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BEAM DYNAMICS ERRORS STUDIES FOR THE IFMIF-DONES SRF-LINAC

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Abstract

The goal of the IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source) project is to build an irradiation facility that will provide a sufficient neutron flux to study and characterize structure materials foreseen for future fusion power plant. In order to accelerate the required 125 mA/40 MeV continuous deuteron beam from 5 to 40 MeV, a superconducting radio-frequency (SRF) linac, housed in five cryomodules, is proposed. The design is based on two beta families ($\beta = 0.11$ and $\beta = 0.17$) of half-wave resonators (HWR) at 175 MHz. The transverse focusing is achieved using one solenoid coil per focusing period. This paper presents the extensive multiparticle beam dynamics simulations that have been performed to adapt the beam along the SRF-linac in such a high space charge regime. As one of the constraints of the IFMIF linac is a low level of beam losses, specific optimizations have been done to minimize the beam occupancy in the line (halo). A Monte Carlo error analysis has also been carried out to study the effects of misalignments or field imperfections (static errors) and also vibrations or power supplies ripple (dynamic errors). The results of these errors studies are presented and discussed.

INTRODUCTION

The IFMIF-DONES facility aims at generating a neutron flux with an energy distribution close to the typical neutron spectrum of a (d-t) fusion reactor. This can be achieved by bombarding a liquid Lithium target with 40 MeV deuteron beam utilizing Li(d,xn) nuclear reactions. To reach the required neutron flux ($\sim 5 \times 10^{18}$ n m^{-2} s^{-1}), the beam intensity delivered by the D^+ accelerator has to be 125 mA [1].

The DONES Accelerator design is based on the IFMIF Accelerator design [2] so that it includes, after the ion source, the LEBT and the RFQ, a Medium Energy Beam Transport (MEBT) line and a cold section, called Superconducting Radio Frequency LINear ACcelerator (SRF-linac), where the 125 mA cw deuteron beam is accelerated from 5 to 40 MeV. Finally a high energy line transports the beam and shapes it before sending it onto a liquid lithium target.

In this document, the IFMIF-DONES MEBT and SRF-linac layout is presented. In order to assess the feasibility of this superconducting accelerator design in a very high space charge regime, beam dynamics calculations and error studies have been performed. Simulation results are exposed and discussed.

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IFMIF-DONES SRF-LINAC LAYOUT

From the beam dynamics point of view, the MEBT and the SRF-linac are treated as a whole, as one of the role of the MEBT is to match the beam, transversely and longitudinally, into the first superconducting cavities of the linac.

MEBT

The MEBT section is designed to transport the beam from the RFQ exit and to adapt it for its injection into the SRF-linac. It is composed by 2 beam scrapers (horizontal and vertical), 2 bunching cavities (five-gap IH resonators with $\beta = 0.073$) at 175 MHz and 5 magnetic quadrupoles with a total length of 2.35 m [3].

SRF-linac

The layout of the DONES SRF-linac is based on the one that has been studied in the framework of the IFMIF project [4]. Nevertheless, the following modifications have been introduced after a detailed design of each component of the SRF-linac.

During the IFMIF/EVEDA project, 175 MHz HWR prototypes equipped with an internal plunger tuning system was initially designed and finally showed some thermal issues. In order to reach the required performances, a new cavity prototype was developed with an external frequency tuner.This new frequency tuner implies a 100 mm increase of each cavity length compared to the initially planned ones.

The last modification by respect to the IFMIF initial design is the space length between two adjacent cryomodules. After an advanced design of the cryomodules, this length from the end of a cavity of one cryomodule to the beginning of the solenoid package of the next one, is 512 mm (instead of 400 mm, initially) .

In a previous work [5], beam dynamics studies have been performed using the initial IFMIF SRF-linac design (4 cryomodules) with the above mentioned additional lengths. Due to unsatisfactory results (beam losses), it was necessary to propose and study an alternative SRF-linac design to address the two most delicate issues of the previous layout: a less aggressive synchronous phase law, in order to keep a reasonably safe longitudinal acceptance and a higher transverse phase advance per meter, especially for the high-β cryomodules.

The first point implies to add some cavities to the SRF-linac in order to accelerate the beam to 40 MeV while applying a smoother synchronous phase law and keeping conservative accelerating field in the HWR.

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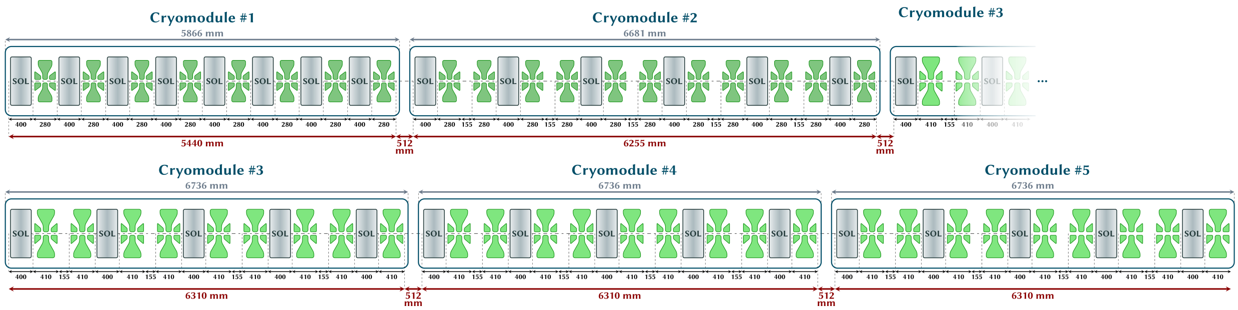

Figure 1: IFMIF-DONES SRF-linac general layout.

A higher transverse phase advance per meter can be simply achieved by designing shorter focusing lattices in the high-β section: periods composed by 1 solenoid and 2 cavities instead of 1 solenoid and 3 cavities. Besides, the cryomodules should end with 1 solenoid and 1 cavity to focus efficiently the beam even with the longer inter-cryomodule drift length.

As a result, the DONES SRF-Linac needs a total of five cryomodules:

- the first cryomodule contains 8 periods of 1 solenoid and 1 resonator ($\beta = 0.115$). This cryomodule is unchanged.
- the second cryomodule contains 5 periods of 1 solenoid and 2 resonators ($\beta = 0.115$) and ends with 1 solenoid and 1 resonator.
- the last three cryomodules, which are identical, contain 4 periods of 1 solenoid and 2 resonators (β=0.175) and ends with 1 solenoid and 1 resonator.

The total length of the SRF-linac, which is represented in Fig. 1, is finally 32.67 m.

Given the beam intensity of 125 mA, the maximum RF power per cavity is 75 kW for the low-β resonators and 150 kW for the high-β resonators.

The axial field of the superconducting solenoid is kept around 6 T in order to use the classical NbTi technology for the coils. The solenoid package includes bucking coils in order to cancel the fringe field at the cavity location and also steering coils, associated with button-type BPMs for orbit correction.

BEAM DYNAMICS SIMULATIONS

Issues and Strategy

For the DONES SRF-linac, hands-on maintenance is required , implying that beam losses must be maintained to a value lower than 1 W m^{-1}. As the beam power is also in the MW range, the global aim is to maintain losses much less than 10^{-6} of the beam, which is one of the main challenging point of beam dynamics activities.

This very limiting constraint is made even more severe by the presence of strong space charge forces, so that every tuning is distribution dependent. As a result, considerations of RMS beam characteristics are no more sufficient: multi-particle simulations with more than 10^{-6} macroparticles are mandatory, which are very time consuming. An uncommon procedure has been adopted then: beam dynamics optimization aim to optimize the extent of the very external beam border, rather than emittance or beta values. We can speak about "halo matching" rather than "envelope matching".

A more detail view of the IFMIF beam dynamics challenges and issues can be found in [6].

Simulation Conditions

All the beam dynamics numerical simulations reported in this paper have been performed with TraceWin [7].

The beam distribution taken as the input of the simulations is the output distribution coming from the latest design of the RFQ, achieved by INFN-LNL [8].

The magnetic fields created by quadrupoles and solenoid coils have been calculated by finite elements method. The half-wave resonators were modeled by a Bessel development of the calculated field on axis.

Optimization Method

In order to be as realistic as possible, the machine optimization have been done using the beam diagnostics that will be available on the prototype accelerator. Concerning the MEBT and the SRF-Linac, a procedure has been applied in order to minimize the excursion of particles at the beam edge, using a particle swarm optimization algorithm [9].

On the real machine, during the commissioning and the operation phases, these sections will be tuned by minimizing the beam losses.

Simulation Results

The beam density in the r plane along the MEBT and the SFR-Linac, obtained after optimization, is represented in Fig. 2.

It can be seen at first sight that no beam loss occurs during the transport through the SRF-linac. Besides, the external beam extend is kept below 14 mm along all the SRF-linac. The resulting margin between the beam outer part and the beam pipe, is higher than 10 mm, which appears to be safe enough.

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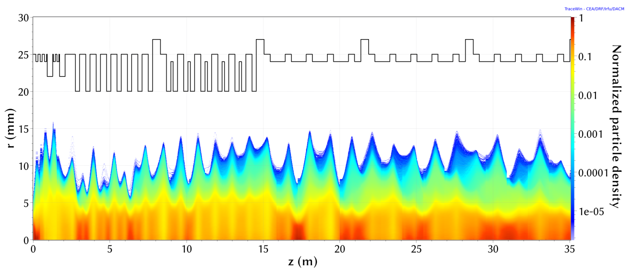

Figure 2: Beam density in r plane along the DONES SRF-linac.

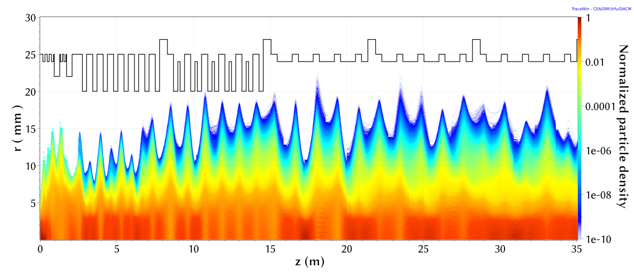

Figure 3: Accumulated beam density for 10^4 linacs with errors in the r plane.

ERRORS STUDY

In order to validate the design of the SRF-linac, one has to study the effect of static and dynamics errors on it. Static errors represent the misalignment or error in applied fields of the accelerator components. The off-axis beam excursions induced by these errors can be limited by using an appropriate correction scheme. Dynamic errors represent imperfections such as vibrations or applied field or phase ripple of the focusing or accelerating elements and therefore no correction scheme is applied.

A Monte-Carlo simulation method has been carried out by tracking 10^6 particles through 10000 different linacs, each of them having a different set of random static and dynamic errors. The static errors are uniformly distributed in the ranges presented in Table 1. Even it may appear a bit conservative, the dynamic error ranges have been chosen to be 10 % of the static ones.

Table 1: Static Error Ranges Used for the Errors Study

Element	Static Error
Resonators Misalignment [x,y]	± 2 mm
Resonators Tilt [φ_x,φ_y]	± 20 mrad
Resonators Field Amplitude	± 1 %
Resonators Field Phase	± 1 deg
Solenoids Misalignment [x,y]	± 1 mm
Solenoids Tilt [φ_x,φ_y]	± 10 mrad
Solenoids Magnetic Field	± 1 %
BPMs Measurement Accuracy	± 0.25 mm

The accumulated particle density of the 10000 simulated SRF-linac with errors is shown in Fig 3. Here again, no beam losses are observed at all, even if no solenoid tuning is done for each set of static errors (which will no be the case on the real machine).

The correction scheme relies on steering coils (horizontal and vertical) associated with downstream beam position monitors. This one-to-one correction scheme maintain the RMS beam orbit displacement below 1 mm while keeping the maximum deviation below 4 mm.

CONCLUSION

The beam dynamics results briefly reported in this paper lead us to conclude that the present layout of the DONES SRF-linac seems robust enough to accelerate safely (i.e. without, or at least while minimizing, beam losses) the required 125 mA D^+ beam to 40 MeV.

Nevertheless, a new cryomodule design recently came out in order to allow top loading that will improve the maintenance operation and therefore the reliability of the whole SRF-linac. Consequently, an additional 254 mm of inter-cryomodule drift length is necessary. Therefore, new beam dynamics studies are to be done to validate this modification of the linac layout.

REFERENCES

[1] A. Ibarra *et al.*, "The European approach to the fusion-like neutron source: the IFMIF-DONES project", *Nuclear Fusion*, vol. 59, no. 6, p. 065002, 2019.

[2] A. Mosnier, "The IFMIF 5 MW Linacs", in *Proc. LINAC'08*, Victoria, Canada, Sep.-Oct. 2008, paper FR201, pp. 1114–1118.

[3] I. Podadera *et al.*, "The Medium Energy Beam Transport Line (MEBT) of IFMIF/EVEDA LIPAc", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper WEPS058, pp. 2628–2630.

[4] N. Chauvin, R. D. Duperrier, A. Mosnier, P. A. P. Nghiem, and D. Uriot, "Optimization Results of Beam Dynamics Simulations for the Superconducting HWR IFMIF Linac", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH5PFP005, pp. 3193–3195.

[5] L. Du, N. Bazin, N. Chauvin, S. Chel, and J. Plouin, "Beam Dynamics Studies For the IFMIF-DONES SRF-Linac", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 687–690. doi:10.18429/JACoW-IPAC2018-TUPAF014

[6] P.A.P. Nghiem *et al.*, "The IFMIF-EVEDA challenges in beam dynamics and their treatment", *Nucl. Instru. Meth. Phys. Res. A*, vol. 654, no. 1, pp. 63-71, 2011.

[7] D. Uriot and N. Pichoff, "Status of TraceWin Code", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 92–94.

[8] M. Comunian and A. Pisent, "Beam Dynamics Redesign of IFMIF-EVEDA RFQ for a Larger Input Beam Acceptance", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper MOPS031, pp. 670–672.

[9] J. Kennedy and R. Eberhart, "Particle swarm optimization", in *Proc. of IEEE international conference on neural networks*, Perth, Australia, 1995, vol. 4, pp. 1942–1948.