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Issues to be verified by IFMIF prototype accelerator for engineering validation

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Abstract

The validation of the accelerator technology providing the 250 mA/40 MeV continuous-wave (CW) deuteron beam with the required quality is a key issue to realize the international fusion materials irradiation facility (IFMIF). As the difficulty of high current accelerator generally comes from the low energy section due to space-charge effects, a prototype test of such a part is planned in the next development phase. The optimal choice of the prototype consists of a full-scale injector, a full-modelled radiofrequency quadrupole, and a short drift tube linear accelerator associated with a beam diagnostics/dump. Through prototype tests, the stable control of the CW accelerator at the various operational conditions will be addressed, and the technical risks of IFMIF accelerator construction can be significantly reduced.

1. Introduction

The international fusion materials irradiation facility (IFMIF) is an accelerator-based intense neutron source for fusion reactor materials development, and the conceptual design [1] and the experimental study of the key elements of the accelerator system (key element technology phase, KEP [2]) have been carried out under IEA collaboration. The neutrons are produced by a $d + \mathrm{Li}$ stripping reaction, and a 40 MeV/125 mA deuteron beam is necessary to simulate the neutron environment at the first wall, with a neutron flux $\phi_n > 10^{14}$ n/cm^2/s (annual wall load ~2 MW/m^2) in an irradiation volume >500 cm^3 [1]. The required beam current of 250 mA is achieved by two identical radiofrequency (RF) linear accelerator (linac) modules. This reduces the engineering difficulties in developing a high current accelerator that is beyond the present technical level, and it helps to maintain the irradiation tests even in the event that one of two accelerator modules fails. Although the technology to produce a 7 MeV/100 mA proton beam has been achieved in the APT/LEDA project with a 350 MHz *proton* radiofrequency quadrupole (RFQ) linac [3], an engineering study to fabricate a prototype is necessary to verify the performance of an IFMIF 175 MHz *deuteron* linac before the design is begun. The verification of steady-state operation should be achieved as early as possible during the start-up phase. Therefore it is presently intended to prove stable operation of the IFMIF accelerator system by the construction of an accelerator prototype integration facility during the forthcoming engineering validation phase (EVP).

This paper explains the experimental issues to be verified for the prototype IFMIF accelerator, under conditions of budget and time. The prototype consists of a full-scale injector and RFQ plus a short section drift

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tube linac (DTL). Some critical design parameters, like final and transition energies of linacs or RF source characteristics have to be optimized for the prototype design. These may not be identical to those of the final machine, due to the high activation that comes along with the D^+ operation. The present status and the expected results of some ongoing verification tests for the key component technology, such as the ion injector and RF system components, are also addressed. Finally, an integrated concept of the prototype accelerator is shown as an EVP proposal as the basis for international discussion.

2. Accelerator system requirements

In the present approach, full performance of the IFMIF is attained through a three-stage process. In the first step, one of two accelerator modules, as shown in Fig. 1, is constructed. This will have a beam current of ~50 mA in order to achieve as early as possible key results under fusion specific conditions, even if the available test volume is small during a transition period. In the second step, the beam current is increased to 125 mA by adding the extra RF source modules. The full performance requirement is satisfied in the third step by adding another 125 mA accelerator module. Therefore, the accelerator facilities need to be designed in an appropriate manner, taking into account this three-step deployment [4]. The beams required for normal operation are deuterons (D^+) and molecular hydrogen (H_2^+), where the latter is operated in pulsed modes at the start up after periodic facility maintenance. An output energy of 40 MeV is selected for most irradiation tests to keep the maximum neutron intensity in the test volume, and 32-MeV operation is selectable to study damage effects as a function of neutron energy. The neutron intensity of the latter becomes ~60% of the former case; and it requires additional beam control, such as RF power switching at the last DTL tank and adjustment of magnetic fields in the drift tubes and in the beam transport line. The availability requirement, >88%, needs to be satisfied by considering both equipment failure modes and radiation safety issues. The radioactivity of the accelerator sub-system will be monitored all the time and the major sources of radioactivation, primary particle beam loss and secondary neutron intensity, are used to estimate the dose level for immediate and upcoming repairs and maintenance.

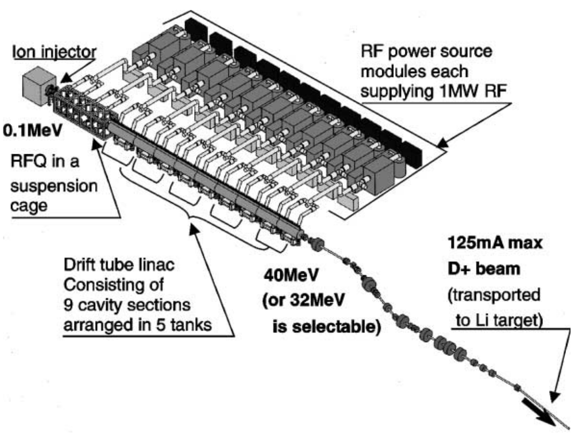

Fig. 1. Layout of the IFMIF accelerator system.

3. Key element technology development

The development in the EVP is devoted to accumulate experience in the design, fabrication, assembly and operation/maintenance of the *key elements* in an integrated system prior to the engineering design for construction of IFMIF. Although the IFMIF accelerator design is based on existing technology developed in previous programs, the integrated systems needed to operate at the required beam intensity and power levels have not yet been built and operated. So the major goal of the EVP is to design, fabricate and test a prototype consisting of the major accelerator components. It is well known that the space charge effects on beam dynamics at the low energy section is critical for an IFMIF-like machine, and the most difficult part is the injector and the consecutive low energy accelerator. So the proposed prototype consists of the injector and a primary portion of the accelerator system with the associated RF sources, diagnostics and beam dump.

3.1. Fundamentals of accelerator development

The technical areas that need to be validated have been identified at the beginning of the conceptual design study as (1) injector system, (2) RF system and (3) linac technology emphasizing low beam loss and activation. Some preliminary and relevant developments have occurred in these areas in other high intensity linac projects, such as APT/LEDA in LANL [3] and IPHI in Saclay [5]. However, progress in developing and testing components have been made during the present IFMIF-KEP activity as described in the next section.

3.2. Verification of key element technology

In the KEP (2000–2002), preliminary development tasks were chosen to verify the technology base of some components, as described in the Ref. [2]. The accelerator tasks were subdivided as described above: (1) injector development and test, i.e. ion source test and analyses, low energy beam transport (LEBT) layout, etc. (2) RF system component test, (RF tube, window, etc.) and (3) component designs (RFQ structure, drift tube, etc.). For the injector development, the design option converged into a single specification as a consequence of the ongoing test results. For the RF component, a ceramic vacuum window necessary to transmit 1 MW CW RF power to the linac cavity is critical for stable operation, and the design for test pieces to avoid local RF heating has been accomplished.

4. Engineering validation tests

The specification of the proposed prototype for the EVP depends on the choice of the final energy of the accelerator to be validated. A solution to extract the maximum technological information from the minimum component development is shown schematically in Fig. 2. It consists of an ion injector, a full-sized RFQ and a short DTL tank with the associated beam diagnostics and a beam dump. The major issues to be addressed in this prototype are (1) full performance tests of the injector using both H_2^+ and D^+ beams, (2) RFQ with the charge/mass ratio (q/m) of 1/2 performance tests using a H_2^+ beam and a short-term D^+ beam test, and (3) a hot model of the first DTL tank with a shorter length, that may be used for H_2^+ and/or D^+ beam tests. The items to be validated by using a prototype are summarized in Table 1 with a short description on the specifications of each component.

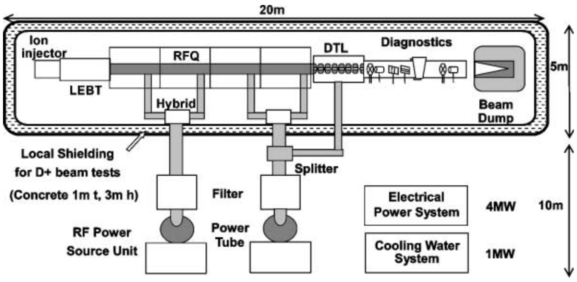

Fig. 2. Layout of the accelerator prototype integration facility foreseen for the IFMIF-EVP.

The RF control for the above configuration is very complicated when beam loading becomes prominent, so that it is better to prepare another independent RF source module for the DTL tank if it is allowed. In that case, the length of DTL tank can be adjusted from ~1/2 to the full value of the first tank design. Most components of the prototype machine can be reused in the construction phase, if the beam induced activity level is kept low enough to transfer the components to the construction site.

4.1. Ion injector prototype

The injector has a high impact on the ability to reach the required availability goal of the IFMIF accelerator system because the system has no mean to recover deteriorated input beam quality along the acceleration and transport line. The individual characteristics of the ion source (current, fraction of atomic beam vs. total beam,

Table 1
Requirements on an IFMIF accelerator prototype

Technical issues	Specifications	Descriptions
Component: injector		
Ion injector performance tests using H^+ dc beam & D^+ pulsed beam	Current: $H^+ > 220$ mA/$D^+ > 155$ mA/ $H_2^+ > 100$ mA; Energy: 0.1 MeV; Emittance: 0.2π mm mrad rms norm;	• Comparison of dc vs. pulsed-mode operations
	Lifetime: ~1000 h; LEBT transmission: >90%	• Pulsed mode used for RFQ injection tests (2 ms, 10 Hz)
Component: RFQ linac		
Cavity tests and beam acceleration tests with H_2^+ & D^+	Surface field: 1.8 Kilpatrick; Output energy: 5 MeV; RFQ transmission: >90%	• Current >90 mA @ 100 mA injection & >125 mA @ 140 mA injection
Component: DTL and diagnostics		
Cavity tests and beam acceleration tests with H_2^+ & D^+	Accelerating field: 1–2 MV/m tunable by post coupler; Output energy: 7 MeV	• Current >90 mA @ 100 mA injection & >125 mA @ 140 mA injection
Drift tube cooling & alignment	Magnetic field central axis	• Realignment of drift tubes after repair of parts
Component: RF power supply system		
Performance tests with dummy load & cavity load/beam loading control	RF window: 500 kW CW; Lifetime: 20 000 h	• Structure types (main amplifier and window) chosen from KEP results

emittance, beam noise, lifetime, etc.) can be achieved based on past developments, however, simultaneous achievement of all of them should be verified in prototype tests. The tests include H_2^+ beam operation, which is necessary to use in the RFQ matching tests described in the next section. The procedures for varying the beam current and duty-factor from tune-up conditions (~1%) to CW (100%) operation is another issue to be faced. The difference in beam characteristics at these various conditions must be characterized to be able to estimate CW operations from the pulsed mode experiments. The control of beam transport with low beam loss is required to use this injector for RFQ beam matching tests.

4.2. RFQ prototype

The IFMIF RFQ is a unique machine to accelerate a beam of particle with $q/m = 1/2$ with the highest quality (current, emittance and stability), close to the technically achievable limit. Previous CW RFQs (other than the FMIT prototype) were designed for proton beams, so it is necessary to demonstrate a deuteron ($q/m = 1/2$) RFQ, designed and fabricated with state of art technology. Operational experience is needed to estimate the availability during long lasting IFMIF operation.

Therefore the main issues to be validated are as follows: (1) fabrication and installation methods applicable to the IFMIF RFQ, (2) achievable RF electric field (>1.8 Kilpatrick), and tune-up method, (3) output beam quality (transverse and longitudinal emittances, transmission, stability, halo formation) and its variation due to change of input beam parameters, and (4) matching between RFQ and DTL at normal and off-normal conditions.

4.3. DTL prototype

The IFMIF DTL employs the conventional approach used in the past machines, so the required technical basis is considered to be established. The prototype DTL focuses on the thermal and mechanical validation of a CW DTL. From the design viewpoint, the most difficult section in the DTL is the first tank, which accepts the beam from the RFQ and makes a transition from RF electric focusing to magnetic focusing in the DTL. The fist tank needs to have a ramped gradient field to match the beam from the RFQ into the following DTL tanks. The drift tube package problem is very severe in the first several drift tubes, and the optimization of post coupler arrangement is also required. So the prototype of the first tank is essential to validate the IFMIF DTL technology. The issues to be resolved are summarized as (1) fabrication and installation methods applicable to the IFMIF DTL, including tank shell, drift tube (gold plating), electromagnet in the drift tube, and post coupler, (2) field gradient ramping method, (3) inter-tank connection method, using dummy quadrupoles in diagnostics beam line, and (4) output beam quality (transverse and longitudinal emittances, transmission, stability, halo formation) and its variation due to change in input beam parameters.

4.4. RF system module

The RF system is the major part of the accelerator cost, and it requires systematic definition of requirements, tolerances, and a detailed control system concept. All of these depend on the final decision on accelerator system design, based on the results of other EVP activities. The basic performance of relevant components of the IFMIF RF system has been verified during the present KEP, including an European endurance test (~940 h) of an RF tube running under CW conditions at 200 MHz and 1 MW. As this frequency is a complete module system needs to be demonstrated for a stable 175 MHz, 1 MW CW output. The issues with highest priority are the final power amplifier and the coaxial window/coupler capable of long-term CW operation at >500 kW. The ideas raised in a reduced cost design, such as removal of the circulator and the use of a small size coaxial line with central conductor cooling, also need to be verified.

4.5. Beam diagnostics

The beam diagnostics instrumentation is an essential part of the prototype tests. There are two kinds of diagnostics to be designed for the prototype: (1) low energy (0.1 MeV) beam diagnostics measuring the long-term stability of the injection beam, and (2) high energy (>7 MeV) beam diagnostics using non-interceptive measurement devices and a halo detector to control the beam loss along the accelerator structure.

Some tests can be performed on individual devices (e.g., injector system evaluation). However, the accelerator prototype integration facility would integrate all individual components and therefore would assure highly realizable, continuous and stable operation of the most complex accelerator system before final approval of IFMIF. As significant fraction of the prototype components could be transferred to the final IFMIF plant and reused, the prototype facility would have only a minor impact on the overall IFMIF cost.

5. Summary and conclusions

The most important step in realizing the IFMIF accelerator facility is the engineering validation test of the critical system components by using a realistic accelerator prototype integration facility. The main purpose of the prototype tests is to provide the technical basis for a highly reliable high current CW linac operating continuously and with sufficient stability. The low energy section is the most difficult, and the present concept of the prototype system consists of an ion injector, a RFQ, and short DTL sections with output energy ~7 MeV. The output energy should be optimized between the total development cost and the degree to which components can be recycled in future construction. The design issues regard in beam loss and associated activation are also important. Finally, the specifications of the prototype components should be refined by the progress of the accelerator technology resulting from the IFMIF-KEP and other on-going projects.

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