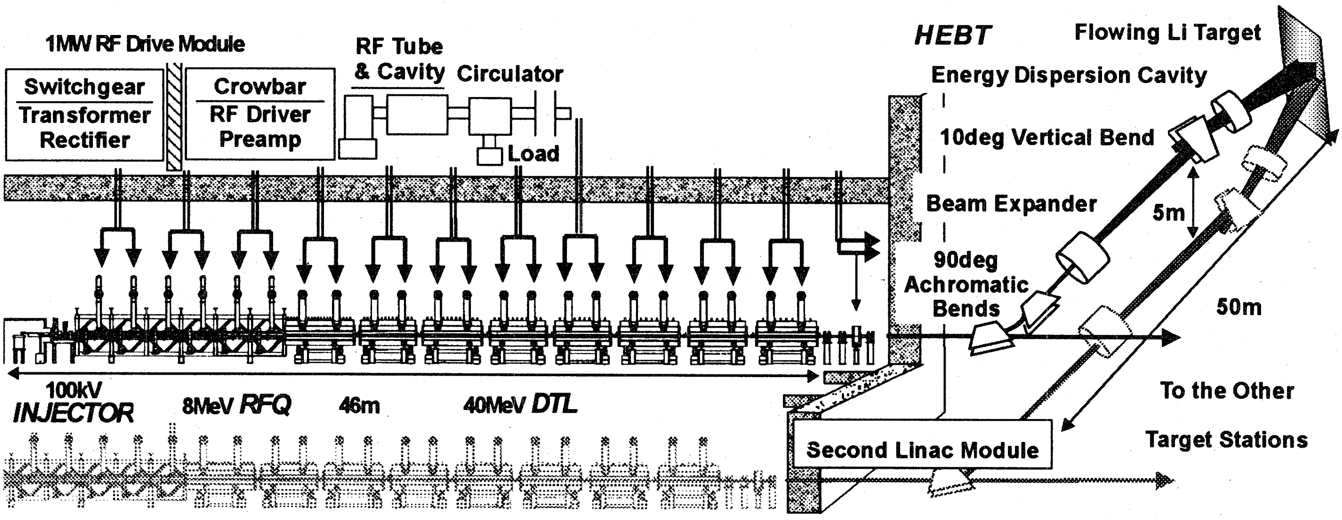

Fig. 1. Layout of the IFMIF accelerator system

alternative approach to use the cw beam with starting from the very low intensity has also a risk to loose the all beam before reaching the operation current. It is required to minimize the time-integrated beam loss by optimizing the startup operation.

(3) The better availability is obtained by removing the unreliable components from the design. In this context, the number of components in the HEBT system is not optimized and may be reduced if the beam requirements at the lithium target are reconsidered. For example, the EDC is required to increase the beam energy spread to ±0.5MeV. Since the natural energy spread during the transport will be ±0.2MeV, it can be unused if the boiling point margin in lithium target is moderate although it depends on the progress of the target technology.

These issues are closely related to the accelerator system dynamics and a simple model to describe its behavior is considered. The top-level block diagram of the dynamical system is shown in Fig. 2. The objective is the beam specification requested for the irradiation tests at each instance. The maximum availability should be kept by minimizing the beam loss and the associated activation, which are caused by the disturbance of the parameters and the component failures.

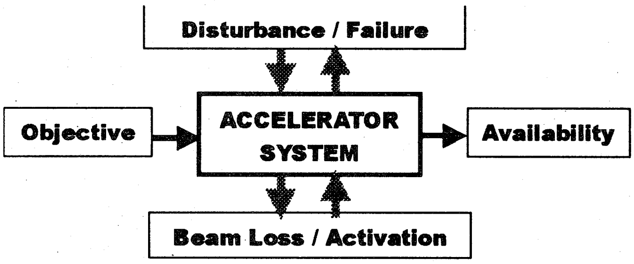

Fig. 2 Top-level Block Diagram of Accelerator System.

### *3.1 Single Module Operation Model*

Two modules of the IFMIF accelerator are operated independently as far as either module is running normally. At the off-normal events like beam trip, the following recovery process can be taken:

(a) a full intensity beam is immediately restored by using an automatic control (recovery time < 10 sec),
(b) the beam is restored by ramping the current with a minor parameter adjustment (< a few min), or
(c) an inspection or a repair is necessary and sometimes both accelerator modules must be shut down to do so.

If it is evident that the recovery process will take more than a minute, the signal is sent to target and test-cell groups to adjust their temperature control systems. The beam trip is caused by failures of accelerator components and by the interlock signals from the other subsystems. However, the latter is neglected in the present analysis.

The component parameters are treated as the system state variables and their behavior is modeled by various stochastic processes (Poisson, Gaussian, etc.). The beam loss is also a state variable to be derived by the parameter values and the beam dynamics calculation. In the case of large beam loss, the accelerator is shut off to avoid the excessive activation. The obtained availability is strongly influenced by the criterion of the acceptable loss level, and a 3 nA/m goal is proposed at the CDA. At present, we are developing the beam dynamics simulation code with a high precision to estimate the correct beam loss for the IFMIF accelerator module. The results of the rough simulation code indicate essentially no beam loss after RFQ and only the component failures are taken into account in this region. As a result the 88% availability can be achieved at the assumed failure rates.

### *3.2 Dual Module Operation Model*

As described before, the operation of two modules has a correlation when the repair is necessary for the components placed except in the accelerator vaults, which are separated by the heavy radiation shields. So the failure rates of the HEBT or RF transport components are treated as the correlated events, such as buncher rf power, EDC, and quads/bend chain at the end of HEBT. Although the reliability of these elements is estimated to be very high and the loss of availability becomes small, we need to pay an attention to the sensitivity of the input parameters (e.g. MTTR/MTBF ratio) to keep the good performance.

### *3.3 Extended Operation Model*

As an upgrade option, the additional two accelerator modules are installed, and the beams from each two modules are paired and transported into the same lithium target. Therefore two lithium targets and test cells are used in parallel. The availability of this extended operation becomes lower than 88% because the correlated operation mode has a larger effect.

## Conclusion

The conceptual design of the IFMIF accelerator system is overviewed and the system availability model is developed to analyze the effects of the component failure and the resulting beam loss. The precise simulation of the beam loss is urgent to obtain the confident activation level during the operation period.

## References

[1] Editors: J.E. Leis et al., Report on International Fusion Irradiation Facility, Workshop San Diego, USA, Feb. 14-17, 1989.
[2] IFMIF CDA Team, ENEA Frascati Report, RT/ERG/FUS/96/11 (1996).