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 continuous beam intensity implies that almost the whole accelerator is concerned by a high power beam which ranges from 0.012 to 1.125 MW. 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 during accelerator tests and exploration. But in the present case, as the ion source is optimised to provide a 140 mA continuous beam, the lowest duty cycle for which the beam is still stable is a few 10^{-3}. Indeed, 1 ms is a typical time scale for the ECR source plasma to be established and for the extracted beam to reach a steady state. Furthermore, the nominal beam intensity implies a very high space charge regime. So, any beam tuning with too low intensity will not be representative of the nominal conditions because of much lower space charge effects. Thus, the ability to lower the beam power is considerably limited. In the same way, a beam stop system is foreseen in the LEBT to shut off the beam in an accidental case in less than 10 µs. It is not sure that such a machine protection system is fast enough for a MW beam power.

This paper will mainly focus on the protocol and methodology that has been employed to simulate different loss situations; then, some results are presented and discussed 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.

Situation 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, if all the accelerator components would be perfectly fabricated and aligned, or else corrected at the source, and the beam would have been 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. It is very unlikely, (although highly desirable!) that this situation will occur on the real machine. At least, this situation is an optimal reference case that can be used as a comparison to the other scenarios described in the following subsections. The losses are obtained by a start-to-end simulation without any error for the nominal tuning [3].

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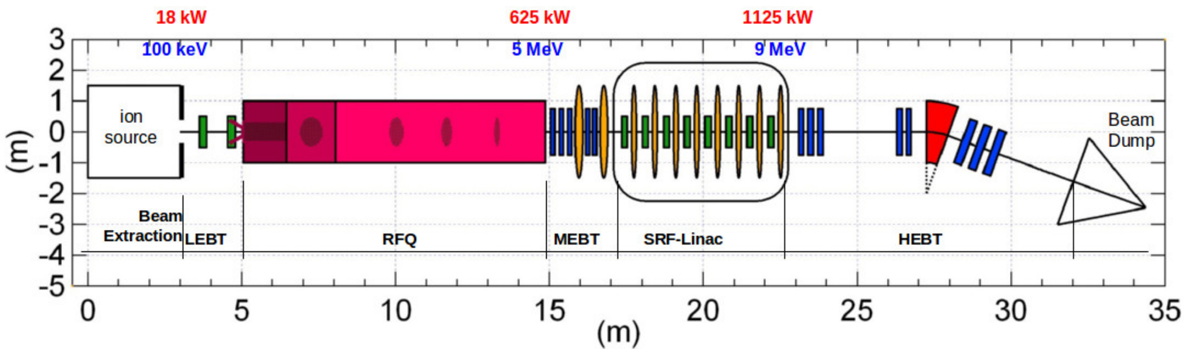

Figure 1: LIPAc general layout.

Situation 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 optimised values given by beam dynamics simulation. We must however expect that the real beam behaviour is not exactly the same as the simulated one (the IFMIF very high space charge regime has never been experimentally observed). This theory-reality difference can be roughly estimated as equivalent to field and gradient variations in a ±10% 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].

Situation 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. Besides, experiments requiring an exploration around a nominal setting can be desirable for beam physics purposes.

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.

Situation 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 trajectory correction.

Situation 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. Reflections and analysis should be carried out for each subsystem to detect what is the worst case, what is the main affected location or equipment, when one tunable parameter (gradient, field, phase, RF power, pressure ...), or a given combination of them, are suddenly switched off. But attention should also be paid to detect if there is an intermediate case which can induce more losses, for example, in the transition from the nominal value to zero for specific field or gradient.

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 LOSS SIMULATION RESULTS

Start-to-end LIPAc simulations with 10^6 macro-particles have been thoroughly carried out with the TraceWin code [4]. The error studies have also been performed with TraceWin, by tracking 10^6 macro-particles in 500 through different linacs, each with different random errors that are uniformly distributed.

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

Beam Losses During Beam Commissioning, Tuning or Exploration

As discussed above, loss probabilities are calculated from results of an error study with mechanical errors randomly distributed within tolerances and tunable parameter (field, gradients) errors randomly distributed within ±10% of their

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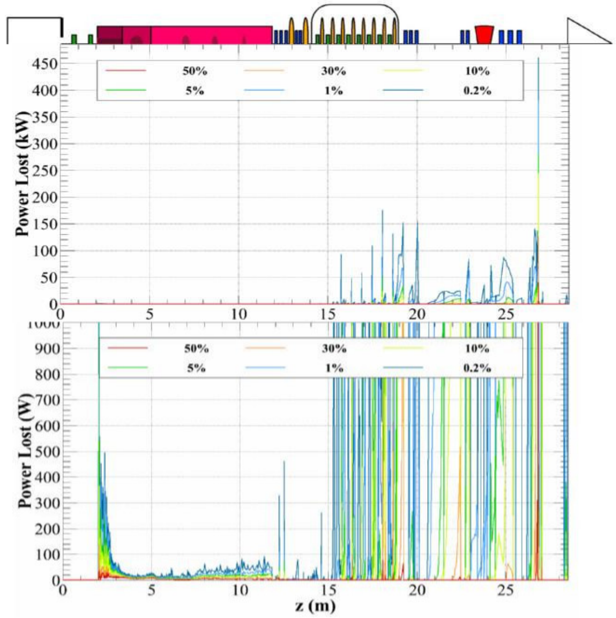

Figure 2: Beam power loss probabilities during beam commissioning, tuning or exploration, for a full-power beam (statistics over 500 machines). The bottom figure is a zoom of the top one toward the low power losses.

nominal values. Here, the beam trajectory are corrected. The correction scheme relies on steering coils (H and V) associated with downstream beam position monitors (H and V). In the LEBT, steerers are located inside the two solenoids. Then, 4 steerers and BPMs are located in the MEBT, 8 in the SRF-linac (at each lattice) and 6 in the HEBT.

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 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 Solenoids of the LEBT and the RFQ voltage.

When all the low-energy part suddenly fails, losses occur mainly at the end of the LEBT and at the RFQ entrance. When the solenoid magnetic fields move around ±5% of their nominal values, the beam is either not focused enough to pass through the injection cone or is so mismatched that it

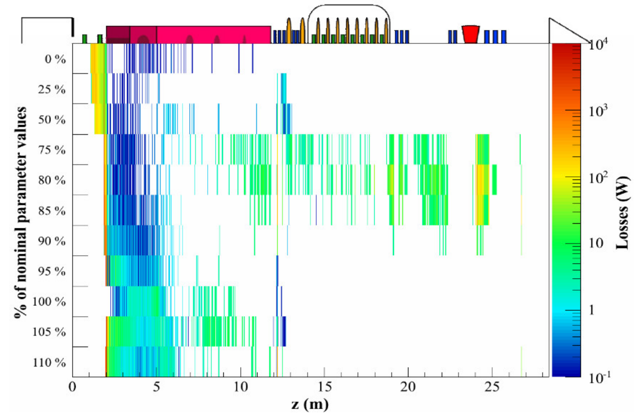

Figure 3: Beam power lost in case of sudden failure of the low energy part (LEBT solenoids and RFQ voltage) at once.

is lost in the first RFQ section. It can be noted that this case is less harmful than that of RFQ failure alone where more important losses occur in the sections downstream the RFQ.

CONCLUSION

Beam dynamics simulations have been performed in order to estimate beam losses during different stages of the LIPAc lifetime. More detailed explanation of this work as well as extensive simulation results for all the stages of the accelerator lifetime that have been identified can be found in [5].

The catalogue of losses is meant to be a starting point for assessing all the accelerator safety aspects. Losses should concern all the accelerator sections by the identified hot points to be protected (facing beam equipment and diagnostics). The impact of those results on almost all the accelerator sub- systems shows 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.

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