# BEAM INDUCED DAMAGE STUDIES OF THE IFMIF/EVEDA 125mA CW 9 MeV D+ LINEAR ACCELERATOR

F. Scantamburlo, B. Bolzon, R. Ichimiya, J. Knaster, A. Marqueta, H. Kobayashi, IFMIF/EVEDA ILIC Unit, Rokkasho,Japan
P.-Y. Beauvais, H. Dzitko, F4E-BFD, Garching, Germany

*Abstract*

IFMIF (International Fusion Material Irradiation Facility) will be a Li(d,xn) neutron source providing equivalent neutron spectrum of DT fusion reactions and comparable neutron flux of future commercial reactors. Such a facility is an essential step in world fusion roadmaps to qualify suitable structural materials capable of holding the unrivalled neutron irradiation inside the nuclear vessel of a fusion reactor. IFMIF, presently in its EVEDA (Engineering Validation and Engineering Design Activities) phase, is installing LIPAc (Linear IFMIF Prototype Accelerator) in Rokkasho (Japan), a 125mA CW 9 MeV deuteron beam as validating prototype of IFMIF accelerators. The MPS of LIPAc manages the interlocks for a fast beam stop during anomalous beam losses or other hazardous situations. High speed processing is essential to achieve MPS goals driven by investment protection principles. Beam losses may lead to severe damages by excessive thermal stresses, annealing or even burn/melting of materials. The assumptions to estimate the practical safe times for a fast beam shutdown during the accelerator operational life are here described.

## IFMIF AND LIPAC, ITS ACCELERATOR PROTOTYPE

Fusion materials research has fuelled for decades the world endeavours towards high current linacs [1]. The required neutron flux $>10^{18}$ $m^2 \cdot s^{-1}$ with a broad peak at 14 MeV to simulate the irradiation conditions of the plasma facing components in a fusion reactor is obtainable through Li(d,xn) stripping reactions; however those fluxes demand deuteron currents in the $10^2$ mA range in CW mode. The first world attempt of such conditions was framed by the Fusion Materials Irradiation Test Facility, FMIT, in the early 80s; with unexpected difficulties and lessons learnt in operating in CW mode [2].

The International Fusion Materials Irradiation Facility, IFMIF, consists of two deuteron accelerators at 125 mA in CW and 40 MeV impacting on a flowing lithium screen. It is since 2007, in its Engineering Validation and Engineering Design Activity phase, EVEDA, where the only remaining activity of its broad mandate (that has provided an engineering design [3] of the plant and, among many other technical challenges, validated the stable operation of its lithium loop [4] and its irradiation modules capable of housing above 1000 specimens and characterize structural materials simultaneously in twelve different irradiation capsules independently cooled [5]) is its Linear IFMIF Prototype Accelerator, LIPAc, presently under installation and commissioning in the International Fusion Energy Research Center (IFERC) in Rokkasho (Japan), by European and Japanese laboratories [6]. A full account of the validation activities under IFMIF/EVEDA has already been provided [7].

Collective phenomena driven by space charge forces become the main limitation on achieving high intensity beams. In low β regions, the beam outward radial Coulomb forces prevail over the inward radial Ampere ones, but they mutually cancel in the relativistic domain. Thus, space charge repulsive forces are stronger the lower the beam energy is. The successful operation of LIPAc, with its deuteron beam current of 125 mA in CW at 9 MeV as the output of the first planned cryomodule of IFMIF will validate the 40 MeV required for the Li(d,xn) source [1,8].

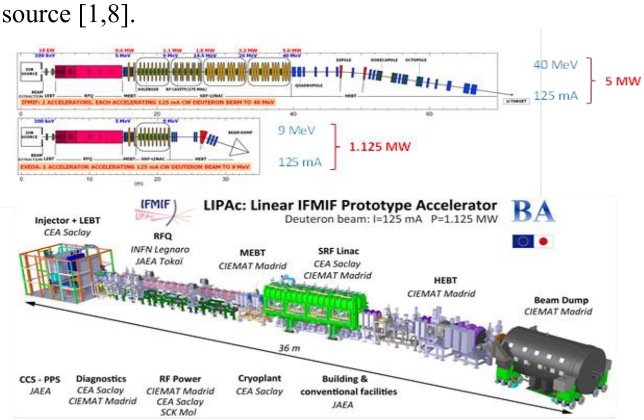


Figure 1: Above - Comparison of IFMIF accelerators and LIPAc, their 1.125 MW beam average power prototype accelerator, matched up to the 1st SRF linac at 9 MeV. Below - breakdown of the contribution for LIPAc.

## IONS INTERACTION WITH MATTER

The physics of heavy ions with matter was first unravelled semi-classically by Bohr in 1913 based on his atomistic model (making use of the impact parameter between target nuclei and impacting particle) [9], and through relativistic quantum mechanics by Bethe in 1932 [10] (making use of the momentum transfer by the particle to the cloud of electrons) being both expressions for the stopping power $-\frac{dE}{dx}$ of the absorber identical for nonrelativistic ions ($\beta \ll 1$), and with the ion only dependent variables its kinetic energy and charge. Among the different possible types of radiation, only ions show a fixed range; a mono-energetic beam of ions traversing matter loses its energy without any change in the number of particles, and eventually all are stopped reaching practically the same depth.

The combination of the logarithmical dependence of the stopping power on the ions speed and their slowing


ISBN 978-3-95450-147-2

down by ionization and excitation of the atoms of the medium (density effects being marginal for light ions) as it penetrates matter, leads to a maximum of the rate of energy loss in proximity to its range. This maximum is called the Bragg peak, however its frequent use as either range in the material or the point of release of ions energy is misleading.

The range $R(E_K)$ of a charged ion at a given kinetic energy, $E_K$, in a given material is the distance it penetrates before coming to rest and it is obtained integrating the inverse of the stopping power. It can be easily shown that for two given ions moving at same velocity the ratio of their ranges follows

$$\frac{R_1(\beta)}{R_2(\beta)} = \frac{z_2^2 M_1}{z_1^2 M_2} \quad (1)$$

where $M_i$ is the ion mass and $z_i$ its charge [11]. This equation allows the straightforward estimation for any ion from the well-known range of protons. The Stopping and Range of Ions in Matter (SRIM) code made available by J.F. Ziegler (***http://www.srim.org/***) has become the worldwide friendly tool for the calculation of the stopping power and range of ions while flying through matter.

## BEAM INDUCED DAMAGES

High current hadron linacs have traversed in recent years the 1 MW beam average power frontier in SNS; next decade beam average powers of 5 MW will be reached in IFMIF-DONES, ESS and MYRRHA [12] and even possibly 15 MW with CADS thanks to its planned 1.5 GeV proton beam at 10 mA CW current. In turn, within few years a beam circulating in HL-LHC will store energies close to 700 MJ, like a Japanese shinkanzen travelling at full speed along the 27 km ring of the LHC. With typically beam radiuses in the order of mm, the power densities handled in case of an accidental mis-steering at these beam powers may cause catastrophic damages in shorter times than any possible fast beam shutdown signal can be executed. Fortunately, this scenario is improbable thanks to the magnets inductive time constants, which are longer than beam fast shutdown times, typically within ~10 μs; however, during commissioning phases and beam injection stages, operational thresholds are to be set before a stable beam is in place.

Beam losses are to be carefully controlled; obviously the higher the current, the more severe potentially becomes their impact. The hands-on maintenance criterion for a proton beam of <1 W/m, or/and $<10^{-4}$ total beam loss remains valid if currents are ~100 mA CW, even with deuterons like in LIPAc despite their substantial stronger activating capability. Though hands-on maintenance should not be impacted by an occasional possible beam mis-handling, in high current accelerators beam halo becomes the main source of beam losses and measures for its minimization and monitoring are to be devised.

The diffusivity, $\alpha = \frac{K}{\rho C_p}$, is the only parameter of the second-order partial differential heat equation that describes the variation of temperature in a given region over time. It is as important for a transient heat conduction scenario as conductivity is for the steady state described by Fourier law. The diffusivity measures how fast a material can carry heat away from a heat source. In processes as fast as a beam mis-steered, what matters is not only the energy content, but the time involved in its diffusion. Diffusivity presents units of $L^2T^{-1}$ and thus, regardless the accurate difficult solution of the heat equation [13], a characteristic thermal diffusion time of the absorbed heat can be easily estimated.

Physics related with a high energy, high current beams accidentally interacting with matter are complex, involving several disciplines. In addition, there is limited practical experience and poor understanding of the behaviour of material exposed to such extreme conditions, where phase transitions involving melting, vaporization and even plasma generation can occur. At the same time, even in absence of changes in material phase, if times constant of heat diffusion are substantially larger than beam heat deposition times, impacted regions can be exposed to high local strains with propagation of severe thermo-elastic stress waves [14] leading potentially to sudden vacuum leaks or damage of structurally weak elements.

Prevention of beam induced accidents drive the design of the Machine Protection System (MPS); however their scarce occurrence makes them be one of the less explored events in accelerators technology. The gap in specialized literature is notorious, with divergence in the analysis approach and occasionally with an unnecessary sophistication. An accurate calculation of beam induced damages, following accelerator structures accidental exposures to the extreme conditions of the planned high intensity hadron facilities is not indispensable given the inherent uncertainties linked both to the exact conditions taking place and to the irradiated materials response. Thus, conservative worst case scenarios defining operational boundaries are suitable as a design operational basis for commissioning and beam injection stages, when MPS is occasionally by-passed and fatal errors can occur.

## LIPAC CASE BRIEF STUDY

LIPAc, with its 9 MeV deuteron beam at 125 mA in CW, will traverse the 1 MW beam average power frontier in 2019. Its 1.125 MW beam average power is equivalent to a full shuttle moving through Japanese national roads. Its beam will fly through the full length of the accelerator in 2.7 μs time.

Four different commissioning Phases are planned, presently at the onset of its Phase B where 5 MeV at 125 mA with 0.1% duty cycle will be extracted at the output of its 9.7 m long RFQ. The 0.625 kW beam average power will be absorbed in a low power beam dump positioned at the output of the MEBT. During Phase C, such a beam will be accelerated to 9 MeV in a SRF Linac formed by 8 HWR operating at 175 MHz; it will only be during Phase D that the duty cycle will be ramped up to CW.

During commissioning phases to minimize accelerator structures exposure to the highly activating deuterons, a proton beam at half nominal current and half nominal energy (which present the same beam perveance [8] and thus, theoretically same space charge physics) will be used. This means that the maximum beam power of protons handled will be four times less than the beam maximum beam power with deuterons. At the same time, at equal β, the range of protons halves the range of deuterons; thus the energy densities accidentally deposited in the accelerator structures during beam operation with deuterons will be double than during beam operation with protons. During commissioning, given that deuteron operation time will be optimized and possibly with higher precautions in place, risks of beam mis-handling are higher with proton operation.

The highest energy densities in case of an accidental scenario are either at injection of the 50 keV proton beam into the RFQ, where the beam size is smallest (~1 mm radius), the current highest (70 mA), and the range shortest (2.7 x $10^{-7}$ m), or with 100 keV and 140 mA deuteron beam. Anyhow, potential damages are limited to the LEBT cone. However, possibly one of the worst case scenarios that one can think of is during Phase C and D with the 4.5 MeV proton beam driven by a mis-operation of the bending magnets in the HEBT, that could cause an air in-rush leak without sufficient time for the fast valve to protect the SRF linac. With a beam radius of ~5 mm at the exit of the SRF linac, proton beam power densities of ~3.5 kW/mm$^2$ would be potentially handled during commissioning phases with 62.5 mA and 4.5 MeV to match the beam perveance of LIPAc. The power densities with deuterons at nominal performance would be ~14 kW/mm$^2$.

Neither heat capacities nor thermal conductivities nor densities are constant with temperature, but since their variation with temperature is not dramatic, the consideration of α as constant from RT to melting is a reasonable assumption. With the equivalent surface area of such flat cylinder, the thermal diffusion characteristic time is typically orders of magnitude longer than the typical time for fast beam shutdowns in the order of 10 µs; thus the consideration of the system as adiabatic is also a good approximation. The increase of $C_p$ with temperature can be also neglected, since this yields a conservative approach for the needed specific energy J/kg to reach fusion temperature from RT conditions. Last but not least, in scenarios were a beam target is regularly impacted, a careful assessment of the potential degradation induced by thermo-elastic stress waves is suitable; however in our exercise of anticipating mitigating measures in case of accidental scenarios, setting operational thresholds on mechanical properties is possibly too severe, but justified under other assumptions [15]. Given the little ranges at LIPAc energies, the consideration of a uniform heat distribution in the disk, though it is not a conservative approach, is adequate.

In conclusion, our assessment considers a deuteron beam at 125 mA and 9 MeV impacting perpendicularly the beampipe under an adiabatic scenario, with a uniform energy release, with constant diffusivity of impacted material and set the operational thresholds at the materials melting point.

## MACHINE PROTECTION SYSTEM OF LIPAC

Our Machine Protection System (MPS) can be defined as the collection of measures implemented to protect LIPAc from beam induced damage. The MPS, together with the beam stop actions, are segregated into fast and slow beam stop methods. Both independent lines are based on a fast FPGA technology, so called “MPS Units”, that gather all the beam stop (rather beam inhibit) signals from the different local subsystems and channel them by means of a multiple AND gate to the final beam inhibit device [16]. In the case of the slow signals, it is a PLC that shuts down the High Voltage Power Supply of the Magnetron RF Generator, while in the case of the fast inhibit mechanism it is a dedicated fast electronic circuit that triggers a crowbar to directly cut the power on the Magnetron RF Generator. This shutdown action is performed in less than 10 µs, which have to be added to the estimated time of the propagation of the inhibit signal through the different MPS Units (approximately another 10 µs) and to the allocated to the detector to activate the shutdown mechanism [17].

An envelope value for the beam fast shutdown in LIPAc is thus 30 µs. Based on the assumptions of the previous section, a conservative estimation of the physics involved if a 5 mm radius 9 MeV 125 mA deuteron beam collides perpendicularly on a stainless steel beam pipe during 30 µs would be as shown in the following table.

Table 1: 5 mm Radius LIPAc Beam on Stainless Steel

| | |
|---|---|
| Power density | ~14 kW/mm$^2$ |
| Range of 9 MeV deuterons in SS | 136 µm |
| Thermal diffusion time | ~ms |
| Energy density released in 30 µs | 270 J/g |

## CONCLUSIONS

Given that the specific energy required to take stainless steel to melting point from RT conditions is >600 J/g, the speed for a beam shutdown of LIPAc within 30 µs is adequate. This is the worst possible scenario with a close to orthogonal collision and an energy density released before beam shutdown <270 J/g. A thorough assessment of all possible mis-operations, including beam halo, based on the approach here explained is under preparation. This will include the niobium HWR superconducting cavities and copper structures potentially exposed to beam halo.

The MPS developed for LIPAc, the validating accelerator prototype, could also be valid for IFMIF’s accelerators since the range of 40 MeV deuterons is substantially bigger than for 9 MeV with around 4 times higher beam power. The ranges of 40 MeV deuterons would become close to bellows typical thickness, what would demand additional careful new considerations.




ISBN 978-3-95450-147-2

## REFERENCES


[1] J. Knaster and Y. Okumura, "Accelerators for Fusion Materials Testing", Reviews of Accelerator Science and Technology Vol. 8 (2015) 115–142

[2] W. D. Cornelius, "CW operation of the FMIT RFQ accelerator", Nucl. Instrum. Methods Phys. Res. B 10/11, 859–863 (1985)

[3] J. Knaster et al., "The accomplishment of the engineering design activities of IFMIF/EVEDA: The European–Japanese project towards a Li(d, xn) fusion relevant neutron source, Nucl. Fus. 55, 086003 (2015)

[4] F. Arbeiter et al., "Design description and validation results for the IFMIF High Flux Test Module as outcome of the EVEDA phase", Nuclear Materials and Energy (2016)

[5] H. Kondo et al., "Validation of IFMIF liquid Li target for IFMIF/EVEDA project", Fusion Eng. Des., 96–97 (2015) 117–122

[6] P. Cara et al., "The Linear IFMIF Prototype Accelerator (LIPAc) design development under the European-Japanese collaboration", these proceedings

[7] J. Knaster et al., "IFMIF: overview of the validation activities", Nucl. Fusion 53 (2013) 116001

[8] F. Scantamburlo et al., "LIPAc, the 125 mA/9MeV CW deuteron IFMIF's prototype accelerator: What lessons have we learnt from LEDA?", Proc. IPAC 2014 (Dresden)

[9] N. Bohr, "On the Constitution of Atoms and Molecules", Philos. Mag. 26, 1 (1913)

[10] H.A. Bethe; "Bremsformel für Elektronen relativistischer Geschwindigkeit", Z. f. Physik 76 (1932) 293

[11] A.N. Kalinovski et al., "Passage of high-energy particles through matter", American Institute of Physics 1989

[12] J. Wei, "The very high intensity future", in Proc. IPAC 2014 (Dresde)

[13] W. Kalbreier et al., "External targets at the SPS", CERN LAB II/BT/74-l

[14] A. Dallocchio, "Study of thermo-mechanical effects induced in solids by high energy particle beams analytical and numerical methods", CERN-THESIS-2008-140

[15] H. Takei and H. Kobayashi, "Derivation of Simple Evaluation Method for Thermal Shock Damage on Accelerator Materials Caused by Out-of-control Beam Pulses and its Application to J-PARC", Journal of Nuclear Science and Technology, Vol. 42, No. 12, p. 1032–1039

[16] K. Nishiyama et al., "FPGA utilization in the accelerator interlock system (about the MPS development of LIPAc)", Proceedings of PCaPAC2014 (Karlsruhe)

[17] A. Marqueta et al., "Machine Protection and Safe Operation of LIPAc Linear Accelerator", these proceedings