ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-TUPTB031

OPERATIONAL CONSIDERATION IN THE LIPAc SRF WITH POTENTIAL SOLENOID FAILURE MODES

T. Ebisawa, K. Kondo, K. Masuda, A. Kasugai, K. Hasegawa, QST, Rokkasho, Japan
E. Kako, H. Sakai, KEK, Tsukuba, Japan
N. Chauvin, CEA Paris-Saclay, Gif-sur-Yvette, France
J. Chambrillon, G. Phillips, D. Gex, H. Dzitko, Y. Carin, Fusion for Energy, Garching, Germany

Abstract

The commissioning of LIPAc (Linear IFMIF Prototype Accelerator) is ongoing for the engineering validation of the high intensity deuteron beam accelerator system. The prototype Superconducting Radio-Frequency linac (SRF) cryomodule has been manufactured and will be assembled and tested on the LIPAc. During the cleaning process for the superconducting solenoid of SRF linac, some concerns appeared about two solenoids. As these two solenoids may not be used at nominal characteristics for the beam operation, the optimum positions of the suspicious solenoids and the condition of the beam transport were estimated as a mitigation action. By beam dynamics study, we concluded the position and condition for the beam operation without some solenoids. In this paper, the details of the beam dynamics simulation with solenoid failure modes will be presented.

INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is an accelerator driven neutron source by D-Li reaction, which will produce high-energy neutrons at high intensity for the irradiation of the candidate materials for the nuclear fusion reactors [1]. One of the major technological challenges of the IFMIF accelerator is the handling the 125 mA deuteron beam at Continuous Wave (CW). Several SRF cryomodules are required for IFMIF to accelerate deuterons from 5 MeV to 40 MeV. In the EVEDA phase, the validation of the low energy section of the IFMIF accelerator up to 9 MeV is a prerequisite. The construction and commissioning of the Linear IFMIF Prototype Accelerator (LIPAc) is being conducted at Rokkasho Institute of QST, Japan in collaboration with EU. The LIPAc consists of the injector with ECR ion source and Low Energy Beam Transport (LEBT), Radio-Frequency Quadrupole accelerator (RFQ), Medium Energy Beam Transport (MEBT), one Superconducting Radio-Frequency Linac (SRF) cryomodule, High Energy Beam Transport (HEBT) and Beam Dump (BD) as shown in Fig 1. The first of these cryomodules is being assembled and will be subsequently installed and tested [2]. In 2019, the deuteron beam operation test of RFQ for 125 mA / 5 MeV at low duty cycle was successful. After the beam operation of the RFQ, a new beam transport line, MEBT Extension Line (MEL), was installed in place of the SRF Linac. It ensure the continuity between the MEBT and the HEBT, allowing their commissioning with the Beam Dump. The high duty beam operation test of the RFQ and newly installed components have been started since 2021 and ongoing [3].

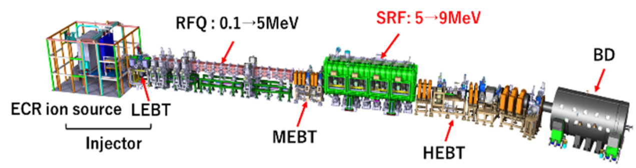

Figure 1: The schematic of the LIPAc.

As shown in Fig 2, the LIPAc SRF cryomodule consists of 8 superconducting Half Wave Resonator (HWR) working at 4.45 K, 175 MHz and RF power couplers for accelerating the beam. In addition, 8 superconducting solenoid magnet packages allow the focusing of the beam [4]. Table 1 shows the main specification of the LIPAc SRF cryomodule. The assembly of the cryomodule was started at QST, Rokkasho in 2019.

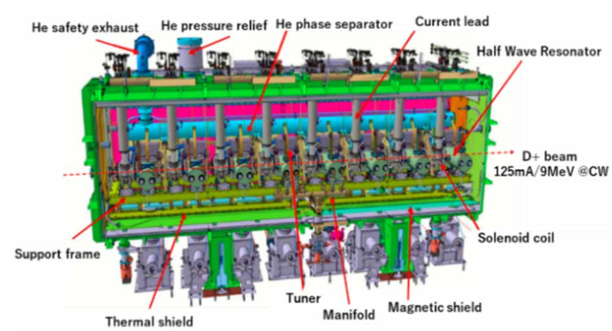

Figure 2: The schematic of the LIPAc SRF cryomodule.

Table 1: Main Specification of the LIPAc SRF

Parameter	Value
Frequency	175 MHz
Relativistic β	~0.1
Temperature	4.45 K
Average accelerating field	4.5 MV/m
Maximum solenoid field	6.0 T

After the fabrication and the tests of the superconducting solenoid packages in 2021, they were delivered to Japan and processed by High Pressure Rinsing (HPR) in clean room. By the completion of the solenoid HPR in 2022, the assembly was resumed. The detail of the progress is summarized in Ref. [5].

During the solenoid cleaning process, some concerns appeared about two solenoids having internal screws and pins disassembled [5]. After careful assessment of the

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consequences, it was not considered as a showstopper by the project, these two solenoids might not be able to perform as expected during SRF beam operation because of magnetic field degradation, breakage, and/or disturbance. It could finally result with beam losses, activation and quench of the SRF cavity. As a mitigation action for these two cases, a beam dynamics study was performed to determine their optimum positions in the cryomodule and the conditions to transport the beam with only six solenoids as a degraded mode.

This paper presents the recommended locations of suspicious solenoids in the cryomodule and resultant beam conditions for the LIPAc beam operation through the beam dynamics study.

POSITIONING AND SIMULATION PLAN

In this section, the positioning conditions of the two suspicious solenoids and the beam simulation plan are summarized. It is assumed that these two solenoids are mounted on the beam line but unable to focus the beam.

At first, the suspicious solenoids cannot be positioned on the No. 1 and 8 position for guiding the beam from MEBT and into HEBT. Position No. 5 should be avoided, as the replacement would require dismounting the vacuum manifold as shown Fig 3. In addition, consecutive positioning is no choice for focusing properly the beam. Therefore, two positions will be selected among No. 2, 3, 4, 6, and 7 without a consecutive positioning, corresponding to a combination of 7 possible patterns.

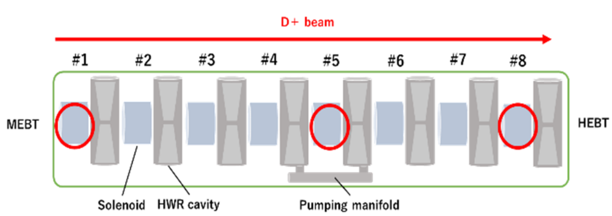

Figure 3: The schematic of the positioning of the equipment of LIPAc SRF. The suspicious solenoids cannot be put in red circle position.

For this study, Particle-In Cell (PIC) simulation code TraceWin developed by CEA was used with 10^6 test particles [6]. The parameters of the magnetic field of solenoid in SRF were adjusted to specify the beam size around 3 mm in the center of the solenoid and avoid the beam loss. The RF parameters for 9 MeV was kept. The magnetic field of the HEBT was tuned to satisfy the BD input condition of the $\sigma_{x,y}$ around 40 mm, and $\sigma_{x',y'}$ around 15-17 mrad, and to avoid a sharp distribution.

SIMULATION RESULT

In this section, the simulation results are summarized.

At first, we tried a parameter survey for one solenoid off cases to grasp the tendency. Apparently, if No.1 and 8 solenoids are off, the decent beam transport from MEBT and to HEBT are impossible. From No. 3, for the easily beam transports, we should reduce the second previous solenoid field and increase the previous solenoid field of unusable solenoid as shown Fig 4. Moreover, we need to reduce the beam current or detune the HWR for some cases to prevent the large beam loss.

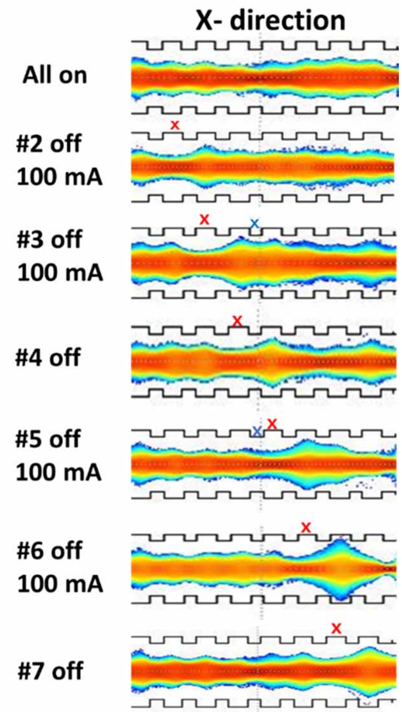

Figure 4: One result of the simulation for one solenoid off. Red x means the solenoid off. Blue x means the HWR off.

As a result, the candidate position of the suspicious solenoid is No. 4 position. Fig 5 shows the result of the beam simulation of No. 4 solenoid off case without and with error study. Error means the misalignment of the equipment ±10 mrad, and electric and magnetic fields ±1 %. Similarly, No. 7 position can be a candidate position. However, the case of No. 4 solenoid off is a little lower than the case of No. 7 off by comparing the error study with 1,000 Linacs as shown in Fig 6. By this survey, we recognized that the first candidate position of the most suspicious solenoids is No. 4, the next candidate position is No. 7.

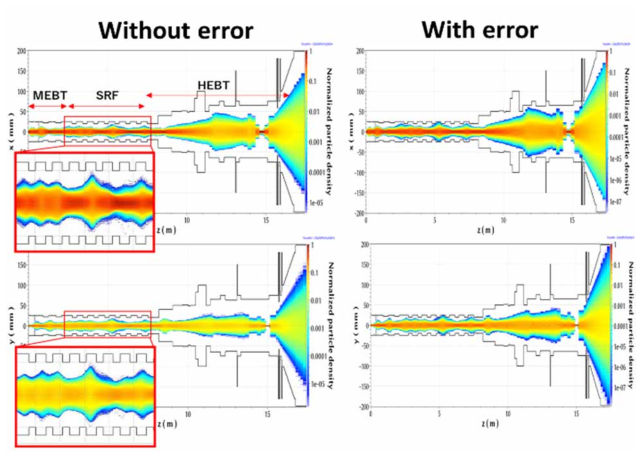

Figure 5: Results of simulation for 125 mA/9 MeV without No. 4 solenoid. Left and right is respectively without and with error.

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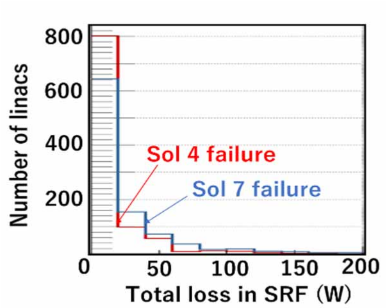

Figure 6: Comparing the error study of the No. 4 off and 7 off case with 1,000 linacs.

Next, the results of beam simulation for the two solenoids off cases with adjusting function of the TraceWin are summarized. For the case of 2&4, 2&6, 2&7, 3&6, 3&7, 4&6 and 4&7 off, the most candidate combination of the suspicious solenoids can be 4&7 as shown in Fig 7. By additional fine tuning, the beam loss completely disappeared. Fortunately, this result is consistent with the simulation for one solenoid off. After the optimization in SRF, the magnetic field of the HEBT was tuned to satisfy the BD input conditions as shown in Fig 8. It is not sharp shape. Beam transport to BD seems no problem. In addition, by reducing the beam current, for example, 125 mA to 80 mA, the beam transport can be easier as shown in Fig 9.

For another possible candidate case of No. 2 and 4 off, the beam expansion is larger than aperture of HWR at No. 2 solenoid position. This expansion was not suppressed by tuning the No. 1 solenoid. This expansion was assumed by RF field so No. 2 HWR was detuned to reduce the risk of beam defocusing. As a result, the beam expansion was suppressed as shown in Fig 10. However, the beam energy was degraded around 8.7 MeV. This expansion is induced due to the handling the high current and low energy beam. When the solenoid from the high energy side is off, the beam acceleration performance cannot be extremely degraded. On the other side, the cavities should be detuned or reduced the field to prevent the beam defocusing when the solenoid from the low energy side is off.

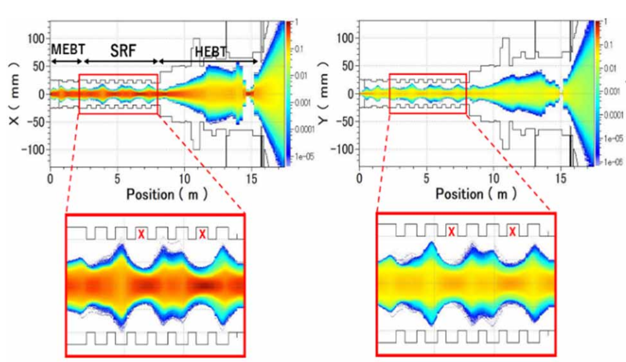

Figure 7: Results of simulation for 125 mA/9 MeV without No. 4 and 7 solenoids.

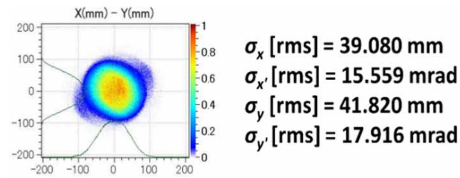

Figure 8: Beam distribution and beam parameters at BD.

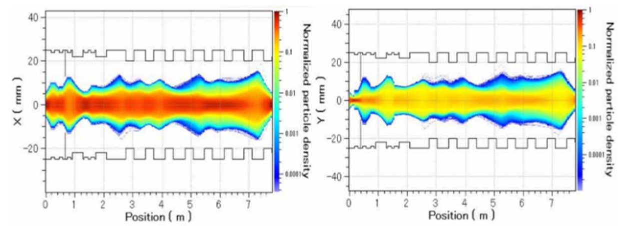

Figure 9: Results of simulation for reducing the beam current to 80 mA without No. 4 and 7 solenoids.

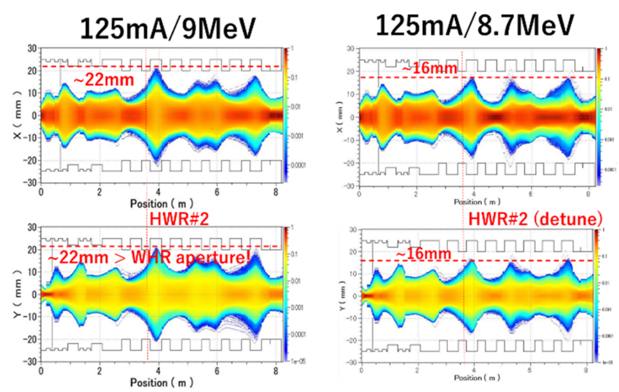

Figure 10: Results of simulation for without No. 2 and 4 solenoids.

For other combination, there were no decent solution to transport the beam without a large beam loss.

The future task are an error study and further parameter study to ensure the safe beam operation.

CONCLUSION

For the LIPAc SRF-Linac, the best pattern in terms of full operation for the two suspicious solenoids are position No. 4 and 7. First candidate is No. 4, the next is No. 7 and a third one is No. 2.

Depending on the case, limiting the performance of the RF cavity or beam current are necessary. The error study and additional survey are future task to ensure the realistic safe beam operation.

Same issues can be occurred in other high intensity Linac. In order to reduce the issue and continue the beam operation, although the operation performance of the beam current or beam energy may be restricted of the severe condition for preventing the degradation, beam loss and quench of the SRF cavities.

However, these facts and its measures can be useful and practical information for the design and operation of the low energy and the high current beam SRF Linac including solenoid focusing system such DONES [7-9], A-FNS [10] and similar high intensity Linac.

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