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BEAM DYNAMICS STUDIES FOR THE IFMIF-DONES SRF-LINAC

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Abstract

The DONES (DEMO oriented neutron source) project is aimed at constructing a DEMO of IFMIF to provide sufficient material damage [1]. In the SRF-Linac of this project, losses can cause harmful material activation and must be maintained much less than 1W/m. It's a challenge to keep losses at such a low level with high beam power and high space charge. This paper presents two designs of the DONES SRF-Linac, one with 4 cryomodules and another with 5 cryomodules. The design details to reduce the losses and the multi-particle simulation results will be shown. The errors studies for these results will also be discussed.

INTRODUCTION

The linear accelerator for the DONES facility [1] will serve as a neutron source for the assessment of materials damage in future fusion reactors. The DONES accelerator, which is based on the design of LIPac [2], will accelerate deuterons from 100 keV up to 40 MeV at full CW current of 125 mA. The main sections of the accelerator system are shown in Fig. 1: a low Energy Beam Transport (LEBT) section to focus the output low energy deuterons of 100 keV from the ion source to match the RadioFrequency Quadrupole (RFQ); a RFQ to accelerate the deuterons from 100 keV to 5 MeV; a Medium Energy Beam Transport (MEBT) section to focus the beam from the RFQ match the SRF Linac; a SRF Linac to accelerate the deuterons from 5 MeV to 40 MeV; a high Energy Beam Transport (HEBT) section to transport the beam from SRF Linac towards the lithium target.

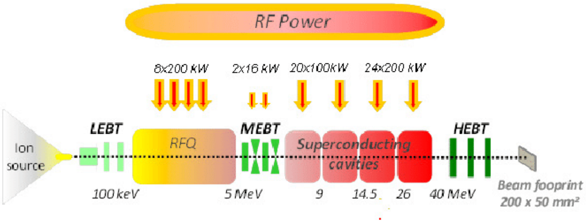

Figure 1: Layout of the DONES accelerator system.

For the DONES SRF-Linac with a deuteron beam of an energy of 5 MeV, beam losses can cause significant material activation. Nevertheless, hands-on maintenance is required for the SRF-linac, implying that beam losses must be maintained to a value lower than 1 W/m. 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.

In this paper, we call losses at such a low level the "micro-losses". The main challenging point of beam dynamics activities is to achieve a SRF-linac design that allows to accelerate and transport a 125 mA D^+ beam while preventing micro-losses in order to meet the hands-on maintenance requirement.

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: multiparticle simulations with more than 106 macroparticles are mandatory, which are very time consuming. An uncommon procedure has been adopted then: beam dynamics optimisations aim to optimize the extent of the very external beam border, rather than emittance or beta values. It's more about "halo matching" rather than "envelope matching". Each of the macroparticle at the external border must be scrutinized and kept as far as possible from the pipe wall [3].

The optimizations based on this cognition are shown in this paper, The beam dynamics simulations have been performed with the TraceWin code [4], developed at CEA/Saclay. Two designs of the DONES SRF-Linac will be presented, an old version with 4 cryomodules based on the IFMIF project and a new version with 5 cryomodules.

4-CYROMODULES SRF-LINAC

SRF-Linac Layout

The design of the 4 cryomodules SRF-linac is closely based on the one that has been studied in the framework of the IFMIF project [5]. Nevertheless, a series of modifications have been introduced after a detailed design of each component of the SRF-linac [6]. As a result, the SRF-linac needs a total of four cryomodules, the layout is shown in Fig. 2.

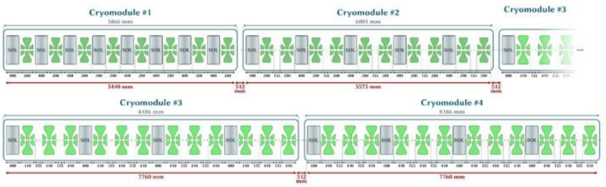

Figure 2: SRF-linac layout of 4-cryomodules option.

Longitudinal Dynamics

In order to reach 40 MeV at the end of the SRF-linac, as it is required, it would be necessary either to apply a more "aggressive" synchronous phase law or to increase the accelerating field in the HWR. As it's presented in

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dark red on Fig. 3, a more aggressive synchronous phase law lead to a smaller longitudinal acceptance, and end with more beam losses in the longitudinal plane (i.e. unstable particles that leave the bunch).

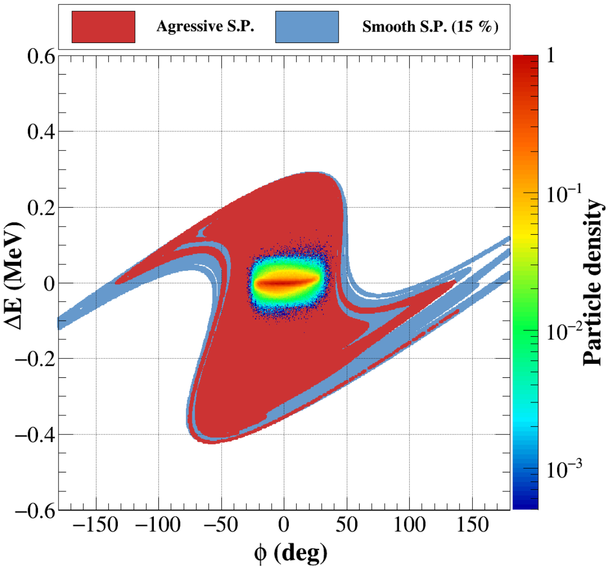

Figure 3: Longitudinal Acceptance of 4-cryomodules SRF-linac.

Transverse Dynamics

As introduced above, the optimisation in the transverse plane consists in tuning the focusing elements, solenoids and bunching cavities, in order to minimise the outermost border of the beam. A special method based on the Particle Swarm Optimization algorithm [7] has been developed for direct halo minimization, along with a concrete tuning procedure to apply on a real machine by means of dedicated micro-loss detectors.

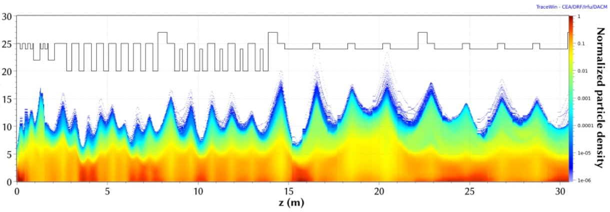

Figure 4: Beam density in the r plane along the MEBT and SRF-linac of 4-cryomodules option.

The beam density along the MEBT and the SFR-linac, obtain after such an optimisation, is represented in Fig. 4.

Error Study

In order to validate and test the sensitivity of the design of the accelerator, it is mandatory to perform an error study. It consists of simulating a large set of different machines, each of them having a different set of errors. In principle, two kind of errors should be considered: static errors and dynamic errors. Static errors represent the misalignment (or error in apply applied field) of the accelerator; dynamic errors represent imperfections such as vibrations or applied field or phase ripple of the focusing/accelerating elements.

A Monte-Carlo simulation method has been carried out by tracking 10^6 particles through 1800 different linacs, each of them having a different set of random static errors. These errors are uniformly distributed in the ranges presented in Table 1.

Table 1: Error Ranges Applied to SRF-linac Components

Element	**Static Error**	**Dynamic Error**
Resonators Misalignment [x,y]	± 2 mm	± 0.2 mm
Resonators Tilt $[\varphi_x,\varphi_y]$	± 20 mrad	± 2 mrad
Resonators Field Amplitude	± 1 %	± 0.1 %
Resonators Field Phase	± 1 deg	± 0.1 deg
Solenoids Misalignment [x,y]	± 1 mm	± 0.1 mm
Solenoids Tilt $[\varphi_x,\varphi_y]$	±10 mrad	± 1 mrad
Solenoids Magnetic Field	± 1 %	± 0.1 %
BPMs Measurement Accuracy	± 0.25 mm	± 0.025 mm

There are many losses, as shown in Fig. 5.

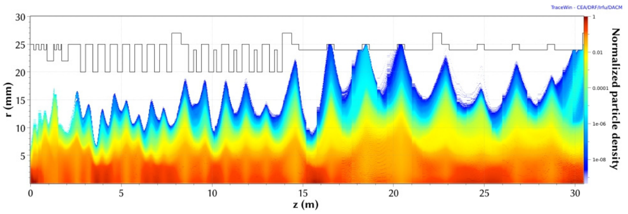

Figure 5: Cumulated density in the r plane for 1800 linacs with static errors.

5-CYROMODULES SRF-LINAC

SRF-Linac Layout

Considering the error study result of 4 cyromodules SRF-linac, it was necessary to study an alternative SRF-linac design, which could be less aggressive and safer from the beam dynamics point of view. Therefore, a 5-cyromodules SRF-linac are designed, and the layout is shown in Fig. 6.

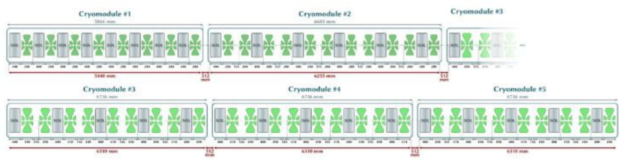

Figure 6: SRF-linac layout of 5-cryomodules option.

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Longitudinal and Transverse Dynamics

To improve the bad longitudinal dynamics caused by longitudinal-transverse coupling, find a way to combine the longitudinal optimization with transverse optimization based on PSO algorithm. The optimization results are shown in Fig. 7 and Fig. 8 respectively. The longitudinal acceptance is much larger than the original one.

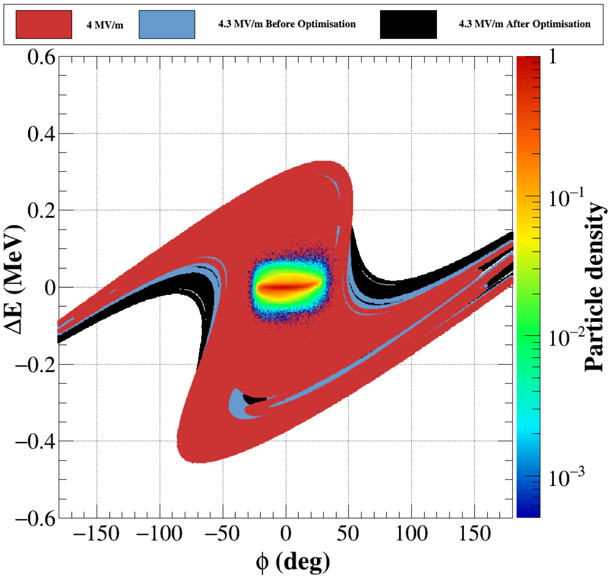

Figure 7: The longitudinal acceptance before and after optimization.

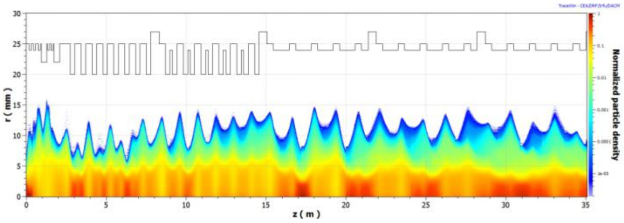

Figure 8: Beam density in the r plane along the MEBT and SRF-linac of 5-cryomodules option.

Error Study

Two series of error studies have been carried out by tracking 10^6 particles through 3000 different linacs. The errors are uniformly distributed in the ranges presented in Table 1. The result with only static errors are shown in Fig. 9. The result with both static and dynamics errors are shown in Fig. 10.

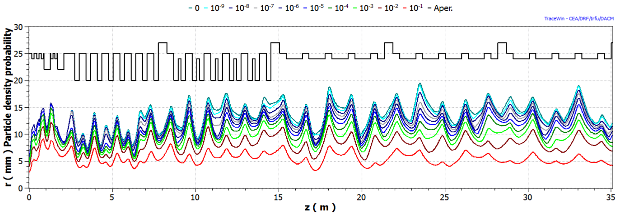

Figure 9: Density probability along the MEBT and SRF-linac with static errors.

Obviously, the outermost border of the beam doesn't touch the pipe wall in both two cases, so there will be no losses with these error conditions.

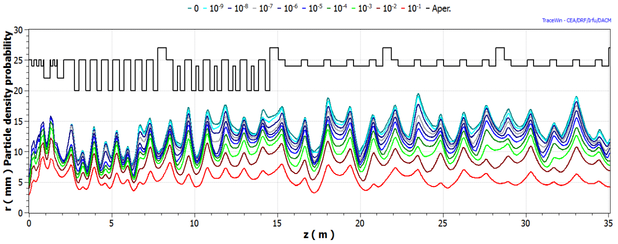

Figure 9: Density probability along the MEBT and SRF-linac with static and dynamics errors.

CONCLUSION

Two SRF-linac designs have been accomplished, and the comparison of the main parameters are summarized in Table 2. The 5-cryomodule option is chosen because of it's robustness for error studies.

Table 2: SRF-linacs Designs Main Parameters

Parameters (number of cryomodules)	**4**	**5**
Cavity β optimal (low/high)	0.115/0.175	0.115/0.175
Number of Solenoids	21	29
Number of low-β cavities	18 (8+10)	19 (8+11)
Number of high-β cavities	24 (2×12)	27 (3×9)
Amplification of high-β cavities field	15%	5%
Cryomodule 2 (low-β) length	6.00 m	6.68 m
High-β cryomodules length	8.19 m	6.74 m
Total Length (with MEBT)	30.42 m	35.02 m

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