MACHINE PROTECTION AND SAFE OPERATION OF LIPAC LINEAR ACCELERATOR

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Abstract

A Li(d,xn) fusion relevant neutron source with a broad peak at 14 MeV is indispensable to characterize and qualify suitable structural materials for the plasma facing components in future fusion reactors. LIPAc (Linear IFMIF Prototype Accelerator), presently under its installation and commissioning phase in Rokkasho, will validate the concept of a 40 MeV deuteron accelerator with its 125 mA CW and 9 MeV deuteron beam for a total beam average power of 1.125 MW.

The Machine Protection System (MPS) of LIPAc provides the essential interlock function of stopping the beam in case of excessive beam loss or other hazardous situations. However, approaching LIPAc beam commissioning Phase B (including RFQ powered by total 1.6 MW RF power) a risk analysis has been performed on all major technical systems to identify the sources of risk, apply the necessary countermeasures and enhance accelerator availability, avoiding unnecessary beam stop triggers and allowing a fast beam recovery whenever possible. The overall strategy for the machine protection at LIPAc is presented in this paper.

INTRODUCTION

The LIPAc linear accelerator, currently under installation and commissioning in Rokkasho, Japan [1], will traverse the frontier of 1 MW beam average power in 2019, with its 9 MeV and 125 mA CW deuteron beam. LIPAc is composed of a H+/D+ source, a Low-Energy Beam Transport (LEBT), a Radio-Frequency Quadrupole (RFQ), a Medium-Energy Beam Transfer (MEBT), a Superconducting Radio Frequency LINAC (SRF Linac), and a High Energy Beam Transport (HEBT) which transports the beam down to the final Beam Dump.

LIPAc installation and commissioning will be divided in different stages (Figure 1). Current results obtained for Phase A show promising performance [2]. The second phase (Phase B - up to 5 MeV) will end by March 2017. The third and fourth phases (C & D) will follow till the end of 2019 with the integrated commissioning of the LIPAc up to 9 MeV, in pulsed and CW.

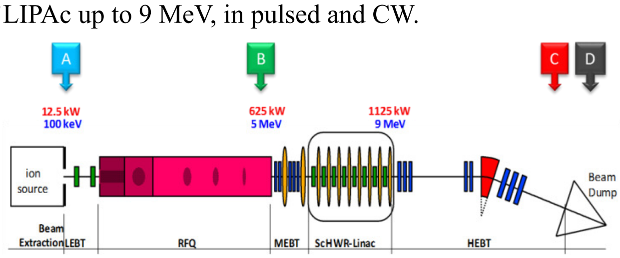

Figure 1: Schematic view of LIPAc layout and commissioning stages.

MACHINE PROTECTION STRATEGY

As the highest beam current and power CW linac ever built [3], LIPAc will face unprecedented challenges in the domain beam dynamics and average beam power [4] that have pushed the requirements in investment protection to new limits. Given its condition of prototype for the future IFMIF facility, the Machine Protection System of LIPAc [5] has the main task of protecting the investment, while allowing enough flexibility during the commissioning phases and minimizing beam inhibit time. A systematic approach has been followed to identify the main risks that could cause serious damage to components and/or important operation downtimes. Besides the first-order effects caused by a mis steered beam and beam losses, also potential damages due to vacuum loss, RF desynchronization or machine operations are analyzed.

Fast Beam Effects

With a focused high current beam, the damage that can be caused when impacting on a surface can be such that in a small amount of time irreversible effects can be observed in the surface of the beam pipe or, in the worst case, cavities. Component damage depends on the beam energy, beam current and current density. Especially in the low energy part of the accelerator thermal stress can be reached within few µs [6]. This scenario, while not very likely to occur (normal incidence of focused beams are not common in linear accelerators, in absence of bending magnets or interceptive diagnostics), normally drives the design of the Machine Protection System as the countermeasure in the form of a fast beam stop that has to be executed fast enough. In the case of LIPAc, it was designed that 30 µs, from occurrence of the event to fast beam shutdown, would be fast enough. A detailed justification of this value and an analysis of beam induced damages for different scenarios have also been performed [7].

In order to detect such events and allow a short reaction time, the main tools available are the Beam Loss Monitors (BLoM). In the case of LIPAc, 20 LHC-type Ion Chambers (IC) [8] are installed along the accelerator, downstream the RFQ. MPS should be alerted in 10 µs, allowing 20 additional µs until full beam stop. Assuming that one IC triggers the MPS when the current reaches 1 nA, even if its position is as far as 1 m from the beam axis, losses correspond to 500 W/m. In this scenario, only 15 mJ are deposited in the beam pipe in 30 µs, with a dispersed beam footprint due to oblique incidence, allowing enough margin before damage.

Nevertheless, BLoMs will be initially calibrated assuming the classical criterion for a proton beam of 1 W/m

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maximum power on the beam pipe, in order to minimize the activation on the accelerator components and allow shorter maintenance periods. It should be noted, though, that the backscattering contribution of the beam dump can be huge compared to the 1 W/m beam losses. Fine tuning of the BLoM thresholds will be required during beam commissioning.

Identification of the beam loss location and power deposition is crucial for the correct management of safety aspects. A careful and detailed loss study, through the use of simulations (TraceWin), was carried out for the different accelerator parts [9], providing essential feedback to define a safe operation of LIPAc minimizing beam loss events. The study mainly focuses on the power losses during normal operation (Figure 2), when all parameters are within specified ranges, and in case of sudden failure of one or several components, or mis-setting of parameters during start-up, commissioning or operation. Cavity phases and RFQ voltage are not considered as tuneable parameters in these simulations.

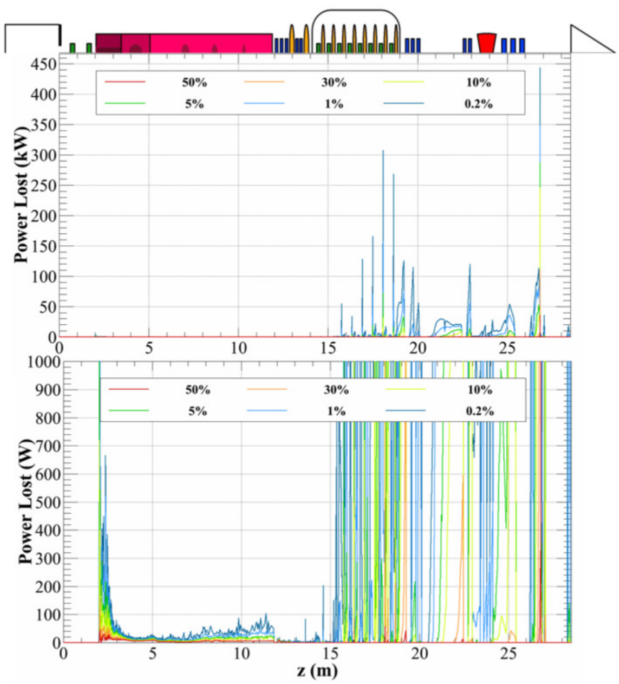

Figure 2: Beam power loss probabilities when starting from scratch for a full-power beam.

In the low-mid energy part, including the RFQ and MEBT (up to 5 MeV), losses are less significant in terms of power. It is assumed that the 9.6 m long RFQ will have to withstand the full beam lost at the entrance during the initial commissioning stages (10-100 W), and up to 1 2 kW integrated along the whole RFQ during CW operation in case of beam loss events. The entrance of the RFQ is protected by a cone [10] that, being cooled down, can withstand instantaneous losses of up to 5 kW (in case of sudden loss of the first solenoid in the LEBT as worst case scenario).

In the highest energy part potential losses are much more important in terms of beam power, reaching up to ~100 kW locally in SRF solenoids, magnets or diagnostic plate for a nominal 125 mA CW beam. In the particular case of the SRF, as no more than ~10 W of heat deposited by the particle beam can be drained away by the cryomodule cryogenic system, only 10-5 of nominal beam power can be accepted during normal operation. Most of the beam losses in this region, in particular in the superconducting elements, will actually be produced by variations in the RFQ cavity voltage; a 5% variation from nominal value should already trigger the fast beam stop, to avoid downstream risks. The high performance of the chopper in the LEBT, with rising times in the order of 1 µs, is essential to minimize losses due to long rise and fall edges of the ion source beam.

Slow Beam Effects

LIPAc injector is capable of delivering beam pulses from 3 ms (50 µs using the chopper) up to CW. The effects described above could already cause damage in one single cycle. Other effects, which include long term thermal effects, can take minutes or even days to become apparent. One example is the beam halo produced in high current accelerators, which tends to become the main source of beam loss and can cause damage on the components surface on the long term [11]. Cryogenic CVD µ-loss monitors have been developed by CEA-Saclay to determine the beam halo along the SRF linac.

Examples have also beam reported where high intensity and power density beams, with low energy or low average beam power, where beam losses are difficult to detect (or when the instrumentation or protection system is inhibited at early stages of commissioning), can cause damage after several minutes of operation [12].

In the case of LIPAc, these cumulative effects should be suffered mostly in the cavities. For the RFQ, given the estimated beam losses of 0.08 mA (~10 W for an overall beam transmission of >90%) in the first cells during normal operation, and assuming a criterion of accepted number of particles of 1022 part/m2, blistering effects could appear in its surface after 250 hours of continuous beam operation [13]. For the bunchers in the MEBT, this blistering effect could be more important given the higher beam power density.

For the superconducting linacs, beam impacting in the cavity can end up degrading the performance of RF or causing the cavity to be more prone to electrical arcs or tripping [14].

RF Power

The two accelerating cavities of LIPAc, will require continuous wave RF power at 175 MHz for the 18 RF power generators [15] feeding the eight RFQ couplers (200 kW), the two couplers of the buncher cavities in the MEBT (20 kW) and the eight couplers of the superconducting half wave resonators of the SRF Linac (105 kW).

The important amount of power delivered by the RF system can be harmful for the cavities, waveguides or circulators, under certain circumstances (electrical arc, multipacting, vacuum loss, and reflected power). The LLRF [16] is in charge of managing these events and shutting down the RF power within a time frame of <10 µs, together with a fast beam stop request to the beam interlock. Amplitude and phase stability in the cavities, mostly in the SRF, is essential to avoid beam losses. LLRF is capable of detecting excess of reflected power, in case of beam-RF misalignment, and shut down rapidly the RF. This effect may also appear in case of fast beam stop, due to high beam loading.

Additionally, incorrect operation of cooling system can put the cavities at risk due to over temperature. Cavity subsystems can also request an RF power stop in case of loss of cooling.

Vacuum

The accidents derived from a localized loss of vacuum are also managed by the MPS. For LIPAc, the beam pipe is subdivided in several isolation valves, managed directly by some of the subsystems. The GVMS (Gate Valve Management System) is directly informed in case of a decrease in the level of vacuum, and manages centrally (through the local controllers) the status of each isolation valve. However, special care will have to be taken once the SRF is in place [17], especially in the boundaries with the MEBT and HEBT shared isolation valves.

MACHINE PROTECTION SYSTEM

The Machine Protection System (MPS) of LIPAc is the system in charge of the implementation of the investment protection countermeasures. The subsystem in charge of the beam interlock actions [18] is based on FPGA on a VME chassis, derived from the experience obtained at J-PARC accelerator. It consists of a series of signal concentrators (through an AND logic) that receive the status (beam permit) from various subsystems alongside the accelerator. The output of this chain, the beam interlock action (inhibit), is segregated into three main beam stop methods: a slow shutdown, through a PLC directly shutting down the High Voltage Power Supply of the Magnetron RF Generator; a fast (~10 µs), through a dedicated fast electronic circuit that triggers a crowbar to directly cut the power on the Magnetron RF Generator; and a third way, the fast unlatched (~50 µs) BRTZ (Beam Reset To Zero) that directly acts on the timing system input to allow a fast recovery of the beam, in case of transient situations like electrical arcs or low threshold triggered BLoM events.

In addition to the beam interlock, other components are part of the investment protection chain:

- Beam Condition generator, to protect chopper downstream components from incorrect duty cycle.
- Gate Valve Management System, to coordinate the status of the sectional valves in case of loss of vacuum and allow/inhibit the beam accordingly.

The different modules of the MPS allow a remote monitoring of the status and an individual inhibit of each signal, to provide an indispensable flexibility during the initial stages of commissioning.

LIPAC OPERATION SCENARIOS

During the early stages of the beam commissioning, LIPAc will also be able to work with H+ at pulsed mode, requiring additional functionality from the RF power system and the LLRF. The following phases have been considered:

- Phase A: injector + LEBT. Pulsed and CW, full intensity.
- Phase B: 1st + RFQ + MEBT; pulsed (0.01%-0.1% duty cycle, 1-10s cycle), H+ and D+ up to full intensity.
- Phase C: full installation (including SRF Linac + HEBT + BD). Pulsed (0.01%-0.1% duty cycle), H+ and D+ up to full intensity.
- Phase D: ramp up to full power. Pulsed (from 0.1% duty cycle) to CW, H+ and D+ at full intensity.

In order to allow a safe initial tuning and commissioning of the different parts of the accelerator, the initial beam pulses will be as short as 50 µs (by using the chopper in the LEBT), with a repetition rate of 0.1 Hz.

As the RFQ was designed for 125 mA of nominal D+ beam intensity, and the expected space charge regime makes beam tuning with too low intensity not representative, lowering the beam current to minimize risk at early stages is not an option. However, the initial commissioning stages will be carried out with protons at half current and half energy than nominal operation with deuterons, since protons at 9 MeV have no activating power.

The majority of beam losses at the initial stages are expected during the RF turn on/off. The beam that enters the cavity while RF is ramping up or down is likely to be lost. This will also be affected by the edges of the beam coming from the source through the chopper (~10 µs measured) or, in future stages, without the chopper (~1 ms). RF feedback and feed forward are also important sources of beam loss; LLRF system must react (and anticipate) to the beam loading caused by the high intensity beam.

The simulations have also proven that during beam tuning or exploration, it is highly recommended to proceed by maximum steps of 5% of the nominal values [9]. This is in line with the experience that demonstrates that an important risk comes from misconfiguration of magnets or RF parameters in the control room. A software interlock layer is under consideration to prevent such hazards.

CONCLUSIONS

The beam commissioning of LIPAc with RFQ and MEBT bunchers is approaching. An identification of the main risks that will be faced during this phase has been performed; detection mechanisms based on beam instrumentation and countermeasures applied have been briefly described. Safe operation of LIPAc cannot solely rely, in any case, on automatic procedures of the Machine Protection System; careful identification of a safe start up and operation is essential for a successful commissioning of LIPAc.

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