

CONCEPTUAL BEAMLINE DESIGN FOR COMPLEMENTARY EXPERIMENTS AT IFMIF-DONES

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Abstract

A deuteron beam of unprecedented intensity will be used at the International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES) to produce a fusion-like neutron flux and characterize the properties of materials in the challenging environment of a fusion reactor. Recently, the possibility of extracting a small fraction of this beam for complementary experiments in a parasitic mode has gained traction within the users community. This paper describes the conceptual design of the extraction system and a proposal for a distribution line capable of serving different experimental stations, without perturbing the main deuteron beam while keeping the same peculiar pulse structure and high peak current.

INTRODUCTION

The International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES) [1-3] is a state-of-the-art facility currently under construction in Spain to study the properties of materials in the challenging environment of fusion reactors like DEMO [4]. Material specimens will be irradiated with a fusion-like neutron source produced by the interaction of an intense deuteron beam, accelerated by a superconducting radiofrequency (SRF) linac, with a liquid lithium target. Given the unprecedented deuteron beam parameters, listed in the middle column of Table 1, the potential users community has recently expressed interest in dedicating a fraction of the fully accelerated beam to parasitic experiments. In particular, the extraction of one deuteron bunch every 1000, while keeping the same pulse structure and peak current as the main beam, can be envisaged resulting in the parameters listed in the rightmost column of Table 1.

Table 1: Parameters of the Dones Main and Parasitic Deuteron Beam, Assuming a 1/1000 Extraction Rate

Quantity	Main beam	Extracted beam
Beam energy	40 MeV	40 MeV
Frequency	175 MHz	175 kHz
Average current	125 mA	125 μ A
Power on target	5 MW	5 kW
Bunch spacing	5.7 ns	5.7 μ s
Bunch length	2 ns	< 10 ns

Proposals for competitive experiments that can exploit the peculiar pulsed time structure of the extracted beam are being investigated [5,6]. A typical application would be a neutron time-of-flight (nTOF) facility to investigate the nuclear cross section of materials relevant for fusion reactors. Direct use for radioactive ion beams production can also

be considered, enabling the production of refractory elements.

A preliminary design of an extraction and distribution line for the parasitic deuteron beam was developed by the Legnaro National Laboratories (LNL) [7].

BEAM EXTRACTION

As shown in Fig. 1, the parasitic deuteron beam must be directed towards the experimental hall, located in the floor below the linac. An extensive study was carried out using TraceWin [8] to design a suitable extraction line.

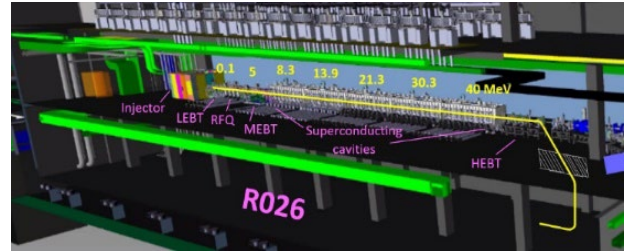


Figure 1: Drawing of the interface between the accelerator floor and the experimental hall R026. The yellow line shows the synchronous particle path.

A travelling-pulse deflector at the beginning of the High Energy Beam Transfer (HEBT) line can be used to apply a kicker field acting on a single bunch while the rest of the beam stays unperturbed. Since the HEBT does not include longitudinal lenses, the deflector must be placed within the first 3.5 m so that the minimum achievable rise/fall time of the kicker pulse, which can be as short as a couple ns [9,10], can still fit within the bunch spacing (see Table 1). At the end of this region, the bunch is about 1.77 ns long, as shown in Fig. 2. Therefore, the kicker field pulse can have the structure represented schematically in Fig. 3.

The deflector itself consists of three sets of two striplines, placed above and below the beam line. Electric field pulses of opposite polarity are sent through the striplines, which are shaped as meander lines to allow the synchronization of the pulses with the bunches to be extracted. Similar solutions are already utilized in various facilities [11-13], but never at such high energy and beam power. This translates into many challenging requirements, such as the procurement of a voltage generator capable of providing pulses of tens of kV at the high repetition rate of up to 175 kHz. A first design, focused on the longest of the three sets of striplines, was developed by LNL. The best solution, identified through electrostatic and time-domain simulations in CST Studio Suite [14], is a copper stripline suspended in vacuum within a beam pipe with rectangular section, like the one shown in Fig. 4. The stripline is kept in tension by alumina supports placed at the extremities. The geometry and choice of materials were defined by the

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trade-off between two competing parameters: coverage factor (i.e. efficient use of the voltage pulse to generate an electric field as high as possible) and transverse field uniformity. The power deposition on the copper strip was investigated in a preliminary fashion combining analytical calculations and simulations, and heat power evacuation by radiation only can be envisaged. More details can be found in [15]. For the moment, this remains a conceptual design, pending prototyping and testing. It is important to note that three quadrupoles are installed in this part of the HEBT. Their bore radius would need to be at least doubled to accommodate the deflector. This would bring the magnetic field at the poles to the acceptable limit of 0.8 T.

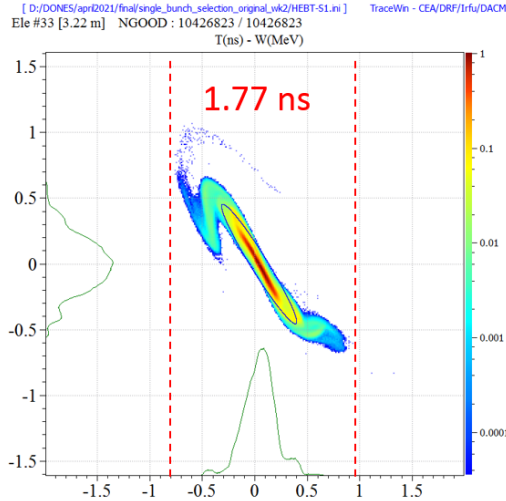


Figure 2: Longitudinal phase-space of the beam at the end of the deflector region. The abscissa reports the energy spread in MeV, while the ordinate reports the time in ns.

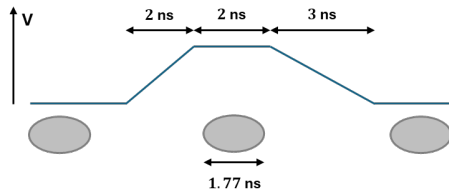


Figure 3: Sketch of the time structure of the bunches and of the meander field pulse at the end of the separation line.

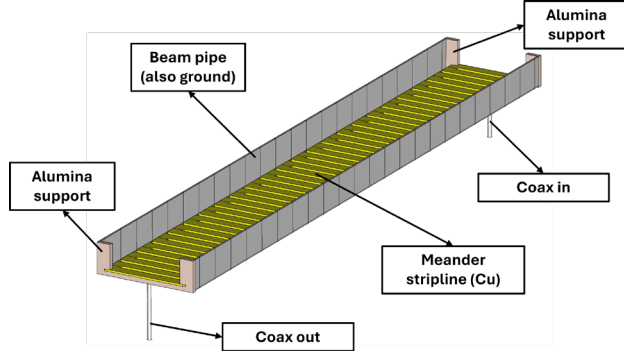


Figure 4: 3D model of a meander line.

The effect of the three sets of meander lines on the selected bunches is a net deflection of just a few mrad over a total length of 3.22 m. A further kick of 1° is applied by an electrostatic septum installed in correspondence with a

minimum of the vertical betatron function at 3.5 m from the linac-HEBT interface, so that the aperture and electric field required are minimized. In this location, the extracted bunches are vertically separated by about 20 mm from the main beam, as shown in Fig. 5. The entrance of the electrostatic septum is the most critical region in terms of power deposition from the main beam and requires a dedicated cooling system. This setup avoids any interference of the parasitic beam line with the fourth quadrupole located closely downstream. Finally, the separation is completed by a magnetic septum, a C type magnet which acts only on the parasitic beam applying a further kick of 32° , while the main beam is untouched.

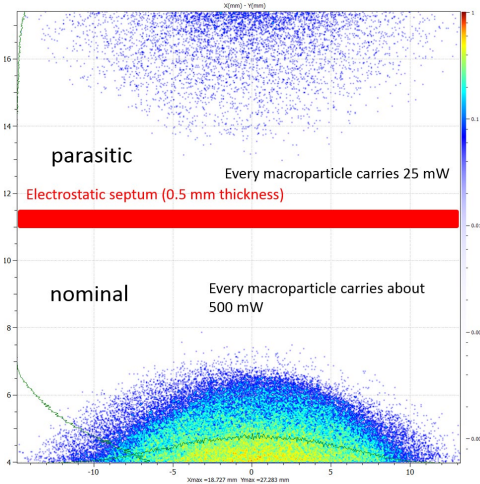


Figure 5: Particle distribution of the main (bottom) and deflected (top) beam at the entrance of the electrostatic septum (red bar).

BEAM DISTRIBUTION

After the extraction is completed, a transfer line composed of two dipoles and eight quadrupoles brings the beam to the experimental hall. The full beam dynamics of the line is shown in Fig. 6.

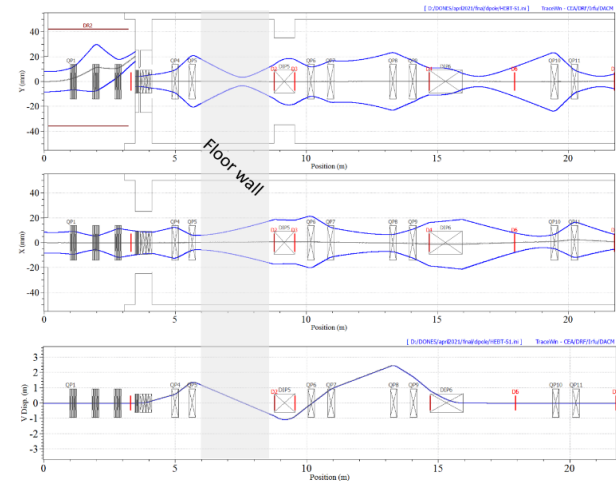


Figure 6: Beam envelope of the extracted beam from the linac-HEBT interface up to the entrance of the experimental hall. The effect of the travelling-wave deflector on the vertical plane can be seen in the top left.

A potential layout of the experimental hall proposed by LNL is shown in Fig. 7. After the vertical beam transport, a kicker magnet guides the beam either to a neutron converter (Line 0), from which various neutron lines depart, or directly to dedicated deuteron experiments (Line 1 and Line 2). Clearly, any layout proposals need to be matched with all practical constraints related to the structure of the building, like for example the position of the pillars. The solution proposed in this paper is well aligned with all requirements known at the time of writing but will be revised accordingly as the design of the facility evolves.

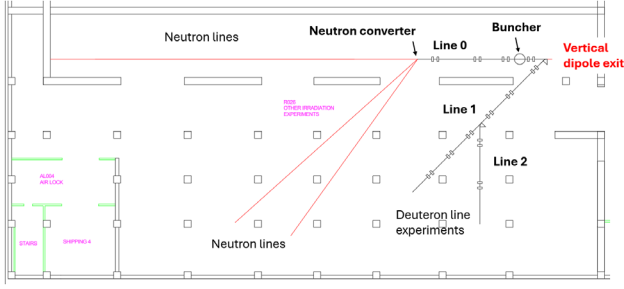


Figure 7: Potential layout of the IFMIF-DONES experimental hall. The installation of a buncher in Line 0 is optional depending on experimental needs.

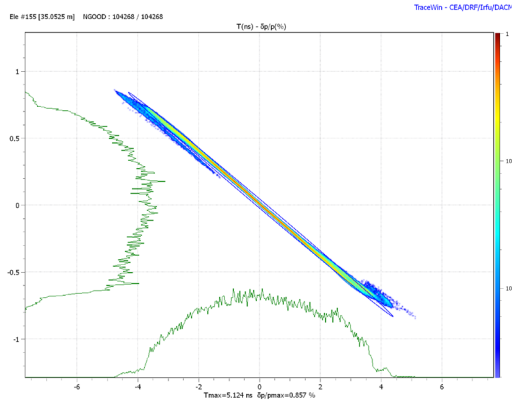


Figure 8: Longitudinal phase-space of the parasitic beam at the neutron converter without bunch compression.

In the base proposal, no means of controlling the longitudinal dynamics are foreseen for any lines. This is of particular concern for the neutron lines, depending on experimental needs: if no further manipulations are applied after extraction, the bunch length of the beam transported up to the neutron converter is 6.2 ns full width at half maximum (FWHM), limiting the energy resolution of TOF experiments. However, exploiting the almost linear time-energy correlation exhibited by the beam at the end of the line, shown in Fig. 8, a bunch compressor can be used to obtain very short pulses. Given the large bunch spacing of the extracted beam, the frequency of the buncher can be chosen with relative freedom. Lower frequencies are favoured to obtain a better beam quality thanks to the more linear field dependence along the pulse. After dedicated studies, a solution involving a superconducting buncher with a resonance frequency of 87.5 MHz and a maximum effective voltage of 1.4 MV was devised. The frequency was chosen

to increase the bunching efficiency without exceeding the typical effective voltage used in existing devices of the same kind. The bunch length could then be reduced to 0.2 ns FWHM, as shown in Fig. 9. The proposed solution is considered feasible since superconducting bunchers with similar characteristics, whose design could be adapted to meet the specific needs of IFMIF-DONES, were developed for SPIRAL2 [16].

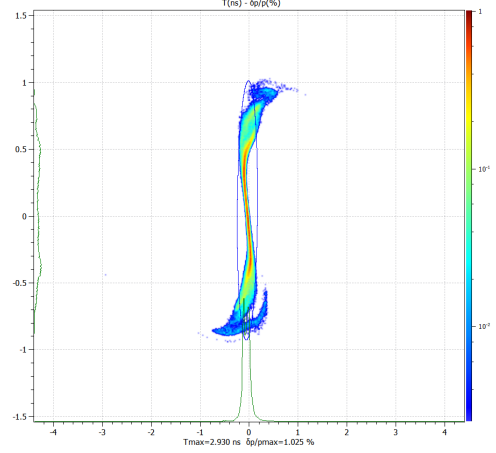


Figure 9: Longitudinal phase-space of the parasitic beam at the neutron converter with bunch compression.

CONCLUSIONS

A system capable of extracting one every 1000 bunches of the IFMIF-DONES fully accelerated deuteron beam without perturbing the main operation was designed at LNL. The line uses a travelling-wave deflector to begin the separation, which is then completed by an electrostatic septum and a kicker magnet. The extracted beam is transported to a dedicated experimental hall for parasitic experiments that can exploit the peculiar pulse structure of the beam for a complementary program to DONES. A potential layout for the experimental hall was proposed, foreseeing dedicated lines hosting experiments that either use the deuteron bunches themselves or convert them into neutrons. The use of a bunch compressor before the neutron converter would allow reaching bunch lengths shorter than 1 ns, improving the energy resolution of TOF experiments.

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REFERENCES

- [1] A. Ibarra *et al.*, “The European approach to the fusion-like neutron source: the IFMIF-DONES project,” *Nucl. Fusion*, vol. 59, no. 6, p. 065002, 2019.
[doi:10.1088/1741-4326/ab0d57](https://doi.org/10.1088/1741-4326/ab0d57)
- [2] W. Królas *et al.*, “The IFMIF-DONES fusion oriented neutron source: evolution of the design,” *Nucl. Fusion*, vol. 61, no. 12, p. 125002, 2021.
[doi:10.1088/1741-4326/ac318f](https://doi.org/10.1088/1741-4326/ac318f)
- [3] D. Bernardi *et al.*, “The IFMIF-DONES Project: Design Status and Main Achievements Within the EUROfusion FP8 Work Programme,” *J. Fusion Energy*, vol. 41, p. 24, 2022.
[doi:10.1007/s10894-022-00337-5](https://doi.org/10.1007/s10894-022-00337-5)
- [4] G. Federici *et al.*, “Overview of the DEMO staged design approach in Europe,” *Nucl. Fusion*, vol. 59, no. 6, p. 066013, 2019. [doi:10.1088/1741-4326/ab1178](https://doi.org/10.1088/1741-4326/ab1178)
- [5] A. Pisent *et al.*, “Extraction line for complementary applications at DONES – User requirements,” presented at *DONES-ConP1 Technical Meeting #02*, Madrid, Spain, 2025, unpublished.
- [6] E. Mendoza, “Status of the design of the TOF-DONES,” presented at *Third DONES Users Workshop*, Zagreb, Croatia, 2024, unpublished.
- [7] A. Pisent *et al.*, “HEBT parasitic beam selection for DONES complementary experiments,” INFN – Laboratori Nazionali di Legnaro, Tech. Rep., 2019.
- [8] TraceWin, <https://dacm-logiciels.fr/tracewin>
- [9] T. Naito *et al.*, “Development of a 3 ns rise and fall time strip-line kicker for the International Linear Collider,” *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 571, no. 3, pp. 599–607, 2007. [doi:10.1016/j.nima.2006.11.062](https://doi.org/10.1016/j.nima.2006.11.062)
- [10] Y. Huang, “Investigation of an ultrafast harmonic resonant RF kicker,” PhD Thesis, University of Chinese Academy of Sciences, Beijing, China, 2016. [doi:10.2172/1368167](https://doi.org/10.2172/1368167)
- [11] S. S. Kurennoy *et al.*, “Meander-line current structure for SNS fast beam chopper,” in *Proc. PAC’99*, New York, NY, USA, Mar. 1999, pp. 932–934.
- [12] F. Caspers *et al.*, “Fast chopper structure for the CERN Superconducting Proton Linac,” in *Proc. EPAC02*, Paris, France, Jun. 2002, pp. 873–875.
- [13] G. Le Dem *et al.*, “A single bunch selector for the next low beta continuous wave ion beam,” in *Proc. PAC07*, Albuquerque, NM, USA, Jun. 2007, pp. 158–160.
- [14] SIMULIA - Dassault Systèmes, “CST Studio Suite,” 2026. <https://www.3ds.com/products/simulia/cst-studio-suite>
- [15] M. D’Andrea *et al.*, “Fast chopper line for DONES,” in *Proc. LINAC’24*, Chicago, IL, USA, Aug. 2024, pp. 476–479.
[doi:10.18429/JACoW-LINAC2024-TUPB073](https://doi.org/10.18429/JACoW-LINAC2024-TUPB073)
- [16] C. Marchand *et al.*, “Performances of SPIRAL2 low and high beta cryomodels,” in *Proc. SRF’15*, Whistler, BC, Canada, Sep. 2015, pp. 967–972.
[doi:10.18429/JACoW-SRF2015-WEBA04](https://doi.org/10.18429/JACoW-SRF2015-WEBA04)