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BEAM DIAGNOSTICS FOR THE MULTI-MW HIGH ENERGY BEAM TRANSPORT LINE OF DONES*

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Abstract

In the frame of the material research for future fusion reactors, the construction of a simplified version of the IFMIF plant, the so-called DONES (Demo-Oriented Neutron Early Source), is under preparatory phase to allow materials testing with sufficient radiation damage for the new design of DEMO. The DONES accelerator system will deliver a deuteron beam at 40 MeV, 125 mA. The 5 MW beam will impact onto a lithium flow target to form an intense neutron source. One of the most critical tasks of the accelerator is the beam diagnostics along high energy beam transport, especially in the high radiation areas close to the lithium target. This instrumentation is essential to provide the relevant data for ensuring the high availability of the whole accelerator system, the beam characteristics and machine protection. Of outmost importance is the control of the beam characteristics impinging on the lithium curtain. Several challenging diagnostics are being designed and tested for that purpose. This contribution will report the present status of the design of the beam diagnostics, focusing on the high radiation areas of the high energy beam transport line.

INTRODUCTION

The linear accelerator for the IFMIF-DONES facility [1] will serve as a fusion-like neutron source for the assessment of materials damage in future fusion reactors. DONES will consist of a linear deuteron RF linear accelerator up to 40 MeV at full CW current of 125 mA. The facility is divided in three major systems: the particle accelerator, the target and the experimental material test area.

The accelerator system is based on the design of LIPAC [2], which is currently in its commissioning phase [3]. The accelerator will be made of 1) a Low Energy Beam Transport (LEBT) section at 100 keV to guide the low energy ions up to the RadioFrequency Quadrupole (RFQ) and match its injection acceptance, 2) an 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, 6) a High Energy Beam Transport (HEBT) lines to transport the beam from SRF Linac towards the lithium target or the beam dump transport line (BDTL), in pulsed mode.

Beam losses along all the accelerator should be kept below 1 W m^{-1}. Besides of the transport function, the HEBT will be mainly responsible of shaping the beam to the rectangle required by the lithium target. For this purpose, multipole magnets (dodecapoles and octupoles) are used along the beamline [4]. In order to fullfill this function, beam diagnostics will provide essential information both during the commissioning and operation phases for the tuning and safe operation of the accelerator.

HEBT REQUIREMENTS

The distribution of the monitors along the HEBT is based on the beam dynamics design requirements [4]. The beamline can be divided in three sections (Fig. 1): a section S1 before the dipole which directs the beam to the target, a section S2 which transforms the beam phase-space using octupoles and dodecapoles, and a section S3 which makes the beam imping in the right spot. This section passes through a separate room downstream the last magnetic expansion – the Target Isolation Room (TIR) – before colliding with the target.

Along section S1 the monitors are focused in monitoring the beam from the SRF Linac. The following properties should permanently monitored to be sured the right beam is delivered to the target: DC current, mean energy and transverse size.

In section S2 it is very important to control the profile and position of the beam at each multipole magnet. In section S3 the essential points are: 1) to point the beam to the center of the target. This can be achieved by using RF pickups tuned to the fundamental frequency, 2) to control the size and uniformity of the transverse profile. A complete discussion of the design of the beamline, including the remote handling requirements in the last sections, is given elsewhere [5].

The DONES environment pose several challenges to the beam diagnostics [6]. The present plan assumes the operation with deuterons from the earliest stage. However a preliminary operation with protons is highly probable/almost mandatory, as it has been found/estimated beneficial at LIPAC. First of all, the availability of the accelerator system [7] is very important to guarantee the irradiation dose rate to the material samples. The monitors should be robust enough to monitor continuously and with high reliability the important beam parameters used to control and protect the machine during operation and tuning status. Therefore, the monitors should withstand the severe environment conditions of the beamline, especially regarding the high neutron and gamma radiation. The present considerations are that

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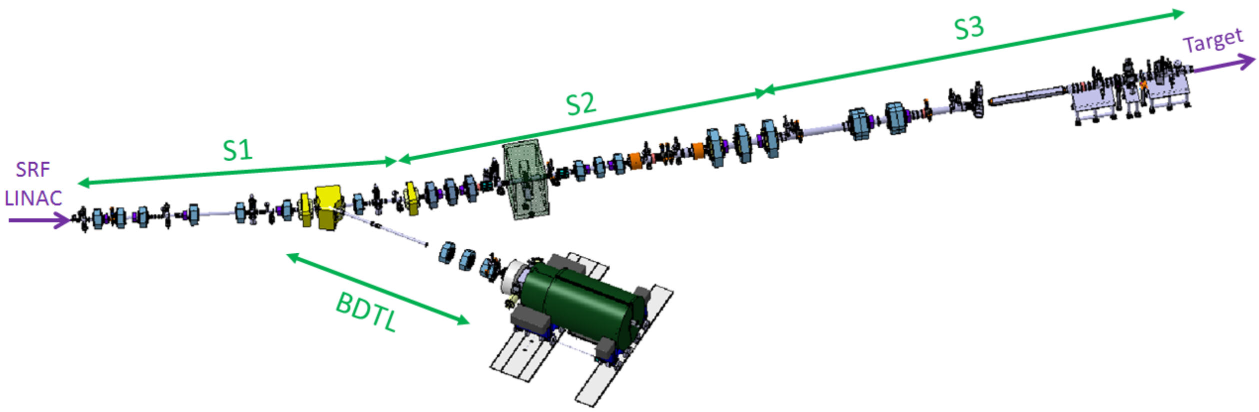

Figure 1: Layout of the different sections of the DONES HEBT.

a gamma dose rate of between $1\,\mathrm{Sv\,h^{-1}}$ to $10\,\mathrm{Sv\,h^{-1}}$ and a neutron fluence of $1 \times 10^{8}\,\mathrm{cm^{-2}\,s^{-1}}$ although those quantities could evolve with the design of the shielding in those areas.

On the other hand, due to the compactness of the design, special beam diagnostics devices cannot be integrated along the beamline.Therefore, the beam cannot be fully characterized once the accelerator is fully assembled. As a consequence of this design decision, it is of highly importance to well characterise each acceleration stage prior to move forward.

DIAGNOSTICS LAYOUT

A first integration of the diagnostics along the beamline has been completed (Fig. 1). The total number of diagnostics per type is given in Tab. 1. In some of the areas the beam dynamics layout was adapted to fit the required space for the beam diagnostics. In some other areas, like around the multipole magnets, the intregration is still complex due to necessity of keeping short distances between the magnetic elements that shape the beam, while maintaining the beam profile diagnostics mandatory at this area.

The characterization and tuning of the beam from the SRF LINAC will be done at the Beam Dump Transport Line – BDTL –, which will concentrate the more specific diagnostics, like the bunch length monitors or diagnostics for phase space characterization. This beamline is still under consideration.

Table 1: List of Diagnostics Along the HEBT

Device	Quantity
Transverse position and phase	20
Average current	8
Pulsed current	7
Beam losses	>16
Profile Monitor box	13
Bunch shape	1

Current Monitors

Three type of commercial current monitors are used along the HEBT. In the first part of the beamline, a new model of treatment of current transformers (CWCT [8]) provides the average current in CW mode in four locations. However, in the sections downstream, where the beampipe is bigger and the bunch is wider, this kind of monitor is not usable. For those regions, a typical DC current transformer has been installed in four areas. To monitor the beam during the commissioning phase in pulsed mode, seven standard AC current transformers will be installed. It is also expected to use the output of the current transfomers to provide a backup solution for the beam loss monitoring by means of differential measurements.

One of the main problems of the current transformers will be the radiation hardness in the last sections. In the TIR, the core of the transformers would suffer from thermal neutron backscattering from the target as mentioned before. The core lifetime under neutron flux has been estimated in $1 \times 10^{17}\,\mathrm{cm^{-2}}$, which means that for a yearly operation of nine months full-time, the current transformer should be repleaced each year and half.

Beam Position

BPM's in the HEBT, longer than in LIPAC due to the higher energy, are installed in twenty places of the beamline. The preliminary design was already presented in [6]. They will serve both to monitor the transverse position of the beam centroid, and the mean energy with the phase measurements (longitdinal position of the bunch centroid). The realibility of the BPM's for those measurements has already been demonstrated in LIPAC [9].

Beam Loss Monitors

In principle, beam loss monitors like the ones in LIPAC are being accepted as first alternative for beam loss monitoring along the HEBT, since they have provided good results during the first deuteron beam commissioning [10].

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However, new alternatives are going to be explored, that could provide a better sensitivity to beam losses on the beampipe [11].

Profile Monitors

Since no beam profile is able to monitor all the range of operation (pulsed and CW mode), a vacuum chamber combining interceptive and non-interceptive beam profilers has been proposed and installed in twelve locations of the beamline. The chamber, so-called PMB – Profile Monitor Box –, is made of a SEM-grid similar to the ones in LIPAc [10], and a fluorescence profile monitor -FPM- for compactness reasons. In the case of the SEM grids, simulations of the resistance of several wire materials under the DONES beam irradaition has been confirmed, and the maximum pulse length and power density deposition has been established. The design of the non-interceptive profile monitor is being improved profiting the results of LIPAc. A new design proposal for the FPM is being considered with a new layout based on the present experience (Fig. 2). Different designs for areas of the accelerator less prone to radiation damage are being considered. A detailed discussion about the new design of the PMB is out of the scope of this contribution and will be presented elsewhere in the coming months.

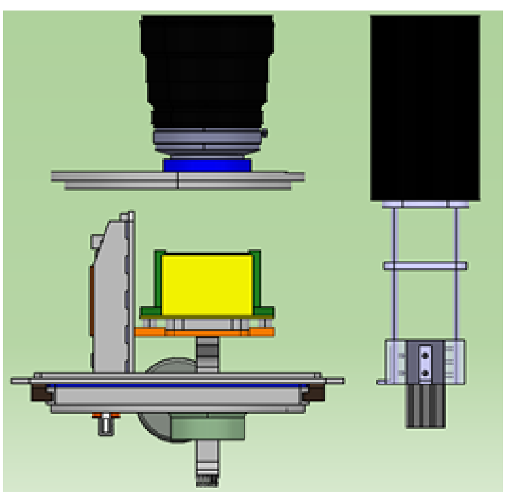

Figure 2: Proposed design of DONES FPM. Body cover is removed.

TARGET BEAM DIAGNOSTICS

The final part of the HEBT S3 after the last magnetic triplet for beam expansion is the TIR room, which will be mainly devoted to install beam diagnostics to safely monitor the properties of the beam delivered to the target. The monitoring of the beam at that region is critical for a proper and safe operation of the machine. The beam properties that should be measured are mainly given by the beam dynamics simulations [4] as listed in Tab. 2. Most of the properties will be easily monitored by well-established instrumentation: 1) current transformers (DCCT and ACCT) will be installed for average and peak beam current measurement respectively, 2) beam position monitors will correct the transverse beam centroid and will control the mean beam energy, 3) beam loss monitors will detect the beam losses along the beampipe, although the radiation background in this area can pose significant challenges for these diagnostics. The major R&D efforts are put today to the development of the transverse beam profile close to the 40 MeV lithium target, as discussed later. A mechanical layout of this area has already been carried out, with one ACCT, one DCCT, three BPM's and one profile box, see Fig. 3.

The DONES beam profile must have a rectangular shape of 20 cm wide and 5 cm height or optionally 10 cm wide and 5 cm height. Both interceptive and non-interceptive profilers are being developed for the control during the pulsed and CW operation respectively. In this area the challenges for this measurement is extreme due to the combination of high radiation, high beam power, low energy deposition and low vacuum residual pressure [5].

Table 2: Main Beam Parameters Requirements at Lithium Target

Peak current	125 mA
Beam energy	(40 ± 5) MeV FWHM
Beam profile	$20(10) \times 5\,\mathrm{cm}^2$
Beam position	± 5 mm
Beam tails	$<0.5\,\mu\mathrm{A\,cm}^{-2}$
Max. beam extension	25 cm in horizontal 10 cm in vertical

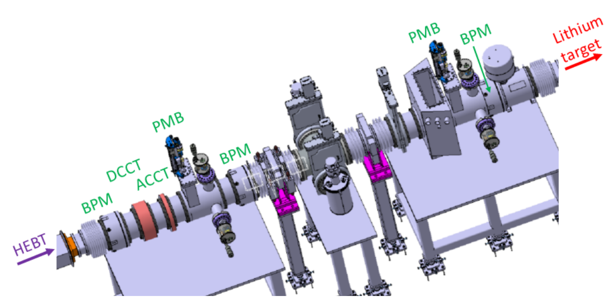

Figure 3: Layout of the beam diagnostics in the target interface room.

Transverse Profile

The non-interceptive profiler should monitor permanently the squared shape of the target, the peak of the distribution, and the flatness of the profile. At the moment two are the most promising candidates: a monitor based on the residual gas fluorescence [12], and one based in the residual gas ionization [13]. Both monitors have been installed in the HEBT beamline of LIPAC for comparison and recently some previous have been obtained for the operation with deuteron at 5 MeV [10]. In parallel, more experiments have been carried out to advance in the verification of the use of those monitors in DONES. In particular, a experiment has been

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performed to study the detection of the lithium fluorescence under similar conditions of beam irradiation. The results of this experiment are being evaluated and will be presented later on.

In the case of the fluorescence version, due to the high radiation background in this area, it is foreseen to use fibers to place the detector outside the TIR and shielded from the radiation.

Electromagnetic Pickup

As discussed in several papers elsewhere [14] [15], electromagnetic pickups are able of sensing the quadrupolar moment of the beam. This property could be interesting to obtain a fast monitoring and interlock system of the transverse profile of the target. However, that looks quite challenging for DONES: 1) the beam will be quite debunched in that region, 2) the profile will not be fully shaped at the TIR, 3) the higher order components of the signal will be quite small, 4) signal amplitude will depend on other factors (beam energy, position, energy). Notwithstanding these problems, a good alternative could be to calibrate the amplitude of the signal at the sensors with the values obtained for the required beam profile at the target. That means at least one first beam profile at the target should be obtained by a second monitor. Once those reference values are obtained, the monitor can act as a fast interlock system in case there is a deviation from the reference values.

To see the feasibility of this pickup, a first preliminary design and simulations have started with CST Particle Studio [16]. The first design is made of eight electrodes, to get a compromise between mechanical complexity, signal strength and profile resolution. Figure 4 shows a sketch of the simulation model.

A first bunch of simulations have been performed with the nominal beam current, energy and bunch size values to see the response of the pickup at the TIR location. Figure 5 shows the response of the pickup under a beam displacement of 10 mm in horizontal and vertical axes . As can be

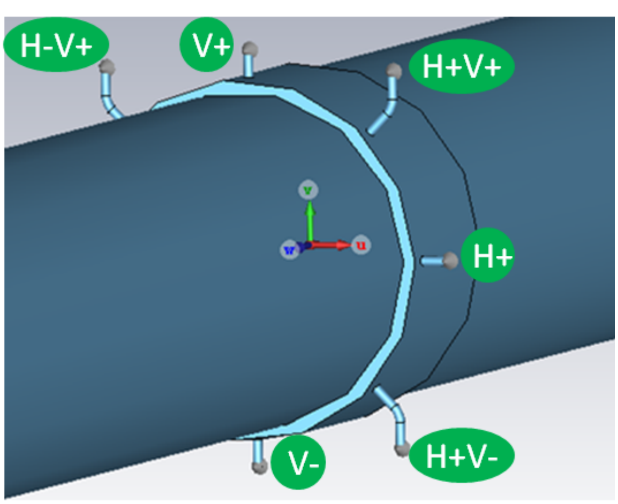

Figure 4: Proposed design of pickup before the target.

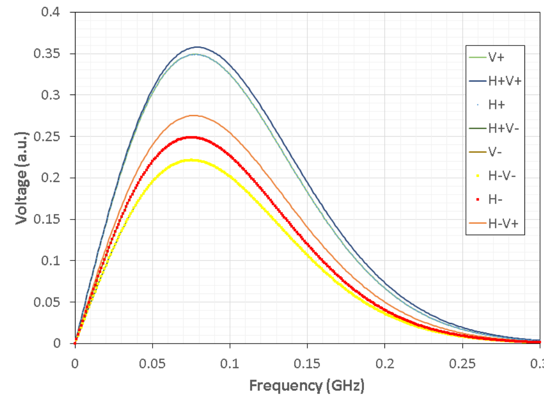

Figure 5: Simulation of the last pickup under nominal deuteron beam conditions with a beam offset of 10 mm in horizontal and vertical axes.

seen, the values obtained for the nominal deuteron beam are quite satisfactory although only the fundamental frequency (175 MHz) is visible due to the bunch spreading at this location.

In order to follow the characterization of the pickup the work is now focused on using the Particle In Cell solver to simulate also the real transverse structure of the beam. However due to the huge number of particles and beam size, the computing resources are too high and no satisfactory results have been obtained so far. Further work will be carried out in order to simplify the model and characterize and validate the pickup completely.

CONCLUSIONS AND OUTLOOK

A full design of the beam diagnostics for DONES HEBT has been integrated in the HEBT and a first version of the complete beamline has been provided. The design of each diagnostics has taken into account all the important aspects of the accelerator: the availability and reliability of the system, the radiation resistance, the beam dynamics requirements, and the mechanical integration. Work is now being focused on the beam diagnostics for the target monitoring and especially on the transverse profile measurement. The design is being reviewed and several experiments have been performed to progress on a solid design. Feedback from the beam commissioning from LIPAC is being also of utmost importance for considering any change in the list and type of diagnostics proposed.

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