CATALOGUE OF LOSSES FOR THE LINEAR IFMIF PROTOTYPE ACCELERATOR

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Abstract

One of the activities of the EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF (International Fusion Materials Irradiation Facility) project consists in building, testing and operating, in Japan, a 125 mA/9 MeV deuteron accelerator, called LIPAc, which has been developed in Europe.

For the accelerator safety aspects, a precise knowledge of beam loss location and power deposition is crucial, especially for a high intensity, high power accelerator like LIPAc. This paper presents the beam dynamics simulations allowing to estimate beam losses in different situations of the accelerator lifetime: starting from scratch, beam commissioning, tuning or exploration, routine operation, sudden failure. Some results of these studies are given and commented. Recommendations for hot point protection, beam stop velocity, beam power limitation are given accordingly.

INTRODUCTION

For a high power megawatt class accelerator, any loss, even a tiny proportion of the beam, can be harmful. A careful and detailed loss study is thus necessary for various loss scenarios. That should be analysed for all the different stages of the accelerator lifetime, from its starting up, beam commissioning through routine operation, as well as for the various accidental breakdowns. Such a catalogue will be useful, or even necessary in the definition of safety procedure, limitations and recommendations, aiming at protecting personnel or facilities.

The linear IFMIF prototype accelerator (LIPAc) is being constructed in Europe and will be assembled in Japan [1]. This machine aims at accelerating a 125 mA D^+ continuous beam at 9 MeV. The general layout of LIPAc is recalled in Fig. 1, where beam energy and power for each subsystem are also given (for more details see Ref. [2]).

The LIPAc very high c.w. beam intensity implies that almost the whole accelerator is concerned by a high power beam which ranges from 0.012 to 1.125 MW. Indeed, it is common to consider that it is safe enough to use the lowest duty cycle and the lowest beam intensity during beam commissioning or exploration. But in the present case, as the ion source is optimised for providing a 140 mA continuous beam, the lowest duty cycle for which the beam is still stable is 10^{-3}; furthermore, the nominal beam intensity implies a very high space charge regime so that any beam tuning with too low intensity will not be representative because of much lower space charge effects.

In the following, the protocol of loss simulations is discussed, then some loss results are presented in a few loss scenarios and finally, consequences on safety measures are drawn.

LOSS STUDY PROTOCOL

In the following, the losses are given in power deposition (Watt). They are obtained with the nominal (maximum) current of 125 mA continuous wave. From that, losses can be reduced if needed, by reducing consequently the duty cycle and even the current if necessary. Theoretically, because space charge effects decrease with intensity, losses at lower current are less than what can be inferred by a linear relation. But as a precaution, it is wise to deduce losses at lower current with a simple linear transformation.

The double issue is to define as exhaustively as possible all the typical loss situations in the accelerator lifetime and to define the procedure to simulate and estimate them. The following stages have been identified: (A) Ideal machine; (B) Starting from scratch; (C) Beam commissioning, tuning, exploration; (C) Routine operation; (E) Sudden failure.

Stage A: Ideal Machine

"Ideal" means here nominal machine parameters and tunings, without any error. That should correspond on the real machine to a completely satisfying situation, once all the accelerator components are perfectly fabricated and aligned, or else corrected at the source, and the beam has been idealy tuned. Losses in such conditions should be minimum; we cannot hope to have less. These are minimum and permanent losses that have to be withstood. They are obtained by a start-to-end simulation without any error for the nominal tuning [3].

Stage B: Starting From Scratch

In this condition, no correction has yet been applied, while we can expect that: (1) The accelerator components have been fabricated and aligned as specified, within the already defined tolerance ranges. (2) The tunable parameters (accelerating and focusing fields and gradients) are set at their optmized values given by beam dynamics simulation. We must however expect that the real beam behavior is not exactly the same as simulated one (the IFMIF very high space charge regime has never been experimentally observed). This simulation-reality difference can be roughly estimated as equivalent to field and gradient variations in a ±10%

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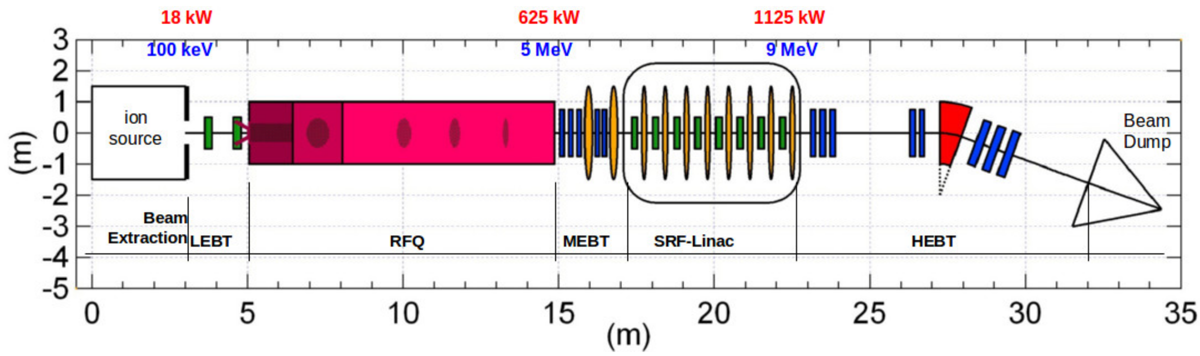

Figure 1: LIPAc general layout.

range of their nominal values, according to the beam dynamics optimization results obtained in different working configurations since the beginning of the project.

Losses when starting from scratch can thus be estimated by performing a start-to-end error study without any correction. Two kinds of "errors" can be applied: mechanical end alignment errors randomly distributed within tolerances and tunable parameter errors randomly distributed within a ±10% range of their nominal values. Tolerance values, including static and dynamic ones, are discussed and presented in Refs. [2, 3].

Stage C: Beam Commissioning, Tuning, Exploration

This occurs during beam commissioning or whenever the beam operation is not as satisfying as expected so that a beam tuning is necessary. However, the induced beam losses can be calculated in the same way. As in the "B" case, we can assume mechanical errors within tolerances and tunable parameter variations of about ±10%. The only difference is that now the beam trajectory is corrected.

Stage D: Routine Operation

This situation happens when the beam characteristics are satisfying, i.e., as expected with all the parameters, mechanical and tunable parameters, as specified within tolerances and the trajectory corrected. Losses can thus be calculated by performing an error study with orbit correction.

Stage E: Sudden Failure

These accidental situations are not easy to be exhaustively studied, especially when a combination of different failures can lead to more important losses than an individual failure. In this work, only two cases are studied: failure of individual components and global failure of all the components at once, from 110% to 0% of their nominal values. This can be due, for example, to power supply failures that accidentally provide a larger power or that can be suddenly switched off, making the fields or gradients returning progressively to zero.

BEAM LOSSES SIMULATION RESULTS

Start-to-end LIPAc simulations with 10^6 macro-particles have been thoroughly carried out with the TraceWin code [4] as well as the error studies.

Due to a lack of space, all the obtained results will not be presented here. As the simulation results for stage A and D can be founded in previous works [2, 3], they will not be exposed in the present paper.

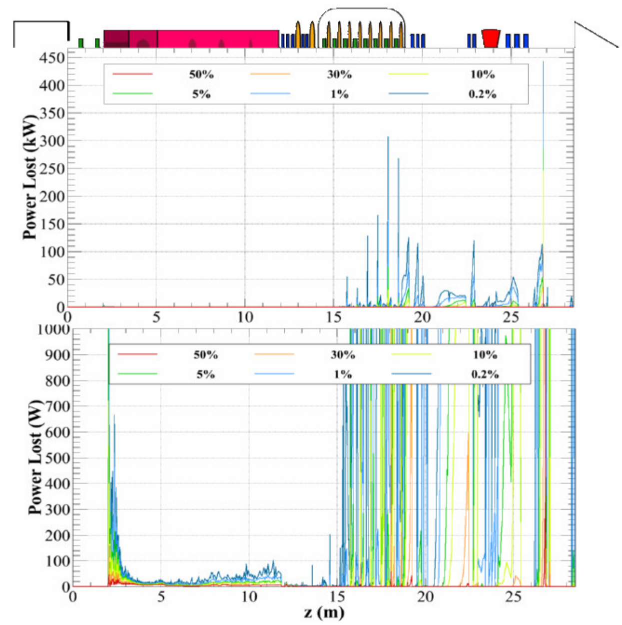

Figure 2: Beam power loss probabilities when starting from scratch for a full-power beam (statistics over 500 machines). The bottom figure is a zoom of the top one.

Beam Losses When Starting from Scratch

As specified above, loss probabilities are calculated from results of 500 start-to-end simulations with mechanical errors randomly distributed within tolerances and tunable parameter (field, gradients) errors randomly distributed within ±10% of their nominal values.

Simulations are performed for the nominal 125 mA c.w. beam current. Once losses are known, a proportional calculation will give the maximum acceptable duty cycle or

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current at starting to avoid harmful losses. Loss probabilities along LIPAc are given in Fig. 2.

Beam Losses in Case of Sudden Failure

Due to the number of distinct accelerator components and their different nature in the low-energy section (from the source until the end of the RFQ, E ≤ 5 MeV) and in the high-energy section (from the MEBT, E ≥ 5 MeV), the loss studies are performed separately for each of them. Nevertheless, even in the case of a failure in the low energy section, the beam has been tracked (and the losses have been recorded) all along the LIPAc.

Power deposition due to beam losses are given in Fig. 3 in the case of sudden failure of the RFQ.

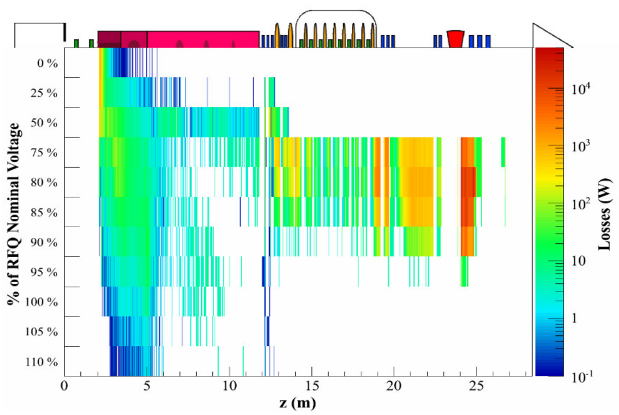

Figure 3: Beam lost power in case of sudden failure of the RFQ.

The RFQ voltage induces losses only when it decreases. In case of sudden breakdown, losses of a few W locally within the RFQ are not worrying until 95% of its nominal value. As soon as the voltage decreases to 90%, losses of about 10 W appear at several solenoids location in the cryomodule, and about 100 W at the dipole exit. These losses are multiplied by 10 when the voltage decreases to 85%

For the high energy section, it is worth mentioning that the failure of some accelerator elements not only induces losses along the LIPAc but they can also result in important beam size variations at the beam dump entrance (that can be withstood within a given range). These variations have also been carefully studied (see Fig. 4).

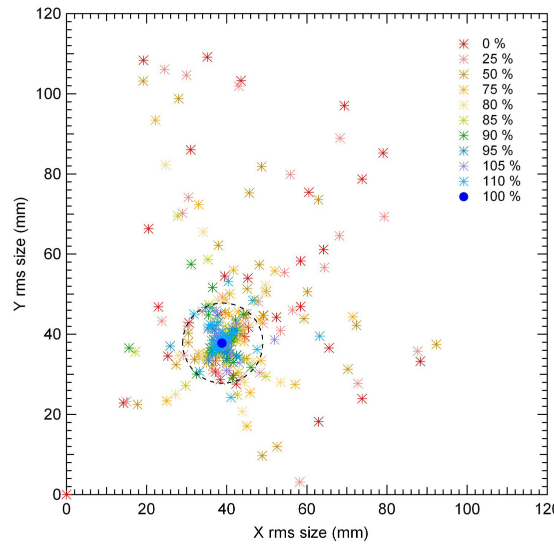

Figure 4: R.m.s. beam size at the beam dump entrance in case of sudden failure of the individual elements of the high-energy section. The dashed circle represents the tolerated beam size variation at the beam dump entrance.

CONCLUSION

Beam dynamics simulations have been performed in order to estimate beam losses during different stages of the LIPAc lifetime. That is meant to be a starting point for assessing all the accelerator safety aspects.

In the "starting from scratch" case, the hot points are the RFQ entrance cone, the cryomodule solenoid exits, and the beam dump scraper. Starting the low-energy part with 10^{-4} – 10^{-3} of the nominal beam power would be fine. The high-energy part should be started with no more than 10^{-5} – 10^{-6} of nominal beam power. Therefore, a high-performance beam chopper in the LEBT is mandatory (rise time < 1 µs).

In the "sudden failures" case, failures of individual elements are generally more harmful than failure of all the elements at once. In order to protect the superconducting elements, the most critical parameter to keep a close eye on is the RFQ voltage. The emergency beam stop system must stop the beam the latest when the RFQ voltage reaches 95% of its nominal value. For the elements of the high-energy part, if the beam dump can only accept variations of r.m.s. beam size less than ± 10 mm, the beam must be stopped for every element variation outside a 95 – 105% range.

The impact of those results on almost all the LIPAc subsystems show the importance of setting up such a catalogue of losses for a high power accelerator or at least the high power part of an accelerator, where the beam power reaches more than hundreds of kW. The protocol of loss studies presented in this article can likely be applied to any accelerator, by appropriately adjusting the numerical values used here.

REFERENCES

[1] A. Mosnier et al., “Present Status and Developments of the Linear IFMIF Prototype Accelerator (LIPAc)”, THPPP075, Proc. of IPAC 2012, New Orleans, USA (2012).

[2] P.A.P. Nghiem et al., *Nucl. Instru. Meth. Phys. Res.* A **654**,63-71 (2011).

[3] N. Chauvin et al., “Start-to-end Beam Dynamics Simulations for the Prototype Accelerator of the IFMIF/EVEDA Project”, MOPS026, Proc. of IPAC 2011, San Sebastiàn, Spain (2011).

[4] http://irfu.cea.fr/Sacm/logiciels/index.php