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SUMMARY OF WORKING GROUP E: INSTRUMENTATION AND INTERCEPTING DEVICES

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Abstract

The contribution summarizes the talks and discussion of Working Group E related to Instrumentation and Intercepting Devices. The discussion topics are summarized in addition.

INTRODUCTION

The HB conference brings together experts from beam dynamics, operation, and instrumentation, providing an optimal platform for discussing topics relevant to high-brightness beams. Modeling of accelerator performance is the basis for any facility. Beam instrumentation should fulfill the appropriate requirements for operation and dedicated machine studies; however, some device limitations might exist, which must be considered for a correct data interpretation, calling for an experience exchange between experts with different application perspectives. Related to the high beam brightness, non-invasive instrumentation is required to monitor undisturbed beam parameters; those instruments have been developed in the last few years as an alternative to traditional intercepting devices. Generally, intercepting devices are used not only for diagnostics but frequently for collimation, injection devices, and, naturally, as targets. Material modifications and handling are essential issues to be discussed at the HB conference. Near targets and further loss locations, the thermal load, radiation level, and activation can be high, leading to material modifications.

The talks within Working Group E (WGE) address those topics and are briefly summarized; for more details, the reader is referred to the individual conference publications.

SESSION 1: BEAM INSTRUMENTATION IN A HIGH RADIATION ENVIRONMENT

The first session of WGE was comprised of four talks focused on beam instrumentation in high-power accelerator target facilities, both currently operating and future facilities. The talks represented the unique intersection of high-power targetry and high-power beam instrumentation, where extremely high radiation background, radiation damage to materials, and thermal energy deposition combine to challenge both the function and the lifetime of instrumentation. The first and third talks highlighted ongoing beam and target health monitoring instrumentation at high-power neutrino target facilities (NuMI at Fermilab and T2K at J-PARC). The second talk presented an upgrade to a passive cavity beam current monitor that has successfully operated under heavy heat load and radiation since 2015 at PSI. The final presentation showed plans for the flowing liquid lithium target diagnostics for the future 5 MW IFMIF-DONES facility. The session prompted several discussions both in the question periods and during the break, where participants discussed common issues, compared techniques, and potential future collaboration.

"Radiation hardened Beam Instrumentations for multi-Mega-Watt Beam Facilities" by Katsuya Yonehara, Fermilab

This talk included a brief summary of the 2022 mini-workshop (virtual) held as a subgroup of the Accelerator Frontier Technology R&D group from Snowmass'21, "Rad Hard Beam Instrumentation Workshop", and an overview of the instrumentation tools used to monitor beam and target health at the NuMI beamline at Fermilab. Highlights include a unique "Target Position Thermometer" (TPT), which gives a measurement of beam profile and position on target at high intensity (up to 1 MW in operation). Drawbacks of the TPT include the time to reach thermal equilibrium (several minutes) and the necessity to use complicated analysis tools to calibrate and extract good data. Another highlight is the results of using Machine Learning to interpret noisy muon monitor data and extract meaningful beamline parameters, such as horn current and beam intensity with accuracy below ±0.1%.

"Improvement Design of a Beam Current Monitor based on a Passive Cavity under Heavy Heat Load and Radiation" by Jilei Sun, PSI

This talk focused on the improvements made to the design of a radiation-hard passive cavity beam current monitor, which has been in use at PSI since 2015. The upgrades to the monitor, termed "MHC5", include changing the resonator cavity material from aluminum to graphite to reduce resonance shifts from thermal expansion. The design is self-compensating, using an aluminum shim that expands to compensate for temperature increase. Other upgrades included four beam position pick-ups and several remote handling features to ease replacement and reduce the dose to a worker. Lab tests with the new design will take place early in 2024.

"Beam Diagnosis and Soundness Check System for Neutrino Production Targets" by Megan Friend, KEK

This talk presented an overview of the beam and target health instrumentation used at both Fermilab's NuMI neutrino beamline (see the first talk above) and J-PARC's T2K neutrino beamline. Unique instruments at T2K include an Optical Transition Monitor just upstream of the target and a new prototype Beam Induced Fluorescence (BIF) monitor. The BIF description generated quite a few discussion points to identify possible additional applications at other

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facilities. The talk also focused on using the neutrino near-detector to monitor the target's health with a vivid example of a degraded graphite target at NuMI being detected by the reduction of the neutrino event rate over several months of running.

"Challenges of Target and Irradiation Diagnostics of the IFMIF-DONES Facility" by Claudio Torregrosa, UGR

The final talk of the first WGE session presented the target design for the IFMIF-DONES facility, an accelerator-based fusion-like neutron source for the qualification of materials for DEMO. The facility, under design at the University of Granada, consists of a 5 MW, 4 MeV Deuteron LINAC, a liquid lithium jet target, followed by irradiation chambers for the material specimens. The liquid lithium jet, or curtain, must have its thickness maintained above the nominal 25 mm within a few millimeters or the supporting back-plate will melt within tens of milliseconds. Diagnostics to measure the beam footprint on the target surface and the thickness of the lithium will be crucial to stable and safe operations. Radiation dose local to the target chamber is predicted to be over 100 MGy/fpy, presenting a challenge to both instruments. Current plans are to use optical (LiDAR) or RF (mmWave radar) techniques to monitor lithium jet thickness and a combination of OTR.

SESSION 2: MATERIAL PROPERTIES UNDER HIGH IRRADIATION

The second session of WGE was comprised of four talks focused on beam intercepting devices (BID) that are typically used in the accelerator facility (as opposed to the target facility), such as collimators, beam dumps, and charge strippers. The majority of the talks represented applications of high-power targetry concepts within the accelerator machine, where losses have to be kept to a minimum while still protecting the accelerator components from the high-intensity beams. The first talk presented an overview of BID at four institutions (CERN, Fermilab, J-PARC, and ORNL) and concentrated on targets, collimators, and dumps. The second talk introduced the concept of crystal collimation and presented results of simulations of associated beam loss reductions in CERN's LHC with validating BLM benchmark measurements. The third talk focused on the world's first demonstrated charge stripping using a liquid lithium jet at FRIB. The final presentation described the use of optical pyrometry to monitor the temperature of diamond stripping foils at the SNS. The session prompted several discussions concerning the use of crystal collimation/extraction and pyrometers for other accelerator BID applications.

"Beam Intercepting Device Challenges for High-Intensity Accelerators - Global Perspective" by Antonio Perillo Marcone, CERN

The first speaker in the second session presented several examples of BID from around the globe. The talk touched upon the common challenges across the applications, such as material specification/characterization/simulation, instrumentation to monitor performance and protect the facility, high heat-flux cooling, operation in inert and vacuum environments, beam line impedance, and radiation damage effects. Highlights included the large, 680 MJ pulse-capable, LHC beam dump at CERN, the liquid mercury spallation neutron targets at SNS-ORNL and MLF-J-PARC, the 1.3 MW neutrino target planned for LBNF at Fermilab, and the new CERN LHC collimators.

"Evaluation of Power Deposition in HL-LHC with crystal-assisted Heavy Ion Collimation" by Volodymyr Rodin, CERN

The second talk focused on evaluating a new collimation system for reducing potential losses (and associated magnet quenches) in downstream components of the LHC at CERN. Specifically, results of extensive FLUKA simulations showed a reduction in losses to the LHC betatron cleaning insertion devices using a crystal collimation system. After introducing the audience to the need for a collimation system to control quench-causing losses to superconducting magnets in the LHC, the crystal channeling concept, and the LHC beam loss monitoring system, the speaker described the simulation process utilized to predict the losses in downstream sections of the LHC. Results of the benchmarking indicated good agreement in most areas, with a factor of three overestimation in other areas and one area of overprediction of a factor of ten. Nonetheless, the results showed that for Beam 2, the crystal-assisted collimation system reduced losses to tolerable levels in the downstream dipole magnets.

"Operational Performance with FRIB Liquid Lithium and Carbon Charge Strippers" by Takuji Kanemura, FRIB

The third talk in the second session of WGE presented the operational experience with the liquid lithium and rotating carbon foil charge strippers at FRIB. Deterioration of carbon foil strippers due to energy deposition and radiation damage has led FRIB to only plan to use carbon foils, even with rotation, to an average energy deposition density of 2 MW/cm^3 (associated with 10 kW of uranium ion beam on target). Since the ultimate operational goal of the new facility is 400 kW of uranium ion beam on target, a liquid lithium charge stripper capable of 58 MW/cm^3 has been developed and commissioned at FRIB. Beams of ^{36}Ar, ^{48}Ca, ^{124}Xe, ^{198}Pt, and ^{238}U have been successfully stripped and accelerated. The talk includes details of the lithium jet target system and recent issues with impurities affecting lithium film stability.

"Two-Dimensional Temperature Measurements of Nanocrystalline Diamond Stripper Foils at High-Intensity Hydrogen Ion Beams at SNS" by Abdurahim Rakhman Oguz, ORNL-SNS

The last talk of the session reported on progress in improving a relatively new technique to measure and monitor the thermal performance of nanocrystalline diamond stripper foils at the SNS (ORNL). The use of two-color optical pyrometry rather than the usual IR thermal camera has the main advantage of independence of the measurement from

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the emissivity of the surface, given that the two wavelengths are close enough to each other to cancel in the ratio. The talk presented results from 2022, where temporal temperature profiles were shown to be proportional to beam power once foils were conditioned. Improvements in a new optical set-up were made in 2023, resulting in higher resolution images and increased light collection efficiency. Data was taken and shown in the presentation but is still under analysis to determine uncertainties and complete calibration studies.

SESSION 3: NON-INVASIVE BEAM INSTRUMENTATION

The third session concerned the non-invasive diagnostics of important beam parameters at LINAC and synchrotrons. Non-invasive methods are of great relevance for LINACs to enable the observation of the entire beam pulse without destroying the instrument. Due to the low signal strength, achieving the required accuracy and time resolution is challenging. The first talk presented a comprehensive overview of various transverse profile measurement techniques. The second talk reported impressive improvements in determining various parameters at the CERN synchrotron LHC without beam excitation. The method is based on a high-performance evaluation of Schottky spectra. The third talk reports on modifications of the tune spectrum performed at Heidelberg Ion Therapy and GSI synchrotron for beams stored close to a third-order resonance motivated by slow extraction investigations. The subject of the fourth talk is shower simulations and measurements from the internal beam dump at CERN synchrotron PS, which are compared to measurements. The session promoted discussion on instrument performance, achievable parameters and time resolution, and the applicability of online display for regular operation.

"Non-Invasive Transverse Profile Invasive Transverse Profile Measurement Methods" by Randy Thurman-Keup, Fermilab

In recent years, significant progress has been achieved concerning four different non-invasive methods for transverse profile measurements, summarized in an overview contribution. Two methods are based on the ionization or excitation of the residual gas, namely Ionization Profile Monitors (IPM) and Beam Induced Fluorescence (BIF) monitors. Relevant examples are depicted, e.g., turn-by-turn measurement for injection optimization at the J-PARC synchrotron. BIF monitors deliver less signal strength but offer a compact installation. Using a gas jet, the signal strength is increased; the applicability has recently been demonstrated at CERN LHC. The deflection of a transverse-oriented electron beam by the space charge of the stored proton beam is used at Fermilab and SNS synchrotrons. An outlook for ion beam deflection is discussed. For H^--beams, photo-detachment can be applied by a scanning transverse laser beam accompanied by detecting the released electron. Measurements with high time resolution determine possible profile variations at the SNS LINAC. The device is in regular operation at SNS. At CERN LINAC4, the spatial-resolved detection of the neutral H^- atom delivers a non-invasive transverse emittance measurement.

"Extraction of LHC Beam Parameters from Schottky Signals" by Kacper Łasocha, CERN

Schottky signal analysis is based on observing the bunched beam frequency spectrum. The talk concerns impressive improvements realized at CERN LHC. No beam influence is required to determine parameters such as tune, chromaticity, momentum spread, synchrotron frequencies, and amplitude distributions with time resolutions down to the second level. The progress is based on a detailed evaluation of the Schottky spectrum with innovative fitting methods. The sidebands related to the incoherent signal generation contain the relevant information. Disturbances by the coherent signal lines can now be separated by the fitting methods, leading to a precision that traditional beam excitation methods can hardly achieve. Further developments include the effect of beam impedance and higher-order magnetic field contributions. The talk shows impressive examples of the applicability even under unfavorable beam conditions.

"Spectral Modification for BTF-based Tune Measurements of Beam close to a 3rd-order Resonance" by Edgar Cristopher Cortes Garcia, GSI and HIT

The beam's tune distribution is of mutual importance for controlling and improving slow extraction by a third-order tune resonance. Beam Transfer Function (BTF) measurements were performed at the therapy synchrotron HIT and GSI SIS18. Related to the non-linear resonance-driving sextupole fields, a significant modification of the BTF spectrum is observed, leading to a double-peak structure. In particular, the dependence on the sextupole strength was investigated experimentally. As model calculations show, the spectra could be explained by the non-linear movement described by the Kobayashi Hamiltonian. Detailed tracking simulations using XSuite lead to high correspondence to the measurement. The modeling of such non-linear behavior is by itself a significant progress. Moreover, the improvement of slow extraction based on the gained knowledge was demonstrated at both facilities.

"Shower Simulations for the CERN Proton Synchrotron Internal Dump and Comparison with Beam Loss Monitor Data" by Samuel Niang, CERN

The LHC injector upgrade provides higher beam currents, which requires an improved projection scheme. In case of an emergency, the beam is kicked towards a movable internal beam dump at CERN PS made of water-cooled graphite and copper alloy. The thermo-mechanical limitations and resulting activations in the dump and the downstream accelerator components were simulated by FLUKA. For validation, detailed experimental machine studies were performed to determine the beam loss monitor signals downstream of the dump and are used to estimate the energy deposition at sensitive accelerator components. The experimental and simulated doses are compared,

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showing a reasonable correspondence. Beam parameters such as close orbit distortions must be considered to improve the agreement. In general, this talk shows that precise measurements and simulations are required to operate a protection system reliably.

SESSION 4: EXPERIENCES AT HIGH-POWER FACILITIES

The last session of WGE comprised three invited presentations from the European Spallation Source (ESS) and linear IFMIF prototype accelerator (LIPAc) facilities regarding development with ongoing beam commissioning and from J-PARC on the high-intensity slow extraction (SX) user operations being conducted there. The initial two talks extensively covered beam interceptive monitors (FC, Slit, and SEM-Grid) utilized in the initial beam commissioning, emphasizing system reliability and safety for high-intensity beam measurements. The final presentation discussed a system aimed at reducing residual dose at the septum magnet of SX by integrating a beam scatterer into the extracted beam. All these systems leverage the interaction between the beam and the target material, prompting discussions on evaluating safety against the heat load caused by high-intensity beam irradiation.

"The Beam Destinations for the Commissioning of the ESS high-power normal conducting LINAC" by Elena Donegani, ESS

Since 2018, the commissioning of the normal conducting LINAC section has progressed through stages:

- Ion source + LEBT
- RFQ + MEBT
- DTL1 + beam dump
- DTL4 + beam dump.

In stages 1 and 2, FCs are installed in LEBT and MEBT, and shields are added around FCs and operated as beam dumps in stages 3 and 4. Notably, beam tuning using FCs, a beam interceptive device, occurred up to DLT4 at the early stage of beam commissioning. In particular, the evaluation of heat load is essential for these devices. In addition, the beam dump is rapidly dismantled when the latter stage acceleration cavity is ready to install. The presentation addressed challenges and solutions regarding workflow strategy from design to actual operation, including beam dump disassembly. Design, performance, and residual dose evaluation during beam dump dismantling were reported.

Questions and discussions:

Q1) What is the measurement accuracy of each FC and beam transmission?

A1) The FC achieves cross-calibration using upstream beam current monitors, with a required current measurement accuracy of 0.1 mA. The three upstream FCs in front of the devices are equipped with repeller electrodes and a bias mechanism for secondary electron suppression. Nonetheless, the DTL4 FC cannot withstand a repeller installed due to space constraints, leading to lower accuracies of less than 0.1 mA.

Q2) Is the signal ringing at the rise and fall of the time signal due to the beam or electronics?

A2) Signal ringing is attributed to the 60 m cable from the FC sensor to the electronics.

Q3) Why choose Graphite as the material for FC?

A3) While LEBT's FC utilizes copper, graphite is chosen for rapid heat dissipation because other materials exhibit issues such as mechanical deformation and high temperatures that exceed the melting point.

Q4) Do you think it is possible to confirm the validity of thermodynamic simulation results?

A4) The temperature undergoes an instantaneous shift from room temperature to 1000 °C. Even with a rapidly responsive temperature sensor, the measurement remains superficial and localized. This limitation arises due to the gradual change in surface temperature, posing challenges in precisely capturing dynamic variations in the core temperature.

Q5) Are vibrations expected in the simulation?

A5) We could only confirm thermal stress and the absence of any permanent damage.

C5) Validating the simulation is crucial, and a sufficient number of beam pulses, along with thermal loading, generate a dynamic stress wave detectable on an external surface as vibration. This vibration measurement serves as a means to assess the accuracy and reliability of the simulation.

"High Beam Current Operation with Beam Diagnostics at LIPAc" by Saerom Kwon, Rokkaso/QST

LIPAc is presently undergoing commissioning in stage B+, where the beam from RFQ is directed straight to the beam dump (BD). In the subsequent commissioning stages, C and D, the superconducting RF cavity will be introduced and fine-tuned to facilitate the delivery of a continuous wave deuteron beam with a beam energy of 9 MeV and a current of 125 mA. The presentation covered results of the beam diagnostic system, including non-interceptive devices (CTs, BPM, BLM, IPM, and BFM) and interceptive devices (SEM-Grids and Slit). Detailed reports on monitor specifics, gain calibration, and emittance measurement methods were presented.

Questions and Discussions:

Q1) How do you calibrate the wire gain of the SEM-Grid monitor?

A1) The beam emittance is measured under certain conditions, determining the gain of each wire to reproduce beam position and image in grids.

Q2) Radiation control measures?

A2) Various neutron detectors and activation foils are installed along the beamline to measure activation levels and determine the adequacy of residual dose post-beam stoppage.

Q3) The beam halo component at the outer edge of the beam has been discussed to exhibit different properties than the center of the beam. Are you considering any special measures for the beam halo component to improve beam transmission efficiency?

A3) I am not aware of any specific measures regarding the beam halo.

Q4) Is there a system to detect a SEM grid wire break?

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A4) Initially, a wire break detection system was in place; however, it has been discontinued. In the event of a broken wire, it becomes necessary to open the chamber and conduct a manual examination.

Q5) Regarding the emittance measurements using Slit and SEM-Grid, which of the two requires careful handling in the vicinity of the super-conducting (SC) LINAC?

A5) Our preference is not to use these monitors near the SC LINAC. However, acknowledging their robust capabilities, I personally advocate their utilization in the 4th commissioning phase when the SC LINAC is expected to be installed.

Q6) What accelerometers are installed in the BD?

A6) This refers to an electric vibration sensor affixed to the cartridge of the beam dump (BD). When the beam dump experiences elevated temperatures, the vibrations in the cooling water bubbles are detected by the accelerometer. Notably, this sensor is highly sensitive to vacuum conditions and may have a potential correlation with radiation, such as neutrons.

"Devices for high-efficiency Slow Extraction at J-PARC Main Ring" by Ryotaro Muto, J-PARC/KEK

By 2021, J-PARC MR achieved user operation with 64 kW beam power extracted slowly to the hadron experimental facility, achieving an extraction efficiency of approximately 99.5%. This efficiency results from the electrostatic septum, dynamic bump scheme, SX collimator, and SX septum magnets. The presentation detailed how the electrostatic septum and the dynamic bump system work. Since the electrostatic septum is a beam interceptive device, it is inevitable that the downstream device will be activated by scattered particles. A collimator device and the newly introduced diffuser system, acting as a scatterer in front of the electrostatic septum, were explained, with results from recent beam tests presented.

Questions and Discussions:

Q) How do the diffuser and collimator contribute to beam impedance?

A) Diffuser impedance measured; contributions to impedance from both diffuser and collimator are negligible.

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