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THE ACCELERATOR SYSTEM OF IFMIF-DONES MULTI-MW FACILITY*

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Abstract

The IFMIF-DONES (DEMO-Oriented Neutron Early Source) facility has passed the preliminary design phase and the detailed design phase is very much advanced. Next step will be the preparation phase for the construction of the facility. The DONES facility aims at developing a database of fusion-like radiation effects on materials to be used in future fusion reactors up to damage levels expected in the EU DEMO. It will be based on an intense neutron source created by an accelerated deuteron beam (125 mA CW, 40 MeV) impinging on a liquid lithium curtain. The DONES Accelerator Systems (AS) will be responsible of delivering this 5 MW D+ beam with very high availability. The beam acceleration will be performed by several stages: an ion source and LEBT, an RFQ, a MEBT, an SRF Linac and a HEBT transporting and delivering an optimized profile down to the target. A high power RF system and several ancillaries will ensure the equipment is properly operated. This contribution will report the present status of the AS design, the main challenges faced, the R&D programme to overcome them, and the prospects for the construction and commissioning of the DONES accelerator in Granada (Spain).

THE DONES ACCELERATOR

The IFMIF-DONES facility [1] will serve as a fusion-like neutron source (1×10^{14} neutrons/cm^2/s) for the assessment of materials damage in future fusion reactors. The neutron flux will be generated by the interaction between the lithium curtain and the deuteron beam from an RF linear accelerator at 40 MeV and nominal CW current of 125 mA. The facility is divided in three major group of systems:1) the ~100 m long AS, grouping those systems involved in the beam production, acceleration and shaping, and 2) the lithium systems where the Li(d,xn) stripping reaction (with a neutron spectrum up to 50 MeV) between the deuterons and the lithium occurs, and 3) the experimental material test areas, where the main component is the High Flux Test Module containing 100 cm^3 of material under test with up to 20 dpa y^{-1} to 50 dpa y^{-1}. IFMIF-DONES is being designed for construction in Escúzar, Spain, near the city of Granada. During the design phase of the project, systems engineering approach has been followed [2], in which the AS are splitted in several systems following each a different function in the production, acceleration and shaping of the beam delivered to the irradiation of the lithium target.

The design of IFMIF-DONES and LIPAc had as precursor the LEDA facility in the 80's [3], which achieved a stable beam operation of a 100 mA CW beam after the RFQ during >100 h.The IFMIF-DONES accelerator is one of the most powerful under planning now. However, several other facilities like CADS, ESS, MYRRHA or PIP-II are being designed or under construction with similar average beam power.

Table 1: Main Beam Accelerator Systems Nominal Parameters

Particle	D$^+$(p)
Peak current	125 mA
Duty cycle	CW
Beam energy	40±5 MeV FWHM
Beam power	5 MW
RF frequency	175 MHz
Beam profile @ target	20 (10) x 5 cm^2

The front end of the accelerator is based on the design of LIPAC [4], which is currently in its commissioning phase [5] whereas the rest is based in the previous engineering design [6]. The main parameters of the accelerator are listed in Table 1. As depicted in Figs. 1 and 2, the accelerator will be formed by: 1) a Low Energy Beam Transport (LEBT)

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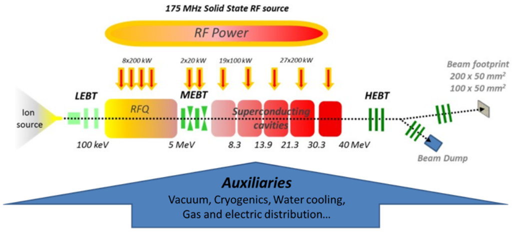

Figure 1: Schematic view of the IFMIF-DONES AS.

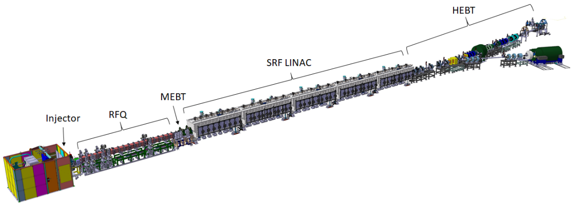

Figure 2: Layout of the IFMIF-DONES AS.

section at 100 keV to guide the low energy ions up to the Radio Frequency Quadrupole (RFQ) and match its injection acceptance, 2) the RFQ to accelerate the ions from 100 keV up to 5 MeV, 3) a Medium energy Beam Transport Line (MEBT) to match the RFQ extracted beam to the injection of the SRF Linac, 4) an SRF Linac of five cryomodules to bring the energy of the deuterons up to 40 MeV, 5) a High Energy Beam Transport (HEBT) lines to transport and shape the beam from SRF Linac towards the lithium target or the beam dump transport line (BDTL), in pulsed mode, and 6) the Ancillaries providing the service to the accelerator. Besides of the nominal operation of the 40 MeV deuteron beam, during the staged commissioning phases the AS will be tested with protons at scaled energy of 20 MeV, and peak beam current of 70 mA.

The design is driven by two main goals: 1) maximize the neutron irradiation of the proper energy spectra, 2) keep the availability of the AS above 87% [7]. The availability of the accelerator is linked with the reliability of each system, and to the ability of the accelerator to recover the normal operation fast after a beam trip or a failure. To minimize the downtime of the machine it is crucial then that hands-on maintenance can be applied to most of the components of the accelerator. For this reason, beam losses along all the accelerator should be kept below 1 W m^{-1}.This represents 2×10^{-7} of the high energy beam, which is obviously a challenge for both beam dynamics and beam diagnostics design.

SYSTEMS DESCRIPTION

INJECTOR

The required 140 mA continuous deuteron beam is produced in a 2.45 GHz ECR ion source of SILHI type. The IFMIF-DONES design of the ion source and the extraction system is based in the successfully tested previously at CEA and LIPAc [8]. The deuteron beam is extracted though a five electrode DC column. The ion source is located on a HV platform inside a Faraday cage able to sustain up to 100 keV DC HV. The main focus is given now to the beam tests carried out in LIPAc with proton and deuteron beams, and to enhance the maintenance operations of several critical components, and the design of the electrostatic chopper for pulsed beams or the beam diagnostics for routine operation.

RFQ

The IFMIF-DONES RFQ [9] is very similar to the LIPAc one. It consists of an 9.8 m length copper structure, divided in three supermodules formed by several modules, and powered by eight RF power chains of up to 200 kW CW each. The RFQ is designed for a voltage of 130 kV, to get a transmission of the nominal beam >90%. The latest has been confirmed already by the recent LIPAc results [10]. One of main concerns of CW RFQ's is the degradation of the vanes during CW operation. A full assessment is being performed in order to estimate the sources and contribution of such degradation, and possibly would estimate the replacement period for some of the modules. Effort is being allocated also to facilitate the exchange of any of the three supermodules if maintenance of any of them is required.

MEBT

The MEBT is a short 2 m transport line containing five magnets (one triplet and one doublet), two-rebuncher cavities and two 4-blades movable copper scrapers. In a very small space the MEBT is able to match the RFQ beam with the SRF LINAC requirements, while overcoming the high space charge forces in this section. The DONES design is practically identical to the LIPAc one [11], which has been already partially validated, obtaining almost full transmission of a 125 mA deuteron beam in pulsed mode. Several modifications have been performed to the design, such as the use of a new type of the current transformer at the output of the RFQ for a new type, able to measure the average current of CW beam and not only pulsed beams, or the modification of the supports of the high vacuum pumps to fit new models, more efficient to the DONES operation. Moreover, the DONES design is being enhanced like the other systems to optimize the logistics and maintenance procedures.

SRF LINAC

The SRF LINAC system [12] groups the 56 superconducting cavities accelerating the beam from 2.5 MeV u^{-1} to 20 MeV u^{-1} and the associated components. Tracewin multiparticle code was used for layout design and simulation [13], with up to 10^7 particles simulated, 0.5 W per particle. The simulations were crosschecked using the GPT code. The SRF LINAC design evolved from four cryomodules and short distances between cryomodules to five cryomodules and longer interfaces in order to obtain higher safety margins for beam losses and for cavity gradients, and the application of the top loaded solution for the cold mass string. In order to improve the efficiency and the maintenance, the cavities are bunched in five cryomodules. The first two cryomodules contain the so-called low-beta cavities (19), optimized for a relativistic $\beta = 0.115$. The three last cryomodules, which are identical, 27 high-beta cavities optimized for $\beta = 0.175$. In between the cavities, 29 solenoid packages with focusing and steering solenoids control the beam trajectory, plus beam position and micro loss diagnostics at the solenoid packages serve to tune the accelerator. A series of low-beta cavities were already manufactured and tested without beam for the LIPAc prototype cryomodule [14]. Cavities will be validated with nominal current beam during the last phase of the LIPAc accelerator. A prototype of high-beta cavity for the last three cryomodules is under development. The resonant cavity has been manufactured and is presently being characterized, with first results expected in the next months. During the IFMIF/EVEDA phases, the high power RF couplers were validated up to 100 kW [15]. Now, upgrades in the design are planned together with full testing at the nominal energy of 200 kW. Regarding the cryomodule integration, unlike the LIPAc prototype cryomodule, in the DONES ones the cold mass string (with cavities and solenoids) will be removed by a top plate at the vessel, instead from one at the side. As pointed out during the beam dynamics chapter, the cryomodule interfaces had to be enlarged to allocate the new design. This will improve the logistics and maintenance of several preventive and corrective actions, improving the availability of the system.

HEBT

Placed at the exit of the SRF LINAC, the main goals of the 45 m long HEBT [16] are the transport of the high energy beam down to the lithium curtain, and the shaping of the beam to form a rectangular profile in the interaction point which maximizes the irradiation performance at the material samples. The design of the beamline starts from the beam dynamics input, where the rectangular beam shape is created by using multipolar magnets. The HEBT beam dynamics design [17,18] is now based in 18 quadrupoles, three dipoles and 16 steers to transport the beam. The steerers are independent to avoid the typical aberrations on combined magnets. Two dodecapoles and two octupoles shape the rectangular transverse footprint delivered to the target. A couple of scrapers, one in the middle of the line, and one near the target, localize the beam losses and remove the halo particles. Both scrapers, stopping several kW's of beam losses, are shielded and maintenance operations are expected by remote handling [19, 20]. Machine protection and facility safety [21] are guaranteed by fast isolation valves at several points.

In addition, during the design phase, an extension line from the MEBT up to the final Beam Dump has been designed. This extension line can be used for the commissioning of the RFQ and staged-commissioning of the SRF LINAC if necessary, using the Beam Dump in the permanent positions. Two alternatives designs are implemented, one based in quadrupole electromagnets and another one based on solenoids.

The beam out of the SRF LINAC is bent 9° to minimize the backstream radiation onto the accelerator, and to fit with the possibility to add a second accelerator impinging onto the target. In addition to these main features, a Beam Dump is placed on a secondary line together with several specific beam diagnostics in order to tune and test the accelerator in pulsed mode (up to 1%). Beam diagnostics control lossless transport along the line and optimization of the beam footptint [22]. Main challenges are to monitor the transverse profile both in CW and pulsed modes in two regions: at the room before the lithium target due to high radiation, and between the multipoles due to the very filamented profile. A complete assessment of those monitors are being planned to complement the ones already performed both in LIPAc and within DONES [23].

RF Power System

Unlike the high power chains in LIPAc, the CW 175 MHz RF Power System to the 56 RF cavities will be based in Solid State Power Amplifiers. The RF Power System of IFMIF-DONES [24] is splitted in eight chains of up to 200 kW for the RFQ, two small chain of 16 kW for the re-buncher cavities, 19 chains of < 100 kW for the low-beta cavities, and 27 chains of 200 kW for the high-beta cavities. Two technologies are presently being tested within DONES for those stations, both based in LDMOS transistors. The main differences of both designs are at the combination stages. In the first alternative [25], the combination is done in a single stage based in a high power cavity combiner, as demonstrated e.g. recently at CERN SPS at 200 MHz [26]. The second alternative is based on progressive and hybrid combiners, similar to the one proved recently successful in the commissioning of the MYRRHA RFQ [27] at 176 MHz CW 200 kW. Complete tests at full power and a full study of the optimum RF driver will be completed during the next programme.

Ancillaries

The last system of the AS groups the main services to the other AS: the vacuum equipment, the cryoplant and cryodistribution, the water cooling, the gas distribution and the low voltage electrical distribution.

CONCLUSIONS AND OUTLOOK

The IFMIF-DONES Accelerator Systems have completed the preliminary design phase, and their systems are designed and integrated with the other systems of the facility. Hereafter, under the next work programme, the integration is planned to be completed to launch the construction phase, focusing in the optimization of the availability of the machine, and the continuation of the R&D program in several critical activities, together with the support and validation to LIPAc. Among these other activities we can mention the validation of high-beta superconducting cavities and couplers and RF SSPA prototypes at 200 kW. Some of the beam diagnostics are also critical and require further development, like the microloss and beam loss monitors along the accelerator, or the non-interceptive and interceptive profile monitors in several sections.

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